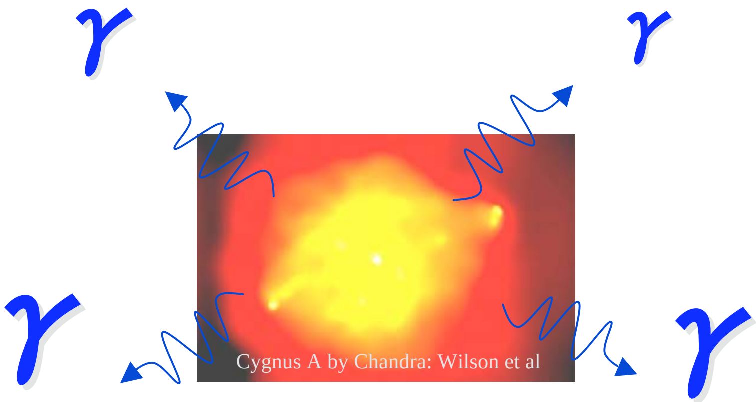
MeV gamma emission from cocoons of young radio galaxies



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~Abstract~

Strong gamma-ray emission from cocoons of young radio galaxies is newly predicted. Considering the process of mass and energy injections of relativistic jet into the cocoon, we find that thermal temperature of the cocoon is typically predicted at MeV. Together with the dynamical evolution of the cocoon, it is found that young cocoons can yield bright thermal bremsstrahlung emission at MeV.

Introduction

The relativistic jets in active galactic nuclei (AGNs) are widely believed to be the dissipation of kinetic energy of relativistic motion with a Lorentz factor of order ~10 produced at the vicinity of a supermassive black hole lying in a galactic center. The jet in powerful radio loud AGNs (FR II sources) is slowed down via strong terminal shocks. The shocked plasma then expand sideways and envelope the whole jet system. This is so called a cocoon. The thermal energy of shocked plasma continuously inflates this cocoon. The existence of the cocoon enveloping the whole jet is theoretically predicted.

Recent observations shows us many pieces of evidence of the existence of cocoons. An important result by Chandra X-ray observatory of radio galaxies was the discovery of so called X-ray cavities in clusters of galaxies. These are productions by the interaction between AGN outflows and surrounding intra-cluster medium (ICM). These cavities are the clear evidence of the cocoons although many of them are so far associated with relatively low power AGNs (FR I sources). Another evidence is that non-thermal X-ray emission associated with radio-lobe. Those have been seen also in powerful radio loud AGNs although the shape of X-ray image is ambiguous because they are not sufficiently luminous. However, there is no direct evidence of thermal emissions originated from the dilute thermal plasma in the cocoon.

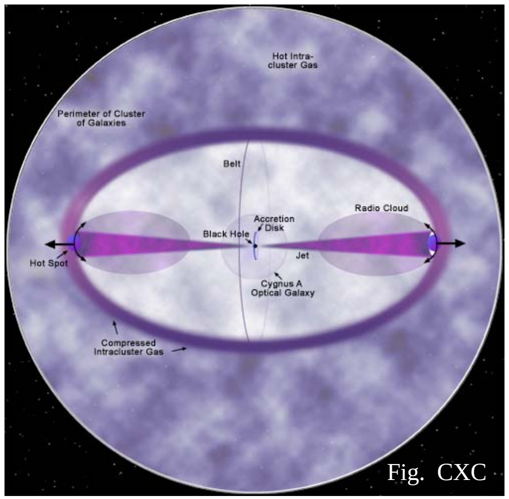
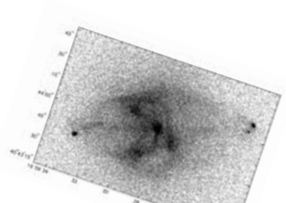


Fig. CXC

Here we propose that “a cocoon of a young radio galaxy‘‘ is a new population as gamma-ray emitters in the universe.

Basic equations



Cygnus A:
Wilson et al. (2000)

The set of Eqs are basically similar to those
In Begelman & Cioffi (1989).

$$\frac{L_{\rm j}}{v_{\rm j}} \simeq \rho_{\rm a}(r_{\rm h}) v_{\rm h}^2(t) A_{\rm h}(t),$$: eq. of motion (jet axis)

ICM mass-density profile

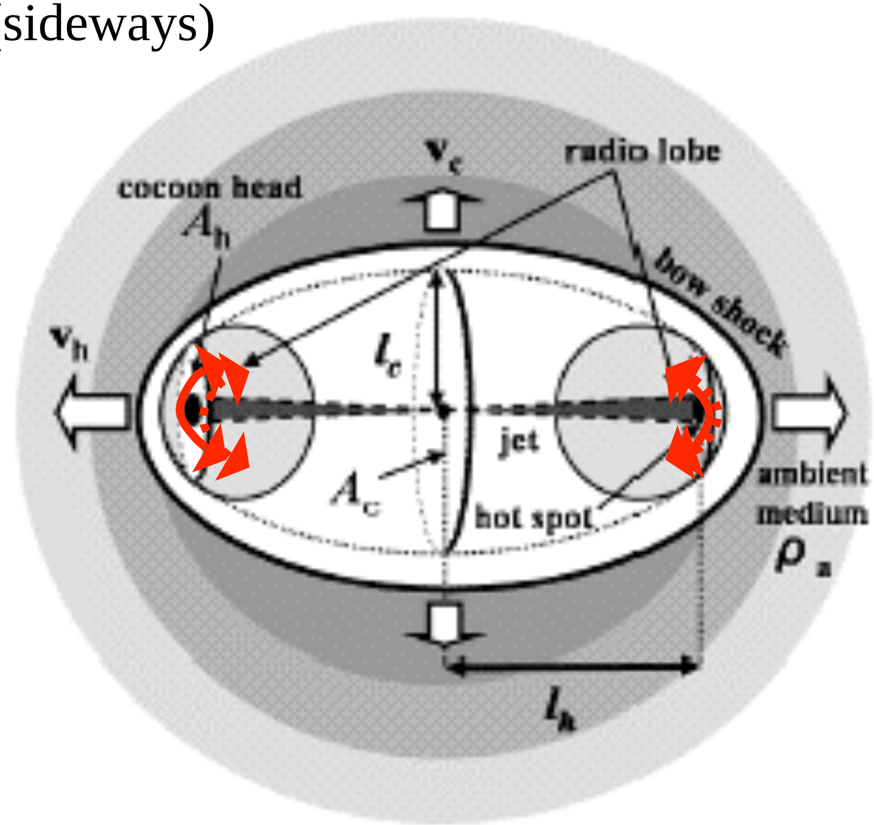
$$\rho_{\rm a}(r) = \bar{\rho}_{\rm a} \left(\frac{r}{r_0}\right)^{-\alpha}$$

$$p_{\rm c}(t) \simeq \rho_{\rm a}(r_{\rm c})\ v_{\rm c}(t)^2$$: eq. of motion (sideways)

$$\frac{\hat{\gamma}_c}{\hat{\gamma}_c - 1} \frac{P_{\rm c} V_{\rm c}}{t_{\rm age}} = \boxed{\rho_{\rm j} c^2 \Gamma_{\rm j}^2 v_{\rm j} A_{\rm j}}$$

$$\frac{\rho_{\rm c} V_c}{t_{\rm age}} = \boxed{\rho_{\rm j} \Gamma_{\rm j} v_{\rm j} A_{\rm j}},$$

energy and mass injection by the jet



What's new?

1. ***Include ICM density profile***
2. ***Solve as functions L_j and t_{age}***
3. ***Mass injection is considered, which enable to determine T_e***

Analytic model of expanding cocoon

Using a control parameter X describing sideways expand velocity

$$v_{\rm c}(t) = \bar{v}_{\rm c}\left(\frac{t}{t_{\rm age}}\right)^{0.5X-1} = \frac{\bar{A}_{\rm c}^{1/2}}{t_{\rm age}}\mathcal{C}_{vc}\left(\frac{t}{t_{\rm age}}\right)^{0.5X-1}$$

Solutions are as follows;

$$P_{\rm c}(t, L_j) = \bar{\rho}_{\rm a}\bar{v}_{\rm c}^2\mathcal{C}_{pc}\left(\frac{\bar{v}_{\rm c}}{v_0}\right)^{-\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(1-\alpha/2)-2},$$

$$v_{\rm h}(t, L_j) = \frac{L_j}{\bar{\rho}_{\rm a}\bar{v}_c^2\bar{A}_{\rm c}}\mathcal{C}_{vh}\left(\frac{\bar{v}_{\rm c}}{v_0}\right)^{\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(-2+0.5\alpha)+2},$$

$$A_{\rm h}(t, L_j) = \frac{L_{\rm j}}{v_{\rm j}\bar{\rho}_{\rm a}\bar{v}_{\rm h}^2}\mathcal{C}_{Ah}\left(\frac{\bar{v}_{\rm h}}{v_0}\right)^{\alpha}\left(\frac{t}{t_{\rm age}}\right)^{X(\alpha-2)(-2+0.5\alpha)+3\alpha-4},$$

$$n_{e^-}(t) \approx 4\times10^{-5}\bar{A}n_{-2}\Gamma_{10}\beta_{-2}^2\left(\frac{t}{10^7 {\rm yr}}\right)^{-2} {\rm cm}^{-3}$$

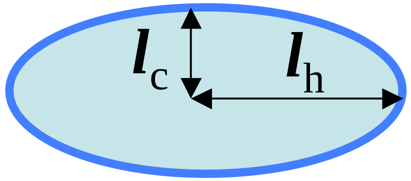
$$kT_e \approx 1\ \Gamma_{10}\ {\rm MeV}$$

$T_{\rm e}$ is uniquely determined by Γ and constant in time!

Aspect ratio of cocoon ($R=l_{\rm c}/l_{\rm h}$)

$$\mathcal{R}(t) = \frac{X(-2+0.5\alpha)+3}{0.5X}\frac{\bar{v}_{\rm c}}{\bar{v}_{\rm h}}\left(\frac{t}{t_{\rm age}}\right)^{X(2.5-0.5\alpha)-3}$$

X is tightly constrained by observed shapes since R is 0.5-1



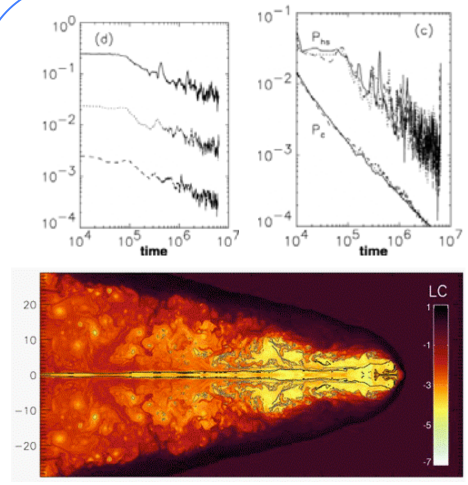
For details, please take our related papers and pre-print
- N. Kawakatu, and M. Kino, MNRAS, in press (astro-ph/0605482)
- M. Kino, N. Kawakatu, and H. Ito, PRL, submitted

Comparison with previous works

Table 1. Comparison with 2D hydrodynamic simulations and self-similar models

—	v_{HS}	A_h	P_c	P_{HS}	ρ_j	$\mathcal{R}$
"1D" Phase[a]						
S02	$l_h^{-0.11}$	const	$l_h^{-0.96}$	const	const	$l_h^{-0.45}$
BC89	const	const	l_h^{-1}	const	—	$l_h^{-0.5}$
This work	const	const	l_h^{-1}	const	const	$l_h^{-0.5}$
"2D" Phase[b]						
S02	$l_h^{-0.55}$	$l_h^{0.90}$	$l_h^{-1.30}$	$l_h^{-1.1}$	$l_h^{-1.0}$	$l_h^{-0.09}$
B96	$l_h^{-2/3}$	$l_h^{4/3}$	$l_h^{-4/3}$	$l_h^{-4/3}$	—	const
This work	$l_h^{-0.56}$	$l_h^{1.1}$	$l_h^{-1.30}$	$l_h^{-1.1}$	$l_h^{-1.1}$	$l_h^{-0.08}$

Good agreement!



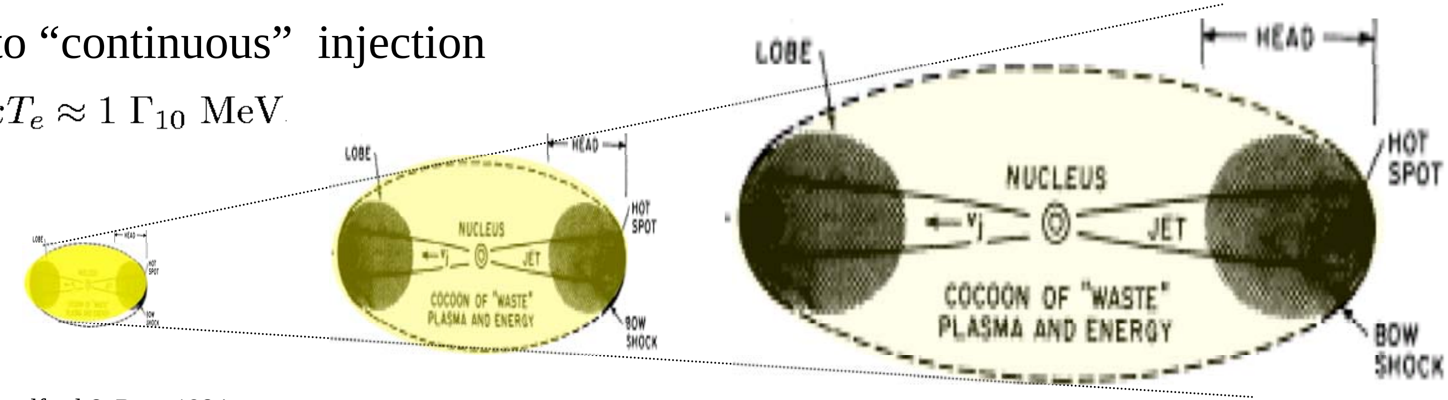
Scheck et al. MNRAS, 331, 615 (2002)

In the ``1D'' phase, the results of S02 can be well described by our model with beta=0 and alpha=0 Note that this ``1D'' phase corresponds to the evolutionary model with constant A_h (BC89). For v_{HS}, the power law index is slightly (10%) different from our model (also BC89) and the results of S02. In this case, $P_c \propto l_h^{-1}$ and P_{HS}=const are predicted by this work and BC89, which coincides with the numerical results of S02 (see Fig. 6 (c) for P_c and P_{HS} in S02). In addition, our model can reproduce the constant ρ_j (see Fig. 5(a) in S02). For comparisons, let us briefly comment on the self-similar model of expanding cocoons in which the growth of the cocoon head is included (e.g., Begelman 1996: hereafter B96). As already pointed out (e.g., Carvalho & O'Dea 2002), the self similar model of B96 cannot represent the behavior of the ``1D'' phase. The behavior of $P_c/P_{HS}$ is also the intriguing issue. The decrease of $P_c/P_{HS}$ with time is reported in Fig. 6 of S02. Using our model, this behavior is clearly explained by the decrease of the cocoon aspect ratio. The ``2D'' phase of S02 is well described by our model with β=1.1 and α =0. We adopt β=1.1 to reproduce the P_c evolution in Fig. 6 (c) of S02 because the other quantities shows much larger fluctuations in Fig.6 of S02. The present model predicts the evolution of the hot spot pressure and mass density of the jet as $P_{HS} \propto l_h^{-1.1}$, $v_{HS} \propto l_h^{-0.56}$ and $\rho_j \propto l_h^{-1.1}$. These coincides with the average value of P_{HS} v_{HS}, and ρ_j. In the ``2D" phase, the cross section of cocoon head grows as $A_h \propto l_h^{1.1}$ unlike the ``1D" phase A_h=const. Thus, the velocity of hot spot decreases with l_h. Actually, the growth of the cross section area of the cocoon head can be seen in their simulations. In this phase, B96 also explains these results of S02. Moreover, the cocoon pressure is proportional to P_{HS} in this phase of S02. From eq. (20), it can be understood with a constant *R*. From above detailed comparison with ``2D" relativistic hydrodynamic simulations, we found that the model represented in this paper can describe the flow and cocoon behaviors seen in the ``1D" and ``2D" phases very well. It should be stressed that our analytic model is more useful than numerical simulations when investigating a longer-term evolution of jets.

Negative luminosity evolution

Due to “continuous” injection

$kT_e \approx 1\ \Gamma_{10}$ MeV



Cocoon Fig.
Begelman, Blandford & Rees 1984

time

Brighter emission;
(baby)

Darker emission;
(grown-up)

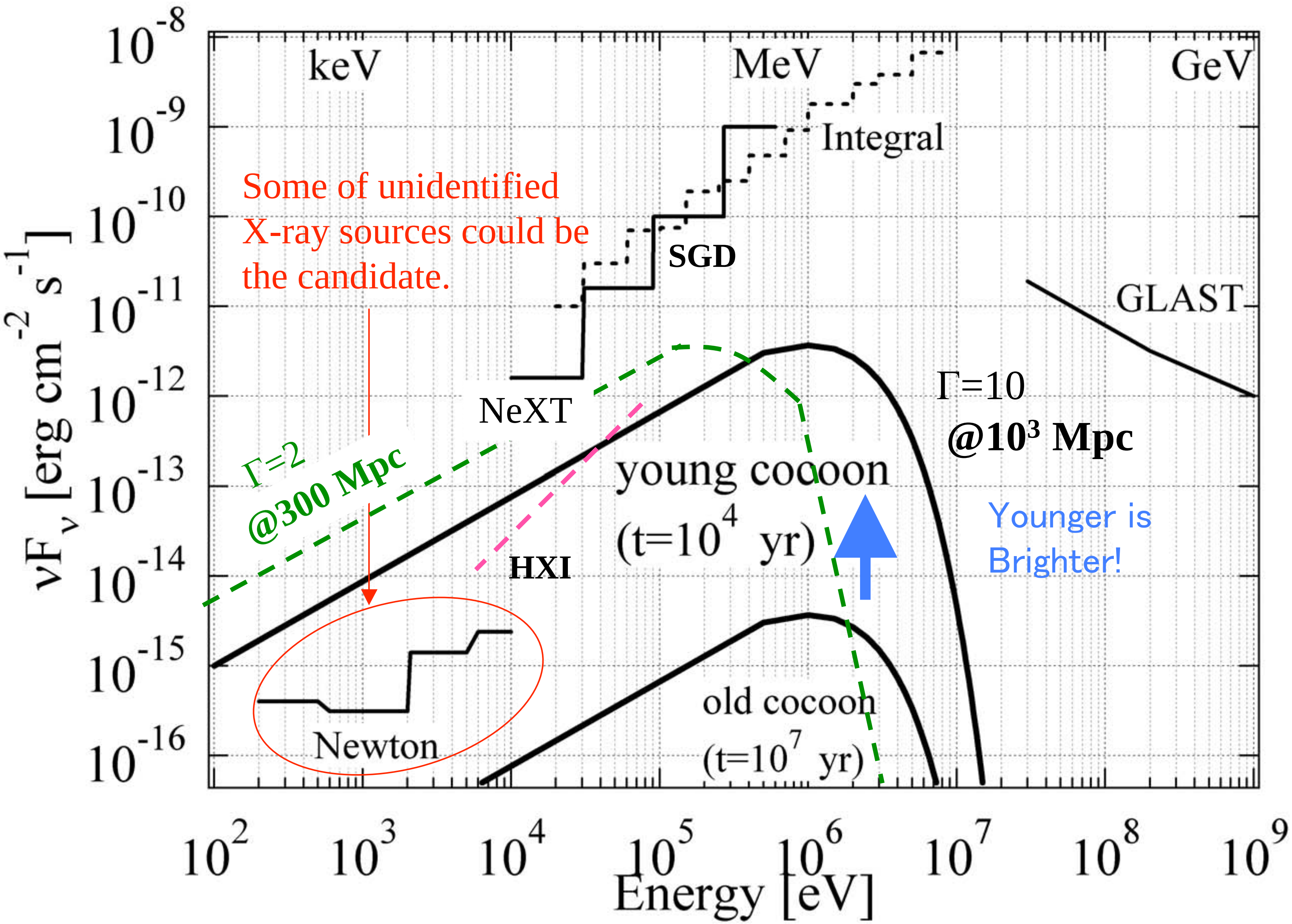
Here we discuss the thermal bremsstrahlung emission from cocoons. The luminosity $L_{\rm brem}$ is proportional to $L_{\rm brem}(t) \propto n_e^2(t) T_e^{3/2} V_c(t) \propto t^{-1}$ in the present case. Hence it is clear that a younger cocoon can be a thermal MeV bremsstrahlung emitter. In a similar way, brighter synchrotron luminosity is expected for younger radio galaxies. With relativistic thermal bremsstrahlung emissivity, the luminosity of the optically thin thermal bremsstrahlung emission νL_ν at energies 1 MeV is

$$L_{\rm brem}(t) \approx 2 \times 10^{40}\ \bar{n}_e^2 \mathcal{R}^2 \Theta_{10}^{3/2} \left(\frac{t}{10^7\ {\rm yr}}\right)^{-1}\ {\rm erg\ s^{-1}}$$

$$\Theta_e \equiv kT_e/m_e c^2 = 10\Theta_{10},$$

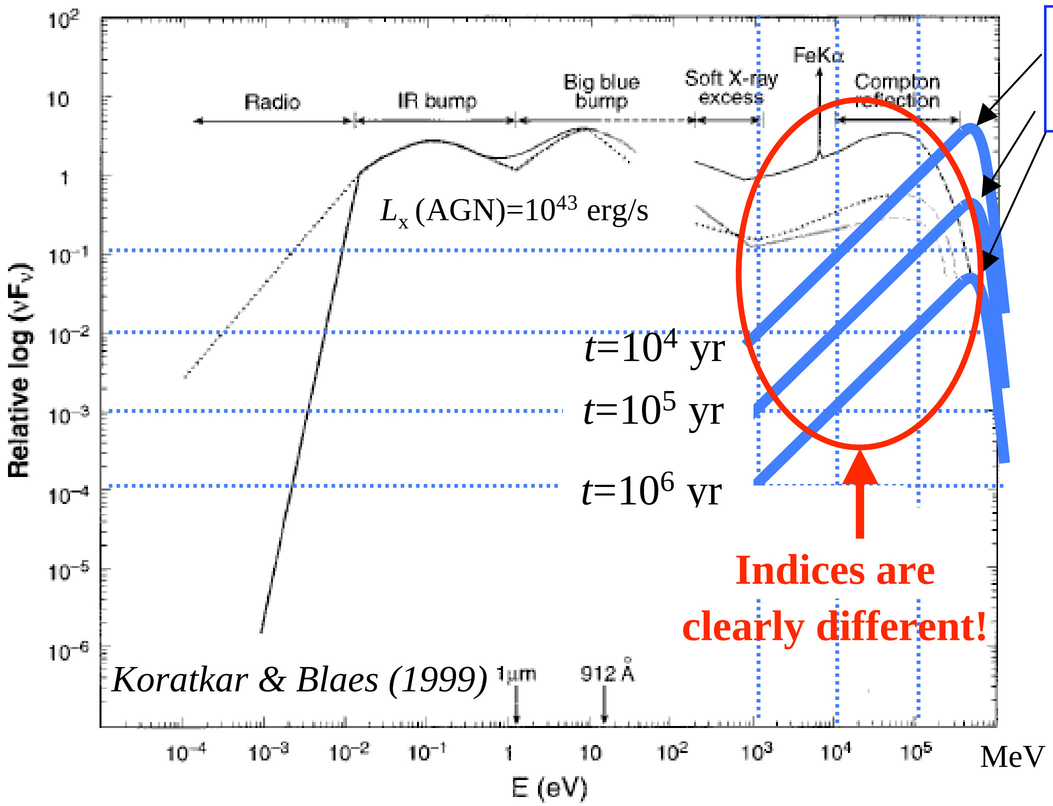
Model prediction of Bremsstrahlung from Cocoons

The Sensitivity of SGD and HXI on board the NeXT satellite (T.Takahashi et al. 2004)



AGN-core or Cocoon?

Mean spectrum of AGN



MeV Cocoon bremsstrahlung newly predicted in the present work

Flux density is normalized by 10^{-12} erg cm^{-2} s^{-1}

Separable by

- Spectrum indices
- Time variability

Time variability of observed spectra is the key to distinguish them. It is obvious that the cocoon emission is steady whilst various Emissions from the core of AGN are highly variable. Hence steady emissions are convincingly originated in cocoons. Furthermore, the averaged spectral index of AGN core emissions at X-ray band are softer than the bremsstrahlung emission discussed in the present work. Hence the difference of the spectral index is also a useful tool to figure out the origin of the emission.

Summary

We model a dynamical evolution of hot spots in radio loud AGNs. In this model, the unshocked flow satisfies the conservations of the mass, momentum, and kinetic energy. We take account of the deceleration process of the jet by shocks, and the cocoon expansion which is identified as the by-product of the exhausted flow. The model describes the evolution of various physical quantities in the hot spot in terms of the distance of the hot spot location . The slope index is expressed as a function of slope Index of ambient density and the growth rate of the cocoon body. **Our analytic model can well explain the results of 2D co-evolution of jets and cocoons obtained by relativistic hydrodynamic simulations.**

N. Kawakatu, and M. Kino, MNRAS, in press (astro-ph/0605482)

The luminosity evolution of thermal bremsstrahlung emission from AGN cocoons is explored. Together with the dynamical evolution of expanding cocoon, we predict the dissipation of relativistic jets in AGNs. **The temperatures of cocoon is controlled only by the bulk Lorentz factor of the jet.** The electron temperature Te relevant to observed emissions is typically predicted in the range of MeV for Γ_j ~10.Since Γ_j is constant in time, Te remains to be constant during the weak cooling regime. Because of their larger number densities of thermal electrons, **younger cocoons are expected to be brighter in MeV-gamma. It will be possible to detect the thermal MeV emission with NeXT satellite.**

M. Kino, N. Kawakatu, and H. Ito, PRL, submitted