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The Blazar Paradigm: Synchro-Compton Emission from Relativistic Jets

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Abstract. I review the current paradigm for nonthermal emission from jets in blazars. The evidence for relativistically flowing jets seems to be more compelling than the case for incoherent synchrotron and self-Compton emission in these objects. I discuss some of the important aspects of current observations of rapid variability at radio frequencies, and stress that one must be careful when calculating the Doppler factor that saves us from the inverse Compton "catastrophe." I discuss the possibilities for the nature of the VLBI components and present evidence that, at high frequencies, the core is a standing shock wave (Mach disk), while the superluminal components are propagating shocks. I expect that high-frequency and space VLBI will resolve many of the major outstanding issues.

1. The Emission Mechanisms in Blazars

The generally accepted paradigm for the radiation mechanism in blazars is that the radio to optical and, in some objects, the ultraviolet and X-ray, emission is incoherent synchrotron radiation. The basis for this in extended radio lobes is solid: the substantial linear, but essentially zero circular, polarization with a power-law spectrum is characteristic of an ensemble of relativistic electrons that spiral in an ambient magnetic field. However, in compact sources, the evidence is not as compelling. The low circular polarization is also possible from coherent mechanisms if the emitting plasma contains an equal number of electrons and positrons. In addition, significant circular polarization has now been found with VLBI in one or two sources (Wardle, these Proceedings, p. 97). As is discussed below, rapid—in many cases intraday— variability at low frequencies is difficult to reconcile with incoherent synchrotron radiation. Furthermore, it is rare in compact sources that the spectrum can be fit by a power law over more than a decade in frequency; the continuity of the spectra from radio to infrared does, however, suggest strongly that the infrared emission mechanism is the same as in the radio (Landau et al. 1986). Independent evidence for the paradigm comes from Readhead (1994), who has found that the brightness temperatures of large samples of compact radio sources seem to obey a brightness temperature limit corresponding to equipartition in energy between the electrons and the magnetic field, as would only occur if the assumption that the radiation is incoherent synchrotron is valid.

From the above critique, it might seem that I am arguing against incoherent synchrotron radiation as the primary emission mechanism. However, I think that the continuity of compact jets with more extended jets, which *do* seem to radiate in the same manner as the extended lobes, is a strong argument in favor of the "conservative" hypothesis that incoherent synchrotron emission dominates in compact jets as well. Therefore, it is my opinion that we are justified in our attempts to reconcile the observations with this paradigm. We should, however, always keep in mind that the data do not support this view as thoroughly as many of us seem to think! (And, there are alternatives, such as the synchrotronmimicking collective plasma bremsstrahlung emission proposed by Weatherall & Benford [1991].)

Synchrotron self-Compton scattered (SSC) emission must occur in a compact synchrotron source, and for years our main difficulty was in understanding why blazars are not even brighter X-ray sources than observed owing to this process. However, there is thus far only weak evidence that this is actually the primary emission mechanism at X-ray (or γ-ray) energies: There is a general correlation between compact radio brightness and X-ray flux (e. g., Worrall et al. 1987), and the 2–10 keV X-ray spectrum is flatter in many blazars than is the continuation of the IR-optical-uv spectrum (see, e. g., the observations of BL Lac by Kawai et al. 1991; the X-ray spectral slope in this object is similar to the optically thin spectral index at submillimeter wavelengths, as required by the model). In addition, in a major outburst of 3C 279 the millimeter–infrared and X-ray fluxes both increased, as expected (Makino et al. 1989).

At γ-ray energies, the main current controversy is whether the emission is SSC or inverse Compton scattering of seed photons that are external to the jet, such as from the central engine (Dermer & Schlickeiser 1993) or from the emission-line region (Sikora, Begelman, & Rees 1994). Each model has some aspects that agree very well, and others that conflict, with the data. Since both processes must operate at some level, it is possible that each one dominates for particular classes (such as external photon scattering in quasars with strong line emission and a high ratio of γ-ray to infrared luminosity and SSC for BL Lac objects). If the γ-ray emission in an object is from inverse Compton scattering of photons external to the jet, the X-rays are likely to arise from the same process.

2. Evidence for Relativistic Flows in the Jets

The observational support for relativistic motion in the jets of blazars is in fact quite impressive, as long as the redshifts are assumed to be cosmological under a Friedmann model of the universe. Bulk motion with a Lorentz factor Γ toward the observer within an angle of $\sim 1/\Gamma$ to the line of sight is still the most straightforward way to reproduce the proper motions of compact radio components. It also explains the one-sided appearance of compact jets in blazars via Doppler boosting of the flux from the approaching halves of the presumably two-sided jets. Relativistic motion also eases the problems associated with rapid variability (see the next section below).

In some of the γ-ray bright blazars, such as 1633+382 (Mattox et al. 1993) and, especially, 3C 279 (in which the X-rays and γ-rays varied simultaneously; McHardy et al., in preparation), relativistic motion is required to reduce the actual luminosities to levels such that the photon density is low enough for the > 100 MeV photons to escape before pair-producing. By implication, variations at lower frequencies that are simultaneous with a γ-ray flare arise from the same physical region with the same bulk Lorentz factor. Data obtained thus far indicate that in some flares there are no time lags between frequencies—which favors shock models, in which the Lorentz factor is the same at all frequencies—but in others there are frequency-dependent time lags or timescales for the flares, which favor either the frequency-stratified shock models (Marscher & Gear 1985) or a model in which the γ-ray emission arises from a region in the ambient jet where the flow accelerates (Maraschi et al. 1992).

As one can see from many of the VLBI images presented at the colloquium and published in the literature, the compact jets of blazars are often rather dramatically bent. This is most readily explained if there is only a small amount of intrinsic bending that is amplified by projection effects when the jet is viewed end-on, as required in the relativistic jet scenario. Many of the twisted structures are being interpreted in terms of helical jets. If one accepts such a geometry, a main question is whether the helix results only from a precession of the nozzle of the jet, with ballistic motion down the jet (as in SS 433; Hjellming & Johnston 1981). It is more difficult to accept the notion that the flow velocity traces out a helical pattern with a high pitch angle, as has been proposed by Conway & Murphy (1993) to explain the clustering around 90° of the difference between large-scale and milliarcsecond-scale structural position angles and by Lobanov & Zensus (1997) to explain the trajectories and spectral evolution of superluminal components in 3C 345. My objection is purely theoretical: relativistic flows contain a lot of momentum density and therefore should not be so easily persuaded to follow a highly non-rectilinear path.

It has been recognized for some time that Doppler beaming creates a selection effect such that relativistic jets of modest luminosity will have very high apparent luminosity, and therefore will be over-represented in a flux-limited sample. The statistics of beamed sources has been considered by Vermeulen & Cohen (1994) and Lister & Marscher (1997; see also these Proceedings, p. 137). In the latter paper, an intrinsic luminosity function and redshift distribution were adopted in order to simulate a realistic parent population from which a flux-limited sample was drawn. The statistics of compact radio sources can be satisfactorily reproduced by these simulations, as long as the parent population constitutes a sizable fraction (3–14%) of elliptical galaxies brighter than L_*. The vast majority of jets, however, should have low luminosities and low bulk Lorentz factors. In other words, objects with blazar luminosities and highly relativistic jets should be rare objects in a volume-limited sample.

3. Rapid Variability and the Brightness Temperature Limit

One of the distinguishing characteristics of blazars is that their flux densities are highly variable. This property provides very useful diagnostics for inferring the physical conditions in the jet. In fact, it was the inability of expanding cloud models to reproduce the spectral evolution that led to the currently popular shock models (Marscher & Gear 1985; Hughes, Aller, & Aller 1985). However, throughout the history of flux-density monitoring there has always been the problem that in many sources the timescales of variability are shorter than can be explained in a straightforward manner by the prevailing theories of the time.

The problem has traditionally been most acute at low frequencies, since variability on timescales of weeks or months at frequencies below 2 GHz implies very high brightness temperatures $T_b(\mathrm{var})$ and is therefore difficult to reconcile with the $T_b(\mathrm{lim}) \sim 10^{12}$ K inverse-Compton limit of the incoherent synchrotron process. This was apparently resolved by Rickett, Coles, & Bourgois (1984), who, having noted that the mean fluxes of pulsars vary at low frequencies on similar timescales as do compact extragalactic sources, proposed that refractive interstellar scintillation is the main cause of this phenomenon. (This had in fact been proposed earlier by Shapirovskaya [1978], prior to the pulsar observations.)

Since the realization that propagation effects extrinsic to the source can cause the low-frequency variations, the focus of concern has been on the intra-day variability at centimeter wavelengths discovered by Heeschen (1984). There are two main controversies: (1) whether the variations are intrinsic or caused by refractive interstellar scintillation, and (2) if intrinsic, whether relativistic effects can explain the rapid timescales under the incoherent synchrotron hypothesis. More than one author (see, e. g., Rickett, these Proceedings, p. 269) at the colloquium has stressed that any radio source sufficiently compact to vary on intraday timescales must also scintillate. There is a question, however, as to whether the significance of the scintillations fades when the frequency exceeds ~ 3 GHz. For a flat-spectrum radio source, the angular size of the dominant emitting region decreases roughly as ν^{-1}, whereas the scattering angular size decreases more steeply, although its precise dependence on frequency is not known owing to our imperfect understanding of interstellar turbulence and the faintness of pulsars at higher frequencies. Arguing against the scintillation model is the difficulty that it has in explaining the polarization variations and the apparent correlation between optical and radio quasi-periodic fluctuations (Wagner & Witzel 1995).

The most extreme cases of intraday variability imply brightness temperatures as high as $\sim 10^{21}$ K if the variations are intrinsic, the characteristic dimension of the emitting region along the line of sight is $\sim c$ times the variability timescale, and the distances are assumed to be cosmological (see the review by Wagner & Witzel 1995 and the paper by Kedziora-Chudczer et al., these Proceedings, p. 267). There seems to be some misunderstanding as to how much relativistic beaming is needed to reconcile these inferred brightness temperatures with the inverse Compton limit. The brightness temperature limit itself transforms as $T_b(\text{lim}) \sim 3 \times 10^{11}[\delta/(1+z)]^{-1.2}$ K, where the power of 1.2 comes from the dependence of the synchrotron to inverse Compton luminosity ratio on $T_b^5 \nu_m$, where ν_m is the self-absorption turnover frequency. (Notice that the limit is actually somewhat lower than 10^{12} K, since at this higher level the inverse Compton luminosity is already ~ 3 orders of magnitude higher than the synchrotron luminosity.) The ratio of the brightness temperature inferred from the timescale of variability (before redshift correction) to that which would be measured directly by VLBI were the resolution high enough (or inferred from scintillations) is proportional to $[\delta/(1+z)]^2$. Hence, the minimum Doppler factor needed to reconcile the inferred brightness temperature $T_b(\text{var})$ with the inverse Compton limit is

$$\delta_{\min} \sim [T_b(\text{var})/(3 \times 10^{11} K)]^{1/3.2}(1+z).$$

Therefore, if the only effect working to mitigate the brightness temperature problem is relativistic bulk motion, Lorentz factors of 100–1000 are required in the most extreme cases of intraday variability, if the phenomenon is intrinsic to the source.

One must be careful, moreover, to distinguish between the cases when the brightness temperature is inferred and when it is measured via VLBI or scintillations. For example, the scintillation models that require angular sizes less than

10 μarcsec at centimeter wavelengths (Walker, these Proceedings, p. 285) refer to a brightness temperature T_b(obs) that would, at least potentially, actually be measured with space VLBI. [In fact, Linfield et al. (1990) reported measurements of brightness temperatures as high as 2.5×10^{12} K using a TDRSS satellite.] One must therefore compare this value with the brightness temperature limit directly; if the variations were actually intrinsic, the Doppler factor required would then be

$$\delta_{\min} \sim [T_b(\mathrm{obs})/(3 \times 10^{11} K)]^{1/1.2}(1+z).$$

We should expect VLBI arrays that include a space-based antenna such as VSOP to measure brightness temperatures up to $\sim 10^{13}$ K, but no higher if the Lorentz factors are limited to $\lesssim 30$. What is wrong with Lorentz factors $\gtrsim 30$? One encounters a problem with the parent population (viz., not enough unbeamed counterparts) when the typical Lorentz factor exceeds $\sim$ 10–20. While a few extreme objects would not pose statistical problems (and in fact should be expected!), the phenomenon of intraday variability seems to be too common to appeal to this.

One way to avoid extreme Doppler factors while still allowing the variations to be intrinsic is to appeal to flattened geometries (Marscher 1992). Unfortunately, because of the low frequencies, radiative losses are unlikely to provide the required thin emission layer behind a shock front. However, the onset of turbulence (or return to laminar flow) behind a shock front might cause the magnetic field geometry to change within a short distance of the shock front. In addition, numerical hydrodynamical simulations (Gómez et al. 1997) have shown that both propagating and standing shocks can be significantly thinner than the width of the jet. For favorable geometries, it is possible for the inferred brightness temperature to be lowered by two powers of the ratio of the line-of-sight thickness of the emission region to the transverse dimension of the jet. Such an effect would be most pronounced when the jet is pointing directly at the observer; this unlikely orientation is made more probable in a flux-limited sample by the extra Doppler boosting that it provides.

4. The Nature of the Core and Superluminal Components

The general structure of a blazar jet consists of the "core" at one end, from which superluminal components emerge and then separate. In the basic relativistic jet model detailed by Blandford & Königl (1979), the core is the narrow end of the ambient jet. At frequencies below the self-absorption turnover in the spectrum (usually at $\sim 2 \times 10^{10}$ to $\sim 10^{12}$ Hz), the core is then the site where the optical depth $\tau \sim 1$, the position of which should be further downstream at lower frequencies. This effect has indeed been observed, for example by Marcaide & Shapiro (1984) using phase-reference VLBI.

I have discussed separately (Marscher 1995, 1996) how the appearance of the core at high frequencies can provide information on the physical nature of the energy transport of the jet. It is only recently, however, that the core has been observed at optically thin frequencies. A sequence of 43 GHz VLBA observations of the quasar 3C 454.3 in 1994–96 is shown in Figure 1. At all epochs, there is a component, somewhat extended in the north-south direction,

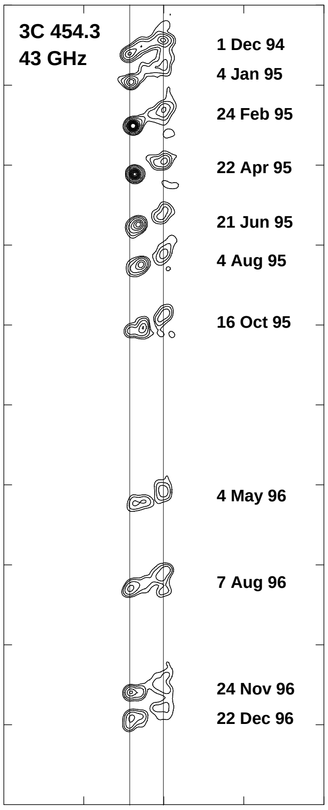

Figure 1. Sequence of images of 3C 454.3 at 43 GHz. The December 1994 image is from Kemball, Diamond, & Pauliny-Toth (1996), while the remainder are from Marscher et al. (1997). The western (right) vertical line corresponds to the centroid of component S1, which is presumed to be stationary and used to register the images. The eastern (left) vertical line indicates the easternmost site at which components appear. The tick marks are 1.5 mas apart.

at the west-northwest end of the portion of the jet seen here. The simplest interpretation is that this is a stationary component, which I will refer to as "S1," and all the images have been registered such that this is so. With this registration, there is a point at the eastern end at which new components appear and then propagate down the jet toward S1. *There is, however, no stationary component at the upstream (eastern) end of the jet!* Rather, there is a roughly stationary component, S2, situated about 0.2 mas downstream of the eastern end. In addition to these features, during the period Dec 1994–Oct 1995, a component brightens and then fades as it moves westward at an apparently superluminal speed ($13 \pm 1c$ for $h = 0.65$ and $q_o = 0.1$).

The fact that the moving component starts *upstream* of the first stationary component is rather striking. The theory that best explains this is a basic hydrodynamic model, as proposed by Daly & Marscher (1988). If the jet is invisible because of previously catastrophic energy losses by the electrons, it can become bright again wherever the particles are reaccelerated, such as is expected to occur at shock fronts. Standing, oblique shocks ("Mach disks") will occur where the pressure of the external medium is lower than the internal jet pressure, as one might expect to take place as the jet propagates from the high-density region in the nucleus to the interstellar and intergalactic media. In this picture, component S2 is a standing shock. In fact, the jet of 3C 454.3 bears remarkable similarity to that of the hydrodynamical simulation of Gómez et al. (1997 and these Proceedings, p. 49), even down to the detail that the position of S2 moves downstream slightly before "snapping back" as the moving component passes it.

The nature of component S1 is less clear, but the 5 GHz images of Pauliny-Toth (these Proceedings, p. 75) show that, prior to 1993, the jet was oriented to the west-southwest, so the extended component S1 might be the result of interactions between the jet and the interstellar medium caused by wiggles in the nozzle. Stationary components can also appear at sites where the jet bends into the line of sight, as apparently happens in 4C 39.25 (Alberdi et al. 1993).

The most popular model for the superluminal knots is a transverse propagating shock caused by a temporary increase in the bulk Lorentz factor or energy density of the jet flow. This should cause the appearance of components that are either strongly polarized with electric vectors parallel to the jet axis or weakly polarized (if the magnetic field in the ambient jet is parallel to the axis). Some moving components in quasars, however, are strongly polarized with perpendicular electric vectors (see the review by Wardle, these Proceedings, p. 97), which is difficult for this model to explain unless the magnetic field is very strongly parallel to the axis prior to being shocked.

5. Conclusions

Any working scientist must occasionally examine the assumptions upon which his/her work is based. I hope that the above review has provided the reader with a synopsis of how firm—or weak!—is the ground upon which we plant the interpretation sections of our observational papers. Indeed, we are in the usual situation for a field that is currently very active: our cherished models are simultaneously well supported and contradicted by the observational data. To be fair, the space given the review is too brief to discuss further supporting evidence, such as observations of the Galactic superluminal sources. Nevertheless, we need to maintain awareness that the relativistic, synchro-Compton jet model is still only a working hypothesis, not a sacred cow.

We can expect some significant observational advances in the near future. Among these include the measurement of brightness temperatures as high as $\sim 5 \times 10^{12}$ K by VSOP-based arrays, as predicted by the relativistic jet models, accurate predictions of self-Compton X-ray flux and comparison with observations (VSOP and RXTE), further mm-VLBI observations of the core region, phase-reference VLBI at high frequencies to determine which components are moving and which are stationary (VLBA), and comparison of very-high resolution mm-VLBI images with numerically simulated jets. Such developments will answer many of the central questions surrounding blazar jets—and undoubtedly pose new ones.

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