Gamma rays from interactions of stars with AGN jets

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ABSTRACT
We have developed a model for gamma ray emission in jets of active galactic nuclei in which particle acceleration takes place at a shock in the relativistic jet plasma due to a massive star in the central region of the host galaxy moving through the jet. The gamma rays are produced in a pair-Compton cascade in the radiation field of the star initiated by accelerated electrons. Our model may account for the observed GeV to TeV gamma ray spectrum and variability of Markarian 421 and other blazars detected by the EGRET instrument on the Compton Gamma Ray Observatory.

Key words: galaxies: active – quasars: jets – blazars: gamma ray emission, variability

1 INTRODUCTION
In recent years many blazar type active galactic nuclei (AGN) have been detected in high energy γ-rays by the EGRET telescope (von Montigny et al. 1995, Thompson et al. 1995). Of these, The BL Lac object Markarian 421 has been observed at TeV energies by the Whipple Observatory (e.g. Punch et al. 1992) and HEGRA (Petry et al. 1996). A further BL Lac object not detected by EGRET, Markarian 501, has also been detected by the Whipple Observatory (Quinn et al. 1995). The γ-ray emission from blazars is strongly variable on different time scales (from less than an hour to weeks) in different energy ranges (see Gaidos et al. 1996, Mattox et al. 1997). In the case of the Markarian 421, the X-ray variability is correlated with TeV variability (Takahashi et al. 1996a, 1996b; Buckley et al. 1996) with a time scale of ~1 week. Interestingly, the X-ray emission from this source seems to vary almost periodically on a time scale of ~1 day (Takahashi et al. 1996a). Such variability is not naturally expected in the present popular scenario for the production of γ-rays in a blob moving relativistically along the jet in a blazar.

Recently, Dar and Laor (1996) proposed that γ-ray production in AGN jets may be due to the collision of small clouds with radii ~10^{12} cm and densities ~10^{12} cm^{-3} with a highly collimated relativistic proton beam with γ ~ 10^4. In the present paper we consider another scenario as a possible explanation of collimated γ-ray production in blazars.

In the central regions of active galaxies the processes of star formation are probably very efficient. For example, in M32 the central stellar density exceeds 10^{7} M_{⊙} pc^{-3} (Lauer et al. 1992). It seems obvious that many stars must collide with the jet plasma. Here we investigate the consequences of such frequent stellar wind - jet plasma collisions for the production of highly collimated γ-ray beams in blazars. The general scenario is illustrated by Fig. 1(a).

2 STAR COLLIDING WITH JET PLASMA
Let us consider a very simple scenario in which a powerful jet, propagating from the central engine of active galactic nuclei, meets a massive star. The jet may consist of relativistic electron-proton (neutral) plasma with power

\[ L_{\gamma} = L_{\rho} + L_{e} \approx N_{\gamma} \gamma (m_{p} + m_{e}) c^{2}, \]

where \( N_{\gamma} \) is the rate of injection of protons with Lorentz factor \( \gamma \sim 10 \) into the jet, and \( m_{p}, m_{e} \) are the proton and electron masses. The kinetic powers of jets in radio-loud AGNs may be up to at least ~10^{47} erg s^{-1} (Rawlings & Saunders 1991, Celotti & Fabian 1993, Falcke & Biermann 1995). Assuming the jet propagates within a cone with opening angle \( \theta \), at a distance \( l \) along the jet the ram pressure of the jet plasma is

\[ P_{J} = L_{\gamma} / \pi d \theta^{2} = 1.5 L_{46} \theta_{5}^{2} l_{5}^{-2} \text{ erg cm}^{-3}, \]  

where \( L_{46} \) is the jet power in units of 10^{46} erg s^{-1}, \( \theta_{5} \) is its opening angle in units of 5°, and \( l_{5} \) is the distance in parsecs.

Stars in the central regions of galaxies move with high velocities, of the order of (3–6) × 10^{3} km s^{-1}, and are characterised by very intense winds and strong surface magnetic fields. For example the mass loss rate of Wolf-Rayet (WR) stars and the terminal velocity of the matter outflow are \( M_{\text{WR}} \sim (0.8–8) \times 10^{-5} M_{\odot} \text{ yr}^{-1} \), and \( v_{\infty} \sim (1–5) \times 10^{3} \text{ km s}^{-1} \) (Lang 1991). Young massive OB stars also have intense stellar winds with \( M_{\text{OB}} \sim 10^{-6} M_{\odot} \text{ yr}^{-1} \), and \( v_{\infty} \sim (1–3) \times 10^{3} \text{ km s}^{-1} \) (e.g. Lang 1991).

Some of these massive stars will obviously cross the jet cone from time to time. When this happens, the interaction of relativistic plasma in the jet with the stellar wind (and the
associated stellar magnetosphere) will result in the formation of shock waves similar to those discussed in the context of collisions of winds in binary systems involving early type stars (e.g. Eichler & Usov 1993). In the present context, the location of the shocks is determined by the parameters of the jet and the star. A double shock structure, with a contact discontinuity between them, should form (see Fig. 1b). The shock in the stellar wind will be non-relativistic while that in the jet plasma will be relativistic.

In principle the jet pressure can be balanced by the stellar wind pressure or the stellar magnetic field pressure. For stars with a dipole magnetic field and a strong wind, the structure and strength of the magnetic field around the star is (Weber & Davis 1967, Usov & Melrose 1992)

$$B(r) \approx B_0 \times \begin{cases} (R/r)^3, & \text{for } R < r < R \xi \text{ (dipole)}, \\ \xi^{-1}(R/r)^2, & \text{for } R \xi < r < R \eta^{-1} \text{ (radial)}, \\ \eta^{-1}(R/r), & \text{for } r > R \eta^{-1} \text{ (toroidal)}. \end{cases}$$

where $\xi \equiv r_A/R$, $r_A$ is the Alfvén radius which depends on the star’s parameters and is in the range $(1-3)R$, where $R$ is the radius of the star (Usov & Melrose 1992), and $\eta \equiv v_{rot}/v_\infty$ where $v_{rot}$ is the surface rotational velocity of the star. Typically for early-type stars $v_{rot} \approx (0.1-0.2)v_\infty$ (e.g. Conti & Ebbets 1977).

If the stellar wind is very strong, the jet pressure is balanced by the wind pressure,

$$P_{\text{wind}} = \frac{\dot{M}v_\infty}{4\pi r^2} \approx 1.6 \times 10^4 \dot{M}_{-5} v_3 R_{12}^{-2} (r/R)^{-2} \text{erg cm}^{-3},$$

where the mass loss rate of the star is $\dot{M} = 10^{-5}\dot{M}_{-5} M_\odot$ yr$^{-1}$, the wind velocity is $v_\infty \approx 3 \times 10^8 v_3$ cm s$^{-1}$, and the radius of a star is $R = 10^{12} R_{12}$ cm. The double shock structure is then located at a distance $r_{sh}$ from the star given by

$$r_{sh}/R \approx 103\dot{M}_{-5} v_3^{1/2} R_{12}^{1/2} \theta_5 l_1 L^{-1/2}. \tag{4}$$

The maximum power which may in principle be extracted from the jet by the shock can be estimated from

$$L_{sh} \approx L_j (r_{sh}/\theta)^2 \approx 1.5 \times 10^{39} \dot{M}_{-5} v_3 \text{ erg s}^{-1}. \tag{5}$$

Note that this depends only on the stellar wind pressure, but not on the jet power or distance from the central engine. If the jet pressure can not be balanced by the stellar wind pressure, it may be balanced by the pressure associated with the star’s magnetic field, $B(r)^2/8\pi$, provided

$$B_3 > 0.6 \dot{M}_{-5}^{1/2} v_3^{1/2} R_{12}^{-1} \tag{6}$$

where $B_3$ is $B_3$ in units of $10^3$ G. Then the shock location would be given by

$$r_{sh}/R \approx 5.5(B_3 \theta_5 l_1 L^{-1/2})^{1/3}. \tag{7}$$

In this case, the maximum power that can be extracted by the shock is

$$L_{sh} \approx 4.4 \times 10^{36} R_{12}^{-1} (B_3 L_{40 \theta_5^{-2}} l_1^{-2})^{2/3}. \tag{8}$$

In the most extreme case of the jet pressure dominating over the wind and magnetic pressures of the star, the jet collides directly with the stellar atmosphere. The jet pressure dominates over the magnetic pressure if

$$L_{46} > 2.7 \times 10^4 B_3^2 \theta_5^2 l_1^2, \tag{9}$$

and the jet pressure dominates over the wind pressure if

$$L_{46} > 10^4 \dot{M}_{-5} v_3^2 B_3^2 l_1^2 R_{12}^{-2}. \tag{10}$$

If both conditions are met, the jet initiates a very strong outflow of matter from the star, which pressure balances the jet pressure very close to the star’s surface.

3 ACCELERATION OF PARTICLES

Electrons and protons are expected to be accelerated by the first order Fermi acceleration mechanism (e.g. see reviews by Blandford & Eichler 1987, Jones & Ellison 1991). If the diffusion coefficient is proportional to energy we can write the acceleration rate as
\[ \dot{E} = \chi Z \varepsilon c B \quad \text{erg s}^{-1} \]  

where \( B \) is in gauss, \( Z \varepsilon \) is in statcoulombs, and \( \chi \) depends on the details of the acceleration mechanism. For acceleration at a shock with velocity 0.1c values of \( \chi \) as high as 0.04 or \( 1.6 \times 10^{-4} \) are possible if the shock is perpendicular or parallel respectively (e.g. Protheroe 1997).

For typical parameters of massive stars (surface temperature of the order of a few \( 10^4 \) K, and other parameters mentioned above, Lang 1991), accelerated protons are not expected to encounter sufficient target matter or radiation for interactions in the shock region. The interaction lengths (in cm) for protons in the wind plasma and stellar radiation are approximately

\[ \lambda_{pp} \approx 3 \times 10^{14} M^{-1} v_3 R_{12}^2 (r_{sh}/R)^2, \]  

\[ \lambda_{pr} \approx 3.4 \times 10^{14} T_4^{-3} (r_{sh}/R)^2, \]  

where the star’s surface temperature is taken to be \( T = 10^4 T_4 \) K. These interaction lengths are longer than the characteristic distance scale, i.e. the shock radius. We therefore concentrate on electron acceleration in this paper. Using the standard formula for the synchrotron energy loss rate one obtains, in the absence of other losses, the maximum electron energy

\[ E_e^{\max} = 6 \times 10^4 \chi^{1/2} B^{-1/2} \text{ GeV}. \]  

As shown in Section 2, collisions of stars with different parameters (\( M, v_{\infty}, B, l \)) with jets having different parameters (\( L_j, \theta \)) will result in the formation of shocks at various distances from the star. Since the shock parameters will be different for the shock in the stellar wind and the shock in the jet plasma, which we shall refer to as “the wind shock” and “the jet shock”, we shall discuss them separately below.

### 3.1 Shock in the jet plasma

The jet shock may be very effective for particle acceleration because it occurs in the relativistic jet plasma. Observations of the inner part of strong jets show that the magnetic field is mainly directed along the motion of the jet plasma (Saikia & Salter 1988). In such cases the region of the shock nearest to the central engine (region A to the left of the dashed line in Fig. 1) is quasi-parallel, while the region of the shock farthest from the central engine (region B in Fig. 1) is quasi-perpendicular. The strength of the longitudinal component of the magnetic field in the shock depends on the total magnetic flux, \( \Phi \), through the jet. At large distances from the base of the jet (\( \theta l \gg r_j^B \), where \( r_j^B \) is the jet radius at the base of the jet), the magnetic field scales inversely with the jet cross-sectional area

\[ B_j \approx 1.5 \times 10^{-3} \Phi_{52} \theta_3^{-1} l_1^{-2}, \]  

where the \( \Phi_{52} \) is the magnetic flux in units of \( 10^{52} \) G cm².

The section of the shock farthest from the central engine (region B in Fig. 1) seems to be the most promising location for the production of directly observable fluxes of \( \gamma \)-rays in the scenario discussed here. The reason being that in this region the relativistic shock is quasi-perpendicular and is likely to accelerate particles which are strongly collimated in the shock surface (see e.g., Kirk & Heavens 1989, Ostrowski 1991). Particles can be also accelerated almost rectilinearly by shock drift acceleration (Jokipii 1987) discussed by Begelman & Kirk (1990). The degree of particle collimation can be of the order of \( 1/\gamma_j \), where \( \gamma_j \) is the Lorentz factor for the velocity of the shock measured along the direction of the magnetic field lines. A very strong anisotropy of accelerated particles is then possible provided that the magnetic field is highly ordered, with no strong turbulence present.

The distance of the shock from the star is given by Eq. (1) and the magnetic field at the shock can be estimated from Eq. (13). This enables us to estimate the acceleration rate and the maximum electron energy allowed by synchrotron losses. Using Eq. (14) and Eq. (13) for the magnetic field in the jet, one finds

\[ E_e^{\max} = 1.5 \times 10^5 \chi^{1/2} \Phi_{52}^{1/2} \theta_3^{-1} l_1 \text{ GeV}. \]

For example, for \( \chi > 0.04 \) (expected for a perpendicular relativistic shock) and \( l_1 = 0.05 \) one obtains \( E_e^{\max} > 1.6 \times 10^6 \) GeV. Higher energies are possible for a highly anisotropic particle distribution because energy losses by synchrotron radiation depend on \( (B \sin \alpha)^2 \) and \( \sin \alpha \) can be small.

### 3.2 Shock in the stellar wind

In this case the shock may form as a consequence of a balance between the jet pressure and the stellar wind pressure, or the magnetic pressure, or as a result of a direct collision of the jet plasma with the stellar atmosphere. The location of the shock in first case is determined by Eq. (1). If \( r_{sh} \gg R \eta^{-1} \), then the shock is quasi-perpendicular because it is formed in the toroidal magnetic field region. If \( r_{sh} < R \eta^{-1} \) then the shock should be quasi-parallel since it is formed in the radial magnetic field region.

Unless the wind shock is formed very far from the star the shock will be non-relativistic \( (v_{\infty} \approx 0.01c) \), quasi-parallel, and the magnetic field in the stellar wind will be higher than in the jet plasma. Hence, the maximum energy will be much lower than for the jet shock, and is likely to be determined by synchrotron losses rather than by inverse Compton scattering. It is therefore likely that electrons accelerated at the wind shock may be responsible for the X-ray emission as a result of synchrotron radiation. To see whether this is reasonable, we consider the energy of synchrotron photons emitted by the highest energy electrons,

\[ \varepsilon_x \approx m_e c^2 \frac{B}{B_{52}} \gamma_{\max}^2 \]  

where \( B_{52} = 4.4 \times 10^{13} \) G, and \( \gamma_{\max} = E_e^{\max}/m_e c^2 \) (given by Eq. (14)). For \( \varepsilon_x = 10 \) keV one obtains an acceleration rate parameter \( \chi \sim 10^{-5} \) which is reasonable for a parallel non-relativistic shock.

It is probable that the accelerated electrons may follow magnetic field lines to region B which are likely to become directed along the jet axis. As the electrons in this region cool, their pitch angles will be decrease such that their X-ray emission will be preferentially directed in the jet direction.

### 4 PAIR-COMPTON CASCADE

We consider the pair-Compton cascade initiated by relativistic electrons accelerated at the jet shock, such that they travel along the shock front, to estimate the spectrum of \( \gamma \)-rays emerging from the AGN in the present scenario. Since
the shock is quasi-perpendicular and relativistic we consider injection of electrons with a power law spectrum index less than or equal to 2. The cut-off in the electron spectrum will be determined by the balance between particle energy gains from shock acceleration and losses by inverse Compton scattering, and can reach $10^4$ GeV or higher as discussed below.

We shall consider cascades in the radiation fields of OB stars for which we adopt $T = 3 \times 10^4$ K and $R = 10^{12}$ cm, and cascades in the radiation fields of Wolf-Rayet stars for which we adopt $T = 10^5$ K and $R = 2 \times 10^{11}$ cm. We have developed a pair-Compton cascade code to calculate the emerging gamma-ray spectrum for the case of injection of electrons at the shock radius at the boundary between regions A and B and travelling in the jet direction (see Fig. 1b). This code takes account of the anisotropic nature of the radiation field and is based on earlier work (Protheroe et al. 1986, Protheroe et al. 1992, Protheroe and Biermann 1996). Using this code, we have calculated the ratio of the shock radius (characteristic distance scale for this problem) to the mean free path of electrons for inverse Compton scattering, and the ratio of the shock radius to the mean free path for photon-photon pair production in the anisotropic radiation field at the injection point. This ratio, multiplied by $(r_{sh}/R)$, is plotted in Fig. 2 and we find that the shock radius equals the mean free path for electrons of $10^4$ GeV at the injection point if $r_{sh} = 5.2R$ for OB stars, or $r_{sh} = 14R$ for Wolf-Rayet stars. Using Eq. (8), we could obtain these shock radii with, for example, the following parameters: $M_{-5} = 0.1$, $v_3 = 1$, $L_{46} = 0.1$, and $l_1 = 0.05$ (OB stars); $M_{-5} = 8$, $v_3 = 1$, $L_{46} = 30$, and $l_1 = 0.05$ (WR stars). Clearly, these are perfectly reasonable sets of parameters which would give rise to pair-Compton cascading by energetic electron injection.

Finally we check whether $10^5$ GeV is a reasonable maximum energy based on the acceleration rate and the energy loss distance for inverse Compton scattering (given approximately by the mean free path in the Klein-Nishina regime). Using Eqs. (3) and (11) the acceleration distance is given by

$$ r_{acc} = 2.2 \times 10^9 \chi^{-1} E_{c} \Phi_{a_2}^{-1} \theta_3^2 l_1^2 \text{cm}, $$

where $E_c$ is in GeV, giving $r_{acc} = 1.4 \times 10^{12}$ cm for $\chi = 0.04$, $\Phi_{a_2} = 1$, $\theta_3 = 1$ and $l_1 = 0.05$. This acceleration distance is comparable to, but somewhat lower than, the shock radii estimated above confirming that $10^4$ GeV is a reasonable maximum energy and that the maximum energy is probably determined by inverse Compton scattering.

We have calculated the emerging gamma-ray spectrum for a power-law injection spectrum of the form

$$ dN_e \over dE_e = \left( \frac{E_e}{1 \text{ GeV}} \right)^{-a} \text{ GeV}^{-1} $$

for the standard shock acceleration spectrum, $a = 2$, and for $a = 1.5$ representing the flatter spectra that are possible for acceleration at relativistic shocks (Ellison et al. 1990). Results are shown in Fig. 3(a) for OB stars and in Fig. 3(b) for Wolf-Rayet stars for a range of shock radii spanning those discussed above. Specifically we show results for $r_{sh}/R = 1.7$ and $r_{sh}/R = 17$ for OB stars, and $r_{sh}/R = 4.7$ and $r_{sh}/R = 47$ for Wolf-Rayet stars.

From Fig. 3 we see that when the shock is located far from the star, i.e. $x_{int}^{\gamma} (10^4 \text{ GeV}) > r_{sh}$, i.e., for less powerful jets and/or large $l$, significant gamma-ray emission will occur at TeV energies. Conversely, if the shock is near the star, i.e. $x_{int}^{\gamma} (10^4 \text{ GeV}) \ll r_{sh}$, the gamma-ray spectrum is significantly steepened by photon-photon pair production in the stellar radiation field. For a flat electron spectrum the TeV gamma-ray flux can be comparable to or dominate the GeV gamma-ray flux (see upper dashed lines in Fig. 3) as observed during TeV gamma-ray outbursts from Mrk 421 (Buckley et al. 1996).

5 DISCUSSION

The expected gamma-ray luminosities (if recalculated for the isotropic case) are

$$ L_\gamma \approx 4 \times 10^6 \mu L_{sh} \alpha^{-2}, $$

where $L_{sh}$ is given by Eq. (4) or (6), $\mu$ is the efficiency of conversion of jet power into gamma rays at the shock, and $\alpha = 10^{-\gamma} \alpha_{-3}$ rad is the angle of the cone of gamma-ray emission. We assume that the axis of the emission cone is directed outwards from the source of the jet, and so the cone sweeps across the sky as the star crosses the jet. The expected variability time scale associated with the line of sight to the observer passing through the cone of emission is then

$$ t_{var} \approx 10^{-\gamma} \chi_{-3}^{-1} v_{t,3}^{-1} l_1, $$

where $v_t = 3 \times 10^8 v_{t,3} \text{ cm s}^{-1}$ is the transverse velocity of the star. For $\alpha_{-3} = 1$, $v_{t,3} = 1$, and $l_1 = 0.05$ this gives $t_{var} \approx 6$ days, which is comparable with the activity period observed simultaneously from Mrk 421 in X-rays (Takahashi et al. 1996a) and TeV gamma-rays (Buckley et al. 1996). It is interesting that Eqs. (19) and (21) predict that for a narrower emission cone gamma-ray fluxes should be higher and variability time scales should be shorter.

A distant observer may see emission modulated with the rotational period of the star if the star’s magnetic axis does not coincide with its rotational axis. In this case, the wind and magnetic field strengths and structures should vary almost periodically in the region of the shock with time scale
Figure 3. Emerging $\gamma$-ray spectra resulting from injection of a power-law electron spectra of the form $E^{-1.5}$ (upper curves) and $E^{-2}$ (lower curves) extending up to $10^4$ GeV at the shock radius in a direction tangential to the shock. (a) $T = 3 \times 10^4$ K, $R = 10^{12}$, $r_{sh}/R = 1.7$ (solid curves) and $r_{sh}/R = 17$ (dashed curves); (b) $T = 10^5$ K, $R = 2 \times 10^{11}$, $r_{sh}/R = 4.7$ (solid curves) and $r_{sh}/R = 47$ (dashed curves).

given by

$$t_{\text{rot}} = 2\pi R v_{\text{rot}}^{-1} \approx (1 - 2) \times R 12 v_3^{-1} \text{ days},$$

(22)

where $v_{\text{rot}} = (0.1 - 0.2) v_{\infty} = 3 \times 10^5 (0.1 - 0.2) v_3$ cm s$^{-1}$ is the star’s rotational velocity. This period is comparable to the possible quasi-periodic variability detected from Mrk 421 (Takahashi et al. 1996a). Note also that winds from early type stars are very unstable, and the jet plasma may contain some irregularities. This may result in a slight change in the location of the shock which may significantly change the direction of a narrow cone in which $\gamma$-rays are emitted, and may be the reason for the flickering of the $\gamma$-ray emission on a time scale of fractions of an hour (Gaidos et al. 1996).

Many stars are likely to be emerged in the jet at any one time. For a stellar density of $\sim 2 \times 10^6 \text{ M}_\odot \text{ pc}^{-3}$ within $\sim 1$ pc (observed in M32, Lauer et al. 1992), about $\sim 40$ stars with an average mass of $\sim 10 \text{ M}_\odot$ would be found inside a jet with opening angle $5^\circ$ within $\sim 1$ pc of the central engine. The presence of many stars inside the jet significantly increases the probability of a distant observer being inside the $\gamma$-ray emission cone of one of the stars.

In conclusion, we have developed a model for gamma ray emission in AGN jets in which particle acceleration takes place at a shock in the relativistic jet plasma produced as a result of a massive star in the central region of the host galaxy moving through the jet. The $\gamma$-rays are produced in a pair-Compton cascade initiated by accelerated electrons in the radiation field of the star. Our model may account for the observed GeV to TeV $\gamma$-ray spectrum and variability of Markarian 421 and other EGRET blazars.

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