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Understanding the *Chandra* Detected X-ray Emission of the Knots and Hot Spots of Powerful Extragalactic Jets

Markos Georganopoulos ⋆

NASA/GSFC, Laboratory for High Energy Astrophysics, Greenbelt, MD 20771, USA

Abstract I present here a short personal view of our understanding of the Chandra detected knots and hot spots of powerful Fanaroff Rilley (FR) II radio galaxies and quasars in the context of leptonic models. Observations of the knots and hot spots strongly suggest that the jets in these powerful sources retain their relativistic velocities at large scales, all the way to the hot spots. The emission mechanism suggested for the knots of quasars and FR II radio galaxies is external Compton (EC) off the cosmic microwave backgounrd (CMB) from a relativistic flow, while for the hotspots Upstream Compton (UC) scattering from a decelerating relativistic flow.

Key words: radiation mechanisms: non-thermal – galaxies: quasars

1 INTRODUCTION

Jets, spanning distances up to ∼1 Mpc, emanate from the core of radio-loud active galaxies. Initially mapped at radio, and recently, mostly through *HST* and *Chandra*, at optical and X-ray energies, they reveal a semi-continuous morphology with bright knots and, in the most powerful of them, hot spots, compact high brightness regions, where the jet flow collides with the intergalactic medium (IGM). Although the subject of intense studies over the past decades, the physics of these objects is not well understood. Little is known of the mechanism of their origin, or their composition (i.e. whether they consist of hadrons or leptons). Regarding the kinematic state of the flows in these objects (i.e. whether they are relativistic or not), in both the powerful FR II/Quasars and the less powerfull FR I sources the flow velocity of the pc-scale jets is relativistic with Lorentz factors $\Gamma \sim 10$. In the case of FR I sources the flow seems to decelerate at kcp scales and the jet becomes sub-relativistic (Laing et al. 1999). Although there have long been reasons to believe (e.g. Wardle & Aaron 1997) that the jets of the powerful FR II radio galaxies and quasars (which according to the unification scheme are sources similar to FR II radio galaxies but closer aligned to the line of sight; e.g., Urry & Padovani 1995) remain relativistic at large distances from the active nucleus, there has been no conclusive evidence for this to date.

Until recently, most of the extended jet observations were confined to radio interferometric studies, which probe the synchrotron radio emitting electrons of the flow. In general it has been

⋆ E-mail: `markos@milkyway.gsfc.nasa.gov`

assumed that the radiating electron energy density is in equipartition with the magnetic field energy density, because equipartiton minimizes the energy content of the source required for producing a given synchrotron power and strong deviations from equipartition can raise the energetic requirements to rather uncomfortable levels.

Recently, astronomers were able to map several extragalactic jets at optical and X-ray frequencies through HST and Chandra, with angular resolution similar to that of VLA. In most, if not all cases where optical emission was detected from a radio knot or hot spot, the optical lies on a smooth or convex continuation of the radio spectrum, suggesting that it is the extention of the synchrotron spectrum. The situation with the X-ray flux of knots and hot spots seems to depend on the source power. In general, in the knots of FR I sources the X-ray spectrum seems to be the high energy tail of the synchrotron emission, altough, in a some cases (e.g. M 87; Marshall et al. 2002), with a spectral break relative to the radio-optical spectrum greater than the canonical value $\Delta\alpha = 1/2$, predicted my synchrotron cooling. In the more powerful sources, i.e. FR II radio galaxies and quasars, the X-ray spectrum is not a continuation of the synchrotron spectrum, either because there is a cutoff of the synchrotron spectrum at optical energies (e.g. in the hot spots of Cygnus A; Wilson et al. 2000) and/or the X-ray flux lies above the extrapolation of the radio spectrum (e.g. in the knots of the quasar PKS 0637-752; Schwartz et al. 2000). The X-rays therefore must be the signature of another spectral component, possibly some kind of Compton scattering, given the presence of relativistic electrons in these environments. Two possible sources of seed photons for inverse Compton scattering are the synchrotron photons produced in the source (synchrotron-self Compton, SSC) and external photons, as the photons of the CMB. In most cases, if the emitting region is not moving relativistically and the source is in equipartition, the SSC emission (SSC in equipartition, SSCE) dominates over the EC emission.

Here I briefly review some of the Chandra knot and hot spot observations of powerful sources (FR II radio galaxies and quasars) that critically affect our understanding of the powerful jet flows, and I show how, through studying two different locations, the knots and the hot spots, and using two different lines of reasoning, the same conclusion is reached: *the large scale jet flow remains relativistic up to $\sim$ Mpc scales, where the advancing jets collide with the IGM.* In § 2, I sketch a simple derivation of the argument that the energy content of a source emiting a given synchrotron luminosity is minimized when the electron energy density is in equipartition with the magnetic field energy density. I then use this result to show that the level of the SSC (EC) emission for a source in equipartition decreases (increases) as the beaming of the source increases. In § 3 I review the observations of the knots PKS 0637-752, and the failure of the SSCE mechanism from a non beamed source to account for the bright X-ray emission of the knots (Chartas et al. 2000). I then proceed to present the solution proposed independently by Tavecchio et al. (2000) and Celotti et al. (2001)': the X-ray emission can be explained as EC scattering from a source in equipartition if the source is moving with a substantial Lorentz factor ($\Gamma \sim 10-15$) forming a small angle to the line of sight. In § 4, following Georganopoulos & Kazanas (2003)[GK03] , after I review the disparate multiwavelength properties of the hot spots of Cygnus A and Pictor A, I show that the two sources differ in orientation. I then show that all the sources with Chandra detected hot spots can be broadly separated into Cygnus-like and Pictor-like and their properties can be understood if the flow in the hot spots is relativistic and decelerating. This suggests that the flow feeding the hot spot is relativistic and therefore the jets remain relativistic all the way to the hot spots. I also present a short discussion of UC scattering, a type of scattering occuring in decelerating flow, and I argue that it is responsible for the strong X-ray flux of the hot spots of Pictor A-like sources. Finally in §5 I discuss some open issues and possible directions of future theoretical and modeling work.

2 EQUIPARTITION AND BEAMING

Equipartition. For simplicity, consider a synchrotron source with a monoenergetic electron population of a fixed Lorentz factor γ. The particle energy density is $U_{\rm p} = n\gamma m_{\rm e}c^2$, where n is the number density of electrons, $m_{\rm e}$ is the electron mass and c is the speed of light. The energy density of the magnetic field B is $U_{\rm B} = B^2/8\pi$. The synchrotron luminosity is

$$L_{\rm s} \propto n\gamma^2 B^2 = \gamma U_{\rm p} U_{\rm B}\,.$$

For fixed $L_{\rm s}$ the product $U_{\rm p}U_{\rm B}$ is constant: $U_{\rm p}U_{\rm B} = C$. The total energy density is $U = U_{\rm p} + U_{\rm B} = U_{\rm p} + C/U_{\rm p}$ and it is minimized when

$$\frac{dU}{dU_{\rm p}} = 0 \Rightarrow U_{\rm p}^2 = C$$

and since $U_{\rm p}U_{\rm B} = C$,

$$U_{\rm p} = U_{\rm B}. \tag{1}$$

Equipartition, therefore, between the radiating particles and the magnetic field energy density minimizes the energy needed to produce a given synchrotron luminosity.

SSC Luminosity As A Function Of Beaming. The SSC luminosity of the source described above is

$$L_{\rm SSC} \propto \gamma U_{\rm p} U_{\rm s},$$

where $U_{\rm s} \propto \gamma U_{\rm p} U_{\rm B} R$ is the synchrotron photon energy density of the source and R is its fixed radius. The SSC luminosity can now be written as

$$L_{\rm SSC} \propto \gamma^2 R\, U_{\rm p}^2 U_{\rm B}\,.$$

If now the source is moving with a bulk Lorentz factor Γ forming an angle θ to the line of sight, then the Doppler factor is $\delta = 1/\Gamma(1-\beta\cos\theta)$ and the observed synchrotron luminosity is $L_{\rm s,obs} = \delta^4 L_{\rm s}$. A fixed observed synchrotron luminosity $L_{\rm s,obs}$ implies a comoving synchrotron luminosity $L_{\rm s} \propto \delta^{-4}$. Also, if the source is in equipartition $L_{\rm s} \propto U_{\rm B}^2 = U_{\rm p}^2$, since $U_{\rm p} = U_{\rm B}$, and $U_{\rm B} = U_{\rm p} \propto \delta^{-2}$. Therefore $L_{\rm SSC} \propto U_{\rm p}^2 U_{\rm B} \propto \delta^{-6}$, and because $L_{\rm SSC,obs} = L_{\rm SSC}\delta^4$ one obtains

$$L_{\rm SSC,obs} \propto \delta^{-2}. \tag{2}$$

If a source of a given observed synchrotron luminosity is assumed to be in equipartition the anticipated SSCE luminosity decreases by δ^2 as the assumed beaming increases. This is the reason relativistic beaming was proposed as an explanation for the expected but not observed high X-ray luminosities of compact radio sources.

EC Luminosity As A Function of Beaming. If the source is propagating through an isotopic photon fiend of energy density $U_{\rm ext}$, its energy density in the source comoving frame will be $\Gamma^2 U_{\rm ext}$. The EC luminosity in the comoving frame will be $L_{\rm EC} \propto \gamma U_{\rm p}\Gamma^2 U_{\rm ext}$. Given that $L_{\rm EC,obs} = L_{\rm EC}\delta^6/\Gamma^2$, and that in equipartition $U_{\rm p} \propto \delta^{-2}$, the observed EC luminosity will scale with beaming as

$$L_{\rm EC,obs} \propto \delta^4. \tag{3}$$

Therefore, for a source with a given observed synchrotron luminosity, assumed to be in equipartition, the observed EC luminosity increases by δ^4 as the assumed beaming increases.

These results, demonstrated here for the limited case of a source with a monoenergetic population of electrons can be appropriately generalized for a power law electron energy distribution. The result that I will use in the rest of this review is that if the observed X-ray emission of a system is higher that the estimated SSCE X-ray emission assuming no beaming, SSCE with beaming will reduce even further the anticipated X-ray emission relative to the unbeamed level. On the other hand, the anticipated EC X-ray level will increase with increasing beaming eventually reaching the observed X-ray flux for an appropriately high value of δ.

3 PKS 0637-752 KNOTS: EXTERNAL COMPTON OFF THE CMB

SSC Is Out. One of the earliest *Chandra* observations was the detection of an one sided large scale X-ray jet in the quasar PKS 0637-752 (Schwartz et al. 2000, Chartas et al. 2000), with strong emission form knots located at a projected distance of ≈ 100 kpc from the nucleus. The knots were also detected in the optical with *HST*, providing the opportunity to study their broadband radio to X-ray spectral energy distribution. The optical flux of the knots falls a factor of ~ 10 below the line joining the radio and X-ray fluxes, indicating that there are two different spectral components and excluding the possibility that the entire spectrum is due to synchrotron emission. A natural candidate then for the X-ray emission is SSC or EC scattering. However, it was quickly pointed out (Chartas et al. 2000) that, in the absense of relativistic beaming, the level of the X-ray emission is much stronger than what would be expected either from SSCE (~ 2 orders of magnitude) or EC scattering off the CMB photons (~ 4 orders of magnitude) assuming equipartition. Reproducing the X rays through SSC requires a magnetic field ~ 50 times below the equipartition level, which in turn increases the energy requirements by $\sim 10^3$. An attempt to explain the X-ray flux through de-beamed SSCE also faces severe problems: As shown in §2 the SSCE flux increases with decreasing Doppler factor. Indeed, the X-ray flux of the knots can be reproduced assuming a Doppler factor $\delta = 0.3$. This requires that the angle of the X-ray jet to the line of sight is $\approx 53°$, given that explaining the X-ray non-detection of the counterjet requires a Lorentz factor $\Gamma \approx 8$ (Schwartz et al. 2000). Such an angle however is in disagreement with the upper limit $\theta < 6.4°$ of the VLBI jet derived from the observed superluminal motions (Lovell et al. 2000), and, given that there is no apparent bend between the VLBI and large scale jet, the only permitted configuration would require a bend jet on a plane perpendicular to the plane of the sky. As Schwartz et al. (2000) pointed out, even in this remote case the apparent radio luminosity of 3×10^{43} erg s^{-1} would correspond to a radio luminosity of 2×10^{46} erg s^{-1} for a similar source pointing toward the observer, exceeding significantly the blazar radio luminosity. It seems therefore that SSC emission is not a viable mechanism for the observed X-ray emission of this source.

EC Is In. The next natural candidate for reproducing the X-ray flux is EC scattering off CMB photons. In this case, as was demonstrated in §2, an increase of the Doppler factor increases the level of the EC emission. EC scattering is also promising because the jet of this particular source forms a small angle to the line of sight, resulting to a substantial value of δ for a given Γ. Tavecchio et al. (2000) and Celotti et al. (2001) showed that if the knot plasma is flowing relativistically with a Lorentz factor $\Gamma \sim 10$, forming an angle $\theta \approx 5°$ to the line of sight, the boosting of the CMB photon energy density by Γ^2 in the comoving with the flow frame, reproduces the observed X-rays through EC scattering, with the source being in equipartition. According to this picture, the electron energy distribution must have a low energy cutoff at $\gamma \approx 10$, otherwise it would overproduce the optical flux (Tavecchio et al. 2000). The total jet power required in this picture is of the order $10^{47} - 10^{48}$ erg s^{-1}, similar to the power carried by the jets of the most powerful blazars. A comparison of the synchrotron to the model EC luminosity shows that in this scenario the EC losses dominate the energetics. At larger angles however, as δ decreases, the EC flux decreases and the SSC flux increases relative to the synchrotron flux assuming equipartition. Therefore, similar sources at larger angles, will have an X-ray output dominated by SSC emission, although the radiative losses will still be dominated by EC scattering. This is an interesting point that has to be taken into account in modeling such sources at large angles: one has to include the EC losses in the calculation of the energy losses and of the electron enectron energy distribution, even though SSC emission may dominate over EC emission at large angles.

For Ever Detectable. An interesting corollary of this picture was recently described by Schwartz (2002): if the X-rays are due to EC scattering on the CMB, then these knots should be detectable with the same surface brightness even if the source is located at much higher redshifts z. This is because the CMB energy density scales as $(1+z)^4$ and exactly compensates the $(1+z)^{-4}$ scaling of the surface brightness (note that the angular size remains practically constant for $z > 1$, almost independently of the cosmology chosen). Therefore, if the X-ray knots are due to EC scattering from the CMB, they should be observable at any redshift at which they exist. On the other hand, the flux from the core, assumed not to depend on the CMB energy density, will decrease with increasing luminosity distance (redshift), and the X-ray observed flux will be dominated by the knots and not by the core at redshifts above $z \approx 3-4$, contrary to the case of nearby sources like PKS 0637-752 and 3C 273 (Marshall et al. 2001). Then, at large z, one expects to see in X-rays only the jet - knot emission, displaced by the optical core (non-detectable in X-rays) by $5'' - 10''$. These X-ray bright-radio quiet jets should be among the unidentified ROSAT sources, and their detection or not will provide a test for the EC knot emission model.

The Cooling Problem: Continuous Jets, Not Knots. Although the radiative cooling length of the electrons responsible for the synchrotron optical and EC γ-rays is ~ 10 kpc (Tavecchio et al. 2000), comparable to the ~ 3 kpc size of the PKS 0637-752 knot size, as Schwartz (2002) noted, the radiative cooling length of the low energy electrons ($\gamma \sim 100$) that produce the X-rays through EC scattering off the CMB is ~ 100 kpc or more, comparable to the total length of the jets, and much larger than the typical observed knot sizes. Therefore, instead of the observed knot morphology, according to the EC scenario one should observe a continuous jet in X-rays. Tavecchio at al. (2003) note that outside the bright knots X-rays dim as fast as optical and radio, and that this behavior is not compatible with radiative losses, which would give at each frequency a size proportional to the corresponding electron loss length scale. They then suggest adiabatic losses as the dominant electron energy loss mechanism for all but the most energetic electrons. The attractive characteristic of adiabatic energy losses is that they cool also the low energy electrons responsible for the EC X-ray emission, thus reducing the size of the X-ray emitting regions. However, for typical values of the physical parameters involved they find that the size of the X-ray emitting regions is still much larger than observed. To overcome this problem and keep the EC/CMB interpretation of the X-rays, they speculated that each observed knot is a collection of micro-knots which expand adiabatically in three dimensions, resulting to strong adiabatic electron losses that keep the cooling length of the X-ray emitting electrons roughly equal to the observed knot size.

A plausible solution to the problem of the size of the knots (Georganopoulos & Kazanas, in preparation) is that low energy electrons are present throughout the jet and there is no need for them to cool catastrophically. The reason then we observe a knot morphology in X-rays is that the needed seed photon energy density is present only in the knot environment. If the flow in the knots is relativistic and decelerating the electrons of the faster part of the flow will see the synchrotron emission of the slower part of the knot relativistically boosted and will radiate X-ray emission (more on this type of Compton emission, in §4). Once they are advected away from the fast part of the flow, they stop radiating in X-rays, not because they do not have the necessary energy, but because they lack the seed photons for Compton scattering. In addition EC off the CMB will be more effective and beamed at the fast part of the flow, where the Lorentz factor is higher, decreasing its power and widening its beaming pattern at the downstream part of the flow. Given that the knots are sites of particle deceleration, which most probably takes place in shocks, it is natural to assume that these shocks are the locations of the needed bulk flow deceleration.

4 HOT SPOTS

The first hot spots to be detected in X-rays were those of the nearby powerful radio galaxy Cygnus A (Harris et al. 1994), whose X-ray flux measured by *ROSAT* was found to be in agreement with SSCE. Because the advance speed of the hot spots through the IGM is slow ($u/c \approx 0.1$, e.g. Arshakian & Longair 2001), it has been implicitly assumed that the plasma flow in the hot spots is also sub-relativistic. The Cygnus A hot spots show no optical emission, suggesting a synchrotron spectral cutoff at lower frequencies. This was therefore the situation before the Chandra era, as confirmed by *ROSAT* observations of Cygnus A: the plasma in the hot spots was assumed to be in equipartition and moving sub-relativistically.

While *Chandra* observations of Cygnus A confirmed the SSCE picture (Wilson et al. 2000), observations of Pictor A, another nearby powerful radio galaxy, present a drastically different picture (Wilson et al 2001): (*i*) An one-sided large scale X-ray jet on the same direction with the known VLBI jet (Tingay et al. 2000). (*ii*) Detection of X-ray and optical emission only from the hot spot on the jet side. (*iii*) SSCE models for the Pictor A hot spots under-produce the observed X-ray flux: The synchrotron photons are not a sufficient source of seed photons for producing the observed SSC emission under equipartition conditions. This last point describes the *problem of the missing seed photons*, which is likely to be germane to other high energy sources (e.g. TeV Blazars; Georganopoulos & Kazanas 2003b): *The synchrotron photon energy density in the SSCE model is lower that the seed photon energy density required to produce the observed inverse Compton emission.* In the SSC model a decrease in the magnetic field leads to an increase of the Compton to synchrotron flux ratio. In the case of Pictor A, a magnetic field ~ 14 times below its the equipartition value is required in order to achieve agreement with the observed the X-ray flux. The problem of the disparate hot spot properties of Cygnus A and Pictor A deepened further with the discovery by *Chandra* of more X-ray emitting hot spots, and the issue is currently a matter of active debate (e.g. Wilson 2001, Hardcastle et al. 2002, Kataoka et al. 2003, GK03).

An Orientation Sequence. An indicator of orientation for radio-loud active galaxies is the ratio R of the core (beamed) to the extended (isotropic) radio emission. Sources with jets closer to the observer's line of sight are expected to have higher values of R than those with jets on the plane of the sky. Cygnus A has $\log R \approx -3.3$, while Pictor A has $\log R \approx -1.2$, suggesting that the jets of Pictor A are closer to the line of sight than those of Cygnus A. Another indicator of source orientation is the detection of broad emission lines in the optical-UV spectrum of the core emission. According to the unification scheme for radio loud active galaxies (e.g. Urry & Padovani 1995), broad line radio galaxies (BLRG) and quasars have jets pointing close to the line of sight, while narrow line radio galaxies (NLRG) have jets closer to the plane of the sky. Cygnus A is a NLRG, and Pictor A is a BLRG, suggesting again that Pictor A is aligned closer to the line of sight.

Motivated by the orientation difference of the two sources, GK03 studied the sources with X-ray hot spot detections, mostly from high resolution *Chandra* observations. A set of correlations with jet orientation emerges from this study:

• As the jet alignment with the observer's line of sight manifest by R increases, the source changes from a NLRG to a BLRG/Quasar.

• Sources with jets closer to the plane of the sky show hot spots of comparable X-ray flux from both lobes, while sources with more aligned jets show X-ray hot spots on the side of the near jet, as identified through VLBI observations.

• While in NLRG the radio-to-X-ray spectra are modeled successfully by SSCE, in the more aligned BLRG and quasars, the hot spot X-ray emission is significantly stronger than its SSCE predicted value, again a manifestation of the *problem of the missing seed photons* facing SSCE models; Hence, in the SSC framework one has to resort to magnetic fields well below equipartition by factors $\sim 10-30$ to reproduce the observed X-ray flux, increasing by orders of magnitude the required jet power.

• Synchrotron optical emission, weak or absent in the NLRG hot spots, appears at the jet side hot spot as the source aligns closer to the line of sight.

• Radio emission is seen from both hot spots, regardless of orientation, although the hot spots on the VLBI jet side of BLRG/quasars are brighter and have a flatter spectrum.

Differential Beaming. GK03 proposed that this orientation sequence can be accounted for by appealing to *frequency dependent* beaming of the hot spot emission. In this case, the synchrotron emission is beamed most at its highest (optical) frequencies. As a result it is observed preferentially in the near hot spot of the more aligned objects (BLRG/quasars). Beaming decreases (i.e. the intensity amplification becomes lower and the beaming pattern broader) with decreasing frequency, with the lowest frequency (radio) emission being the least beamed, thus observed in the hot spots of both jets of all objects (albeit with higher flux from the near jet hot spot).

The X-ray emission is generally attributed to the Compton component of the SSC process by the electrons responsible for the radio emission. As such, the orientation dependence of these two components should be virtually identical. This is in agreement with the X-ray detection from both hot spots in NLRG and their successful modeling with SSCE. It would then appear that the X-ray detection from single hot spots, as the source alignment increases, is at odds with this picture. However, detections of X-rays from only the near hot spot are also accompanied by an increase in the radio-to-X-ray ratio beyond that of the SSCE models, indicating the presence of an additional component more sensitive to orientation than SSCE.

Decelerating Relativistic Flows and Upstream Compton Scattering. GK03 argued that this frequency dependent beaming and the excess X-ray emission in the more aligned sources can be accounted for in terms of a relativistic, decelerating flow at the hot spots. This possibility has not been explored in view of their sub-relativistic ($u/c \approx 0.1$, e.g. Arshakian & Longair 2000) advance speed through the IGM. However hot spot flow patterns with Lorentz factors up to $\Gamma \sim 3$, decelerating to the sub-relativistic hot spot advance speed are routinely seen in relativistic hydrodynamic simulations (Aloy et al. 1999, Komissarov & Falle 1996), and have been invoked (Komissarov & Falle 1996) to account for the observed higher radio brightness of emission from the near hot spots compared to that of the far ones.

In such decelerating flows, the highest frequencies of the synchrotron component originate at thw fast base of the flow where the electrons are more energetic and its Lorentz factor largest. As both the flow velocity and electron energy drop with distance, the locally emitted synchrotron spectrum shifts to lower energies while its beaming pattern becomes wider. The observed synchrotron spectrum is the convolution of the comoving emission from each radius weighted by the beaming amplification at each radius, with the high energy photons beamed in a more narrow angular pattern than the low energy ones.

The inverse Compton emission of such flows behaves in a more involved way: Electrons upscatter the locally produced synchrotron seed photons, giving rise to a local SSC emission with a beaming pattern identical to that of synchrotron. In addition to this, Upstream Compton (UC) takes place, a process in which synchrotron photons from its slower downstream section serve as seed photons for Compton scattering by electrons in its upstream faster part. The energy density of these downstream produced synchrotron photons, is boosted in the fast (upstream) part of the flow by $\sim \Gamma_{\rm rel}^2$ (Dermer 1995), where $\Gamma_{\rm rel}$ is the relative Lorentz factor between the fast and slow part of the flow. Also, the beaming pattern of the UC radiation is narrower (see Appendix A) than that of the synchrotron/SSC pattern of $\delta^{2+\alpha}$, where α is the radiation spectral index, approaching the $\delta^{3+2\alpha}$ beaming pattern of external Compton (EC) scattering

(Dermer 1995, Georganopoulos et al. 2001). It is the combination of higher synchrotron photon energy density measured at the comoving with the fast flow frame and the more narrow than synchrotron/SSC beaming of UC scattering that explain why the additional X-ray emission, which gives rise to the missing seed photon problem in the framework of SSCE models, is evident only in the more aligned sources.

The following simplified model, involving relativistic decelerating flows, was used to reproduce the multi-object, multi-frequency phenomenology of hot spot emission: A relativistic EED $N_e(\gamma) \propto \gamma^{-s}$, $s = 2$ with high energy cut-off at $\gamma_{\rm max} \simeq 2\times10^6$ is injected impulsively at the base the flow, in equipartition with the ambient magnetic field and assumed to remain so as the flow decelerates. A plane-parallel flow geometry is assumed with bulk Lorentz factor decreasing with the distance z from the shock as $\Gamma(z) = \Gamma_0(z/z_0)^{-3}$, with $\Gamma_0 = 3$ and $z_0 \simeq 1$ kpc, in agreement with *Chandra* observations. The synchrotron and Compton emission coefficients are computed using approximate formulae and the hot spot spectra are obtained by integrating these over the volume of the flow taking into account both their $z-$ and $\theta-$ dependent beaming amplification (θ is the angle between the flow velocity and the observer's line of sight) assuming a "pill-box" geometry for the flow, i.e. transverse dimension $D = 2z_0$. The resulting spectra under typical BLRG/Quasar ($\theta = 20°$, solid line) and NLRG ($\theta = 70°$, dashed line) orientations are given in Fig. 1.

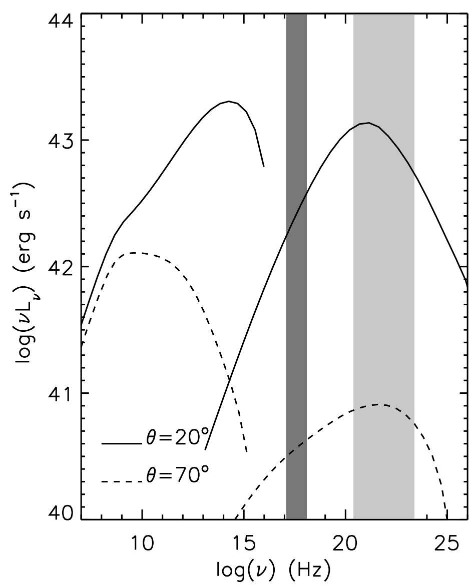

Fig. 1 The synchrotron and inverse Compton emission of a decelerating relativistic flow observed under two different angles.

Several important points are apparent in this figure:

• The ($\theta = 70°$) spectrum exhibit an X-ray to radio ratio very similar to that observed in Cygnus A and the rest of the NLRGs, while, the ($\theta = 20°$) spectrum, has a significantly higher X-ray to radio ratio due to UC scattering, in agreement with those observed in BLRG/quasars, including Pictor A.

• The synchrotron component is prominent at optical frequencies for $\theta = 20°$, while essentially cuts off for $\theta = 70°$, in agreement optical hot spot detections only from the hot spots of the approaching jet.

• The change of slope at the "cooling" break at $\nu \simeq 1$ GHz is much smaller for $\theta = 20°$ and generally consistent with the spectrum observed in Pictor A (Wilson et al. 2001), while at $\theta = 70°$ there is a stronger break similar to that observed in Cygnus A, and with a slope with the canonical value $\Delta\alpha = 1/2$.

•The synchrotron spectra of the hot spots viewed at smaller angles are *flatter* than those at large angles, and also flatter than those of the receding jets (not shown here). This is a well known fact (Dennett-Thorpe et al. 1997) but without any clear explanation todate. Decelerating flows provide a straightforward account for it: At small angles, the decelerating flow amplifies the emission of higher synchrotron frequencies more than that of lower frequencies, leading to flatter spectra than those observed at large angles for which relativistic boosting is not significant. For the same reason, the break at large angles and/or rapid decelerations can increase up to $\Delta\alpha \approx 0.7$, something that has been observed in the X-ray detected knots of the FR I galaxy M87 (Marshall et al. 2002).

• In some of the nearby ($z \leq 0.1$) Pictor A- type sources, the hot spot high energy $\gamma-$ray flux in the 10 MeV−10 GeV band of *GLAST* will be both detectable and its position sufficiently well determined to be distinguished from the (potential) emission from the AGN "core".

I stress that the existence of relativistic flows in the hot spot requires that the jet flow remains relativistic up to its termination at the hot spots at distances up to $\sim$ Mpc from the AGN "core".

5 CONCLUSIONS

Chandra offers us the unique opportunity to study extragalactic jets in X-rays with arcsecond resolution. This capability resulted to the discovery of an increasing number of X-ray emitting knots and hot spots in extragalactic jets. The study of both the knots and the hot spots of powerful jets support the idea that these jets remain relativistic all the way to the hot spots, where the jets collide with the IGM. Previous arguments for large scale relativistic flows (e.g. Wardle & Aaron 1997) were based on radio data only. It now seems safe to state that sub-relativistic large scale flow velocities in the jets cannot reproduce the multi-wavelength multi-object observations of knots and hot spots.

Assuming that, aside the idiosyncracies of individual sources, all powerful extragalactic jets are at first order similar, a unified phenomenological framework, based on the orientation of the sources, seems promising; such a scheme should in the future also include the source power to accomodate the knots of the less powerful sources like FR Is and their aligned population BL Lacertae objects (in these sources the knot X-ray emission seems to be dominated by synchrotron radiation). A similar situation emerges in blazars, where a recent study by Padovani et al. (2003) shows that powerful blazars avoid the extreme synchrotron peak frequencies that BL Lacertae objects can reach.

From the theoretical/modeling point of view the first step to be taken is to establish the energy loss and radiation mechanisms responsible for the broadband spectra of hot spots and knots. Since the source orientation is involved, it is imperative to have observations of several sources with jets oriented at different angles, and, if possible, observations of the counter jet/counter hot spot. Note here that, while inverse Compton scattering either as EC off the CMB or UC may be the dominant energy loss mechanism, if the source is misaligned the X-ray output will mostly be due to SSC. The broadband hot spot spectra of broad line (i.e. closer aligned) objects as well as narrow line (i.e. closer to the plane of the sky) objects, seem to fit in the scheme of GK03, according to which the flow in the hot spots is relativistic and decelerating.

In this scheme the higher than anticipated X-ray flux of the broad line objects is attributed to UC scattering. Further *Chandra* observations will check and quantitiatively constrain this scheme.

The knot broadband emission of the aligned superluminal quasar PKS 0637-752 has been interpreted by Tavecchio et al. (2000) and Celotti et al. (2001) as EC scattering off the CMB background. A serious difficulty this scheme encounters is the fact that the cooling length of the $\gamma \sim 100$ X-ray emitting electrons is much larger that the observed knot size. A solution of this problem can be reached assuming either that the electrons cool catastrophically inside the knot, or that the electrons just lack the appropriate seed photons outside the knot. The first alternative prompted Tavecchio et al. (2003) to suggest that each knot is composed of several micro-knots and that adiabatic losses cool the electrons of these micro-knots below $\gamma \sim 100$, after they have propagated for a distance similar to the macroscopic hot spot. The second alternative naturally occurs in a decelerating flow, where both the UC and EC emission off the CMB are confined at the fast base of the flow (EC emission will obviously be produced downstream, albeit at a lower total power, since the comoving CMB photon density scales as $\sim \Gamma^2$, and with a wider beaming pattern. These alternatives give different variability and orientation behaviors which can be tested through future observations.

After establishing the radiation mechanisms, an interesting question, similar in nature to the one still being open in blazar research should be addressed: why the synchrotron spectrum of the most powerful sources (cores, knots, hot spots) cannot reach X-rays energies? In the case of the cores of the powerful blazars , it was suspected that this is due to the photon field of the broad line region increasing the radiative losses of the electrons and reducing the maximum electron energy. However this cannot be the explanation for the extended jet features that are far from the broad line photon fields. This opens the possibility that the spectral difference between weak and powerful sources reflects an intrinsic different that persists throughout the extended jet.

The ground for studying the large scale extended jets is very fertile. Our new observational capabilities offer a foundation we can use to advance our understanding of extended jets. Hopefully, this will bring within our reach the solution of an old persistent problem, that of the matter content of the jets.

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Appendix A: THE BEAMING OF UC SCATTERING

I outline here the argument that the UC beaming is more tight than the Synchrotron/SSC beaming. Consider for simplicity a two-zone flow, a fast part with Lorentz factor Γ_1 followed by a slower part with Lorentz factor Γ_2. Consider also an observer located at an angle θ such that the Doppler factors of the two zones are δ_1, δ_2. The beaming pattern of the UC radiation in the frame of the slow part of the flow will be $\delta_{1,2}^{3+2\alpha}$, where $\delta_{1,2}$ is the Doppler factor of the fast flow in the frame of the slow flow. To convert this beaming pattern to the observer's frame we need to boost it by $\delta_2^{2+\alpha}$. The beaming pattern is then written as $\delta_{1,2}^{3+2\alpha}\,\delta_2^{2+\alpha}$. To write $\delta_{1,2}$ as a function of δ_1, δ_2, we note that a photon emitted in the fast part of the flow is seen by the observed boosted in energy by a factor δ_1. The same boosting can take place is two stages: first going to the frame of the slow flow by being boosted by $\delta_{1,2}$ and then going to the observer's frame by being boosted by δ_2. Because the final photon energy in the observer's frame does not depend on the intermediate transformations, $\delta_{1,2} = \delta_1/\delta_2$. The beaming pattern of UC scattering is therefore $\delta_1^{3+2\alpha}/\delta_2^{1+\alpha}$. Note that, as expected, for $\delta_1 = \delta_2$, we recover the beaming pattern of SSC, while for $\delta_2 = 1$, that of EC radiation.

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