X-RAY EMISSION PROPERTIES OF LARGE SCALE JETS, HOTSPOTS AND LOBES IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We examine a systematic comparison of jet-knots, hotspots and radio lobes recently observed with $Chandra$ and $ASCA$. The data was compiled at radio (5 GHz) and X-ray frequencies (1keV) for more than 40 radio galaxies. We examined three models for the X-ray production: synchrotron (SYN), synchrotron self-Compton (SSC) and external Compton on CMB photons (EC). For the SYN sources, X-ray photons are produced by ultrarelativistic electrons with energies $10-100$ TeV that must be accelerated in situ. For the other objects, a simple formulation of calculating the "expected" SSC or EC fluxes under an equipartition hypothesis is presented. We confirmed that the observed X-ray fluxes are close to the expected ones for non-relativis tic emitting plasma velocities in the case of radio lobes and majority of hotspots, whereas considerable fraction of jet-knots is too bright at X-rays to be explained in this way. We concluded, if the inverse-Compton model is the case, the X-ray bright jet-knots are most likely far from the minimum-power condition. We however prefer the other possibility, namely that the observed X-ray emission from all of the jet-knots is synchrotron in origin.

Key words: galaxies: jets — magnetic fields — radiation mechanism: non-thermal.

1. INTRODUCTION

The excellent spatial resolution of $Chandra$ X-ray Observatory has opened a new era to study the large scale jets in powerful extragalactic radio sources. More than 40 radio-loud AGNs are known to possess X-ray counterparts of radio jets on kpc to Mpc scales (Harris & Krawczynski 2002, Kataoka & Stawarz 2005). Bright X-ray knots are most often detected, but the X-ray emissions from the hotspots and radio lobes are also reported in a number of FR II radio galaxies and quasars. It is believed that the relativistic jet is decelerated in a hotspot converting part of its energy into relativistic electrons and part in magnetic field. Then the shocked plasma moves inside the head region just behind the hotspot, and expands almost adiabatically to form diffuse, extended radio lobes. Even though this picture appears to be simple, much of the fundamental physics behind it remains unclear (see, e.g., recent monograph by de Young 2002).

Unfortunately, present radio-to-X-ray observations are not sufficient to discriminate conclusively between different models proposed in order to explain multiwavelength emission of the large-scale structures of powerful radio sources, and of their kpc/Mpc jets in particular. However, we believe that a systematic comparison between jet-knots, hotspots, and lobes will provide important clues to dynamics and the physics of large scale jets, and to put some constraints on the theoretical models.

2. DATA AND MODEL APPLICATION

We collected all existing data of "X-ray jet sources" at well sampled radio (5 GHz) and X-ray (1 keV) frequencies and analyzed them in a systematic manner (see Kataoka & Stawarz 2005). This gives a large number of objects known to us as of 2004 June, which contains 44 X-ray jet sources (56 jet-knots, 24 hotspots, and 18 radio lobes). Fig 1 presents the correlation between radio and X-ray luminosities, in two dimensional space. One finds several important tendencies which cannot be accounted by the sampling bias effect. First, hotspots and radio lobes occupy only the high-luminosity part of the plot, namely $\geq 10^{40}$ erg s^{-1}. Secondly, low-luminosity hotspots tend to be brighter in X-ray, as has been pointed out by Hardcastle et al. (2004). Thirdly, $L_{\rm R} \geq L_{\rm X}$ for most of the hotspots and radio lobes, but most of the jet-knots show an opposite trend.

In order to determine the X-ray emission properties of large scale jets, we first derive a simple formulation of computing an equipartition magnetic field strength $B_{\rm eq}$ from an observed radio flux $f_{\rm R}$ measured at a radio frequency $\nu_{\rm R}$. Next, we calculate the "expected" inverse

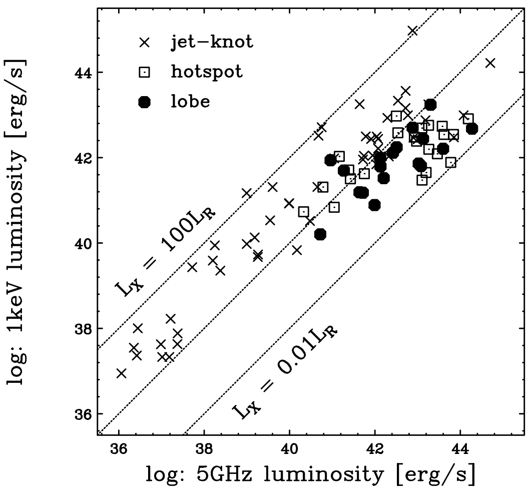

Figure 1. Relation between $L_{\rm 5GHz}$ and $L_{\rm 1keV}$

Compton luminosities for $B_{\rm eq}$, to compare them with the observed X-ray luminosities. In the analysis, we include possible relativistic bulk velocity of the jet plasma. Taking the obtained results into account, and analyzing additionally the observed broad-band spectral properties of the compiled sources, we follow the "conservative" classification of the compiled X-ray sources into three groups, namely (i) synchrotron involving single/broken power-law electron energy distribution (SYN), (ii) synchrotron self-Compton (SSC) and (iii) external Compton of CMB photons (EC). Full details are given in Kataoka & Stawarz (2005).

3. DISCUSSION

One formal possibility of understanding extremely bright jet-knots is that equipartition hypothesis may not be valid in the considered jet-knots. For a given synchrotron luminosity $L_{\rm sync} \propto u_{\rm e} u_B$ and for a given emitting region volume V, an expected SSC luminosity is $L_{\rm SSC} \propto u_{\rm e}$. We therefore expect ratio $R_{\rm SSC} \propto L_{\rm SSC}^{-1} \propto u_B$. Similarly, for the EC case, $R_{\rm EC} \propto L_{\rm EC}^{-1} \propto u_B$. Hence, in both models, the expected X-ray luminosity will be increased by decreasing the magnetic field strength. Fig 2 shows the ratio of B to the equipartition value. Interestingly, B in the lobe and most of the hotspots are almost consistent with the equipartition ($B/B_{{\rm eq},\delta=1} \sim 1$), whereas that of the non-SYN jet-knots and of some of the hotspots is much weaker from what is expected ($B/B_{{\rm eq},\delta=1} \sim 0.01-0.1$). It must be noted, however, that the idea of sub-equipartition magnetic field is often rejected since it implies a very high kinetic power of the jets.

As an alternative, we also consider a case when the difference between the "expected" and "observed" X-ray fluxes is due to the relativistic beaming effect, and the minimum-power condition is fulfilled. Again, the lobes and the hotspots exhibit relatively narrow distribution at $\delta \sim 1$, whereas for most of the jet-knots large beaming factors of $\sim$ 10 are required. Such a large beaming factor is indeed expected for some of blaza-type objects, but is very unlikely for most of the radio galaxies observed with $Chandra$. Furthermore, it is well known that the VLA studies of the large-scale jets in quasars and FR IIs indicate that bulk Lorentz factors of the radio-emitting plasma in these sources cannot be much greater than $\Gamma_{\rm BLK} \sim 3$ (Wardle & Aaron 1997). If one insists on applying the homogeneous one-zone model (as a zero-order approximation), as presented in this paper, self-consistency requires a consideration of $\Gamma_{\rm BLK} \leq 5$. In such a case, a departure from the minimum power conditions within the non-SYN X-ray jets is $inevitable$.

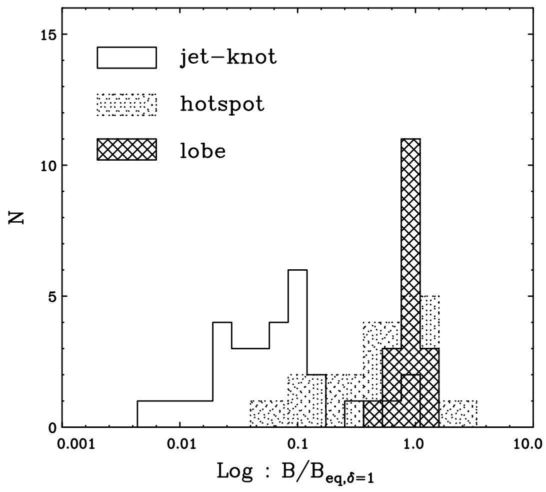

Figure 2. Distribution of the ratio between the magnetic field B (for δ = 1) and the equipartition value $B_{{\rm eq},\,\delta=1}$.

We have discussed two different versions of the EC model to account for extremely bright X-ray jet-knots: (1) non-equipartition case and (2) significant relativistic beaming case. Both of these options are in many ways problematic. We may therefore suggest a new idea that the X-ray photons from the powerful quasar jets are not inverse-Compton, but the synchrotron emission in origin. Recent detailed re-analysis of the $Chandra$ data for 3C 120, again "conservatively" classified as an EC source, strongly support this idea (Harris et al. 2004).

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