Unifying X-ray Emission Properties of Large Scale Jets, Hotspots and Lobes in AGN

Jun Kataoka* and Łukasz Stawarz†

*Tokyo Institute of Technology, Meguro, Tokyo, Japan
†Obserwatorium Astronomiczne, Uniwersytet Jagielloński, Kraków, Poland

Abstract. We examine a systematic comparison of jet-knots, hotspots and radio lobes recently observed with Chandra and ASCA. This report will discuss the origin of their X-ray emissions and investigate the dynamics of the jets. The data was compiled at well sampled 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 — mostly jet-knots in nearby low-luminosity radio galaxies — X-ray photons are produced by ultrarelativistic electrons with energies $10^{-100}$ TeV that must be accelerated in situ. For the other objects, conservatively classified as SSC or EC sources, a simple formulation of calculating the “expected” X-ray fluxes under an equipartition hypothesis is presented. We confirmed that the observed X-ray fluxes are close to the expected ones for non-relativistic 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 examined two possibilities to account for the discrepancy in a framework of the inverse-Compton model: (1) magnetic field is much smaller than the equipartition value, and (2) the jets are highly relativistic on kpc/Mpc scales. We also briefly discuss the other possibility, namely that the observed X-ray emission from all of the jet-knots is synchrotron in origin.

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. At the time of this writing, more than 40 radio-loud AGNs are known to possess X-ray counterparts of radio jets on kpc to Mpc scales (Harris & Krawczynski 2002, Stawarz 2004 and references therein). Bright X-ray knots (hereafter “jet-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 (e.g., Hardcastle et al. 2002b; 2004, Tashiro et al. 1998).

In the standard picture of FR II radio galaxies and quasars, 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 2002a). For example, the velocity and dynamics of the large-scale jets is unknown. From the analogy to sub-pc jets in blazar-type AGNs, it is plausible that some of the FR II and quasar jets are highly relativistic even on kpc/Mpc scales, but no direct evidence has been obtained.

As for the velocity of jet plasma, the strength of magnetic field in radio galaxies is
an open matter. Assuming an equipartition field value in the lobes (1−10 μG), which seems to be supported by the X-ray lobes’ observations, a simple flux conservation argument predicts the magnetic field in the jets as high as 0.01−1 G. Such a strong magnetic field is problematic, since numerical simulations of Poynting-flux dominated jets cannot correctly reproduce the observed large-scale morphologies of powerful radio sources. Thus, an amplification of the magnetic field to the equipartition value in strong jet terminal shock and in its turbulent downstream region is required, although only little theoretical investigations of this issue has been reported (see de Young 2002b).

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. Therefore the purpose of this paper is to obtain a rough, but unified picture which may link these jet-related structures, rather than modeling individual sources in a sufficiently detailed manner.

**DATA AND ANALYSIS**

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 2004). Before compiling the data, we have performed quick re-analysis of Chandra data to check the published results, and found no discrepancy. We therefore refer to published results (fluxes and spectral indices) unless otherwise stated in this paper. 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 (left) shows the distribution of the spectral indices in the radio band ($\alpha_R$; upper)
and in the X-ray band ($\alpha_X$; lower), respectively. Note that radio spectral index shows a relatively narrow distribution centered at 0.8 and there is no clear difference between the jet-knots, hotspots and radio lobes. As is widely believed, the radio emissions of these sources are most likely due to the synchrotron radiation from the low-energy population of relativistic electrons. Meanwhile, the X-ray energy index, $\alpha_X$, is widely distributed from 0.2 to 1.6. Steep X-ray sources are most frequently found in nearby FR I radio galaxies and thought to be the highest energy tail of the synchrotron radiation, whereas the origin of “flat” X-ray emission from other jet-knots is less clear. Such flattening is consistent with the inverse Compton models of the X-ray emission, but synchrotron origin of X-ray photons are also suggested (Harris, Mossman & Walker 2004).

Fig 1 (right) 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, $L_R \geq L_X$ for most of the hotspots and radio lobes, but most of the jet-knots show an opposite trend.

**MODEL APPLICATION TO DATA**

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 $B_{eq}$ from an observed radio flux $f_R$ measured at a radio frequency $\nu_R$. Next, we calculate the “expected” inverse Compton luminosities for $B_{eq}$, 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).

For a relativistically moving plasma, the equipartition magnetic field measured in the emitting plasma rest frame is written as

$$B_{eq} = 123 \eta^{2/7} (1+z)^{11/7} \left( \frac{d_L}{100\text{Mpc}} \right)^{-2/7} \left( \frac{\nu_R}{5\text{GHz}} \right)^{1/7} \left( \frac{f_R}{100\text{mJy}} \right)^{2/7} \times \left( \frac{\theta}{0.3''} \right)^{-6/7} \delta^{-5/7} [\mu\text{G}],$$

where $d_L$ is the luminosity distance to the source, $\theta$ is the angular radius and $\delta$ is the Doppler beaming factor (Kataoka & Stawarz 2004). Considering the ratio of synchrotron luminosity to the inverse Compton luminosity, we predict the SSC and EC (CMB) flux.
densities measured at $v_X$ to be roughly

$$f_{X,SSC} = 2.8 \times 10^{-3} \eta^{-1/2}(1+z) \left( \frac{d_L}{100 \text{Mpc}} \right)^{1/2} \left( \frac{v_R}{5 \text{GHz}} \right)^{5/4} \left( \frac{v_X}{v_{1 \text{keV}}} \right)^{-3/4} \times \left( \frac{f_R}{100 \text{mJy}} \right)^{3/2} \left( \frac{\theta}{0.3''} \right)^{-1/2} \delta^{-5/2} \text{ [nJy]},$$  \hspace{1cm} (2)

and

$$f_{X,EC} = 5.9 \times 10^{-4} \kappa^{7/4} \eta^{-1/2}(1+z) \left( \frac{d_L}{100 \text{Mpc}} \right)^{1/2} \left( \frac{v_R}{5 \text{GHz}} \right)^{1/2} \left( \frac{v_X}{v_{1 \text{keV}}} \right)^{-3/4} \times \left( \frac{f_R}{100 \text{mJy}} \right)^{1/2} \left( \frac{\theta}{0.3''} \right)^{3/2} \delta^{3} \text{ [nJy]},$$  \hspace{1cm} (3)

respectively. It is interesting to note that $f_{X,EC}$ goes as $\propto \delta^3$, meaning that the EC flux significantly increases as the beaming factor increases, which is the exact opposite trend in the SSC case ($f_{X,SSC} \propto \delta^{-5/2}$). Note also, that $f_{X,EC} \propto \theta^{3/2}$, i.e. for smaller emission region with given $f_R$ and $B = B_{eq}$ the EC X-ray emission decreases, again opposite to what is expected in the case of the SSC process ($f_{X,SSC} \propto \theta^{-1/2}$).

We then group the sources by the X-ray spectral index $\alpha_X$ and the X-ray flux $f_X$ observed at 1 keV. If the X-ray emission smoothly connects with the radio/optical spectra, we consider the X-rays to be produced via the synchrotron emission as for the radio to optical photons. Note that for all the synchrotron sources, electrons must be accelerated very efficiently up to $\gamma_X \approx 10^7 - 10^8$ for $B = B_{eq}$.

For remaining X-ray sources, we compare the ratio between the observed flux density to that expected one from SSC and EC models, $R_{SSC}$ and $R_{EC}$, to determine which process may dominate for the X-ray production. For example, the hotspot of 3C 123 is well explained by SSC, because $R_{SSC} = 1.5$ and $R_{EC} = 140$. This means that observed X-ray luminosity is 1.5 times larger than that expected from the SSC model under equipartition hypothesis, whereas 140 times of the expected EC flux. In contrast, a good example of the EC source are the lobes in 3C 15, where $R_{SSC} = 59$ and $R_{EC} = 1.2$.

However, in a number of jet-knots classified as SSC and EC, the observed X-ray luminosities cannot be reproduced satisfactorily. For example, knot-A1 of 3C 273 results in $R_{SSC} \approx R_{EC} = 48,000$, meaning that the observed X-ray flux is about 48,000 times brighter than those expected from both the EC and SSC models. Such discrepancy could be reduced by taking the relativistic beaming effect into account, by giving up the equipartition hypothesis, or by postulating a synchrotron origin of the X-ray photons due to an additional flat-spectrum electron population. None of these possibilities can be simply excluded. We will consider more about it in the next section.

**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 lumi-
nosity $L_{\text{sync}} \propto u_c u_B$ and for a given emitting region volume $V$, an expected SSC luminosity is $L_{\text{SSC}} \propto u_c$. We therefore expect ratio $R_{\text{SSC}} \propto L_{\text{SSC}}^{-1} \propto u_B$. Similarly, for the EC case, $R_{\text{EC}} \propto L_{\text{EC}}^{-1} \propto u_B$. Hence, in both models, the expected X-ray luminosity will be increased by decreasing the magnetic field strength.

Fig 2 (left) shows the distribution of the “best-fit” magnetic field $B$ if we allow for the deviation from the equipartition condition and assume nonrelativistic velocities for the emitting regions. One finds that both the non-SYN jet-knots and radio lobes are distributed around $B \simeq 1 - 10 \mu G$, whereas hotspots have a relatively narrow peak at higher field strength, $B \simeq 50 - 300 \mu G$, plus a “tail” extending down to $\sim \mu G$. Fig 2 (right) 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 ($B/B_{\text{eq},\delta=1} \sim 1$), whereas that of the non-SYN jet-knots and of some of the hotspots is much weaker from what is expected ($B/B_{\text{eq},\delta=1} \sim 0.01 - 0.1$).

As an alternative idea, 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. Relativistic beaming changes the observed X-ray luminosities significantly both for the SSC and the EC models (Eqn (2) and (3)). The Doppler factors thus calculated are shown in Fig 3 (left). One can see that 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.

Fig 3 (right) shows the distribution of equipartition magnetic field in the framework of relativistically moving jet model. Similarly to Fig 2 (left), we find again that the narrowly distributed strength of the magnetic field in the hotspots, $B \sim 100 - 500 \mu G$, is an order of magnitude larger than that of the jet-knots and radio lobes.

Usually, in applying the EC model to the quasar jet-knots’ X-ray emission, the idea of sub-equipartition magnetic field is rejected since it implies a very high kinetic power of the jets. For this reason, large values for the jet Doppler factors are invoked. However
such an approach does not solve all the problems with the total energy requirements (see discussion in Stawarz 2004). 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 $\Gamma_{BLK} \leq 5$. In such a case, these jets are most likely particle dominated ($u_e \gg u_B$). The jet magnetic field must be then significantly amplified in the hotspot, where an approximate equipartition is expected to be reached. Then the shocked plasma moves slowly to the radio lobe, where the equipartition field becomes close to the intergalactic value ($B \sim \text{a few } \mu G$).

Pressure of radio-emitting electrons within the lobes of quasars and FR IIs computed from the equipartition condition is often found to be below the thermal pressure of the ambient medium (Hardcastle & Worrall 2000). Such a discrepancy can be removed only by postulating deviations from the equipartition condition, or presence of non-radiating relativistic protons within the lobes. The presented analysis of the X-ray data suggests that the magnetic field–radiating electrons energy equipartition within the lobes is generally fulfilled, and thus that the relativistic protons are very likely to constitute a significant fraction of the lobes’ non-thermal pressure.

REFERENCES

- de Young, D. S., 2002b, NewAR, 2002b, 46, 393