High Energy Observations of AGN Jets and Their Future Prospects

Jun KATAOKA

Tokyo Institute of Technology, 2-12-1 Ohokayama, Meguro, Tokyo, 152-8551, JAPAN

Abstract. In next five years, dramatic progress is anticipated for the AGN studies, as we have two important missions to observe celestial sources in the high energy regime: GLAST and Suzaku. In this talk, I will summarize recent highlights in studies of AGN jets, focusing on the high-sensitivity X-ray observations that may shed new light on the forthcoming GLAST era. I will especially present some examples from most recent Suzaku observations of blazars, which provides important hints for the shock acceleration in sub-pc scale jets, as well as particle content in jets. Then I will focus on the neutral iron-line feature observed in some broad line radio galaxies, as a probe of jet launching and/or the disk-jet connection. Finally, I will discuss new results of large scale (kpc to Mpc) jets recently resolved with Chandra X-ray observatory. Simultaneous monitoring observations in various wavelengths will be particularly valuable for variable blazar sources, allowing the cross correlations of time series as well as detailed modeling of the spectral evolution between the X-ray and gamma-ray energy bands. Possible impacts of these new observations across the electromagnetic spectrum on various spatial scales are discussed to challenge the long-standing mystery of AGN jet sources.

Keywords: galaxies: active – galaxies: jets – galaxies: quasars

PACS: 95.85.Nv, 95.85.Pw, 95.84.Aj, 95.84.Gr

1. INTRODUCTION

Powerful, highly-collimated outflows called jets are commonly observed in a wide variety of astronomical sources. It has been a long-standing mystery, however, where and how the relativistic jets are formed, and what is their composition. From a theoretical standpoint, the relativistic AGN jets considered here can be launched as outflows dominated by Poynting flux generated in the force-free magnetospheres of black holes, or as hydromagnetic winds driven centrifugally from accretion discs (see review by [1]). In either case, strong magnetic fields are involved in driving the outflows, although many (if not most) observations indicate that eventually, particles carry the bulk of the jet’s energy (e.g., [2]). This apparent discrepancy, however, can be resolved if the jets are indeed initially dominated by the Poynting flux but are efficiently converted into matter-dominated form at some later stage, most likely prior to the so-called “blazar zone” (see [3] and references therein). Such a “blazar zone,” the region where the bulk of the observed nonthermal radiation is produced, is most likely located at \( r \approx 10^3 - 10^4 \ r_g \), where \( r_g = GM/c^2 \) is the gravitational radius ([4, 5, 6]).

This may indicate a scenario where a jet is launched near a rapidly rotating black hole, presumably at the innermost portions of the accretion disk (see, e.g., [7]). Such a jet, initially consisting of protons and electrons, is accelerated by large scale magnetic field stresses and within 100 \( r_g \) can be loaded by electron/positron (\( e^- e^+ \)) pairs via interactions with the coronal soft gamma-ray photons (note that such photons are directly...
seen in the spectra of Seyfert galaxies; see, e.g., [8]). Hence, it is possible that relativistic jets in quasars (beyond the jet formation zone) may well contain more electron/positron pairs than protons, but are still dynamically dominated by cold protons. Apparently, observational evidence is strongly awaited to test this hypothesis, which provides a direct hint for the connection between the jet and accretion disk at the very inner-site (≤ 1 mpc scale) of the jet.

Meanwhile, extragalactic jets constitute the longest collimated structures in the Universe. They transport huge amounts of energy from the nuclei of active galaxies out to kpc or Mpc distances, significantly affecting the properties of the surrounding intra-cluster/intergalactic medium. These large scale jets have been extensively studied in the radio domain on different scales since the very beginning of the development of modern radio interferometers (e.g., [9]). More recently, the excellent spatial resolution of the Chandra X-ray Observatory (and, to a lesser extent, of other X-ray satellites like XMM-Newton) has allowed us to image large-scale structures in powerful extragalactic radio sources at X-ray frequencies as well, and thus has opened a new era in studying the high energy emission of these objects. More than 100 radio-loud AGNs are now known to possess X-ray counterparts to their radio jets, hotspots or lobes on kpc-to-Mpc scales (e.g., [10, 11, 12, 13] and references therein). Here we briefly overview recent highlights from the X-ray/gamma-ray observations of AGN jets on various scales from 1 mpc to 1Mpc, as a new challenge to the jet physics.

2. SUB-PC JETS: BLAZARS

Observations with the EGRET instrument on board the Compton Gamma-Ray Observatory in the gamma-ray band have opened a new window for studying AGN jets, and revealed that many radio-bright and variable AGN are also the brightest extragalactic MeV—GeV gamma-ray emitters (see, e.g., [14]). The properties of the gamma-ray emission in those objects — often termed “blazars” — supported earlier inferences based on radio and optical data, and independently indicated significant Doppler boosting, implying the origin of broad-band emission in a compact, relativistic jet pointing close to our line of sight. Generally, the overall spectra of blazar sources (plotted in the log(ν)-log(νFν) plane, where Fν is the observed spectral flux energy density) have two pronounced continuum components: one peaking between IR and X-rays and the other in the gamma-ray regime (see, e.g., [15, 16]). The lower energy component is believed to be produced by the synchrotron radiation of relativistic electrons accelerated within the outflow, while inverse Compton (IC) emission by the same electrons is most likely responsible for the formation of the high energy gamma-ray component.

It is widely believed, in addition, that the IC emission from quasar hosted blazars (QHBs) is dominated by the scattering of soft photons external to the jet (external Compton process, ERC), which are produced by the accretion disk, either directly or indirectly via scattering/reprocessing in the broad line region (BLR) or dusty torus (see, e.g., [17]). Other sources of seed photons can also contribute to the observed IC component, in particular the synchrotron photons themselves via the synchrotron self-Compton process (SSC) which is often the case for BL Lacertae objects (e.g., [15]). In some cases, gamma-ray emissions seen to extend to the TeV range; the X-ray and
TeV gamma-ray bands corresponds to the highest energy end of the synchrotron/IC emission. As we see below, detailed modeling of broad-band blazar emission as well as temporal variability can provide information about the location of the dissipative regions in blazars, the energy distribution of relativistic electrons/positrons, the magnetic field intensity, and the jet power.

### 2.1 1ES 1218+304 (HBL)

1ES 1218+304 is categorized as a high-frequency BL Lac object (HBL), as a redshift $z = 0.182$. It was discovered as a TeV emitter by MAGIC at energies $\geq 100$ GeV ([18]) and subsequently confirmed by VERITAS ([19]). The source was observed with Suzaku during 2006 May 20-21 UT, yielding a net exposure time of 79.9 ks ([20]). Figure 1 shows the averaged light curves of the four XISs in the lowest (0.3−1.0 keV) and the highest (5−10 keV) X-ray energy bands. Interestingly, the observed flare shows the following characteristics: (1) The flare shape is asymmetric in time ($t_{r}/t_{d} \leq 1$) especially in the lower energy band (but note $t_{r}/t_{d} \approx 1$ for 5−10 keV light curve). (2) The flare amplitude becomes larger as the photon energy increases. (3) The risetime of the flare is almost constant below 2 keV, while it becomes gradually longer at higher energy bands.

In this context, we try to evaluate lags of temporal variations in various energy bands. We found that the hard X-ray (5−10 keV) peak lagged behind that in the soft X-ray (0.3−1 keV) by $(2.3 \pm 0.7) \times 10^4$ sec.

This is completely opposite to a well-known “soft-lag”, as has been obtained from the past observations (e.g., [21,22]). In the theoretical context, however, hard-lag is actually expected especially in the X-ray variability of TeV blazars, but has never been observed so clearly before. It has been suggested that a hard-lag is observable only at energies closer to the maximum electron energy ([23]), where the acceleration time is almost...
FIGURE 2. SED of 1ES 1218+304. The solid line shows a one-zone SSC model assuming the parameters: $B = 0.047$ G, $\delta = 20$, $s = 1.7$, $\gamma_{\text{min}} = 1$, $\gamma_{\text{brk}} = 8 \times 10^{3}$ and $\gamma_{\text{max}} = 8 \times 10^{5}$, where $s$ is the electron spectral index. See [20] for more detail.

comparable to the cooling time scale of radiating electrons: $t_{\text{acc}}(E_{\text{max}}) \simeq t_{\text{cool}}(E_{\text{max}})$. Noting that the typical synchrotron emission frequency, averaged over pitch angles, of an electron with energy $\gamma m_{e}c^{2}$ is given by $\nu \sim 3.7 \times 10^{6} B \gamma^{2}$ Hz, we obtain;

$$t_{\text{acc}}(E) = 9.65 \times 10^{-2} (1 + z)^{3/2} \xi B^{-3/2} \delta^{-3/2} E^{1/2} s,$$

$$t_{\text{cool}}(E) = 3.04 \times 10^{+3} (1 + z)^{1/2} B^{-3/2} \delta^{-1/2} E^{-1/2} s,$$

where $E$ is the observed photon energy in unit of keV, $z$ is the redshift, $B$ is the magnetic field strength, and $\delta$ is the beaming factor. Note, for lower energy photons ($E \ll E_{\text{max}}$), $t_{\text{acc}}(E)$ is always shorter than $t_{\text{cool}}(E)$ because higher energy electrons need longer time to be accelerated ($t_{\text{acc}}(\gamma) \propto \gamma$) but cools rapidly ($t_{\text{cool}}(\gamma) \propto \gamma^{-1}$). This energy dependence of acceleration/cooling time-scales may qualitatively explain observed characteristics of X-ray light curves of 1ES 1218+304.

It is thus interesting to consider a simple toy model in which the rise time of the flare is primarily controlled by the acceleration time of the electrons corresponding to observed photon energies, while the fall time of the flare is due to the synchrotron cooling time scale. In this model, the amount of hard-lag is simply due to the difference of $t_{\text{acc}}$, and independent of the energy dependence of $t_{\text{cool}}$:

$$\tau_{\text{lag}} = E_{\text{acc}}(E_{\text{hi}}) - E_{\text{acc}}(E_{\text{low}}) \sim 9.65 \times 10^{-2} (1 + z)^{3/2} \xi B^{-3/2} \delta^{-3/2} (E_{\text{hi}}^{1/2} - E_{\text{low}}^{1/2}) s,$$

where $E_{\text{low}}$ and $E_{\text{hi}}$ are the lower and higher X-ray photon energies to which the time-lag is observed. Assuming $\delta = 20$ from multiband spectral fitting (see Figure 2), the best fit parameter of the magnetic field $B$ can be written as $\sim 0.05 \xi_{5} G$, where $\xi_{5}$ is the gyro-factor in units of $10^{5}$. As discussed in detail in [20], the above toy model
qualitatively well represents the observed spectral/temporal features of 1ES 1218+304, in particular: (1) the synchrotron component peaks around the Suzaku XIS energy band in the multiband spectrum and (2) the observed light curve is symmetric in shape when measured at the high energy band, while being asymmetric at the lower energy band.

2.2 PKS 1510-089 (QHB)

In contrast to the HBLs as presented above, the X-ray band corresponds to the low-energy end of the inverse Compton emission for most QHB-type blazars. For these sources, a probe of the low energy electron/positron content in blazars was proposed by [24], and extensively studied in the literature (e.g., [2, 25, 26]). The gamma-ray emission is produced by electrons/positrons accelerated in situ, and thus before reaching the blazar dissipative site the electrons/positrons are expected to be cold. If they are transported by a jet with a bulk Lorentz factor $\Gamma_{\text{jet}} \geq 10$, they upscatter external UV photons up to X-ray energies and produce a relatively narrow feature expected to be located in the soft/mid X-ray band, with the flux level reflecting the amount of cold electrons and the jet velocity. Unfortunately, such an additional bulk-Compton (BC) spectral component is difficult to observe because of the presence of strong non-thermal blazar emission, which dilutes any other radiative signatures of the active nucleus. In this context, QHBs may constitute a possible exception, since their non-thermal X-ray emission is relatively weak when compared to other types of blazar sources.

PKS 1510–089 is a nearby ($z = 0.361$) QHB detected in the MeV–GeV band by EGRET. It is a highly superluminal jet source, with apparent velocities of $v_{\text{app}} \geq 10 c$ observed in multi-epoch VLBA observations (e.g., [27]). Recent observations by BeppoSAX ([28]) confirmed the presence of a soft X-ray excess below 1 keV, that may be among the best candidates for detecting the BC bump. The observational campaign of PKS 1510-089 in 2006 August commenced with a deep Suzaku observation lasting three days for a total exposure time of 120 ks, and continued with Swift monitoring over 18 days ([29]). Besides Swift observations, which sampled the optical/UV flux in all 6 UVOT filters as well as the X-ray spectrum in the 0.3–10 keV energy range, the campaign included ground-based optical and radio data, and yielded a quasi-simultaneous broad-band spectral energy distribution from $10^9$ Hz to $10^{19}$ Hz.

Figure 3 (left) shows an overall SED of PKS 1510-089, whereas Figure 3 (right) shows in detail the optical–to–X-ray region of the SED. In the right panel, the hump on the left mimic an excess emission from the dusty torus as suggested by IRAS with a dust temperature of $kT \simeq 0.2$ eV and $L_{\text{dust}} \simeq 3.7 \times 10^{45}$ erg s$^{-1}$. The hump on the middle is our attempt to account for the blue bump assuming an inner-disk temperature of $kT \simeq 13$ eV and $L_{\text{disk}} \simeq 4 \times 10^{45}$ erg s$^{-1}$. From the spectral fitting of the Suzaku data, we found that the 0.3–50 keV spectrum is well represented by an extremely hard power-law with photon index $\Gamma = 1.2$, augmented by a black-body–type emission of $kT \simeq 0.2$ keV ([29]). Figure 4 shows count rate variations during the Suzaku observation. The time variation of underlying power-law component and the soft X-ray excess are separately shown in this figure. This clearly indicates different variability properties: count rates only slightly decreased for PL component, while it reached a delayed maximum $\sim 1.5$ day from the
start of the *Suzaku* observation for the soft X-ray hump.

We investigate below whether such excess can be produced by a bulk Comptonization of external diffuse radiation by cold inhomogeneities (with bulk Lorentz factors $\Gamma_1$ and $\Gamma_2$) and/or density enhancements prior to their collisions. At $r > r_{\text{BLR}}$, where $r_{\text{BLR}}$ is the distance of the broad line region from the nucleus, density of the diffuse external UV radiation is very small, while bulk-Compton features from upscatterings of dust infrared radiation falls into the invisible extreme-UV band. However, if acceleration of a jet has already occurred at $r \leq r_{\text{BLR}}$, upscattering of photons from broad-emission line region should lead to formation of bulk Compton features, with peaks located around $\nu_{\text{BC},i} \sim \mathcal{D}_i \Gamma_i \nu_{\text{UV}} / (1 + z)$ and luminosities

$$L_{\text{BC},i} = \frac{4}{3} c \sigma_{\text{TeBLR}} \Gamma_i^2 \mathcal{D}_i^4 N_{e,\text{obs},i},$$  

where $i = 1, 2$, $u_{\text{BLR}}$ is the energy density of the broad emission lines, $\mathcal{D}_i$ is the Doppler factor, and $N_{e,\text{obs},i}$ is the number of electrons and positrons contributing to the bulk-Compton radiation at a given instant (see [25]). For the conical jets the Doppler factor should be replaced by the 'effective' Doppler factor which for $\theta_{\text{obs}} \leq \theta_{\text{jet}}$ is $\mathcal{D}_i = \kappa \Gamma_i$, where $1 < \kappa < 2$. For our model parameters

$$N_{e,\text{obs},1} \simeq \frac{N_{\text{inj}}}{2} \frac{r_{\text{BLR}}}{\lambda_0 \mathcal{D}_1},$$  

and

$$N_{e,\text{obs},2} \simeq \frac{N_{\text{inj}}}{2} \frac{r_{\text{BLR}}}{\lambda_0 \mathcal{D}_2} \frac{\Gamma_{\text{sh}}^2}{2 \Gamma_2^2},$$  

where $\lambda_0$ is the proper width (longitudinal size) of the cold inhomogeneities (see Appendix A3 in [25]). With the above approximations and $\kappa = 1.5$ our model predicts...
FIGURE 4. The variability of PKS 1510-089 observed with Suzaku. While the underlying power-law component is stable, soft X-ray excess is highly variable with a delayed maximum.

location of the bulk-Compton features at $\sim 1$ keV and $\sim 18$ keV, and luminosities of $\sim 2 \times 10^{44}$ erg s$^{-1}$ and $2 \times 10^{46}$ erg s$^{-1}$, respectively. Thus it seems that within the uncertainties regarding the details of the jet geometry and model parameters, bulk-Compton radiation produced by slower inhomogeneities is sufficiently luminous to be responsible for the soft X-ray excess observed by Suzaku, while the faster one can be tentatively identified with a small excess at $\sim 18$ keV seen in Figure 3 (right).

Finally, we shortly comment on the pair content of a jet. In our SED modeling (Figure 3 left), the amount of electrons/positrons injected into shell by the end of the shock operation is

$$N_{e,\text{inj}} = t'_{sh} \int_{\gamma_{\text{min}}}^{\gamma} Q_{\gamma} d\gamma \approx \frac{\Delta r}{c \Gamma_{sh} (p - 1) \gamma_{\text{min}}^{p - 1}} \gamma_{\text{inj}} \approx 2.9 \times 10^{53},$$

(5)

where $t'_{sh} = \Delta r/(c \Gamma_{sh})$ is the lifetime of the shock as measured in the shock (discontinuity surface) rest frame. The electrons/positrons are accelerated/injected resulting in an average energy $\bar{\gamma}_{\text{inj}} = \int Q_{\gamma} d\gamma / \int Q d\gamma \simeq 22$. Assuming that this energy is taken from protons, we have the electron/positron to proton ratio

$$\frac{N_e}{N_p} = \eta_e \frac{m_p (\bar{\gamma}_p - 1)}{m_e \bar{\gamma}_{\text{inj}}},$$

(6)

where $\eta_e$ is the fraction of the proton thermal energy tapped by electrons and positrons. The value of $\gamma_{\text{p}} - 1$, which actually represents efficiency of the energy dissipation, depends on properties and speeds of colliding inhomogeneities, and is largest if they
have same rest densities and masses. In this case, assuming $\Gamma_2 > \Gamma_1 \gg 1$,
\[ \gamma_p - 1 = \frac{(\sqrt{\Gamma_2/\Gamma_1} - 1)^2}{2\sqrt{\Gamma_2/\Gamma_1}}, \tag{7} \]
and $\Gamma_{sh} = \sqrt{\Gamma_1 \Gamma_2}$ \cite{25}. For reasonable choice of $\Gamma_1 = 10$ and $\Gamma_2 = 40$, we obtain $N_e/N_p \sim 20\eta_p$. The result supports our original hypothesis that the power of the jet is dominated by protons but with a number of electrons/positrons exceeding a number of protons by a factor $\sim 10$ \cite{29}.

3. DISK-JET CONNECTION: 3C 120

All AGNs are thought to be powered by accretion of matter onto a supermassive black hole, presumably via an equatorial accretion disk. Recent VLBI observations of a nearby active galaxy M87 confirmed that the jet is already launched within $\sim 60 \, r_g$ (where $r_g = GM/c^2$ is the gravitational radius), with a strong collimation occurring within $\sim 200 \, r_g$ of the central black hole \cite{30}. These results are consistent with the hypothesis that jets are formed by an accretion disk, which is threaded by a magnetic field. Therefore the observational properties of the accretion disk and corona are essential ingredients to jet formation (e.g., \cite{31} and references therein).

In this meaning, the profile of the iron $K_{\alpha}$ (6.4 keV) line can be used to probe the structure of the accretion disk, because it is thought to result from fluorescence of the dense gas in the geometrically thin and optically thick regions of the inner accretion disk ($\sim 10 \, r_g$). The most famous example is the spectrum of the Seyfert 1 (Sy-1) galaxy MCG–6-30-15, which shows a relativistically broadened Fe $K_{\alpha}$ emission line, first detected by ASCA \cite{32}. Similar broad relativistic iron line profiles have been detected in several other type-1 AGNs, although they are perhaps somewhat less common than anticipated from the ASCA era (e.g., \cite{33}). In this context, studies of the iron line profile in radio-loud AGN provides important clues to the disk-jet connection, particularly when compared with Sy-1s.

3C 120 ($z = 0.033$) is the brightest broad line radio galaxy (BLRG), exhibiting characteristics intermediate between those of FR-I radio galaxies and BL Lacs. It has a onesided superluminal jet on 100 kpc scales \cite{34}, and superluminal motion (with an apparent velocity $\beta_{app} = 8.1$) has been observed for the jet component. This provides an upper limit to the inclination angle of the jet to the line of sight of 14 deg \cite{35}. Interestingly, \cite{36} found that dips in the X-ray emission of 3C 120 are followed by ejections of bright superluminal knots in the radio jet, which clearly indicates an important connection between the jet and the accretion disk. In X-rays, 3C 120 has been known to be a bright ($\sim 5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ at 2–10 keV), variable source with a canonical power-law spectral shape that softened as the source brightened (e.g., \cite{37}). A broad iron $K_{\alpha}$ line was first detected by ASCA in 1994, with its width $\sigma = 0.8$ keV and EW $\sim 400$ eV \cite{38}. Most recently, 3C 120 was observed for nearly a full orbit (130 ksec) with XMM-Newton on 26–27 August 2003 \cite{39,40}. This clearly confirmed the presence of the neutral Fe line emission ($57\pm7$ eV in EW), which was slightly broadened with a FWHM of $\sigma = 9000\pm3000$ km s$^{-1}$. Both of these papers argued that the line profile is
rather symmetric and no evidence was found for relativistic broadening, or alternatively the line arises from an accretion disk radius of $\geq 75 \, r_g$ at an inclination angle of $\sim 10$ deg (where relativistic gravitational effects are almost negligible).

3C 120 was observed with Suzaku four times in February and March 2006 with a total (requested) duration of 160 ksec (41). It was in a relatively high state during the 1st 40 ksec observation (#1; the summed count rates of 4 XISs detectors was $15.94 \pm 0.01$ counts s$^{-1}$), then its count rate dropped by $\sim 20\%$ in the 2nd observation, and finally reached a minimum in the 4th observation (#4; $12.02 \pm 0.01$ counts s$^{-1}$). As given in Figure 5 (left), Suzaku has successfully resolved the iron K line complex of 3C 120 and also was first to verify the broad component’s asymmetry. We showed that the iron line complex is composed of (1) a relatively narrow, neutral iron K line core (6.4 keV), (2) broad iron line emission possibly emitted from the accretion disk, and (3) an ionized $\sim 6.9$ keV line. The residuals present after subtracting the iron line core are poorly modeled either by adding a simple broad Gaussian or by adding the Compton shoulder of the K$_\alpha$ line. A significant red-tail below 6.4 keV (in the rest frame of source) favors diskline emission from the inner accretion disk of $r_{in} \simeq 8.6^{+1.0}_{-0.6} \, r_g$ (41).

If indeed the broad line really originates from the inner accretion disk, it provides important clues to jet formation in the accretion disk. For example, [42] have discovered a similar broad iron line in the Suzaku/XMM-Newton spectra of MCG–5-23-16, which is thought to originate from inner accretion disk ($r_{in} \simeq 20 \, r_g$). These observations may imply that both the radio-loud 3C 120 and the radio-quiet MCG–5-23-16 have similar accretion disk structure, in contrast to suggestions that the optically-thick accretion disk is truncated in 3C 120 to a hot, optically thin flow at a distance of $r_{in} \sim 100 \, r_g$ ([43, 44, 39]). Observations of the iron line profiles in various other broad line radio galaxies are important for the systematic comparison between Seyferts and BLRGs. We are planning to submit further deep observations of other BLRGs in the next Suzaku observation program to test this.

Finally, another interesting discovery made by Suzaku is that the variable component in 3C 120 is much steeper ($\Gamma \simeq 2.7$) than the power-law emission component reported in literature ($1.6 \leq \Gamma \leq 1.8$). One interesting idea to account for this steep, variable emission is the beamed radiation from the jet, though this component contributes only $\sim 20\%$ at most, of the Sy-1 like X-ray emission in 3C 120 (i.e., emitted from the disk and corona). The low inclination angle implies that 3C 120 may have some “blazar-like” characteristics, such as rapid X-ray variability or a non-thermal spectrum extending to the gamma-ray energy band. Future deep Suzaku observations, as well as continuing VLBI monitoring coincident with X-ray monitoring (as the campaigns reported by [36]), sensitive measurements with GLAST, in quite different states of source activity will be crucial to understanding the nature of 3C 120. Figure 5 (right) clearly indicates that many BLRGs, including 3C 120, can be detected with GLAST at MeV–GeV energy band near future.

4. LARGE SCALE JETS: 3C 353

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. Bright X-ray knots (so-
called “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. The X-ray emission observed from the extended lobes is well understood and modeled in terms of the inverse Comptonization of the cosmic microwave background photons by the low-energy electrons (IC/CMB; see the discussion in [13, 45]), providing strong evidence for approximate energy equipartition between the radiating electrons and the lobe magnetic field (with the particle pressure dominating over the magnetic pressure by up to one order of magnitude).

However, the most controversial issue is the origin of the intense X-ray emission detected from knots in powerful quasar jets, such as PKS 0637−752 or 3C 273 ([46, 47], respectively). Here the X-ray knot spectra are much brighter than expected from a simple extrapolation of the radio-to-optical synchrotron continua, indicating that an additional or separate spectral component dominates the jet’s radiative output at high (X-ray) photon energies. Very often, this emission is modeled in terms of inverse-Comptonization of the CMB photon field by low-energy ($\gamma \leq 10^3$) electrons ([48, 49]), which typically requires highly relativistic jet bulk velocities of $\Gamma_{\text{jet}} \geq 10$ even on kpc-Mpc scales. On the other hand, if there is significant beaming in powerful jets on large scales, then the detection of bright X-ray jet emission from FR II radio galaxies, which are believed to be analogous systems to radio loud quasars but to be viewed with the jets at large angles to the line of sight, should be considered as unlikely. Such emission has, however, been detected in several objects (e.g., 3C 303, 3C 15, Pictor A, or 3C 403; see [50, 51, 52, 53], respectively). Obviously, detection of any X-ray counterjet would be of primary importance in this respect, since it would automatically exclude significant beaming, and thus impose very severe constraints on the jet emission models.

3C 353 ($z = 0.0304$) is the fourth strongest radio source in the 3C catalog, with a total flux density $S_\nu \approx 57$ Jy at 1.4 GHz, and a projected size $\sim 4.5'$. It exhibits hotspots and
FIGURE 6. An X-ray image of 3C 353 (Chandra 0.4–8.0 keV) overlaid with radio contours (VLA, 1.4 GHz). The contour levels are 1.2, 4.6, 8.1 and 11.5 mJy beam$^{-1}$.

a pair of large-scale FR II-type jets, clearly visible within filamentary lobes (54). The jets in 3C 353, constituting about 1% of the entire source luminosity, are well collimated trains of knots with an average width $\simeq 4''$ and jet-counterjet radio brightness asymmetry $\simeq 2$ (55). Both total and polarized intensity profiles across the jets indicate that the bulk of the jet radio emission is produced at the jet edges, and so presumably within a boundary shear layer. Since these jets are among only a very few FR II jets wide enough to be resolved in X-rays, we planned and conducted a deep Chandra observation of 3C 353, in order to investigate the multiwavelength structure of powerful FR II outflows. 3C 353 was observed with Chandra in July 2007 with a total (requested) duration of 90 ks (56). Figure 6 shows an exposure corrected image of 3C 353 in the energy band 0.4 – 8.0 keV, with 1.4 GHz radio contours (1.2, 4.6, 8.1, and 11.5 mJy beam$^{-1}$) overlaid. The X-ray image has been smoothed with a two-dimensional Gaussian function with $\sigma = 1.5$ pixels (1 Chandra pixel is 0.492$''$). A zoom-up of the central region is separately given in Figure 7. Most strikingly, the X-ray image clearly shows not only
the East (main) jet-knots, but also a bright knot in the West counterjet (W47), that seems to be identified with the CJ2 radio knot as given in [54]. Also X-ray emission near the West hotspot region is (W120a,b) detected in the image.

As discussed in [54], the width of the radio jet in all these figures is much broader than the resolution of the radio map (1.3″ for 1.4 GHz and 0.44″ for 8.4 GHz). The transverse profile in the radio cannot be well represented by a simple Gaussian function, but instead shows a flat-topped profile which is especially clear in W47. For quantitative comparison, the width of the jet, at which the intensity becomes half of the maximum (FWHM) are 3.43″/3.32″ (W47), where the widths are quoted for the 1.4 GHz and 8.4 GHz radio maps respectively. In contrast, the X-ray knots show no evidence for the flat-topped profiles seen in the radio images and are instead well represented by a smooth Gaussian function, as shown in Figure 8 (left). The observed FWHM of the X-ray jets are 1.79″ ± 0.36″ (W47), respectively, as compared to the PSF width of 0.93″ ± 0.01″. Therefore the X-ray knots in 3C 353 are possibly narrower than their radio counterparts (which are also situated further away from the active nucleus), suggesting that the observed X-ray jet emission must be restricted to the central spine of the jet rather than to the jet boundary layer [56].

Finally, we constructed the spectral energy distributions of the bright jet knots E23, W47 and hotspot E88. Figure 8 (right) compares the spectral energy distributions, showing that the overall spectral features are remarkably similar to each other, suggesting that the same physical process is at work for the X-ray production in the E23, E88 and W47 knots. One may note, however, that the X-ray spectral points cannot be connected smoothly with the extrapolation of the radio data, whether we assume either a single or a broken power-law form for the radio-to-X-ray continuum. Note that [54] constrained the jet inclination to the line of sight in 3C 353 to be 60° < θ_j < 90°; these large angles to the line of sight are strongly supported by the observed two-sidedness of both the radio and X-ray jets. Accordingly, we can approximately substitute δ_j ~ 1/Γ_j, obtaining
TABLE 1. A list of “VIP” blazars to be simultaneously observed with GLAST and Suzaku during in 2008/09 season.

| Source Name    | Redshift | Class | Flux (2-10 keV) 10^{-12} erg/cm^{2}/s | Flux (\geq 100 MeV) 10^{-5} ph/cm^{2}/s |
|----------------|----------|-------|--------------------------------------|----------------------------------------|
| PKS 0208-512   | 1.00     | HPQ   | 9.5                                  | 85.5±4.5                               |
| Q 0827+243     | 0.94     | LPQ   | 4.8                                  | 24.9±3.9                               |
| PKS 1127-145   | 1.18     | LPQ   | 11.0                                 | 38.3±8.0                               |
| PKS 1510-089   | 0.36     | LPQ   | 10.0                                 | 18.0±3.8                               |
| 3C 454.3       | 0.86     | HPQ   | 11.0                                 | 53.7±4.0                               |
| 3C 279         | 0.54     | HPQ   | 13.0                                 | 89.0±3.2                               |
| PKS 0528+134   | 2.06     | LPQ   | 30.0                                 | 60.0±3.0                               |
| PKS 2126-15    | 3.30     | LPQ   | 12.0                                 | Non detection                          |

the observed luminosity ratio $L_{\text{IC/cmb}}/L_{\text{syn}}$ independently of the jet kinematic factors. The resulting value, $\sim 10^{-3}$, is in strong disagreement with the observed X-ray-to-radio luminosity ratio $L_X/L_R \geq 1$. Thus, we conclude that the IC/CMB model cannot explain the observed X-ray emission of the 3C 353 jets, unless very large departures from energy equipartition, $B \ll 100 \Gamma_j^{-1} \mu \text{G}$, are invoked.

The only possibility left is therefore that the observed X-ray emission of 3C 353 results from the synchrotron radiation of some flat-spectrum high-energy electron population, most likely separate to the one producing the observed radio emission. The required Lorentz factors of the electrons emitting synchrotron photons with the observed keV energies are $\gamma_X \sim (\nu_{\text{keV}}/4.2 \times 10^6 B \delta_j)^{1/2} \sim 3 \times 10^7 \Gamma_j$ (assuming the scaling of the magnetic field as given in equation 2 above and, again, $\delta_j \sim 1/\Gamma_j$). It has already been shown that stochastic acceleration processes taking place in large-scale extragalactic outflows may easily account for the production of electrons with these Lorentz factors (e.g., [57]) and they are already invoked to explain observations of the hotspots of FR II sources and the jets of FR Is.

5. FUTURE CHALLENGES: GLAST

It is widely expected that GLAST will detect a large number (probably between 3,000 and 10,000) of extragalactic sources, most of which will be identified as blazars. Moreover, the LAT large field-of-view combined with scanning mode will provide a very uniform exposure over the sky, allowing constant monitoring of all detected blazars and flare alerts to be issued. Apparently, contemporaneous/simultaneous multiwavelength campaigns are essentially important for both “EGRET blazars” (i.e., well-established sources) as well as newly detected sources. In X-ray, many observatories are already being actively prepared. For example, we are planning dedicated campaigns of 7 QHBs as a part of Suzaku-AO3 as listed in Table 1. Assuming a large flare as that observed for 3C 279 in 1991, Suzaku can determine the X-ray spectrum up to 300 keV with an unprecedented accuracy. Coordinated observations between GLAST and Suzaku are crucial for further understanding the nature of various types of blazars.

In addition to classical gamma-ray blazars discussed above, we expect that several
nearby FR-I and FR-II radio galaxies can be detectable by *GLAST* as “mis-aligned” blazars. This is actually expected if a unification scheme between blazars and radio galaxies is indeed applicable. In fact, *Suzaku* revealed that a power-law continuum of Centaurus A extends up to 200 keV without spectral break or reflection component ([58]), and the SED is well fit by synchrotron and inverse Compton model as usually applied for blazars ([59]). Another interesting possibility is to detect broad line radio galaxies (BLRGs) with *GLAST*, as we have discussed in §3. In fact, careful reanalysis of archival EGRET data reveals that one of the BLRGs (3C 111), which is analogous to 3C 120, may have been detected as a possible gamma-ray emitter ([60]). Finally, we expect an important new area of investigation will be developed via ToO (Target of Opportunity) observations of AGNs by “*GLAST* trigger” in next few years.

ACKNOWLEDGMENTS

JK acknowledges all the *Suzaku* members who helped us in analyzing the data, and all the *GLAST*-AGN members for careful planning of multiwavelength campaigns. JK thanks support by JSPS KAKENHI (19204017/14GS0211).

REFERENCES

1. Lovelace, R. V. E., Ustyugova, G. V., & Koldova, A. V. 1999, Active Galactic Nuclei and Related Phenomena, IAU Symposium, 194, 208
2. Sikora, M. & Madejski, G. M. 2000, ApJ, 534, 109
3. Sikora, M., Begelman, M. C., Madejski, G. M., & Lasota, J.-P. 2005, ApJ, 625, 72
4. Spada, M., Panaitescu, A., & Meszaros, P. 2000, ApJ, 537, 824
5. Kataoka, J., et al. 2001, ApJ, 560, 659
6. Tanihata, C., Takahashi, T., Kataoka, J., & Madejski, G. M. 2003, ApJ, 584, 153
7. Koide, S., Meier, D., Shibata, K., & Kudoh, T. 1999, ApJ, 536, 668
8. Zdziarski, A. A., Poutanen, J., & Johnson, W. N. 2000, ApJ, 542, 703
9. Begelman, M. C., & Sikora, M. 1987, ApJ, 322, 650
10. Harris, D.E., & Krawczynski, H., 2002, ApJ, 565, 244
11. Harris, D.E., & Krawczynski, H., 2006, ARA&A, 44, 463
12. Sambruna, R.M., Gambill, J.K., Maraschi, L., Tavecchio, F., Cerutti, R., Cheung, C.C., Urry, C.M., & Charts, G., 2004, ApJ, 608, 698
13. Kataoka, J., & Stawarz, Ł., 2005, ApJ, 622, 797
14. Hartman R.C., et al. 1999, ApJS, 123, 79
15. Kubo, H., Takahashi, T., Madejski, G., Tashiro, M., Makino, F., Inoue, S., & Takahara, F. 1998, ApJ, 504, 693
16. Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451
17. Sikora, M., Begelman, M. C., & Rees, M. J., 1994, ApJ, 421, 153
18. Albert, J., et al. 2007, ApJ, 669, 862
19. Fortin, P. et al., astro-ph/0709.3657
20. Sato, R., Kataoka, J., Takahashi, T., Madejski, G. M., Rugamer, S., and Wagner, S. J., 2008, ApJ, 680, L9
21. Takahashi, T. et al. 1996, ApJ, 470, L89
22. Kataoka, J., et al. 2000, ApJ, 528, 243
23. Kirk, J., Ringer, F., & Mastichiadis, A. 1998, A&A, 333, 452
24. Begelman, M. C., & Sikora, M. 1987, ApJ, 322, 650
25. Moderski, R., Sikora, M., Madejski, G. M., & Kamae, T. 2004, ApJ, 611, 770
26. Celotti, A., Ghisellini, G., & Fabian, A. C. 2007, MNRAS, 375, 417
27. Homan D. C., et al. 2001, ApJ, 549, 840
28. Tavecchio, F., et al. 2000, ApJ, 543, 535
29. Kataoka, J., et al. 2008, ApJ, 672, 787
30. Junor, W., Biretta, J. A., & Livio, M., Nature, 1999, 401, 891
31. Livio, M. 1999, Phys. Rep. 311, 225
32. Tanaka, Y., et al. 1995, Nature, 375, 659
33. Nandra, K., George, I. M., Mushotzky, R. G., Turner, T. J., Yaqoob, T. 1997, ApJ, 477, 602
34. Walker, R. C., Benson, J. M., & Unwin, S. C. 1987, ApJ, 316, 546
35. Eracleous, M., & Halpern, J. P. 1998, ApJ, 505, 577
36. Marscher, A. et al. 2002, Nature, 417, 625
37. Maraschi, L. et al. 1991, ApJ, 368, 138
38. Grandi, P., Sambruna, R. M., Maraschi, L., Matt, G., Urry, C. M., Mushotzky, R. F., 1997, ApJ, 487, 636
39. Ballantyne, D. R., Fabian, A. C., & Iwasawa, K. 2004, MNRAS, 354, 839
40. Ogle, P., et al. 2005, ApJ, 618, 139
41. Kataoka, J., et al. 2007, PASJ, 59, 279
42. Reeves, N. J., et al. 2007, PASJ, 59, 201
43. Eracleous, M., Sambruna, R., & Mushotzky, R. F., 2000, ApJ, 537, 654
44. Zdziarski, A. A., & Grandi, P., 2001, ApJ, 551, 186
45. Croston, J.H., Hardcastle, M.J., Harris, D.E., Belsole, E., Birkinshaw, M., & Worrall, D.M., 2005, ApJ, 626, 733
46. Schwartz, D.A., et al., 2000, ApJ, 540, L69
47. Marshall, H. L., et al., 2001, ApJ, 549, L167
48. Tavecchio, F., Maraschi, L., Sambruna, R.M., & Urry, C.M., 2000, ApJL, 544, L23
49. Celotti, A., Ghisellini, G., & Chiaberge, M., 2001, MNRAS, 321, L1
50. Kataoka, J., Edwards, P., Georganopoulos, M., Takahara, F., & Wagner, S., 2003a, A&A, 399, 91
51. Kataoka, J., Leahy, J. P., Edwards, P.G., Kino, M., Takahara, F., Serino, Y., Kawai, N., & Martel, A.R., 2003b, A&A, 410, 833
52. Hardcastle, M.J., & Croston, J.H., 2005, MNRAS, 363, 649
53. Kraft, R.P., Hardcastle, M.J., Worrall, D.M., & Murray, S.S., 2005, ApJ, 622, 149
54. Swain, M.R., Bridle, A.H., & Baum, S.A., 1998, ApJL, 507, L29
55. Swain, M.R., 1996, Ph.D. Thesis, University Rochester
56. Kataoka, J. et al., 2008, ApJ, in press (astro-ph/0806.1260)
57. Stawarz, Ł., & Ostrowski, M., 2002, ApJ, 578, 763
58. Markowitz, A., et al. 2007, ApJ, 665, 209
59. Chiaberge, M., Capetti, A., & Celotti, A., 2001, MNRAS, 324, L33
60. Nandikotkur, G., et al. 2007, ApJ, 657, 706