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HADRONIC PRODUCTION OF TeV GAMMA-RAY FLARES FROM BLAZARS

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ABSTRACT

We propose that TeV γ-ray emission from blazars is produced by collisions close to the line of sight of high-energy jet protons with gas targets ("clouds") from the broad emission-line region (BLR). Intense TeV γ-ray flares (GRFs) are produced when BLR clouds cross the line of sight close to the black hole. The model reproduces the observed properties of the recently reported very short and intense TeV GRFs from the blazar Markarian 421. Hadronic production of TeV GRFs from blazars implies that it is accompanied by a simultaneous emission of high-energy neutrinos and of electrons and positrons with similar intensities, light curves, and energy spectra. Cooling of these electrons and positrons by emission of synchrotron radiation and inverse Compton scattering produces delayed optical, X-ray, and γ-ray flares.

Subject headings: BL Lacertae objects: general — BL Lacertae objects: individual (Markarian 421, Markarian 501) — gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

The Fred Lawrence Whipple Observatory has recently reported (Gaidos et al. 1996) the detection of two dramatic outbursts of TeV γ-rays from the γ-ray blazar Markarian 421 (Mrk 421). The first one, on 1996 May 7, had a doubling time of about 1 hr during which its flux increased above the quasi-quiescent value by more than a factor of 50. The second outburst, on 1996 May 15, lasted approximately 30 minutes during which its flux increased by a factor of 20–25. These reports followed previous reported detections by the Whipple Observatory of very strong bursts of TeV γ-rays from Mrk 421 that did not seem to be accompanied by a similar enhancement in GeV γ-ray emission (Kerrick et al. 1995; Macomb et al. 1995; Schubnell et al. 1996) and from Markarian 501 (Quinn et al. 1996). Although more than 50 active galactic nuclei (AGNs) have been detected before in GeV γ-rays by the Energetic Gamma Ray Telescope Experiment (EGRET) on the *Compton Gamma Ray Observatory* (see, e.g., von Montigny et al. 1995; Thompson et al. 1995), all belonging to the blazar type of AGNs. Of all the EGRET γ-ray blazars, only the nearest, Mrk 421 at redshift $z = 0.031$, has been detected in TeV γ-rays (Punch et al. 1992; Lin et al. 1992; Macomb et al. 1995; Gaidos et al. 1996). Also, the blazar Mrk 501 at $z = 0.034$, which is below the level of detectability by EGRET, has been detected in TeV γ-rays (Quinn et al. 1996). It has been suggested that perhaps all γ-ray blazars emit TeV γ-rays, but the opacity of the intergalactic space to TeV photons due to e^+e^--pair production on the infrared background photons prevents us from seeing them in TeV photons (see, e.g., Stecker et al. 1993). Therefore, it is natural to assume that the two closest blazars, Mrk 421 and Mrk 501, are not unique and that they well represent TeV γ-ray blazars. Although Mrk 421 seems to flare in TeV γ-rays quite often, most of the EGRET blazars seem to show, within observational limitations, less variability over very short time scales in the 30 MeV–30 GeV energy range (see, however, Mattox et al. 1997).

The observed GeV and TeV γ-ray emissions from blazars are usually both interpreted as being produced by inverse Compton scattering of highly relativistic electrons from their jets on soft photons, internal or external to the jet (see, e.g., Maraschi et al. 1992; Bloom & Marscher 1993; Dermer & Schlickeiser 1993, 1994; Coppi et al. 1993; Sikora et al. 1994; Blandford & Levinson 1995; Inoue & Takahara 1996). Although the radio, X-ray, and MeV–GeV γ-ray emissions are naturally explained by synchrotron radiation and inverse Compton scattering of high-energy electrons in the jet, there are inherent difficulties in explaining TeV γ-ray emission as inverse Compton scattering of soft photons by highly relativistic electrons or positrons in pure leptonic jets. The main difficulty is fast cooling of electrons and positrons by inverse Compton scattering when they are accelerated to TeV energies in the very dense photon field of an AGN. Here we would like to propose an alternative model for TeV emission from blazars based on the assumption that AGN jets consist of normal hadronic matter (see, e.g., Mannheim & Biermann 1992). TeV γ-rays are produced efficiently by the interaction of the high-energy protons in the jet with diffuse gas targets of sufficiently large column density that cross the jet. Such targets may be atmospheres of bloated stars, stellar winds, or gas clouds in the broad emission-line region (BLR) around the AGN. We show that the simple properties of hadronic production of high-energy γ-rays, which are well known from lab experiments, together with the properties of the BLR of AGNs that are known from optical, ultraviolet, and X-ray studies, explain both the observed quasi-quiescent emission and the outbursts of TeV γ-rays from blazars. We also predict the prompt emissions of TeV neutrinos and the delayed optical, X-ray and MeV–GeV γ-ray emissions that accompany TeV γ-ray flares (GRFs).

2. THE HADRONIC COLLIDER MODEL

We assume that γ-ray blazars are AGNs with highly relativistic jets of normal hadronic matter that point in the observer direction. Coulomb coupling of electrons to protons overcomes the Compton drag in its very dense photon field and makes it possible to accelerate the jet particles to very large Lorentz factors, $\Gamma = 1/(1 - \beta^2)^{1/2} \gg 1$. For $\Gamma \gg 1$, the kinetic energy of the jet resides mainly in protons. This energy is converted quite efficiently into TeV γ-rays that are beamed toward the observer by $pp \rightarrow \pi^0 X$; $\pi^0 \rightarrow 2\gamma$ when "clouds" with high column density from the BLR that surrounds the central region cross the jet near the line of sight. The quasi-quiescent emission is due to jet interactions with many, relatively distant, gas "clouds" in the BLR. Strong GRFs are produced when "clouds" cross the line of sight much closer to the central engine. By "clouds" we mean diffuse material in the form of the atmosphere of bloated stars (Alexander & Netzer 1994), stellar winds, or real gas clouds. Hadronic production of TeV γ-rays is accompanied by a simultaneous emission of TeV neutrinos, electrons, and positrons mainly via $pp \rightarrow \pi^{\pm} X$; $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$; $\mu^{\pm} \rightarrow e^{\pm}\nu_e\nu_{\mu}$. The subsequent cooling of these electrons and positrons by synchrotron radiation, inverse Compton scattering, and annihilation in flight produces optical photons, X-rays, and MeV–GeV γ-rays.

3. HADRONIC PRODUCTION OF GAMMA RAYS

The cross section for inclusive production of high-energy γ-rays with a small transverse momentum, $cp_T = E_T < 1$ GeV in pp collisions (see, e.g., Neuhoffer et al. 1971; Boggild & Ferbel 1972; Ferbel & Molzon 1984), is well represented by

$$\frac{E}{\sigma_{\rm in}}\frac{d^3\sigma}{d^2p_T\, dE_\gamma} \approx (1/2\pi p_T)e^{-E_T/E_0}f(x), \qquad (1)$$

where $E \approx m_p\Gamma$ is the incident proton energy, $\sigma_{\rm in} \approx 35$ mb is the pp total inelastic cross section at TeV energies, $E_0 \approx 0.16$ GeV, and $f(x) \sim (1-x)^3/x^{1/2}$ is a function of only the Feynman variable $x = E_\gamma/E$ and not of the separate values of the energies of the incident proton and the produced γ-ray. The exponential dependence on E_T beams the γ-ray production into $\theta < E_T/E \sim 0.17/\Gamma$ along the incident proton direction. When integrated over transverse momentum, the inclusive cross section becomes $\sigma_{\rm in}^{-1}\, d\sigma/dx \approx f(x)$. If the incident protons have a power-law energy spectrum, $dF_p/dE \approx AE^{-\alpha}$, then, because of Feynman scaling, the produced γ-rays have the same power-law spectrum:

$$\frac{dF_\gamma}{dE_\gamma} \approx N_p\sigma_{\rm in}\int_{E_\gamma}^{\infty}\frac{dF_p}{dE}\frac{d\sigma}{dE_\gamma}\, dE \approx N_p\sigma_{\rm in}IAE_\gamma^{-\alpha}, \qquad (2)$$

where N_p is the column density of the target and $I = \int_0^1 x^{\alpha-1}f(x)\, dx$.

4. THE BROAD EMISSION-LINE REGION

Detailed studies of broad optical and ultraviolet emission lines, whose atomic physics is well understood, have been used to obtain detailed information on the BLRs of AGNs. From their line shapes, relative strengths, and their time lag response to the variations with time of the central continuum source, it was concluded that the BLR consists of high column density broad emission-line clouds (BLCs) that move with very large random velocities in the BLR:

1. The size of the BLR has been estimated from reverberation mapping of both Seyfert 1 galaxies (see, e.g., Peterson 1993) and quasars (see, e.g., Maoz 1997), with typical lag times between 10 days for Seyfert 1 galaxies and 100 days for quasars, respectively. Typically, $R_{\rm BLR} \approx 3 \times 10^{16}L_{44}^{1/2}$ cm, where $L = L_{44} \times 10^{44}$ ergs s^{-1} is the luminosity of the AGN in ionizing radiation.

2. The column density and mean density of the clouds were estimated from the ionizing flux of the central source and the relative line strengths from the partially ionized clouds. Very high column densities and densities were inferred. Typical values are $N_p \sim 10^{23\text{–}24}$ cm^{-2} and $n_p \sim 10^{10\text{–}12}$ cm^{-3}, respectively.

3. For spherical clouds of uniform density, $N_c = (4/3)n_c r_c$. Consequently, the radii of BLCs are typically $r_c = 10^{12}\, r_{12}$ cm, with $r_{12} \sim 0.1$–100.

4. The velocity distribution of the BLCs has been estimated from the profiles of the broad emission lines. Their full widths at half-maximum indicate typical velocities of a few 10^3 km s^{-1} extending beyond 10^4 km s^{-1} at the base of the lines. Reverberation mappings have clearly established that the velocities are not a radial flow (Maoz 1997). They seem to be consistent with the expected velocities of clouds orbiting massive black holes, $v_c \approx (GM/R)^{1/2} \approx 1.15 \times 10^9(M_8/R_{16})^{1/2}$ cm s^{-1}, where $M = M_8 \times 10^8\, M_\odot$ is the mass of the black hole and $R = R_{16} \times 10^{16}$ cm is the distance from the black hole.

5. The covering factor, i.e., the fraction of the AGN sky covered by BLCs, was estimated from the ratio of Lyα photons emitted by the BLCs to the H-ionizing photons produced by the central continuum to be $C_{\rm BLR} \sim 0.1$.

6. The total number of BLCs in the BLR was estimated from the sizes of the BLR and BLCs and the covering factor. Assuming $C_{\rm BLR} \ll 1$, one finds $N_{\rm BLR} = (4/3)C_{\rm BLR}R_{\rm BLR}^2/r_c^2$.

The UV spectrum of Mrk 421 does not show BLR and $\nu L_\nu(1200$ Å$) \sim 1.3 \times 10^{43}\, h^2$ ergs s^{-1} (Kinney et al. 1991). The BLR may be swamped by beamed UV power-law emission from the jet. Since the broad-line equivalent width is ≥ 30, weaker than in other AGNs, the isotropic ionizing continuum should be $\leq 10^{42}$ ergs s^{-1}, and thus we estimate that $R_{\rm BLR} \approx 3 \times 10^{15}$ for Mrk 421.

5. QUASI-QUIESCENT EMISSION AND GRFS

The hadronic collider model predicts that the TeV γ-ray emission from blazars fluctuates with time and shows spectral evolution, even if the jet properties do not vary with time on short time scales. The exact properties of individual flares depend on many unknown parameters of both the clouds (their geometry, density distribution, speed, and trajectory relative to the jet and line of sight) and the jet (opening angle $\theta_{\rm jet}$, exact orientation relative to the observer, particle composition, and differential energy spectrum of its high-energy particles as function of distance from the jet axis and along the jet). The general properties of the quasi-quiescent emission and the flares, however, can be estimated using some simplifying assumptions.

Consider a conical jet of particles from a source that is incident on a cloud at a distance R from the source. Let b and θ denote their impact parameter and angle relative to the jet axis. For the sake of simplicity, let us assume that the observer is located at infinity on the jet axis. Most of the γ-rays seen by the observer must arrive from impact parameters smaller than the critical impact parameter $b_c \approx RE_0/E_\gamma < R\theta_{\rm jet}$ because of the exponential dependence of their production cross section (eq. [1]) on E_T. The number of clouds with $b < b_c$ in the BLR is $N_{\rm BLR}E_0^2/4E_\gamma^2$. A quasi-quiescent background is formed by jet-cloud interactions only if this number is large, i.e., if $E_\gamma \ll$

$E_{\rm crit} = (N_{\rm BLR})^{1/2}E_0/2 \approx (C_{\rm BLR})^{1/2}(R_{16}/r_{12})$ TeV. In that case, the jet produces a quasi-quiescent γ-ray flux of

$$\frac{dF_\gamma}{dE_\gamma} \approx C_{\rm BLR}\bar{N}_p\sigma_{\rm in}IAE_\gamma^{-\alpha}, \quad (3)$$

and the BLR acts as a target with an effective column density of $C_{\rm BLR}\bar{N}_p$, as long as $E_\gamma > E_0/\theta_{\rm jet}$ (below this energy, the produced γ-rays are not beamed effectively toward the observer). For $E_\gamma > E_{\rm crit}$, the BLR emission is expected to fluctuate considerably. A flare with a large intensity contrast ratio (≡ maximal intensity/quasi-quiescent intensity) is formed when a cloud crosses the line of sight at a relatively small distance. If the radius of the cloud is larger than the critical impact parameter, i.e., $r_c > RE_0/E_\gamma$, then when the cloud blocks the line of sight, the γ-ray flux at photon energies $E_\gamma > (R/r_c)E_0 \sim 1.6R_{16}/r_{12}$ TeV flares up with a maximum intensity

$$\frac{dF_\gamma}{dE_\gamma} \approx N_p\sigma_{\rm in}IAE_\gamma^{-\alpha}, \quad (4)$$

where N_p is the average column density of the cloud. Thus, the maximal intensity contrast of TeV GRFs compared with the quasi-quiescent emission is $N_p/C_{\rm BLR}\bar{N}_p \approx 10-100$. The duration of TeV emission in such flares is of the order of the time it takes the whole cloud to cross the line of sight, i.e.,

$$T_{\rm GRF} \sim 2r_c/v_c \sim 1.7 \times 10^3 r_{12}R_{16}^{1/2}M_8^{-1/2}\ {\rm s}. \quad (5)$$

The mean time between such strong flares is

$$\Delta t \approx \bar{T}_{\rm GRF}R_{\rm BLR}/C_{\rm BLR}b_c \approx 0.5L_{44}^{1/2}C_{0.1}^{-1}E_{\rm TeV}^{-1}r_{12}^{-1}T_3\ {\rm days}, \quad (6)$$

where $C_{\rm BLR} = 0.1C_{0.1}$ and $\bar{T}_{\rm GRF} = 10^3T_3$ s. For $E_\gamma < 1.6R_{16}/r_{12}$ TeV, the maximal GRF intensity is reduced by $(r_cE_\gamma/RE_0)^2$, and the duration of the GRF is approximately the time it takes the cloud to cross the beaming cone:

$$T_{\rm GRF} \sim 2RE_0/v_cE_\gamma \sim 3 \times 10^3E_{\rm TeV}^{-1}R_{16}^{3/2}M_8^{-1/2}\ {\rm s}. \quad (7)$$

Hence the GRF has the following general behavior when a cloud crosses the line of sight at a distance R: At energies below $E_\gamma \sim 1.6 \times R_{16}/r_{12}$ TeV, the intensity contrast increases with increasing energy while the duration becomes shorter. Above this energy, both the intensity contrast and the duration become independent of energy. This behavior results in a spectrum that becomes harder when the intensity increases and softens when the intensity decreases. The averaged quasi-quiescent emission spectrum therefore is softer than the spectrum of strong flares at peak intensity.

The above-predicted properties of the quasi-quiescent emission and the flaring of blazars in TeV γ-rays seem to explain quite well those observed for Mrk 421 and Mrk 501 (Punch et al. 1992; Lin et al. 1992; Kerrick et al. 1995; Macomb et al. 1995; Quinn et al. 1996; Gaidos et al. 1996).

6. NEUTRINOS FROM GAMMA-RAY BLAZARS

Hadronic production of photons in diffuse targets is also accompanied by neutrino emission through $pp \to \pi^\pm \to \mu^\pm\nu_\mu$; $\mu^\pm \to e^\pm\nu_\mu\nu_e$. For a proton power-law spectrum, $dF_p/dE = AE^{-\alpha}$ with a power index of $\alpha \sim 2$, one finds (see, e.g., Dar & Shaviv 1996) that the produced spectra of γ-rays and ν_μ's satisfy

$$dF_\nu/dE \approx 0.7dF_\gamma/dE. \quad (8)$$

Consequently, we predict that γ-ray emission from blazars is accompanied by emission of high-energy neutrinos with similar fluxes, light curves, and energy spectra. The number of ν_μ events from a GRF in an underwater/ice high-energy ν_μ telescope is $SN_{\rm A}T_{\rm GRF}\int R_\mu(d\sigma_{\nu\mu}/dE_\mu)\,(dF_\nu/dE)\,dE_\mu\,dE$, where S is the surface area of the telescope, $N_{\rm A}$ is Avogadro's number, $\sigma_{\nu\mu}$ is the inclusive cross section for $\nu_\mu p \to \mu X$, and R_μ is the range (in g cm^{-2}) of muons with energy E_μ in water/ice. For a GRF with $F_\gamma \sim 10^{-9}$ cm^{-2} s^{-1} above $E_\gamma = 1$ TeV and a power index $\alpha = 2$ that lasts 1 day, we predict three neutrino events in a 1 km^2 telescope. Since the universe is transparent to neutrinos, they can be used to detect TeV GRFs from distant γ-ray blazars. If the reported GeV GRF from the brightest EGRET γ-ray blazar PKS 1622−297, which had a maximal flux of $F_\gamma \sim 1.7 \times 10^{-5}$ cm^{-2}s^{-1} photons above 100 MeV (Mattox et al. 1997), was accompanied by a TeV GRF, it could have produced $\sim 30\nu_\mu$ events within a day in a 1 km^2 neutrino telescope.

7. X-RAY, MeV, AND GeV GRFs

The production chain $pp \to \pi^\pm \to \mu^\pm \to e^\pm$ that follows jet-cloud collisions suddenly enriches the jet with high-energy electrons. Because of Feynman scaling, their differential spectrum is proportional to the γ-ray spectrum

$$dn_e/dE \approx 0.5dn_\gamma/dE, \quad (9)$$

and they have the same power index α as that of the incident protons and the produced high-energy photons and neutrinos. Their cooling via synchrotron emission and inverse Compton scattering produces X-rays and MeV and GeV γ-rays with a differential power-law spectrum

$$dn_\gamma/dE \sim E^{-(\alpha+1)/2}, \quad (10)$$

where $(\alpha + 1)/2 \approx 1.5$–2. Hence, the emission of TeV γ-rays is accompanied by delayed emission of optical photons, X-rays, and MeV and GeV γ-rays. The peak emission of synchrotron radiation by electrons with a Lorentz factor Γ_e traversing a perpendicular magnetic field $H_\perp$(G) moving with a Doppler factor $\delta = (1 - \beta\cos\theta)/\Gamma_H$ along the jet occurs at photon energy (Rybicki & Lightman 1979) $E_\gamma \sim 5 \times 10^{-12}H_\perp\Gamma_e^2\delta$ keV. The electrons lose ∼50% of their initial energy by synchrotron radiation in

$$\tau_c \approx 5 \times 10^8\Gamma_e^{-1}H_\perp^{-2}\delta\ {\rm s} \approx 1.2 \times 10^3H_\perp^{-3/2}E_\gamma^{-1/2}\delta^{-1/2}\ {\rm s}. \quad (11)$$

Consequently, the time lag of X-rays is inversely proportional to the square root of their energy. Similar time lags for MeV–GeV γ-rays are expected if they are produced by inverse Compton scattering from the self-produced synchrotron photons. The integrated burst energy over the keV–GeV range is limited by the total electron energy to less than ∼50% of the total energy in the TeV GRF. The spectral evolution of the X-ray flare (XRF) is a convolution of the spectral evolution of the high-energy electrons and their cooling time. It is hardest around maximum intensity and softens toward both the beginning and the end of the flare. Because of electron cooling, the spectrum should be harder during rise time than during decline of the flare. Indeed, all these features have been observed by *ASCA* (Takahashi et al. 1996) in the XRF that followed the

TeV GRF from Mrk 421 on 1995 May 15. Detailed comparisons will be presented elsewhere (Dar & Laor 1997).

8. SUMMARY AND CONCLUSIONS

We have proposed a hadronic collider model to explain TeV γ-ray emission from blazars. We have used simplifying assumptions to derive from the model the main properties of quasi-quiescent emission and outbursts of TeV γ-rays, neutrinos, and X-rays from blazars. The predictions agree with the Whipple, EGRET, and *ASCA* observations of high-energy γ-ray emission from Mrk 421 and Mrk 501. This seems to support a hadronic origin of TeV γ-rays emission from blazars. Although further optical, UV, and X-ray studies of the broad emission-line region in AGNs and observations of TeV γ-ray emission from blazars may provide more evidence for the hadronic nature of AGN jets, decisive evidence will be provided by the detection of the predicted TeV neutrino fluxes from γ-ray blazars.

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