NASA-CR-203215

NAS 5-1506
IN-93-CR
603 326

Multi-Waveband Studies of Compact Extragalactic Radio Sources[1]

Alan P. Marscher and Steven D. Bloom
Boston University, Boston, MA, USA

Abstract
The authors and their collaborators have observed a number of blazars at wavebands ranging from radio to γ-ray. From these studies, it is apparent that bright γ-ray emission is associated with strong synchrotron flares observed at lower frequencies. However, no other obvious observational characteristics are possessed by γ-ray bright blazars that separate them from those not detected by CGRO. The X-ray flux and entire radio spectrum of 4C 39.25 have each increased in strength by 30% over a 2-year period, in agreement with the prediction of the bent relativistic jet model.

1 Introduction

Perhaps the most exciting recent development in the study of compact extragalactic radio sources has been the detection of bright, variable γ-ray emission from blazars (Fichtel *et al.* 1993). In those sources in which γ rays are detected, they dominate the apparent luminosity of the object. It is therefore a compelling quest to determine the origin of the γ-ray emission. The natural technique to use is a multiwaveband analysis of the spectrum and variability of the nonthermal emission from γ-ray bright blazars.

γ-ray emission has thus far been detected from about 40 blazars (see Kurfess *et al.* 1994 and Thompson *et al.* 1994). Although the emission tends to be variable, most γ-ray bright blazars are still detected when observed a second time. The apparent γ-ray luminosity is typically 1–2 orders of magnitude greater than that observed at other wavebands. Therefore, unless the γ-ray emission is more highly beamed than that at lower frequencies, most of the nonthermal energy emerges as very high energy photons during the γ-ray high states. With timescales of variability as short as a few days, the flares almost surely originate deep within the jet, perhaps near its base. By measuring time delays of variations in brightness as a function of frequency, it is potentially possible to determine the geometry of the inner jet as well as infer the steepness of gradients in magnetic field, relativistic electron density, and bulk Lorentz factor of the jet flow (e.g., Marscher 1993). With these goals in mind, here we review the progress made thus far in understanding the γ-ray emission and its relation to the compact jets observed at lower frequencies.

2 Models for γ-Ray Emission

Since γ rays are electromagnetic waves, they must in general be produced by charged particles, which in turn must have total energies exceeding the energies of the γ rays they generate. The largest cross-section for creating a high-energy γ ray is that of inverse

[1]In *Compact Extragalactic Radio Sources*, ed. J. A. Zensus and K. I. Kellermann (Socorro, NM: National Radio Astronomy Observatory), pp. 179–184 (1994)

Compton scattering, which is equal to the Thomson cross-section if the energy of the initial photon $h\nu_i \ll \frac{m_e c^2}{\gamma}$, where γ is the Lorentz factor of the kinetic motion of the electron (as opposed to the bulk motion of the plasma containing the electron). In this limit, the photon is scattered up to energy $h\nu_f \sim \gamma^2 h\nu_i$. One can combine these two equations to find that the Thomson cross-section is valid as long as $h\nu_f \ll \gamma m_e c^2$, which is similar (but not quite identical) to the original condition that the electron energy must exceed the final photon energy. Above this limit, the smaller Klein-Nishina cross-section must be used. *The most efficient way that nature has to produce γ rays of energy ~ 1 GeV is therefore to scatter sub-keV "seed" photons by electrons with energies exceeding 1 GeV.* By "most efficient" we mean that the cross-section is highest.

The physical conditions under which inverse Compton scattering is important correspond to highly relativistic electrons immersed in a high-density soft (radio to X-ray) photon field: the energy expended per electron is proportional to the Thomson cross-section times the energy density of photons with frequencies below the Klein-Nishina limit. *Such high photon densities are known to exist in the nonthermal jets of blazars.* In fact, one of the classical problems of radio astronomy has been the high brightness temperatures (with photon energy density being roughly proportional to T_b^5) inferred by converting timescales of variability into maximum size scales, $R \lesssim ct_{var}$ and redshifts into distances. (In some cases, the high values of T_b are measured directly with VLBI; e.g., Marscher and Broderick 1981). The "synchrotron self-Compton" (SSC) scattered emission from such regions emerges at X-ray and γ-ray energies. As is well known, relativistic beaming lowers the predicted X-ray and γ-ray flux densities; whether it lowers them to values at or to values well below the level observed is an important, as yet unanswered, question.

The SSC process must therefore be a leading candidate for the γ-ray production mechanism in blazars. However, one weakness is its tendency to produce curved rather than strictly power-law γ-ray spectra. Also, as Collmar *et al.* (1994) and Sikora and Begelmen (1994) point out, breaks as high as 1.0 between the X-ray and hard γ-ray regions are demanded by the data and are not readily produced by current SSC models. However, SSC calculations using more realistic geometries (jets and shocks) are in progress (Travis and Marscher, in preparation) and are expected to produce spectra different from the case of a uniform sphere used in previous calculations.

The seed photons in the inverse Compton scattering need not originate from the nonthermal jet containing the relativistic electrons. Dermer, Schlickeiser, and Mastichiadis (1992; see also the more detailed calculations in Dermer and Schlickeiser 1993) and Coppi, Kartje, and Königl (1993) have proposed that the electrons in the jet scatter ultraviolet photons from the accretion disk imagined to exist in the innermost regions of an active galaxy according to the standard paradigm. This process is only efficient deep in the jet, at distances from the putative central black hole of order 10^{16} cm, below which the opacity to pair production is too high and above which the photons strike the flowing plasma too close to tail-on for the process to be efficient. Sikora, Begelman, and Rees (1994) have suggested that the seed photons might come from a nonrelativistic scattering or broad emission line region (i.e., reprocessed accretion disk radiation).

The main advantage of these external inverse Compton scattering (EICS) models is that, if the seed photons strike the relativistic jet from the front or side (actually, from any direction other than nearly tail-on), the photon energies and density are Doppler boosted in the rest frame of the scattering plasma, thereby enhancing the efficiency of the process. In

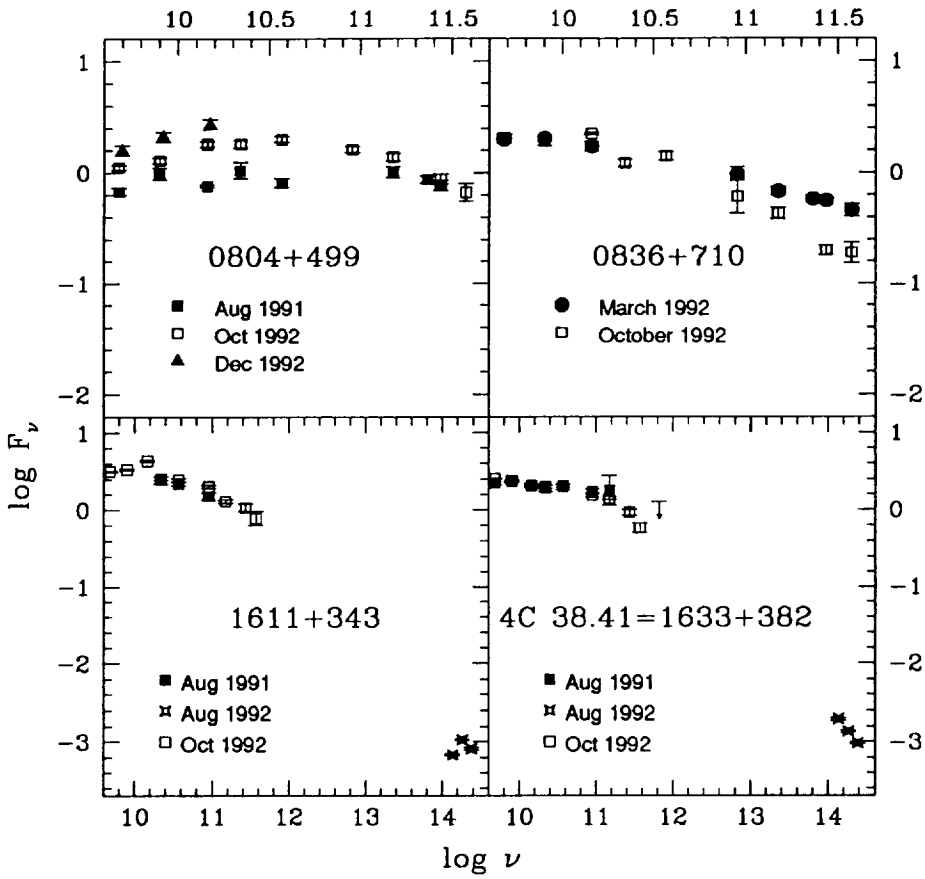

Figure 1: Simultaneous radio to submillimeter spectra of four blazars. Epochs of measured strong γ-ray emission are: 0804+499 and 0836+710 — Jan & Mar 1992; 1611+343 and 4C 38.41 — Sept 1991. Note that the frequency scales are different for the top two panels than for the bottom two. From Bloom *et al.* (1994).

addition, the spectra tend to show less curvature and sharper breaks than the SSC spectra if the seed photon spectrum is strongly peaked, as for thermal radiation. The main problem with EICS models is that the blazars detected by EGRET include both quasars, with strong emission lines and "big blue bumps" considered by many to be thermal radiation from an accretion disk, and BL Lac objects, in which the emission lines are faint or absent and the big blue bump is undetected. Why should objects with such different seed photon luminosities all produce detectable γ rays?

All of these γ-ray production mechanisms (as well as others; e.g., hadron collisions) must be occurring at some level in blazars. The question of which of these mechanisms dominate the γ-ray emission can only be answered observationally. We therefore turn now to a discussion of the observational status of blazars detected at γ-ray energies.

3 Relation between γ-ray and Lower Frequency Emission

It appears to be well established that the radio emission from blazars is relativistically beamed (see, e.g., papers in Zensus and Pearson 1987). It is also clear that the γ radiation is beamed. Photons with energies exceeding about 100 MeV cannot penetrate an ambient X-ray photon field of the high densities implied by X-ray variability studies without being lost to pair production. Mattox *et al.* (1993) provide a handy formula in terms of observed parameters, and demonstrate that the Doppler factor ($\delta \equiv [\Gamma(1-\beta\cos\theta)]^{-1}$, where βc is the bulk velocity) must be at least 7.6 in the quasar 1633+382 for the observed hard γ rays to escape, a value similar to those derived for superluminal motion in the radio.

The author is part of a massive collaboration that is in the midst of studies involving contemporaneous multiwaveband observations of blazars, consisting of VLBI, radio–submm, IR (for a few sources), and γ-ray observations, in many cases at multiple epochs. Instruments used include the VLBA and VLBI network, the U. Michigan and Metsähovi radio antennas, IRAM, SEST, the JCMT, UKIRT, and CGRO (mainly the EGRET detector).

The most useful observations for testing models are those that measure simultaneous multiwaveband spectra at multiple epochs with good time coverage. Unfortunately, for various logistical reasons, such observations were not undertaken during the first two years of CGRO's lifetime. What do exist are multiwaveband spectra obtained from data that are not quite simultaneous except at certain well-sampled frequencies.

Early results for γ-ray bright quasars are shown in Fig. 1 (Bloom *et al.*, in preparation). In two of the cases, *periods of high γ-ray flux are contemporaneous with enhanced levels of synchrotron emission.* Given the timescales — as short as one month or less — of many high-amplitude synchrotron flares (Robson *et al.* 1993), the sparse time coverage of these observations could easily have caused us to miss millimeter-wave to infrared variations associated with the high γ-ray states. So, two out of four ain't bad. Reich *et al.* (1993) also find that times of high γ-ray flux correspond to times of high millimeter flux.

Multiwaveband spectra of a small number of sources show that the X-ray luminosity is not midway (on a logarithmic scale) between the γ-ray and infrared luminosities (Marscher and Bloom 1994; Hartman *et al.*, in preparation). Because of this, the spectra are inconsistent with second-order (but *are* consistent with first-order) SSC emission as the origin of the γ rays (see Bloom and Marscher 1993).

The multiple CGRO observations of PKS 0528+134 provide an opportunity to compare γ-ray and radio emission, since the light curve has been well sampled since mid-1991 at 4.8, 8.0, 14.5, 22, and 37 GHz (Zhang *et al.* 1994). As shown in Fig. 2, γ-ray high states (Hunter *et al.* 1993; Sreekumar *et al.* 1993) occurred near the beginning of a major high-frequency radio flare in mid-1991, which later propagated to lower frequencies as the outburst became progressively less opaque. The very high γ-ray flux of March 1993 preceded the peak of the strongest 37 GHz flux observed thus far by 25 days, whereas the factor of ~ 10 lower γ-ray flux observed in late May 1993 (Nolan *et al.* 1993) was measured during the declining phase of the 37 GHz outburst. The source was opaque at this frequency (the turnover frequency increased from 7 to 60 GHz, indicating that the core had become very active after a quiescent period), hence the 37 GHz peak was probably time delayed relative to the optically thin maximum at $\nu \gtrsim 100$ GHz. Nevertheless, these observations show that lags between γ-ray and synchrotron flares can be measured given sufficient time coverage with millimeter, submillimeter, infrared, and optical telescopes during and after (and before,

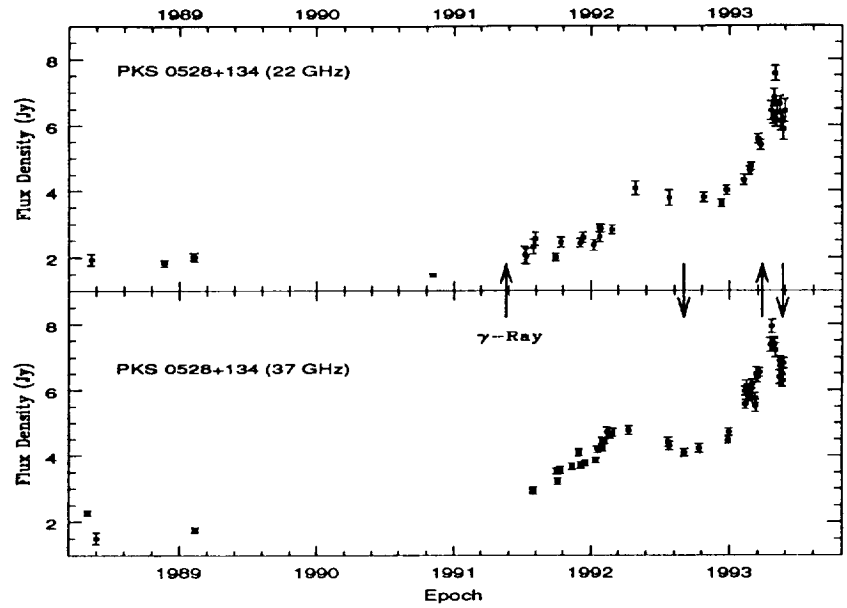

Figure 2: 22 and 37 GHz light curves of PKS 0528+134. Epochs of CGRO γ-ray observations are indicated by the arrows; up-arrows: very strong detections; down arrows: upper limits to flux, $\sim$ 10 times lower than the strongest detection. From Zhang *et al.* (1994).

if possible) the CGRO pointings. This is crucial for testing the theoretical models: time delays of variations across wavebands provide crucial information on the relative positions of the emission regions; this in turn allows one to infer the geometry and physical conditions of the jet (Marscher 1993).

It may be that all γ-ray flares are associated with synchrotron outbursts; better time coverage at optically thin frequencies will tell. The converse is not true, however. In the quasar 4C 39.25, the site of the synchrotron flare is a knot in the jet rather than the VLBI core region (Marscher *et al.* 1991; Alberdi *et al.* 1993). Despite a flux density that has risen to over 10 Jy at radio wavelengths, no γ rays were detected by CGRO in September–October 1992 (von Montigny *et al.*, in preparation). We tentatively conclude that the synchrotron outburst must be in the core for there to be a γ-ray flare. The above authors model the radio behavior of 4C 39.25 in terms of a bent relativistic jet, with the fractional time rate of increase of flux density being the same at all observed radio frequencies above 4.8 GHz. Zhang and Marscher (1994) find that this extends to the X-ray emission, as predicted by the bent jet model if the X-rays arise from SSC emission: both the X-ray and radio flux densities increased by 30% between April 1991 and April 1993. Also, the observed X-ray flux is in good agreement with the SSC emission expected according to the model presented by Alberdi *et al.* (1993).

4 Conclusion

The best way to establish and study the connections between γ-ray and X-ray emission and lower frequency synchrotron emission is through simultaneous multiwaveband monitoring.

In general, past programs have not had sufficient time coverage to fulfill the promise of this technique. Still, much has been learned. More intensive monitoring is planned during the next few years, which should result in major advances in our knowledge of the physics of blazars.

This work was supported in part by NSF grant AST-9116525 and by NASA grants NAG5-1637, NAG5-1943, and NAG5-1566 (ROSAT and CGRO Guest Investigator Programs).

References

Alberdi, A., Marcaide, J. M., Marscher, A. P., Zhang, Y. F., Elósegui, P., Gómez, J. L., and Shaffer, D. B. 1993, *Astrophys. J.*, **402**, 160.

Begelman, M. C., and Sikora, M. 1994, in *Second Compton Symposium, AIP Conference Series* (New York: American Institute of Physics), in press.

Bloom, S. D., *et al.* 1994, *Astron. J.*, , submitted.

Bloom, S. D., and Marscher, A. P. 1993, in *Compton Gamma-Ray Observatory, AIP Conference Series*, **280**, ed. M. Friedlander, N. Gehrels, and D. J. Macomb (New York: American Institute of Physics), p. 578.

Collmar, W., *et al.* 1994, in *Second Compton Symposium, AIP Conference Series* (New York: American Institute of Physics), in press.

Coppi, P. S., Kartje, J. F., and Königl, A. 1993, in *Compton Gamma-Ray Observatory, AIP Conference Series*, **280**, ed. M. Friedlander, N. Gehrels, and D. J. Macomb (New York: American Institute of Physics), p. 559.

Dermer, C. D., and Schlickeiser, R. 1993, *Astrophys. J.*, **416**, 458.

Dermer, C. D., Schlickeiser, R., and Mastichiadis, A. 1992, *Astron. Astrophys.*, **256**, L27.

Fichtel, C., *et al.* 1993, in *Compton Gamma-Ray Observatory, AIP Conference Series*, **280**, ed. M. Friedlander, N. Gehrels, and D. J. Macomb (New York: American Institute of Physics), p. 461.

Hunter, S. D., *et al.* 1993, *Astrophys. J.*, **409**, 134.

Kurfess, J. D., *et al.* 1994, in *IAU Symposium 159, Active Galactic Nuclei across the Electromagnetic Spectrum*, ed. A. Blecha and T. Courvoisier (Dordrecht: Kluwer), in press.

Marscher, A. P. 1993, in *Astrophysical Jets, STScI Symposium Series* 6, ed. D. Burgarella, M. Livio, and C. O'Dea (Cambridge University Press), p. 73.

Marscher, A. P., and Bloom, S. D. 1994, in *IAU Symposium 159, Active Galactic Nuclei across the Electromagnetic Spectrum*, ed. A. Blecha and T. Courvoisier (Dordrecht: Kluwer), in press.

Marscher, A. P., and Broderick, J. J. 1981, *Astrophys. J. (Letters)*, **247**, L49.

Marscher, A. P., Zhang, Y. F., Shaffer, D. B., Aller, H. D., and Aller, M. F. 1991, *Astrophys. J.*, **371**, 491.

Mattox, J. R., et al. 1993, *Astrophys. J.*, **410**, 609.

Nolan, P. L., *et al.* 1993, *IAU Circular* no. 5802.

Reich, W., *et al.* 1993, *Astron. Astrophys.*, **273**, 65.

Robson, E. I., *et al.* 1993, *Monthly Notices Roy. Astron. Soc.*, **262**, 249.

Sikora, M., Begelman, M. C., and Rees, M. J. 1994, *Astrophys. J.*, **421**, 153.

Sreekumar, P., *et al.* 1993, *IAU Circular* no. 5753.

Thompson, D. J., *et al.* 1994, in *IAU Symposium 159, Active Galactic Nuclei across the Electromagnetic Spectrum*, ed. A. Blecha and T. Courvoisier (Dordrecht: Kluwer), in press.

Zhang, Y. F., and Marscher, A. P. 1994, in *Proceedings of the 1993 ROSAT Science Symposium*, ed. E. Schlegel and R. Petre (New York: American Institute of Physics), in press.

Zhang, Y. F., Marscher, A. P., Aller, H. D., Aller, M. F., Teräsranta, H., and Valtaoja, E. 1994, *Astrophys. J.*, , in press.

Zensus, J. A., and Pearson, T. J. (ed.) 1987, *Superluminal Radio Sources* (Cambridge: Cambridge University Press).