Correlated Spectral and Temporal Variability in the High-Energy Emission from Blazars

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ABSTRACT Blazar flare data show energy-dependent lags and correlated variability between optical/X-ray and GeV-TeV energies, and follow characteristic trajectories when plotted in the spectral-index/flux plane. This behavior is qualitatively explained if nonthermal electrons are injected over a finite time interval in the comoving plasma frame and cool by radiative processes. Numerical results are presented which show the importance of the effects of synchrotron self-Compton cooling and plasmoid deceleration. The use of INTEGRAL to advance our understanding of these systems is discussed.

KEYWORDS: blazars; galaxies: jets; radiation mechanism: nonthermal

1. INTRODUCTION

Correlated X-ray and γ-ray observations provide important constraints on processes operating in blazars. For example, correlated variability is evident between the optical and 100 MeV - GeV emission in flat spectrum radio sources such as 3C 279 (e.g., Hartman et al. 1996) and BL Lacertae (Bloom et al. 1997), and between the X-ray and TeV emission in the X-ray selected BL Lac objects Mrk 421 and Mrk 501 (e.g., Macomb et al. 1995; Buckley et al. 1996; Catanese et al. 1997). The simplest explanation is that the same population of electrons produces both the optical/X-ray and the 100 MeV - TeV emission. Flare data for Mrk 421 (Takahashi et al. 1996) and PKS 2155-304 (Urry et al. 1997) exhibit time lags which increase with decreasing photon energies. The Mrk 421 data follow a well-defined clockwise “hysteresis” trajectory in a spectral index/flux display, and this behavior is also found in several other BL Lac objects (e.g., OJ 287, Idesawa et al. 1997; PKS 2155-304, Sembay et al. 1993).

These observations motivated recent studies (Dermer 1998; Kirk et al. 1998) to determine whether the lags and hysteresis diagrams can be explained through well-known processes. Here we briefly review these results, and present calculations which treat additional cooling of the electrons through the synchrotron self-Compton (SSC) process. Plasmoid deceleration can introduce important effects...
which resemble radiative cooling processes, and must also be considered in detailed
treatments (see Chiang & Dermer 1998; Chiang 1998a; Dermer & Chiang 1998).
Blazar studies will be significantly advanced using INTEGRAL, which will provide
observations which span the X-ray/soft $\gamma$-ray regime.

2. RADIATIVE PROCESSES

The simplest model for variability in blazars (Tashiro et al. 1995; Dermer 1998;
see also Kirk et al. 1998, who additionally consider electron acceleration) assumes
that a nonthermal power-law distribution of electrons is injected uniformly through-
out a relativistically moving blob over an extended period of time, and that the
electrons cool by synchrotron processes only. The blob is assumed not to accelerate
or decelerate, and energy losses from Compton scattering of photons which impinge
from outside the jet are assumed to be small in comparison with synchrotron losses.
The qualitative behavior of the energy-dependent lags and the hysteresis diagrams
is reproduced. Moreover, by examining the energy-dependence of flare data at $\gamma$-
ray energies, one can discriminate between SSC and external Compton-scattering
origins of the photons (Dermer 1998).

We (Li et al. 1998) have developed a code which includes the following ra-
diative and cooling processes: (1) Coulomb scattering (which is, however, gener-
ally not important); (2) Compton scattering and electron energy losses from arbi-
trary soft isotropic photon sources, using the full Klein-Nishina cross section; and
(3) Cyclo-synchrotron emission, including synchrotron self-absorption and “syn-
chrotron boiler” effects on the electrons (Ghisellini et al. 1988). The particle in-
jection is spatially uniform but may be time-dependent. Particle acceleration and
escape and additional soft photon injection is possible, though only synchrotron
photons are considered here.

The importance of the SSC process is determined by comparing the energy
density $U_{\text{syn}}$ of synchrotron photons in the comoving frame with the magnetic-
field energy density $U_B = B^2/(8\pi)$. We can estimate the maximum value that
$U_{\text{syn}}$ can obtain by assuming that electron cooling has not appreciably changed the
spectrum of injected electrons at the end of the injection episode. If $U_{\text{syn}}/U_B < 1$ at
this moment, then the Compton cooling of the electrons can be neglected compared
with the synchrotron cooling.

Let $E$ represent the energy injected in nonthermal electrons, which we assume
can be described by a power law with lower and upper Lorentz factors of the
electron injection function given by $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, respectively. If we write the
differential electron number spectrum as $N(\gamma) = N_0 \gamma^{-p}$, where $p$ is the elec-
tron injection index, then $N_0 = (2 - p)E/[m_e c^2 (\gamma_{\text{max}}^{3-p} - \gamma_{\text{min}}^{3-p})]$. The value of
$U_{\text{syn}} \cong L_{\text{syn}}/(4\pi R^2 c) \cong [m_e c^2/(4\pi R^2 c)] \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma |N(\gamma)|$, where the electron en-
ergy loss rate through synchrotron radiation is given by $-\dot{\gamma} = [4\pi T/(3m_e c)]U_B \gamma^2$.
Thus
\[
\frac{U_{\text{syn}}}{U_B} = \frac{\sigma_T}{3\pi R^2} \frac{N_0}{3 - p} (\gamma_{\text{max}}^{3-p} - \gamma_{\text{min}}^{3-p}) = \frac{\sigma_T}{3\pi R^2} \frac{\mathcal{E}(\gamma_{\text{max}} - \gamma_{\text{min}})}{m_e c^2 \ln(\gamma_{\text{max}}/\gamma_{\text{min}})},
\]
(1)
where the last expression applies to the case $p = 2$ (see Dermer et al. 1997 for comparison with energy losses due to photons which originate from outside the jet).

In the runs shown, we let $B = 0.1$, $\gamma_{\text{min}} = 10$ and $\gamma_{\text{max}} = 10^6$, and let $p = 2$. The radius of the spherical blob is $R = 1.5 \times 10^{16}$ cm, and the Doppler factor $D = 10$. Using eq. (1), we see that $U_{\text{syn}}/U_B \simeq 0.7 \mathcal{E}_{46}/R_{16}^2$ for these parameters, where $R_{16} = R/(10^{16}$ cm) and $\mathcal{E}_{46} = \mathcal{E}/(10^{46}$ ergs). We therefore choose two extreme values for $\mathcal{E}$ where the effects of SSC are negligible and are dominant. In Figs. 1 and 2, $\mathcal{E} = 10^{44}$ and $10^{49}$ ergs, respectively. This energy in nonthermal electrons is injected over a comoving time scale of $10^6$ s. These figures show the evolving electron energy distribution $E^2n(E)$ and the evolving $\nu L_\nu$ photon spectrum at different times in the observer’s frame. Here $n(E) = N(E)/V$ is the differential electron energy spectrum, $V = 4\pi R^3/3$ is the blob volume, and $E = \gamma m_e c^2$.

The labels in Figs. 1 and 2 indicate time in units of the comoving dynamical time scale $R/c = 5 \times 10^5$ s. The maximum intensity of the electron spectrum is therefore reached at 2 dynamical time scales. The evolution of the electron spectrum is obviously fastest at the highest energies. In Fig. 1, where only synchrotron losses are important, the electron spectrum cuts off abruptly. The synchrotron peak evolves to lower energies due to the electron cooling. Even in this limit where SSC effects are not important, features from the Comptonized synchrotron emission are imprinted on the synchrotron spectrum, though at low levels. By contrast, Fig. 2 shows the
case when SSC is very important on the electrons. Multiple Compton scattering features are evident at late times in the $\nu L_\nu$ spectra. Due to the exponential escape $\propto \exp(-ct/R)$ of the photons from the emitting region, high-energy ($>10^5$ MeV) radiation is still being received at several dynamical time scales after which electrons which could produce such emission have cooled. There are no strong spectral softenings between hard X-ray and soft $\gamma$-ray energies in Figs. 1 and 2. We have also checked that compactness effects are unimportant in the two calculations.

Fig. 3 shows light curves calculated at different photon energies for the runs of Figs. 1 and 2. The light curves are calculated for a source at redshift $z = 1$. The comoving time is Doppler contracted and redshifted as measured by an observer; thus the observed dynamical time scale $(1 + z)(R/Dc) \approx 10^5$ s. Consequently, these light curves peak at roughly twice the dynamical time scale, or about 2 days. By comparing the eV and keV light curves, and the GeV and TeV light curves for the $10^{44}$ ergs case, one can see that the effects of synchrotron cooling is to make lower energy light curves lag the high energy light curves. In the limit where synchrotron cooling dominates, the energy dependence of the lag is $\propto \epsilon^{-1/2}$ for the synchrotron component of the spectrum, but is $\propto \epsilon^{-1/4}$ for the SSC component (Dermer 1998). Here $\epsilon$ is the observed photon energy. When SSC losses cannot be neglected, the behavior is more complicated as can be seen by examining the $10^{49}$ ergs case. Surprisingly, the keV light curves can lag the eV light curves due to the contribution of the SSC component.

Model trajectories in the spectral index/flux plane (the so-called “hysteresis”
FIGURE 3. Light curves at eV, keV, MeV, GeV, and TeV photon energies for the cases where $10^{44}$ ergs (bottom) and $10^{49}$ ergs (top) are injected into the comoving frame over a period of $10^6$ s, corresponding to the runs shown in Figs. 1 and 2, respectively.

FIGURE 4. Model trajectories in the spectral index/flux plane at photon energies of 2 keV and 100 keV, for the cases where $10^{44}$ ergs (bottom) and $10^{49}$ ergs (top) are injected into the comoving frame over a period of $10^6$ s, corresponding to the runs shown in Figs. 1 and 2.
d) for the flares corresponding to the runs of Figs. 1 and 2 are shown in Fig. 4. Clockwise rotation is found at 2 keV and 100 keV for the case where synchrotron losses dominate the electron cooling. When SSC losses are dominant, we see that the hysteresis diagrams can rotate in the opposite sense at 2 keV, and exhibit even more complicated behavior at 100 keV. This is related to the contribution of the SSC component which can produce a high energy component that leads rather than lags, as just mentioned. Additional photon sources which impinge from outside the jet could produce even more complicated behavior, and remains to be studied.

3. PLASMOID DECELERATION

Observations of afterglows from gamma-ray bursts (GRBs) have directed attention to the importance of extracting energy from the bulk kinetic energy of the outflowing plasma as the mechanism for energizing the nonthermal electrons in the comoving frame. A simple review of the blast wave physics used to analyze deceleration effects due to sweeping-up material from the surrounding medium has recently been presented by Dermer & Chiang (1999). We (Chiang 1998, 1999) have also recently examined spectral and temporal effects from blob deceleration. Since the characteristic electron energy in the comoving frame is proportional to the bulk Lorentz factor of the blob, the energy of the synchrotron peak decreases with time as the blob decelerates. This effect yields a spectral-index/flux behavior similar in character similar to that resulting from synchrotron cooling.

In Fig. 5, we show a calculation using the blast-wave code developed for GRBs by Chiang & Dermer (1999), though with parameters appropriate to blazars. As shown by Dermer & Chiang (1999), the overall spectral properties of blazars and GRBs are similar except for the value of their initial bulk Lorentz factor $\Gamma_0$. In this calculation, $\Gamma_0 = 40$, the total energy injected per $4\pi$ sr is $10^{52}$ ergs and the plasmoid expands into a medium with a proton density of $10^3$ cm$^{-3}$. When it sweeps up particles, nonthermal electrons are injected with a minimum Lorentz factor $m_p\Gamma_0/m_e$, and with a very soft power law slope $p = 6$. In this calculation, the magnetic equipartition parameter $\xi_B = 10^{-6}$ (see Chiang & Dermer 1999).

The left-hand panel of Fig. 5 shows the time evolution of the observed $\nu L_\nu$ spectrum. As time increases, the peak of the $\nu L_\nu$ spectrum migrates from right to left due to the deceleration of the plasmoid. The declining magnitude of the $\nu L_\nu$ flux after it reaches its peak is due to plasmoid deceleration rather than radiative cooling, which is negligible in this calculation. The right-hand panel of Fig. 5 shows the trajectory followed in the spectral index/flux plane when the plasmoid emission is observed at 2 keV. This behavior resembles that produced by radiative cooling, even though radiative cooling plays essentially no role in the variability behavior of this calculation. The importance of plasmoid deceleration in the interpretation of GRB spectral data has been recently pointed out by Chiang (1999).

Because plasmoid deceleration can produce an observed decaying flux, this effect must be considered whenever temporal variability observations are used to infer properties of blazars. It is therefore not possible to simply interpret variability
observations in terms of radiative cooling time scales. This may weaken tests for beaming in blazars (see Dermer 1997), or for inferences about the mean magnetic fields in the radiating plasma (e.g., Catanese et al. 1997; Dermer 1998). If variability behavior is due to plasmoid deceleration rather than to the radiative cooling time scale, hadronic models for blazar emissions (see, e.g., Mannheim 1993) no longer have to contend with the difficulty of demonstrating a short cooling time scale.

4. CONCLUSIONS

With the launch of INTEGRAL, we can look forward to high-quality data showing the energy-dependence of the “hysteresis” curves and lags over a broad energy range from the X-ray through the soft $\gamma$-ray regime. Correlated variability observed with the OMC on INTEGRAL will also contribute to studies of the variability behavior. The calculated phase lags and trajectories are rather simply understood when synchrotron processes dominate the cooling, but become significantly more complicated when the SSC process represents an important electron coolant, and when plasmoid deceleration is important.

Blazar science to which INTEGRAL will contribute and about which future studies should focus includes:

- The magnitude of the spectral breaks between the X-ray and soft $\gamma$-ray regimes, and whether this is consistent with an SSC origin of the $\gamma$ rays.
• Phase lags as a function of photon energy, and whether higher energy emission leads lower energy emission when the Compton component dominates.

• Photon-energy dependent “hysteresis” diagrams, and under what conditions they can originate from radiative cooling or plasmoid deceleration, or exhibit counterclockwise rotation.

• Variability time scales in the hard X-ray/soft $\gamma$-ray regime, and discriminants between radiative cooling or plasmoid deceleration as the origin of the variability behavior.

• Implications of plasmoid deceleration on inferences of blazar properties of blazars, including the entrained magnetic field, the minimum Doppler factors, and the dominant radiation processes.

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REFERENCES
Bloom, S. D., et al. 1997, ApJ, 490, L145
Buckley, J. H., et al. 1996, ApJ, 472, L9
Catanese, M., et al. 1997, ApJ, 487, L143
Chiang, J., & Dermer, C. D. 1999, ApJ, 512, in press (astro-ph/980339)
Chiang, J. 1998, ApJ, 508, 752
Chiang, J. 1999, ApJ, in press (astro-ph/9810238)
Dermer, C. D. 1998, ApJ, 501, L157
Dermer, C. D. 1997, in Proceedings of the St. Malo INTEGRAL Workshop, ed. C. Winkler and T. Courvoisier, (Noordwijk: ESA), 405.
Dermer, C. D., Sturner, S. J., & Schlickeiser, R. 1997, ApJS, 109, 103
Dermer, C. D., & Chiang, J. 1999, in High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson, in press (astro-ph/9810222)
Ghisellini, G., Guilbert, P. W., & Svensson, R. 1988, ApJ, 334, L5
Hartman, R. C., et al. 1996, ApJ 461, 698
Idesawa, E., et al. 1997, PASJ, 49, 631
Kirk, J. G., Rieger, F. M., & Mastichiadis, A. 1998, A&A, 333, 452
Li, H., Dermer, C. D., & Kusunose, M. 1998, in preparation
Macomb, D. J., et al. 1995, ApJ, 449, L99; (e) 1996, ApJ, 459, L111
Mannheim, K. 1993, A&A, 369, 67
Sembay, S., et al. 1993, ApJ, 404, 112
Takahashi, T., et al. 1996, ApJ, 470, L89
Tashiro, M., et al. 1995, PASJ, 47, 131
Urry, C. M., et al. 1997, ApJ, 486, 799