CORRELATION OF PHOTON AND NEUTRINO FLUXES IN BLAZARS AND GAMMA-RAY BURSTS

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ABSTRACT

Relativistic black hole jet sources are leading candidates for high-energy (\(\sim\)TeV) neutrino production. The relations defining (1) efficient photopion losses of cosmic-ray protons on target photons and (2) \(\gamma\gamma\) opacity of \(\gamma\)-rays through that same target photon field imply clear multiwavelength predictions for when and at what energies blazars and gamma-ray bursts should be most neutrino-bright and \(\gamma\)-ray–dim. The use of multiwavelength observations to test the standard relativistic jet model for these sources is illustrated.

Subject headings: black hole physics – galaxies: jets – gamma rays: bursts – neutrinos – radiation mechanisms: nonthermal

Online material: color figure

1.INTRODUCTION

Multiwavelength observations provide us with important information about the radiation processes and the properties of astrophysical sources that cannot be obtained by observations in a narrow wave band. The opening of the high-energy neutrino telescope (for review, see Learned & Mannheim 2000) will provide a new channel of information that, in conjunction with photon observations, will test models of these sources. The kilometer-scale IceCube (Ahrens et al. 2004) will reach a total exposure of \(\sim\)1 km\(^3\) yr by 2009 and its design sensitivity by 2012. Plans are also being made for a Northern Hemisphere KM3NeT neutrino telescope in the Mediterranean Sea.\(^3\)

Because of their rapid variability, large luminosity, and relativistic outflows, gamma-ray bursts (GRBs) and blazars have been considered as the most likely sources of ultra–high-energy cosmic rays and neutrinos (Waxman & Bahcall 1997; Vietri 1998; Rachen & Mészáros 1998; Alvarez-Muñiz et al. 2000). The expected low neutrino-induced muon event rate, even for the brightest \(\gamma\)-ray blazars (Atoyan & Dermer 2001; Neronov & Semikoz 2002) and GRBs (Dermer & Atoyan 2003; Guetta et al. 2004), and the increasing importance of the cosmic–ray–induced neutrino background at lower energies (Karle et al. 2003; Gaissier et al. 1995) mean that event detection is greatly improved by choosing appropriate time windows during periods of highest neutrino luminosity. The important time windows for neutrino detection from blazars might be thought to be during \(\gamma\)-ray flaring states, and the important time windows for neutrino detection from GRBs might be thought to be around the \(t_{90}\) time or during some hours around the burst trigger, as suggested by the extended 100 MeV to GeV emission for GRB 940217 (Hurley et al. 1994) and the delayed anomalous \(\gamma\)-ray emission components in GRB 941017 and a few other GRBs (González et al. 2003; González 2005), because that is when energetic particle acceleration is most vigorous. But photopion production is enhanced in conditions of high internal photon target density, so that the times of most favorable neutrino detection could also be argued to take place during periods of low \(\gamma\)-ray flux as a result of attenuation by the dense internal photon gas.

Here we explore this issue, considering how to use multiwavelength observations (at optical, X-ray, and \(\gamma\)-ray energies for blazars and at X-ray and \(\gamma\)-ray energies for GRBs) to define the most favorable conditions for efficient neutrino production. Violation of these predictions will call into question the underlying assumptions currently used in models of GRBs and blazars.

2.ANALYSIS

Blazars and GRBs are widely thought to be black hole jet sources powered ultimately by accretion onto a black hole or by the spin energy of the black hole. In both cases, observations show that collimated outflows of highly relativistic plasma are ejected by processes taking place in compact regions. In the internal shock model (Mészáros 2006; Piran 2005), collisions between faster and slower shells dissipate directed kinetic energy in the form of field energy and accelerated particles that radiate. After the collision, the energized shocked fluid shell expands on the light-crossing timescale \(t'_{\gamma\gamma}\) or longer, where \(t'_{\gamma\gamma}\) is the characteristic size of the radiating fluid element in the comoving frame, assumed spherical and isotropic in the comoving frame. The causality constraint implies that the size scale of the emitting region \(r'_{\gamma}\) \(\approx\) \(\epsilon\beta_{\gamma\gamma}t_{\text{var}}/(1 + z)\), where the measured variability timescale \(t_{\text{var}} = 10^{\tau_s}\), \(s\), and \(\beta_0\) is the Doppler factor.

Within this geometry, the relation between the measured \(n'\gamma\) flux \(f'\) and the target photon emissivity \(j'(\epsilon', \Omega') = d\epsilon'dW' dt'd\Omega'/d\Omega\) is \(f' = \delta c^\prime V'\epsilon'^{j'}(\epsilon', \Omega')/d\epsilon'^{j'}\), where \(\epsilon' = h\nu/m_ec^2\), \(\Omega'\) is the solid angle of the comoving frame, and \(\epsilon'^{(j') \Omega'} = \epsilon u_t^{(j') 4\pi r_d^2}\) for radiation emitted isotropically in the comoving frame, where \(u_t = m_ec^2\epsilon^{1/2}n'(\epsilon')\) is the spectral energy density of the radiation field.

We write the flux \(n'\gamma\) as \(f' = S(\lambda), S(\lambda)\) is a spectral function of the variable \(x = \epsilon\epsilon_{\gamma\gamma}\). Here \(\epsilon_{\gamma\gamma} = 10^9\) is the measured photon energy (in units of \(m_ec^2\)) and the peak of the \(n'\gamma\) spectrum with peak flux \(f_{\gamma\gamma} = 10^9\) ergs cm\(^{-2}\) s\(^{-1}\). Thus, \(\epsilon n'(\epsilon') \equiv 3dJ_f S(\lambda)/(c\epsilon\epsilon_{\gamma\gamma}^2 m_ec^2\epsilon')\). The rate at which protons lose energy through photodisproportion production is \(t_{\gamma\gamma}^{-1} = \epsilon n'(\epsilon')\delta c\), where \(\delta \approx 70\) \(\mu\)barns is the product of the...
\( \gamma p \) photohadronic cross section and inelasticity (Atoyan & Dermer 2003), and the threshold condition \( 2\gamma_p' \epsilon' \equiv \epsilon'_{\text{thr}} \approx 400 \) relates the proper frame proton Lorentz factor \( \gamma_p' \) and the internal photon energy.

The target comoving photon spectral energy distribution (SED) from quasi-isotropic emissions, whether the synchrotron and synchrotron self-Compton (SSC) fields or a cascade radiation field, is approximated as a broken power law \( S(x) = x^{-\alpha}H(1-x) + x^\alpha H(x-1) \), with \( n_p' \) indices \( a \) and \( b \) (see Fig. 1; more general spectral forms can easily be treated). Here the Heaviside function \( H(x) = 1 \) for \( x > 0 \) and \( H(x) = 0 \) for \( x < 0 \). The photopion energy-loss rate of ultrarelativistic protons interacting with photons with energy \( \epsilon_p' \) near the peak of the \( n_p' \) spectrum is, from the proceeding considerations,

\[
\rho_{os} = \frac{3\delta d_0^2 f_{\text{os}}(1+z)}{m_c \epsilon' \delta_{\text{os}}^2 \epsilon_p'}. \tag{1}
\]

For the model target photon spectrum with \( 0 < a < 3, b < 0 \),

\[
\epsilon_p'^{-1}(\gamma_p') \approx \rho_{os} \begin{cases} 
2y^{y-1}[(1-b)(3-b)], & y \gg 1, \\
2y^{-y}[(1-a)(3-a)], & y \ll 1, 0 < a \leq 1, \\
(a-b)[(a-1)(1-b)], & y \ll 1, 1 \leq a < 3
\end{cases}
\tag{2}
\]

(Dermer 2007), where \( y = \epsilon_\text{in}/2\gamma_p' \epsilon_p' \approx \delta_{\text{os}} \epsilon_\text{in}/2\gamma_p(1+z)\epsilon_p' \) and the Lorentz factor \( \gamma_p = E_p'/m_c \epsilon_p' \) of an escaping proton as measured by a local observer is \( \gamma_p \approx \delta_{\gamma_p} \). The condition \( y = 1 \) for protons with energy \( E_p = E_p'^{\alpha} \) interacting with photons with energy \( \epsilon_p' \) implies that

\[
E_p'^{\alpha} = \frac{m_c \epsilon' \delta_{\gamma_p}}{2(1+z)\epsilon_p'} = 1.9 \times 10^{14} \delta_{D} \epsilon_p' \text{ eV}. \tag{3}
\]

The radiating fluid element will expand explosively following its rapid energization through shell collisions or through external shocks formed when the outflow sweeps through the surrounding medium. Photopion processes can be certain to be efficient—assuming of course that ultrarelativistic protons are accelerated in black hole jets—if the photopion energy-loss rate \( \rho_{os} \), (1), is greater than the inverse of the light-accelerated protons, \( 1/\tau_p' \approx 1/\tau_{\text{os}} \), of the photopion energy-loss rate \( \tau_{\text{os}} \), and assuming of course that ultrarelativistic protons are accelerated in black hole jets, then the \( \gamma \gamma \) opacity of \( \gamma \)-ray photons with energy \( E_{\gamma} \approx 800 \text{ keV} \). The \( \gamma \gamma \) opacity is less than unity at photon energies \( \lesssim E_{\gamma}^{1/4} \text{ keV} \). The heavy and light curves for \( \gamma \gamma \) production cross section \( \sigma_{\gamma \gamma} \) (Zdziarski & Lightman 1985) gives

\[
\tau_{\gamma \gamma}(\epsilon_1) \approx \tau_{\gamma \gamma}^{\text{th}}[\epsilon_1(\epsilon_1^{1/3}H(\epsilon_1^{1/3} - \epsilon_1) + (\epsilon_1 \epsilon_1^{1/3}H(\epsilon_1 - \epsilon_1^{1/3})))]
\]

(Dermer 2005; see also Lithwick & Sari 2001 and Baring 2006), where

\[
\tau_{\gamma \gamma}^{\text{th}} = \frac{\sigma_{\gamma \gamma} d_0^2 f_{\text{os}}}{4m_c \epsilon_1 \delta_{\text{os}} \epsilon_1}
\tag{6}
\]

and

\[
\epsilon_1^{1/3} = 2\delta_{D}^{1/3} \epsilon_1.
\tag{7}
\]
energies. This energy is the jet Doppler factor in which photopion processes are important. The quantity is the jet Doppler factor in which photopion production is important, whenever photopion production is important, the energy is, after substituting equation (4) into equation (6),

\[ \delta_{\gamma\gamma} = \frac{\sigma_p}{12 \delta} \approx 800. \]  

Whenever photopion production is important, \( \gamma \)-rays with energies given by equation (7) have to be highly extincted by \( \gamma \gamma \) processes when interacting with peak target photons with energy \( \sim \epsilon_{pk} \), making it impossible to detect \( \gamma \)-rays at these energies. This energy is

\[ E_{\gamma} = \frac{2m_e c^2 \delta_{\gamma\gamma}^2}{(1+z)^2 \epsilon_{pk}} = \frac{2m_e c^2 d_\gamma}{(1+z)^2 \epsilon_{pk}} \frac{3 \delta_{\gamma\gamma}}{m_e c \tau_{var}} \approx 10^{-24.26+\epsilon_{\gamma} (y-3) / 2} \text{GeV} \approx 0.055 d_{28} f_{10}^{1/2} \frac{f_{10}^{1/2}}{(1+z)^2} \text{GeV}. \]  

(9)

The energy of protons that interact most strongly with peak target photons through photopion processes (under conditions when photopion processes must be important) is, from equation (3),

\[ E_p = \frac{m_e c^2 \delta_{\gamma\gamma}^2 \epsilon_{thr}}{2(1+z) \epsilon_{pk}} \approx 10^{-10+\epsilon_{\gamma} (y-3) / 2} \text{eV} \]

\[ \approx 1.0 \times 10^{13} d_{28} f_{10}^{1/2} \text{eV}. \]  

(10)

3. RESULTS

Table 1 lists the important quantities derived in this Letter. The quantity \( \delta_{\gamma\gamma} \) is the jet Doppler factor in which photopion losses are guaranteed to be important for protons of escaping energy \( E_p \). Photons with this energy undergo photopion interactions primarily with peak target photons with energy \( \sim \epsilon_{pk} \). \( E_{\gamma} \) is the energy of \( \gamma \)-rays that are attenuated through \( \gamma \gamma \) pair production primarily by peak target photons.

Consider the target photon variability time for the following source classes: flat-spectrum radio quasars (FSRQs) and GRBs, both known sources of GeV radiation, and X-ray–selected BL Lac (XBL) objects, of which over a dozen are known TeV sources. We define the variability timescale \( \tau_{var} \) as the measured time over which the absolute flux varies by a factor of 2; if a source varies by \( N\% \) over time \( \Delta t \), then \( \tau_{var} = 100 \Delta t/N \), keeping in mind that this is a conservative assumption for temporal variability given that quiescent or unrelated emissions can add a separate slowly varying or nonvarying background. R-band optical and RXTE PCA (\( \approx 2–60 \text{keV} \)) observations of 3C 279 and PKS 0528+134 show that day timescale optical and X-ray variability can be expected for FSRQs (Hartman et al. 2001; Mukherjee et al. 1999). Day timescale optical/UV and X-ray variability is also observed for TeV BL Lac objects (Pian et al. 1997; Blazêjowski et al. 2005).

For canonical FSRQ values taken from observations of 3C 279 or PKS 0528+134, Table 1 shows that photopion production is already important at Doppler factors of \( \sim 9–16 \) during times of day-scale optical flaring, and these optical photons effectively extinguish all \( \gamma \)-rays with energies \( \sim E_{\gamma}/800 \) (Fig. 1), which would certainly include all \( \approx 100 \text{GeV} \) to TeV photons. Unfortunately, TeV telescopes have so far not been successful in detecting FSRQs, but the monitoring of an FSRQ during an optical flare with a low-energy threshold air Cerenkov telescope such as MAGIC would identify periods of likely neutrino emission. Photohadronic neutrino secondaries have energies \( E_{\nu} \approx E_{\gamma}/20 \) and so would be produced at \( \sim 10^{17}–10^{18} \text{eV} \), providing possible sources for ANITA (Barwick et al. 2006), although outside IceCube’s optimal energy range.

For guaranteed importance of photohadronic production implied by day-scale X-ray variability, the Doppler factors of FSRQs and TeV BL Lac objects like Mrk 421 have to be unexpectedly small, \( \sim 3 \). If the X-ray flaring timescale of FSRQs were hourly rather than daily, then \( \delta_{\gamma\gamma} \) would more nearly correspond to Doppler factors \( \sim 5–10 \) inferred from unification studies and superluminal motion observations of blazars (Vermeulen & Cohen 1994; Urry & Padovani 1995). During episodes of highly variable X-ray flux, such sources should be invisible to GLAST, and \( \approx \) TeV neutrinos should be created if FSRQs are sources of ultra–high-energy cosmic rays. For the XBL estimate, a 15 minute X-ray flaring timescale has already been assumed. Thus, FSRQs are more likely than BL Lac objects to be high-energy neutrino sources for IceCube, which also follows if, as is likely, the external radiation field plays a strong role in neutrino production (Bednarek & Protheroe 1999; Atoyan & Dermer 2001, 2003).

The outcome of this analysis to identify periods of high-energy neutrino production is best for bright GRBs with peak fluxes of \( \approx 10^{-6} \text{ ergs cm}^{-2} \text{ s}^{-1} \) and peak photon energy in the range 50 keV–0.5 MeV that show \( \approx 1 \text{ s} \) spikes of emission. The bulk factors, \( \approx 100 \), are consistent with widely considered outflow speeds in GRBs (see, e.g., Razzano et al. 2004, who...
also treat $\gamma\gamma$ attenuation in GRBs). Perhaps 100 MeV photons could be observed, but the GLAST Large Area Telescope (LAT) should see no $\gtrsim$GeV photons if $\delta_{\nu} \approx \delta_{\gamma}$, which is the most favorable time for detecting 100 TeV to PeV neutrinos and is at an optimal energy for detection with kilometer-scale neutrino telescopes. Bright X-ray flares with durations $\sim10^{3}$ s observed hundreds to thousands of seconds after the GRB trigger, like those discovered with Swift (O’Brien et al. 2006; Burrows et al. 2007; Murase & Nagataki 2006), with blast wave Doppler factors $\approx50$, are also promising times to look for neutrinos and a $\gamma$-ray spectrum attenuated above $\approx100$ GeV $\gamma$-rays.

The condition $\tau_{\gamma}(\gamma_{i}) < 1$ for detected $\gamma$-rays with energy $\gamma_{i}$ gives a minimum Doppler factor

$$\delta_{D}^{\min} = \left( \frac{\sigma_{\gamma} d_{L}^{2} f_{\nu, r}}{4m_{e}c^{3} \tau_{\nu, e} \epsilon_{pk}} \right) \frac{1}{2} \left( \frac{1 + z}{2} \epsilon_{i} \right)^{1-\lambda} (10-2 \lambda)$$

(Dermer 2005), with $A = b$ if $\epsilon_{i} < \epsilon_{pk}$ and $A = a$ if $\epsilon_{i} > \epsilon_{pk}$. If $\delta_{D}^{\min} \geq \delta_{\nu}$, we should not expect GRBs to be neutrino-bright. Synchro-Compton analysis of high-quality radio and gamma-ray blazar SED data with resolved VLBI cores and self-absorption frequencies gives the Doppler factor directly, provided the SSC component can be identified and separated from external Compton and photohadronic emission components. Should high-energy neutrinos be detected when the Doppler factor inferred from these tests is greater than $\delta_{\nu}$, then this would call into question our understanding of the structure of black hole jets, for example, the assumption of isotropy of target photon distributions in the comoving jet frame.

4. SUMMARY AND CONCLUSIONS

We have presented a detailed treatment of combined photomeson and gamma-ray opacity, which is a crucial problem that unites the neutrino particle physics and the electromagnetic worlds. This problem has been numerically treated for GRBs (Dermer & Atoyan 2003), but no detailed analytical treatment is present in the scientific literature. GLAST observations will reveal if $\gamma$-ray spectra of FSRQ blazars and GRBs show evidence of strong $\gamma$-ray absorption during periods of variable target photon emissions, signifying favorable conditions for high-energy neutrino production.

To illustrate the use of these results, suppose that a blazar or GRB with measured redshift $z$ is monitored at optical, X-ray, or soft $\gamma$-ray energies, giving a light curve $f_{\gamma}(t)$ at photon energy $\epsilon_{\gamma}(t)$. The structure of the light curve implies $\tau_{\gamma}(t)$. From these observables, the Doppler factor $\delta_{\nu}(t)$ for guaranteed importance of photomeson production is derived from equation (4). If high-energy neutrinos are detected, then the source must be opaque at $\gamma$-ray energies given by equation (9). If $\gamma$-rays are detected at these energies, then the basic relativistic jet model must be wrong. Suppose instead that $\gamma$-rays at some energy $\epsilon_{i}$ are detected. In this case, the minimum Doppler factor $\delta_{D}^{\min}(t)$ can be inferred from equation (11) to define times when these sources can and cannot be neutrino-bright.

Times and locations of bright, variable MeV $\gamma$-ray and extinguished GeV fluxes from GRBs can be observed exclusively with the GLAST Burst Monitor (GBM) and LAT, whereas other tests for $\gamma$-ray/multiwavelength correlations giving the most favorable times for high-energy neutrino detection in blazars require the collaboration and coordination of separate facilities. The necessary organization is already underway between GLAST and the ground-based $\gamma$-ray telescopes, e.g., HESS and VERITAS, but blazar observations with, e.g., Swift, Suzaku, and RXTE correlated with GLAST, AGILE, and ground-based high-energy $\gamma$-ray telescopes will be crucial for neutrino discovery science and testing models of relativistic jet sources.

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