What TeV observations tell us about the base of AGN jets

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Abstract

When X-ray observations of synchrotron spectra of TeV blazars can be used to deduce the electron spectra in the sources, one gets a good fit to the observed TeV spectra taking these to be inverse Compton scattering of the synchrotron photons, if the jets have magnetic field strength in the range 0.02-0.1 gauss, and bulk Lorentz factors 15 or more. The spectrum in the TeV range is predicted to change surprisingly little when the keV photons radiated by the same electrons in Mrk501 change considerably. As yet, the author has not been able to explain the observations with a proton-cascade model, but further attempts will be reported at the conference. The jet must start, pre-shock, with a Lorentz factor much higher than 15, and the start may possibly contain episodic ejections, or at least a highly-variable flow.

1 How and where are TeV gamma rays produced in AGN jets?

Three processes for forming the observed gamma-rays have had advocates:

(i) A localized clump of relativistic electrons is formed (probably by a shock within the jet), moving along the jet, providing an intense source of synchrotron radiation, and the electrons scatter synchrotron photons to produce gamma-rays (e.g. Jones, O'Dell and Stein 1974, Marscher 1985, Marscher and Gear 1985, Maraschi, Ghisellini and Celotti 1992, Ghisellini et al. 1986).

(ii) A similar situation, but with the density of ambient infra-red photons arising from the environs of the galactic nucleus much higher than the local density of synchrotron photons emitted by the electrons, so scattering of these ambient photons is the dominant source of gamma-rays (Dermer, Schlickeiser and Mastichiadis 1992, Sikora, Begelman and Rees 1994).

(iii) Or, there is postulated to be a beam of protons of $> 10^{17}$ eV generated in the nuclear region, and traveling down the jet, and photopion production in an intense ambient photon flux near the nucleus results in gamma-rays and electrons up to $> 10^{16}$ eV due to $\pi^\circ \rightarrow \gamma$ and $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ processes (Mannheim 1993). The observed gamma rays then arise from a resulting cascade in the photon-magnetic field environment, and come largely as synchrotron radiation of very energetic electrons. In this scenario, the X-ray peak arises from a quite independent population of electrons, that in scenarios (i) and (ii) are believed to be capable themselves of generating the gamma-rays.

A satisfactory description of the spectrum by scattering of ambient photons (model ii) has not been obtained for the objects Markarian 421 and Markarian 501 (Hillas 1999), because of absorption of the emitted gammas by $\gamma\gamma \rightarrow e^+e^-$ interactions. In AGNs other than BL Lacs the ambient photon flux around the base of the jet can be very much higher, and this process can be important for the production of less energetic gammas (Sikora et al.).

The present author has found it difficult to set up the right scenario for a proton-initiated cascade process (iii) to produce gamma-rays which agree with observations on TeV blazars in the TeV and GeV ranges. The results appear to be very sensitive to the magnetic field, B, the shape of the energy spectrum of the ambient photons, and the longitudinal profiles, so the results cannot be summarized yet, and an update of the conclusions reached about the possible application of the proton-initiated cascade to explain current TeV observations will be given at the conference.

Pending this, it appears that the processes (ii) and (iii) will only be important if some factors suppress the expected intensity of photons from process (i) in the objects being considered here. In the case of Markarian 421, another factor biasing my initial investigations against model (iii) is that the GeV flux has appeared to rise

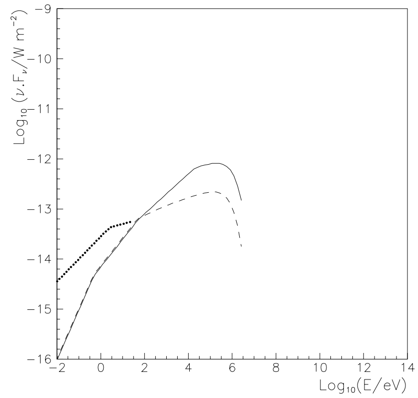

Figure 1: Representation of X-ray spectra reported by Pian et al. from BeppoSAX observations of Markarian 501 in April 1997. Full line: highest state, observed by BeppoSAX on April 16, dashed line: “medium-high” state (BeppoSAX April 7); dotted line: supposed component also present with less variability.

much less than the TeV flux in flares, whereas in the proton-initiated cascade, these both arise as synchrotron radiation of very much more energetic electrons, with very short radiation lifetimes, so both should respond quickly to a burst of particle production; but in the inverse-Compton models, the time scales associated with production of GeV radiation are much longer, and the GeV flare is much weaker and slower, according with the observation. However, the GeV observations have not been very sensitive, and this last consideration is not yet conclusive. If there is evidence in favour of the proton-initiated cascade, this is of interest to neutrino astronomy, as this model leads to the prediction of fluxes of high-energy neutrinos from these jets, whereas the other models do not.

1.1 Does the SSC model have problems with spectral range?

(a) It is sometimes suggested that the electronic models would not be capable of producing gamma rays of such high energy as can come from proton-initiated cascades, but with the figures found in this work (Section 2) for the magnetic field in the jet, this does not yet appear to be a serious limitation. If accelerated electrons are responsible for the gamma rays (scenarios i and ii), the competition between acceleration and radiative energy loss (synchrotron and inverse Compton) will limit their maximum energies. However, in a relativistic shock an electron might well double its energy in one gyro-rotation at the shock, and in this case gains exceed losses until the electrons reach an energy of about $17B^{-1/2} \times 2\Gamma$ TeV in our reference frame (B in gauss, but measured in the jet frame), which would permit energies of at least 10^{15} eV with the values of Γ and B derived below.

(b) Another disturbing observation has been that from flare to flare (Mrk 501), or during the course of a strong flare (Mrk 421), the spectrum of gamma rays in the TeV domain has not generally been seen to change detectable, even though considerable change has occurred in the keV spectrum, supposed to arise (by synchrotron radioation rather than by inverse Compton scattering as is the case for the gamma rays) from the same population of electrons (of many TeV energy in our reference frame). However, the expected change is shown to be indeed rather small, because of the (Klein-Nishina) drop in scattering rate of the most energetic electrons (Section 2).

2 Spectral changes in Markarian 501:

The Beppo-SAX satellite team has reported a remarkably hard and variable X-ray spectrum from Markarian 501 in April 1997, extending to ~ 100 keV, and shown schematically in figure 1. Because of the rapid changes (both here and even more notably for Markarian 421 – though no Beppo-SAX observations are available for

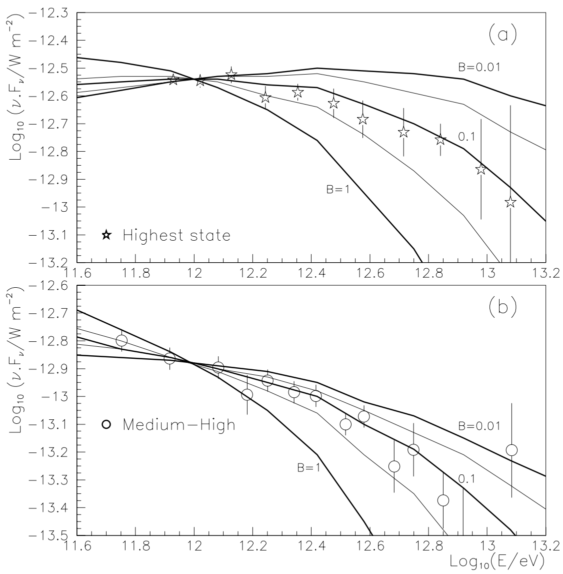

Figure 2: Predicted inverse Compton spectra for Markarian 501 based (a) on extreme high state of synchrotron spectrum, shown in figure 6, (b) on "medium-high" synchrotron state. Experimental data for (a) highest observed TeV state and (b) other high states excluding extreme, taken from Rodgers, 1997.$\Gamma = 10$ is assumed. (NB The intergalactic absorption is not included here!)

its major flares), it can be assumed that the emission occurs in a small region, and as a first approximation one can assume that the magnetic field strength does not vary greatly over this region. By assuming, in turn, various values for the magnetic field strength, one can calculate the number and spectrum of electrons required in the source to produce the observed X-rays by synchrotron emission. The present treatment assumed a head-on view of the approaching jet, in which the emisision occurs, for simplicity – and it is necessary to take (in turn) particular Lorentz factors Γ for the speed of the jet. The narrowing-down of the range of possibilities will not be discussed here: it suffices to say that for each B and Γ, a certain photon density is required, and some low values of Γ are rejected because the high photon density causes internal absorption, or else – more especially in the case of short Mrk 421 flares – the light travel time across the electron blob makes flares too slow (Hillas 1999). Seen in the jet frame, the magnetic field lines are assumed to be tangled and roughly isotropic.

Then the flux of photons produced by these electrons scattering the synchrotron photons can be calculated (using full cross-sections with all angles correctly treated), and the radius of the electron cloud adjusted to normalize the intensity of these photons to match the Whipple observations at 1 TeV.

Figure 2 shows the resulting predicted spectrum in the TeV range, corresponding to (fig. 8a) the highest and (fig. 8b) the "medium-high" keV state, compared with data points given by Rodgers (1997) for (a) the highest TeV state of Markarian 501 observed by the Whipple telescope in that period, and (b)for a more typical fairly high state. The predicted changes of spectral shape in the TeV domain are smaller than in the keV range, and are not very easy to detect. The form of the electron-photon scattering cross-section, which greatly depresses the effectiveness of the most energetic electrons, de-emphasizes these spectral changes in the electrons, when one looks at the scattered TeV photons. (The shape of the spectrum of the target photons also plays a part.) The conclusion is that the smallness of the change in the spectrum of the TeV photons, when the synchrotron photon spectrum changes considerably, is not an argument against both arising from the same population of electrons.

A magnetic field strength 0.1-0.2 gauss and a jet Lorentz factor $\Gamma = 10$ ($\delta = 20$ for head-on viewing) is in accord with the single-zone SSC analysis of Kataoka et al. (1998), who made comparisons with HEGRA dsata, and who also neglected intergalactic photon absorption. Radio VLBI observations of Mrk 501 by Giovannini et al. (1998) show a possible superluminal motion of 6.7c, which would imply a true Lorentz factor of the radio source, $\Gamma, > 6.8$. However, allowing for interactions with intergalactic infra-red photons, the transmission factor from the distance of Markarian 421 would be about $0.83 \exp(-\mathrm{E}/13\mathrm{TeV})$, a formula which approximates the transmission predicted by MacMinn and Primack (1996) for a CHDM "model 1 or 2" between 0.5 and 20 TeV (their figure 2). Incorporating this, the best fits of the present calculation to the highest-state data arise with $\Gamma = 10$ $(B \sim 0.03)$ or 20 (0.1 gauss), though Γ could be higher.

3 Start of the jet:

One striking result of these interpretations is that the jets must start out with a Lorentz Γ much greater than 15, since it is the bulk motion of the plasma after shock that is observed. This is surely evidence of an electromagnetic origin. Another area of interest is that in Markarian 421 (which may be seen more nearly head-on), the emission is largely composed of short flares. Why does the emission vanish so quickly? Mechanisms other than normal radiative cooling may be required, and these could arise if thin pieces of matter are ejected.

If flares are due to ejection of thin pieces of fast plasma which collide with slower material, the collision would result in shocks at the front and back of a compressed zone, each generating TeV electrons. Both populations would emit synchrotron X-rays, but only the back-shock electrons would be well placed to scatter synchrotron photons (most concentrated in the compressed zone) towards the observer. The back shock and its TeV electrons would soon disappear when the ejected blob was fully compressed: thus there is a possible scenario in which all of the gamma rays and half of the X rays switch off suddenly. The X-ray time profiles of Schubnell (1997) for Markarian 421 on May 7 1996 might possibly show such an instance. Other geometries are possible, however: the "target" photons may be older optical photons lying a little further down the jet. In scenario (iii) there is no expectation of such a close connection between the onset of X-ray and gamma-ray flares.

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