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GAMMA-RAY EMISSION FROM BLAZARS

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ABSTRACT

I discuss implications of gamma-ray emission from blazars based on electron acceleration by shock waves in a relativistic jet. The number spectrum of electrons turns out to be a broken power law; while at low energies the power law index has a universal value of 2, at high energies it steepens to an index of 3 because of strong radiative cooling. This spectrum can basically reproduce the observed spectral break between X-rays and gamma-rays. I show that energetics of relativistic jets can be well explained by this model. I estimate physical quantities of the relativistic jets by comparing the prediction with observations. The results show that the jets are particle dominated and are comprised of electron-positron pairs. A connection between gamma-ray emission and radiation drag is also discussed.

Key Words : Active Galactic Nuclei, Gamma-Ray Astronomy, Particle Acceleration, Relativistic Jets

I. INTRODUCTION

BL-Lac objects and optically violent variable quasars, called together blazars, are characterized by rapid time variability, strong optical polarization, superluminal expansion and strong gamma-ray emission. Such properties are understood in the framework of a relativistic jet emanated from the central powerhouse. Blazars are considered to be objects for which the direction of the jet is very close to the line of sight (Blandford and Konigl 1979). Since radio to optical emission is produced by synchrotron radiation of relativistic electrons, gamma-rays are most naturally to be produced by the inverse Compton scattering of soft photons by the same electron population (Maraschi, Ghisellini and Celottii 1992; Sikora, Begelman and Rees 1993; Dermer and Schlickeiser 1993; Inoue and Takahara 1996). The gamma-ray emission will provide an important clue to the electron acceleration mechanism and the nature of the relativistic jets.

EGRET on board the CGRO satellite has identified more than 40 sources with blazars (von Montigny et al. 1995). The estimated isotropic luminosity is very large amounting to above 10^{48}erg s^{-1} for the brightest. The gamma-ray luminosity dominates over those at other frequencies and the number index of gamma-ray spectrum seems to be clustered around 2 at the GeV range but shows a distribution of ±0.5 around 2. For 3C 279, the prototypical gamma-ray blazar (Hartman et al. 1992), variabilities on the time scale of a few days were reported (Kniffen et al. 1993). Rapid time variabilities seem to be common for blazar gamma-ray emission. Combined with OSSE and X-ray observations, the spectrum reveals a break at around 1-10MeV (McNaron-Brown et al. 1995). For Mkn 421, which is one of the nearest BL-Lac objects and was detected with EGRET (Lin et al. 1992), gamma-ray emission is shown to continue up to a TeV range using the Cerenkov telescope at the Whipple Observatory (Punch et al. 1992). This object occasionally reveals TeV-keV flares on a time scale as short as a few hours (Macomb et al. 1995).

In the following, I discuss gamma-ray emission from blazars and its implications on jet physics in terms of shock acceleration of electrons in a relativistic jet. Numerical estimates are made on these two typical blazars, 3C279 and Mkn421.

II. GENERAL CONSTRAINTS

There are two restrictions on the modeling of the gamma-ray emission from blazars. First, the size of the emitting region should be small enough to explain the observed rapid time variability. On the other hand, it should be large enough to avoid the absorption of gamma-rays due to pair creation by a collision off soft photons. These restrictions prove the necessity of the relativistic beaming. The beaming factor is defined by

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}, \tag{1}$$

where β and Γ are the velocity in units of the light velocity and the Lorentz factor of the beam whose direction makes an angle θ to the line of sight. For simplicity we take a spherical emission region of a radius R. The observed variability time scale $\Delta t_{\rm ob}$ should satisfy

$$R > c\Delta t_{\rm ob}\delta = 8.4\times10^{-3}\frac{\Delta t_{\rm ob}}{\rm day}\frac{\delta}{10}{\rm pc}. \tag{2}$$

On the other hand, gamma-ray transparency requires that optical thickness of a gamma-ray photon with an observed energy $\epsilon_{\rm ob}$ to pair absorption should be smaller than 1. The typical energy of target photons is $\epsilon_{\rm t,ob} = 2(\delta m_e c^2)^2/\epsilon_{\rm ob}$ in the observer frame. Numerically, $\epsilon_{\rm t,ob}$ is about 10keV and 0.1keV for $\epsilon_{\rm ob}$=10GeV and 1TeV, respectively. The number density of target photons is estimated by using the observed luminosity at the corresponding energy as

$$L_{\rm t,ob} = 4\pi R^2 c(2\epsilon_{\rm t,s})^2 n_{\rm t}(2\epsilon_{\rm t,s})\delta^4, \tag{3}$$

where the subscript s means quantities in the jet frame. Noting that the cross section is an order of the Thomson cross section, we have the restriction

$$R > 1.0 \times 10^{-5} \frac{\epsilon_{\rm ob}}{\rm GeV} \frac{L_{\rm t,ob}}{10^{46}{\rm erg\ s^{-1}}} (\frac{\delta}{10})^5 {\rm pc}. \qquad (4)$$

Thus, a consistent solution exists only for $\delta >\sim 7$ for 3C279 with the observed maximum energy of gamma-ray photons $\epsilon_{\rm ob} = 10{\rm GeV}$ and the observed luminosity of target photons $L_{\rm t,ob} = 10^{47}{\rm erg\ s^{-1}}$. If we tentatively take $\delta = 10$ as has been suggested by the superluminal motion of radio blobs, we obtain $\sim 0.001{\rm pc} < R < 0.008{\rm pc}$. Similar constraints are obtained for Mkn421, too.

III. ELECTRON ACCELERATION

In this section, I investigate shock acceleration of electrons and resultant emission spectrum (Takahara 1994). Diffusive shock acceleration theory predicts that the power law spectrum is obtained with the canonical index of 2 up to the maximum possible energy under several plausible assumptions (Bell 1978; Blandford and Ostriker 1978). If we apply this theory to AGN environment, several cautions of course are needed. Especially, effects of radiative cooling should be incorporated. Shocks in AGN jets are expected to be relativistic and the jet plasmas may consist of electron-positron pairs instead of a usual electron-proton plasma. Notwithstanding, I still make use of the canonical theory expecting that the key features are not much changed.

The acceleration time scale $t_{\rm acc}$ is estimated in terms of the shock speed $V_{\rm s} \equiv \beta_{\rm s} c$ and the mean free path of electrons $\lambda(\gamma)$ as

$$t_{\rm acc} = \frac{20}{3}\frac{\lambda(\gamma)c}{V_{\rm s}^2}, \qquad (5)$$

where γ is the Lorentz factor of an electron. The cooling time $t_{\rm cool}$ due to the synchrotron radiation and inverse Compton scattering is given by

$$t_{\rm cool} = \frac{3}{4}\frac{m_{\rm e}c}{u_{\rm soft}\sigma_{\rm T}\gamma}, \qquad (6)$$

where $u_{\rm soft}$ is the sum of the energy densities of the magnetic field and soft photons. The advection time scale is defined by

$$t_{\rm ad} = \frac{R}{V_{\rm s}}. \qquad (7)$$

The maximum energy $\gamma_{\rm max} m_{\rm e}c^2$ of electrons accelerated by shocks can be estimated by equating $t_{\rm acc}$ with the shorter one of $t_{\rm cool}$ and $t_{\rm ad}$. Since $t_{\rm cool}$ is much shorter than $t_{\rm ad}$ at high energies, the maximum Lorentz factor becomes

$$\gamma_{\rm max} = \frac{9}{80}\beta_{\rm s}^2 \frac{m_{\rm e}c^2}{\sigma_{\rm T}} \frac{1}{u_{\rm soft}\lambda(\gamma_{\rm max})}. \qquad (8)$$

Near to the shock front, the electron spectrum takes the universal power law shape. As electrons are conveyed to the escaping boundary in the downstream with the fluid flow, they cool radiatively and their spectrum steepens; if $t_{\rm cool}$ is shorter than $t_{\rm ad}$, the spectrum steepens by 1 in the power law index since the cooling time is inversely proportional to the energy. The energy of electrons $\gamma_{\rm br} m_{\rm e}c^2$ at which the spectral index changes is estimated by equating $t_{\rm cool}$ and $t_{\rm ad}$. We obtain

$$\gamma_{\rm br} = \frac{3}{4}\beta_{\rm s}\frac{m_{\rm e}c^2}{\sigma_T}\frac{1}{u_{\rm soft}R} = 30\beta_{\rm s}\frac{0.01{\rm pc}}{R}\frac{1{\rm erg\ cm^{-3}}}{u_{\rm soft}}. \qquad (9)$$

If we assume that the mean free path is ξ times the Larmor radius, we have

$$\gamma_{\rm max} = 9.0 \times 10^6 \beta_{\rm s} (\frac{B}{\xi u_{\rm soft}})^{1/2}. \qquad (10)$$

The energy spectrum of electrons is given by

$$n(\gamma) = \left\{ \begin{array}{ll} K\gamma^{-2}, & \text{for } \gamma < \gamma_{\rm br} \\ K\gamma_{\rm br}\gamma^{-3}, & \text{for } \gamma_{\rm br} < \gamma < \gamma_{\rm max} \end{array} \right. \qquad (11)$$

Corresponding energy density of electrons is given by

$$u_{\rm rel} = K m_{\rm e}c^2 \ln(\gamma_{\rm br}/\gamma_{\rm min}). \qquad (12)$$

The resultant emission spectra of synchrotron radiation and inverse Compton scattering are a power law with an energy index of 1.0 at high energies, while 0.5 at lower energies. Those break features are seen in the MeV break for many of gamma-ray blazars.

IV. MODEL PREDICTIONS

For simplicity, we assume that relativistic electrons are uniformly distributed in a sphere of a radius R with a bulk Lorentz factor of Γ. Further, we assume that energy densities of magnetic field, relativistic electrons and external soft photons are given there. Then, we can predict the energy densities of various radiation components. For example, energy density of synchrotron photons is given by

$$\begin{aligned} u_{\rm syn} &= \frac{R}{3c}\int_{\gamma_{\rm br}}^{\gamma_{\rm max}} \frac{4}{3}\sigma_{\rm T} c u_{\rm mag}\gamma^2 K\gamma_{br}\gamma^{-3} d\gamma \\ &= \frac{\beta_{\rm s}}{3}\frac{u_{\rm mag}}{u_{\rm soft}} u_{\rm rel} \frac{\ln(\gamma_{\rm max}/\gamma_{\rm br})}{\ln(\gamma_{\rm br}/\gamma_{\rm min})}. \qquad (13) \end{aligned}$$

For sources where cooling is dominated by synchrotron radiation, we should take $u_{\rm soft} = u_{\rm mag}$ and have $u_{\rm syn} \approx \beta_{\rm s} u_{\rm rel}$ which should be less than $u_{\rm mag}$ for consistency. We thus find that synchrotron dominance is realized only for Poynting dominated jets for $\beta_{\rm s} \approx 1$. If $u_{\rm syn}$ is larger than $u_{\rm mag}$, $u_{\rm soft}$ should be taken as $u_{\rm syn}$ and the sources become synchrotron self Compton (SSC) dominated. In this case, we have $u_{\rm syn} \approx \sqrt{\beta_{\rm s} u_{\rm mag} u_{\rm rel}}$ and $u_{\rm ssc} \approx \beta_{\rm s} u_{\rm rel}$. We see that

SSC dominance is realized for particle dominated jets. When external Compton radiation dominates, $u_{\rm soft}$ should be taken to be the enegy density of external soft photons $u_{\rm ext}$. Then, we have $u_{\rm syn} \approx \beta_{\rm s} u_{\rm mag}(u_{\rm rel}/u_{\rm ext})$, $u_{\rm ssc} \approx u_{\rm mag}(\beta_{\rm s} u_{\rm rel}/u_{\rm ext})^2$, and $u_{\rm ec} \approx \beta_{\rm s} u_{\rm rel}$. These estimates are valid as long as $u_{\rm soft}$ is not so large as to break the condition $\gamma_{\rm br} > 1$.

Above arguments have several consequences. First, particle acceleration by relativistic shock naturally leads to near equipartition among several emission components provided that $u_{\rm mag}$, $u_{\rm rel}$ and $u_{\rm ext}$ are within an order of magnitudes to each other. Second, this leads to the similar power among various components since the power is determined by

$$L_i = \pi R^2 c u_i \Gamma^2, \qquad (14)$$

except for the external soft photons. Third, if external Compton component dominates over others, radiation drag necessarily occurs to decelerate the radiating blob. Further implications on jet physics are discussed later.

V. OBSERVATIONAL COMPARISONS

In this section we apply the model prediction in the previous section to typical observations (Takahara 1994; Inoue and Takahara 1996). From the synchrotron component ranging from radio to UV and possibly to X-rays, we can obtain

$$u_{\rm syn} = 2.8 \times 10^{-3} \ \frac{L_{\rm syn,ob}}{10^{46}{\rm erg\ s^{-1}}}\left(\frac{R}{0.01{\rm pc}}\right)^{-2} \left(\frac{\delta}{10}\right)^{-4}{\rm erg\ cm^{-3}}. \qquad (15)$$

The strength of the magnetic field is then estimated as

$$B = 0.27 \ \left(\frac{L_{\rm syn,ob}}{L_{\rm ssc,ob}}\right)^{1/2}\left(\frac{L_{\rm syn,ob}}{10^{46}{\rm erg\ s^{-1}}}\right)^{1/2} \left(\frac{R}{0.01{\rm pc}}\right)^{-1}\left(\frac{\delta}{10}\right)^{-2}{\rm G}. \qquad (16)$$

From the high energy cutoff of the synchrotron spectrum, we can infer the maximum energy of accelerated electrons as

$$\gamma_{\rm max} = 1.8 \times 10^4 \left[\frac{\nu_{\rm syn,max,ob}}{10^{15}{\rm Hz}} \frac{1G}{B} \frac{10}{\delta}\right]^{1/2} \qquad (17)$$

For 3C279, taking $R = 0.003$pc, $L_{\rm syn,ob} = L_{\rm ssc,ob} = 3 \times 10^{46}$erg s^{-1}, we obtain $u_{\rm syn} = u_{\rm mag} = 0.1$erg cm^{-3} and $\gamma_{\rm max} = 3 \times 10^4$. This value implies that the gamma-ray emission from 3C279 should be cutted off slightly above the EGRET limit and does not extend to TeV range as is often assumed in various papers studying cosmological problems. The gamma ray emission is presumed to be external Compton radiation with a luminosity of 3×10^{47}erg s^{-1}, then we have $u_{\rm ext} =$ 1erg cm^{-3}. This leads to $\gamma_{\rm br} = 100$ just inferred from the observed break feature around MeV. The energy density of relativistic electrons is $u_{\rm rel} = 3$erg cm^{-3} and the kinetic power of the jet amounts to 3×10^{45}erg s^{-1}.

For Mkn421, taking $R = 0.001$pc, $L_{\rm syn,ob} = L_{\rm ssc,ob} = 1 \times 10^{44}$erg s^{-1}, we obtain $u_{\rm syn} = u_{\rm mag} = 3 \times 10^{-3}$erg $\cdot$ cm^{-3} and $\gamma_{\rm max} = 10^6$. The gamma ray emission due to external Compton radiation is at most comparable to the SSC component, which restricts $u_{\rm ext} \leq 3 \times 10^{-3}$erg cm^{-3}. This leads to $\gamma_{\rm br} = 10^5$. The energy density of relativistic electrons is $u_{\rm rel} = 5 \times 10^{-2}$erg cm^{-3} and the kinetic power of the jet amounts to 4×10^{42}erg s^{-1}.

From this consideration, we suggest that TeV emission is expected only for objects with a high $\gamma_{\rm max}$ which is realized for low luminosity sources with a high cutoff frequency of the synchrotron radiation. Observed value of the maximum energy suggests that the mean free path of electrons is many orders of magnitudes larger than the Larmor radius, but still many orders of magnitudes less than the source size. The number density of electrons derived above is consistent with synchrotron self-absorption frequency.

Although the derived kinetic power seems to be less than the Eddington luminosity, they will significantly exceed it if the jet consists of usual proton-electron plasma since the kinetic power becomes about a thousand times larger. This suggests that the relativistic jets are comprised of electron-positron pairs.

VI. CONCLUDIND REMARKS

I have shown that radio through gamma-ray emission from blazars can be interpreted in term of shock acceleration of relativistic electrons in the relativistic jets. The resultant electron spectrum has a broken power law shape due to the radiative cooling at high energies. X-rays and gamma-rays produced by the inverse Compton scattering of external ultraviolet photons also have a broken power law spectrum. Our model suggests that TeV emission is expected for objects with high $\gamma_{\rm max}$ which is realzed for low luminosity sources with a high synchrotron cutoff frequency. We have estimated the energetics of relativistic jets taking examples of 3C279 and Mkn421. Most important feature is that the jet is strongly particle dominated and that a large kinetic power of electrons suggests that the jet is comprised of electron-positron pairs rather than a usual electron-proton plasma.

Other implication of the strong gamma-ray emission is that the energy density of external soft photons is relatively low for gamma-ray blazars. If we assume that accretion disk emits thermal radiation as strong as the kinetic power, the energy density of such photons becomes a few orders of magnitudes larger than the derived $u_{\rm ext}$. This means that the scattering optical thickness in the near environment is very small. Previous considerations of radiative acceleration of jets have always suggested strong radiative drag prevents the jet from obtaining a high bulk Lorentz factor (Phinney 1987). The observations suggests that the radiation field is somewhat directed to the jet direction to avoid such a large radiation drag. This in turn may revive the possibility of radiative acceleration mechanism, although the origin of electron-positron pairs and jet acceleration mechanisms are still open problems.

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