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Interpretation of the Radio/X-ray knots of kilo parsec scale AGN jets within the internal shock model framework

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We study the dynamics of relativistically moving blobs ejected out of a central AGN. Due to the variation in their velocities the blobs collide and the collision is assumed to be completely inelastic. The bulk kinetic energy released in the collision heats up the electrons to relativistic energies through internal shocks which then cool off by radiative losses. The model is applied to the observed radio/X-ray knots of AGN jets and the typical blob ejection time-scale forming knots is found to be $\approx 10^{10}$ sec. The collision time-scale is approximated to be the cross-over time of the blobs and can be longer than the age of the knots. Hence the non-thermal particles are continuously injected giving rise to a characteristic spectral break in the observed spectrum. This is in contrast to an instantaneous one time injection model which gives rise to a high-energy cutoff in the spectrum.

1. Introduction

Jets of active galactic nuclei (AGNs) are observed to extend up to kilo parsec scales with bright knots in various bands. *Chandra*, due to its excellent spatial resolution is able to resolve these knots in X-rays and many are coincident with their radio/optical counterpart [1, 2, 3, 4]. The radio and the optical emission from the knots are generally accepted to be of synchrotron origin whereas X-ray can be due to synchrotron or inverse Compton scattering of cosmic microwave background (IC/CMBR) depending upon the optical-to-X-ray index [3, 5, 2, 1, 6, 4, 7, 8]. However one cannot rule out the possibility of X-ray emission from a second population of non-thermal electrons [9]. Also if the Klein-Nishina losses where important then the electron spectrum hardens at high energy thereby flattening the spectrum at X-ray energies [10].

Various models have been proposed to understand the emission mechanism from these knots. In many models, non-thermal particles are assumed to be generated through a short duration acceleration process [2, 1, 4, 11, 12, 13]. These one time injection models predicts an exponentially decreasing photon spectrum at X-ray energies. However the acceleration process can be longer than the age of the knot with a continuous injection of non thermal particles into the knots. This gives rise to a time-dependent break in the particle spectrum at energy at which the cooling time-scale is equal to the age of the knot [14, 15]. The standard approach to explain the origin of these non-thermal particles is the internal shock scenario [16, 17]. In this model, the central engine of the AGN sporadically ejects matter at relativistic speeds. Particles are accelerated to relativistic energies by shocks produced due to the collision of such relativistic blobs.

In this work, we attempt to model the knot as an outcome of internal shock with simple assumptions. We studied the temporal evolution of the non-thermal particles and compare our result with the observed fluxes at various energies and their relative positions in the sky plane.

2. Model

In the internal shock model we assume the central engine of the AGN ejects blobs of matter sporadically at relativistic speeds. In a simplified version we consider two blobs with equal masses, $M_1 = M_2 = M$, ejected one after the other with Lorentz factors Γ_1 and Γ_2. The blobs collide forming a knot at a distance predetermined by their ejection time and the speed. The Lorentz factor of the knot (Γ) and the energy dissipated during collision (ΔE_K) can be estimated from the conservation of momentum and energy (all terms with subscript K denotes the quantities in knot's frame). This energy ΔE_K is injected into the system for a duration $T_{ON,K}$ approximated to be the crossing-over time of the blobs. This dissipated bulk kinetic energy is assumed to get converted to the energy of the nonthermal particles efficiently by the shock formed due to collision. The injection of this non-thermal particles into the knot per second is approximated to be

$$Q_K(\gamma)d\gamma = A\gamma^{-p}d\gamma \quad \text{for} \quad \gamma > \gamma_{min}; \tag{1}$$

where γ is the Lorentz factor of the electrons, p is the particle index and the normalization constant A is

$$A = \frac{\Delta E_K}{T_{ON,K}} \frac{(p-2)}{mc^2} \gamma_{min}^{(p-2)} \tag{2}$$

The evolution of the particles $N(\gamma, t_K)$ in the knot is described by the kinetic equation

$$\frac{\partial N_K(\gamma, t_K)}{\partial t_K} - \frac{\partial}{\partial \gamma}[(\dot{\gamma}_S(t_K) + \dot{\gamma}_{IC}(t_K))N_K(\gamma, t_K)] = Q_K(\gamma) \tag{3}$$

where $\dot{\gamma}_S(t_K)$ is the synchrotron cooling rate due to a tangled magnetic field B_K and $\dot{\gamma}_{IC}(t_K)$ inverse Compton scattering loss rate of CMBR respectively [8]. The resultant photon spectrum due to synchrotron and inverse Compton cooling are computed at an observation time $t_K = t_{K,O}$. From the various parameters involved and from the observed location of the knot in the sky plane, the time delay Δt_{12} between the ejection of the two blobs can be estimated.

3. Results and Discussion

The internal shock model is applied to two brightest knots of the AGNs 1136-135 and 3C 371 [2, 6, 19]. The nomenclature of the knots are same for 1136-135 as in the literature whereas for 3C 371 A and B are reversed. Four blobs are ejected from the central engine with appropriate time delay to reproduce the observed two knots. The parameters are adjusted to reproduce the observed flux in radio, optical and X-ray bands available in the literature and their location in the sky plane. The values of the parameters used to fit each source is given in table 1. and the computed spectra along with the observed flux is shown in fig 1.

The number of parameters involved in the model are large compared with the available observed information. This makes almost impossible to deduce a unique set of parameters for a particular fit. However a couple constrains can be imposed on the parameters based on physical arguments viz. total number of non-thermal electrons injected should not exceed the total number protons and the input magnetic field to be less than the equi partition magnetic field.
The properties of the jet and the knots derived from this model are given in table 2. The ejection timescales t^{AB} (time delay between the ejection of the first blobs of the two knots) and Δt_{12} are nearly equal and varies between 10^{11} to 10^{12} s. This gives an overall single time scale activity for each source if else a more complex temporal behaviour of ejection would have to be proposed.

The distance travelled by the knot during the injection duration ($T_{ON,K}$) is significant compared to the overall length of the jet. So it is possible that the spectra of the observed knots can be fitted at an observation time ($t_{O,K}$) smaller than ($T_{ON,K}$) and hence there will be a continuous injection of particle into the system. This gives rise to a characteristic break in the particle spectrum at an energy for which the cooling time-scale is

Table 1. Model Parameters

Source	Knot	θ	Γ_1	Γ_2	Γ^*	t_{KO}	t_c^*	t_{tot}^*	log M	γ_{min}	p	B
$1136-135$	A	11.5	4.6	5.4	5.0	0.25	12.0	12.0	38.0	2	2.4	1.0
	B		4.1	5.9	5.0	8.5	13.0	17.0	36.6	20	2.9	4.0
$3C371$	A	15.8	1.6	2.4	2.0	5.9	0.18	1.4	35.3	20	2.5	1.4
	B		2.0	2.4	2.2	2.3	0.39	0.75	36.5	10	2.4	0.6

The size of the blob $\Delta x_K = 5.0 \times 10^{21}$ cm for all sources. Columns marked with $*$ are derived quantities and not parameters. Columns:- 1: Source name. 2: Knot. 3: Viewing angle (in degrees). 4: Lorentz factor of the first blob. 5: Lorentz factor of the second blob. 6: Lorentz factor of the Knot. 7: Observation time (in 10^{11} sec). 8: Collision time (in 10^{12} sec). 9: Total time (in 10^{12} sec). 10: Mass of the blobs (in g). 11: Minimum Lorentz factor of the particle injected into the knot. 12: Injected particle spectral index. 13: Magnetic field (in 10^{-5}G).

Table 2. Knot/Jet Properties

Source	Knot	Δt_{12}	t^{AB}	$\frac{B}{B_{equ}}$	$\frac{N_{nth}}{N_K}$	$T_{ON,K}$	$\frac{t_{K,O}}{T_{ON,K}}$
$1136-135$	A	1.1	3.2	0.55	0.88	20.0	0.01
	B	2.5		0.54	0.76	9.1	0.93
$3C371$	A	1.4	1.5	0.71	0.88	7.2	0.82
	B	1.0		0.63	0.29	16.0	0.14

Columns:- 1: Source name. 2: Knot. 3: Time delay between the ejection of the blobs (in 10^{11} sec). 4: Time delay between the ejection of the first and the third blob (in 10^{11} sec). 5: Ratio of the magnetic field to equipartition magnetic field. 6: Ratio of non-thermal electrons to the total number of electrons. 7: The instantaneous power (in ergs/sec). 8: Time averaged power (in ergs/sec). 9: Time-scale over which non-thermal particles are injected (in 10^{11} sec). 10: Ratio of the observation time to particle injection time-scale.

equal to the observation time.

The X-ray flux of the knots of 3C 371 and for knot A of 1136-135 lies below the extrapolation of radio/optical flux. Hence one can interpret the X-ray emission by synchrotron radiation [1, 6, 8]. From the fit, for knot B of 3C 371 and knot A of 1136-135 the spectral break occurs at X-ray energies indicating them to be relatively younger sources. The ratio $t_{O,K}/T_{ON,K}$ is indeed smaller for these sources.

In summary, the observed fluxes at radio, optical and X-ray bands are reproduced using a simplified internal shock model. More realistic models [17] involving the formation of shock and the acceleration mechanisms are complicated and with the limited number of observables it is almost impossible to obtain a meaningful conclusion. Such detailed analysis is possible with future high resolution data which can prove whether internal shock model is a viable one to explain the knots of AGN jets.

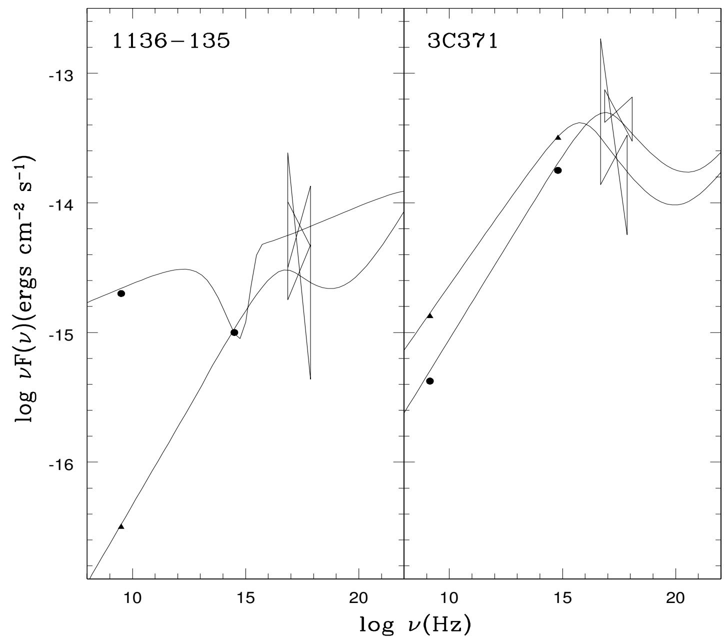

Figure 1. The observed fluxes in radio, optical and X-ray compared with model spectra using parameters given in Table 1. Knot A fluxes are represented by filled triangles and knot B fluxes are represented by filled circles. Errors are typically 30% or larger.

References

[1] Sambruna, R. M. et al., 2002, ApJ, 571, 206
[2] Sambruna. R. M. et al., 2001, ApJ, 549, L161
[3] Chartas, G. et al., 2000, ApJ, 542, 655
[4] Tavecchio, F., Maraschi, L., Sambruna, R. M., and Urry, C. M., 2000, ApJ, 544, L23
[5] Worall, D. M., Birkinshaw, M., & Hardcastle, M. J., 2001, MNRAS, 326, L7
[6] Pesce, J. E. et al., 2001, ApJ, 556, L79
[7] Schwartz, D. A. et al., 2000, ApJ, 540, L69
[8] Sahayanathan, S., Misra, R., Khembhavi, A. K., and Kaul, C. L., 2003, ApJ, 588, L77
[9] Atoyan, A., and Dermer, C., 2004, ApJ, 613, 151.
[10] Dermer, C, & Atoyan, A,2002, ApJ, 568, L81
[11] Jaffe, W. J. & Perola, G. C., 1973, A&A, 26, 412
[12] Kardashev, N. S., 1962, Soviet Astron.-AJ, 6, 317
[13] Pacholczyk, A. G., 1970, Radio Astrophysics (San Fransisco : Freeman)
[14] Heavens, A., & Meisenheimer, K., 1987, MNRAS, 225, 335
[15] Meisenheimer, K. et al., 1989, A&A, 219, 63
[16] Rees, M. J., 1978, MNRAS, 184, 61
[17] Spada, M., Ghisellini, G., Lazzati, D., and Celotti, A., 2001, MNRAS, 325, 1559
[18] Mimica, P, Aloy, M, A, Muller, E, and Brinkmann, W, 2005, astro-ph/0506636
[19] Sahayanathan, S., Misra, R., 2005, astro-ph/0504197