X-Ray Studies of Evolved Supernova Remnants

Satoru Katsuda

Department of Earth and Space Science, Graduate School of Science, Osaka University
1-1 Machikaneyama, Toyonaka, Osaka, 560-0043, Japan

This Thesis Submitted to Department of Earth and Space Science, Graduate School of Science, Osaka University on January 2008 in Partial Fulfillment of the Requirement for the Degree of Doctor of Philosophy in Physics
Abstract

We present X-ray studies of the brightest evolved supernova remnants (SNRs) in the X-ray sky, i.e., the Vela SNR, the Puppis A SNR, and the Cygnus Loop. We focus on elemental distributions and compositions in the three SNRs which are revealed by our spatially resolved spectral analyses.

Using XMM-Newton data, we perform X-ray spectroscopy for Vela shrapnels A, D, and E which were identified as explosion fragments protruding beyond the primary blast wave of the Vela SNR (Aschenbach et al. 1995). We find/confirm highly non-solar metal-abundance ratios in the three shrapnels: Si/O is $\sim$10 times the solar value in the shrapnel A; O/Fe, Ne/Fe, and Mg/Fe are $\sim$5, $\sim$10, and $\sim$10 times the solar values, respectively in the shrapnel D; Ne/Fe is $\sim$6 times the solar value in the shrapnel E. These facts strongly supports the idea that they originate from explosion ejecta. From our spatially resolved spectral analyses for the shrapnels A and D, we find that the temperature increases toward the leading edge in both of the two shrapnels, which is in stark contrast with the temperature structures generally seen behind the shock front of SNRs. We also find that the ejecta material are well mixed with the swept-up interstellar medium (ISM) in the shrapnel A, whereas such mixing has not yet occurred in the shrapnel D.

We analyze five XMM-Newton observations nearly covering the entire Galactic Oxygen-rich SNR, Puppis A. We generate “equivalent width” (EW) images for the elements of O, Ne, Mg, Si, S, and Fe. The EW images of all elements but Fe reveal regionally enhanced line features which are most likely caused by overabundance of these species. EWs for Si and S are enhanced only in a relatively compact region in the northeast (NE) of the remnant, which suggests asymmetric ejection of these elements during the SN explosion itself. In addition, we also find a knotty ejecta feature with blue-shifted emission lines in the NE portion of Puppis A. On the other hand, proper motion of the stellar remnant behind the SN explosion was recently measured to be directed toward the southwest with a high velocity (Hui & Becker 2006b; Winkler & Petre 2007). We suggest that the metal-rich ejecta in the NE portion of Puppis A disclosed here are parts of the recoiled materials to the high velocity stellar remnant according to momentum conservation.

We have observed the Cygnus Loop in eleven pointings by Suzaku and seven pointings by XMM-Newton. Extended low-energy coverage of Suzaku, for the first time, allow us to detect emission lines from highly-ionized Carbon and Nitrogen from the Cygnus Loop. Our spatially resolved spectral analyses reveal that hot ($\sim$0.5 keV) metal-rich ejecta, surrounded by cool ($\sim$0.2 keV) swept-up matter, distribute inside a large area of the Cygnus Loop. Si, S, and Fe ejecta turn out to be distributed more in the south than in the north of the Cygnus Loop by a factor of $\sim$2. The degree of the ejecta asymmetry is
consistent with that expected by recent supernova explosion models (e.g., Burrows et al. 2007). In addition to the ejecta distributions, we find abundance inhomogeneities in the NE rim of the Cygnus Loop where the swept-up matter dominates the X-ray emission: the values of metal abundances in the northern outermost region in the NE rim are consistent with the solar values within a factor of $\sim$2, whereas they are depleted by a factor of $\sim$5 in the rest of the region. The abundance inhomogeneity is also confirmed from our follow-up spectral analysis with Chandra data. Judging from the measured abundances, we suggest that the plasma in the abundance-enhanced region originates from the ISM. On the other hand, the origin of the abundance depletion in the rest of the region still remains as an open question.
Contents

1 Introduction 1

2 Review 3
  2.1 Supernova (SN) .......................................................... 3
    2.1.1 Explosion mechanism ........................................... 5
    2.1.2 Nucleosynthesis .................................................. 12
  2.2 Supernova Remnant (SNR) .............................................. 15
    2.2.1 Shock Wave ...................................................... 15
    2.2.2 Evolution of SNRs ............................................... 16
    2.2.3 Classification of SNRs .......................................... 21
  2.3 Non-Equilibrium in Shock-Heated Plasmas .......................... 23
    2.3.1 Thermal Non-Equilibrium ...................................... 23
    2.3.2 Non-Equilibrium Ionization ................................... 24
  2.4 X-Ray Emission from SNR ............................................ 27

3 Instruments 31
  3.1 Suzaku ................................................................. 31
    3.1.1 Overview of the Satellite ................................... 31
    3.1.2 X-Ray Imaging Spectrometer (XIS) .......................... 32
  3.2 XMM-Newton .......................................................... 35
    3.2.1 Overview of the Satellite ................................... 35
    3.2.2 European Photon Imaging Camera (EPIC) .................... 36
  3.3 Chandra ............................................................... 41
    3.3.1 Overview of the Satellite ................................... 41
    3.3.2 Advanced CCD Imaging Spectrometer (ACIS) ............... 42

4 Vela SNR 45
  4.1 Previous Results .................................................. 45
    4.1.1 Discovery of Shrapnels ...................................... 45
CONTENTS

4.1.2 Shrapnel A ......................................................... 46
4.1.3 Shrapnel D ......................................................... 48
4.2 Observations and Data Reductions ................................. 50
4.3 Shrapnel A .......................................................... 51
  4.3.1 Image Analysis .................................................. 51
  4.3.2 Spectral Analysis .............................................. 52
  4.3.3 Discussion and Conclusion ..................................... 61
4.4 Shrapnel D .......................................................... 64
  4.4.1 Image Analysis .................................................. 64
  4.4.2 Spectral Analysis .............................................. 65
  4.4.3 Discussion ...................................................... 73
  4.4.4 Conclusion ..................................................... 75
4.5 Shrapnel E .......................................................... 77
  4.5.1 Analysis ........................................................ 77
  4.5.2 Discussion and Conclusion ..................................... 80

5 Puppis A SNR 83
  5.1 Previous Results .................................................. 83
  5.2 Observations and Data Reduction ................................. 84
  5.3 Image Analysis .................................................... 87
  5.4 Spectral Analysis ................................................. 91
  5.5 Discussion ........................................................ 98
    5.5.1 Overall Structures ........................................... 98
    5.5.2 Mass and Origin of the Ejecta Feature ...................... 99
  5.6 Conclusion ....................................................... 102

6 The Cygnus Loop 103
  6.1 Previous Results .................................................. 103
  6.2 Observations and Data Reductions ................................. 105
    6.2.1 Suzaku Observations ......................................... 105
    6.2.2 Chandra Observations ....................................... 105
    6.2.3 XMM-Newton Observations ................................... 109
  6.3 Northeastern Rim ................................................ 111
    6.3.1 Suzaku View ................................................ 111
    6.3.2 Chandra View ............................................... 123
  6.4 Radial Structures ................................................ 136
    6.4.1 XMM-Newton View ............................................ 136
6.4.2  *Suzaku* View ............................................. 152

7  Discussion ............................................. 161
   7.1  Global Ejecta Distributions in SNRs and Neutron Star Recoil .......... 161
      7.1.1  Galactic O-rich SNRs .................................. 161
      7.1.2  The Cygnus Loop ..................................... 167
   7.2  Ejecta Knots ........................................... 168
      7.2.1  Observational Point of View ............................. 168
      7.2.2  Theoretical Point of View .............................. 170

8  Summary and Conclusions ..................................... 173
List of Tables

2.1 Explosive nucleosynthesis (Thielemann et al. 1996). 13
3.1 Suzaku XIS characteristics - an overview 33
3.2 XMM-Newton EPIC characteristics - an overview 39
3.3 Chandra ACIS characteristics - an overview 44
4.1 XMM-Newton Observations of the Vela Shrapnels 50
4.2 Spectral-fit parameters 53
4.3 Spectral-fit parameters 68
4.4 Spectral-fit parameters 80
5.1 XMM-Newton observations of the Puppis A SNR 85
5.2 Energy bands used for generating the EW images 88
5.3 Spectral-fit parameters in the two regions shown in Fig. 5.4 (c) 94
5.4 Redshift values ($\times10^{-3}$) 97
5.5 Line center energies of spectra from regions shown in Fig. 5.4 97
5.6 Densities (cm$^{-3}$) and masses ($\times10^{-4}$ M$_{\odot}$) in the two regions in Fig. 5.4 (d) 100
6.1 Observations of the Cygnus Loop and Lockman Hole 107
6.2 Spectral-fit parameters for the cells 1 and 2 114
6.3 Mean elemental abundances in Region A and the rest of the region 119
6.4 Spectral-fit parameters for the example two spectra in Fig 6.13 127
6.5 Spectral-fit parameters 141
6.6 Spectral-fit parameters 144
6.7 Calculated VEM ($= \int n_e n_H dV$) of the Cygnus Loop ejecta 149
6.8 Spectral-fit parameters for the example spectra 155
6.9 Summary of VEM ($= \int n_e n_i dV$ for the ejecta component in units of $10^{52}$ cm$^{-3}$) in each FOV 157
7.1 SNRs with FMKs and Features of the FMKs 168
7.2 Ejecta masses in nucleosynthetic models .......................... 169
List of Figures

2.1 Classification scheme of SNe based on optical spectra (Harkness, Wheeler 1990). ................................................................. 4

2.2 Comparison of the mean blue light curves for SN I, II P and II L (Doggett and Branch 1985). ...................................................... 4

2.3 SN1987A observed with HST [Credit: NASA and Kirshner, R. (Harvard-Smithsonian Center for Astrophysics)]. The ring is material from the stellar wind of the progenitor that were ionized by the ultraviolet flash from the supernova explosion, and consequently began emitting in various emission lines. The elliptically distributed ejecta which are heated by radioactive $^{44}$Ti can be seen in the central portion of the ring. ............................................. 7

2.4 Entropy color map (Burrows et al. 2007) for the 20 M$_\odot$ model (Woosley et al. 2002). Time after bounce is 1.4205 sec. The vector length has been saturated at a value of 10000 km sec$^{-1}$, relevant only for the infalling matter exterior to the shock. ....................................................... 9

2.5 Upper: H$\alpha$ image (observed by Palomer Observatory) showing a bow-shock nebula produced by the high-velocity pulsar B2224+65. Left-lower inset shows the expanded H$\alpha$ image obtained by HST. Lower: X-ray image (observed with ROSAT HRI) of the entire Puppis A SNR. The inset shows the position of the neutron star observed with Chandra X-ray observatory; left in 1999 and right in 2005 (Winkler & Kirshner 2007; or http://www.asahi.com/special/space/TKY200712060042.html). ........ 10

2.6 Abundance distribution against the enclosed mass, $M_r$, after the core-collapse explosion of 20 M$_\odot$ star (Thielemann et al. 1996). ............... 14

2.7 Relative abundances to Oxygen in the total ejecta for various nucleosynthetic models: Type-Ia (W7 and CDD1 model) data from Iwamoto et al. (1999), while core-collapse (whose progenitor masses are 13, 15, 20, and 25 M$_\odot$) data from Thielemann et al. (1996). .............................. 14
2.8 Evolution of the forward shock, the contact discontinuity, and the reverse shock radius with time. The dashed line shows the outgoing weak shock wave caused by the reflection of the reverse shock wave at the center (Wang & Chevalier 2002). .................................................. 18

2.9 The radial profiles for the velocity, density, pressure (upper), and temperature (lower) in Sedov similar-solution. All the parameters are normalized at the values just behind the shock front. ........................................ 19

2.10 Temperature dependence of the cooling coefficient for an optically-thin thermal plasma with solar abundances. The individual contributions from several elements are also shown as dashed lines. This plot is calculated from APEC model in XSPEC v12.3.1 using ccurve_create.tcl script provided by Strickland (2007). ...................................................... 20

2.11 Chandra broad band (0.3–10keV) X-ray images with radio contours; VLA 1.375 GHz for (a) Tycho’s SNR, VLA 21 cm for (b) 3C58 and (c) G11.2-0.3, and VLA 1.4 GHz for (d) W44. These images are taken from Kawasaki Ph.D. thesis (2003). .................................................. 21

2.12 Compilation of current electron–ion equilibration measurements at SNR shocks (Rakowski 2005). ............................................................. 24

2.13 Ion fractions for O (upper-left), Ne (upper-right), Mg (lower-left), and Si (lower-right) at the CIE condition as a function of the electron temperature. Thick lines are responsible for ions with closed-shell structures. ................. 26

2.14 Emissivities from ions in various ionization states for O, Ne, Mg, and Si. 28

2.15 Center energies of triplets from He-like ions for O, Ne, Mg, and Si plotted in the $kT_e$–log($\tau$) plane. ......................................................... 29

2.16 Continuum spectrum from plasma at $kT_e = 0.28$ keV and log($\tau$) = 11.5. Free-free, free-bound, two-photon decay, and the total emission are shown as dashed, dash-dotted, dotted, and solid lines, respectively. ............... 30

3.1 Left: Side view of Suzaku with internal structures after EOB deployment. Right: Schematic view of the Suzaku satellite in orbit. Both solar paddles and the EOB are deployed. .................................................. 32

3.2 Left: The picture of CCD chip. Right: Schematic view of the XIS CCD (top view). The CCD consists of four segments (A, B, C, and D), each with a dedicated read-out node. .................................................. 33

3.3 Effective area of one XRT+XIS system, for both the FI (XIS0, 2, 3) and BI (XIS1) CCDs. ................................................................. 34
3.4 Sketch of the XMM-Newton payload. The mirror modules, two of which are equipped with Reflection Grating Arrays, are visible at the lower left. At the right end of the assembly, the focal X-ray instruments are shown: The EPIC MOS cameras with their radiators (black/green “horns”), the radiator of the EPIC pn camera (violet) and those of the (light blue) RGS detectors (in pink). The OM telescope is obscured by the lower mirror module.

3.5 Left: The CCDs of one of the MOS cameras in the cryostat. Right: The CCDs of the pn camera. The picture shows the twelve chips mounted and the connections to the integrated preamplifiers.

3.6 A rough sketch of the field of view of the two types of EPIC camera; MOS (left) and pn (right). The shaded circle depicts a 30′ diameter area. For the alignment of the different cameras with respect to each other in the XMM-Newton focal plane refer to the text.

3.7 The net effective area of all XMM-Newton X-ray telescopes, EPIC and RGS.

3.8 Expanded view of the Chandra flight system, showing several subsystems (Weisskopf et al. 2002).

3.9 The ACIS CCD focal plane. The ten CCD detectors are arranged in two subarrays.

3.10 Locations and orientations of chips chosen for ACIS flight focal plane.

3.11 Comparison of the on-axis effective areas for observing a point source (integrated over the PSF) of the HRMA HRC-I, the HRMA/ACIS(F1), and the HRMA/ACIS(BI) combinations. The ACIS curves show the predicted values for the middle of Cycle 9 (2008-05-15).

4.1 ROSAT all-sky survey image of the entire Vela SNR. The intensity is logarithmically scaled. The data have been smoothed with a Gaussian of σ = 2′3. The locations of seven shrapnels are indicated as from “A” to “F”. The brightest feature in the NW rim of the Vela SNR is the Puppis A SNR. The faint blue circle (whose radius of ~ 2°) in the SE portion is a non-thermal dominated young SNR, RXJ0852.0–4622 discovered by Aschenbach (1998). North is up and West is right. Hereafter, all the images have the same direction.

4.2 Magnified X-ray images of the seven shrapnels indicated in Fig. 4.1 (AET).

4.3 Chandra ACIS image of Vela shrapnel A (MTAM).
4.4 EPIC MOS1 + MOS2 logarithmically scaled image in the energy range of 0.2–3.0 keV. The data have been smoothed with a Gaussian of $\sigma = 12''$. The spectra from the ellipse and square are shown in Fig. 4.6.  

4.5 Upper: Same as Fig. 4.4 but focused on the shrapnel A and rotated such that the moving direction becomes horizontal. Lower: The X-ray intensity projected from the upper image. Note that obvious point sources were not removed from the profile.  

4.6 X-ray spectra extracted from the head region. Upper panel shows an example spectrum from one of the $2' \times 2'$ boxes of the head region while lower panel shows the spectra from the entire head region shown in Fig. 4.4. The best-fit curves are shown with solid lines and the lower panels show the residuals.  

4.7 X-ray spectrum of MOS1 from Fig. 4.5 right. The solid line represents the best-fit model, while the broken lines represent the individual component. The lower panel shows the residuals.  

4.8 The predicted fluxes of C He$\alpha$ and the C He$\beta$ as a function electron temperature and ionization timescale (solid, dashed and dotted correspond to 10.75, 11 and 12 of log ($\tau$), respectively). The fluxes measured are indicated as the upper shaded region (for C He$\alpha$) and the lower shaded region (for C He$\beta$). The lower panel shows the ratio of C He$\alpha$ to C He$\beta$.  

4.9 X-ray spectra extracted from the tail region. Upper panel shows an example spectrum from one of the $4' \times 10'$ boxes of the tail region while lower panel shows the spectra from the entire tail region shown in Fig. 4.4. The best-fit curves are shown with solid lines and the lower panels show the residuals.  

4.10 Upper: Same as Fig. 4.4 but with an overlaid the regions where we extracted spectra in order to investigate the variation of $kT_e$, $n_e$ and $p_e$ in the shrapnel A. Lower: The variation of $kT_e$, $n_e$ and $p_e$ in the regions shown in Fig. 4.10  

4.11 ROSAT PSPC logarithmically scaled image of the Eastern Limb of the Vela SNR. The black circle indicates the FOV of our XMM-Newton observation.  

4.12 EPIC MOS1 + MOS2 logarithmically scaled image in the energy range 0.3–2.0 keV. The data have been smoothed with a Gaussian of $\sigma = 6''$. The contours show a linearly scaled optical intensity map.  

4.13 Same as Fig. 4.12 with an overlaid all the regions where we extracted spectra. The spectrum from the white rectangle is shown in Fig. 4.14.
4.14 X-ray spectra extracted from the white rectangle in Fig. 4.13. The best-fit curves are shown with solid lines and the lower panels show the residuals. . 67

4.15 Linearly scaled contour map of $kT_e$ and $\log \tau$ in the western part of the X-ray ridge overlaid on an X-ray image the same as Fig. 4.12. The values of $kT_e$ are in units of keV. The data were smoothed with a Gaussian of $\sigma = 4'$. ......................................................... 69

4.16 Linearly scaled contour map of each metal abundance overlaid on an X-ray image the same as Fig. 4.12. The values shown in each figure are those relative to the solar abundance. The data were smoothed with a Gaussian of $\sigma = 4'$. ......................................................... 70

4.17 (a) Same as Fig. 4.12. The white rectangles adjacently lined up are the regions where we extracted the spectra. The large upper-left region indicates the region where we extracted the band ratio map. (b) EPIC (MOS1 + MOS2 + PN) band ratio map (O Ly$\alpha$ band / O He$\alpha$ band). The circles are the regions where we extracted spectra. .................. 71

4.18 Variation of EM of two components in the region between the optical filament and the X-ray ridge indicated in Fig. 4.17 by white rectangles. . . . 72

4.19 X-ray spectra extracted from the dashed circle in Fig. 4.17 (b). The solid line is the total model, while the broken lines represent the individual contributions. The lower panels show the residuals. ......................... 72

4.20 ROSAT PSPC image of the Vela shrapnel E. The intensity scale is square root. The data have been smoothed with a Gaussian of $\sigma = 2'5$. The white circle indicates the FOV of our XMM-Newton observation. . . . . . . 78

4.21 EPIC MOS1/2 + PN image in the energy range 0.3–1.5 keV. The intensity scale is also square root. The data have been smoothed with a Gaussian of $\sigma = 22''$. The overlaid circles indicate two regions; one for the source region as the circular region located in the center of the FOV, the other for the background region as the annular region surrounding the circular region. 78

4.22 X-ray spectra from the circular region shown in Fig. 4.21. The best-fit curves are shown with solid lines and the lower panels show the residuals. The best-fit curves shows the NEI model. ......................... 79
5.1 Upper: ROSAT HRI image of the entire Puppis A SNR. The data have been smoothed by Gaussian kernel of $\sigma = 15''$. The intensity scale is square root. XMM-Newton FOV are indicated as white circles. Lower: Three-color XMM-Newton image of the merged MOS1/2, PN data from five XMM-Newton observations. Red, green, and blue represent 0.4–0.7, 0.7–1.2, and 1.2-5.0 keV, respectively.

5.2 EW images for O Ly$\alpha$, Ne He$\alpha$, Mg He$\alpha$, Si He$\alpha$, S He$\alpha$, and Fe L. The color scales are in units of keV. We adjusted the color codes for all the images so that we can see blue color in the bright eastern knot which is believed to be a shocked ISM. All the locations for (1–4) sample spectral regions (1–4) are shown.

5.3 Example MOS1 spectra from the four (from 1 to 4) regions indicated in Fig. 5.2.

5.4 (a) Same as Fig. 5.1 lower but with arrows which represent proper-motion vectors for $\sim$1000 yr (Winkler & Kirshner 1988) of OFMKs. Two open circles located at the bright eastern and northern knots are the regions where we extract spectra for a verification of line shifts observed in the X-ray ejecta knotty feature (see, text). The box represents the area covered in Fig. 5.4 (b), (c), and (d). (b) Same as Fig. 5.4 (O Ly$\alpha$ EW) but expanded in the NE portion of Puppis A. The area is shown as a box region in Fig. 5.4 (a). (c) XMM-Newton three-color image in the same area shown in Fig. 5.4 (b). Note that the color scale is different from that shown in Fig. 5.1 lower. (d) XMM-Newton wide band (0.4–5.0 keV) image in the same area shown in Fig. 5.4 (b). Spectral extraction regions are shown as solid (for source spectra) and dashed (for BG spectra) white lines.

5.5 Left column: MOS1 (black) and MOS2 (red) spectra from the two regions in Fig. 5.4 with the best-fit model (redshift = 0). The lower panels show the residuals. Right column: Same as the left column but with the revised model (redshift is free).

6.1 ROSAT HRI image of the entire Cygnus Loop. All of the Suzaku, Chandra, and XMM-Newton FOV are shown as white solid rectangles, white dashed rectangles, and white solid circles, respectively.
6.2 Merged *Suzaku* XIS1 three color image of the four pointings of the NE rim of the Cygnus Loop (Red: 0.31–0.38 keV band, i.e., C He$\alpha$, Green: 0.38–0.46 keV band, i.e., N He$\alpha$, Blue: 0.60–0.69 keV band, i.e., O Ly$\alpha$). The data have been binned by 8 pixels and smoothed by Gaussian distribution of $\sigma = 25''$. The effects of exposure, vignetting, and contamination are corrected. .............................................. 108

6.3 Three color image merged by seven XIS FOV from the NE rim to the SW rim (Red: O He$\alpha$, Green: Ne He$\alpha$, Blue: Fe L). The data have been binned by 8 pixels and smoothed by Gaussian kernel of $\sigma = 25''$. The effects of exposure, vignetting, and contamination are corrected. .............................................. 108

6.4 *Left*: Exposure and vignetting corrected *Chandra* three-color FI CCDs image. Red, green, and blue colors correspond to narrow energy bands of 0.3–0.6 keV, 0.6–0.9 keV, and 0.9–2 keV, respectively. In addition to detailed spatially resolved spectral analyses in S3 chips, we extract spectra from two white ellipses indicated in this figure. *Right*: Same as left but for BI CCDs. .............................................. 109

6.5 Exposure and vignetting corrected *XMM-Newton* three-color image. Red, green, and blue colors correspond to narrow energy bands of 0.52–0.61 keV (O He$\alpha$), 0.87–0.98 keV (Ne He$\alpha$), and 0.78–0.86 keV (Fe L), respectively. .............................................. 110

6.6 Spatially integrated XIS1 spectrum of the four pointings. Emission lines from C He$\alpha$, N He$\alpha$, O He$\alpha$, O Ly$\alpha$, Ne He$\alpha$, and Mg He$\alpha$ are clearly detected. The emission below 0.3 keV, so-called “C-band”, is originated from Si L and Fe M lines. ........................................................................ 111

6.7 Same as Fig. 6.2. White small rectangles are the cells where we extracted spectra. We showed example spectra from cells 1 and 2 in Fig. 6.8. The red polygon identifies Region A (see text). ........................................................................ 112

6.8 *Upper*: X-ray spectra extracted from cell 1 in Fig. 6.7. The best-fit curves are shown with solid lines for the four XIS’s. The contribution of each component is shown by the dotted lines only for XIS1. The dashed line represents the low temperature component while the dotted line represents the high temperature component. The lower panels show the residuals. *Right*: Same as left but for cell 2. ........................................................................ 115

6.9 Maps of the best-fit parameters. The units are $10^{22}$ cm$^{-2}$ for $N_H$, keV for $kT_{e1}$ and $kT_{e2}$, cm$^{-3}$ sec for $\tau$, $10^{19}$ cm$^{-5}$ for EM$_1$ and EM$_2$, and solar values for abundances. ........................................................................ 116
6.10 Each elemental abundance or ionization timescale versus O is plotted for
the 184 cells. Red data points come from Region A while black points come
from the remaining cells. The dashed line from upper right to lower left
represents the solar ratio. ................................................................. 117

6.11 $N_H$, $kT_{e2}$, $\log(\tau)$, EM$_2$, and EM$_1$ versus $kT_{e1}$ are plotted for the 184 cells.
Red data points come from Region A while black points come from the
remaining cells. ................................................................. 121

6.12 Upper: Exposure and vignetting corrected Chandra S3 chip image for Ob-
sid. 2821. The spectral extraction regions are shown as white annuli. Sev-
eral point sources indicated by white circles are excluded from our spectral
analysis. An arrow seen in the upper right indicates the position of the
discontinuity of the X-ray intensity. Lower: Same as Fig. 6.12 Upper but
for ObsID. 2822. ................................................................. 124

6.13 Example spectra (crosses) with the best-fit model (solid lines). Lower panel
shows the residuals. Upper left, upper right, lower left, and lower right
spectra are from Reg-3 in Area-1, Reg-3 in Area-2, the northern ellipse in
Fig. 6.4, and the southern ellipse in Fig. 6.4, respectively. ......................... 126

6.14 Abundance, $kT_e$, $\tau$, and EM as a function of region number. Open circles
represent data points from area-1, while open triangles represent those from
area-2. ................................................................. 129

6.15 Confidence contour maps of O abundance against $kT_e$ or $\tau$. Upper panels
are those for Reg-3 in area-1, while lower panels are those for Reg-3 in area-
2. Solid, dashed, and dotted lines represent 68%, 90%, and 99% confidence
levels, respectively. ................................................................. 130

6.16 Same as Fig. 6.16 upper left but with the best-fit power-law+vpshock
model. The two components are separately shown as dotted lines. .......... 133

6.17 Spectral extraction regions overlaid on an XMM-Newton three-color image
shown in left figure ................................................................. 136

6.18 MOS1 spectra for the seven pointings; each is the sum of the entire FOV. . 137

6.19 Comparison of spectra between Pos-1 (circles) and Pos-4 (triangles). They
are equalized in intensity at O-He$\alpha$. ................................................................. 138

6.20 Distribution of the reduced-$\chi^2$ as a function of R along the north path
(upper panel) and the south path (lower panel). The single-component
model is shown in black and the two-component model is shown in red. . . 140
6.21 Upper: An example spectrum that comes from the sector at $R = -74.25'$. The best-fit curves are shown with solid lines and the lower panels show the residuals. Lower: Same as left but for the sector at $R = +10'$. Both the ejecta and cavity components are shown only for MOS1 spectrum as dashed lines. ................................................................. 143

6.22 Temperature distributions of the two components as a function of position. Filled circles show the ejecta component, while crosses show the cavity component. Black shows the north path and red shows the south path. Typical errors are ±5% for both components. ....................... 145

6.23 Flux distributions of the two components as a function of position. The marks in this figure are the same as those in Fig. 6.22. ......................... 145

6.24 Distributions of EM for various metals [O(=C=N), N, Mg, Si, S, and Fe(=Ni)] in the ejecta. Black indicates the north path and red indicates the south path. Data points showing only upper limits are excluded in these figures. ................................................................. 148

6.25 Number ratios of Ne, Mg, Si, S, and Fe relative to O of the high-$kT_e$ component estimated for the entire Loop (black solid line). Dash-dotted red lines represent CDD1 and W7 model of Type-Ia (Iwamoto et al. 1999). Dotted green, blue, light blue, and magenta lines represent core-collapse models whose progenitor masses are 13, 15, 20, and 25 $M_\odot$, respectively (Woosley & Weaver 1995). ................................................................. 150

6.26 Same as Fig 6.3 but with the cells where we extracted spectra. We show example spectra from black cells for <2 keV and green cells for >2 keV in Fig. 6.27. ................................................................. 152

6.27 Top-left panel: X-ray spectra extracted from the black cell in P16 indicated in Fig. 6.26. The best-fit curves for one-component NEI model are shown with solid lines and the lower panels show the residuals. The small gap around 2 keV is due to the fact that we extracted spectra below 2 keV from each small cell while above 2 keV from half of each FOV. Top-right panel: Same as top left but with two-component NEI best-fit models. The contribution of each component is shown by the dotted lines only for XIS1. Other panels: Same as top-right panel but from black cells in P8, P12, P13, P14, P15, and P17, respectively. ................................................................. 156
6.28 Maps of the best-fit parameters. The values of $N_H$, $kT_e$, $EM_L$ are in units of $10^{22}\text{cm}^{-2}$, keV, and $10^{19}\text{cm}^{-5}$, respectively. Lower six maps show EMs of O, Ne, Mg, Si, S, and Fe for the high-$kT_e$ component in units of $10^{14}\text{cm}^{-5}$. We adjusted the color code such that we can see the differences in each figure.

7.1 Chandra 1 megasecond image of Cas A with the locations of the 1825 identified outer ejecta knots (M.C. Hammell & R.A. Fesen 2006, in preparation) color-coded by their emission properties. Red open circles indicate knots with strong [N II] line emission, green open circles knots with strong [O II] emission, and blue open circles strong [S II] FMK-like outlying knots (Fesen et al. 2006).

7.2 Upper: Plot of extrapolated 320 yr proper motions for the 1825 identified outer knots based on actual proper motions. The central white circle has a radius of 5 arcsec and marks the remnant’s estimated COE (Thorstensen et al. 2001). Lower: Plot of 1825 outer knot positions and their expected motions away from the remnant’s known COE. The circle represents the radial distance of 200 arcsec, corresponding to a measured proper motion of $0''\cdot65\text{ yr}^{-1}$ and thus an implied 10,000 km s$^{-1}$ transverse velocity at the assumed remnant distance of 3.4 kpc. These images are taken from Fesen et al. (2006). Lower-left inset: A 2001 STIS HST image of the central region of Cas A near the XPS with the Thorstensen et al. (2001) expansion center marked ($\alpha = 23^h23^m27^s.77\pm0^s.05$, $\delta = 58^\circ48'49''.4\pm0''.4$ [J2000.0]) along with the CCO’s current position ($\alpha = 23^h23^m27^s.943\pm0^s.05$, $\delta = 58^\circ48'42''.51\pm0''.4$ [J2000.0]) as derived from Chandra image data (see, Fesen et al. 2006). The circles marking these positions are 1 arcsec in diameter.

7.3 Chandra half-megasecond color image of G292.0+1.8 (Park et al. 2007). Red-color regions are responsible for where the X-ray emission is dominated by O Ly$\alpha$ and Ne He $\alpha$, orange for Ne Ly$\alpha$, green for Mg He$\alpha$, and blue for Si He$\alpha$ and S He$\alpha$. The radio SNR center (Gaensler & Wallace 2003) is marked with a black cross. The position of PSR J1124–5916 (Hughes et al. 2003) is marked with white bars near the SNR center.
Chapter 1

Introduction

The mechanism of supernova (SN) explosions has not yet been understood in spite of a number of efforts in theoretical speculations and numerical explorations for more than 40 years. Since the discovery of the global asymmetry of the mass ejection in SN1987A, recent theorists as well as observers are involved in asymmetries of the SN explosions themselves. In theoretical aspects, hydrodynamic instabilities during SN explosions are considered to play an important role to yield successful SN explosions as well as to explain observed features of SN explosions. In observational aspects, critical clue to the explosion mechanism is considered to be provided by the accumulating evidence for asymmetries in SN explosions. The evidence of explosion asymmetries comes from spectropolarimetry of young SN, asymmetric emission-line profiles in late-time SN (about one year after SN explosions), and high pulsar velocities. In addition to these observational approaches, we here propose that observations of SN remnants (SNRs) can be also an important method to obtain informations on SN explosions. The apparent large expansions of the explosion ejecta in SNRs, that are not expected in young SNe, allow us to investigate detailed geometries of the explosion ejecta which is especially critical to understand the SN explosion mechanism.

Due to extremely large energies of SN explosions (typically $10^{51}$ ergs), the explosion ejecta are spew-out into the ambient medium with high Mach-number velocities. The interaction between the high-velocity ejecta and the ambient medium initiates strong shocks propagating into both the ambient medium (forward shock) and the ejecta (reverse shock). As a result, both the swept-up ambient medium and the ejecta become so hot ($10^6 - 10^7$ K) that they emit X-rays. Together with the fact that X-ray emission little suffers from foreground absorbing material due to its strong penetrating power, we thus detect a number of X-ray bright SNRs in our galaxy. In addition, such a hot plasma in SNRs emits K-shell transition lines from highly ionized (e.g., H-like, or He-like) elements.
whose atomic physics are best understood. Therefore, X-ray spectroscopy is one of the
best tools to investigate the elemental abundances in SNRs.

Since the first successful space flight use of X-ray CCDs on board the ASCA satellite
(launched in 1993 as the fourth Japanese X-ray satellite), CCD cameras became a standard
focal plane detectors on board X-ray satellites. The spectral resolving power of the CCD
was sufficient to resolve individual K-shell lines from heavy elements in different ionization
states, which allowed us to determine metal abundances and plasma conditions (i.e.,
temperature and ionization states). Relics of metal-rich ejecta have been detected in
many SNRs by ASCA. With the generation of the XMM-Newton (launched in 1999 by
ESA) and Chandra (launched in 1999 by NASA) satellites, it became possible to extract
spatially resolved spectra in good resolution (down to arc seconds). The two satellites are
capable of revealing metal-rich ejecta knots as well as global ejecta distributions in many
SNRs. The most recent X-ray astronomy satellite, Suzaku (launched in 2005 as the fifth
Japanese X-ray satellite), has excellent sensitivity at an extended low energy range with
good energy resolving power. Utilizing the Suzaku satellite, we can detect emission lines
from highly ionized Carbon and Nitrogen for the first time.

The main focus of this thesis is measuring distributions as well as compositions of
X-ray–emitting metal-rich ejecta in largely expanded SNRs, using the Suzaku, XMM-
Newton, and Chandra satellites. In young SNRs, a large fraction of the explosion ejecta
has not yet been heated by the reverse shock so that we can detect only some parts of
the total ejecta. Thus, in order to study global ejecta distributions, it is a good idea to
study evolved SNRs in which the reverse shock heated all the ejecta. Furthermore, large
expansions of evolved SNRs enable us to study fine geometries of the ejecta. We perform
spatially resolved spectral analyses for the brightest evolved SNRs in the X-ray sky, i.e.,
the Vela SNR, the Puppis A SNR, and the Cygnus Loop. We successfully detect ejecta
features in all the three SNRs. In the Vela SNR and the Puppis A SNR, we detect fast-
moving metal-rich ejecta knots, while we, for the first time, quantitatively reveal global
ejecta distributions in the Cygnus Loop. We not only compare our results with theoretical
SN explosion models but also attempt to constrain the models.

This thesis is organized as follows. In the next chapter, we briefly review SNe, SNRs,
and non-equilibrium states as well as X-ray emission in the shock-heated plasma. We then
introduce the instruments on board the Suzaku, XMM-Newton, and Chandra satellites in
chapter 3. In chapters 4, 5, and 6, we present the individual observations, analyses, results,
and discussions for the Vela SNR, Puppis A SNR, and the Cygnus Loop, respectively. In
chapter 7, we give a summary discussion on the ejecta features through all the results.
The summary and conclusions of this thesis is described in chapter 8.
Chapter 2

Review

2.1 Supernova (SN)

A supernova (SN; plural SNe) is a stellar explosion that creates an extremely luminous object. The luminosity is so large that it can be match for its entire host galaxy before fading from view over several weeks or months. If SNe occur in our galaxy and they are not too heavily obscured by the interstellar medium (ISM), they can be seen as very spectacular events in the sky. Although modern estimates predict that in every few decades one supernova should occur in a galaxy (e.g., van den Bergh & Tammann 1991), there have been a handful SN events in our own galaxy which were observed and recorded by human civilizations during the past 1000 years. The historical SNe are SN1006 (Lupus), SN1054 (Crab), SN1181 (3C58), SN1572 (Tycho’s SNR), SN1604 (Kepler’s SNR), SN1667 or SN1680 (Cas A). Unfortunately, none of them has been well visible since the invention of the telescope.

Classification of SNe was first introduced by Minkowski (1941) to distinguish two different spectral appearances of SNe (see, Fig. 2.2 upper). In the maximum light spectra, Type I SNe exhibit no hydrogen lines, whereas Type II SNe do show hydrogen lines. The physical interpretation for the difference is that stars which will explode as Type I SNe have shed their outer hydrogen layer at the end of their evolution while stars which will produce Type II SNe have retain them up to the explosion. Type I SNe are further divided into three subclasses: Type Ia with Si features, Type Ib without Si features but with He features, and Type Ic without Si nor He features.

In addition to the spectral features, the light curves can also be used to classify SNe (see, Fig. 2.2 lower). All the Type I SN events display similar light curves. The intensity rises quickly to the maximum, reaching a luminosity of more than $10^9 L_\odot$ in about two weeks. An initial rapid decay is followed by a long slow decline in brightness. The
SUPERNova CLASSIFICATION

MAXIMUM LIGHT SPECTRA

\[ H / no \ H \]

\[ SN \ H \]

Light Curve Shape
Maximum Light Continuum

\[ SN \ I \]

Si / no Si

\[ Ia \]

\[ He : no He \]

\[ Ib \]

\[ Ic \]

\[ II \ L \]

\[ II \ P \]

\[ SN \ 1987A \]

\[ SN \ 1987K \]

Figure 2.1: Classification scheme of SNe based on optical spectra (Harkness, Wheeler 1990).

Figure 2.2: Comparison of the mean blue light curves for SN I, IIP and IIL (Doggett and Branch 1985).
luminosity falls exponentially with a characteristic time of about 55 days until the SN fades to the level of invisibility. On the other hand, Type II SN events display at least two distinct light curves. One subclass exhibits “plateau” in the post-maximum phase (Type IIp), producing a nearly constant luminosity about 50 days. Other subclass exhibits little or no plateau, having a linear decline after the maximum (Type IIl).

2.1.1 Explosion mechanism

It is now believed that the explosion mechanisms that drive SNe are divided into two groups: Type Ia are triggered by an explosive C and O ignition in a C+O white dwarf, while all the other classes of SNe are results of the collapse of cores of massive stars, hence named as “core-collapse” SNe.

Type Ia SN

The thermonuclear-fusion mechanism was originally proposed by Hoyle & Fowler (1960) for Type Ia SNe. They pointed out that explosive carbon burning in accreting degenerate stellar cores produce Type Ia SNe, leaving no compact stellar remnant behind. The idea was developed into a carbon supersonic burning (“detonation”) SN model by Arnett (1969). In a view of nucleosynthesis, the detonation-type models do not synthesize appreciable amounts of intermediate mass elements such as Ca, Ar, S, Si, and O. Nomoto et al. (1976; 1984) proposed slow subsonic carbon burning (“deflagration”) in accreting C+O white dwarf. This model successfully explained observed light curves as well as spectra of Type Ia SNe.

However, the mechanism whereby such accreting C+O white dwarfs explode continues to be still uncertain (see, Hillebrandt & Niemeyer 2000 for a review). Recent observations of Type Ia SNe show asymmetric ejecta distributions. For example, spectropolarimetry observation of SN2001el shows that minor to major axis ratio of the ejecta distribution is about 0.9 (Wang et al. 2003), flat-topped Fe line of SN2003hv shows a large shift (from $-3000$ to $1000$ km sec$^{-1}$ with respect to the host galaxy) in their line center (Motohara et al. 2006). These observations suggest the occurrence of an off-center or non-spherical SN explosion. In recent multidimensional models, the ignition of deflagration may be off-center, producing a non-spherical burning region (Wunsch & Woosley; Plewa et al. 2004). In addition, the deflagration to detonation transition (DDT) may occur in some cases (delayed detonation models; Khokhlov 1991). The DDT may also take place non-spherically (Livne 1999), even if the deflagration does not have a bulk kinematic offset. The asymmetric explosion may be a key for the complete explanation to the explosion
mechanism of Type Ia.

**Core-Collapse SN**

A core-collapse supernova results from the evolution of a massive star. For most of their existence, stars burn H into He. In stars at least eight times as massive as the Sun (8 $M_\odot$), temperatures and densities become sufficiently high to burn through C to O, Ne, and Mg; in stars of at least 10 $M_\odot$, burning continues through Si to Fe group elements. The Fe group nuclei are the most tightly bound, and here burning in the core ceases. The Fe core is compressed and the temperature increases to $\simeq 3 \times 10^9$ K. Then, the following decomposition of $^{56}$Fe occurs

$$^{56}\text{Fe} + \gamma \rightarrow ^{13}\text{He} + 4n - 124.4 \text{ MeV}. \quad (2.1)$$

As a result, the energy is absorbed, reducing the pressure and causing the inner portion of the core undergoes homologous collapse (velocity proportional to radius), and the outer portion collapses supersonically. Electron capture on nuclei is one instability leading to collapse, and this process continues throughout collapse, producing neutrinos. These neutrinos escape freely until densities in the collapsing core become so high that even neutrinos are trapped.

Collapse is halted soon after the matter exceeds nuclear density ($\simeq 1 \times 10^{15}$ cm$^{-3}$). At this point, neutron stars (radius of about 10 km) which consist of extremely closely packed neutrons are formed at the center. Then, a shock wave forms at the boundary between the neutron star and supersonically collapsing regions (“bounce”). The shock begins to move out, but after the shock passes some distance beyond the surface of the newly-born neutron star, it stalls (at around 200 km from the neutron star) as the energy is lost to neutrino emission and endothermic dissociation of heavy nuclei falling through the shock.

It is natural to consider neutrino heating as a mechanism for shock revival (Colgate & White 1966), because neutrinos dominate the energetics of the post-bounce evolution. Initially, the nascent neutron (or proto–neutron) star is a hot thermal bath of dense nuclear matter, electron/positron pairs, photons, and neutrinos, containing most of the gravitational potential energy released during core collapse. Neutrinos, having the weakest interactions, are the most efficient means of cooling; they diffuse outward on a time scale of seconds, and eventually escape with about 99% of the released gravitational energy. In 1982, simulations showing the stalled shock re-energized by neutrino heating on a time scale of hundreds of milliseconds were first performed (Wilson 1982). This was initially achieved in a simulation with a total of 2 dimensions (spherical symmetry, and energy-
dependent neutrino transport). But with the introduction of full general relativity and a correction in an outer boundary condition (Mayle 1990), it became clear that these models would not explode without a mock-up of a doubly-diffusive fluid instability in the newly-born neutron star that serves to boost neutrino luminosities (Mayle 1990; Mayle & Wilson 1991; Wilson & Mayle 1993; Miller et al. 1993).

Figure 2.3: SN1987A observed with HST [Credit: NASA and Kirshner, R. (Harvard-Smithsonian Center for Astrophysics)]. The ring is material from the stellar wind of the progenitor that were ionized by the ultraviolet flash from the supernova explosion, and consequently began emitting in various emission lines. The elliptically distributed ejecta which are heated by radioactive $^{44}$Ti can be seen in the central portion of the ring.

On February 23 in 1987, a supernova (SN 1987A) appeared in Large Magellanic Cloud (LMC). The light curve and spectra of SN 1987A (which is thought to be a core-collapse SN) brought unambiguous evidence that nucleosynthesis products were distributed strongly anisotropically and that large-scale mixing took place during the explosion. This was interpreted as a clear sign that the onion-shell structure of the progenitor star was destroyed during the explosion (Arnett et al. 1989). We can directly see the anisotropic (elliptically-shaped) ejecta distributions in a Hubble Space Telescope (HST) image of the remnant shown in Fig. 2.3. In addition to SN1987A, some evidence for asymmetric explosions was derived from spectropolarimetry in Type-II SN, SN2004dj (Leonard et al. 2006) and a few Type-Ib/c SNe (Wang et al. 2001), and in the broad-lined Type-Ic SN, SN2002ap (Kawabata et al. 2002; Leonard et al. 2002; Wang et al. 2003). Also, Late-time (about one year after SN explosions) spectroscopy tells us geometries of
the inner ejecta (e.g., Maeda et al. 2008).

Motivated by the observational evidence that the explosion of core-collapse SNe are anisotropic, recent multi-dimensional supernova models involved in the asymmetric explosions. In those models, sufficiently strong radial mixing of radioactive nuclei requires that hydrodynamic (convective) instabilities have developed in layers near the stellar core and already during the earliest stages of the explosion. In fact, simulations of the onset of the explosion demonstrated that strong convective overturn can occur in the Ledoux-unstable region of neutrino energy deposition behind the stalled supernova shock (Herant et al. 1994; Burrows et al. 1995; Janka & Müller 1996).

Meanwhile, it is clear that convection is not the only source of asymmetry during the shock stagnation phase. The standing accretion shock has been recognized to be generically unstable to non-radial deformation, even in situations where convection is damped or suppressed. This so-called “standing accretion shock instability” (SASI; Blonding et al. 2003) shows a preferential growth of low shock-deformation modes (dipole, $\ell = 1$, and quadrupole, $\ell = 2$, modes in terms of an expansion in spherical harmonics). This SASI phenomenon plays a very important role in the SN core. It was not only found to induce a large asymmetry of the shock wave and ejecta distributions but also to facilitate neutrino-driven explosions by stretching the time accreted matter can stay in the gain layer and can be exposed to neutrino heating.

More recently, Burrows et al. (2006a, 2007) pointed out that the SASI itself is insufficient to explode the core-collapse SNe when proper account is taken of the neutrino losses, the nuclear EOS, and the inner boundary. They proposed an acoustic mechanism for exploding core-collapse SNe. In the model, the progressive growth of the SASI and of the entropy, and Mach number of the accreted shocked matter long after the outer shock has stalled results in anisotropic accretion onto the inner core. As the result, the compact remnant is instigated to large-amplitude bipolar oscillations. The pulsating compact remnant sends pressure waves into its environment, which carry a sizable energy flux and can even steepen into shocks, thus dissipating their energy in the surrounding medium and raising entropy there. The ringing neutron star acts as a transducer that converts some part of the gravitational binding energy released by the accreted gas into sonic power. Then, energy and momentum are deposited aspherically into outer shocked mantle and explodes the SNe by the acoustic power. The blast is fundamentally aspherical, favoring one side (see, Fig. 2.4). The inner ejecta asymmetries of 2:1 or 3:1 expected in the model can explain the polarizations observed in the inner debris of Type Ic (Wang et al. 2003) and Type II (Leonard et al. 2006). This acoustically-driven mechanism appears as an interesting alternative to initiate the SN explosion, if neutrino-driven mechanism fails.
High-Velocity Pulsar

– Observations –

It has long been recognized that neutron stars have space velocities much greater than those of their progenitors. Recent studies of pulsar proper motion give 200–500 km s\(^{-1}\) as the mean three-dimensional velocity of neutron stars at birth (e.g., Lyne & Lorimer 1994; Lorimer, Bailes, & Harrison 1997; Hansen & Phinney 1997; Cordes & Chernoff 1998), with a significant population having velocities greater than 1000 km s\(^{-1}\). Direct evidence for pulsar velocities \(>1000\) km s\(^{-1}\) comes from observations of the bow shock produced by the Guitar Nebula pulsar (B2224+65) in the ISM (see, Fig. 2.5 Upper; Cordes, Romani, & Lundgren 1993). Recent proper-motion measurement for the neutron star, RXJ0822-4300, associated with the Puppis A SNR also shows further high velocity of \(~1600\) km s\(^{-1}\) (see, Fig. 2.5 Lower, Winkler & Petre 2007).

From statistical point of view, there is no evidence for a correlation between velocity and magnetic moment for radio pulsars (Lorimer et al. 1997; Cordes & Chernoff 1998) or between velocity and rotation (Deshpande, Ramachandran, & Radhakrishnan 1999). However, we should note that observations of the pulsars and the surrounding compact X-ray nebulae for Vela and Crab reveal a two-sided asymmetric jet at a position angle coinciding with the position angle of the pulsar’s proper motion (Pavlov et al. 2000;
Figure 2.5: *Upper:* Hα image (observed by *Palomer Observatory*) showing a bow-shock nebula produced by the high-velocity pulsar B2224+65. Left-lower inset shows the expanded Hα image obtained by *HST*. *Lower:* X-ray image (observed with *ROSAT HRI*) of the entire Puppis A SNR. The inset shows the position of the neutron star observed with *Chandra* X-ray observatory; left in 1999 and right in 2005 (Winkler & Kirshner 2007; or http://www.asahi.com/special/space/TKY200712060042.html).
2.1. SUPERNOVA (SN)

Helfand, Gotthelf, & Halpern 2001; Caraveo & Mignani 1999; Weisskopf et al. 1999). The symmetric morphology of the nebula with respect to the jet direction strongly suggests that the jet is along the pulsar’s spin axis, resulting in the alignment of the pulsar’s velocity and spin axis.

– Possible Mechanism for the High-Velocities –

Three mechanisms are proposed for the origin of the high-velocity pulsars: (a) binary disruptions, (b) postnatal or (c) natal kicks from the SN explosions (see, Lai et al. 2001 for a review).

a) Binary Disruption

The “binary disruption” was proposed by Zwicky (1957) and Blaauw (1961). Two massive stars comprise a binary system; ultimately the more massive component reaches the end of its life and explode as a core-collapse SN. The binary system will become unbound if sufficient mass is lost in a sufficiently short time; the remaining star then leaves with nearly its orbital velocity as a “runaway” star. Many binary systems have orbital velocities as high as 100–200 km sec$^{-1}$, but this is still too low speed to explain the average pulsar speed. Also, binary disruptions would yield orthogonal spin and velocity vectors if pre-explosion binaries have aligned spin and orbital angular momenta (e.g., by virtue of tidal coupling) and if the neutron star’s spin is in the same direction as the progenitor’s. Therefore, the alignment between the projected spin axis and proper motion (for Vela and Crab) immediately demonstrates that binary breakup along with symmetric supernova explosions is not likely to be responsible for the observed proper motion.

b) Postnatal Kick

An asymmetric emission of radio waves could occur if the pulsar’s dipole magnetic field is off-centered and inclined to the axis of rotation. Harrison & Tademaru (1975) have suggested that such radio waves could accelerate the newly born pulsar. However, the predicted final velocity falls short of the observed speeds of the faster pulsars, which exceed 1000 km s$^{-1}$.

c) Natal Kick

The failure of the two mechanisms described above lead us to focus on natal kicks imparted to neutron star at birth. A natal kick could be due to asymmetric neutrino emission in the presence of super-strong magnetic fields ($B \gtrsim 10^{15}$ G) in the proto–neutron star (e.g., Blandford et al. 1983), or it could be a result from global hydrodynamical perturbations in the SN core (e.g., Goldreich et al. 1996; Sheck et al. 2006 and references therein).

The mechanism based on asymmetric neutrino emission takes advantage of the fact that most of the energy and momentum released in the collapse of a massive star is in the
form of neutrinos, and asymmetries of a percent are sufficient to produce the observed kicks. The proposed mechanisms range from collective effects caused by e.g., turbulence near the neutrino-sphere (Socrates et al. 2005), to elementary processes involving neutrinos, including neutrino oscillations (e.g., Kusenko & Segre 1996, 1997; Kusenko 2004). All these mechanisms require strong magnetic fields of at least $10^{16}$ G although magnetic fields of ordinary radio pulsars are estimated to be of the order of $10^{12}$–$10^{13}$ G. Of course, soft gamma-ray repeaters and anomalous X-ray pulsars may possess magnetic fields in excess of $10^{14}$ G ("magnetars"; e.g., Thompson & Duncan 1996; Vasisht & Gotthelf 1997), it is unclear that radio pulsars had $B \gtrsim 10^{15}$ G at birth for these neutrino–magnetic field driven kicks to be relevant.

Hydrodynamically (or ejecta)-driven kicks can occur if a sufficient degree of anisotropy develops in the hydrodynamics of the explosion. A number of ejecta asymmetries have been proposed: asymmetric collapse (Burrows & Hayes 1996), low-mode convection (Herant et al. 1992; Buras et al. 2003), the related low-mode convection in SASI (Blondin et al. 2003), and an acoustic power (Burrows et al. 2006a; 2006b). In fact, recent calculations successfully propelled the neutron star to velocities of more than $1000 \text{ km sec}^{-1}$ (Scheck et al. 2004; 2006).

The two kinds of models for natal kicks lead to unambiguously different predictions from one another: neutrino-driven mechanisms predict the motion of the ejecta roughly in the same direction of the neutron star kick (Fryer & Kusenko 2006), while the ejecta-driven mechanisms predict that neutron star velocity should be directed opposite to the momentum of the gaseous SN ejecta caused by momentum conservation. Therefore, we can determine which model is at work for the high-velocity neutron stars by observations of distributions of gaseous remnants and the proper-motion vectors of stellar remnants (i.e., neutron star).

### 2.1.2 Nucleosynthesis

SN explosion spew heavy elements synthesized not only in a hydrostatic core in a progenitor star but also in an explosive burning by the shock wave penetrating the stellar mantle during the SN explosion itself. The most significant parameter in the explosive nucleosynthesis is the temperature (see, table 2.1). During the shock wave propagates in the stellar mantle, the temperature, $T$, behind the shock is written by the explosion energy, $E$, and the radius, $R$ as

$$E \sim \frac{4\pi}{3}R^3aT^4,$$  
(2.2)
where \( a \) is the radiation-density constant, \( 7.57 \times 10^{-15} \text{ ergs cm}^{-3} \text{ K}^{-4} \). This equation shows that the temperature becomes lower and lower toward the outer layer. The edges of explosive burning zones correspond to the following radii: complete Si burning (3700 km), incomplete Si burning (4980 km), explosive O burning (6430 km), and explosive Ne/C burning (11,750). These relate to enclosed masses of 1.7, 1.75, 1.81, and 2.05 \( M_\odot \) in the case of the 20 \( M_\odot \) (Thielemann et al. 1996). The radii are model independent and vary only with the SN energy. Figure 2.6 shows the abundance distribution in the ejecta of the 20 \( M_\odot \) normal SN \( (E = 10^{51} \text{ ergs}) \). The relative abundances in the total ejecta from various SNe are plotted in Fig. 2.7 (Thielemann et al. 1996; Iwamoto et al. 1999). Comparing relative abundances obtained in supernova remnants with the theoretical calculations, we can study the progenitor star which produced the remnant.

<table>
<thead>
<tr>
<th>Burning Site</th>
<th>Main products</th>
<th>Ignition temperature [10^9 K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/Ne burning</td>
<td>O, Mg, Si, Ne</td>
<td>2.1</td>
</tr>
<tr>
<td>O burning</td>
<td>O, Si, S, Ar, Ca</td>
<td>3.3</td>
</tr>
<tr>
<td>Incomplete Si burning</td>
<td>Si, S, Fe, Ar, Ca</td>
<td>4</td>
</tr>
<tr>
<td>Complete Si burning</td>
<td>Fe, He</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 2.6: Abundance distribution against the enclosed mass, \( M_r \), after the core-collapse explosion of 20 \( M_\odot \) star (Thielemann et al. 1996).

Figure 2.7: Relative abundances to Oxygen in the total ejecta for various nucleosynthetic models: Type-Ia (W7 and CDD1 model) data from Iwamoto et al. (1999), while core-collapse (whose progenitor masses are 13, 15, 20, and 25 \( M_\odot \)) data from Thielemann et al. (1996).
2.2 Supernova Remnant (SNR)

The relics of SNe, supernova remnants (SNRs), are expected to be seen in many wavelength for tens, even hundreds of thousands of years. Extended radio emissions are produced by interactions between shock waves resulting from SNe and the interstellar magnetic field. Most SNRs have been discovered as spatially extended sources in the radio sky. Currently, Green (2006) identified 265 radio-emitting SNRs in our galaxy, of which 102 (including 4 possible detections) SNRs are also associated with X-ray emissions. The X-ray emission originates from optically-thin thermal plasma heated by the shock wave or from relativistic electrons accelerated by the shock wave.

2.2.1 Shock Wave

A shock wave occurs in compressive media when pressure gradients are large enough to generate supersonic compressive motions. The shock compresses, heats up, and accelerates the medium. As a result, a discontinuity of thermodynamic parameters occurs at the surface of the shock wave (i.e., shock front). Here, we describe fluid equations and relations between some physical parameters (see, McKee & Hollenbach 1980; Draine & McKee 1993 for a complete explanation). The boundary conditions at the shock front are given below,

\[
\rho_0 v_0 = \rho_1 v_1 \quad \text{(conservation of mass flux)} \quad (2.3)
\]

\[
p_0 + \rho_0 v_0^2 = p_1 + \rho_1 v_1^2 \quad \text{(conservation of momentum flux)} \quad (2.4)
\]

\[
\rho_0 v_0 \left( w_0 + \frac{1}{2} v_0^2 \right) = \rho_1 v_1 \left( w_1 + \frac{1}{2} v_1^2 \right) \quad \text{(conservation of energy flux)}, \quad (2.5)
\]

where \( \rho, v, p, \) and \( w \) are the density, velocity, pressure, and enthalpy per mass unit \((w = \gamma p/\rho(\gamma - 1) \) for the ideal gas, where \( \gamma \) is the specific-heat ratio). The subscripts 0 and 1 represent upstream and downstream, respectively. From the fluid equations, we obtain following Rankin & Hugoniot relations,

\[
\frac{\rho_0}{\rho_1} = \frac{v_1}{v_0} = \frac{(\gamma + 1)p_0 + (\gamma - 1)p_1}{(\gamma - 1)p_0 + (\gamma + 1)p_1} \quad (2.6)
\]

\[
\frac{T_0}{T_1} = \frac{p_1}{p_0} \frac{(\gamma + 1)p_0 + (\gamma - 1)p_1}{(\gamma - 1)p_0 + (\gamma + 1)p_1}. \quad (2.7)
\]

We can derive some useful equations in terms of the Mach number, \( M_0 = v_0/C_0 \), where \( C_0 = \gamma p/\rho \) is the sound velocity.

\[
\frac{\rho_1}{\rho_0} = \frac{\gamma + 1)M_0^2}{(\gamma - 1)M_0^2 + 2} \quad (2.8)
\]
\[
\frac{T_0}{T_1} = \frac{(2\gamma M_1^2 - (\gamma - 1))((\gamma - 1)M_1^2 + 2)}{(\gamma + 1)^2 M_1^2} \tag{2.9}
\]

In cases of strong shocks \((p_1 \gg p_0 \text{ or } M_0 \ll 1)\) for a mono-atomic gas \((\gamma = 5/3)\), \(\rho_1/\rho_0 \approx 4\) and \(T_0/T_1 \approx 5/16 M_0^2\).

The velocities can be written by,

\[
v_0^2 = \frac{1}{2} (\gamma + 1) \frac{p_1}{\rho_0} \tag{2.10}
\]

\[
v_1^2 = \frac{1}{2} (\gamma - 1) \frac{p_1}{(\gamma + 1)\rho_0} \tag{2.11}
\]

Using the equation of state, we obtain a relation between a post-shock thermal-equilibrated \((\text{mean})\) temperature, \(T_s\), and a shock velocity \(v_s = v_1\) as

\[
k T_s = \frac{3}{16} \mu m_H v_s^2. \tag{2.12}
\]

where \(\mu\) is the mean atomic weight and \(k\) is the Boltzmann constant. In a fully-ionized solar-metallicity plasma \((n_{\text{He}} = 0.1 n_H)\), the mass density is \(\rho = (n_H + 4 n_{\text{He}}) m_H = 1.4 m_H n_H\), whereas the number electron density and total density are taken as \(n_e = (n_H + 2 n_{\text{He}}) = 1.2 n_H\) and \(n = (n_H + n_{\text{He}} + n_e) = 2.3 n_H\). Therefore, \(\mu\) is calculated to be \(1.4/2.3 \approx 0.61\).

### 2.2.2 Evolution of SNRs

The evolution of SNRs is generally divided into following four phases: free expansion phase, adiabatic phase, radiative phase, and disappearance phase. For simplicity, we assume that the evolution of SNRs occurs in uniform surroundings.

**Free Expansion Phase**

After the SN explosion, the stellar materials are ejected into the surroundings. The ejected materials (ejacta) expand without deceleration (“free expansion”), sweeping up the ambient medium at the leading edge of the ejecta. Since the velocity of the ejecta \([(5 - 10) \times 10^8 \text{ cm s}^{-1}]\) is much larger than the sound speed in the ISM considered here (about \(10^6 \text{ cm s}^{-1}\)), a strong shock wave propagates in the ISM, namely the blast wave (or forward shock). The radius and velocity of the shock are simply expressed by

\[
R_s = v_0 t \tag{2.13}
\]

\[
E_0 = \frac{1}{2} M_0 v_0^2, \tag{2.14}
\]
2.2. SUPERNOVA REMNANT (SNR)

where $E_0$ is the initial explosion kinetic energy and $M_0$ is the total mass of the ejecta. This phase will last until that the swept-up mass becomes comparable to the ejecta mass. The blast wave then gradually decelerates with sweeping up the ISM. The deceleration initiates another shock wave which propagates into the ejecta, that is, a reverse shock (McKee 1974). The boundary between the swept-up ISM and the ejecta is called a “contact discontinuity”. Both the swept-up matter and the ejecta are hot enough to emit X-rays. In this stage, the X-ray emission dominantly comes from the ejecta due to its relatively high density to that of the swept-up ISM. Figure 2.8 displays evolutions of the forward shock, the contact discontinuity, and the reverse shock based on one-dimensional hydrodynamic simulation by Wang & Chevalier (2002). In the plot,

$$t' = \left( \frac{t}{1271 \text{yr}} \right) \left( \frac{M_0}{10 M_\odot} \right)^{-5/6} \left( \frac{E_0}{10^{51} \text{erg}} \right)^{1/2} \left( \frac{n_{am}}{1 \text{ cm}^{-3}} \right)^{1/3} \quad (2.15)$$

$$r' = \left( \frac{r}{4.1 \text{pc}} \right) \left( \frac{M_0}{10 M_\odot} \right)^{-1/3} \left( \frac{n_{am}}{1 \text{ cm}^{-3}} \right)^{1/3} \quad (2.16)$$

where $n_{am}$ is ambient density. At $t' \geq 2.5$, the reverse shock starts turn over in a fixed frame. At $t' \geq 5.7$, the reverse shock reaches the explosion center. The expansion approximately reaches the Sedov phase (see, the next section) at $t' \geq 10$ (Wang & Chevalier 2002).

**Adiabatic Phase**

The mass of the swept-up material is now large compared with the mass of the ejecta. The total energy radiated by the material in the shell is still negligibly small compared with its internal energy, resulting in an adiabatic expansion of the remnant. In this adiabatic stage, we can approximately describe a blast wave of a SNR by a shock wave generated by a point explosion in a uniform medium (Shklovskii 1962). The point explosion is well explained by a self-similar solution (Sedov 1959), and thus, the adiabatic phase is also termed as Sedov phase.

The pattern of the gas flow is completely determined by only two parameters, the density of the surrounding medium, $n_0$, and the initial energy deposited by the explosion, $E_0$. One dimensionless parameter is combined by these parameters and the other two independent parameters, age, $t$, and the position from the center, $r$. It is expressed by

$$\xi = r \left( \frac{n_{am}}{E t^2} \right)^{1/5} . \quad (2.17)$$

The radius of the blast wave, $R_s$, the mean temperature just behind the shock front, $T_s$, and the velocity of the blast wave, $v_s$, are respectively written as
Figure 2.8: Evolution of the forward shock, the contact discontinuity, and the reverse shock radius with time. The dashed line shows the outgoing weak shock wave caused by the reflection of the reverse shock wave at the center (Wang & Chevalier 2002).
2.2. SUPERNOVA REMNANT (SNR)

\[ R_s = 5.0 \left( \frac{E_0}{10^{51} \text{erg}} \right)^{1/5} \left( \frac{n_{am}}{1 \text{cm}^{-3}} \right)^{-1/5} \left( \frac{t}{1000 \text{ yr}} \right)^{2/5} \text{pc}, \quad (2.18) \]

\[ T_s = 4.5 \left( \frac{E_0}{10^{51} \text{erg}} \right)^{2/5} \left( \frac{n_{am}}{1 \text{cm}^{-3}} \right)^{-2/5} \left( \frac{t}{1000 \text{ yr}} \right)^{-6/5} \text{keV}, \quad (2.19) \]

\[ v_s = \frac{2}{5} \frac{R_s}{t} \propto t^{-3/5}. \quad (2.20) \]

The gas flow of physical parameters inside the blast wave can be also derived analytically. Figure 2.9 shows the radial profiles of velocity, density, pressure, and temperature normalized by the values just behind the shock wave.

![Figure 2.9: The radial profiles for the velocity, density, pressure (upper), and temperature (lower) in Sedov similar-solution. All the parameters are normalized at the values just behind the shock front.](image)

**Radiative Cooling Phase**

According to the equation 2.19, the temperature just behind the shock front decreases with time. As shown in Fig. 2.10, the cooling rate increases by enhanced emissivities of line emissions from heavy elements when the temperature of the plasma decreases to \( \sim 10^6 \) K. At this stage, the radiation-energy loss is not negligibly small compared with the initial energy. The remnant thus will be no longer adiabatic (“radiative cooling phase”). The material behind the blast wave, where the density is relatively high to the inner region, cools more efficiently than those in the inner high temperature region. Pressure equilibrium causes dense shell behind the blast wave. Then, the dense shell is driven by
the internal hot gas. Assuming that the internal hot gas expands adiabatically, we can derive the following relations (McKee & Ostriker 1977),

\[ R_s \propto t^{2/7} \]  
\[ v_s \propto t^{-5/7} \]  

This stage is called a pressure-driven snowplow (PDS) stage. Cioffi et al. (1988) calculated the equation of motion of the shell taking into account the transition from Sedov phase to PDS phase, \( R_s \propto t^{3/10} \). As the internal gas cools, the shell still expands due to the momentum conservation. At this so-called momentum-conserving snowplow (MCS) stage, we can derive the following relations,

\[ R_s \propto t^{1/4} \]  
\[ v_s \propto t^{-3/4} \]  

**Dissappearance Phase**

When the expansion velocity of the dense shell drops to the sound speed in the ISM, the shock wave stands no longer. As the result, the emission from the dense shell became
quite faint. After the velocity of the dense shell is comparable to the random motion of the ISM, the remnant becomes indistinguishable from the surrounding medium. The remnant merges into the ISM.

2.2.3 Classification of SNRs

<table>
<thead>
<tr>
<th>a) Shell Type</th>
<th>b) Plerion Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tycho</strong></td>
<td><strong>3C 58</strong></td>
</tr>
<tr>
<td>c) Composite Type</td>
<td>d) Mix-Morphology Type</td>
</tr>
<tr>
<td><strong>G11.2-0.3</strong></td>
<td><strong>W44</strong></td>
</tr>
</tbody>
</table>

Figure 2.11: *Chandra* broad band (0.3–10 keV) X-ray images with radio contours; VLA 1.375 GHz for (a) Tycho’s SNR, VLA 21 cm for (b) 3C58 and (c) G11.2-0.3, and VLA 1.4 GHz for (d) W44. These images are taken from Kawasaki Ph.D. thesis (2003).

Based on the radio-wavelength morphology, SNRs are classified into three types, “shell”, “filled-center”, and “composite” (e.g., Green 2006). The “composite” type tradi-
tionally represents SNRs that have both central (center-filled) and shell components.

**Shell-Type SNRs**

Shell-type SNRs have limb-brightened morphologies in both X-ray and radio bands. These SNRs are further divided into two sub-types in terms of the nature of the X-ray emission: one is the thermal emission from optically-thin hot plasma, the other is the synchrotron non-thermal emission from relativistic electrons accelerated by a shock wave. Typical examples in the former sub-types are the Cygnus Loop, Cassiopeia A SNR, Tycho’s SNR (see, Fig. 2.11 a), and Kelper’s SNR, while those for the latter sub-types are SN1006, RXJ1713.7–3946, RXJ0852–4622. We should note that recent studies of the remnants show that almost all the young remnants such as Cassiopeia A, Tycho’s SNR, and Kelper’s SNR are associated with non-thermal emission (e.g., Bamba et al. 2005).

**Center-Filled-Type (or Plerion/ Crab-like) SNRs**

Center-filled-type SNRs have filled-center morphologies in radio wavelength. The X-ray emission associated with the radio emission is non-thermal origin. The radio and X-ray emission is due to central neutron stars and/or nebulae around the neutron stars. The most typical example in this class is the Crab SNR. Therefore, the “filled-center” type is also called “Plerion” or “Crab-like” type. The other examples are CTB87 and 3C58 (see, Fig. 2.11 b).

**Composite-Type SNRs**

The composite-type SNRs show both limb-brightened and filled-center morphologies. This type has two sub classes by whether the central component is non-thermal origin (traditional composite-type) or thermal origin [mixed-morphology (MM) type named by Rho & Petre (1998)]. On the other hand, the shell component is always the same thermal origin as those of the shell-type SNRs. The Vela SNR, Puppis A, CTB109, G11.2-0.3 (see, Fig. 2.11 c), and so on are included in the traditional composite type, whereas W28, W44 (see, Fig. 2.11 d), and 3C391, etc belong to the MM type.
2.3 Non-Equilibrium in Shock-Heated Plasmas

In the SNR plasmas, we have to consider two non-equilibrium conditions: thermal non-equilibrium and non-equilibrium ionization (NEI). For the explosion ejecta as well as the surrounding ISM, the shock transition occurs on a length scale much shorter than particle mean free paths to Coulomb collisions (so-called “collisionless shock”) due to their extremely low density ($\sim 1 \text{ cm}^{-3}$). In the limit of true collisionless plasma, the temperature $T_a$ reached by particle species, “a”, with mass $m_a$ is given by conservation of energy, momentum, and particles across the shock discontinuity by

$$kT_a = \frac{3}{16} m_a v_s^2.$$  

(2.25)

Therefore, ions which are much heavier than electrons will have much higher temperature than that of electrons (thermal non-equilibrium). Then, electrons are gradually heated due to Coulomb collisions with ions so as to achieve thermal equilibrium. The heated electrons start to ionize the heavy elements by collisions. Since the time scale to reach collisional ionization equilibrium (CIE) is so long that we can see plasmas in the NEI condition for a number of SNRs.

2.3.1 Thermal Non-Equilibrium

We consider Coulomb equilibration between electrons and ions. We assume that the electrons and ions have Maxwellian velocity distributions with different temperature, $T_e$ and $T_i$, respectively. The equipartition of energy between electrons and ions is expressed by (Spitzer 1962)

$$-\frac{dT_e}{dt} = \frac{T_e - T_i}{\tau_{eq}},$$

(2.26)

$$\tau_{eq} = \frac{1}{2} \frac{503 A_i T_e^{1.5}}{n_e Z_i^2 \ln \Lambda} \text{ sec.}$$

(2.27)

where $A_i$, $T_e$, $n_e$, and $Z_i$ are the ion mass in atomic units, electron temperature in K, the electron number density in cm$^{-3}$, and ion charge, respectively. The $\ln \Lambda$ is the Coulomb logarithm ($\sim 30$ in X-ray-emitting plasma of $n_e \approx 1$). This time scale is $\approx 10$ thousand years in a plasma of $A_i = Z_i = n_e = 1$ and $T_e = 1.16 \times 10^7 \text{ K}$. We should note, however, that the initial fraction of the total thermal energy, which is converted from bulk flow energy of roughly $3/16 m_H v_s^2$, going into electrons and protons is controlled by collisionless heating at the shock front and has not yet been understood well. Some authors (McKee 1974; McKee & Hollenbach 1980) argued that plasma instabilities might
heat electrons to the equipartition instantaneously at the shock front. From observational aspects, the degree of equilibration between electrons and protons just behind the shock front seems to have an inverse relationship in terms of the shock velocity as shown in Fig. 2.12 (Rakowski 2005 and references therein).

Figure 2.12: Compilation of current electron–ion equilibration measurements at SNR shocks (Rakowski 2005).

### 2.3.2 Non-Equilibrium Ionization

We here consider processes to reach the CIE condition from the NEI condition. A characteristic timescale for a plasma to reach the CIE condition was derived by Masai (1994, 1984). The collisional ionization rate equation for an element of atomic number $Z$ is written by

\[
\frac{df_z}{d(ndt)} = S_{z-1}f_{z-1} - (S_z + \alpha_z)f_z + \alpha_{z+1}f_{z+1}
\]  

(2.28)

\[
\sum_{z=0}^{Z} f_z = 1
\]

(2.29)

\((z = 0, 1, \ldots, Z),\)
where $f_z$ is an ionic fraction of the element which is ionized $z - 1$ times. $S_z$ and $\alpha_z$ are the ionization and recombination rate coefficients from the $z$-th ion, respectively. The characteristic timescale ($t_{\text{Ieq}}$) to reach an ionization equilibrium can be derived from the solution of the rate equation. At the zero-th order estimation, the timescale is written as follows,

\[
\sum_{z=0}^{Z} (S_z + \alpha_z)^{-1} \approx \left[\min (S_z + \alpha_z)\right]^{-1} \approx 10^{12}\text{cm}^{-3}\text{s}.
\] (2.30)

This value is nearly independent of $Z$ or $T_e$. Assuming that $n_e \sim 1\text{ cm}^{-3}$ as the density of ambient matter of SNRs, $t_{\text{Ieq}} \sim 10^{12}\text{ sec} \sim 10^5\text{ year}$. Figure 2.13 shows the ionic fractions of O, Ne, Mg, and Si species for various temperatures at the CIE condition.
Figure 2.13: Ion fractions for O (upper-left), Ne (upper-right), Mg (lower-left), and Si (lower-right) at the CIE condition as a function of the electron temperature. Thick lines are responsible for ions with closed-shell structures.
2.4  X-Ray Emission from SNR

Most of SNRs may be in the NEI condition due to the long time scale to reach the CIE condition. We here describe some important properties to analyze X-ray spectra from plasmas in the NEI condition.

X-ray spectra from thin thermal plasmas consist of line emission and continuum emission. First, we focus on the line emission. Figure 2.14 shows emissivities of O, Ne, Mg, and Si species for various ionization states as a function of ionization timescale, $n_e t$, at a constant temperature of 1 keV. We employ neiline software provided by Raymond & Smith (Raymond & Smith 1977; updated by Brickhouse et al. 1993) in the calculations. We can constrain the ionization timescale by measuring flux ratios of line emission from the same element but in different ionization states. Also, we can investigate the plasma condition, using K-shell transition lines in He-like ions (hereafter, Heα). Heα line consists of three lines (triplets), i.e., forbidden, inter-combination, and resonance (e.g., Porquet et al. 2000). With the moderate spectral resolution of CCD detectors, it is not possible to resolve the triplets into the individual three lines so that we detect them as a narrow peaked one emission line in our CCD data. Emissivities of the individual lines of the triplets depend on electron temperature as well as ionization timescale. This causes a variation of the center energy of Heα detected in our data. We show the expected center-energy variations of Heα lines for O, Ne, Mg, and Si as functions of electron temperature and ionization timescale in Fig. 2.15. Measuring center energies of the Heα lines and plotting them into the maps in Fig. 2.15, we can constrain the plasma condition.

Continuum emission consists of three components: free-free (or bremsstrahlung) emission, free-bound emission, and two-photon decay emission. Figure 2.16 shows the individual continuum spectra at $kT_e = 0.28$ keV and log($\tau$) = 11.5, based on the calculation by Masai (1984).
Figure 2.14: Emissivities from ions in various ionization states for O, Ne, Mg, and Si.
Figure 2.15: Center energies of triplets from He-like ions for O, Ne, Mg, and Si plotted in the $kT_e$–log($\tau$) plane.
Figure 2.16: Continuum spectrum from plasma at $kT_e = 0.28\text{keV}$ and $\log(\tau) = 11.5$. Free-free, free-bound, two-photon decay, and the total emission are shown as dashed, dash-dotted, dotted, and solid lines, respectively.
Chapter 3

Instruments

3.1 Suzaku

3.1.1 Overview of the Satellite

The fifth in a series of Japanese X-ray astronomy satellites, Suzaku (Mitsuda et al. 2007), devoted to observations of celestial X-ray sources, was launched by Japan Aerospace Exploration Agency (JAXA) with the M-V launch vehicle from JAXA’s Uchinoura Space Center (USC) on 2005 July 10. After launch, Suzaku first deployed its solar paddles and an extensible optical bench (EOB), and performed ∼ 10 days of a perigee-up orbit maneuver to get into a near circular orbit at 570 km altitude with an inclination angle of $31^\circ$. The orbital period was about 96 minutes.

The scientific payload of Suzaku (Fig. 3.1) initially consisted of three distinct co-aligned scientific instruments. There are four X-ray sensitive imaging CCD cameras (X-ray Imaging Spectrometer, XIS, Koyama et al. 2007), three front-illuminated (FI: energy range 0.4-12 keV) and one back-illuminated (BI: energy range 0.2-12 keV), capable of moderate energy resolution. Each XIS is located in the focal plane of a dedicated X-ray telescope (XRT, Serlemitsos et al. 2007). The second instrument is a non-imaging, collimated Hard X-ray Detector (HXD, Takahashi et al. 2007), which extends the bandpass of the observatory to much higher energies with its 10–600 keV bandpass (Kokubun et al. 2007). The last instrument is a X-Ray Spectrometer (XRS: Kelley et al. 2007) with superior energy resolving power (7 eV in the energy range 0.3 to 12 keV). Due to a thermal short between the helium and neon tanks which resulted in the liquid helium coolant venting to space, the system became inoperable. Since we use data taken by XIS detector, we will show abilities of the XIS in the following section. The detailed explanation for the Suzaku satellite can be found in http://heasarc.gsfc.nasa.gov/docs/astroe/.
3.1.2 X-Ray Imaging Spectrometer (XIS)

The X-ray Imaging Spectrometer (XIS) employs X-ray sensitive silicon charge-coupled devices (CCD), which are operated in a photon-counting mode, similar to that used in the ASCA SIS (Burke et al. 1994; Yamashita et al. 1997), Chandra ACIS (Garmire et al. 1992; Bautz et al. 1998), and XMM-Newton EPIC (Strüder et al. 2001; Turner et al. 2001). The XIS consists of four sets: one set of the XIS, XIS1, uses a back-illuminated CCD, while the other three (XIS0, XIS2, XIS3) use front-illuminated CCDs1. Each XIS sensor has one CCD chip, which is a Metal Oxide Semi-conductor (MOS)-type three-phase CCD operated in the frame transfer mode. The picture of the CCD chip is displayed in Fig. 3.2 left. The CCD consists of four segments (A, B, C, and D), each with a dedicated read-out node. A schematic view of the CCD can be seen in Fig. 3.2 right. The specification of the XIS CCD combined with the XRT is summarized in table 3.1.2. Fig. 3.3 shows the on-axis effective areas of XIS.

There are two kinds of modes in XIS, i.e. normal and parallel sum (P-sum) modes.

- Normal Mode

---

1Note that XIS2 suddenly showed anomaly on Nov 9, 2006, 1:03 UT. About 2/3 of the image was flooded with a large amount of charge, which was leaked somewhere in the imaging region. In spite of efforts by the Suzaku team, it seems to be difficult to recover XIS2. It is unlikely to resume the operation of XIS2 in future.
Table 3.1: Suzaku XIS characteristics - an overview

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandpass</td>
<td>0.2-12 keV</td>
</tr>
<tr>
<td>Number of Pixels (1 chip)</td>
<td>1024×1024</td>
</tr>
<tr>
<td>Pixel size</td>
<td>24 μm (1&quot;) square</td>
</tr>
<tr>
<td>Field of view</td>
<td>17.8 square</td>
</tr>
<tr>
<td>PSF (HPD)</td>
<td>2&quot;</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>8 s (normal) / 7.8 ms (P-sum)</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>∼70 eV at 1 keV (FWHM)</td>
</tr>
</tbody>
</table>

The exposure time is 8 seconds, and all the pixels on the CCD are read out every 8 seconds.

- Parallel Sum (P-sum) Mode
  The pixel data from multiple rows are summed in the Y-direction on the CCD, and the sum is put in the Pixel RAM as a single row. The number of rows to add is commandable, but only 128-row summation is supported at present. The Y coordinate is used to determine the event arrival time. As a result, no spatial resolution is available in the Y-direction. The time resolution of the Parallel Sum Mode is 8 s/1024 ∼ 7.8 ms.

![Figure 3.2: Left: The picture of CCD chip. Right: Schematic view of the XIS CCD (top view). The CCD consists of four segments (A, B, C, and D), each with a dedicated read-out node.](image-url)
Figure 3.3: Effective area of one XRT+XIS system, for both the FI (XIS0, 2, 3) and BI (XIS1) CCDs.
3.2 XMM-Newton

3.2.1 Overview of the Satellite

*XMM-Newton* is the second of European Space Agency (ESA)’s X-ray astronomy satellite which was launched on December 10th, 1999 and carries two distinct types of telescope: three Wolter type-1 X-ray telescopes, with different X-ray detectors in their foci, and a 30-cm optical/UV telescope with a microchannel-plate pre-amplified CCD detector in its focal plane. Thus, XMM-Newton offers simultaneous access to two windows of the electromagnetic spectrum: X-ray and optical/UV. The details are described in *XMM-Newton* User’s Handbook which is available from http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/.

Figure 3.4: Sketch of the *XMM-Newton* payload. The mirror modules, two of which are equipped with Reflection Grating Arrays, are visible at the lower left. At the right end of the assembly, the focal X-ray instruments are shown: The EPIC MOS cameras with their radiators (black/green “horns”), the radiator of the EPIC pn camera (violet) and those of the (light blue) RGS detectors (in pink). The OM telescope is obscured by the lower mirror module.

XMM-Newton provides the following three types of science instrument:
• European Photon Imaging Camera (EPIC)
Three CCD cameras for X-ray imaging, moderate resolution spectroscopy, and X-ray photometry; the two different types of EPIC camera, MOS and pn. A bit more detailed explanation of EPIC cameras are described in the following section. *XMM-Newton* carries two MOS cameras and one pn. We used these detectors in this thesis.

• Reflection Grating Spectrometer (RGS)
Two essentially identical spectrometers for high-resolution X-ray spectroscopy and spectro-photometry.

• Optical Monitor (OM) For optical/UV imaging and grism spectroscopy.

The three EPIC cameras and the two detectors of the RGS spectrometers reside in the focal planes of the X-ray telescopes, while the OM has its own telescope. A sketch of the *XMM-Newton* payload is displayed in Fig. 3.4. There are in total six science instruments on board *XMM-Newton*, which are operated simultaneously. The instruments can be operated independently and each in different modes of data acquisition. Observers receive data from all science instruments.

### 3.2.2 European Photon Imaging Camera (EPIC)

Two of *XMM-Newton*’s X-ray telescopes are equipped with EPIC MOS (Metal Oxide Semi-conductor) CCD arrays (Turner et al. 2001), the third carries a different CCD camera called EPIC pn (Strüder et al. 2001). The two types of EPIC camera are fundamentally different. This does not only hold for the geometry of the MOS chip array and the pn chip array, but other properties as well, like e.g., their readout times. In a nutshell, the *XMM-Newton* EPIC cameras offer the possibility to perform extremely sensitive imaging observations over a field of view of 30′ and the energy range from 0.152 to 15 keV, with moderate spectral ($E/\Delta E \sim 20–50$) and angular resolution (6′ FWHM; 15′ HPD). The pn type camera can be operated with very high time resolution down to 0.03 ms in the timing mode and 0.007 ms (but with a very low duty cycle of 3%) in the burst mode. The absolute timing accuracy is determined by the process which correlates the on-board time to the universal time.

The detector layout and the baffled X-ray telescope FOV of both types of EPIC camera are shown in Figs. 3.5 and 3.6. The MOS chip arrays consist of 7 individual identical, front-
Figure 3.5: *Left:* The CCDs of one of the MOS cameras in the cryostat. *Right:* The CCDs of the pn camera. The picture shows the twelve chips mounted and the connections to the integrated preamplifiers.

Figure 3.6: A rough sketch of the field of view of the two types of EPIC camera; MOS (left) and pn (right). The shaded circle depicts a 30' diameter area. For the alignment of the different cameras with respect to each other in the XMM-Newton focal plane refer to the text.
illuminated chips\textsuperscript{3}. The MOS cameras are mounted on those X-ray telescopes that also carry RGS instruments. Therefore, they receive only 44% of the reflected light. The heart of the pn camera is a single Silicon wafer with 12 CCD back-illuminated chips integrated. The most important characteristics of XMM-Newton are compiled in Table 3.2.2. The on-axis effective areas of EPIC and RGS folded through the response of the different focal instruments are shown in Fig. 3.7.

The EPIC cameras allow several modes of data acquisition. Note that in the case of MOS the outer ring of 6 CCDs remain in standard imaging mode while the central MOS CCD can be operated separately. Thus all CCDs are gathering data at all times, independent of the choice of operating mode. The pn camera CCDs can be operated in common modes in all quadrants for full frame, extended full frame and large window mode, or just with one single CCD (CCD number 4 in Fig. 3.6) for small window, timing and burst mode.

- “full frame” and “extended full frame” (pn only)
  
  In this mode, all pixels of all CCDs are read out and thus the full FOV is covered.

- “partial window”
  
  a) MOS
  
  In a partial window mode the central CCD of both MOS cameras can be operated in a different mode of science data acquisition, reading out only part of the CCD chip.
  
  b) pn
  
  In large window mode only half of the area in all 12 CCDs is read out, whereas in small window mode only a part of CCD number 4 is used to collect data.

- “timing”
  
  a) MOS + pn In the timing mode, imaging is made only in one dimension, along the column (RA WX) axis. Along the row direction (RA WY axis), data from a predefined area on one CCD chip are collapsed into a one-dimensional row to be read out at high speed. Since the 2 MOS cameras orientation differ by 90 degrees, the

\textsuperscript{3}Note that at about 01:30 hrs. UT on 09 March, 2005, during XMM-Newton revolution 961, an event was registered in the focal plane of the EPIC MOS1 instrument. The characteristics of the event might be attributed to a micrometeoroid impact scattering debris into the focal plane. In the period immediately following a light flash it became apparent that MOS1 CCD6 was no longer recording events, and that all CCD6 pixels were, in effect, returning signal at the saturation level raising the possibility that CCD6 had sustained significant damage. At the time of writing, scientific observations are continuing normally with XMM-Newton, including MOS1, but with the peripheral CCD6 (see, Fig. 3.6) switched off.
3.2. **XMM-NEWTON**

Table 3.2: **XMM-Newton EPIC characteristics - an overview**

<table>
<thead>
<tr>
<th></th>
<th>EPIC MOS</th>
<th>EPIC pn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination method</td>
<td>Front Illuminated</td>
<td>Back Illuminated</td>
</tr>
<tr>
<td>Bandpass</td>
<td>0.15*-12 keV</td>
<td>0.15*-15 keV</td>
</tr>
<tr>
<td>Number of Pixels (1 chip)</td>
<td>600×600 (Full Frame)</td>
<td>378×64 (Full Frame)</td>
</tr>
<tr>
<td>Pixel size</td>
<td>40 µm (1″.1) square</td>
<td>150 µm (4″.1) square</td>
</tr>
<tr>
<td>Field of view</td>
<td>30′ diameter</td>
<td>30′ diameter</td>
</tr>
<tr>
<td>PSF (FWHM/HPD)</td>
<td>5″/14″</td>
<td>6″/15″</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>1.75 ms</td>
<td>0.03 ms</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>~70 eV</td>
<td>~80 eV</td>
</tr>
</tbody>
</table>

*In practice, we cannot obtain useful data below 0.5 keV due to significant tail events.

“imaging” directions in the 2 MOS are perpendicular to each other.

b) pn only

A special flavour of the timing mode of the EPIC pn camera is the “burst” mode, which offers very high time resolution, but has a very low duty cycle of 3%.
Figure 3.7: The net effective area of all *XMM-Newton* X-ray telescopes, EPIC and RGS.
3.3. CHANDRA

3.3.1 Overview of the Satellite

The Chandra X-ray Observatory (Weisskopf et al. 2002) was launched by National Aeronautics and Space Administration (NASA)'s space shuttle Columbia on July 23, 1999. The Chandra spacecraft carries a high resolution mirror assembly (HRMA), two imaging detectors, and two sets of transmission gratings. The most important Chandra feature is an order of magnitude higher spatial resolution among other X-ray satellites. The details are described in http://cxc.harvard.edu/proposer.

![Chandra Flight System Diagram](image)

Figure 3.8: Expanded view of the Chandra flight system, showing several subsystems (Weisskopf et al. 2002).

There are two focal plane instruments. One is an array of charged coupled devices, the Advanced CCD Imaging Spectrometer (ACIS). A two-dimensional array of these small detectors does simultaneous imaging and spectroscopy. Pictures of extended objects can be obtained along with spectral information from each element of the picture. The second instrument is a High Resolution Camera (HRC). It is used for high resolution imaging, fast timing measurements, and for observations requiring a combination of both. There are two transmission grating spectrometers, formed by sets of gold gratings placed just behind the mirrors. One set is optimized for low energies (LETG) and the other for high energies (HETG). Spectral resolving powers (E/ΔE) in the range 100 to over 1000 can be achieved with good efficiency. These produce spectra dispersed in space at the focal plane. Either the ACIS array or the HRC can be used to record data.
3.3.2 Advanced CCD Imaging Spectrometer (ACIS)

The engineering model ACIS focal plane is shown in Fig. 3.9. The ACIS has two arrays of CCDs, one (ACIS-I) optimized for imaging wide fields (16×16 arc minutes) the other (ACIS-S) optimized as a readout for the HETG transmission grating. One chip of the ACIS-S (S3) can also be used for on-axis (8×8 arc minutes) imaging and offers the best energy resolution of the ACIS system. The schematic locations of the ACIS CCD chips are shown in Fig. 3.10. Chips S3 and S1 are BI chips. The other chips are all FI. The specification of the ACIS combined with the XRT is summarized in table 3.3.2. The effective area of the XRT/ACIS combination for the S3 chip is shown in Fig. 3.11.

There are two operating modes (Timed Exposure/Continuous Clocking) for the ACIS CCDs.

- Timed Exposure (TE) Mode
  A timed exposure refers to the mode of operation wherein a CCD collects data (integrates) for a preselected amount of time - the Frame Time. Once this time interval has passed, the charge from the 1024×1024 active region is quickly (∼41 ms) transferred to the framestore region and subsequently read out through (nominally) 1024 serial registers. If the data from the entire CCD are utilized (full frame) then the nominal frame time is 3.2 s.

- Continuous Clocking (CC) Mode
  The continuous clocking mode is provided to allow 3 msec timing at the expense of one dimension of spatial resolution. In this mode, one obtains 1 pixel × 1024 pixel images, each with an integration time of 2.85 msec. Details as to the spatial distribution in the columns are lost - other than that the event originated in the sky along the line determined by the length of the column.
Figure 3.9: The ACIS CCD focal plane. The ten CCD detectors are arranged in two subarrays.

Figure 3.10: Locations and orientations of chips chosen for ACIS flight focal plane.
Table 3.3: Chandra ACIS characteristics - an overview

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandpass</td>
<td>0.2-10 keV</td>
</tr>
<tr>
<td>Number of Pixels (1 chip)</td>
<td>1024×1024</td>
</tr>
<tr>
<td>Pixel size</td>
<td>24 μm (0′.492) square</td>
</tr>
<tr>
<td>Field of view (ACIS-I array)</td>
<td>16′.9 square</td>
</tr>
<tr>
<td>Field of view (ACIS-S array)</td>
<td>8′.3 by 50′.6</td>
</tr>
<tr>
<td>PSF (FWHM)</td>
<td>0′.5</td>
</tr>
<tr>
<td>Timing resolution (FWHM)</td>
<td>3.2 s (TE Mode) / 2.8 ms (CC Mode)</td>
</tr>
<tr>
<td>Spectral resolution (FWHM)</td>
<td>~70 eV at 1 keV</td>
</tr>
</tbody>
</table>

*In practice, we cannot obtain useful data below 0.5 keV due to significant tail events.*

Figure 3.11: Comparison of the on-axis effective areas for observing a point source (integrated over the PSF) of the HRMA HRC-I, the HRMA/ACIS(FI), and the HRMA/ACIS(BI) combinations. The ACIS curves show the predicted values for the middle of Cycle 9 (2008-05-15).
Chapter 4

Vela SNR

4.1 Previous Results

4.1.1 Discovery of Shrapnels

The nucleosynthetic process inside a star generates heavy elements, and SN explosions spew them out into the interstellar space. Fragments of the ejecta have been found in some SNRs, e.g., fast-moving knots in Cas A (e.g., Kirshner & Chevalier 1977; Fesen et al. 2002), southeastern knots in Tycho SNR (Decourchelle et al. 2001) and several X-ray-emitting regions in the vicinity of the Vela SNR (Aschenbach et al. 1995, hereafter AET).

The Vela SNR is one of the representative SNRs in the X-ray sky. The age is estimated to be \(\sim 11400\) years old (Taylor et al. 1993) and the distance to the SNR is estimated to be \(\sim 250\) pc (Cha et al. 1999; Bocchino et al. 1999). It is so close to us that the angular diameter of the Vela SNR is very large, making it an ideal target for studying fine structures of the SNR. Figure 4.1 shows the three-color entire Vela SNR obtained by ROSAT all sky survey. Red corresponds to 0.1–0.4 keV, green to 0.5–1.3 keV, and blue to 1.3–2.0 keV. Large molecular clouds interacting the blast wave in the NE portion of the remnant (Moriguchi et al. 2001) is considered to cause the enhanced red color there. The image reveals that the Vela SNR has an almost circular appearance with a diameter of \(8^\circ.3\) (AET) which corresponds to \(\sim 36\) pc at a distance of 250 pc. There are a significant amount of protruding features beyond the primary blastwave. Some of them have boomerang structures whose opening angles suggest supersonic motion in a tenuous matter. The configuration and symmetry suggest that all the shrapnels originated from the center of the main shell which is very close to the Vela pulsar, PSR B0833–45 (Taylor et al. 1993). AET named them 'shrapnels' (from “A” to “F”). The locations and the
expanded *ROSAT* images for the seven shrapnels are shown in Fig. 4.1 and Fig. 4.2, respectively. We note that recent *XMM-Newton* observations of the northern portion of the Vela SNR revealed possible candidates of shrapnels observed, in projection, inside the Vela shell (Miceli et al. 2008) which we cannot identify in Fig. 4.1.

Figure 4.1: *ROSAT* all-sky survey image of the entire Vela SNR. The intensity is logarithmically scaled. The data have been smoothed with a Gaussian of $\sigma = 2'.3$. The locations of seven shrapnels are indicated as from “A” to “F”. The brightest feature in the NW rim of the Vela SNR is the Puppis A SNR. The faint blue circle (whose radius of $\sim 2^\circ$) in the SE portion is a non-thermal dominated young SNR, RXJ0852.0–4622 discovered by Aschenbach (1998). North is up and West is right. Hereafter, all the images have the same direction.

### 4.1.2 Shrapnel A

Vela shrapnel A was observed with *ASCA* (Tsunemi et al. 1999, hereafter TMA). It was clarified that the abundance of Si is about 10-times higher than that of O. Therefore, TMA concluded that the shrapnel A was an explosion ejecta from a Si-rich layer of a progenitor star. If it is ejecta of a SN explosion, the interstellar matter would be swept
Figure 4.2: Magnified X-ray images of the seven shrapnels indicated in Fig. 4.1 (AET).
CHAPTER 4. VELA SNR

up in the leading edge while the ejecta material would be peeled off in the trailing edge. However, the spatial distribution of Si could not be measured due to the poor spatial-resolving power of ASCA. In order to investigate the spatial structure of the shrapnel A, Miyata et al. (2001; hereafter MTAM) observed it with Chandra. The Chandra image reveals a bright X-ray region at the head position of the shrapnel A and a fainter extended tail (Fig. 4.3). They confirmed an overabundance of Si in the head region, but could not obtain a strong constraint on the parameters of the tail region. To reveal the abundance distributions in the shrapnel A was left as future work.

![Figure 4.3: Chandra ACIS image of Vela shrapnel A (MTAM).](image)

### 4.1.3 Shrapnel D

While the shrapnels are considered to originate from fragments of supernova (SN) ejecta that are beyond the position of the main blast wave, there is an alternative explanation that the features are “break-outs” of shock in which inhomogeneities in the ambient medium cause the shock to be non-spherical. The shrapnel D, the eastern limb of the Vela SNR, is the closest to the main shell and the brightest in X-rays of the seven shrapnels. The optical nebula RCW 37 (Rodgers et al. 1960) lies along the outer edge of the shrapnel D, which clearly shows that the shrapnel D is now interacting with an interstellar cloud. Sankrit et al. (2003) observed this optical filament and found that the shrapnel
D was a bow shock propagating into an interstellar cloud with normal (i.e., about solar) abundances. In order to understand the nature of the shrapnel D, Plucinsky et al. (2002) observed it two times with Chandra, one at the head of the shrapnel and the other in the trailing “wake”. If the X-ray emission associated with the shrapnel D is produced by shock-heating of the ambient medium by supersonic motion of the ejecta, one would expect the abundances to be enhanced at the head region and close to the ISM value at the wake region. They found that the spectra from the different locations in the shrapnel are remarkably similar to each other. They did not show the abundance variations that might be expected from a fragment of ejecta. However, they could not obtain strong constraints on the elemental abundances: the O and Ne abundances vary from 0.5 to 5.0 × solar and 1.6 to 6.4 × solar, respectively. They therefore concluded that the origin of the shrapnel D is more consistent with a shock breakout hypothesis than with an ejecta hypothesis, although they could not rule out the ejecta hypothesis.
4.2 Observations and Data Reductions

Table 4.1: \textit{XMM-Newton} Observations of the Vela Shrapnels

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Coordinate (RA, DEC)</th>
<th>Roll</th>
<th>Obs. Date</th>
<th>GTI (ksec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0112870101 (&quot;A&quot;)</td>
<td>134.417, -41.852</td>
<td>127°.5</td>
<td>2000.12.07</td>
<td>MOS=45, PN=29.9</td>
</tr>
<tr>
<td>0136010101 (&quot;D&quot;)</td>
<td>134.884, -45.755</td>
<td>277°.8</td>
<td>2002.05.02</td>
<td>MOS=21.0, PN=14.0</td>
</tr>
<tr>
<td>0112870201 (&quot;E&quot;)</td>
<td>119.900, -44.376</td>
<td>274°.2</td>
<td>2001.04.17</td>
<td>MOS=5.1, PN=5.0</td>
</tr>
</tbody>
</table>

With the large effective area and FOV as well as moderate energy and spatial resolution of the \textit{XMM-Newton} satellite, we can precisely determine elemental abundances in the shrapnels, which is the key point to understand the origin of the shrapnels. Also, we can reveal elemental distributions in good constraints by \textit{XMM-Newton} observations. Therefore, we observed the shrapnel D with \textit{XMM-Newton}. In addition, we analyzed archival \textit{XMM-Newton} data of the shrapnel A and E. The main information of the observations analyzed here is summarized in table 4.1.

The EPIC MOS cameras are operated in the standard full-frame mode and the EPIC PN camera in the extended full-frame mode. We select X-ray photons corresponding to patterns 0–12 for MOS and patterns 0 (0–4 for the shrapnel D) for PN, respectively. In order to subtract background data from the same region as the source region on the CCD, we use observations of the Lockman Hole as background data for the shrapnels A and D. As for the shrapnel A, we use observation ID 0123700401 for MOS1 and PN and observation ID 0147511701 for MOS2, respectively. Note that we have to select background data such that the optical blocking filters used correspond to those used in the observation of the shrapnel A. We use the observation ID 0147511701 as background for all the data sets of the shrapnel D. On the other hand, for the shrapnel E, we subtract background emission from the same data set since the data are affected by flaring events (details are shown in the following section).

We have used the XMM Science Analysis System (XMMSAS, version 6.1.0, version 5.4.1 only for the exposure map) for data reduction of shrapnels A and D, while XMMSAS version 6.5.0 for the shrapnel E.
4.3 Shrapnel A

We present results of XMM-Newton observation of the shrapnel A, which were published in Katsuda & Tsunemi (2006).

4.3.1 Image Analysis

Figure 4.4: EPIC MOS1 + MOS2 logarithmically scaled image in the energy range of 0.2–3.0 keV. The data have been smoothed with a Gaussian of $\sigma = 12''$. The spectra from the ellipse and square are shown in Fig. 4.6.

Figure 4.4 shows an exposure-corrected MOS1 + MOS2 image of the shrapnel A that is seen as a triangular-shaped feature located from the center to the southwestern edge of the FOV. We extract the image in the energy range of 0.2–3 keV and extract the exposure map using XMMSAS v 5.4.1 (the `exppmap` command). We smooth the image by a Gaussian of $\sigma = 12''$. We can see a bright X-ray knot feature and extended trailing emission toward the main shell of the Vela SNR as MTAM found by Chandra. Figure 4.5 Upper is the image of the shrapnel A along the direction to the center of the Vela SNR. Figure 4.5 lower shows the projection of the intensity of the upper image. We can see a bright knot region as well as a trailing part. Hereafter, we define the bright region as the head and the following region as the tail as shown in Fig. 4.5 lower. There is also several point sources in the FOV. The brightest one is CU Velorum, located at the eastern edge of the FOV.
Figure 4.5: *Upper:* Same as Fig. 4.4 but focused on the shrapnel A and rotated such that the moving direction becomes horizontal. *Lower:* The X-ray intensity projected from the upper image. Note that obvious point sources were not removed from the profile.

### 4.3.2 Spectral Analysis

We investigate spectral variations from various regions in detail. We extract spectra from a rectangle of $2' \times 2'$ for the head region and from that of $4' \times 10'$ for the tail region, respectively. The size is selected such that we can obtain sufficient number of photons in each rectangle (1700~4500 photons for the MOS1 detector). We arrange rectangles such that each rectangle overlaps each other by half of its size and all the rectangle fully cover the shrapnel A, obtaining 24 spectra for head region and 5 spectra for tail region in total. We remove visible point-like sources for the spectral analysis.

**Head Region**

We find that all the spectra in the head region are remarkably similar to each other. The spectra from one of the $2' \times 2'$ boxes in the head region and the spectra from the entire head region indicated in Fig. 4.4 are shown in Fig. 4.6 *Upper* and *lower*, respectively. We can see a prominent Si Ly$_\alpha$ line in the spectra which is consistent with those from *ASCA* (TMA) and *Chandra* (MTAM). The high efficiency and the high energy resolution of the EPIC instrument clearly show the emission lines from O He$\alpha$ triplets at 0.57 keV and Ly$\alpha$ at 0.65 keV for the first time. Moreover, we can see emission like structures below
We fit all the spectra by an absorbed NEI model \texttt{wabs} (Morrison & McCammon 1983) and \texttt{vnei} model (NEI version 2.0) (Hamilton et al. 1983; Borkowski et al. 1994, 2001; Liedahl et al. 1995) in XSPEC v11.3.1 (Arnaud 1996) with a single electron temperature, $kT_e$, and a single ionization parameter, $\tau$, where $\tau$ is the number density of electron ($n_e$) times the elapsed time after the shock heating. Our free parameters are the $kT_e$, $\tau$, the column density, $N_H$, the emission measure (hereafter EM, $EM = \int n_e n_H dl$, where $n_H$ is the number densities of hydrogen, and $dl$ is the plasma depth); and abundances of C, N, O, Ne, Mg, Si, Fe. All the abundances listed above are allowed to vary separately from each other. We set the abundances of other elements to the solar values (Anders & Grevesse 1989). All the spectra are well represented by our model. All the reduced $\chi^2$ are about unity. We find that the best-fit parameters from all the spectra in the head region are identical to each other from the statistical point of view. Table 4.2 shows the best-fit parameters of the spectra from the entire head region. We re-fit all the spectra in the head region by the \texttt{vnei} model whose parameters of abundances fixed to the values

### Table 4.2: Spectral-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Head region in Fig. 4.4</th>
<th>Tail region in Fig. 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H[10^{20}\text{cm}^{-2}]$</td>
<td>$3.2^{+1.4}_{-0.4}$</td>
<td>$1.4^{+0.02}_{-0.01}$</td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>$0.52\pm0.01$</td>
<td>$0.37\pm0.01$</td>
</tr>
<tr>
<td>C</td>
<td>$2.5\pm0.2$</td>
<td>$2.6^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>N</td>
<td>$0.55^{+0.06}_{-0.08}$</td>
<td>$0.5^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>O</td>
<td>$0.34\pm0.01$</td>
<td>$0.4^{+0.01}_{-0.02}$</td>
</tr>
<tr>
<td>Ne</td>
<td>$1.07\pm0.04$</td>
<td>$1.28^{+0.09}_{-0.07}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$0.87\pm0.08$</td>
<td>$0.96^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>Si</td>
<td>$3.3\pm0.3$</td>
<td>$3.7^{+0.7}_{-1.0}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$0.96\pm0.03$</td>
<td>$1.10^{+0.08}_{-0.07}$</td>
</tr>
<tr>
<td>log($\tau$) [s cm$^{-3}$]</td>
<td>$10.75\pm0.02$</td>
<td>$10.97^{+0.04}_{-0.03}$</td>
</tr>
<tr>
<td>EM[cm$^{-5}$]</td>
<td>$(2.35^{+0.1}_{-0.03}) \times 10^{17}$</td>
<td>$(0.53^{+0.04}_{-0.02}) \times 10^{17}$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>705/465</td>
<td>698/544</td>
</tr>
</tbody>
</table>

Other elements are fixed to those of solar values.

The values of abundances are multiples of solar value.

The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.
Figure 4.6: X-ray spectra extracted from the head region. Upper panel shows an example spectrum from one of the $2' \times 2'$ boxes of the head region while lower panel shows the spectra from the entire head region shown in Fig. 4.4. The best-fit curves are shown with solid lines and the lower panels show the residuals.
Figure 4.7: X-ray spectrum of MOS1 from Fig. 4.5 right. The solid line represents the best-fit model, while the broken lines represent the individual component. The lower panel shows the residuals.

obtained for the entire head region, finding acceptable fits for all the regions (\(\chi^2/d.o.f.\) are 0.9\textasciitilde1.2). This fact confirms the uniformity of the elemental abundances in the head region. The temperature shown in table 4.2 is about 0.5 keV which is consistent with the result by MTAM. The values of \(\tau\) measured indicate that the plasma is far from the ionization equilibrium that is consistent with the result obtained by Chandra (MTAM, 11.1\pm0.2). The abundance of Si is about 3 times solar value, whereas that of O is about 0.3 times solar value, which is also consistent with the result from MTAM. The absolute abundance predicted by the spectral fits depends on the model employed, and is strongly correlated with the other parameters. The absolute values depend on the model while the abundance ratio between Si and O, 10\pm1 is relatively reliable.

It is doubtful that the small peaks at \(~0.36\text{ keV}\) and \(~0.44\text{ keV}\) really come from the emission lines from C He\(\alpha\) and C He\(\beta\), respectively since they can be seen only in the MOS1 spectrum shown in Fig. 4.6 Upper. Therefore, the fact that the abundance of C obtained by the vnei model is significantly higher than the solar value (see, table 4.2) is also doubtful. In order to reveal whether the two peaks seen in the MOS1 spectrum really come from C or not, we compare the flux ratio of C He\(\alpha\) / C He\(\beta\) obtained by MOS1 spectrum with expected values at various \(kT_e\) and \(\tau\). We determine the fluxes of C He\(\alpha\)
Figure 4.8: The predicted fluxes of C Heα and the C Heβ as a function electron temperature and ionization timescale (solid, dashed and dotted correspond to 10.75, 11 and 12 of log (τ), respectively). The fluxes measured are indicated as the upper shaded region (for C Heα) and the lower shaded region (for C Heβ). The lower panel shows the ratio of C Heα to C Heβ.
and C He\(\beta\) using a combination model; a vnei model with the abundance of C fixed to zero and two Gaussians (one for C He\(\alpha\) the other for C He\(\beta\)). We show the best-fit curve and the separated three components in Fig. 4.6 Upper. We obtain the line flux for C He\(\alpha\) and C He\(\beta\) to be \(5.5_{-0.8}^{+0.9} \times 10^{-4}\) photons sec\(^{-1}\) cm\(^{-2}\) and \(1.6_{-0.3}^{+0.4} \times 10^{-4}\) photons sec\(^{-1}\) cm\(^{-2}\), respectively. Therefore, the flux ratio of C He\(\alpha\) to C He\(\beta\) is estimated to be \(3.6_{-0.9}^{+1.0}\). We compare this value to that obtained by the NEI plasma model by using neiline software. The neiline software calculates \((n_Z/n_H)\odot(n_z(\tau)/n_Z)\epsilon_i(T)\) at constant temperature and \(\tau\) where the code evolves the plasma using the Raymond & Smith (1977; update by Brickhouse et al. 1993) plasma code, where \(n_Z/n_H\) is the abundance of the element in question relative to hydrogen, \(n_z(\tau)/n_Z\) is the ionization fraction of the ionization species responsible for the line, \(\epsilon_i(T)\), a function of temperature, is the intrinsic emissivity of the line. We show the expected fluxes of C He\(\alpha\) and C He\(\beta\) from the plasma with solar abundance as a function of electron temperature in Fig. 4.8 Upper. We calculate the emissivities for three cases; they are log(\(\tau\)) to be 10.75, 11 and 12 where 10.75 is the best fit value in Fig. 4.6 right. The emissivities measured are indicated by the shaded areas; upper for C He\(\alpha\) and lower for C He\(\beta\). We confirmed the over abundance of C at \((kT_e, \log(\tau))=(0.52\text{ keV, } 10.75)\) which were the best-fit values obtained by the vnei model. Figure 4.8 lower shows the ratio of C He\(\alpha\) to C He\(\beta\). The ratio measured is plotted as the meshed region in Fig. 4.8 lower. The flux ratio measured can be achieved only above \(\sim 3\) keV of electron temperature whatever the ionization parameter is. The \(kT_e\) is far from the value obtained by the vnei model. Since there is no indication of another high temperature component in the spectrum, it is natural to consider that the peaks at 0.36 keV and 0.44 keV do not come from C He\(\alpha\) and C He\(\beta\). In conclusion, the abundance of C determined by the vnei model is highly uncertain considering the ratio of flux.

The difference in spectra between the MOS1 and the MOS2 might come from the difference of the optical blocking filters employed; MOS1 was operated using a thin filter while MOS2 was operated using a medium filter. The MOS1 spectrum is probably suffering from pile-up effects that produced spurious peaks at 0.36 keV and 0.44 keV.

Tail Region

We apply an absorbed vnei model to each spectrum and obtained relatively good fits (the reduced \(\chi^2\) ranged from 1 to 1.3, depending on degrees of freedom from 315 to 457). We find that the \(kT_e\), \(\tau\) and abundances obtained by each spectrum does not show significant differences with each other. The spectra from one of the \(4' \times 10'\) boxes in the tail region and the spectra from the entire tail region indicated in Fig. 4.4 are shown in Fig. 4.9 Upper and lower, respectively. The spectra from the tail region are slightly different from
Figure 4.9: X-ray spectra extracted from the tail region. Upper panel shows an example spectrum from one of the 4'×10' boxes of the tail region while lower panel shows the spectra from the entire tail region shown in Fig. 4.4. The best-fit curves are shown with solid lines and the lower panels show the residuals.
those of the head region. The apparent difference of the spectra between the head region and the tail region are the flux ratio of O He\(\alpha\) and O Ly\(\alpha\). The best-fit parameters for the spectrum from the entire tail region are shown in the table 4.2 (Tail region). We are able to determine the abundance of Si for the tail region to be higher than solar value. The abundance ratio of Si to O, \(\frac{11}{16}^{+5}_{-4}\), is in good agreement with that of the head region whereas the \(kT_e\) is significantly lower than that of the head region.

Temperature, Density and Pressure Distribution in the Shrapnel A

The electron pressure, \(p_e\) in the head region is estimated to be about 10 times higher than that in the tail region (AET and MTAM). We find that \(kT_e\) in the tail regions are significantly lower than those of head regions. What is the distribution of the \(kT_e\) in the shrapnel A? In this section, we investigate the variation of the \(kT_e\), \(n_e\) and \(p_e\) in the shrapnel A.

In order to investigate the variation, we divide the shrapnel A into small rectangles shown in Fig. 4.10 Upper. The width of each rectangle is selected to cover the X-ray bright region. All the spectra are well represented by the same vnei model as before. We must assume the plasma depth for each region so as to estimate \(n_e\) and \(p_e\). We assume that the shape of the shrapnel is a conical structure which is axial symmetric along the direction to the center of the Vela SNR. It is reasonable to consider that the longer side of rectangles where we extract spectra corresponds to the plasma depth. Then, we can roughly estimate the plasma depth for each regions. Assuming that the electron density is equal to that of hydrogen density, we calculate the electron density from EM and the plasma depth. Then, we calculate \(p_e\) from the equation of state using \(kT_e\) and \(n_e\) obtained. Therefore, \(p_e\) depends on both \(kT_e\) and \(n_e\) while \(kT_e\) and \(n_e\) are derived independently from each other. Figure 4.10 lower shows the variation of \(kT_e\), \(n_e\) and \(p_e\) for those regions. The values of \(kT_e\), \(n_e\) and \(p_e\) gradually decrease from head region to tail region. There is another estimation of the plasma depth for the tail region. Based on the figures from Jones et al. (1994) and Anderson et al. (1994), almost all the gas in the tail region is compressed in a shell region after the shock front. The depth of the shell region is lower than one quarter of the radius of the conical structure of the shrapnel so that the plasma depth for the tail region approximately reduces to lower than one quarter of that estimated above. If it is the case, \(n_e\) and \(p_e\) for the tail region increase by at least factor 2.
Figure 4.10: **Upper.** Same as Fig. 4.4 but with an overlaid the regions where we extracted spectra in order to investigate the variation of $kT_e$, $n_e$ and $p_e$ in the shrapnel A. **Lower.** The variation of $kT_e$, $n_e$ and $p_e$ in the regions shown in Fig. 4.10 **Upper.**
4.3.3 Discussion and Conclusion

We performed spatially resolved spectral analysis of Vela shrapnel A with the XMM-Newton satellite. The X-ray image clearly reveals that the shrapnel A consists of a bright knot (head region) and a faint trailing wake (tail region). We find that the spectra are similar to each other at any portion in the shrapnel A. They are represented well by a single-temperature NEI model. We confirm the abundance of Si is a few times higher than that of solar value while other metal abundances are solar or subsolar values; O~0.3, Ne~0.9, Mg~0.8, Si~3, Fe~0.8. The absolute abundances depend on the model employed while the relative abundances between heavy elements are relatively robust. Therefore, it is reasonable to consider that the shrapnel A is extremely rich in Si. We estimate masses of each element relative to O. They are ∼0.5, ∼0.2, ∼0.7, ∼0.5, for Ne, Mg, Si and Fe, respectively. Thielemann et al. (1996) calculated the isotopic composition of the ejecta of core-collapse SNe from 13, 15, 20 and 25 M_☉ stars. We compared the mass ratio relative to O with those models. We can easily find that there is no such layer satisfying the ratio obtained. This indicates that the shrapnel A is strongly contaminated by the swept-up ISM. TMA presumed that Vela SN occurred in a bubble of hot tenuous gas which was considered to be an old SNR. Therefore, the abundance of the swept-up ISM might be different from solar values so that it is difficult to estimate the masses of metals from the swept-up ISM in the shrapnel A. O and Si are the most massive elements in the shrapnel A so that they might reflect the initial composition. When we employ only the relative mass of O to Si for comparison with theoretical models, the shrapnel A turns out to come from the layer inside the progenitor star whose mass radius is 1.55~2 M_☉ (depending on the mass of the progenitor star).

The vnei model indicates an extreme over abundance of C in the shrapnel A. In our data, we found that the plasma with temperature beyond 3 keV could explain the measured flux ratio of C Heα to C Heβ. There is no other indication of existence of such a high temperature plasma. This fact suggests that the abundance of C determined by the vnei model is highly uncertain, probably due to the uncertainty of the calibration below 0.5 keV. The CCD camera, XIS, on board Suzaku has high performance below 0.5 keV that will clearly detect C emission lines if they are there.

We find that the electron temperature, the electron density and the electron pressure gradually decreases toward the shell of the Vela SNR. If the hot plasma is generated by a simple blast wave, the temperature increases toward the center of the explosion. Therefore, the variation of $kT_e$ supports the idea that the shrapnel A originates not from the blast wave but from the explosion ejecta. The electron pressure in the head region is estimated to be about 10 times higher than that of the tail region from the observation
of ROSAT (AET) and ASCA (MTAM). However, we estimate the electron pressure to be $\sim 4 \times 10^{-10}$ erg cm$^{-3}$ at the top of the shrapnel A and decreases down to $\sim 1 \times 10^{-10}$ erg cm$^{-3}$ i.e. the electron pressure decreases only by a factor of 4. If we employ a thick hollow conical structure in the tail region (Jones et al. 1994, Anderson et al. 1994), the decreases are reasonably reduced to lower than a factor of 2.

We assume that the head region of the shrapnel A has a conical structure with a diameter $9'$ and a height $4'$ and the tail region has a cylinder with a diameter $10'$ and a height $11'$. We estimate the X-ray emitting volume for head region and tail region to be $\sim 1 \times 10^{54}$ cm$^3 \times (d/250)^3$ and $\sim 1 \times 10^{55}$ cm$^3(d/250)^3$, respectively, where $d$ is the distance to Vela shrapnel A in units of pc. Using the density, 0.5 for head regions and 0.2 for tail regions, mass of the shrapnel A is estimated to be $\sim 5 \times 10^{-3} M_\odot$, which is smaller than that of the shrapnel D ($0.1 \times M_\odot$; Katsuda & Tsunemi 2005). There are fast-moving knots in Cas A that show a pure O or O with products of O burning, S, Ar, Ca (Kirshner & Chevalier 1977, Chevarier & Kirshner 1978, 1979). The optically emitting mass of the knots in Cas-A is only about $10^{-4} M_\odot$ (Raymond 1984). The mass of the shrapnel A is larger than those of the optically emitting knots found in the Cas-A SNR. The mass of the shrapnel A was estimated on the assumption that they mainly consists of the hydrogen. However, the shrapnels might be lacking in hydrogen instead consisting purely of metal from the progenitor star. If it is the case, the heavy elements make an important contribution to the continuum emission, which causes a change of the inferred mass of X-ray emitting gas (e.g., Vink et al. 1996). If we assume that the shrapnel A consists of only metal, then the mass will reduce to one quarter of that obtained above.

The interaction of clumps with a uniform medium has been studied in two-dimensional simulations by Anderson et al. (1994) and Jones et al. (1994). They identified in the evolution of clumpy ejecta: a bow-shock phase, an instability phase and a dispersal phase. The three evolutionary phases will occur well before the nominal ram pressure “stopping time”, defined as the timescale over which the clump intercepts its own mass from the ambient medium (Anderson et al. 1994). If the shrapnel A has been keeping its shape and sweeping-up the ambient medium since the explosion, the shrapnel turns out to sweep-up the ambient medium by $\rho_0 L S = \rho_0 (L/d) (S/d^2)d^3$, where $\rho_0$, $L/d$, $S/d^2$ are the density of ambient medium, the angular distance from the center of the Vela SNR, the angular size of the shrapnel. Using the number density of the ambient medium estimated by TMA, we can estimate the mass of the swept-up ambient medium to be $\sim 7 \times 10^{-3}$ ($\rho_0/0.02$ cm$^{-3})(5.3')((\pi \times 36 \text{ arcmin}^2)(d/250 \text{ pc})^3 M_\odot$. This value exceeds the obtained mass of the shrapnel A, which indicates that the shrapnel should be in the dispersal phase. Nonetheless, the shrapnel clearly shows a bright X-ray knot feature that is defined as the
head region here, which implies that the shrapnel has not reached the dispersal phase yet. Therefore, the view studied by Wang et al. (2002) might be the case, that is the shrapnel A is comoving with the surrounding ejecta for a long time and passed over a blast wave.
4.4 Shrapnel D

We present results of *XMM-Newton* observation of the shrapnel D, which were published in Katsuda & Tsunemi (2005).

4.4.1 Image Analysis

Since the shrapnel D is larger than the field of view (FOV) of the EPIC (30′), we selected the brightest region in the shrapnel. Figure 4.11 shows a *ROSAT* Position Sensitive Proportional Counter (PSPC) image of the shrapnel D with an overlay of the FOV of our observation. Figure 4.12 shows an exposure-corrected MOS1 + MOS2 image of the shrapnel D in the energy range of 0.3–2 keV with an overlaid optical contour map. We extracted the exposure map using XMMSAS v5.4.1 (the `expmap` command), and smoothed the image by a Gaussian of $\sigma = 6''$. We found a bright X-ray ridge structure running from north to south in the region east of the FOV. The X-ray emission from the eastern part of the ridge abruptly weakens to the background level, while that from the western part of the X-ray ridge gradually weakens. There is also an optical bright ridge structure, a pencil nebula RCW 37, running parallel to the X-ray ridge at about 3′ in the east. This suggests that the shrapnel D is now interacting with an interstellar cloud (Sankrit et al. 2003).

Figure 4.11: *ROSAT* PSPC logarithmically scaled image of the Eastern Limb of the Vela SNR. The black circle indicates the FOV of our *XMM-Newton* observation.
4.4. SHRAPNEL D

Figure 4.12: EPIC MOS1 + MOS2 logarithmically scaled image in the energy range 0.3–2.0 keV. The data have been smoothed with a Gaussian of $\sigma = 6''$. The contours show a linearly scaled optical intensity map.

4.4.2 Spectral Analysis

We investigate spectral variations from various regions in detail. According to the X-ray ridge structure, we divide our FOV into many small rectangles ($2' \times 4'$, a side with $2'$ is perpendicular to the ridge and that of $4'$ is parallel to that). The scale of the rectangle is larger than the half-power beam width of XMM-Newton. The scale is selected such that we could obtain sufficient photon statistics in each rectangle. For the purpose of more detailed investigations, we arrange rectangles such that each rectangle overlapped each other by half of its size, obtaining 243 spectra in total. Figure 4.13 shows those regions overlaid on a MOS1 + MOS2 image that is the same as Fig. 4.12. In the spectral analysis, we include the uncertainties among CCDs by 5% on the model in quadrature (see, e.g., Nevalainen et al. 2003; Kirsch 2004). We find that the spectra from the western part of the X-ray ridge are quite different from those from the eastern part (the boundary is indicated in Fig. 4.13). Therefore, we divide the data into two regions by the X-ray ridge. We present our results in the following sections.
CHAPTER 4. VELA SNR

Figure 4.13: Same as Fig. 4.12 with an overlaid all the regions where we extracted spectra. The spectrum from the white rectangle is shown in Fig. 4.14.

**Western Part of the X-Ray Ridge**

Figure 4.14 shows an example spectrum from the white rectangle in Fig. 4.13. We can see prominent O Heα triplets at $\sim 0.57\text{ keV}$, O Lyα at $\sim 0.65\text{ keV}$, Ne Heα triplets at $\sim 0.91\text{ keV}$, Ne Lyα at $\sim 1.02\text{ keV}$, Mg Heα triplets at $\sim 1.35\text{ keV}$ lines. These features are clearly seen in all of the spectra from the western part of the X-ray ridge. We applied an absorbed NEI model (the vnei model in XSPEC v11.3.1) to each spectrum. The free parameters in our analysis are $kT_e$, $\tau$, EM, abundances and hydrogen column density, $N_H$, of the absorbing foreground material. Only the abundances of C, N, O, Ne, Mg, Fe are free, and the others are frozen to the solar values (Anders & Grevesse 1989). We set the abundances of C and N equal to that of O. All of the spectra are represented by a single-temperature vnei model.

The reduced $\chi^2$ is 1–1.5 for about 85% of the region to the west of the X-ray ridge. The remaining (only 15% in the west of the ridge) regions, which are located near the ridge and have a high surface brightness, show about 1.5–1.8. These values are far from acceptable from a statistical point of view. These regions are very close to the interaction region with the interstellar cloud. We can not obtain better fits by adding extra components there. Therefore, our model is too simple to reproduce the entire region. A more advanced model will be needed to obtain a better fit, particularly near the X-ray ridge. In table 4.3, we
Figure 4.14: X-ray spectra extracted from the white rectangle in Fig. 4.13. The best-fit curves are shown with solid lines and the lower panels show the residuals.

show the best-fit parameters of the spectrum from the white rectangle.

Figure 4.15 shows the values of $kT_e$ and a log $\tau$ contour map in the western part of the X-ray ridge overlaid on the MOS1 + MOS2 image. The value of $kT_e$ shows the highest ($0.32 \pm 0.01$ keV) at the ridge and a gradual decrease in the west down to $0.25 \pm 0.02$ keV. The spatial variation of log $\tau$ shows an anti-correlation with that of $kT_e$. Most of the regions, having relatively low $kT_e$, show $\tau > 10^{12}$ s cm$^{-3}$, which indicates a collisional ionization equilibrium condition. However, the regions near the X-ray ridge, having a relatively high $kT_e$, show that $\tau$ is $(4.8-7.2) \times 10^{11}$ s cm$^{-3}$, which indicates a nonequilibrium ionization condition. Figure 4.16 shows contour maps of metal abundances. They are heavily overabundant, except for Fe, at any regions in the map; the values of the abundances relative to the solar values are O $\sim$ 5, Ne $\sim$ 10, Mg $\sim$ 10, Fe $\sim$ 1. These values support the idea that the shrapnel D originates from the explosion ejecta.

**Eastern Part of the X-Ray Ridge**

A weak X-ray emission comes from the eastern part of the X-ray ridge. We find that the spectra from the eastern part of the X-ray ridge are quite different from those of the western part. We divide the eastern part into two regions.
Table 4.3: Spectral-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>White rectangle in Fig. 4.13</th>
<th>Dashed circle in Fig. 4.17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{H}}[10^{20}\text{cm}^{-2}]$</td>
<td>$2.9^{+0.2}_{-0.4}$</td>
<td>$1.9^{+0.2}_{-0.4}$</td>
</tr>
<tr>
<td>Low temperature component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td></td>
<td>$0.16^{+0.01}_{-0.02}$</td>
</tr>
<tr>
<td>O(=C=N)</td>
<td></td>
<td>$0.11^{+0.06}_{-0.04}$</td>
</tr>
<tr>
<td>$\tau[\text{s cm}^{-3}]$</td>
<td></td>
<td>$&gt;3 \times 10^{11}$</td>
</tr>
<tr>
<td>EM$[\text{cm}^{-5}]$</td>
<td></td>
<td>$(13 \pm 2) \times 10^{17}$</td>
</tr>
<tr>
<td>Plasma depth [pc]</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>Electron density [cm$^{-3}$]</td>
<td></td>
<td>$0.77^{+0.07}_{-0.06}$</td>
</tr>
<tr>
<td>Electron pressure $[10^{-10}\text{erg cm}^{-3}]$</td>
<td></td>
<td>$1.99^{+0.22}_{-0.22}$</td>
</tr>
<tr>
<td>High temperature component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>$0.30^{+0.01}_{-0.01}$</td>
<td>$0.38^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>O(=C=N)</td>
<td>$6.4^{+0.2}_{-0.1}$</td>
<td>$4.5^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>Ne</td>
<td>$13.7^{+0.8}_{-0.3}$</td>
<td>$11.5^{+0.3}_{-0.8}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$14^{+2}_{-2}$</td>
<td>$8.9^{+1.2}_{-2.1}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$1.4^{+0.2}_{-0.1}$</td>
<td>$1.00^{+0.13}_{-0.15}$</td>
</tr>
<tr>
<td>$\tau[\text{s cm}^{-3}]$</td>
<td>$(6.1 \pm 0.2) \times 10^{11}$</td>
<td>$(1.9 \pm 0.06) \times 10^{11}$</td>
</tr>
<tr>
<td>EM$[\text{cm}^{-5}]$</td>
<td>$(2.60 \pm 0.02) \times 10^{17}$</td>
<td>$2.66^{+0.06}_{-0.06} \times 10^{17}$</td>
</tr>
<tr>
<td>Plasma depth [pc]</td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Electron density [cm$^{-3}$]</td>
<td>$0.197^{+0.001}_{-0.001}$</td>
<td>$0.627^{+0.007}_{-0.007}$</td>
</tr>
<tr>
<td>Electron pressure $[10^{-10}\text{erg cm}^{-3}]$</td>
<td>$0.96^{+0.06}_{-0.06}$</td>
<td>$3.86^{+0.25}_{-0.25}$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>$436/303$</td>
<td>$362/257$</td>
</tr>
</tbody>
</table>

Other elements are fixed to those of solar values.
The values of abundances are multiples of solar value.
The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.
In the fits, 5% systematic errors are included.
4.4. SHRAPNEL D

![Figure 4.15: Linearly scaled contour map of $kT_e$ and $\log \tau$ in the western part of the X-ray ridge overlaid on an X-ray image the same as Fig. 4.12. The values of $kT_e$ are in units of keV. The data were smoothed with a Gaussian of $\sigma = 4^\prime$.](image)

Southeastern Region near the Optical Filament

We find that the spectrum from the region near the optical filament can be well fitted with a single component with solar abundances. It shows a relatively low $kT_e$ ($\sim 0.15$ keV). Sankrit et al. (2003) find that optical emission comes from a shock-excited cloud with solar abundances. Therefore, we conclude that the low-$kT_e$ component represents plasma originating from the cloud.

We also find that the spectrum varies between the optical filament and the X-ray ridge. We analyze the spatial variation of the spectra between them. We extract spectra from rectangular regions ($1^\prime \times 8^\prime$) drawn by the white line in Fig. 4.17 a, each of which overlapped adjacent regions by the half width. In this way we extract 5 spectra. We find that the spectra are not represented by a single-temperature vnei model. Therefore, we add an extra component with different $kT_e$. Due to the insufficient photon statistics of the low-$kT_e$ component above the O-line energy, we assume solar abundances for all elements, except O. The extra component improves the fit (e.g., reduced-$\chi^2$ is improved from 1.7 to 1.2), which is in contrast to that of the western part. The $kT_e$ values of these two components are 0.15 keV and 0.35 keV, while the intensity fraction varies from east to west. The abundances of the high $kT_e$ component are similar to those of the western part of the X-ray ridge, which shows that it comes from the ejecta. The abundance of O and
Figure 4.16: Linearly scaled contour map of each metal abundance overlaid on an X-ray image the same as Fig. 4.12. The values shown in each figure are those relative to the solar abundance. The data were smoothed with a Gaussian of $\sigma = 4'$. 
Figure 4.17: (a) Same as Fig. 4.12. The white rectangles adjacently lined up are the regions where we extracted the spectra. The large upper-left region indicates the region where we extracted the band ratio map. (b) EPIC (MOS1 + MOS2 + PN) band ratio map (O Ly$\alpha$ band / O He$\alpha$ band). The circles are the regions where we extracted spectra.

$kT_e$ for the low-$kT_e$ component are similar to those for the cloud component. Therefore, the low-$kT_e$ component is considered to originate from the cloud. The fraction of the cloud component decreases toward the X-ray ridge. We show the variation of EM corrected by the interstellar absorption as a function of the location in Fig. 4.18. The EM of the cloud component decreases toward the X-ray ridge, while that of the ejecta increases toward the same direction. It is reasonable to consider that this feature is due to the projection effect, as looking obliquely between the cloud and the ejecta. We consider that the boundary region between these two plasmas is a contact discontinuity.

**Northeastern Region**

In the X-ray surface brightness map, we find wavelike structures at the northeastern region of the FOV in Fig. 4.17 (a). Figure 4.17 (b) shows a band ratio map of the O Ly$\alpha$ band (624–684 eV) / the O He$\alpha$ band (545–603 eV), in which the wavelike structures are prominent. The arrow in Fig. 4.17 b shows $\lambda_0$, a typical length of the wavelike structure, to be $\sim 0.3$ pc.

In order to investigate the feature of the wavelike structure, we extract spectra from regions indicated in Fig. 4.17 (b). The circular regions with the thick solid line and dashed line are responsible for the regions where the O Ly$\alpha$ band is dominant, while those with thin line are responsible for the regions where the O He$\alpha$ band is dominant. All of the spectra are represented by a two-component vnei model, just as those applied in the
Figure 4.18: Variation of EM of two components in the region between the optical filament and the X-ray ridge indicated in Fig. 4.17 by white rectangles.

Figure 4.19: X-ray spectra extracted from the dashed circle in Fig. 4.17 (b). The solid line is the total model, while the broken lines represent the individual contributions. The lower panels show the residuals.
4.4. SHRAPNEL D

southeastern region. It is reasonable to consider that the low-temperature component represents an interstellar cloud, while the high-temperature component represents the ejecta. Then, the cloud dominates in the circular regions with thin line and the ejecta dominate in the circular regions with thick line. We consider that there is a contact discontinuity in those regions. Figure 4.19 shows the spectrum from the dashed circle indicated in Fig. 4.17 (b) and the best-fit parameters are given in table 4.3. The value of the plasma depth of the ejecta comes from the assumption that the circular shape in Fig. 4.17 is due to the spherical shape. This result suggests that the surface of the contact discontinuity has wavelike structures with a typical length, $\lambda_o$.

4.4.3 Discussion

X-ray spectra in the western region of the X-ray ridge can be represented with a single-temperature vnei model. The abundances of heavy elements, except for Fe, are significantly higher than those of solar values in any region in the western part of the X-ray ridge: $O \sim 5$, $Ne \sim 10$, $Mg \sim 10$, $Fe \sim 1$. The absolute abundance obtained by the spectral fits depends on the model employed, whereas the relative abundances among the heavy elements are robust. The relative abundances, $(O/Fe, Ne/Fe$ and $Mg/Fe)$ are $\sim 5$, $\sim 10$ and $\sim 10$, respectively. High-Z elements, like Ar, Ca, and Fe, are generated dominantly in a Type-Ia SN (Nomoto et al. 1984), while low-Z elements, like O, Ne, Mg, and Si, are generated in a core-collapse SN (Thielemann et al. 1996). The relative abundances indicate a core-collapse SN origin rather than Type-Ia. Since Vela SNR is believed to be a core-collapse SN, we conclude that the shrapnel D is ejecta originating from an explosion of Vela SN.

We estimate the total mass of the ejecta of Vela shrapnel D. We assume that the shrapnel D has a conical structure with a diameter 80$'$ and a height of 45$'$. Using a distance of 250 pc, and the assumption of uniform electron density of $\sim 0.2 \text{cm}^{-3}$, we can estimate the total mass to be about $10^{-2} M_\odot$.

We find that the shrapnel D is ejecta coming from O, Ne and Mg-rich layer of a progenitor star. This is contrast to the fact that the shrapnel A comes from the Si rich layer (TMA, MTAM, and Katsuda & Tsunemi 2006). These findings suggest that the shrapnel D comes from an outer layer of the progenitor star than shrapnel A. We compare the present distance from the center of Vela SNR to the shrapnel D with that to the shrapnel A. AET inferred the temperature of the shrapnel D to be $0.34 \pm 0.07 \text{keV}$ from the opening angle of the feature and the temperature of the ambient medium. The opening angle was estimated based on the assumption that the shrapnel is moving in the plane of the sky. The measured temperature ($0.32 \pm 0.01 \text{keV}$) is in good agreement with
that inferred from the geometry, which supports that the shrapnel D is moving in the plane of the sky. Therefore, the actual distance of shrapnel D from the center of Vela SNR is shorter than that of the shrapnel A. Since the shrapnel D is considered to have come from the outer layer of a progenitor star than the shrapnel A, it suggests that a part of the inner layer has a higher initial velocity than that of the outer layer.

We find that the electron temperature, the electron density and the electron pressure gradually decreases toward the shell of the Vela SNR. A similar structure in temperature is seen in the shrapnel A (Katsuda & Tsunemi, 2006). Therefore, the temperature variation appears to be a common property of the explosion ejecta.

In the southeastern region of the FOV, there is an optical filament, a pencil nebula, RCW 37, running parallel to the X-ray ridge about 3′ to the east. We confirm that the emission from the optical filament region comes from a shock-excited cloud (Sankrit et al. 2003). We find the spectrum variation in the region between the X-ray ridge and the pencil nebula. An extra component is needed to fit the spectrum. The low-temperature component shows solar abundances, while the high-temperature component shows high metal abundances. The fraction of the low-temperature component gradually decreases toward the X-ray ridge, while that of the high-temperature component increases. Therefore, the low-temperature component is considered to come from the cloud and the high-temperature component is considered to come from the ejecta.

We find wavelike structures in the northeastern region of the FOV in the X-ray surface brightness map. This structure is more apparent in the band ratio map between the O Lyα band and the O Heα band. Furthermore, our spectral analysis indicates that a contact discontinuity between the ejecta and the interstellar cloud has wavelike structures. The wavelike structures remind us of the Rayleigh–Taylor (R–T) instability, which occurs where a heavy fluid is accelerated by a light one (i.e., the pressure of the light fluid is higher than that of the heavy one). In our case, the temperature of the measured ejecta ($T_{ej}$) exceeds that of the cloud ($T_{cl}$). Therefore, if this is the case, the heavy fluid must be the cloud and the light one must be the ejecta. The typical scale of R–T instability is given by (Velazquez et al. 1998)

$$\lambda = 0.39 \times \left( \frac{T_7^{5}}{g_2 \alpha n_1^2} \right)^{1/3} \text{pc},$$

where

$$T_7 = \frac{T_{cl}}{10^7 \text{K}}, \quad n_1 = \frac{n_{cl}}{1 \text{cm}^{-3}},$$

$$g_2 = \frac{g_{eff}}{10^{-2} \text{cm s}^{-2}}, \quad \alpha = \frac{n_{cl} - n_{ej}}{n_{cl} + n_{ej}}.$$
Here, $g_{\text{eff}}$ is the effective gravity (inertial force on a frame of the contact discontinuity), $n_{\text{cl}}$, the number density of the cloud and $n_{\text{ej}}$ that of the ejecta. We assume the cloud depth to be 0.73 pc ($=10^\prime$) in order to estimate $n_{\text{cl}}$. The value of $g_{\text{eff}}$ is given by $(1/\rho_m)(dP/dr)$ (Ebisuzaki et al. 1989), where $dP/dr$ is the pressure gradient and $\rho_m$ is the mean density between the cloud and the ejecta. We used the approximation that $dP/dr \sim \Delta P/\lambda$, where $\Delta P$ represents the pressure difference between two fluids. We consider that the temperatures of the cloud and the ejecta come from shock heating. After shock heating, the ion temperature would not be equal to that of the electron. Then, the electron and ion temperatures vary smoothly to reach the thermal equilibrium. The postshock electron and ion temperatures equilibrate rapidly after a slow shock, even when the shock is collisionless (Ghavamian et al. 2001). Therefore, we assume thermal equilibrium between the ion and the electron, $P_i = P_e$ ($P_i$, $P_e$ are the ion and the electron pressure, respectively), because the shock speed is only about 150 km s$^{-1}$ (Sankrit et al. 2003) in our case. Based on the assumption of $P_i = P_e$, the pressure difference between the cloud and the ejecta becomes $2 \times \Delta P_e$ ($\Delta P_e$ is the electron pressure difference between the cloud and the ejecta). Using the values obtained by the spectral fitting (from the dashed circle shown in table 1), we obtain $\lambda$ as

$$\lambda \sim 0.2 \times \left(\frac{T_7}{0.186}\right)^{5/2} \left(\frac{n_{m1}}{0.7}\right)^{1/2} \left(\frac{P_{10}}{3.7}\right)^{-1/2} \left(\frac{\alpha}{0.1}\right)^{-1/2} \left(\frac{n_1}{0.77}\right)^{-1} \text{ pc},$$

where

$$n_{m1} = \frac{\rho_m}{1.67 \times 10^{-24} \text{ g cm}^{-3}},$$

$$P_{10} = \frac{\Delta P}{1 \times 10^{-10} \text{ erg cm}^{-3}}.$$

We find that $\lambda$ is close to $\lambda_o$. Since the value of $n$ strongly depends on the plasma depth, the value of $\lambda$ also depends on the plasma depth. It is highly probable that the wavelike structures are caused by the R–T instability.

In the southeastern region of the FOV (around the optical filament), we cannot see wavelike structures. In this region, we find $n_{\text{ej}} < n_{\text{cl}}$, and the pressure of the ejecta is lower than that of the cloud, where the contact discontinuity is stable.

### 4.4.4 Conclusion

We observed the shrapnel D with the XMM-Newton satellite. We find an X-ray bright ridge structure running from north to south. We find that the spectra from the western part of the X-ray ridge can be represented by a single $kT_e$ component with high metal abundances: O $\sim 5$, Ne $\sim 10$, Mg $\sim 10$, Fe $\sim 1$. This clearly shows that the origin of the
shrapnel D is ejecta from Vela SN. The spectra from the eastern part of the X-ray ridge are represented by two $kT_e$ components. The low-temperature component having solar abundance is considered to come from the interstellar cloud, while the high-temperature component is considered to come from the ejecta. This is the place where the ejecta are interacting with the interstellar cloud. In the southeastern region of the FOV, it is reasonable to think that we see the interaction obliquely due to the projection effect. In the northeastern region of the FOV, it is highly probable that we see the wavelike structure of the R–T instability.
4.5 Shrapnel E

4.5.1 Analysis

Figure 4.20 shows the FOV of XMM-Newton superposed on the ROSAT PSPC image. Figure 4.21 shows the MOS1/2 + PN image in the 0.3-2 keV energy band. We can see several point sources and relatively bright region around the center of the FOV.

Unfortunately, the data heavily suffered from high-background flares due to soft protons. We screen the data by eye and reject the high background periods, resulting that the effective exposure time is reduced to \( \sim 5.1 \) ks for MOS1/2 cameras and to \( \sim 5 \) ks for PN camera. We further need to subtract the cosmic X-ray background at low energy and the Cosmic Ray (CR) induced background at energies above typically 1.5 keV (Arnaud et al. 2001).

Judging from the ROSAT image, the X-ray enhanced region associated with the shrapnel E completely covers the entire FOV. Therefore, we have to carefully subtract the background. Since the data are heavily contaminated by particles, we obtain short exposure time, resulting it difficult to analyze a weak extended emission. In this paper, we concentrate the analysis of the central bright region of the shrapnel E. We pick up a circular region (radius = 5′.3) around the center of the FOV as the source and its surrounding circular region as the background see, Fig. 4.21). The emission above 2 keV becomes statistically 0, which confirms the validity of the background subtraction. Since Al-K and Si-K lines are not uniform over the detectors (e.g., Lumb et al. 2002, Katayama et al. 2004), we cannot expect to properly subtract the background of them. Therefore, we employ the data below 1.45 keV in the following spectral analysis.

As we already mentioned above, we extract the spectrum from the central region of the FOV (relatively bright region in the FOV). We excluded prominent 14 point sources from the spectral analysis. In this way, we obtained the spectrum shown in Fig. 4.22. We can see prominent emission lines from O He\( \alpha \) at \( \sim 0.57 \) keV, the complex of O Ly\( \alpha \) and O He\( \beta \) at \( \sim 0.65 \) keV, Ne He\( \alpha \) at \( \sim 0.91 \) keV and the faint emission from the complex of Ne Ly\( \alpha \) and Ne He\( \beta \) at \( \sim 1.05 \) keV.

At first, we apply an absorbed CIE model with a single-\( kT_e \) (the \texttt{wabs} and \texttt{vmekal} model in XSPEC v11.3.1; Morrison & McCammon 1984; Mewe et al. 1986; Liedahl et al. 1995) to the spectra as Tsunemi et al. (1999b) did. We fix the column density, \( N_H \) to be \( 3.0 \times 10^{20} \)cm\(^{-2} \) (Dubner et al. 1998). Our free parameters are \( kT_e \); EM, and abundances of C, N, O, Ne, Mg and Fe. We set the abundances of C and N equal to that of O while other elements are fixed to the solar values (Anders & Grevesse 1989). This model gives us an acceptable fit from the statistical point of view. The parameters obtained are
CHAPTER 4. VELA SNR

Figure 4.20: *ROSAT* PSPC image of the Vela shrapnel E. The intensity scale is square root. The data have been smoothed with a Gaussian of $\sigma = 2.5$. The white circle indicates the FOV of our *XMM-Newton* observation.

Figure 4.21: *EPIC MOS1/2 + PN* image in the energy range 0.3–1.5 keV. The intensity scale is also square root. The data have been smoothed with a Gaussian of $\sigma = 22''$. The overlaid circles indicate two regions; one for the source region as the circular region located in the center of the FOV, the other for the background region as the annular region surrounding the circular region.
Figure 4.22: X-ray spectra from the circular region shown in Fig. 4.21. The best-fit curves are shown with solid lines and the lower panels show the residuals. The best-fit curves shows the NEI model.

summarized in table 4.4 (CIE). In order to calculate the electron density, we assume that the inner circular region in Fig. 4.21 has a sphere shape and the density profile inside is Gaussian shape with \( \sigma = 5' \). Assuming that the electron density is equal to that of ion, we estimate the electron density at the center portion of the inner circular region, \( n_e(c) \), to be \( 0.5 \text{ cm}^{-3} (D/250 \text{ pc})^{-0.5} \), where \( D \) is the distance to the Vela SNR. If the shrapnel E is generated by the explosion of the Vela SNR, we can estimate \( \tau \), the product of the density and the elapsed time after the shock heating. We find \( \tau \) to be \( 1.8 \times 10^{11} (n_e(c)/0.5)(t/11400 \text{ yr}) \text{ cm}^{-3} \text{ sec} \), where \( t \) is the age of the Vela SNR (Taylor et al. 1993). The value indicates that the plasma is not in the CIE condition. If the plasma is in the CIE condition, it suggests the origin of the shrapnel E other than the ejecta.

Then, we apply an NEI model (the vnei model (NEI version 2.0) in XSPEC v 11.3.1) with a single-\( kT_e \) and a single \( \tau \). We also fix the \( N_H \) to be \( 3.0 \times 10^{20} \text{ cm}^{-2} \). Our free parameters are \( kT_e \), \( \tau \), EM and abundances C, N, O, Ne, Mg and Fe. We set the abundances of C and N equal to that of O while the other elemental abundances to the solar values just as we did for the CIE model. We also obtain an acceptable fit by adopting the vnei model. Best-fit curves are shown in Fig. 4.22 and the parameters obtained are also summarized in table 4.4 (NEI). The ionization age calculated from the electron density
Table 4.4: Spectral-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CIE</th>
<th>NEI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H[10^{20}\text{ cm}^{-2}]$</td>
<td>3.0 (fixed)</td>
<td>3.0 (fixed)</td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>$0.17\pm0.01$</td>
<td>$0.45^{+0.05}_{-0.09}$</td>
</tr>
<tr>
<td>C=N=O</td>
<td>$0.8^{+0.2}_{-0.1}$</td>
<td>$1.2^{+0.2}_{-0.4}$</td>
</tr>
<tr>
<td>Ne</td>
<td>$5.6^{+1.2}_{-0.9}$</td>
<td>$3.9^{+1.7}_{-0.7}$</td>
</tr>
<tr>
<td>Mg</td>
<td>$&lt;8.3$</td>
<td>$&lt;3.3$</td>
</tr>
<tr>
<td>Fe</td>
<td>$0.9^{+0.6}_{-0.4}$</td>
<td>$0.7^{+0.7}_{-0.4}$</td>
</tr>
<tr>
<td>log $\tau[\text{cm}^{-3}\text{ sec}]$</td>
<td>$10.22^{+0.14}_{-0.10}$</td>
<td></td>
</tr>
<tr>
<td>EM$[\text{cm}^{-3}]$</td>
<td>$9.0\pm0.1\times10^{53}$</td>
<td>$0.6\pm0.1\times10^{53}$</td>
</tr>
<tr>
<td>$n_e(c)[\text{cm}^{-3}]$</td>
<td>$0.5\pm0.1$</td>
<td>$0.13\pm0.03$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>189/197</td>
<td>186/196</td>
</tr>
</tbody>
</table>

Other elements are fixed to those of solar values.

The values of abundances are multiples of solar value.

The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.

obtained by the vnei model is $4.8\times10^{10} (n_e(c)/0.15)(t/11400 \text{ yr}) \text{ cm}^{-3}\text{ sec}$ which is about twice times larger than that obtained by the vnei model (see, table 4.4). However, the electron density, $n_e(c)$ is the maximum value in the circular region. Therefore, it is reasonable to consider the ionization time derived from $n_e(c)$ times the age of the Vela SNR is comparable with that from the vnei model.

4.5.2 Discussion and Conclusion

The spectrum can be well fitted with either the CIE or NEI model. Each model is statistically accepted, probably due to the insufficient number of photons. However, taking into consideration of the age of the Vela SNR multiplied by the electron density, the NEI model supports the ejecta origin while the CIE does not.

The absolute abundance predicted by the spectral fits depends on the model employed and is correlated with other parameters. On the other hand, the abundance ratios between heavy elements are robust. The shrapnel D showed high abundances for O, Ne and Mg, showing the abundance ratio of Ne relative to O is $2.14^{+0.14}_{-0.06}$. If the shrapnel E originates from the Vela SN explosion, the NEI model should be the case. Then, we find that the abundance ratio of Ne relative to O obtained is $3.2^{+1.6}_{-1.3}$. If it is the case, the overabundance of Ne relative to O is a common characteristics of the Vela shrapnels. In core-collapse nucleosynthesis models, the abundance of Ne relative to O in the O-Ne-Mg-rich zone shows
about 2 times higher value than that of solar value (Rauscher et al. 2002). Therefore, the hypothesis that the shrapnel E originates from the O-Ne-Mg-rich layer of a progenitor star can explain the overabundance of Ne. If the shrapnel E shows the CIE model, the abundance ratio of Ne relative to O obtained is \(7 \pm 2\). In this case, it is difficult to explain the overabundance of Ne since the SN ejecta origin is inconsistent with the assumption.

On the assumption mentioned in the previous section, we estimate the mass in the inner circular region in Fig. 4.20 to be only \(\sim 5 \times 10^{-4} M_\odot (D/250 \text{ pc})^{2.5}\) that is much smaller than those of shrapnels A and D since they are \(5 \times 10^{-3} M_\odot\) and \(1 \times 10^{-1} M_\odot\). The masses of fast-moving O-rich knots seen in Cas A, G292.0+1.8, and Puppis A are estimated to be \(1 \times 10^{-4} M_\odot\) (Reymond 1984), \(1 \times 10^{-3} M_\odot\) (Park et al. 2004), and \(1 \times 10^{-2} M_\odot\) (Winkler et al. 1988), respectively. The mass estimated here is in between those in Cas A and those in G292.0+1.8. The surface brightness of the shrapnel E is much fainter than those knots. There is an age difference between the shrapnel E and knots in young SNRs. Furthermore, we should note that the shrapnel E protrudes the main shell while knots in young SNR did not. Therefore, the shrapnel E was also a dense knot as seen in young SNR. In this calculation, we do not include the mass of the surrounding region. We need to have longer exposure to precisely estimate the mass of entire shrapnel E.

The angular distance from the explosion center to the shrapnel E is about \(6.6^\circ\) which corresponds to \(29 (D/250 \text{ pc}) \text{ pc}\) in the plane of the sky. Therefore, the mean velocity of the shrapnel E is estimated to be \(\sim 2500 (D/250 \text{ pc})(t/11400 \text{ yr}) \text{ km sec}^{-1}\), whereas the current velocity of the shrapnel E is about \(600 (kT_{e}/0.45 \text{ keV})^{0.5} \text{ km sec}^{-1}\). This indicates an order-of-magnitude deceleration, which is a common feature among the Vela shrapnels.

*XMM-Newton* observed the western protrusion beyond the main shell of the Vela SNR which is so-called Vela shrapnel E. The protrusion extends so large that the FOV of *XMM-Newton* covers only a part of it. Due to the relatively short exposure time, we analyzed a bright circular region in the center of the FOV. The spectrum can be well fitted either with the CIE model or with the NEI model. The ejecta origin can explain the relative metal abundance as well as the NEI model rather than the CIE model. In conclusion, the shrapnel E is likely to originate from the Vela SN explosion. Since the shrapnel E extends over the FOV of *XMM-Newton* with relatively weak surface brightness, we need longer exposure time to study the evolution in detail as well as to clarify its origin.
Chapter 5

Puppis A SNR

We present results from *XMM-Newton* observations of Galactic Oxygen-rich SNR Puppis A. Parts of them will be published in Katsuda et al. (2008e).

5.1 Previous Results

Puppis A is located at the NE rim of the Vela SNR. Due to its high surface brightness, we can identify the remnant in Fig. 4.1 (the circular-shaped bright region with radius of $\sim 30'$ at the very rim of the Vela SNR). Puppis A is categorized as an “oxygen-rich” supernova remnant (SNR) based on the optical spectroscopy (Winkler & Kirshner 1985). Only two other members in our Galaxy, Cassiopeia A (Chevalier & Kirshner 1979) and G292.0+1.8 (Goss et al. 1979), and a few SNRs in the SMC and the LMC belong to this O-rich SNR group. In the optical wavelength, these SNRs show fast-moving metal-rich ejecta knots ($v > 1000\,\text{km sec}^{-1}$) which are typically enriched in O, Ne, C, and Mg. High-Z elements, like Ar, Ca, and Fe, are dominantly generated in a Type-Ia supernova (Nomoto et al. 1984), while low-Z elements, like O, Ne, and Mg, are generated in a core-collapse SN explosion (Thielemann et al. 1996). These facts suggest that O-rich SNRs are core-collapse origin. The detection of metal-rich ejecta from these SNRs thus provides us with an opportunity to make a direct test of core-collapse SN nucleosynthesis models.

O-rich fast-moving optical knots (hereafter, OFMKs) in Puppis A, whose proper motions are all consistent with undecelerated expansion from a common center (Winkler & Kirshner 1985; Winkler et al. 1988), have been found only in the northeastern quadrant, suggesting asymmetric mass ejection during SN explosion which produced Puppis A. On the other hand, proper motion of a central compact object (CCO), RX J0822-4300, associated with the Puppis A SNR was recently measured to be directed toward the southwest
CHAPTER 5. PUPPIS A SNR

with a high velocity of $\sim 1600 \text{ km sec}^{-1}$ (see, Fig. 2.5 Lower; Winkler & Petre 2007). The CCO is considered to be kicked by asymmetric mass ejection during the SN explosion according to momentum conservation, from which we can study SN explosion mechanisms (e.g., Scheck et al. 2006).

A filament which is so-called “omega” filament by Winkler & Kirshner (1985) is one of the the best studied OFMKs. Winkler & Kirshner (1985) observed the “omega” filament and found that the spectra were dominated by O lines, and quite weak Balmer lines. The mass ratio of O to H was estimated to be 30, i.e., $\sim 2000$ times the solar value. Furthermore, they found that the O lines were blue-shifted by $1500 \pm 100 \text{ km sec}^{-1}$. These facts led them to consider that the “omega” filament was nearly pure O ejecta from the core of the SN progenitor that had remained more or less intact.

In X-ray wavelengths, Puppis A generally showed sub-solar metal abundances, suggesting that the X-ray emission from Puppis A was dominated by the swept-up interstellar medium (Tamura 1995; Hwang et al. 2008). The complex interstellar environment such as a gradient in the ambient density (Petre et al. 1982) as well as the relatively old age of $\sim 4000$ years (Blair et al. 2003) might have made it difficult to detect clear signs of metal-rich ejecta in its spectra. However, recent Suzaku observations revealed metal-rich ejecta features in the northeastern part of the remnant (Hwang et al. 2008). Here we present XMM-Newton results, focusing on regions showing the enhanced emission lines which are revealed by “equivalent width” (EW) images for O, Ne, Mg, Si, and S.

5.2 Observations and Data Reduction

Puppis A has been observed by XMM-Newton five times by different PIs with different objectives, resulting in an almost complete coverage of this large ($\sim 1^\circ$ diameter) X-ray remnant (see, Fig. 5.1). First (ObsID: 0113020101) and second (ObsID: 0113020301) observations were targeted at the compact central object (CCO), and thus covered the center portion of this remnant. The third (ObsID: 0150150101) and fourth (ObsID: 0150150301) observations were aimed to study cloud-shock interactions in the northern knot and the bright eastern knot, respectively. Recently, we observed the western part of Puppis A (ObsID: 0303530101) motivated by an enhanced X-ray line emission from highly ionized Ne found in the ASCA spectrum in this region (Tamura 1995). The main information of these observations are summarized in table 5.1.

All the raw data are processed with version 6.5.0 of the XMMSAS. We select X-ray events corresponding to patterns 0–12 for MOS and pattern 0 for PN, respectively. We further clean the data by rejecting the high background (BG) intervals and remove all
### Table 5.1: XMM-Newton observations of the Puppis A SNR

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Camera</th>
<th>Instrument Mode</th>
<th>Filter</th>
<th>Obs. Date</th>
<th>GTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0113020101</td>
<td>MOS1</td>
<td>PrimeFullWindow</td>
<td>Medium</td>
<td>2001-04-15</td>
<td>22.0 ksec</td>
</tr>
<tr>
<td></td>
<td>MOS2</td>
<td>PrimeFullWindow</td>
<td>Medium</td>
<td>2001-04-15</td>
<td>22.0 ksec</td>
</tr>
<tr>
<td>0113020301</td>
<td>MOS1</td>
<td>PrimeFullWindow</td>
<td>Thick</td>
<td>2001-11-08</td>
<td>10.8 ksec</td>
</tr>
<tr>
<td></td>
<td>MOS2</td>
<td>PrimeFullWindow</td>
<td>Thick</td>
<td>2001-11-08</td>
<td>10.8 ksec</td>
</tr>
<tr>
<td>0150150101</td>
<td>MOS1</td>
<td>PrimePartialW3</td>
<td>Medium</td>
<td>2003-04-17</td>
<td>6.3 ksec</td>
</tr>
<tr>
<td></td>
<td>MOS2</td>
<td>PrimePartialW3</td>
<td>Medium</td>
<td>2003-04-17</td>
<td>6.3 ksec</td>
</tr>
<tr>
<td></td>
<td>PN</td>
<td>PrimeLargeWindow</td>
<td>Medium</td>
<td>2003-04-17</td>
<td>4.2 ksec</td>
</tr>
<tr>
<td>0150150301</td>
<td>MOS1</td>
<td>PrimePartialW3</td>
<td>Medium</td>
<td>2003-06-25</td>
<td>4.3 ksec</td>
</tr>
<tr>
<td></td>
<td>MOS2</td>
<td>PrimePartialW3</td>
<td>Medium</td>
<td>2003-06-25</td>
<td>4.3 ksec</td>
</tr>
<tr>
<td></td>
<td>PN</td>
<td>PrimeLargeWindow</td>
<td>Medium</td>
<td>2003-06-25</td>
<td>3.3 ksec</td>
</tr>
<tr>
<td>0303530101</td>
<td>MOS1</td>
<td>PrimeFullWindow</td>
<td>Thin1</td>
<td>2005-10-09</td>
<td>9.8 ksec</td>
</tr>
<tr>
<td></td>
<td>MOS2</td>
<td>PrimeFullWindow</td>
<td>Thin1</td>
<td>2005-10-09</td>
<td>9.8 ksec</td>
</tr>
<tr>
<td></td>
<td>PN</td>
<td>PrimeFullWindow</td>
<td>Thin1</td>
<td>2005-10-09</td>
<td>9.8 ksec</td>
</tr>
</tbody>
</table>

We give information only on the data we analyzed. We did not use the PN data from ObsID=0113020101 and ObsID=0113020301 since those data were obtained in PrimeSmallWindow mode and covers only small region around the CCO, RX J0822–4300.
Figure 5.1: Upper: *ROSAT* HRI image of the entire Puppis A SNR. The data have been smoothed by Gaussian kernel of $\sigma = 15''$. The intensity scale is square root. *XMM-Newton* FOV are indicated as white circles. Lower: Three-color *XMM-Newton* image of the merged MOS1/2, PN data from five *XMM-Newton* observations. Red, green, and blue represent 0.4–0.7, 0.7–1.2, and 1.2-5.0 keV, respectively.
the events in bad columns listed in Kirsch (2006). The GTIs after data cleaning are summarized in table 5.1. After the filtering, the data are vignetting-corrected using the sas task evigweight.

There is a X-ray emission from the Vela SNR in the foreground. In order to estimate contamination from the Vela SNR, we extracted spectra from various regions outside Puppis A in our FOV. Then, we estimated the fraction of the X-ray emission from the Vela SNR to be at most 10% of the total (Vela + Puppis A) X-ray emission even in the southern part of Puppis A where the surface brightness of Vela is relatively high and that of Puppis A is relatively low. The contamination by Vela is small and thus the effects on our spectral analysis of Puppis A are not

5.3 Image Analysis

An X-ray three-color image of the merged MOS1/2, PN data from all the five XMM-Newton observations is displayed in Fig. 5.1 lower. As was noticed by previous studies of this remnant (Aschenbach 1993; Aschenbach 1994; Tamura 1995; Hwang et al. 2005; Hui & Becker 2006a), we can see a relatively strong blue-color (hard energy band) region across the remnant from NE to SW. It is pointed out that intervening absorption materials along the line of sight might absorb the soft X-ray photons in this region (Aschenbach 1993). Another noticeable feature is the western limb that is obviously enhanced in red (soft energy band) in Fig. 5.1 lower. This feature indicates that the electron temperature in this region are relatively lower than that in the other regions. We confirm that these features are indeed mainly caused by the absorption or temperature structures in this remnant later in this section.

The XMM-Newton spectrum of Puppis A shows broad emission line complexes from elemental species of O, Ne, Mg, Si, S, and Fe. In order to trace the elemental distribution across the SNR, we construct EW images by selecting photons around the broad-line complexes (Table 5.2), following methods in the literatures (Hwang et al. 2000, Park et al. 2003). Figure 5.2 shows the EW images from the merged MOS1/2 and PN data. Note that that two EW images separately generated from MOS and PN detectors are similar to each other in spite of the difference in the energy resolution of these two detectors. The continuum and line images for O, Ne lines are extracted with 20″ pixels and 40″ for the others. Then, they are smoothed by a Gaussian with σ = 60″ and 80″, respectively. The underlying continuum is calculated by logarithmically interpolating between images made from the higher and lower “shoulders” of each broad line. The estimated continuum flux is integrated over the selected line width, assuming that the spectrum of the under-
Table 5.2: Energy bands used for generating the EW images

<table>
<thead>
<tr>
<th>Elements (Line)</th>
<th>Low (eV)</th>
<th>High (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O (Lyα)</td>
<td>610-690</td>
<td>400-450</td>
</tr>
<tr>
<td>Fe L . . . .</td>
<td>690-860</td>
<td>400-450</td>
</tr>
<tr>
<td>Ne (Heα)</td>
<td>860-950</td>
<td>400-450</td>
</tr>
<tr>
<td>Mg (Heα)</td>
<td>1280-1420</td>
<td>1200-1250</td>
</tr>
<tr>
<td>Si (Heα)</td>
<td>1750-1950</td>
<td>1650-1750</td>
</tr>
<tr>
<td>S (Heα)</td>
<td>2300-2550</td>
<td>1950-2080</td>
</tr>
</tbody>
</table>

The high- and low-energy bands around the selected line energies used to estimate the underlying continuum.

lying continuum is constant in the selected line width. Then, we subtract the estimated continuum emission from the line emission. The continuum-subtracted line intensity is then divided by the estimated continuum on a pixel by pixel to generate the EW images for each emission line. In order to avoid noise due to poor photon statistics, we analyze pixels in which the number of MOS1/2 + PN photons for each line bandpass is higher than 15 cts and the line flux exceeds the integrated continuum flux.

For BG subtractions, we use the data set accumulated from observations of blank skies in high Galactic latitudes (Read & Ponman 2003). We investigate that the count rate in the energy range 0.65–4 keV of BG estimated near Puppis A [Obs.ID 0159360701 whose offset angle from Puppis A is (∆l, ∆b) = (∼ 4°, ∼ 1°)] is consistent with that of the BG prepared by Read & Ponman (2003) within less than 10%. Due to the high surface brightness of Puppis A especially below 4 keV, our results are not affected by the BG selected either in the low latitude or in the high latitude in our galaxy. Although the BG data are cleaned with the same criteria as those for the source data, the count rates in the energy range above 6 keV, where the emission is free from the contamination from known astrophysical sources, are different between the source and the BG data. We attribute the discrepancy to the difference in the particle radiation environments of the source and BG data observations, and subtract the BG data adjusting its normalization to the source data in the energy range between 6 keV and 12 keV (see e.g., Fujita et al. 2004, Sato et al. 2005).

To investigate the overall validity of the metallicity structure of the SNR implied by the EW images, we extract four example spectra from the regions indicated in Fig. 5.2 (from region 1 to 4). All the extracted spectra are shown in Fig. 5.3. The region 1
Figure 5.2: EW images for O Lyα, Ne Heα, Mg Heα, Si Heα, S Heα, and Fe L. The color scales are in units of keV. We adjusted the color codes for all the images so that we can see blue color in the bright eastern knot which is believed to be a shocked ISM. All the locations for (1–4) sample spectral regions (1–4) are shown.
Figure 5.3: Example MOS1 spectra from the four (from 1 to 4) regions indicated in Fig. 5.2
5.4 SPECTRAL ANALYSIS

The four spectra in Fig. 5.2 also explain the overall feature of Fig. 5.1 lower. The spectra from regions 2 and 4 which are located in the blue-color region in Fig. 5.1 lower show steepening in the lower energy compared with others. The steepening is a clear sign of the high column density of foreground material. Also, region 3 covers the enhanced red-color region of the western limb. The region 3 spectrum is apparently softer than those for the other regions, which is due to the low temperature there.

We find that the EW images are generally divided into three groups in terms of their similarity: O-Ne, Si-S, and Fe. The O and Ne EWs are enhanced in the faint south regions compared with the bright north and east regions while the Si and S EWs show apparent enhancement only in the relatively small region in the NE portion of the remnant. We note that Hwang et al. (2008) independently discovered the Si-rich region with their Suzaku observations. The Fe EW image is more or less featureless although the EW appears to be lower in the west.

5.4 Spectral Analysis

In addition to the overall structure, a small O, Ne, and Mg-EW-enhanced region can be found at the NE edge of the central FOV (the south of the region 2 in Fig. 5.2). We superimpose proper-motion vectors of 11 measured OFMKs in the XMM-Newton three-color image as well as O EW image in Fig. 5.4 (a), (b) and (c) (proper-motion vectors from Winkler e al. 1988; or Fig. 5 in Winkler & Petre 2007). A cluster of four OFMKs seen in the center of Fig. 5.4 (b) and (c) turns out to be positionally coincident with an X-ray knotty feature with the enhanced O EW. The cluster of OFMKs is a fast-moving O-rich optical filament, sometimes referred as the “omega” filament (Winkler & Kirshner 1985). On the other hand, there seems no X-ray features with high O EW apparently...
corresponding to other OFMKs.

We extract two spectra from the north and south of the X-ray knotty feature because the feature is divided into two regions in terms of color: the NE portion of the feature shows purple color while the SW portion of the feature looks red see, Fig. 5.4 b). Note that the southern region in the X-ray knotty feature includes the “omega” filament. We simultaneously fit the MOS1 and MOS2 spectra, allowing the normalizations between the two detectors to vary by introducing the constant model in XSPEC. As BG, we subtract the X-ray emission in their surrounding regions i.e., areas enclosed by dashed lines around each region shown in Fig. 5.4 c) after normalizing the intensities at the ratios of source areas to BG areas.

We apply an absorbed single component NEI model for the two spectra (the \texttt{wabs} (Morrison & McCammon 1983) and \texttt{vpshock} model (NEI version 2.0) (e.g., Borkowski et al. 2001) in XSPEC v12.3.1). Initially, we allow the individual element abundances to be freely fitted relative to H and find that enhanced values were required\footnote{In this fitting, we obtained only lower limits of metal abundances that were typically several hundred times the solar values.}. This fact clearly shows that the knotty feature consists of metal-rich ejecta\footnote{We note that Hwang et al. (2008) independently detect metal-abundance enhancements positionally coincident with the X-ray knotty feature disclosed here from their \textit{Suzaku} observations.}. We then set O/H at the optically determined value of 2000 (Winkler & Kirshner 1985) in order to obtain element abundances relative to O. Free parameters are hydrogen column density, \(N_H\); electron temperature, \(kT_e\); ionization timescale, \(n_e t\); volume emission measure (VEM; \(\text{VEM} = \int n_e n_H dV\), where \(n_e\) and \(n_H\) are number densities of electrons and protons, respectively and \(V\) is the X-ray–emitting volume); abundances of Ne, Mg, Si, S, Fe, and Ni. Above, \(n_e t\) is the electron density times the elapsed time after shock heating and the \texttt{vpshock} model assumes a range of \(n_e t\) from zero up to a fitted maximum value. We set the abundance of Ni equal to that of Fe. Abundances of the other elements were fixed to the solar values (Anders & Grevesse 1989).

The two spectra with the best-fit models are shown in Fig. 5.5 (left column). Note that we exclude data in the energy range below 0.65 keV where apparent differences between MOS1 and MOS2 data were seen. The difference might be due to the contamination on the MOS1 chip (Pradas & Kerp 2005). The best-fit parameters and fit statistics are summarized in table 5.4. We find that the fit level for the northern spectrum is far from acceptable while that for the southern one is moderate. We notice that the residuals in the northern spectrum have wavy structures around line emissions such as Ne \(\text{He}\alpha\), Mg \(\text{He}\alpha\), or Si \(\text{He}\alpha\). These features suggest that the line center energies are systematically shifted from those expected by the best-fit model.
Figure 5.4: (a) Same as Fig. 5.1 lower but with arrows which represent proper-motion vectors for \( \sim 1000 \text{ yr} \) (Winkler & Kirshner 1988) of OFMKs. Two open circles located at the bright eastern and northern knots are the regions where we extract spectra for a verification of line shifts observed in the X-ray ejecta knotty feature (see, text). The box represents the area covered in Fig. 5.4 (b), (c), and (d). (b) Same as Fig. 5.4 (O \( \text{Ly}\alpha \) EW) but expanded in the NE portion of Puppis A. The area is shown as a box region in Fig. 5.4 (a). (c) \textit{XMM-Newton} three-color image in the same area shown in Fig. 5.4 (b). Note that the color scale is different from that shown in Fig. 5.1 lower. (d) \textit{XMM-Newton} wide band (0.4–5.0 keV) image in the same area shown in Fig. 5.4 (b). Spectral extraction regions are shown as solid (for source spectra) and dashed (for BG spectra) white lines.
Table 5.3: Spectral-fit parameters in the two regions shown in Fig. 5.4 (c)

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_H$</th>
<th>$kT_e$ (keV)</th>
<th>log($\tau$)</th>
<th>Ne/O</th>
<th>Mg/O</th>
<th>Si/O</th>
<th>S/O</th>
<th>Fe/O</th>
<th>EM</th>
<th>redshift ($\times 10^{-3}$)</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>0.37$^{+0.03}<em>{-0.02}$ &amp; 1.36$^{+0.11}</em>{-0.08}$ &amp; 10.65$^{+0.05}<em>{-0.05}$ &amp; 0.8±0.1 &amp; 0.8±0.1 &amp; 0.5±0.1 &amp; 0.4±0.3 &amp; 0.22$^{+0.08}</em>{-0.06}$ &amp; 4.0 ± 0.6 &amp; —</td>
<td>462/216</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>0.43±0.02 &amp; 0.36±0.02 &amp; 10.59$^{+0.06}<em>{-0.08}$ &amp; 1.4$^{+0.3}</em>{-0.1}$ &amp; 1.7$^{+0.5}_{-0.3}$ &amp; &lt;1.1 &amp; &lt;0.7 &amp; &lt;0.3 &amp; 9±1 &amp; —</td>
<td>290/191</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.40$^{+0.03}<em>{-0.06}$ &amp; 0.60$^{+0.08}</em>{-0.05}$ &amp; 11.20$^{+0.07}<em>{-0.06}$ &amp; 1.04$^{+0.06}</em>{-0.05}$ &amp; 0.95$^{+0.19}<em>{-0.05}$ &amp; 0.7±0.1 &amp; &lt;0.8 &amp; 0.16±0.03 &amp; 7.1 ± 0.2 &amp; −11.4$^{+0.4}</em>{-0.3}$</td>
<td>288/215</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>0.43$^{+0.01}<em>{-0.02}$ &amp; 0.35±0.01 &amp; 10.71$^{+0.02}</em>{-0.14}$ &amp; 1.5±0.1 &amp; 1.7$^{+0.2}<em>{-0.3}$ &amp; &lt;0.5 &amp; &lt;0.7 &amp; &lt;0.3 &amp; 8±1 &amp; −5.5$^{+0.1}</em>{-1.0}$</td>
<td>266/190</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The best-fit parameters for the two spectra in Fig. 5.4 (c).
Results are from the *vpshock* model in which the redshift is fixed to zero (upper two rows) and allowed to vary (lower three rows).
The units of $N_H$ and EM are $\times 10^{22}$ cm$^{-2}$ and $\times 10^{16}$ cm$^{-5}$, respectively.
Quoted errors are at 90% confidence level.
The values of the abundance ratios are relative to those of the solar ratios.
Other elements are fixed to those of the solar values (Anders & Grevesse 1989).
The errors are calculated after fixing the $kT_e$ to the best-fit value.
Errors for EM are calculated after fixing the $kT_e$ and Ne abundance to the best-fit values.
Figure 5.5: Left column: MOS1 (black) and MOS2 (red) spectra from the two regions in Fig. 5.4 with the best-fit model (redshift = 0). The lower panels show the residuals. Right column: Same as the left column but with the revised model (redshift is free).
We thus introduce a variable redshift in the same \texttt{vpshock} model. The two spectra with the revised best-fit model are also shown in Fig. 5.5 (right column). The revised model significantly (significance level of greater than 99.9\% based on the $F$-test) improved the fits for both of the two spectra. In particular, the wavy structures of residuals seen in the previous fit (i.e., redshift is fixed to zero) for the northern spectrum successfully disappear in the revised fit (i.e., redshift is free). Table 5.4 summarized the best-fit parameters for the two spectra obtained from the revised model fitting. The value of the redshift for the northern portion of the knotty feature turned out to be higher than that for the southern portion. We found that relatively low temperatures and no Si and S abundances in the south of the knotty feature while relatively high temperatures and significant Si and S abundances in the north of the feature. Those features result in the color variation seen in Fig. 5.4 (b). Ionization timescales for the two regions are significantly lower than that expected for the collisional ionization equilibrium.

Doppler velocity measurements with X-ray CCD detectors have been successfully demonstrated by several different groups (e.g., Willingale et al. (2002) using data from \textit{XMM-Newton} MOS). However, small redshifts of $\lesssim 10$ eV require a careful investigation of systematic uncertainties and/or artifacts due to the detector calibration (the uncertainty of absolute energy scale is $\lesssim 5$ eV; Kirsch 2007). To estimate systematic errors of the Doppler shifts derived as well as to ensure that the line shifts are not due to the calibration uncertainty, we further perform spectral analysis in the following three cases: (1) individual fit of MOS1 and MOS2 spectra, (2) individual fit of spectra from the two observations (whose rotation angles are different from each other), (3) different BG spectra in intensities (50\% larger or lower than the original intensity). We summarize all the derived values of the redshift in table 5.4. We find significant blueshifts in all the cases for the two regions, suggesting that the blueshifts obtained in the regions were not due to uncertainties of the calibration nor BG estimations. The systematic uncertainties are beyond the statistical ones and dominates the significance of the redshift. The Doppler velocities considering all the systematic uncertainties are $-3400^{+1000}_{-800}$ km sec$^{-1}$ for the north of the knotty feature and $-1700^{+700}_{-800}$ km sec$^{-1}$ for the south of the knotty feature. The dominant uncertainty comes from the systematic uncertainty between the two detectors and/or that introduced by possible variations of the BG intensities.

Next, we investigate whether or not the calibration uncertainty of the MOS energy scale is serious in our data. We measure line center energies in the two regions and the local BG region for each region, applying a phenomenological model, i.e., a thermal continuum and 14 Gaussian line profiles. In this investigation, we examine two more spectra extracted from bright northern and eastern knots (white open circles in Fig. 5.4 a). Both of the
5.4. SPECTRAL ANALYSIS

Table 5.4: Redshift values ($\times 10^{-3}$)

<table>
<thead>
<tr>
<th>Region</th>
<th>Case-1$^a$</th>
<th>Case-2$^b$</th>
<th>Case-3$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MOS1 MOS2</td>
<td>Obs1 Obs2</td>
<td>0.5</td>
</tr>
<tr>
<td>North</td>
<td>$-8.6^{+0.2}<em>{-0.7}$ $-12.4^{+0.6}</em>{-0.4}$</td>
<td>$-8.6 \pm 0.4$</td>
<td>$-12.6^{+0.7}_{-0.5}$</td>
</tr>
<tr>
<td>South</td>
<td>$-5.6^{+1.6}<em>{-0.9}$ $-5.6^{+2.2}</em>{-2.8}$</td>
<td>$-5.1 \pm 0.2$</td>
<td>$-6.7^{+3.5}_{-1.7}$</td>
</tr>
</tbody>
</table>

Quoted errors are at 90% confidence level.

$^a$Case-1; we individually analyzed MOS1 and MOS2 data. In this case, we included both of the two observations and subtracted the local BG with original intensity.

$^b$Case-2; we separately analyzed the data from the two observations. Obs1 and Obs2 are Obs.ID 0113020101 and Obs.ID 0113020301, respectively. In this case, we used data from both MOS1 and MOS2 detectors and subtracted the local BGs with original intensities.

$^c$We artificially varied the intensities of the local BGs (0.5 and 1.5 times the original intensity). In this case, we used all the data sets (MOS1+MOS2+Obs1+Obs2).

$^d$Same as listed in table 5.4.

Table 5.5: Line center energies of spectra from regions shown in Fig. 5.4

<table>
<thead>
<tr>
<th>line</th>
<th>North</th>
<th>North (BG)</th>
<th>South</th>
<th>South (BG)</th>
<th>Northern Knot</th>
<th>Eastern Knot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne Heα (eV)</td>
<td>930$^{+6}_{-5}$</td>
<td>917$\pm2$</td>
<td>922$^{+5}_{-3}$</td>
<td>917$\pm1$</td>
<td>914$\pm1$</td>
<td>916$\pm1$</td>
</tr>
<tr>
<td>Mg Heα (eV)</td>
<td>1357$\pm2$</td>
<td>1344$^{+1}_{-2}$</td>
<td>1351$^{+3}_{-3}$</td>
<td>1346$^{+1}_{-3}$</td>
<td>1343$\pm2$</td>
<td>1343$\pm2$</td>
</tr>
<tr>
<td>Si Heα (eV)</td>
<td>1878$^{+5}_{-8}$</td>
<td>1856$^{+4}_{-3}$</td>
<td>ND$^a$</td>
<td>1857$^{+3}_{-2}$</td>
<td>1851$^{+5}_{-2}$</td>
<td>1859$\pm2$</td>
</tr>
</tbody>
</table>

Quoted errors are at 90% confidence level.

$^a$We could not determined the value due to the poor statistics.

Knots are most likely the shocked ISM (Hwang et al. 2005) and are thus expected to show no Doppler shift. Free parameters are center energy, line width, normalization of each Gaussian line, $kT_e$, and normalization of the thermal continuum. The derived line center energies for Ne Heα, Mg Heα, and Si Heα are summarized in table 5.5. Then, we confirm that the line center energies obtained in the local-BG-subtracted spectra are indeed significantly higher than those obtained in the surrounding BG regions as well as those in the eastern/northern knots. These facts strongly support that the line shifts seen in the ejecta feature are not due to calibration uncertainties of the MOS energy scale.

Finally, we investigate whether the variations of line center energies are caused by the plasma condition (i.e., ionization states, electron temperature) rather than Doppler shifts. According to the NEI code in Hughes et al. (2000), line center energies of the
K-shell complex, including all lines from all charge states excluding Lyα and all higher energy lines are calculated to be 0.872–0.918 keV for Ne, 1.269–1.350 keV for Mg, and 1.744–1.862 keV for Si. The results in Table 5.5 shows that the shifts in line centroids from the northern region cannot be related to temperature/ionization effects, while the effects cannot be ruled out for the south region. However, the agreement with optical Doppler velocity makes it plausible that we detect blueshift in the south region.

In this context, we are convinced that the line shifts observed in the two regions are not due to instrumental origin nor plasma conditions (i.e., $kT_e$ and $\tau$) but reflect the Doppler-shifts caused by its fast motion toward us. In conclusion, we observe blue-shifted line emissions from the north and south of the feature with Doppler velocities $\sim 3400^{+1000}_{-800}$ km sec$^{-1}$ and $\sim 1700^{+700}_{-800}$ km sec$^{-1}$, respectively. The Doppler velocity estimated in the south of the feature, where the optical “omega” filament is included, is consistent with that measured for the optical “omega” filament ($1500\pm100$ km sec$^{-1}$; Winkler & Kirshner 1985).

We should note that the Doppler velocity in the northern portion of the X-ray knotty feature is different from that in the southern portion, although it is not significant taking into consideration of the systematic uncertainties. If the velocity difference is real, the moving directions should be different between the northern portion and the southern portion in the feature. This means that we might see two different ejecta knots along the line of sight so that they appear to form one knot. On the other hand, in the case that the Doppler velocities in the two regions are same with each other, the two spectra must come from one knot. If it is the case, it is interesting to note that there are variations of metal composition in the knot: the northern portion is rich in heavy elements of O, Ne, Mg, Si, S, and Fe while the southern portion is rich in only O, Ne, and Mg. Further X-ray observations will reveal the nature of the ejecta feature.

5.5 Discussion

5.5.1 Overall Structures

The entire three-color image clearly shows a blue-color region across the remnant from NE to SW which was noted by previous observations and considered to be produced by cold gas located close to the shock front of the Vela SNR (Aschenbach 1993) or interstellar clouds associating with Puppis A (Arendt et al. 1990). We confirmed the blue-color region was due to foreground absorption of Puppis A, although we could not clarify whether the absorption materials were located close to the Vela SNR or Puppis A.
The EW images of all elements but Fe reveal regionally enhanced line features. These line enhancements are most likely caused by overabundance of these species as the actual regional spectra indicate. Enriched O-group species are considered to be typical remains of He-burning process which was produced in the relatively outer layers of a massive progenitor and then subsequently was ejected during the explosion, while a bulk of Fe-core may be collapsed. The observed enhancements of O-group elements and the lack of Fe-rich ejecta self-consistently support a core-collapse origin of Puppis A, which has also been suggested by the presence of the CCO and the O-rich optical knots.

The O and Ne EW images are generally similar to each other, showing an overall enhancement in the south of the remnant. This asymmetric appearance is more or less anti-coincident with an overall X-ray intensity and most likely due to ambient medium density variation. Since the ambient medium density is decreasing toward SW by a factor of 4 (Petre et al. 1982), the emission from the ejecta-material may be easier to be detected in the SW region where the dominance of the shocked ISM is considered to be weak. We found a Mg-Si-S-EW enhanced region only in the NE portion of the remnant. We suggest that this feature represent the asymmetric ejection of those elements at the SN explosion. Asymmetric distributions of the innermost ejecta such as Si, S, and Fe have been recently reported for a middle aged SNR, the Cygnus Loop (Tsunemi et al. 2007; Katsuda et al. 2008c), showing the degree of anisotropy of 1:2 to the geometric center. The anisotropy can be considered to reflect an asymmetric SN explosion resulting from hydrodynamic instabilities which are described in recent theoretical models of SN explosions (e.g., Burrows et al. 2007). In Puppis A, we detected a relic of Si-S-ejecta only in the NE portion of the remnant. This fact suggests higher anisotropic ejection of these elements than that estimated in the Cygnus Loop.

5.5.2 Mass and Origin of the Ejecta Feature

An ejecta-dominated X-ray bright knotty feature is found on the position of the optically O-rich knots discovered by Winkler & Kirshner (1985) and Winkler et al. (1988). We perform spectral analysis for the bright X-ray knotty feature dividing it into two (north and south) regions.

Under the assumption of metal abundance of O/H to be 2000 times the solar value, the electrons are dominantly supplied by O ions or other metals such as Si or S. We assume that the value of $n_e$ is 7 times that of O ion density, $n_O$, because O ions mainly exist as the He like or H like ionization states at the electron temperature and the ionization timescale obtained for the feature (table 5.4). Assuming that the depth of the X-ray-emitting plasma is the same as apparent width (1’), we estimate each elemental densities
Table 5.6: Densities (cm$^{-3}$) and masses ($\times10^{-4}$ M$_{\odot}$) in the two regions in Fig. 5.4 (d)

<table>
<thead>
<tr>
<th></th>
<th>$n_e$</th>
<th>$n_O$</th>
<th>$n_{Ne}$</th>
<th>$n_{Mg}$</th>
<th>$n_{Si}$</th>
<th>$n_S$</th>
<th>$n_{Fe}$</th>
<th>$M_O$</th>
<th>$M_{Ne}$</th>
<th>$M_{Mg}$</th>
<th>$M_{Si}$</th>
<th>$M_S$</th>
<th>$M_{Fe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>0.7</td>
<td>0.09</td>
<td>0.014</td>
<td>0.004</td>
<td>0.003</td>
<td>0.0007</td>
<td>0.0008</td>
<td>70</td>
<td>14</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>South</td>
<td>0.7</td>
<td>0.1</td>
<td>0.02</td>
<td>0.008</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>18</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Typical errors are about a factor of 2.

and masses in each region and summarize them in table 5.5.2. We obtain the total masses in both north and south of the knotty feature to be $\sim$0.01 M$_{\odot}$.

The masses of OFMKs seen in Cas A and Puppis A are estimated to be $1\times10^{-4}$ M$_{\odot}$ (Raymond 1984) and $1\times10^{-2}$ M$_{\odot}$ (Winkler et al. 1988), respectively. The masses of Fe-rich knots in Cas A and O-Ne-rich knot in G292.0+1.8 are estimated to be from $4\times10^{-5}$ to $1\times10^{-3}$ M$_{\odot}$ (Hwang & Laming 2003) and $1\times10^{-3}$ M$_{\odot}$ (Park et al. 2004), respectively. The masses of Vela shrapnels A (Si-rich knot) and D (O-Ne-Mg-rich knot) are estimated to be $5\times10^{-3}$ and 0.1 M$_{\odot}$, respectively (Katsuda & Tsunemi 2006; 2005). Therefore, the ejecta knotty feature disclosed here has the similar mass as those of OFMKs in Puppis A, and is categorized as relatively massive ejecta knots.

We investigate the origin of this ejecta material by comparing the observed metal abundance ratios with those of theoretical models. We employed models for progenitor masses of 15, 20, 25, and 30 M$_{\odot}$ with initial composition of solar values. We examine two sets of models by Rauscher et al. (2002) and Tominaga et al. (2007). For the southern region of the feature, we compare the relative abundances of Ne and Mg to O with those expected in the models. We find that Tominaga’s 25 and 30 M$_{\odot}$ models can reproduce the derived relative abundances in the explosive Ne/C-burning cores while Rauschers’s 15 M$_{\odot}$ model also reproduces the data in the explosive Ne/C-burning core. On the other hand, the composition of the feature in the north turns out not to be reproduced in any models at any mass radius. If we compare the mass ratios of S and Fe to Si to those of the models, we find that all the models examined can reproduce the mass ratios in incomplete explosive Si-burning layers. The progenitor mass and specific burning process are not well constrained by the current data analysis. To reveal the origin of the feature, follow-up works for data with better spatial resolution which can be obtained with Chandra and/or XMM-Newton will be required.


**5.5. DISCUSSION**

**Kinematics of the Ejecta Feature**

Assuming that the X-ray knotty feature has suffered negligible deceleration since the SN event, with the blueshift value obtained, we can estimate the angular distance along the line of sight since the SN explosion to be \( \sim 20 \left( \frac{v}{3400 \text{ km sec}^{-1}} \right) \left( \frac{a}{3700 \text{ yr}} \right) \left( \frac{d}{2.2 \text{ kpc}} \right)^{-1} \) arcmin (the Doppler velocity from the northern portion of the feature, distance from Reynoso et al. 1995). In the plane of the sky, the tangential angular distance of the feature from the optical explosion center (Winkler & Kirshner 1988) is about 7.5. Then, we can estimate the actual angular distance to the explosion center to be 21'. Therefore, the X-ray feature turned out to be located in a relatively outer region in Puppis A whose radius is about 25'. This leads us to consider that it is now interacting with a dense swept-up ISM shell. Dividing the ionization timescale, \( \sim 2 \times 10^{10} \text{ cm}^{-3} \text{ sec} \), by the electron density, \( \sim 0.7 \text{ cm}^{-3} \) in the feature, we estimate the time after the shock heating to be 900 yrs.

Considering that OFMKs in Puppis A are believed to be recoiled materials to the high-velocity CCO (Hui & Becker 2006b; Winkler & Petre 2007), we suggest that the ejecta features which we find near the OFMKs (i.e., ejecta feature and Mg-Si-S-rich ejecta) are also part of the recoiled materials. Winkler & Petre (2007) measured the proper motion of the stellar remnant and estimated the momentum to be \( \sim 4 \times 10^{41} \text{ g cm s}^{-1} \) in the plane of the sky. We estimated the total momentum of the ejecta feature toward the opposite direction to the traveling direction of the CCO to be \( \sim 0.07 \times 10^{41} \text{ g cm s}^{-1} \), which was responsible for about 2% of the required momentum to balance that of the CCO. To estimate the total ejecta mass (or momentum) in Puppis A, detailed spectral analysis for the Mg-Si-S-rich ejecta as well as the entire remnant should be performed, which is beyond the scope of this paper.

As introduced in chapter 2, there are mainly three mechanisms proposed to explain the origin of high-velocity neutron stars such as the CCO in Puppis A: binary disruptions, natal or postnatal kicks from the SN explosions (see, Lai et al. 2001 for a review). Recent theoretical studies have focused on natal kicks imparted to neutron stars at birth rather than the other two mechanisms. A natal kick could be due to global hydrodynamical perturbations in the SN core (e.g., Goldreich et al. 1996), or it could be a result from asymmetric neutrino emission in the presence of super strong magnetic fields (\( B \geq 10^{15} \text{ G} \)) in the proto–neutron star (e.g., Blandford et al. 1983). The two models lead to distinct predictions: the measured neutron star velocity should be directed opposite to the momentum of the gaseous SN ejecta caused by linear momentum conservation in the hydrodynamically-driven mechanisms (e.g., Scheck et al. 2006) while neutrino-driven mechanisms predict the motion of the ejecta roughly in the same direction of the neutron star kick (Fryer & Kusenko 2006). Therefore, our data as well as the distributions of
OFMKs suggest that the hydrodynamically- (or ejecta-) driven mechanisms are at work to produce the high-velocity CCO in Puppis A.

5.6 Conclusion

We analyzed five XMM-Newton observations of the Galactic O-rich supernova remnant Puppis A. The five observations covers almost the entire X-ray remnant.

We present the EW images of Puppis A for the elements of O, Ne, Mg, Si, S, and Fe which are statistically allowed to be made with our current data set. The EW images of all elements but Fe reveal regionally enhanced line features which are most likely caused by overabundance of these species. We find that the O-Ne-EW images were generally similar to each other, showing an overall enhancement in the SW region of the remnant. This asymmetric appearance is likely due to the fact that the emission from the ejecta-material may be easier to be detected in the SW region. On the other hand, Si-S-EW images are only enhanced in a relatively compact NE region of the remnant, suggesting that a highly asymmetric SN explosion produced Puppis A.

We find an X-ray knotty feature with high O-Ne-Mg-EW positionally coincident with OFMKs. Based on our spectral analysis for the X-ray knotty feature, we confirm high metal abundances, clearly showing that the knotty feature consists of metal-rich ejecta. Furthermore, we discover that line emissions in the feature are significantly blue-shifted, showing a Doppler velocities of $-3400^{+1000}_{-800}$ km sec$^{-1}$ for the northern portion of the feature and $-1700^{+700}_{-800}$ km sec$^{-1}$ for the northern portion of the feature. The momentum of the X-ray knot is measured to be $\sim 0.5 \times 10^{41}$ g cm s$^{-1}$ toward the opposite direction to the traveling direction of the CCO, which can account for $\sim 2\%$ of the required momentum to balance that of the CCO.
Chapter 6

The Cygnus Loop

6.1 Previous Results

The Cygnus Loop is a nearby (540 pc: Blair et al. 2005) proto-typical middle-aged (∼10,000 yr) SNR located at (l, b)=(74°, −8°.5). The foreground neutral hydrogen column density, $N_H$, is estimated to be $\sim 0.04 \times 10^{22}$ cm$^{-2}$ (Inoue et al. 1980; Kahn et al. 1980). The low foreground absorbing material and high surface brightness enable us to study the soft X-ray emission from the Cygnus Loop. In addition, the very large apparent size of the Cygnus Loop, $2°.5 \times 3°.5$ (see, Fig. 6.1 or Leahy et al. 1997), makes it an ideal target to study the spatial distribution of elemental abundances and plasma conditions in the remnant.

Miyata et al. (1994) observed the northeastern (NE) rim of the Cygnus Loop with ASCA. They found NEI conditions and depleted metal abundances relative to the solar values by factor of ∼5 for the O abundance. The low metal abundances led them to consider that the plasma in the NE-rim of the Cygnus Loop originated from swept-up matter rather than SN ejecta. Recently, Miyata et al. (2007, hereafter M07) observed the same region with Suzaku and performed spectral analysis from 2′ thick annular regions. They confirmed the metal deficiency as well as the NEI conditions there. Chandra observation revealed that oxygen abundance in the SW rim of the Loop is also depleted by the same factor as that observed in the NE rim (Leahy 2004). So far, the origin of the abundance depletion remains as an open question.

Hatsukade & Tsunemi (1990) detected a hot plasma inside the Cygnus Loop that is not expected in the simple Sedov model. They reported that the hot plasma was confined inside the Loop. Miyata et al. (1998) detected strong emission lines from Si, S and Fe-L from inside the Loop. They found that the metal abundance is at least several times higher than that of the solar value, indicating that a few tens of higher than that of the shell
region. They concluded that the metal rich plasma was a fossil of the SN explosion. The abundance ratio of Si, S and Fe indicated the progenitor star mass to be $25M_\odot$. Miyata & Tsunemi (1999) measured the radial profile inside the Loop and found a discontinuity around $0.9R_s$ where $R_s$ is the shock radius. They measured the metallicity inside the hot cavity and estimated the progenitor mass to be $15M_\odot$. Levenson et al. (1998) estimated the size of the cavity and the progenitor mass to be $15M_\odot$. Therefore, the progenitor star of the Cygnus Loop is a massive star.
6.2 Observations and Data Reductions

We have observed the Cygnus Loop in many pointings by \textit{Suzaku} and \textit{XMM-Newton}. All of FOV analyzed here are shown in Fig. 6.1. Obs. IDs, the nominal point, roll angle, observation date, and the effective exposure times after the screening are summarized in table 6.1.

6.2.1 \textit{Suzaku} Observations

Using the \textit{Suzaku} satellite, we observed the NE rim of the Cygnus Loop in four pointings (NE1–4) during the science working group (SWG) observing time. In addition, we observed the Cygnus Loop from the NE rim to the SW rim (P8, P12–17) in the AO1 phase in order to reveal ejecta structures in this SNR. We employ revision 1.2 of the cleaned event data and exclude the time region where the attitude is unstable. Furthermore, we exclude data taken in the low cut-off rigidity $<6$ GV. We subtract a blank-sky spectrum obtained from the Lockman Hole. We select two observations of the Lockman Hole that were performed close to the observation dates of the Cygnus Loop.

Figure 6.2 and 6.3 show the \textit{Suzaku} XIS1 (BI CCD) three color images for the NE rim (\textit{Upper}) and the NE-SW path (\textit{Lower}), respectively. The narrow energy bands for the three color are different in each image; Red: 0.31–0.38 keV (C $\text{He}\alpha$) band, Green: 0.38–0.46 keV (N $\text{He}\alpha$) band, Blue: 0.60–0.69 keV (O $\text{Ly}\alpha$) band for the NE rim, while the three colors correspond to narrow energy bands of 0.54–0.59 keV (O $\text{He}\alpha$), 0.88–0.94 keV (Ne $\text{He}\alpha$), and 0.69–0.85 keV (Fe L), respectively for the NE-SW path observations.

6.2.2 \textit{Chandra} Observations

\textit{Chandra} ACIS observed the NE rim of the Cygnus Loop in two pointings. The nominal position of one pointing (ObsID. 2821), which covers the northern portion of the NE rim, is $[(\text{RA}, \text{DEC})=(20^h54^m38.8, 32^\circ16'27''.9) \ J2000]$, while that of the other pointing (ObsID. 2822), which covers the southern portion of the NE rim, is $[(\text{RA}, \text{DEC})=(20^h56^m10.6, 31^\circ55'19''.3) \ J2000]$. The observation dates are 2001 December 24 and 16 for ObsID. 2821 and 2822, respectively. The total FOV of twelve CCDs for the two pointings are shown as white boxes in Fig. 6.1. We start our analysis from level 2 event files processed with calibration data files in CALDB ver. 3.3.0. We exclude the high-background periods for data from ObsID. 2821. On the other hand, there seems no significant background flares for the data from ObsID. 2822 so that we reject no data from the level 2 event file for our analysis. The resulting net exposure times for ObsID. 2821 and 2822 are 35 ks and 59 ks,
Figure 6.1: *ROSAT* HRI image of the entire Cygnus Loop. All of the *Suzaku, Chandra,* and *XMM-Newton* FOV are shown as white solid rectangles, white dashed rectangles, and white solid circles, respectively.
Table 6.1: Observations of the Cygnus Loop and Lockman Hole

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Coordinate (RA, DEC)</th>
<th>Roll</th>
<th>Obs. Date</th>
<th>Effective Exposure (ksec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suzaku (Cygnus Loop)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500020010 (NE1)</td>
<td>314.178, 31.745</td>
<td>58°.5</td>
<td>2005.11.23</td>
<td>16.6</td>
</tr>
<tr>
<td>500021010 (NE2)</td>
<td>313.956, 31.961</td>
<td>58°.0</td>
<td>2005.11.24</td>
<td>21.0</td>
</tr>
<tr>
<td>500022010 (NE3)</td>
<td>313.747, 32.189</td>
<td>57°.8</td>
<td>2005.11.29</td>
<td>18.8</td>
</tr>
<tr>
<td>500023010 (NE4)</td>
<td>313.489, 32.375</td>
<td>57°.6</td>
<td>2005.11.30</td>
<td>23.2</td>
</tr>
<tr>
<td>501028010 (P8)</td>
<td>314.005, 31.464</td>
<td>58°.5</td>
<td>2006.05.13</td>
<td>4.7</td>
</tr>
<tr>
<td>501029010 (P12)</td>
<td>313.751, 31.263</td>
<td>58°.7</td>
<td>2006.05.09</td>
<td>13.2</td>
</tr>
<tr>
<td>501030010 (P13)</td>
<td>313.498, 31.061</td>
<td>58°.9</td>
<td>2006.05.10</td>
<td>13.9</td>
</tr>
<tr>
<td>501031010 (P14)</td>
<td>313.245, 30.859</td>
<td>59°.1</td>
<td>2006.05.12</td>
<td>18.2</td>
</tr>
<tr>
<td>501032010 (P15)</td>
<td>312.993, 30.653</td>
<td>59°.3</td>
<td>2006.05.25</td>
<td>17.4</td>
</tr>
<tr>
<td>501033010 (P16)</td>
<td>312.745, 30.450</td>
<td>59°.5</td>
<td>2006.05.22</td>
<td>20.0</td>
</tr>
<tr>
<td>501034010 (P17)</td>
<td>312.207, 30.005</td>
<td>60°.0</td>
<td>2006.05.22</td>
<td>13.9</td>
</tr>
<tr>
<td><strong>Suzaku (Lockman Hole)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100046010 (for SWG)</td>
<td>163.399, 57.600</td>
<td>32°.4</td>
<td>2005.11.14</td>
<td>66.9</td>
</tr>
<tr>
<td>101002010 (for AO1)</td>
<td>162.938, 57.267</td>
<td>32°.7</td>
<td>2006.05.17</td>
<td>69.0</td>
</tr>
<tr>
<td><strong>Chandra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2821</td>
<td>313.629,33.000</td>
<td>320°.0</td>
<td>2001.12.24</td>
<td>35</td>
</tr>
<tr>
<td>2822</td>
<td>314.016,31.951</td>
<td>312°.7</td>
<td>2001.12.16</td>
<td>59</td>
</tr>
<tr>
<td><strong>XMM-Newton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0082540101 (Pos-1)</td>
<td>313.848, 31.771</td>
<td>241°.7</td>
<td>2002.11.25</td>
<td>MOS=14.1, PN=5.6</td>
</tr>
<tr>
<td>0082540201 (Pos-2)</td>
<td>313.531, 31.514</td>
<td>241°.7</td>
<td>2002.12.03</td>
<td>MOS=14.4, PN=11.7</td>
</tr>
<tr>
<td>0082540301 (Pos-3)</td>
<td>313.213, 31.324</td>
<td>241°.7</td>
<td>2002.12.05</td>
<td>MOS=11.6, PN=9.1</td>
</tr>
<tr>
<td>0082540401 (Pos-4)</td>
<td>312.895, 31.000</td>
<td>241°.7</td>
<td>2002.12.07</td>
<td>MOS=4.9, PN=3.4</td>
</tr>
<tr>
<td>0082540501 (Pos-5)</td>
<td>312.577, 30.743</td>
<td>231°.4</td>
<td>2002.12.09</td>
<td>MOS=12.6, PN=10.0</td>
</tr>
<tr>
<td>0082540601 (Pos-6)</td>
<td>312.258, 30.486</td>
<td>241°.7</td>
<td>2002.12.11</td>
<td>MOS=11.5, PN=5.9</td>
</tr>
<tr>
<td>0082540701 (Pos-7)</td>
<td>311.941, 30.229</td>
<td>241°.7</td>
<td>2002.12.13</td>
<td>MOS=13.5, PN=7.5</td>
</tr>
</tbody>
</table>
Figure 6.2: Merged *Suzaku* XIS1 three color image of the four pointings of the NE rim of the Cygnus Loop (Red: 0.31–0.38 keV band, i.e., C Heα, Green: 0.38–0.46 keV band, i.e., N Heα, Blue: 0.60–0.69 keV band, i.e., O Lyα). The data have been binned by 8 pixels and smoothed by Gaussian distribution of $\sigma = 25''$. The effects of exposure, vignetting, and contamination are corrected.

Figure 6.3: Three color image merged by seven XIS FOV from the NE rim to the SW rim (Red: O Heα, Green: Ne Heα, Blue: Fe L). The data have been binned by 8 pixels and smoothed by Gaussian kernel of $\sigma = 25''$. The effects of exposure, vignetting, and contamination are corrected.
6.2. OBSERVATIONS AND DATA REDUCTIONS

Figure 6.4: *Left:* Exposure and vignetting corrected *Chandra* three-color FI CCDs image. Red, green, and blue colors correspond to narrow energy bands of 0.3–0.6 keV, 0.6–0.9 keV, and 0.9–2 keV, respectively. In addition to detailed spatially resolved spectral analyses in S3 chips, we extract spectra from two white ellipses indicated in this figure. *Right:* Same as left but for BI CCDs.

respectively.

Figure 6.4 shows three-color *Chandra* images. Red, green, and blue colors correspond to energy bands of 0.3–0.6 keV, 0.6–0.9 keV, and 0.9–2 keV, respectively. Because of the different sensitivity especially at low energy band between FI CCDs (I2, I3, S2, and S4) and BI CCDs (S1 and S3), we separately showed the FI CCD image (Fig. 6.4 *left*) and BI CCD image (Fig. 6.4 *right*).

6.2.3 XMM-Newton Observations

We performed seven pointing observations of the Cygnus Loop with *XMM-Newton* so that we could cover the full diameter from the NE rim to the SW rim (from Pos-1 to Pos-7) during the AO-1 phase. We concentrate on the data obtained with the EPIC MOS and PN cameras. All the data were taken by using medium filters and the prime full window mode. Fortunately, all the data other than Pos-4 suffered very little from background flares. All the raw data are processed with version 6.5.0 of the XMMSAS. We select X-ray events corresponding to patterns 0–12 and 0 for MOS and PN, respectively. We further clean the data by removing all the events in bad columns listed in the literature (Kirsch 2006). After filtering the data, they are vignetting-corrected using the XMMSAS task *evigweight*. For the background subtraction, we employ the data set accumulated
CHAPTER 6. THE CYGNUS LOOP

Figure 6.5: Exposure and vignetting corrected XMM-Newton three-color image. Red, green, and blue colors correspond to narrow energy bands of 0.52–0.61 keV (O He\(\alpha\)), 0.87–0.98 keV (Ne He\(\alpha\)), and 0.78–0.86 keV (Fe L), respectively.

from blank sky observations prepared by Read & Ponman (2003). After adjusting its normalization to the source data by using the energy range between 5 keV and 12 keV, where the emission is free from the contamination (Fujita et al. 2004; Sato et al. 2005), we subtract the background data set from the source.
6.3 Northeastern Rim

6.3.1 Suzaku View

We present results from the Suzaku observations of NE rim of the Cygnus Loop, which were published in Katsuda et al. (2008b).

Spatially Resolved Spectral Analysis

Figure 6.6 shows the spatially integrated XIS1 (BI CCD) and XIS0 (FI CCD) spectra in the entire FOV. The extended 0.2–12 keV energy range of the Suzaku X-ray CCD XIS camera (Koyama et al. 2007), combined with its superior energy resolution, allows us to detect emission lines from highly-ionized C and N for the first time from the Cygnus Loop (M07).

Figure 6.6: Spatially integrated XIS1 spectrum of the four pointings. Emission lines from C Heα, N Heα, O Heα, O Lyα, Ne Heα, and Mg Heα are clearly detected. The emission below 0.3 keV, so-called “C-band”, is originated from Si L and Fe M lines.

We divide the entire FOV into 184 cells (shown as small rectangles on Fig. 6.7) such that each cell contains 2500–5000 photons for XIS0 to equalize the statistics. We extract spectra from them and performed spectral analysis. We can investigate the plasma structures along the azimuthal direction as well as the radial direction from this analysis.
Figure 6.7: Same as Fig. 6.2. White small rectangles are the cells where we extracted spectra. We showed example spectra from cells 1 and 2 in Fig. 6.8. The red polygon identifies Region A (see text).

Since the energy scale is not perfectly calibrated, we manually adjust the energy scale by shifting the energy within the uncertainty of the calibration ($\pm 5$ eV; Koyama et al. 2007) so that we can obtain better fits. In order to generate the response matrix file (RMF) and the ancillary response file (ARF), we employ xisrmfgen (Ishisaki et al. 2007) and xissimarfgen (version 2006-10-26), respectively. The low energy efficiency of the XIS’s shows degradation caused by the contaminants accumulated on the optical blocking filter (Koyama et al. 2007). This is taken into account in the generation of the ARF file. For spectrum fitting, we use photons in the energy range of 0.2–3.0 keV for XIS1 and 0.4–3.0 keV for XIS0, 2, and 3 (FI CCD).

Since the analysis in M07 already revealed that at least two NEI components with different $kT_e$ were required to represent the spectra, we apply an absorbed two-$kT_e$-component NEI model for all the spectra (the wabs and vnei model (NEI version 2.0) in XSPEC v11.3.1; e.g., Borkowski et al. 2001). Free parameters are $N_H$; electron temperature, $kT_e$; $\tau$; EM; abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set the abundance of Ni equal to that of Fe. The other elemental abundances are fixed to the solar values (Anders & Grevesse 1989). We individually varied $kT_e$ and EM while other parameters were tied in the two components. We confin the variation of $N_H$ to be 0.01 to
0.06×10^{22} \text{cm}^{-2} \text{ (Inoue et al. 1980; M07). We refer to this model as a } vnei1 \text{ model. This model gives us fairly good fits for all the spectra (the reduced } \chi^2 \text{ ranges from 0.90 to 1.27). The fit statistics are dramatically improved compared to those obtained in M07 (the maximum reduced } \chi^2 \text{ is 2.81). This is mainly due to the fact that the post-launch degradation of the XIS energy resolution is now included in our spectral response function which was not possible at the time M07 was written. Figure 6.8 shows example spectra from cells 1 and 2 in Fig. 6.7 with the best-fit models. The best-fit parameters for the cells are summarized in table 6.2 (vnei1). Maps of the best-fit values are presented in Fig. 6.9.}

**Results**

--- Abundances ---

The abundances of O, Ne, Mg, and Fe are consistent with those in M07. On the other hand, C and N in our analysis are systematically higher, while Si and S are systematically lower than those in M07. There are two main reasons which can explain this discrepancy. Firstly, we allow the abundance of S to vary freely in our models, while in M07 it was fixed to the solar value. Since strong emission lines of S L fall around C K (\sim 0.35 \text{keV}) and N K (\sim 0.5 \text{keV}) emission lines, the abundances of C and N are affected by that of S. In our spectral analysis, the typical abundance of S is \sim 0.2 times the solar value, resulting in higher abundances of C and N than those in M07. Secondly, we include data in the Si K band (1.7–1.9 keV), while in M07 were excluded due to calibration uncertainty. Since the Si K line is not so strong in our data, we find that the calibration uncertainty does not play an important role in our results. Due to limited available atomic data for these transitions, the emissivities of Si L lines in our models are expected to contain large uncertainty relative to those of Si K lines. Therefore, we believe that our results are more reliable than M07 in which the abundance of Si was determined by the emission lines of Si L.

We obtain abundances within 184 spatial cells as shown in Fig. 6.10. In Fig. 6.11 (a)–(g), we plot the correlations between each elemental abundance versus O abundance for all these regions. The absolute abundances (relative to H) for all the elements vary significantly from cell to cell. The relative abundances of C, Ne, Si, and S to O are similar in all the cells, while those of Mg and Fe are divided into two groups: one shows lower values than the solar value (red crosses in Fig. 6.10) while the other shows about twice higher values than the solar value (black crosses in Fig. 6.11). We indicate the regions of red crosses in a red polygon in Fig. 6.7. We find that those regions are concentrated in the north of our FOV where the absolute abundances are relatively higher than those in the
Table 6.2: Spectral-fit parameters for the cells 1 and 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>cell 1 (vnei1)</th>
<th>cell 1 (vnei2)</th>
<th>cell 1 (vpshock)</th>
<th>cell 2 (vnei1)</th>
<th>cell 2 (vnei2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_H \times 10^{22} \text{cm}^{-2})</td>
<td>0.024±0.001</td>
<td>0.023±0.002</td>
<td>0.024±0.003</td>
<td>&lt; 0.021</td>
<td>&lt; 0.020</td>
</tr>
<tr>
<td>(kT_{e1} [\text{keV}])</td>
<td>0.27±0.01</td>
<td>0.27±0.01</td>
<td>0.26±0.01</td>
<td>0.39±0.02</td>
<td>0.39±0.01</td>
</tr>
<tr>
<td>(kT_{e2} [\text{keV}])</td>
<td>0.09±0.01</td>
<td>0.08±0.02</td>
<td>0.08±0.01</td>
<td>0.21±0.02</td>
<td>0.23±0.02</td>
</tr>
<tr>
<td>C</td>
<td>1.06±0.08</td>
<td>1.03±0.08</td>
<td>1.2±0.1</td>
<td>0.24±0.04</td>
<td>0.20±0.04</td>
</tr>
<tr>
<td>N</td>
<td>1.03±0.06</td>
<td>1.04±0.06</td>
<td>1.08±0.01</td>
<td>0.09±0.02</td>
<td>0.10±0.02</td>
</tr>
<tr>
<td>O</td>
<td>0.53±0.02</td>
<td>0.53±0.02</td>
<td>0.54±0.02</td>
<td>0.13±0.004</td>
<td>0.13±0.004</td>
</tr>
<tr>
<td>Ne</td>
<td>0.84±0.04</td>
<td>0.84±0.04</td>
<td>0.91±0.03</td>
<td>0.29±0.01</td>
<td>0.28±0.01</td>
</tr>
<tr>
<td>Mg</td>
<td>0.35±0.12</td>
<td>0.35±0.12</td>
<td>0.39±0.13</td>
<td>0.20±0.03</td>
<td>0.20±0.03</td>
</tr>
<tr>
<td>Si</td>
<td>1.9±0.2</td>
<td>1.8±0.2</td>
<td>1.9±0.14</td>
<td>0.24±0.04</td>
<td>0.24±0.04</td>
</tr>
<tr>
<td>S</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
<td>&lt;0.4</td>
<td>0.14±0.01</td>
<td>0.16±0.12</td>
</tr>
<tr>
<td>(\log(\tau/\text{cm}^{-3} \text{sec}))</td>
<td>10.65±0.08</td>
<td>10.63±0.04</td>
<td>11.62±0.09</td>
<td>11.24±0.05</td>
<td>11.00±0.1</td>
</tr>
<tr>
<td>(\log(\tau_{1}/\text{cm}^{-3} \text{sec}))</td>
<td>10.63±0.04</td>
<td>10.63±0.04</td>
<td>11.62±0.09</td>
<td>11.24±0.05</td>
<td>11.00±0.1</td>
</tr>
<tr>
<td>(\log(\tau_{2}/\text{cm}^{-3} \text{sec}))</td>
<td>10.6</td>
<td>10.6</td>
<td>11.00±0.1</td>
<td>11.00±0.1</td>
<td>11.00±0.1</td>
</tr>
<tr>
<td>(\log(\tau_{lower}/\text{cm}^{-3} \text{sec}))</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>(\log(\tau_{upper}/\text{cm}^{-3} \text{sec}))</td>
<td>11.00±0.03</td>
<td>11.00±0.03</td>
<td>11.00±0.03</td>
<td>11.00±0.03</td>
<td>11.00±0.03</td>
</tr>
<tr>
<td>(EM_1 \times 10^{19} \text{cm}^{-5})</td>
<td>0.48±0.01</td>
<td>0.48±0.01</td>
<td>0.52±0.02</td>
<td>1.4±0.04</td>
<td>1.39±0.04</td>
</tr>
<tr>
<td>(EM_2 \times 10^{19} \text{cm}^{-5})</td>
<td>0.9±0.2</td>
<td>0.9±0.2</td>
<td>0.5±0.2</td>
<td>2.4±0.1</td>
<td>2.4±0.1</td>
</tr>
<tr>
<td>(\chi^2/\text{d.o.f.})</td>
<td>611/508</td>
<td>611/507</td>
<td>619/508</td>
<td>706/699</td>
<td>706/698</td>
</tr>
</tbody>
</table>

*Other elements are fixed to those of solar values.
The values of abundances are multiples of solar value.
The errors are in the range \(\Delta \chi^2 < 2.7\) on one parameter.
The subscript 1 denotes the high temperature component while 2 denotes the low temperature component.
Figure 6.8: *Upper:* X-ray spectra extracted from cell 1 in Fig. 6.7. The best-fit curves are shown with solid lines for the four XIS’s. The contribution of each component is shown by the dotted lines only for XIS1. The dashed line represents the low temperature component while the dotted line represents the high temperature component. The lower panels show the residuals. *Right:* Same as left but for cell 2.
Figure 6.9: Maps of the best-fit parameters. The units are $10^{22}\text{cm}^{-2}$ for $N_H$, keV for $kT_{e1}$ and $kT_{e2}$, $\text{cm}^{-3}\text{sec}$ for $\tau$, $10^{19}\text{cm}^{-5}$ for EM$_1$ and EM$_2$, and solar values for abundances.
Figure 6.10: Each elemental abundance or ionization timescale versus O is plotted for the 184 cells. Red data points come from Region A while black points come from the remaining cells. The dashed line from upper right to lower left represents the solar ratio.
other regions. Hereafter, we refer to the region outlined by the red polygon in Fig. 6.7 as Region A. We summarize mean abundances, mean 90% errors, and standard deviations of abundances for both Region A and the other regions in Table 6.3.

In our model, the ionization timescale is imposed to be the same for the two components for simplicity of the model just as employed in M07. In this paragraph, we investigate whether or not the introduction of separate ionization timescales for the two components changes the results. We fit the spectra in cells 1 and 2 with a two-component vnei model whose free parameters are the same as those used in the vnei1 model but separate ionization timescales for the two components that we call as a vnei2 model. The best-fit parameters and fit statistics are summarized in Table 6.2 (vnei2). We find that all the best-fit parameters are consistent with those obtained with the vnei1 model. We should note that the results are quite similar to those from the vnei1 model. We check the value of $\chi^2$ as a function of $\tau_2$ over a large range value (i.e., $2 \times 10^{10} - 1 \times 10^{12}$ cm$^{-3}$ sec) and confirm that the results are not due to secondary local minima. We thus conclude that the abundances obtained are not affected by the introduction of separate ionization timescale for the two components.

Figure 6.9 clearly shows that Region A is the location of a significantly different best-fit value for the ionization timescale. We plot correlation between ionization timescale and O abundance in Fig. 6.10 (h). It shows anti-correlation, which causes us some worry about the derived abundances, since the NEI models we employ are really just very simplistic approximations to the true physical conditions under which these plasmas emit. Fig. 6.9 also indicates that Region A has a rapidly changing ionization state throughout it: from $\tau = 0$ at the shock front to $\tau = \sim 10^{11}$ cm$^{-3}$ sec. Our models, however, assume a single ionization timescale (vnei). In this context, we fit the spectrum in cell 1 (which is within Region A) with the vpshock model (e.g., Borkowski et al. 2001) in XSPEC, which assumes a constant temperature and a distribution of ionization timescale which we take all ionization timescales up to a fitted maximum value starting from zero. We employ a two-temperature vpshock model with the same number of free parameters as the case of the vnei model. The best-fit values and fit statistics are summarized in Table 6.2. We find that the abundances are almost equal between the vnei model and the vpshock model, which supports the idea that abundances in Region A are really different from those in the rest of our FOV.

$- kT_e, \tau, N_H, \text{ and EM } -$ 

In the NE2 region, the values of both $kT_{e_1}$ and $kT_{e_2}$ increase from the outermost cells toward the innermost cells. This trend is consistent with previous X-ray observations of the relevant regions obtained with ASCA (Miyata et al. 1994; Miyata & Tsunemi 1999),
6.3. NORTHEASTERN RIM

Table 6.3: Mean elemental abundances in Region A and the rest of the region

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Region A</th>
<th>Excluding Region A</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$0.74^{+0.06}_{-0.08}$ (0.26)</td>
<td>$0.36^{+0.07}_{-0.08}$ (0.18)</td>
</tr>
<tr>
<td>N</td>
<td>$0.66\pm0.05$ (0.27)</td>
<td>$0.17\pm0.02$ (0.08)</td>
</tr>
<tr>
<td>O</td>
<td>$0.38\pm0.02$ (0.13)</td>
<td>$0.16\pm0.01$ (0.05)</td>
</tr>
<tr>
<td>Ne</td>
<td>$0.63\pm0.03$ (0.22)</td>
<td>$0.31\pm0.02$ (0.09)</td>
</tr>
<tr>
<td>Mg</td>
<td>$0.32\pm0.08$ (0.12)</td>
<td>$0.24\pm0.04$ (0.08)</td>
</tr>
<tr>
<td>Si</td>
<td>$0.9\pm0.1$ (0.5)</td>
<td>$0.41\pm0.06$ (0.18)</td>
</tr>
<tr>
<td>S</td>
<td>$0.2\pm0.2$ (0.1)</td>
<td>$0.2^{+0.2}_{-0.1}$ (0.2)</td>
</tr>
<tr>
<td>Fe(=Ni)</td>
<td>$0.34\pm0.02$ (0.12)</td>
<td>$0.26\pm0.01$ (0.07)</td>
</tr>
</tbody>
</table>

The values in brackets represent the standard deviations. Errors quoted are mean values for each cell.

XMM-Newton (Katsuda & Tsunemi 2008a; Tsunemi et al. 2007), and Suzaku (M07). The values are also quantitatively consistent with those in M07. Also, we confirm that the ionization state is far from the CIE condition in the NE2 region and find that the ionization state is in NEI condition everywhere in NE1–4 regions. The ionization states in the outermost cells in NE3 and 4 regions (which correspond to Region A) are relatively lower than those in the other regions. The EMs for the hot component in the responsible regions are relatively lower than those in the other regions, suggesting low electron densities there. Since almost all the emission lines come from the hot component (see, Fig. 6.8 Upper), the ionization states obtained represent those for the hot component. Therefore, the relatively low ionization states are likely due to the low density. We found that the $N_{\text{H}}$ for almost all regions is around $0.02\times10^{22}\text{cm}^{-2}$ while we see about twice enhanced column density in the NE4 region.

To check the significance level of the observed variations for $kT_{e}$, $\tau$, $N_{\text{H}}$, and EMs, and also to look for possible correlations among those parameters, we plot the correlations between each parameter versus $kT_{e1}$ in Fig. 6.11. We find that all the parameters are constrained enough to confirm the observed variations in our FOV. We also find that the ionization states in Region A are significantly lower than those in the other region. We can not find any significant correlations among those parameters although the distribution of $kT_{e1}$ is clustered around $\sim0.28\text{keV}$ and $\sim0.35\text{keV}$. As shown in Fig. 6.9, the low- and high-temperature clusters are generally located in the outer and inner regions of the remnant, respectively that is at least qualitatively consistent with what we expect from
Discussion and Conclusion

We observed the northeastern rim of the Cygnus Loop with the Suzaku observatory in four pointings. Then, we divide the FOV into 184 cells and perform spatially resolved spectral analysis. Following the analysis in M07 in which the authors concluded that there was a multi-temperature plasma along the line of sight, we apply a two-component NEI model with different $kT_e$ for all the spectra.

Assuming a spherically-symmetric uniform emitting region and that the two temperature components are in pressure equilibrium, we can estimate the plasma depth for the two components in each cell. We calculate the total masses of low and high temperature components in Region A and the rest of the region, respectively, to be $\sim 0.7 M_\odot$ and $\sim 6 M_\odot$. In these calculations, we assume that $n_e = n_H$ and the volume filling factor is unity.

The relative abundances of C, Ne, Si, and S to O are almost constant in our FOV while those of Mg and Fe are divided into two groups: one shows lower values than the solar value while the other shows two times higher values than the solar value. Regions with low relative abundances are concentrated into the very northernmost cells (Region A). The absolute abundances in Region A turn out to be relatively higher than those in the rest of the region.

The low abundances in regions other than Region A confirms the absence of SN ejecta contamination at the northeast rim and argues for a swept-up origin. Depleted abundances at the rim of the Cygnus Loop have now been reported by several X-ray studies. For example, ASCA observation of the NE rim (which overlaps the NE2 region here) revealed the abundance of O to be 0.2 times the solar value (Miyata & Tsunemi 1999). Chandra observation of the southwestern rim showed the O-group abundance to be 0.22 times the solar value [Leahy 2004; in his spectral analysis, he fixed the abundances of C and N to be relatively the same as O (O-group)]. Low abundances appear to be a common result of X-ray spectral analysis of the rim of the Cygnus Loop. Possible explanation for this will be proposed in the next section (Sec.6.3.2).

The abundances in Region A are higher than those in the rest of the region by factors of $\sim 2.1$ (C), $\sim 3.9$ (N), $\sim 2.4$ (O), $\sim 2.1$ (Ne), $\sim 1.3$ (Mg), $\sim 2.4$ (Si), $\sim 1.2$ (S), and $\sim 1.3$ (Fe). Since there is evidence in many SNe that the circumstellar medium (CSM) frequently shows enhanced abundance ratios of N/C and N/O (Fransson et al. 2005; Chevalier et al. 2005) relative to the solar values as a result of CNO processing in progenitor stars, the strongly enhanced abundance of N in Region A relative to the rest of the region may lead
Figure 6.11: \( N_H \), \( kT_{c2} \), \( \log(\tau) \), \( EM_2 \), and \( EM_1 \) versus \( kT_{c1} \) are plotted for the 184 cells. Red data points come from Region A while black points come from the remaining cells.
us to consider that CSM contamination is evident. However, theoretical nucleosynthetic calculations show that the CSM is only rich in N abundance compared with the initial composition of a progenitor star (e.g., Rauscher et al. 2002). This cannot fully explain that all the metal abundances in Region A are enhanced relative to those in the rest of the region. Can fragments of ejecta from the SN explosion explain the enhanced metal abundances? Fragments of ejecta observed in many SNRs (e.g., Cas A; Fesen et al. 2001, Vela; Aschenbach et al. 1995, Tycho; Decourchelle et al. 2001) commonly show knotty shapes or head-tail structures. There is no such structure in Region A, showing no indication of fragments of ejecta. Then, we consider the possibility of abundance inhomogeneities of the local interstellar medium in the vicinity of the Cygnus Loop. Observations of optically thin 1356 Å resonance line and H Lyα in 13 sight lines showed remarkable homogeneity of the interstellar gas-phase O/H ratio at a level of ~5% within about 500 pc of the Sun (Meyer et al. 1998). More recent observations for 36 sight lines confirmed the homogeneity of O/H abundance ratio and revealed that the ratio is uniform within 800 pc of the Sun (Cartledge et al. 2004). Therefore, it is difficult to explain such a strong variation in the abundances at these very small scales by abundance inhomogeneities of the local interstellar medium. The nature of the abundance inhomogeneity observed is left as an open question for future works.
6.3.2 Chandra View

We present results from the Chandra observations of NE rim of the Cygnus Loop, which will be published in Katsuda et al. (2008d).

Spatially Resolved Spectral Analysis

In order to investigate the post-shock plasma structures in detail, we perform spatially resolved spectral analysis for the cleaned Chandra data. To this end, we concentrate on the data taken by the S3 (BI) chip, since its energy resolving power is better than that of another BI (S1) chip, and the numbers of photons detected in BI chips are richer than those in FI chips for the spectra from the Cygnus Loop. Figure 6.12 shows ACIS S3 chip images. We hereafter name the area covered by the S3 chip in ObsID. 2821 as “area-1” (see, Fig. 6.12 Upper), while that covered by the S3 chip in ObsID. 2822 as “area-2” (see, Fig. 6.12 Lower). Area-1 includes the abundance-enhanced region, while area-2 is located on the region with “normal” abundances in the NE rim of the Cygnus Loop. As indicated by arrows in Fig. 6.12, discontinuities in X-ray intensity can be seen inside the X-ray boundaries in both of the two areas. This fact suggests that the shock structures in these regions can be considered as multiple shocks along the line of sight. We extract spectra from 20″-spaced (annular for area-1, rectangle for area-2) regions inside the discontinuities of X-ray intensity (from Reg-1 to Reg-26/19 for area-1/2). We arrange the regions such that each region overlaps with each other by half of its size. Outside the discontinuities, X-ray surface brightness is relatively low so that we extract spectra from only one region to obtain enough photons to perform spectral analysis in good statistics. The region is named as Reg-0. We show all the spectral extraction regions in Fig. 6.12.

We subtract background emission from a source free (i.e., outside the X-ray boundary of the Cygnus Loop) region in the same chip for area-1 (see, Fig. 6.12 Upper). On the other hand, it is quite difficult to subtract background emission from the same chip for area-2, since the X-ray emission from the Cygnus Loop is extended in almost the entire FOV of the chip (see, Fig. 6.12 Lower). We thus subtract background emission from a source free region in the S1 chip of the same observation, after we investigate that the spectral shape and count rate in the energy band of 3–5 keV, where the emission from the Cygnus Loop is negligible, are similar between the S1 and S3 chip. We should note that the background-subtraction method was successfully performed by Miyata et al. (2001). We use data in the energy range of 0.5–2.0 keV for our spectral analysis.

We apply an absorbed NEI model with a single temperature (the wabs; Morrison &
Figure 6.12: *Upper:* Exposure and vignetting corrected *Chandra* S3 chip image for ObsID. 2821. The spectral extraction regions are shown as white annuli. Several point sources indicated by white circles are excluded from our spectral analysis. An arrow seen in the upper right indicates the position of the discontinuity of the X-ray intensity. *Lower:* Same as Fig. 6.12 *Upper* but for ObsID. 2822.
McCammon (1983) and the \texttt{vps}hock model (NEI version 2.0); e.g., Borkowski et al. (2001) in XSPEC v 12.3.1). Free parameters are electron temperature, $kT_e$; $\tau$; EM; abundances of C, N, O, Ne, Mg, Si, and Fe. Above, $\tau$ is the electron density times the elapsed time after shock heating and the \texttt{vps}hock model assumes a range of $\tau$ from zero up to a fitted maximum value. Based on previous \textit{Suzaku} observations of these regions (Katsuda et al. 2008b), we here fix the values of $N_H$ and abundance of S to be $0.02 \times 10^{22}$ cm$^{-2}$ and 0.2 times the solar value, respectively. We also set abundance ratios of C/O and N/O to be 2 and 1.4 times the solar values which are mean values measured in the NE rim of the Cygnus Loop [calculated from Table 2 in Katsuda et al. (2008b)], because emission lines from C and N are not visible in our data. We set abundances of Ni equal to that of Fe. Abundances of other elements included in the \texttt{vps}hock model (i.e., Ar and Ca) are fixed to the solar values (Anders & Grevesse 1989). In this way, we fit all the spectra by the one-component \texttt{vps}hock model. We then find apparent discrepancies between our data and the best-fit model in the energy band around 0.73 keV. Around this energy band, the dominant emission comes from either Fe-L shell lines or K-shell lines from O He$\alpha$ and O Ly$\alpha$. However, the poorly known atomic physics of Fe-L shell lines and missing O-K shell lines in the model employed are reported by Warren & Hughes (2004) and Yamaguchi et al. (2008), respectively. We thus introduce systematic error of 5% on the model in quadrature, following as Warren & Hughes (2004) did. This model give us fairly good fits for all the spectra (reduced $\chi^2$ ranges from 0.8 to 1.4). Figure 6.13 shows the example spectra in Reg-3 from both area-1 and area-2. The spectra are remarkably different; emission lines are stronger for the spectrum in area-1 than those for the one in area-2. The best-fit parameters and fit statistics for the two example spectra are summarized in Table 6.4.

Figure 6.14 shows abundances of O, Ne, Mg, and Fe, $kT_e$, log($\tau$), EM as a function of region number. Data points with open circles are from area-1, while those with open triangles are from area-2. In area-2, abundances are constant at O$\sim$0.1, Ne$\sim$0.2, Mg$\sim$0.15, and Fe$\sim$0.2, while in area-1 they increase toward the outer region of the Loop. They start to increase from around Reg-10 ($\sim$200" behind the shock front) to the outer regions. Inside Reg-10, the values of abundances are the same level as those in area-1, while they become up to the solar values or even higher than the solar values in the outermost three regions. The electron temperature is almost constant at $\sim$0.2 keV in area-2, while it gradually increases from inner regions (0.25 keV) toward outer regions (0.35 keV) in area-1. These values are similar to those of the hot component among the two components revealed by \textit{Suzaku} data (Miyata et al. 2007). The ionization states for the abundance-enhanced region show NEI conditions that are consistent with the previous results from \textit{Suzaku}. On
Figure 6.13: Example spectra (crosses) with the best-fit model (solid lines). Lower panel shows the residuals. Upper left, upper right, lower left, and lower right spectra are from Reg-3 in Area-1, Reg-3 in Area-2, the northern ellipse in Fig. 6.4, and the southern ellipse in Fig. 6.4, respectively.
Table 6.4: Spectral-fit parameters for the example two spectra in Fig 6.13

<table>
<thead>
<tr>
<th>Model</th>
<th>Reg-3 in Area-1</th>
<th>Northern Ellipse</th>
<th>Reg-3 in Area-2</th>
<th>Southern Ellipse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vpshock</td>
<td>vpshock</td>
<td>power-law+vpshock</td>
<td>srcut+vpshock</td>
</tr>
<tr>
<td>Photon Index(^a)</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
</tr>
<tr>
<td>Flux(^b)</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
</tr>
<tr>
<td>(\nu_{\text{rolloff}} \times 10^{14}) Hz</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
<td>...............</td>
</tr>
<tr>
<td>(kT_e) (keV)</td>
<td>0.32±0.04</td>
<td>0.32±0.03</td>
<td>0.19±0.01</td>
<td>0.27±0.05</td>
</tr>
<tr>
<td>(\log(\tau/\text{cm}^{-3}\text{sec}))</td>
<td>10.58(^{+0.20}_{-0.16})</td>
<td>10.90(^{+0.14}_{-0.16})</td>
<td>11.8(&lt;)</td>
<td>11.2(^{+0.4}_{-0.2})</td>
</tr>
<tr>
<td>O</td>
<td>1.4(^{+0.2}_{-0.3})</td>
<td>0.8(^{+0.2}_{-0.1})</td>
<td>0.10±0.02</td>
<td>1 (fixed)</td>
</tr>
<tr>
<td>Ne</td>
<td>2.3(^{+0.7}_{-0.4})</td>
<td>1.3(^{+0.5}_{-0.3})</td>
<td>0.19(^{+0.06}_{-0.04})</td>
<td>1.6±0.2</td>
</tr>
<tr>
<td>Mg</td>
<td>1.1(^{+0.7}_{-0.5})</td>
<td>0.7(^{+0.4}_{-0.2})</td>
<td>0.14(^{+0.11}_{-0.07})</td>
<td>1.2±0.4</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;20</td>
<td>&lt;0.3</td>
<td>&lt;1</td>
<td>&lt;3</td>
</tr>
<tr>
<td>Fe(=Ni)</td>
<td>1.4(^{+0.7}_{-0.4})</td>
<td>0.75(^{+0.25}_{-0.19})</td>
<td>0.23(^{+0.16}_{-0.07})</td>
<td>1.2(^{+0.3}_{-0.2})</td>
</tr>
<tr>
<td>EM (\times 10^{19} ) cm(^{-5})</td>
<td>0.20(^{+0.05}_{-0.03})</td>
<td>0.3(^{+0.09}_{-0.07})</td>
<td>6.5(^{+2.9}_{-1.9})</td>
<td>0.27(^{+0.15}_{-0.06})</td>
</tr>
<tr>
<td>(\chi^2/\text{d.o.f.})</td>
<td>56/52</td>
<td>111/92</td>
<td>60/54</td>
<td>52/52</td>
</tr>
</tbody>
</table>

Note. The best-fit parameters for example spectra in Fig. 6.13 and Fig. 6.16. The errors are in the range \(\Delta \chi^2 < 2.7\).

Errors for abundances and fluxes in power-law and srcut models are estimated with the EM fixed at the best-fit value.

Errors for the EM are estimated with the O abundance fixed at the best-fit value.

\(^a\)Photon index in the power-law model is determined by the X-ray spectrum, while it is determined in a radio spectrum for the srcut model.

\(^b\)The units are \(10^{-5}\) photons cm\(^{-2}\) sec\(^{-1}\) keV\(^{-1}\) at 1 keV for the power-law model, and Jy at 1 GHz for the srcut model.
the other hand, we find that the other regions show almost CIE conditions. In contrast to the electron temperature and abundances, the ionization timescale as well as the EM gradually decreases toward the outer regions in area-1.

We can see apparent correlations between abundances and thermodynamic parameters (i.e., $kT_e$ and $\tau$). Therefore, we investigate whether the abundance enhancements in the outermost (∼200″-thickness) region in area-1 are significant or not, by generating confidence contours between O abundance and the thermodynamic parameters. Figure 6.15 shows the confidence contours of O abundance against $kT_e$ and $\tau$ for Reg-3 in area-1 (abundance-enhanced region) and Reg-3 in area-2 (the region with “normal” abundances). We confirm that O abundance for the abundance-enhanced region is significantly higher than that in the region with “normal” abundances. We thus conclude that the metal abundances in the northern outermost region (∼200″-thickness regions behind the shock front) of the NE rim are significantly enhanced relative to those in the rest of the NE rim.

The analyses above are all concentrated in data taken by the S3 chip. For the sake of consistency, we analyze data from adjacent FI chips. We extract spectra from two regions which are located in the northernmost chips of ObsID. 2821 and 2822, respectively. These regions are shown in Fig. 6.4 as white ellipses. Subtracting the background emission from the same chips, we apply the same \texttt{vpshock} model used before. The two spectra with their best-fit models are shown in Fig. 6.13. The apparent difference between the two spectra is the intensity of line emission, as seen in the two example spectra from the S3 chip in each observation (see, Fig. 6.13 \textit{upper left} and \textit{upper right}). The best-fit parameters and fit statistics are summarized in Table. 6.4. Both absolute and relative abundances for the northern ellipse are almost consistent with those outside Reg-10 in area-1 (i.e., abundance-enhanced region), whereas those in the southern ellipse are consistent with those in area-2 (i.e., the region with “normal” abundances). Therefore, we confirm that the abundances derived are independent on ACIS chips.

Discussion

– Possible Origin of the Plasma in the Abundance-Enhanced Region –

We confirm the enhanced abundances in the northern outermost region in the NE rim of the Cygnus Loop and reveal that the abundance-enhanced region is confined in a ∼200″-thickness region behind the shock front. The abundances derived here are higher than those derived by \textit{Suzaku} by factor of ∼2. The width, ∼200″, of the abundance-enhanced region is comparable to the half-power diameter, ∼120″, of the \textit{Suzaku} X-ray telescope (Serlemitsos et al. 2007) so that significant amount of emission from the plasma with “normal” abundances should have contaminated in the abundance-enhanced region.
Figure 6.14: Abundance, $kT_e$, $\tau$, and EM as a function of region number. Open circles represent data points from area-1, while open triangles represent those from area-2.
Figure 6.15: Confidence contour maps of O abundance against $kT_e$ or $\tau$. Upper panels are those for Reg-3 in area-1, while lower panels are those for Reg-3 in area-2. Solid, dashed, and dotted lines represent 68%, 90%, and 99% confidence levels, respectively.
for the *Suzaku* data. The superior spatial resolution of the *Chandra* XRT allows us to accurately determine the metal abundances in the abundance-enhanced region as well as to reveal the detailed plasma structures there.

Are the abundance enhancements caused by metal-rich ejecta such as fragments of ejecta in the vicinity of the Vela SNR (i.e., Vela shrapnels; Aschenbach et al. 1995)? In the Vela shrapnels A and D, anomalous abundance ratios between heavy elements are observed: Si/O ~10 times the solar value in the Vela shrapnel A (Katsuda & Tsunemi 2005), Ne/Fe ~10 times the solar value in the Vela shrapnel D (Katsuda & Tsunemi 2006). On the contrary, we measure abundance ratios among metals in the abundance-enhanced region of the NE rim of the Cygnus Loop to be consistent with the solar values within a factor of ~2. Furthermore, the feature that the EM in the abundance-enhanced region gradually decreases toward the shock front is in contrast with those observed in the Vela shrapnels A and D. These facts lead us to consider that the origin of the abundance enhancements in the NE rim is not likely due to fragments of ejecta. Therefore, a natural explanation of the abundance enhancements is the ISM origin, since the abundances are roughly consistent with the solar values.

We should note that the electron temperature in the abundance-enhanced region tends to increase toward the shock front. This feature resembles those in the Vela shrapnels A and D, rather than that expected in Sedov phase SNRs where we expect to see temperature decrease toward the shock front as seen in the other NE rim of the Cygnus Loop found in previous observations (e.g., Miyata et al. 1994; Katsuda & Tsunemi 2008a).

– Non-Thermal Emission? –

What causes such depleted (typically ~0.2 times the solar value) abundances observed in the rest of the NE rim? One possibility is resonance scattering which can affect our abundance estimation. Raymond et al. (2003) studied effects of resonance scattering of O VI photons in the NE rim of the Cygnus Loop, by using FUV observations. They concluded that resonance scattering affected O VI intensities by a factor of 2 level. More recently, Miyata et al. (2008) also investigated the resonance-scattering effect in their *Suzaku* data covering the NE rim of the Cygnus Loop. In their analysis, the abundances derived were all depleted to typically 0.23 times the solar values with exception of O; O is depleted by an additional factor of two, which is well consistent with the results obtained here by Chandra. Miyata et al. (2008) concluded that about a factor of 2 depletion for only O abundance can be attributed to resonance scattering, while it is not sufficient to account for the abundance depletion observed. The other possibility is dust sputtering (Spitzer & Jenkins 1976). However, this mechanism is also ruled out due to the fact that even Ne is measured to be depleted to the solar values; Ne is a rare gas so that there is
no observational evidence of Ne depletion. These facts require the other mechanisms for the origin of the abundance depletion.

We here consider effects of non-thermal emission. If the spectra are contaminated by non-thermal emission, we should have overestimated thermal continuum emission in our spectral modeling in which we attempt to reproduce spectra by only thermal emission. This will result in underestimation of metal abundances. We thus investigate whether the spectra require non-thermal emission or not. First, we introduce a power-law model in addition to the vpshock model for the spectral modeling. In this fitting procedure, we fix O abundance to the solar value, since absolute abundances (i.e., relative to H) are not constrained due to difficulty in dividing continuum emission into two (i.e., thermal and non-thermal) components. Free parameters are photon index and normalization of the power-law component and electron temperature, ionization timescale, EM, and abundances of Ne, Mg, Si, and Fe(=Ni) in the vpshock component. Abundances of other elements are fixed to the solar values (Anders & Grevesse 1989). In this way, we re-fit all the spectra by this model. From statistical point of view alone, this model significantly improves the fits for some spectra. As an example, we show the spectrum from Reg-3 in area-1 with the best-fit model in Fig. 6.16. The best-fit parameters are summarized in Table 6.4. The improvements of this power-law + vpshock model compared with the previous vpshock model (see, Fig. 6.13 right) mainly comes from the energy band around 0.73 keV. Since the uncertainty of the plasma code is reported in this energy range, we should carefully judge whether the power-law component is really required or not.

In this context, we evaluate multi-wavelength emission. For this purpose, instead of the power-law model, we employ the srcut model, which describes synchrotron radiation from an exponentially cut off power-law distribution of electrons in a homogeneous magnetic field (Reynolds & Keohane 1999). In this model, we fix radio spectral index to 0.42 (Uyaniker et al. 2004), while rolloff frequency and flux at 1 GHz are left as free parameters. The other parameters are treated as the same in the previous power-law + vpshock model fitting. The best-fit parameters are summarized in Table 6.4. We find that the derived best-fit value of the flux at 1 GHz obtained in the example spectrum (which is extracted from a small portion of the remnant), 1400 Jy, is about an order of magnitude higher than that estimated in the entire remnant of about 170 Jy (Uyaniker et al. 2004). Therefore, the derived flux of non-thermal emission in the example spectrum seems to be unreasonably high. However, we can not conclude whether or not non-thermal emission is significant in the NE rim of the Cygnus Loop, without radio data for the region which exactly corresponds to our spectral extraction region, as well as a more sophisticated model for non-thermal emission.
Figure 6.16: Same as Fig. 6.16 upper left but with the best-fit power-law+vpshock model. The two components are separately shown as dotted lines.
– Speculation on the Origin of the Abundance Inhomogeneity in the Rim of the Cygnus Loop –

It is believed that the Cygnus Loop is a result from a core-collapse SN (e.g., Miyata et al. 1998) which exploded in a pre-existing cavity (e.g., McCray et al. 1979). There are a number of evidence that the blast wave is recently encountered into a rigid wall of the cavity; the NE rim (Hester et al. 1994; Miyata & Tsunemi 1999), the southeast rim (Graham et al. 1995; Miyata & Tsunemi 2001), the eastern rim (Levenson et al. 1996), and the western rim (Levenson et al. 2002). According to previous X-ray observations, deficient metal abundances are commonly reported in these regions; metal abundances are typically $\sim 0.2$ times the solar values in the NE rim (e.g., Miyata & Tsunemi 1999; this work), O group abundance is $\sim 0.2$ times the solar value in the western rim (Leahy 2004). In these regions, the X-ray–emitting plasma should be the shock heated gas originating from either the cavity wall or swept-up matter in the cavity. Although the reason of the depletion still remains as an open question, these plasma seem to show depleted abundances.

Meanwhile, there is an apparent break of the cavity wall that is seen as the south blowout region (see, e.g., figures in Aschenbach & Leahy 1999). The wall of the cavity there is considered to be so thin (or negligible) that the blast wave already overran the wall, although Uyaniker et al. (2002) proposed another possibility, i.e., a different SNR interacting with the Cygnus Loop, for the south blowout region. The similar structure is expected at the circular shell in the northwest of the Cygnus Loop along the line of sight (Tsunemi et al. 2007). Looking at the NE rim of the Loop, we see somewhat large expansion of the X-ray boundary at the abundance-enhanced region (see, Fig. 6.1 or Fig. 6.7). Therefore, we presume that the blast wave here also overran the cavity wall and now is proceeding into the surrounding ISM with about solar metallicity, resulting in relatively enhanced abundances there. In this context, we predict that abundances show about solar values around the X-ray boundaries where cavity wall seems to be broken. This will be checked by future X-ray observations.

Conclusion

We analyzed archival Chandra data of the Cygnus Loop NE rim (PI: Gaetz, T.) where abundance inhomogeneities were found by recent Suzaku observations (Katsuda et al. 2008b). Thanks to the superior spatial resolving power of Chandra, we were able to carry out detailed spatially resolved spectral analyses for the region. We revealed that the abundance-enhanced region was concentrated in a $\sim 200''$-thickness region behind the shock front and confirmed that the values of abundances were consistent with the solar
values by a factor of $\sim 2$. Also, we found that the emission measure decreased toward the shock front. These features showed stark contrast with those seen in the Vela shrapnels, indicating that the abundance enhancements in the NE rim of the Cygnus Loop were not likely due to fragments of ejecta. We suggested that the plasma in the abundance-enhanced region originated from the ISM, whereas the plasma in the rest of the NE rim (i.e., abundance-depleted region) originated from the cavity wall or the gas in the cavity.
6.4 Radial Structures

6.4.1 XMM-Newton View

We present results from the XMM-Newton observations of the NE-SW path of the Cygnus Loop, which were published in Tsunemi et al. (2007).

Analysis

![Figure 6.17: Spectral extraction regions overlaid on an XMM-Newton three-color image shown in left figure](image)

Figure 6.17: Spectral extraction regions overlaid on an XMM-Newton three-color image shown in left figure

Figure 6.17 (inset) displays an exposure-corrected XMM-Newton color images of
6.4. RADIAL STRUCTURES

Figure 6.18: MOS1 spectra for the seven pointings; each is the sum of the entire FOV.

The NE rim is the brightest in our FOV, showing a bright filament at 45° to the radial direction corresponding to NGC6992. The SW rim is also bright in our FOV where there is a V-shape structure (Ashchenbach & Leahy 1999). In the center of the Loop, an X-ray bright filament runs through Pos-4 and Pos-5 forming a circular structure. In the ROSAT image, we can see it and find that it forms a large circle within the Cygnus Loop. In this way, there are many fine bright filaments in intensity. However, we find that there is a clear intensity variation along our scan path: dim in the center and bright in the rim.
Figure 6.18 shows spectra for seven pointings; each is the sum of the entire FOV. The NE rim (Pos-1) and the SW rim (Pos-7) show strong emission lines below 1 keV including O, Fe-L and Ne, while the center (Pos-4) shows strong emission lines from Si and S. We can see that the equivalent width of Si and S emission lines are bigger in the center and gradually decrease toward the rim. We show the comparison of spectra between Pos-1 and Pos-4 in Fig. 6.19. Prominent emission lines are O-He\(\alpha\), O-Ly\(\alpha\), Fe-L complex, Ne-He\(\alpha\), Mg-He\(\alpha\), Si-He\(\alpha\), and S-He\(\alpha\). We see that the emission-line shapes for O are quite similar to each other while there is a large difference at higher energy band. Since the spectrum in the NE rim can be well represented by a single temperature plasma model (Miyata et al. 1994), we need an extra component in the center.

**Radial Profile**

Although there are many fine structures, no matter how finely we divide our FOV, each region would contain different plasma conditions due to the integration of the emission along the line of sight. Therefore, we concentrate on large scale structure along the scan path. First of all, we divide our FOV into two parts along the diameter: the north path and the south path. Then we divide them into many small annular sectors whose center is located at \(20^h51^m34^s.7, 31^\circ00'00''\), i.e., the center of the nominal position of Pos-4. There are 141 and 172 annular sectors for the north path and the south path, respectively.
These small annular sectors, shown in Fig. 6.17, are divided such that each has at least 60,000 photons (∼20,000 for MOS1/2 and ∼40,000 for PN) to equalize the statistics. We extract the spectrum from each sector using the data set accumulated from blank sky observations as sky background. We have confirmed that the emission above 3 keV is statistically zero. In this way, we obtained 313 spectra. These sectors can be identified by the angular distance, “R”, from the center (east is negative and west is positive as shown in Fig. 6.17).

The width of the sector depends on \( R \). The sector widths range from 3′.8 to 0′.2 in the north path and from 3′.0 to 0′.2 in the south path. The widest sectors are in Pos-4 due to its short exposure because of the background flare. The narrowest sectors are in the NE rim where the surface brightness is the highest.

- Single Temperature NEI Model –

We fit the spectrum for each sector with an absorbed NEI model with a single \( kT_e \), using the Wabs (Morrison & McCammon 1983) and vnei model (NEI version 2.0, Borkowski et al. 2001) in XSPEC v12.3.1). We fix \( N_H \) to be \( 4.0 \times 10^{20} \text{cm}^{-2} \) (e.g., Inoue et al. 1980; Kahn et al. 1980). Free parameters are \( kT_e \), \( \tau \), EM, and abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set abundances of C and N equal to that of O, that of Ni equal to Fe, and other elements fixed to the solar values (Anders & Grevesse 1989). In the fitting process, we set 20 as the minimum counts in each spectral bin to perform the \( \chi^2 \) test. We determine the value of the minimum counts such that it does not affect the fitting results. Figure 6.20 shows the distribution of the reduced-\( \chi^2 \) in black as a function of \( R \) along both the north path and the south path. We find that values of reduced-\( \chi^2 \) for all the sectors are between 1.0 and 2.0. If we take into account a systematic error (Nevalainen et al. 2003, Kirsch 2006) of 5%, the reduced-\( \chi^2 \) is around 1.5 or less.

In general, values of the reduced-\( \chi^2 \) are a little higher in the central part of the Cygnus Loop. Miyata et al. (1994) observed the NE rim with ASCAand found that the spectra were well represented with a one-temperature vnei model with a temperature gradient towards the inside. The Suzaku observation in the NE rim (M07) reveals that the X-ray spectrum can be represented by a two-temperature model: one component is 0.2–0.35 keV and the other is 0.09–0.15 keV. In our fitting, the value of \( kT_e \) obtained is 0.2–0.25 keV. Therefore, we detect a hot component that Suzaku detected. There may be an additional component with low temperature that seems difficult to detect with XMM-Newton due to the relatively lower sensitivity below 0.5 keV compared to Suzaku.

The ASCA observation (Miyata et al. 1994) also shows that the metal abundance in the NE rim is deficient. The authors concluded that the plasma in the NE-rim consists of the ISM rather than the ejecta. This is confirmed with the Suzaku observation (M07) that
indicates the abundances of C, N and O to be \( \sim 0.1, 0.05 \) and 0.1 solar, respectively. We also obtain the metal deficiency in our XMM-Newton data; the best-fit results are given in Fig. 6.21 (left) and in table 6.5. The abundance difference between XMM-Newton data and those from Suzaku may be due to the difference in the detection efficiency at low energy. As already pointed out in previous sections, the X-ray measurements of the Cygnus Loop show that the metal abundances are depleted.

Cartledge et al. (2004) measured the interstellar oxygen along 36 sight lines and confirmed the homogeneity of the O/H ratio within 800 pc of the Sun. We find that they measured it in the direction about 5° away from the Cygnus Loop. The oxygen abundance they measured is about 0.4 times the solar value (Anders & Grevesse 1989). Wilms et al. (2000) employed 0.6 of the total interstellar abundances for the gas-phase ISM oxygen abundance, and suggest that this depletion may be due to grains. Although the ISM near the Cygnus Loop may be depleted, the abundances are still much higher than what we obtained at the rim of the Cygnus Loop. It is difficult to explain such a low abundance of oxygen in material originating from the ISM. Since the Cygnus Loop is thought to have exploded in a pre-existing cavity, we can say that the cavity material shows low metal abundance, which was already pointed out in the previous section (Sec.6.3.2). Taking into account the projection effect, the plasma of the rim regions consists only of the cavity
Table 6.5: Spectral-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>region—74.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H[10^{20} \text{ cm}^{-2}]$</td>
<td>4 (fixed)</td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>0.23 ±0.01</td>
</tr>
<tr>
<td>O(=C=N)</td>
<td>0.068 ±0.002</td>
</tr>
<tr>
<td>Ne</td>
<td>0.17±0.01</td>
</tr>
<tr>
<td>Mg</td>
<td>0.14±0.03</td>
</tr>
<tr>
<td>Si</td>
<td>0.3±0.1</td>
</tr>
<tr>
<td>S</td>
<td>0.6±0.2</td>
</tr>
<tr>
<td>Fe(=Ni)</td>
<td>0.157±0.006</td>
</tr>
<tr>
<td>log($\tau/\text{cm}^{-3}\text{sec}$) .</td>
<td>11.31 ±0.02</td>
</tr>
<tr>
<td>EM$^{1}[\times10^{19} \text{ cm}^{-5}]$</td>
<td>$11.0^{+1.4}_{-0.5}$</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>420/314</td>
</tr>
</tbody>
</table>

Note. Other elements are fixed to solar values.
The values of abundances are multiples of solar value.
The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.

$^1$EM denotes emission measure, $\int n_e n_H dl$. 
material while that of the inner regions consists both of the cavity material and of an extra component filling the interior of the Loop.

- Two-temperature NEI model -

To further constrain the plasma conditions, we apply a two-component NEI model with different temperatures. In this model, we add an extra component to the single temperature model. The extra component is also an absorbed vnei model with $kT_e$, $\tau$, and EM as free parameters. The metal abundances of the extra component are fixed to those determined at the NE rim so that the extra component represents the cavity material. Figure 6.21 shows reduced-$\chi^2$ values in red along the path. Applying the $F$-test with a significance level of 99% to determine whether or not an extra component is needed, we find that most of the spectra require a two-component model, particularly in the central part of the Loop. Sectors that do not require two-component model are mainly clustered in $R<+65'$, $+25'<R<+40'$, and $+60'<R$. Therefore, we consider that the outer sectors ($|R|>70'$) can be safely represented by a one-component model while other sectors can be represented by a two-component model. In this way, we perform the analysis by applying a two-component vnei model with different temperatures. We assume that the low temperature component comes from the surrounding region of the Cygnus Loop and the high temperature component occupies the interior of the Loop.

We find that the values of reduced-$\chi^2$ are 1.0–1.8 even employing a two-component model. This is partly due to the systematic errors. Looking at the image in detail, there are fine structures within the sector. Furthermore, the spectrum from each sector is an integration along the line of sight. Since we only employ two vnei plasma models, the values of reduced-$\chi^2$ are mainly due to the simplicity of the plasma model employed here. Therefore, we think that the plasma parameters obtained will represent typical values in each sector.

Figure 6.21 (right) and table 6.6 shows an example result that comes from the sector at $R=+10'$. Fixed parameters in the low $kT_e$ component come from the fitting result at the NE rim obtained by Suzaku observations (Uchida et al. 2006). Metal abundances for the high $kT_e$ component show higher values by an order of magnitude than those of the low $kT_e$ component, surely confirming that the high $kT_e$ component is dominated by fossil ejecta.

Figure 6.22 shows temperatures as a function of position. The low $kT_e$ component is in the temperature range of 0.12–0.34 keV, while the high $kT_e$ component is above 0.35 keV. There is a clear temperature difference where a two-component model is required rather than a single temperature model. The low $kT_e$ component represents the cavity material surrounding the Cygnus Loop while the high $kT_e$ component represents the
Figure 6.21: *Upper:* An example spectrum that comes from the sector at R=−74.25′. The best-fit curves are shown with solid lines and the lower panels show the residuals. *Lower:* Same as left but for the sector at R=+10′. Both the ejecta and cavity components are shown only for MOS1 spectrum as dashed lines.
### Table 6.6: Spectral-fit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>region+10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H[10^{20}\text{ cm}^{-2}]$</td>
<td>4 (fixed)</td>
</tr>
<tr>
<td><strong>Low temperature component</strong></td>
<td></td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>0.20 ±0.01</td>
</tr>
<tr>
<td>C</td>
<td>0.27 (fixed)</td>
</tr>
<tr>
<td>N</td>
<td>0.10 (fixed)</td>
</tr>
<tr>
<td>O</td>
<td>0.11 (fixed)</td>
</tr>
<tr>
<td>Ne</td>
<td>0.21 (fixed)</td>
</tr>
<tr>
<td>Mg</td>
<td>0.17 (fixed)</td>
</tr>
<tr>
<td>Si</td>
<td>0.34 (fixed)</td>
</tr>
<tr>
<td>S</td>
<td>0.17 (fixed)</td>
</tr>
<tr>
<td>Fe(=Ni)</td>
<td>0.20 (fixed)</td>
</tr>
<tr>
<td>$\log(\tau/\text{cm}^{-3}\text{ sec})$</td>
<td>12 &lt;</td>
</tr>
<tr>
<td>$EM^1[\times10^{18}\text{ cm}^{-5}]$</td>
<td>$1.34^{+0.03}_{-0.04}$</td>
</tr>
<tr>
<td><strong>High temperature component</strong></td>
<td></td>
</tr>
<tr>
<td>$kT_e[\text{keV}]$</td>
<td>0.48 ±0.01</td>
</tr>
<tr>
<td>O(=C=N)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Ne</td>
<td>0.15 $^{+0.06}_{-0.07}$</td>
</tr>
<tr>
<td>Mg</td>
<td>0.21±0.08</td>
</tr>
<tr>
<td>Si</td>
<td>2.5±0.3</td>
</tr>
<tr>
<td>S</td>
<td>5±1</td>
</tr>
<tr>
<td>Fe(=Ni)</td>
<td>1.03±0.04</td>
</tr>
<tr>
<td>$\log(\tau/\text{cm}^{-3}\text{ sec})$</td>
<td>11.12±0.05</td>
</tr>
<tr>
<td>$EM^1[\times10^{19}\text{ cm}^{-5}]$</td>
<td>$0.094^{+0.005}_{-0.004}$</td>
</tr>
<tr>
<td>$\chi^2/\text{d.o.f.}$</td>
<td>531/377</td>
</tr>
</tbody>
</table>

Note. Other elements are fixed to solar values.
The values of abundances are multiples of solar value.
The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.

$^1$EM denotes emission measure, $\int n_e n_H d\ell$. 
6.4. RADIAL STRUCTURES

Figure 6.22: Temperature distributions of the two components as a function of position. Filled circles show the ejecta component, while crosses show the cavity component. Black show the north path and red shows the south path. Typical errors are ±5% for both components.

Figure 6.23: Flux distributions of the two components as a function of position. The marks in this figure are the same as those in Fig. 6.22.
fossil ejecta inside the Loop. Figure 6.23 shows the fluxes for the two components as a function of position. The low $kT_e$ component shows clear rim brightening. The east part is stronger than the west part, showing asymmetry of the Loop. On the other hand, the high $kT_e$ component has a relatively flat radial dependence. From the center to the SW, we see that the flux of the high $kT_e$ component is stronger than that of the low $kT_e$ component.

– Distribution of the Cavity Material –

As shown in Fig. 6.22, the low $kT_e$ component shows relatively constant temperature with radius. The distribution of the flux shown in Fig. 6.23 shows peaks in the rim and relatively low values inside the Loop. There are some differences between the north path and the south path. The largest one is a clear difference in peak position in the NE rim that is due to the bright filament at 45° to the radial direction, as seen in Fig. 6.17. However, these two paths show a globally similar behavior in flux. Therefore, we can see that they are quite similar to each other from a large scale point of view.

We notice that there are many aspects showing asymmetry and non-uniformity. The NE half is stronger in intensity than the SW half. The flux in the inner part of the Loop shows relatively small values in the west half, particularly at $+25' < R < +40'$. The NE half is brighter by a factor of 5–10 than the SW half. Furthermore, the SW half shows stronger intensity variation than the NE half. This suggests that the thickness of the cavity shell is far from uniform. The cavity shell in the SW half is much thinner than that in the NE half. Since we assume the metal abundances of the low $kT_e$ component equal to those of the NE rim, we can calculate the EM. Furthermore, we assume the ambient density to be $0.7 \text{ cm}^{-3}$ based on the observation of the NE rim, and we estimate the mass of the low $kT_e$ component to be $130 \text{ MO}$. However, we should note that there are evidence that the SN explosion which produced the Cygnus Loop occurred within a preexisting cavity (e.g., Hester et al. 1994; Levenson et al. 1998; Levenson et al. 1999). The model predicts that the original cavity density, $n_c$, is related to the wall density $n_w$ by $n_c = 5$. Assuming that $n_0$ equals the ambient density, $n_w$, we estimate $n_c$ to be $0.14 \text{ cm}^{-3}$. Then, we calculate the total mass in the preexisting cavity to be $\sim 25 \text{ M}_\odot$.

– Ejecta Distribution –

The flux distribution from the ejecta along the path is shown with filled circles in Fig. 6.23. It has a relatively flat structure with two troughs around $R = -35'$ and $R = +50'$. Since we leave the metal abundances as free parameters, we obtain distributions of EM of various metals (C=N=O, Fe=Ni, Ne, Mg, Si and S) in the ejecta. These are shown in Fig. 6.24, where black crosses trace the north path and red crosses trace along the south path. If we assume uniform plasma conditions along the line of sight, the EM represents
the mass of the metal. Most elements show similar structure between the north path and the south path, while there is a large discrepancy in Fe (or Ni) distribution at $-10' < R < +30'$. In this region, the south path shows two times more abundant Fe (or Ni) than the north path. A similar discrepancy is seen in O ($-30' < R < -10'$) and in Ne (at $-10' < R < +10'$). Therefore, the distribution of metal abundance shows a north-south asymmetry along the path.

The distributions of O and Ne show a central bump and increase at the outer sectors. However, those of Mg, Si, S and Fe only show a central bump. The increase of O and Ne at the outer sectors indicates that the outer parts of the ejecta mainly consists of O and Ne and they may be well mixed. Similarly heavy elements, Mg, Si, S and Fe (or Ni) forming central bumps may show that they are well mixed. Therefore, a significant convection has occurred in the central bumps while an “onion-skin” structure remains in the outer sectors.

**Discussion**

The Cygnus Loop appears to be almost circular with a blowout in the south. The ROSAT image indicates no clear shell in this blowout region. Levenson et al. (1997) revealed that there is a thin shell left at the edge of the blowout region. Therefore, there is a small amount of cavity material in this region that surrounds the ejecta. This also indicates the non-uniformity of the cavity wall. If the cavity wall is thin, the ejecta can produce a blowout structure.

Looking at the component of the cavity material along our path shown in Fig. 6.24, the flux is very weak at $+15' < R < +40'$. This indicates that the cavity wall is very thin in this region. When we calculate the flux ratio between the ejecta plasma and the cavity material, we find that the ratio becomes high (larger than 4) at $+15' < R < +35'$ in the north path and $+30' < R < +35'$ in the south path. Therefore, we guess that the thin-shell region is larger in the north path than in the south path. This also shows the asymmetry between the north and the south as well as that between the east and the west. If the thin shell region corresponds to a blowout similar to that in the south blowout, this region must have a blowout structure along the line of sight either in the near side or far side or both. This structure roughly corresponds to Pos-5 and will extend further in the northwest direction. Looking at the ROSAT image in Fig. 6.17, we see a circular region with low intensity. It is centered at $(20^h49^m11^s, 31°05'20'')$ with a radius of 30'. We guess that this circular region corresponds to a possible blowout in the direction of our line of sight. CCD observations just north of our path will answer this hypothesis.

We obtain EMs of O, Ne, Mg, Si, S, and Fe for the ejecta along the north path
Figure 6.24: Distributions of EM for various metals \([\text{O}(=\text{C}=\text{N}), \text{Ne}, \text{Mg}, \text{Si}, \text{S}, \text{and Fe}(=\text{Ni})]\) in the ejecta. Black indicates the north path and red indicates the south path. Data points showing only upper limits are excluded in these figures.
Table 6.7: Calculated VEM ($= \int n_e n_H dV$) of the Cygnus Loop ejecta

<table>
<thead>
<tr>
<th>Element</th>
<th>$10^{54} \text{cm}^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>7.4±0.5</td>
</tr>
<tr>
<td>Ne</td>
<td>1.5±0.2</td>
</tr>
<tr>
<td>Mg</td>
<td>0.34±0.1</td>
</tr>
<tr>
<td>Si</td>
<td>2.9±0.5</td>
</tr>
<tr>
<td>S</td>
<td>1.2±0.3</td>
</tr>
<tr>
<td>Fe</td>
<td>1.30±0.05</td>
</tr>
</tbody>
</table>

and the south path. Multiplying the EMs by the area of each sector, we obtain volume emission measure (hereafter VEM, VEM=$\int n_e n_H dV$, $dV$ is the X-ray-emitting volume) along the path. Since we only observed the limited area of the Cygnus Loop from the NE rim to the SW rim, we have to estimate the VEMs for the entire remnant in order to obtain the relative abundances as well as the total mass of the ejecta. Therefore, we divide our observation region into four parts: left-north part, right-north part, left-south part, and right-south part. We assume that each part represents the average VEMs of the corresponding quadrant of the Loop. In this way, we can calculate the total VEMs for O, Ne, Mg, Si, S, and Fe that are described in table 6.7. The south quadrant, corresponding to the right-south path, contains the largest mass fraction of 31%, while the other quadrants contain 23% each. Then, we calculate the relative abundances of Ne, Mg, Si, S, and Fe to O in the entire ejecta. Since we cannot measure the abundance of light elements like He, it is quite difficult to estimate the absolute abundances. However, the relative abundance to O is robust.

Since the Cygnus Loop is believed to be a result from a core-collapse SN, we compared our data with core-collapse SN models. There are many theoretical results from various authors (e.g., Woosley & Weaver 1995; Thielemann et al. 1996; Rauscher et al. 2002; Tominaga et al. 2007). We also employ a SN Type-Ia model (Iwamoto et al. 1999) for comparison. We calculate the relative abundance for various elements to O and compared them with models. Figure 6.25 shows comparisons between the model calculations and our results where we pick up Woosley’s model with one solar abundance (Anders & Grevesse 1989) for the core-collapse case (Woosley & Weaver 1995). The Type-Ia model yields more Si, S and Fe than our results, but less Ne. Models with massive stars produce better fits to our results than the Type-Ia model. Among them, we find that the model with 15 MO shows good fits to our results. They fit within a factor of two with an exception
Figure 6.25: Number ratios of Ne, Mg, Si, S, and Fe relative to O of the high-\(kT_e\) component estimated for the entire Loop (black solid line). Dash-dotted red lines represent CDD1 and W7 model of Type-Ia (Iwamoto et al. 1999). Dotted green, blue, light blue, and magenta lines represent core-collapse models whose progenitor masses are 13, 15, 20, and 25 M\(\odot\), respectively (Woosley & Weaver 1995).

Assuming that the ejecta density is uniform along the line of sight, we estimate the total mass of the fossil ejecta to be 21 M\(\odot\). In this calculation, we assume that the electron density is equal to that of hydrogen and that the plasma filling factor is unity, although the fossil ejecta might be deficient in hydrogen. If it is the case, the total mass of the fossil ejecta reduces to \(\sim 12\) M\(\odot\) whereas the relative abundances are not affected. The most suitable nucleosynthetic model predicts that the total mass ejected is about 6 M\(\odot\) without H. Therefore, there might be a significant amount of contamination from the swept-up matter into the high-\(kT_e\) component, which we consider the ejecta. Otherwise, the assumption that the density of the ejecta is uniform might be incorrect since rim-brightening for the EMs of O, Ne, Mg, and Fe is clearly seen in Fig. 6.24. Non-uniformity reduces the filling factor and also the mass of the high-\(kT_e\) component.

There is observational evidence of the asymmetry of SN explosions both for massive stars (Leonard et al. 2006) and for Type Ia (Motohara et al. 2006). We find that the
6.4. **RADIAL STRUCTURES**

ejecta plasma shows asymmetric structure between NE half and SW half. Ne and Fe are evenly divided while two thirds of O and Mg are in the NE half. On the contrary, two third of Si and S are in the SW half. We calculate the ejecta mass for each quadrant and find that the south quadrant contains the largest ejecta mass. Similar asymmetries are seen in other SNR, such as Puppis A, which shows asymmetric structure with OFMKs (Winkler & Kirscher 1985; Winkler et al. 1988) . The CCO in Puppis A is on the opposite side of the SNR from the O-rich, fast-moving knots (Petre et al. 1996). If the asymmetry of the ejecta in the Cygnus Loop is similar to that of Puppis A, we may expect a CCO to be in the north direction.

**Conclusion**

We have observed the Cygnus Loop along the diameter from the NE rim to the SW rim employing XMM Newton. The FOV is divided into two paths: the north path and the south path. Then it is divided into many small annuli so that each annulus contains a similar number of photons to preserve statistics.

The spectra from the rim regions can be expressed by a one-\(kT_e\) component model while those in the inner region require a two-\(kT_e\) component model. The low \(kT_e\) plasma shows relatively low metal abundance and covers the entire FOV. It forms a shell that originates from the preexisting cavity. The high \(kT_e\) plasma shows high metal abundance and occupies a large part of the FOV. The origins of these two components are different: the high \(kT_e\) plasma with the high metal abundance must come from the ejecta while low \(kT_e\) plasma with low metal abundance must come from the cavity material. We find that the thickness of the shell is very thin in the south west part where, we guess, the ejecta plasma is blow out in the direction of our line of sight.

We estimate the mass of the metals. Based on the relative metal abundance, we find that the Cygnus Loop originated from a 15 M\(_\odot\) star. The distribution of the ejecta is asymmetric, suggesting an asymmetric explosion.
6.4.2 *Suzaku* View

We present results from the *Suzaku* observations of the NE-SW path of the Cygnus Loop, which were published in Katsuda et al. (2008c).

Spatially Resolved Spectral Analysis

![Diagram of spectral analysis](image)

Figure 6.26: Same as Fig.6.3 but with the cells where we extracted spectra. We show example spectra from black cells for $<2\,\text{keV}$ and green cells for $>2\,\text{keV}$ in Fig. 6.27.

We divide the entire FOV into 119 rectangular small cells indicated in Fig. 6.26 such that each cell contains 2,500–5,000 photons for XIS0 to equalize the statistics. The sizes of small cells range from 1/32 FOV to 1/8 FOV. Then, we extract spectra from them. Generally, count rates above 2 keV are so low that the statistics are too poor in each cell. It is quite difficult to constrain the abundance of S. Therefore, dividing each FOV into the NE part and the SW part, we accumulate photons in the energy range above 2 keV from the NE or SW half where each small cell is included whereas we extract spectra below 2 keV from each small cell. Example regions in each FOV, a black cell for $<2\,\text{keV}$ and a green cell for $>2\,\text{keV}$, are shown in Fig. 6.26. In this way, we obtain much better...
6.4. RADIAL STRUCTURES

constraints on S abundance for each cell than those determined by fitting entire-energy-band spectra extracted from each small cell. The S abundances are different for each small cell due to the spectral differences below 2 keV. To generate the RMF and the ARF, we employ \texttt{xisrmfgen} and \texttt{xissimarfgen} (Ishisaki et al. 2007) (version 2006-10-26), respectively. The low energy efficiency of the XIS shows degradation caused by the contaminants accumulated on the optical blocking filter (Koyama et al. 2007), which is taken into account in the generation of the ARF file.

Firstly, all the spectra are fitted by an absorbed NEI model with a single component (the wabs; Morrison & McCammon (1983) and the \texttt{vnei} model (NEI version 2.0); e.g., Borkowski et al. (2001) in XSPEC v11.3.1). Free parameters are \(N_{\text{H}}, kT_e, \tau, \text{EM} \), abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set abundance of Ni to be equal to that of Fe. Abundances of other elements included in the \texttt{vnei} model (i.e., Ar and Ca) are fixed to the solar values (Anders & Grevesse 1989). An example spectrum from the black cell in P16 shown in Fig. 6.26 is presented in Fig. 6.27 indicated as P16 (left) together with the best-fit model. This model gives us quite good fits except for the energy bands around Si- and S-K lines where we can see large discrepancy between our data and the model. Since the emission from both the ejecta and the swept-up matter are detected as a projection effect around the center portion of the Cygnus Loop (Miyata et al. 1998; Tsunemi et al. 2007; Katsuda & Tsunemi 2008a), it is natural to consider that we need at least two (i.e., the swept-up matter and the ejecta) components to reproduce our data.

Then, we apply two-component NEI model for all the spectra. In this model, \(kT_e, \tau, \text{and EM} \) are free parameters for both components. \(N_{\text{H}} \) is also left as a free parameter but tied in the two components. Assuming that the swept-up matter surrounds the ejecta, we fix metal abundances for the swept-up matter component to those of the NE rim regions of the Cygnus Loop where we expect no ejecta component (Uchida et al. 2006). The metal abundances are described in the footnote of table 6.8. Then, we leave metal abundances of O(=C=N), Ne, Mg, Si, S, and Fe(=Ni) for the ejecta component as free parameters. We confin the values of \(N_{\text{H}} \) in the range from 0.01 to 0.06 \(\times 10^{22} \text{ cm}^{-2} \) (Inoue 1980; Miyata et al. 2007). Figure 6.27 shows example spectra from seven black cells shown in Fig. 6.26. We summarize the best-fit parameters for the example spectra in table 6.8. Based on table 6.8, we find that the two components clearly show different temperature with each other. The low-\(kT_e \) component is responsible for the swept-up matter while the high-\(kT_e \) component is responsible for another component. We find that the metal abundances for at least one element of the high-\(kT_e \) component are about an order-of-magnitude higher than those for the low-\(kT_e \) component, which clearly shows that the high-\(kT_e \) component represents the ejecta component. In this way, we perform spectral fitting for all the
spectra from 119 small cells. Applying the F-test with a significance level of 99%, we find that this model gives us better fits than those for one-component NEI models for almost all the spectra (e.g., from Fig. 6.27 P16 (left) to P16 right). We obtain fairly good fits for all the spectra by the two-component NEI model (reduced $\chi^2 < 1.7$). If we consider the calibration uncertainty of the energy scale ($\pm 5$ eV; Koyama et al. 2007), the values of reduced $\chi^2$ become lower than 1.4. Nonetheless, the fits are not acceptable for many spectra from the statistical point of view, which suggests that our model is too simple. However, we believe that the two-component model is a good approximation to represent our data. Taking into consideration that spectra from almost all the cells require two-component model, the ejecta turn out to be distributed inside a large fraction (at least our FOV) of the Cygnus Loop. Since the outer edge of our FOV is located around $0.85 R_s$, our result matches the view from XMM-Newton observations that the ejecta distribute inside $\sim 0.85 R_s$ of the Cygnus Loop.

Figure 6.28 shows maps of the best-fit parameters obtained from the two-component NEI model. The subscript, H, denotes the high-$kT_e$, i.e., the ejecta component while L denotes the low-$kT_e$, i.e., the swept-up matter component. We show EMs of O, Ne, Mg, Si, S, and Fe for the ejecta component. We mark the geometric center of the Cygnus Loop (RA=20h51m19s, DEC=31°02′48″ [J2000]: Ku et al. 1984) as a white dot in each figure. There is a point source, 1RXH J205036.4 + 302448, within P16 (see, Fig.6.1). We exclude the responsible cell from our analysis, and this can be seen as a black box in the map of log($\tau_H$) shown in Fig. 6.28. $N_H$'s tend to show relatively large values around the center in each FOV to those in the edge regions. Since such $N_H$ variations must be due to the contamination problem of the XIS (Koyama et al. 2007), the current model of a spatial variation of the contaminants accumulated on the optical blocking filter should be modified properly. We find that the value of $kT_e$ for the swept-up matter component is $\sim 0.2$ keV in our entire FOV other than P15 and P16 where we can see slightly higher values ($\sim 0.3$ keV). The values of $kT_e$ for the ejecta component show a significant variation from the SW ($\sim 0.35$ keV) to the NE ($\sim 0.7$ keV) portion in our FOV as Miyata et al. (2000) already noted the hard X-ray-emitting region in the NE portion by ASCA GIS observations and suggested that the hard X-ray might come from the ejecta. The CIE has already been established for both components in most cells in P17, which seems consistent with the results from Chandra observations of the SW rim of the Cygnus Loop (Leahy 2004).

We notice the clear unti-correlation between $kT_{eH}$ and $\tau_H$, and the correlation between $\tau_H$ and EMs of Si, S, and Fe in the ejecta component. We examine the systematic effect between ionization age (and/or temperature) and the distributions of Si-, S-, and Fe-
Table 6.8: Spectral-fit parameters for the example spectra

<table>
<thead>
<tr>
<th>Parameter</th>
<th>P8</th>
<th>P12</th>
<th>P13</th>
<th>P14</th>
<th>P15</th>
<th>P16</th>
<th>P17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H [\times 10^{22} \text{cm}^{-2}]$</td>
<td>0.044$^{+0.005}_{-0.003}$</td>
<td>0.049$^{+0.005}_{-0.003}$</td>
<td>0.060$^{+0.004}_{-0.004}$</td>
<td>0.060$^{+0.004}_{-0.004}$</td>
<td>0.049$^{+0.006}_{-0.003}$</td>
<td>0.060$^{+0.003}_{-0.003}$</td>
<td>0.031$^{+0.002}_{-0.002}$</td>
</tr>
</tbody>
</table>

**High temperature component**

- $kT_{e1}$ [keV]: 0.55±0.01, 0.73$^{+0.03}_{-0.01}$, 0.60±0.04, 0.60±0.04, 0.38±0.01, 0.39±0.01, 0.35±0.01
- O(=C=N): 0.9±0.1, 0.6±0.1, 0.47$^{+0.09}_{-0.08}$, 1.2±0.4, 0.30±0.05, 0.5±0.1, 0.20±0.05
- Ne: 0.8±0.1, 0.7±0.1, 0.8±0.2, 0.7±0.2, 0.29±0.06, 0.46$^{+0.07}_{-0.08}$, 0.15±0.05
- Mg: 0.5±0.1, 0.5±0.1, 0.8±0.2, 0.6±0.2, 0.16±0.09, 0.14±0.09
- Si: 0.6±0.2, 1.0±0.2, 5.1±0.6, 6.1±0.7, 3.6±0.4, 4.1±0.4, 2.7$^{+0.5}_{-0.6}$
- S: 1.2±0.4, 2.8±0.5, 10±1, 11±1, 7.1±0.9, 7.5±0.8, 4.3
- Fe(=Ni): 0.62$^{+0.06}_{-0.08}$, 1.1±0.1, 3.3±0.1, 3.9±0.2, 2.04±0.04, 2.30±0.05, 0.75±0.03
- log($\tau_1$/cm$^{-3}$ sec): 11.2$^{+0.04}_{-0.09}$, 10.73$^{+0.06}_{-0.04}$, 11.11$^{+0.07}_{-0.11}$, 11.5±1, 11.76$^{+0.10}_{-0.07}$, 11.76$^{+0.08}_{-0.09}$, 12.0$^{+1.7}_{-0.2}$
- $\text{EM}$[$\times 10^{19}$ cm$^{-5}$]: 0.22±0.01, 0.072$^{+0.006}_{-0.005}$, 0.043±0.001, 0.061±0.002, 0.166±0.003, 0.131±0.002, 0.102±0.003

**Low temperature component**

- $kT_{e2}$ [keV]: 0.24±0.01, 0.23±0.01, 0.23±0.01, 0.21±0.01, 0.18±0.01, 0.15±0.01, 0.22±0.01
- Abundances (fixed to those determined for the NE rim of the Cygnus Loop)$^\dagger$
- log($\tau_2$/cm$^{-3}$ sec): 11.33±0.04, 11.3±0.1, 11.21±0.05, 11.67$^{+0.09}_{-0.08}$, 13.1$^{+0.6}_{-1.1}$, 12.0$^{+1.7}_{-0.2}$, 11.58±0.04
- $\text{EM}_2$[$\times 10^{19}$ cm$^{-5}$]: 4.4$^{+0.2}_{-0.1}$, 2.8$^{+0.1}_{-0.2}$, 1.91±0.06, 2.16$^{+0.10}_{-0.09}$, 0.67±0.05, 1.5$^{+0.2}_{-0.1}$, 0.63±0.01
- $\chi^2$/d.o.f.: 772/643, 749/617, 524/492, 653/576, 654/549, 751/525, 769/523

$^\ast$Other elements are fixed to those of solar values.
The values of abundances are multiples of solar value.
The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.
$^\dagger$EM denotes the emission measure, $\int n_e n_H dl$.
$^\ddagger$C=0.27, N=0.10, O=0.11, Ne=0.21, Mg=0.17, Si=0.34, S=0.17,$ and Fe(=Ni)=0.20 (Uchida et al. 2006).
Figure 6.27: Top-left panel: X-ray spectra extracted from the black cell in P16 indicated in Fig. 6.26. The best-fit curves for one-component NEI model are shown with solid lines and the lower panels show the residuals. The small gap around 2 keV is due to the fact that we extracted spectra below 2 keV from each small cell while above 2 keV from half of each FOV. Top-right panel: Same as top left but with two-component NEI best-fit models. The contribution of each component is shown by the dotted lines only for XIS1. Other panels: Same as top-right panel but from black cells in P8, P12, P13, P14, P15, and P17, respectively.
6.4. RADIAL STRUCTURES

Table 6.9: Summary of VEM ($\int n_e n_i dV$ for the ejecta component in units of $10^{52} \text{ cm}^{-3}$) in each FOV

<table>
<thead>
<tr>
<th>Elements</th>
<th>P8</th>
<th>P12</th>
<th>P13</th>
<th>P14</th>
<th>P15</th>
<th>P16</th>
<th>P17</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>$5.3^{+0.8}_{-0.7}$</td>
<td>2.4±0.4</td>
<td>2.6±0.4</td>
<td>$2.0^{+2.3}_{-1.9}$</td>
<td>2.9±0.6</td>
<td>3.0±0.5</td>
<td>1.8±0.2</td>
</tr>
<tr>
<td>Ne</td>
<td>1.2±0.1</td>
<td>0.50^{+0.09}_{-0.08}</td>
<td>0.26±0.08</td>
<td>0.26±0.12</td>
<td>0.44±0.09</td>
<td>0.51±0.08</td>
<td>0.30±0.05</td>
</tr>
<tr>
<td>Mg</td>
<td>0.26±0.05</td>
<td>0.12±0.02</td>
<td>0.10±0.03</td>
<td>0.06^{+0.05}_{-0.03}</td>
<td>0.036^{+0.038}_{-0.025}</td>
<td>0.03±0.02</td>
<td>0.06±0.03</td>
</tr>
<tr>
<td>Si</td>
<td>0.25±0.10</td>
<td>0.24±0.03</td>
<td>0.49±0.06</td>
<td>0.7±0.1</td>
<td>1.3±0.2</td>
<td>1.2±0.1</td>
<td>0.5±0.2</td>
</tr>
<tr>
<td>S</td>
<td>0.18±0.07</td>
<td>0.23±0.03</td>
<td>0.40±0.04</td>
<td>0.63±0.06</td>
<td>0.9±0.1</td>
<td>0.9±0.1</td>
<td>0.18^{+0.10}_{-0.09}</td>
</tr>
<tr>
<td>Fe</td>
<td>0.24±0.04</td>
<td>0.29±0.02</td>
<td>0.44±0.01</td>
<td>0.57±0.02</td>
<td>0.89±0.02</td>
<td>0.82±0.02</td>
<td>0.30±0.01</td>
</tr>
</tbody>
</table>

Errors quoted are the mean 90% confidence level for each cell.

We re-fit the example spectrum in P15, employing the same two-component model used in this paper but with fixed ionization age of $1 \times 10^{11} \text{ cm}^{-3} \text{ sec}$ for the ejecta component (which is the typical value in P8, 12, 13). We notice a slight increase of $kT_{eH}$ that is still significantly lower than that in the northern part of our FOV. We find that the emission measures of Si, S, and Fe are, respectively, reduced by 30%, 30%, and 15% from those obtained in the case that we left ionization age as a free parameter. These values are still higher than those obtained in P8, 12, and 13 by $\sim$50%. Therefore, we can safely conclude that the EMs of Si-, S-, and Fe-ejecta in the southern part of our FOV are higher than those in the northern part of our FOV.

The ionization states for the ejecta component in P15 and P16 also reach the CIE condition. Apart from P15, P16, and P17, the ionization states for both components are in NEI condition in almost all the cells. We find that all the elements are distributed asymmetric to the geometric center. The EMs for O, Ne, and Mg are enhanced in P8, while no enhancements are seen for the other elements there. Also, the EMs for all the elements other than Mg show enhancements in P15 and P16.

We obtain EMs of O, Ne, Mg, Si, S, and Fe for the ejecta component in 119 cells. Multiplying the EM by the area of each cell, we obtain EI of all the elements for each cell and sum up the VEMs for all the cells within each FOV. The summed-up VEMs are summarized in table 6.9.
Figure 6.28: Maps of the best-fit parameters. The values of $N_H$, $kT_e$, $EML$ are in units of $10^{22}\text{cm}^{-2}$, keV, and $10^{19}\text{cm}^{-5}$, respectively. Lower six maps show EMS of O, Ne, Mg, Si, S, and Fe for the high-$kT_e$ component in units of $10^{14}\text{cm}^{-5}$. We adjusted the color code such that we can see the differences in each figure.
Discussion and Conclusions

We observed the Cygnus Loop from NE to SW with Suzaku in seven pointings. Dividing the entire FOV into 119 cells, we extract spectra from all the cells and perform spectral analysis for them. Almost all the spectra are significantly better fitted by a two-component NEI model rather than a one-component NEI model. Judging from the abundances, the high-$kT_e$ component must be ejecta while the low-$kT_e$ component comes from the swept-up matter.

- Swept-up Matter Distribution –

The temperature for the swept-up matter component is significantly lower than that for the ejecta component. On the other hand, it is similar to that obtained for the rim of the Loop where we expect no contamination of the ejecta (e.g., M07). Therefore, we believe that we surely separate the X-ray emission of the ejecta inside the Loop from that of the surrounding matter. The EM distribution of the swept-up matter ($EM_L$) is inhomogeneous in our FOV as shown in Fig. 6.28. The shell of the swept-up matter seems thin in the SW part (i.e., P15 and P16) of the Loop relative to that in the NE part. Such trend is also reported by XMM-Newton observations covering just north of our Suzaku path (Tsunemi et al. 2007). As Tsunemi et al. (2007) mentioned, there might be a blowout in the direction of our line of sight around P15 and P16 such as a south blowout of the Loop (see, Fig. 6.1). The relatively high temperature in P15 and P16 suggests that the velocity of the blast wave is higher than that in the other regions. This fact indicates that the density of ambient matter in P15 and P16 is lower than that in the other regions, supporting the thin swept-up-matter shell.

- Metal Distribution in the Ejecta Component –

We divide our FOV into two parts: the NE part (P8, P12, P13, and P14) and the SW part (P15, P16, and P17). There is a gap between P16 and P17 where we did not observe. Assuming VEMs of the ejecta in the gap to be averages of those in P16 and P17, we calculate the ratios between VEMs in the NE part and those in the SW part. They are O~1.2, Ne~1.3, Mg~3.2, Si~0.44, S~0.57, and Fe~0.60. For simplicity, we assume that the mass ratios of those elements are equal to the VEM ratios. Regarding the O-Ne group, the similar amounts of those elements exist in the NE and SW part. In contrast to the O-Ne group, the other elements show non-uniform distributions: Mg is distributed more in the NE part by a factor of ~3 while Si, S, and Fe are distributed more in the SW part by a factor of ~2 (Note that the mass ratio being proportional to a product of the density times the emitting volume will be lower than that of the VEM ratio).

A natural explanation for the asymmetries is an asymmetry at the time of the SN explosion of the Cygnus Loop. The degree of north-south (1:2) asymmetry of innermost
ejecta such as Si-, S-, and Fe-ejecta is consistent with that expected from asymmetric explosions resulting from hydrodynamic instabilities which are described in recent theoretical models of SN explosions (e.g., Burrows et al. 2007). However, we should keep in mind that there are some other possibilities which can produce the asymmetries of ejecta. The X-ray emission is sensitive to temperature and density, i.e., dense ejecta emit more strongly than thin ejecta do and cooled ejecta will not continue to emit X-rays. Furthermore, an asymmetric environment which might be created by stellar winds (e.g., Blondin et al. 1996; Dwarkadas et al. 2007) as well as hydrodynamic instabilities during the remnant evolution (Jun et al. 1995) can make a ejecta distribution distorted.

If the mass ejection are anisotropic, it would lead a recoil of a stellar remnant due to momentum conservation. Therefore, we expect to see the velocity of the stellar remnant directed opposite to the momentum of the gaseous SN ejecta (e.g., Scheck et al. 2006). In fact, recent observations of a stellar remnant in Puppis A SNR revealed that its velocity was very high (>1000 km sec\(^{-1}\)) and directed opposite to the momentum of OFMKs (Winkler & Petre 2007; Hui & Becker 2006b). Since the Cygnus Loop is believed to be a remnant of a core-collapse SN explosion, the presence of a stellar remnant is strongly expected. So far, we do not find the stellar remnant associated with the SN explosion of the Cygnus Loop (e.g., Miyata et al. 2001). Taking into consideration that the momentum of innermost ejecta (which is considered to be strongly related to the stellar remnant) seems to be directed toward the south of the Loop, we might find the stellar remnant associated with the Cygnus Loop in the north of the Loop. We have observed the Cygnus Loop from the NE rim to the SW rim with \textit{Suzaku} as well as \textit{XMM-Newton}. The observation paths cover about one seventh of the entire Loop. Further \textit{Suzaku} and/or \textit{XMM-Newton} observations of the rest of the area are required to obtain the relative abundances for the total ejecta as well as to reveal the ejecta structure in the entire Loop.
Chapter 7

Discussion

7.1 Global Ejecta Distributions in SNRs and Neutron Star Recoil

We discuss on global ejecta distributions in the entire SNRs in conjunction with directions of proper-motion vectors of stellar remnants associated with the SNRs. Since Galactic O-rich SNRs, i.e., Puppis A, Cas A, and G292.0+1.8, are the best studied SNRs in this respect, we first focus on the three remnants. Next, we will discuss on the Cygnus Loop.

7.1.1 Galactic O-rich SNRs

Puppis A

We construct EW images for O, Ne, Mg, Si, S, and Fe of the almost entire area of the X-ray Puppis A SNR. We find that the overall structures of the O and Ne EW images are similar to each other. They are enhanced in the faint south and west regions compared with the bright east and north regions. This fact generally matches a view that the ambient density is significantly higher in the east and north and the emission from the shocked ISM overwhelms there. On the other hand, we find a Si-S-EW enhanced region only in the NE portion of the remnant. The enhancement is most likely due to the abundance effect. Together with the fact that we find fast-moving X-ray ejecta knot(s) positionally coincident with optically emitting OFMKs in the NE portion of Puppis A, we suggest that the mass ejection during the SN explosion was asymmetric: a large fraction of the total ejecta was spew-out in the NE direction. On the other hand, the transverse space velocity of the CCO associated with this remnant was recently measured to be \( \sim 1600 \text{ km sec}^{-1} \) toward the west-SW direction (Hui & Becker 2006b; Winkler & Petre 2007). These facts strongly support the idea that asymmetrically ejected material kicked the newly born
neutron star to the high velocity according to momentum conservation. Therefore, among several proposed mechanisms which attempt to explain the high velocities of neutron stars, our result prefers the ejecta-driven mechanism (e.g., Scheck et al. 2006 and references there in).

We should keep in mind that there are some other possibilities which can produce the asymmetries of ejecta, i.e., temperature and density effects, or asymmetric environments which might be created by either stellar winds (e.g., Blondin et al. 1996; Dwarkadas 2007) or hydrodynamic instabilities during the remnant evolution (Jun 1995).

Cas A

Recent *HST* observations identified 1825 high-velocity, outlying ejecta knots through measured proper motions of $0''.35–0''.90\ yr^{-1}$, corresponding to transverse velocities of 5,500–14,500 km sec$^{-1}$ at a distance of 3.4 kpc (Fesen et al. 2006). The knots positions are marked with open circles color coded either red, green, or blue to indicate those knots with spectra dominated by strong [N II], [O II], or [S II] line emission in Fig. 7.1. The FMK distributions show highly asymmetrical structure due to NE and SW jets (NE jet: position angle (P.A.) = 45°–70°, SW jet: P.A. = 230°–270°). Also, the *HST* image reveals a lack of outlying ejecta knots along the remnant’s northern and southern regions. Not a single ejecta knot can be found along a 55° wide region in remnant’s southern portion of P.A. = 145°–200° and in a narrow 15° position angle zone along the north (P.A. = 335°–350°). These features are more apparent in Fig. 7.2; the *Upper* figure shows extrapolated 320 yr proper-motion vectors of the 1825 ejecta knots and predicted center of explosion (COE; Thorstensen et al. 2001).

The CCO in the remnant (Tananbaum 1999) is first noticed by *Chandra*’s first-light images of Cas A taken in 1999. The displacement of the CCO from the predicted COE is $7''.0 \pm 0''.8$, with an implied motion in the SE direction as shown in Fig. 7.2 *Lower*. Assuming that a current remnant age of 320 yr, the transverse velocity is estimated to be 350 km sec$^{-1}$ for a distance of 3.4 kpc (Fesen et al. 2006). Interestingly, the projected motion of the CCO is toward the middle of the broad southern gap in the distribution of the outlying ejecta knots, which suggests that the neutron star get its kick aligned with the progenitor’s slowest velocity expansion. If it is the case, the ejecta-driven mechanism for the high-velocity CCO is also at work in Cas A. Measurement of the proper motion of the CCO, which is expected to be possible by *Chandra* observations in a few years later, is strongly required to confirm the expected transverse velocity.
Figure 7.1: *Chandra* 1 megasecond image of Cas A with the locations of the 1825 identified outer ejecta knots (M.C. Hammell & R.A. Fesen 2006, in preparation) color-coded by their emission properties. Red open circles indicate knots with strong [N II] line emission, green open circles knots with strong [O II] emission, and blue open circles strong [S II] FMK-like outlying knots (Fesen et al. 2006).
Figure 7.2: **Upper**: Plot of extrapolated 320 yr proper motions for the 1825 identified outer knots based on actual proper motions. The central white circle has a radius of 5 arcsec and marks the remnant’s estimated COE (Thorstensen et al. 2001). **Lower**: Plot of 1825 outer knot positions and their expected motions away from the remnant’s known COE. The circle represents the radial distance of 200 arcsec, corresponding to a measured proper motion of $0'.65$ yr$^{-1}$ and thus an implied 10,000 km s$^{-1}$ transverse velocity at the assumed remnant distance of 3.4 kpc. These images are taken from Fesen et al. (2006). **Lower-left inset**: A 2001 STIS HST image of the central region of Cas A near the XPS with the Thorstensen et al. (2001) expansion center marked ($\alpha = 23^h23^m27^s.77\pm0'.05, \delta = 58^\circ48'49''.4\pm0''.4$ [J2000.0]) along with the CCO’s current position ($\alpha = 23^h23^m27^s.943\pm0'.05, \delta = 58^\circ48'42''.51\pm0''.4$ [J2000.0]) as derived from *Chandra* image data (see, Fesen et al. 2006). The circles marking these positions are 1 arcsec in diameter.
G292.0+1.8

Figure 7.3 shows an X-ray color image of the G292.0+1.8 SNR generated from recent half-megasecond Chandra data (Park et al. 2007). The outer boundary of the radio SNR is overlaid with a white contour. Red is the sum of the 0.58–0.71 and 0.88–0.95 keV bands (dominated by emission from O Lyα and Ne Heα), orange is the 0.98–1.10 keV band (Ne Lyα), green is the 1.28–1.43 keV band (Mg Heα), and blue is the sum of the 1.81–2.05 and 2.40–2.62 keV bands (Si Heα+S Heα). The SNR interior contains a complex network of knots and filaments with a variety of colors and morphologies. The overall color distribution of these features is highly asymmetric: red-orange emission is dominant in the south-SE, while the west-NW regions are bright in emission appearing green-blue in color. Park et al. (2007) suggest that these variations largely reflect differences in the underlying distributions of the gas temperature and ionization state in the metal-rich ejecta based on their hardness ratio maps as well as equivalent width maps of Ne Heα and Ne Lyα in their previous work (Park et al. 2002). They also suggest that catastrophic radiative cooling in the SE ejecta is responsible for the SE-NW gradient in observed asymmetric properties. Such ejecta asymmetries can not be produced by variation in the ambient medium density surrounding the remnant, taking into consideration that there is no evidence for a higher density in the SE regions (Braun et al. 1986). Park et al. (2007) thus suggest that the ejecta asymmetry observed has its origin in some intrinsic asymmetry of the SN explosion itself such as a variation in the density or velocity distribution from SE to NW, which will be tested from detailed spatially resolved spectral analysis for this remnant.

We here note that the position of the stellar remnant, known to be the pulsar J1124–5916 (white bars near the SNR center in Fig. 7.3; Camilo et al. 2002; Hughes et al. 2003), is displaced by ∼1′ toward the east-SE direction from the geometrical center of the remnant (black cross near the SNR center in Fig. 7.3; Gaensler & Wallace 2003). At a distance of 4.8 kpc and an age of ∼3000 yrs (Gonzalez & Safi-Harb 2003), the transverse velocity is estimated to be ∼500 km sec⁻¹. Hughes et al. (2001) proposed two possibilities for the origin of the offset: the high transverse velocity of the pulsar or the slower expansion of the SNR toward SE. Park et al. (2002) suggested an advanced ionization state in the NW region of the remnant and thus likely a higher ISM density there. If this is the case, we expect to see slower expansion toward NW (not SE). Therefore, the high pulsar velocity interpretation seems more likely. Then, we notice that the direction of the pulsar motion, east-SE, is opposite to the direction in which the inner ejecta such as Si or S are dominantly distributed; we can see enhanced-blue color in western region of the remnant (see, Fig. 7.3). This suggests that the ejecta-driven mechanism for the origin of the high-velocity pulsar is at work for this remnant, too. Future direct measurement of the proper
motion of the pulsar as well as detailed spatially resolved spectral analysis for the entire remnant is strongly required to check whether or not the ejecta-driven mechanism is at work for this remnant.

Figure 7.3: *Chandra* half-megasecond color image of G292.0+1.8 (Park et al. 2007). Red-color regions are responsible for where the X-ray emission is dominated by O Ly$\alpha$ and Ne He $\alpha$, orange for Ne Ly$\alpha$, green for Mg He$\alpha$, and blue for Si He$\alpha$ and S He$\alpha$. The radio SNR center (Gaensler & Wallace 2003) is marked with a black cross. The position of PSR J1124–5916 (Hughes et al. 2003) is marked with white bars near the SNR center.
7.1.2 The Cygnus Loop

We have observed the Cygnus Loop by *Suzaku* and *XMM-Newton* in many pointings. As a result, we obtain a large data set covering the Cygnus Loop, which allows us to perform detailed spatially resolved spectral analysis for this SNR. Although the Cygnus Loop is an evolved SNR, we successfully detect metal-rich ejecta in a large portion of the remnant, as expected by previous *ASCA* observations (Miyata et al. 1998; Miyata & Tsunemi 1999).

We first quantitatively reveal the entire ejecta distributions in the Cygnus Loop. The inner ejecta such as Si, S, or Fe turn out to be asymmetrically distributed by a factor of $\sim 2$; more ejecta are distributed in the south of the remnant. The degree of the inner ejecta asymmetry of factor $\sim 2$ is consistent with that expected from asymmetric explosions resulting from hydrodynamic instabilities which are described in recent theoretical models of SN explosions (e.g., Burrows et al. 2007).

Since the Cygnus Loop is believed to originate from a core-collapse SN (e.g., Levenson et al. 1998), a stellar remnant behind the SN explosion should remain. However, the candidate has not yet been found so far (Miyata et al. 2001). We expect to detect it in the northern direction to the geometric explosion center, if the ejecta-driven mechanism is at work during the SN explosion which produced the Cygnus Loop, too.
7.2 Ejecta Knots

7.2.1 Observational Point of View

There are several SNRs in which fast-moving metal-rich ejecta knots are discovered. We list up these SNRs in Table 7.1. Dominant metals and masses of the ejecta knots in these SNRs and SN types which produced the remnant are also summarized in the table.

<table>
<thead>
<tr>
<th>Host SNR</th>
<th>SN type</th>
<th>Ejecta Knots</th>
<th>Main metals</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela</td>
<td>II P a</td>
<td>Si (Shrapnel A) b,c,T</td>
<td>O, Ne, Mg (Shrapnel D) T</td>
<td>$&lt;0.01 , M_\odot$ b,T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O, Ne, Mg (Shrapnel E) T</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Puppis A</td>
<td>II L/b d</td>
<td>OFMK e</td>
<td>O, Ne, Mg T</td>
<td>$\sim0.04 , M_\odot$ e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>G292.0+1.8</td>
<td>II L/b d</td>
<td>OFMK f</td>
<td>O, Ne, Mg g</td>
<td>$\sim10^{-3} , M_\odot$ g</td>
</tr>
<tr>
<td>Cas A</td>
<td>Ib d</td>
<td>OFMK h</td>
<td>Fe i</td>
<td>$10^{-5}–10^{-3} , M_\odot$ i</td>
</tr>
<tr>
<td>N49</td>
<td>Ib j</td>
<td>O, Si k</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>N132D</td>
<td>Ib j</td>
<td>OFMK l</td>
<td>$\sim1.5 \times 10^{-3} , M_\odot$ l</td>
<td></td>
</tr>
<tr>
<td>SN0540–69.3</td>
<td>SN1987A-like m</td>
<td>OFMK m</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>1E0102.2–7219</td>
<td>II L/b d</td>
<td>OFMK n</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Tycho</td>
<td>Ia p</td>
<td>Si, S o,p</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>


As introduced in chapter 2, core-collapse SNe can be divided into four categories, depending on the amount of mass loss from the progenitor star at the SN explosions: red supergiant stars with most of the H envelope intact (Type-II P), blue supergiant stars with massive H envelope (SN 1987A-like), stars with some H but most lost (Type-II L and II b), stars with all H lost (Type-Ib, Ic). From a theoretical point of view, Heger et al. (2003) have summarized results on the end point of massive single stars. In this view,
Type-IIP come from stars of mass \( \sim 9\text{--}25 M_\odot \), Type-Ib/c from stars of mass \( \sim 35 M_\odot \), and Type-IIIL/b from the intermediate range. They also estimated that the rate of core-collapse SNe was dominated by Type-IIP events; the ratio of Type-IIP to IIIL/b rates was \( \sim 10 \) and IIP to IIIL/b was \( \sim 5 \). In addition, Capellaro et al. (1997) found that SN 1987A–like events were not large contributors to the core-collapse SNe and also find that Type-Ia rate is \( \sim 20\% \) of total core-collapse. These results show that Type-IIP SN rate is expected to occupy a most fraction of the total SN rate. Interestingly, Type-IIP SNe are however very rare events in table 7.1. This fact means that almost no ejecta knots are created nor can survive in Type-IIP/L. Only the SN of the Vela SNR is categorized into Type-IIP class, based on a “preliminary” analysis which indicated that relatively small size of the remnant compared with those of wind-driven bubbles and shells created by more massive and luminous stars (Gvaramadze 1999). However, we should note that the small size of the Vela SNR might be caused by the interaction between the blast wave and the CO clouds located toward the NE remnant (Moriguchi et al. 2001). Therefore, the SN type of the Vela SNR is still controversial. It is quite interesting to investigate the SN type from independent ways, such as a comparison of metal abundances in the ejecta with theoretical nucleosynthetic models.

We compare the masses of the ejecta knots with the totally ejected masses expected in SN nucleosynthetic models. Table 7.2 summarizes theoretical results for 25 and 30 \( M_\odot \) progenitor stars calculated by two groups (Rauscher et al. 2002; Tominaga et al. 2007). We find that the mass ratios of the ejecta knots (summarized in table 7.1) relative to the totally ejected masses of the relevant elements (summarized in table 7.2) are at most 5%.

<table>
<thead>
<tr>
<th>Element</th>
<th>( 25^* M_\odot )</th>
<th>( 30^* M_\odot )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rauscher( ^\dagger )</td>
<td>Tominaga( ^\dagger )</td>
</tr>
<tr>
<td>O ( (M_\odot) )</td>
<td>3.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Ne ( (M_\odot) )</td>
<td>0.54</td>
<td>0.87</td>
</tr>
<tr>
<td>Mg ( (M_\odot) )</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Si ( (M_\odot) )</td>
<td>0.37</td>
<td>0.13</td>
</tr>
<tr>
<td>S ( (M_\odot) )</td>
<td>0.15</td>
<td>0.050</td>
</tr>
<tr>
<td>Fe ( (M_\odot) )</td>
<td>0.14</td>
<td>0.36</td>
</tr>
</tbody>
</table>

\( ^* \)Progenitor mass. \( ^\dagger \)Rauscher et al. (2002). \( ^\dagger \)Tominaga et al. (2007).
7.2.2 Theoretical Point of View

Wang & Chevalier (2001; 2002) performed hydrodynamical simulations on instabilities and clumping in Type-Ia SNR (especially for the case of Tycho’s remnant) and core-collapse SNR (especially for the case of the Vela SNR). They investigated whether or not the R-T instabilities between the expanding ejecta and the swept-up ISM could produce ejecta knots seen in both Tycho’s and Vela SNRs. They showed that the structures formed as a result of R-T instabilities were decelerated and were confined to a region $\leq 85\%$ of the remnant’s radius with the dynamical age of Tycho’s SNR. This was not consistent with the knots observed in Tycho’s SNR. They also showed that the protrusion even beyond the forward shock seen in the Vela SNR could not be explained by protrusions growing from the R-T instabilities. Therefore, they concluded that the ejecta knots initially had high densities relative to the surrounding ejecta. They thus included artificial clumping of the ejecta in their calculations. In order to survive crushing and to have a bulging effect on the forward shock, the clump’s initial density ratio to the surrounding ejecta must be at least 100 for the condition in Tycho’s remnant, while Vela shrapnels are likely to be the ejecta clumps with an even higher density contrast of 1000 compared to the surroundings.

The origin of such high-density ratio clumps is uncertain. One possibility is that the expanding low-density gas of $^{56}$Ni which decays to Fe compresses the surrounding non-radioactive ejecta (Li et al. 1993). Basko (1994) show that Ni bubble sweeps up a shell with density compression up to a factor of $\sim 10$ that is much lower than the required density contrast. It is not clear whether or not the Ni bubble effect can give the required compression ratio for the clumps.

Wang & Chevalier (2002) pointed out another mechanism that could operate in the Vela SNR: the sweeping up of ejecta by a pulsar bubble as is observed to occur in the Crab Nebula. In the Crab Nebula, the average density of the ejecta would be $n_H \sim 4 \text{ cm}^{-3}$, while the density in ionized filaments is $\sim 10^3 \text{ cm}^{-3}$ (Davidson & Fesen 1985), resulting in density contrast of $\sim 250$. However, we should note that the Puppis A SNR has no pulsar nebula in spite of the existence of fast-moving ejecta knots.

Kifonidis et al. (2000; 2003) proposed the third mechanism that R-T instabilities at the (Ni+Si)/O and (C+O)/He composition interfaces, seeded by convective overturn during the early stages of the explosion, could produce dense metal-rich clumps. They showed that newly formed iron group elements were distributed throughout the inner half of the helium core. Subsequently, ballistically moving metal-rich clumps with high velocities were ejected. However, the density contrast of metal-rich clumps to the surrounding ejecta are lower than 100 in their models, which requires modifications of the models in order to explain the survival of the Vela shrapnels. On the other hand, they predicted
that ejecta knots in Type-Ib SN have larger velocities than those in Type-IIP SN. Despite comparably high initial maximum nickel velocities between Type-IIP and Type-Ib model, there were large differences in the final maximum nickel velocities between both cases: the maximum velocities of metals remained frozen at $\sim 3500–5500 \text{ km sec}^{-1}$ for $t \geq 300$ in Type-Ib model, while they dropped to $\leq 1500 \text{ km sec}$ for $t \geq 1500$ in Type-IIP model. In the latter case, the dense shell that was left behind by the shock passing the boundary between the He core and the H envelope caused substantial decelerations of the clumps. Their prediction will be tested by future SN and/or SNR observations.
Chapter 8

Summary and Conclusions

We observed the brightest evolved SNRs in the X-ray sky, i.e., the Vela SNR, the Puppis A SNR, and the Cygnus Loop, with recent X-ray astronomy satellites, *Suzaku*, *XMM-Newton*, and *Chandra*. It was generally considered that detections of ejecta signatures in these SNRs were difficult, since the X-ray–emitting plasma was dominated by the swept-up ISM rather than the ejecta in evolved SNRs. However, we successfully detected metal-rich ejecta in all of the three remnants.

We perform X-ray spectroscopy for the shrapnels A, D, and E, which were identified as fragments of ejecta from the SN explosion, located outside the main shell of the Vela SNR. Their metal abundances were expected to be higher than the solar values, since they were considered to originate from the progenitor’s core. We indeed find/confirm high metal abundances in the three shrapnels: Si/H is $\sim3$ times the solar value in the shrapnel A; O/H, Ne/H, and Mg/H are $\sim5$, $\sim10$, and $\sim10$ times the solar values, respectively in the shrapnel D; and Ne/H is $\sim5$ times the solar value in the shrapnel E. Abundance ratios between heavy elements are also highly non-solar values: Si/O is $\sim10$ times the solar value in the shrapnel A; O/Fe, Ne/Fe, and Mg/Fe are $\sim5$, $\sim10$, and $\sim10$ times the solar values, respectively in the shrapnel D; and Ne/Fe is $\sim6$ times the solar value for the shrapnel E. These facts strongly support the idea that they originate from the progenitor’s core.

We perform spatially resolved spectral analyses for the shrapnels A and D. We find that the temperature increases toward the shock front in both of the two shrapnels, which is in stark contrast with the temperature variation generally seen behind the shock front of SNRs. In the shrapnel A, metal abundances are uniform in our FOV, and the values of metal abundances except for Si are lower than the solar values. These facts lead us to consider that the metal (Si)-rich ejecta in the shrapnel A are well mixed with the swept-up local ISM whose metal abundances are depleted to the solar values. On the contrary, we find non-uniform metal abundances in the shrapnel D: metal abundances outside the
X-ray ridge, \( \sim 3' \) behind the shock front, are consistent with the solar values, suggesting the origin of the plasma there is the swept-up ISM, while values of metal abundances inside the X-ray ridge are higher than the solar values, suggesting that the plasma there originates from the explosion ejecta. The condition of the interaction between the ejecta and the swept-up ISM is different between the southern and the northern leading edge of the shrapnel D: we obliquely see the stable contact discontinuity in the south, suggesting that the ejecta and the swept-up ISM are still not mixed with each other, whereas we see indication of the R–T instability at the contact discontinuity in the north, suggesting the mixing has just begun there.

We analyze five \textit{XMM-Newton} observations of the Galactic O-rich SNR Puppis A. The five observations almost cover the entire X-ray remnant. In the NE portion of the Puppis A SNR, we disclose an X-ray knotty feature on the position of one of OFMKs discovered by Winkler & Kirshner (1985) and Winkler et al. (1988). We find that the X-ray knotty feature consists of metal-rich ejecta with blue-shifted emission lines. Interestingly, the composition of the metal-rich ejecta is not uniform in the feature: O-Ne-Mg-Si-S-Fe-rich in the northern region, while O-Ne-Mg-rich in the southern region. Also, the Doppler velocity in the northern region, \(-3400^{+1000}_{-800} \) km sec\(^{-1}\), is different from that in the southern region, \(-1700^{+700}_{-800} \) km sec\(^{-1}\). In addition to the discovery of the fast-moving ejecta feature, we find other ejecta features of O, Ne, Mg, Si, and S in the remnant, based on our EW images of these elements. Si-S-rich ejecta are detected only in the NE portion of the remnant, suggesting highly asymmetric distributions of these elements. The Si-S-rich ejecta asymmetries as well as the fact that the fast-moving X-ray (and also optically)—emitting ejecta knots are detected only in the NE portion of the remnant indicate that the SN explosion which produced Puppis A was highly asymmetric. The high-velocity CCO moving in the SW direction recently measured by Hui & Becker (2006b) and Winkler & Kirshner (2007) is likely to be kicked by the anisotropic ejection of the gaseous ejecta according to momentum conservation. This fact favors the ejecta-driven mechanism (e.g., Scheck et al. 2006) for the origin of the high velocity of the CCO.

We perform spatially resolved spectral analysis across the Cygnus Loop from the NE rim to the SW rim with \textit{XMM-Newton}, \textit{Suzaku}, and \textit{Chandra}. Extended low-energy coverage of \textit{Suzaku}, for the first time, allow us to detect emission lines from highly-ionized C and N from the Cygnus Loop. In addition, we reveal the plasma structure that a low-temperature component with low abundances (hence, we consider it as the swept-up matter) surrounds a high-temperature one with high abundances (hence, we consider it as the ejecta). We then confirm a large expansion of the ejecta inside the Cygnus Loop, which was indicated by previous \textit{ASCA} observations (Miyata & Tsunemi 1999). Furthermore,
we quantitatively reveal the ejecta distributions inside the Cygnus Loop for the first time. The inner ejecta such as Si, S, or Fe turn out to be distributed asymmetrically to the geometric center of the Loop: they are distributed more in the south than in the north by a factor of $\sim 2$. The degree of the ejecta asymmetry is consistent with that expected in recent SN explosion models which consider hydrodynamic instabilities (e.g., Burrows et al. 2007). In addition, we find abundance inhomogeneities in the NE rim of the Cygnus Loop where the swept-up matter dominates the X-ray emission: the northern outermost region, $\sim 200''$-thickness region behind the shock front, has enhanced absolute abundances (that is consistent with the solar values within a factor of $\sim 2$) compared with those in the rest of the region (where we measured depleted abundances to the solar values by a factor of $\sim 5$). Judging from the abundances, we suggest that the origin of the plasma in the abundance-enhanced region is the ISM. On the other hand, a factor of $\sim 5$ depletion to the solar values measured in the rest of the region is not expected in the ISM around the Cygnus Loop, requiring reasonable explanations for the depletion. Introduction of non-thermal emission in our model fitting can not naturally resolve the depletion problem. The origin of the depletion still remains as an open question.

In this thesis, we find relics of metal-rich ejecta from SN explosions in the Vela SNR, the Puppis A SNR, and the Cygnus Loop. Considering that they are all evolved SNRs, we suggest that we will detect ejecta signatures in almost all the X-ray–emitting SNRs. We reveal global ejecta distributions in Puppis A and the Cygnus Loop; they are asymmetric to the geometric center in both of the two remnants. Furthermore, Puppis A (and possibly the other two Galactic O-rich SNRs) shows that the mass ejection during the SN explosion prefers one side in the opposite direction to the proper-motion vector of the CCO. To make further progress in our understanding of the mechanism of core-collapse SNe, it is essential to know whether or not this picture, i.e., asymmetric global ejecta distributions against the proper-motion vectors of the stellar remnants, is a common feature. In this context, future systematic analysis for the other SNRs is strongly required.
Acknowledgement

First of all, I am very grateful to my supervisor, Prof. Hiroshi Tsunemi for his continuous guidance and encouragement through the graduate course. I also deeply appreciate Prof. Koji Mori (Miyazaki University) for his continuous advice. I would like to thank all the members of the X-ray astronomy group in Osaka University, especially to Prof. Kiyoshi Hayashida, Drs. Emi Miyata, Ken’ichi Torii, Masaaki Namiki, Naohisa Anabuki, Hideki Ozawa, and Hiroshi Nakajima. I thank all members of Suzaku team.

This study is carried out as a part of the 21st Century COE Program, ‘Towards a new basic science: depth and synthesis’. This study is also supported by a JSPS Research Fellowship for Young Scientists.

I also thank my friends, Noriaki Tawa, Norbert Nemes, Hiroya Yamaguchi (Kyoto University), and many other graduate students in Osaka University for fruitful discussions and enjoyable times. Finally, I deeply appreciate the supports and encouragements of all the people in Osaka University and my family.
Bibliography


[34] Burrows, A., Livne, E., Dessart, L., Ott, C. D., & Murphy, J. 2006b, NewAR, 50, 487


[204] Shklovskii, I. S. 1962, Sov.Astron, 6, 162


loq. 101: Supernova Remnants and the Interstellar Medium, ed. R. S. Roger & T. L. 
Landecker, 65−+ 


[247] Yamaguchi, H., Koyama, K., Katsuda, S., Nakajima, H., Hughes, J. P., Bamba, A., 
