Synergy Between Observations of AGN with GLAST and MAXI

– Detecting X–ray Precursors of Gamma-ray Flares in Blazars

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ABSTRACT

In five years' time we will witness the launch of two important missions developed to observe celestial sources in the high energy regime: GLAST, sensitive in the high energy γ–ray band, and MAXI, the all-sky X–ray monitor. Simultaneous monitoring observations by the two instruments will be particularly valuable for variable sources, allowing cross-correlations of time series between the two bands. We present the anticipated results from such observations of active galaxies, and in particular, of the jet-dominated sub-class of AGN known as blazars. We discuss the constraints on the structure and emission processes – and in particular, on the internal shock models currently invoked to explain the particle acceleration processes in blazars – that can be derived with simultaneous γ–ray and X–ray data.

KEY WORDS: active galaxies — blazars — gamma–rays

1. Introduction

Blazars are active galaxies where the entire observed radiation is believed to be dominated by the emission from material moving at relativistic speed close to our line of sight. This is supported, among others, by the following observational characteristics: compact radio cores, rapid and large amplitude variability in all accessible spectral bands, strong radio and optical polarization, and spectra described locally as power laws. Blazars are often detected as γ–ray sources, and in some cases, the emission extends up to the TeV range. The overall electromagnetic spectra of those sources consist of two broad components, one peaking in the infrared – to – X–ray range, and the other in the γ–ray range. The most commonly invoked scenarios have the emitting matter moving with relativistic speed in a form of multiple clouds or shells, or even as a quasi-continuous jet with a Lorentz factor $\Gamma_{\rm jet} \sim 5 - 10$. The most viable emission mechanisms are the synchrotron process for the low-energy component, and Compton upscattering of lower energy photons for the high energy component. Presumably the same population of radiating electrons is responsible for both mechanisms; the required electron Lorentz factors must reach the range up to $10^3 - 10^6$, depending on a particular source. Very short radiative lifetimes of such particles imply that the acceleration occurs *in situ* – most likely a light-day or more away from the central source. At least in the blazars where strong emission line flux is detected, the most likely source of the "seed" photons

for Compton upscattering is external radiation from the broad line region. One of the crucial questions regarding astrophysical jets is thus that of the conversion of the kinetic energy of the jet to the random energy of radiating particles.

2. Internal Shock Scenario

Models for production of nonthermal flares in blazars as well as Gamma–ray Burst sources (GRBs) often involve collisions between shells containing relatively cold matter, propagating down the jet with different velocities. Such shells approximate inhomogeneities which can result from modulation of the relativistic outflow by a central engine. Adopting this model, we demonstrate that nonthermal flares, produced by relativistic particles accelerated in shocks excited by colliding shells, must be preceded by soft X–ray flares, produced by Comptonization of external radiation by the material in the cold shells *before the collision*. This external radiation is in fact the same source which is providing the "seed" photons for production of γ–rays. To demonstrate the effect in a simple way, we consider an idealized case, where two colliding shells are 'symmetrical', i.e. identical in their rest frames (equal densities, total masses and negligible pressures). They are assumed to propagate down the conical jet with bulk Lorentz factors, $\Gamma_2 > \Gamma_1 \gg 1$, each carrying N_p protons.

Provided that the ratio of the electron density n_e to

proton density n_p obeys $n_e/n_p \ll m_p/m_e$, the protons dominate inertia of the shells, and the total energy of two shells before collision is

$$E = E_1 + E_2 = N_p(\Gamma_1 + \Gamma_2)m_p c^2. \qquad (1)$$

From energy and momentum conservation one can find that fraction of energy dissipated during the collision is

$$\eta_{diss} \equiv \frac{E_{diss}}{E} = 1 - \frac{2\Gamma_{1+2}}{\Gamma_1 + \Gamma_2} \simeq 1 - \frac{2\sqrt{\Gamma_2/\Gamma_1}}{\Gamma_2/\Gamma_1 + 1}, \qquad (2)$$

where

$$\Gamma_{1+2} \simeq \sqrt{\Gamma_1 \Gamma_2} \qquad (3)$$

is the bulk Lorentz factor of the shocked plasma enclosed between the forward and reverse shock fronts. Denoting by η_{el} the fraction of dissipated energy consumed to accelerate relativistic electrons/positrons, and by η_{rad} the average radiative efficiency of electrons, one can find that the proton content, N_p, required to produce a nonthermal flare with the apparent total luminosity L_{fl} and lasting t_{fl} is

$$N_p = \frac{1}{\eta_{diss}\eta_{el}\eta_{rad}} \frac{L_{fl} t_{fl}}{m_p c^2 \mathcal{D}_{1+2}^3} \frac{1}{(\Gamma_2/\Gamma_1)^{1/2} + (\Gamma_2/\Gamma_1)^{-1/2}}, \qquad (4)$$

where we used Eqs. (1)-(3) and relations:

$$L'_{fl} = \frac{E'_{rad}}{t'_{coll}} = \frac{\eta_{diss}\eta_{el}\eta_{rad}E'}{t'_{coll}}, \qquad (5)$$

$$E = E'\Gamma_{1+2}, \qquad (6)$$

$$t_{fl} = \frac{t'_{coll}}{\mathcal{D}_{1+2}}, \qquad (7)$$

$$L_{fl} = \mathcal{D}_{1+2}^4 L'_{fl}, \qquad (8)$$

and the usual definition of $\mathcal{D}$,

$$\mathcal{D}_{1+2} = \frac{1}{\Gamma_{1+2}(1 - \beta_{1+2}\cos\theta_{obs})}, \qquad (9)$$

where t'_{coll} is the time scale of the collision, and all primed quantities are measured in the comoving frame of the shocked plasma.

Number of protons N_p gives us the constraint on the minimum number of electrons contained by each shell. These electrons, which are assumed to be cold before collision, are predicted to Comptonize external radiation and produce two spectral features, peaked around frequencies

$$\nu_i \simeq \frac{4}{3}\mathcal{D}_i\Gamma_i\nu_{diff}, \qquad (10)$$

where ν_{diff} is the averaged frequency of the diffuse external radiation field. The luminosities of these features are

$$L_{SX,i} \simeq N_e \dot{E}_{el,i}\mathcal{D}_i^4, \qquad (11)$$

$$\dot{E}_{el,i} \simeq \frac{4}{3}\Gamma_i^2 c\sigma_T u_{diff}, \qquad (12)$$

$$\mathcal{D}_i = \frac{1}{\Gamma_i(1 - \beta_i\cos\theta_{obs})}, \qquad (13)$$

where u_{diff} is the energy density of the diffuse radiation field, and $i = 1, 2$. The precursors should precede the nonthermal flares by

$$\delta t_i \sim \frac{r_{fl,0}}{c}(1 - \beta_i\cos\theta_{obs}) \qquad (14)$$

where $r_{fl,0}$ is the distance from the location where the jet was launched to that where the cold shells start to collide.

Adopting the following (fiducial) observables: $L_{fl} = 10^{48}$ erg s^{-1}; $t_{fl} = 1$ day; $u_{BEL} = 0.03$ erg cm^{-3} (energy density of the broad emission line flux); $\nu_{diff} = 10$ eV, and assuming $\Gamma_{1+2} = 10$, $\Gamma_2/\Gamma_1 = 3$ (corresponding to $\eta_{diss} \simeq 0.134$), $\eta_{rad} = 0.5$, $\eta_{el} = 1/3$ (equipartition between protons, electrons and magnetic fields), and $\theta_{obs} = 1/\Gamma_{1+2}$, we obtain that the brighter precursor (that produced by the faster shell) should peak at ~ 2 keV and should have luminosity

$$L_{SX,2} \sim 1.5 \times 10^{45} \text{ erg s}^{-1} \frac{n_e}{n_p} \frac{u_{diff}}{u_{BEL}}, \qquad (14)$$

while a precursor produced by the slower shell should peak around ~ 0.7 keV and should be $(\Gamma_2/\Gamma_1)^2(\mathcal{D}_2/\mathcal{D}_1)^4 \simeq 9$ times fainter. These preliminary results suggest that during luminous outbursts, a brighter precursor should be detected by a moderately sensitive detector even if there are no pairs and jet formation and collimation is so distant that contribution of the accretion disc radiation to u_{diff} is negligible. Assuming that $r_{fl,0} \sim ct_{fl}\Gamma_{1+2}^2$, the occurrence of such soft X–ray precursors should precede the bright γ–ray flares by $\sim 0.7t_{fl}$ and $\sim 2t_{fl}$ respectively for the brighter and the fainter X–ray precursor.

3. Consequences for GLAST and MAXI

Any studies of correlation of variability in X–rays and γ–rays require simultaneous observations, and it is fortuitous that GLAST and MAXI will be operational at the same time. GLAST is the next generation γ–ray observatory, shown schematically in Fig. 2. It features an effective area given in Fig. 3, which is about 8 times better than that of the highly successful EGRET detector flown aboard the Compton Gamma–ray Observatory; EGRET is of course the detector originally responsible for the discovery of γ–ray flares from many blazars. The design of GLAST allows monitoring simultaneously of more than 2 steradians of the sky, so such a large number of such flares will be detected and monitored from multiple blazars at the same time.
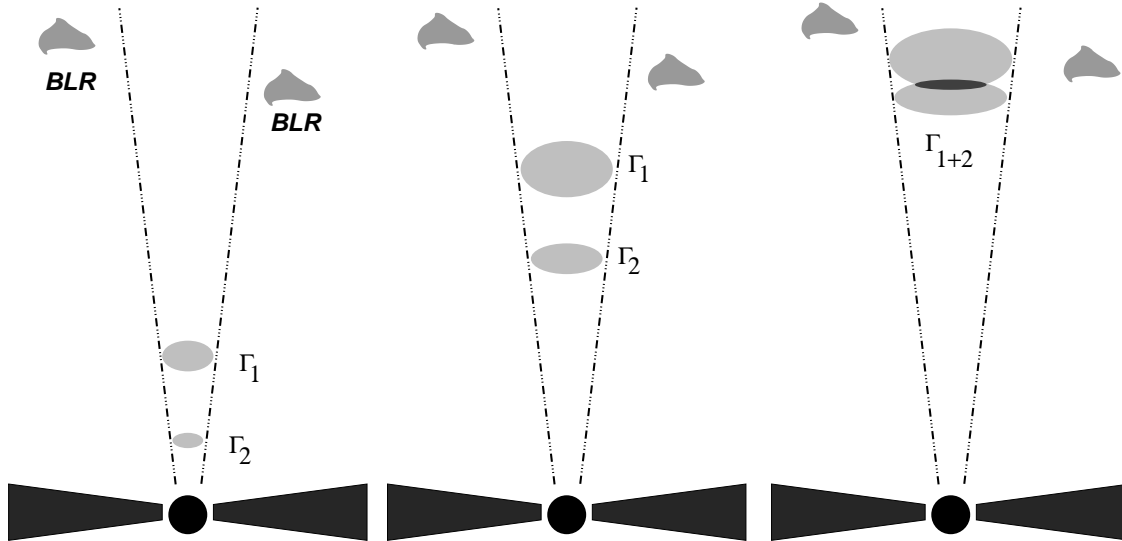
Fig. 1. Illustration of the scenario for the internal shock mechanism discussed in the text, with time progressing to the right. Two cold clouds or shells of plasma, moving with Lorentz factors Γ_1 and Γ_2 (where $\Gamma_2 > \Gamma_1$) collide, and the shocks resulting from the collision provide the site for particle acceleration. BLR denotes the Broad Line Region, which is assumed to be the source of "seed" photons for Comptonization, resulting in X–ray precursors in the left and middle panels, and γ–ray flare in the right panel.

In contrast, most current X–ray detectors feature a relatively narrow field of view, typically less than 1×1 degree. It is of course possible to train an X–ray observatory on a blazar discovered to be flaring in γ–rays, but the crucial observation is the history of X–ray flux *prior* to such a flare: with this, the monitoring of the entire sky in the X–ray band is required. Without an X–ray monitoring instrument which would detect such a flare *before* it is measured by GLAST, one would have to rely on a rare coincidence that an X–ray telescope would be observing a blazar which is about to flare in the γ–ray band. These preliminary results suggest that during luminous outbursts, at least relatively bright precursors should be detected by an all-sky sensitive instrument such as MAXI. Finally, its energy resolution also plays an important role in making detailed estimates of the physical conditions in the "early" phases of the formation of jets in blazars.

We would like to emphasize that our predictions regarding soft X–ray precursors are independent on the specific model of nonthermal radiation mechanism. Eventual lack of precursors can jeopardize the internal shock models and favor the external, reconfinement shocks and/or reconnection of magnetic fields as the source of energy for relativistic electrons. In case of positive detection, the detailed analyses can be used to trace the structure of innermost parts of relativistic jets and to put constraints on a pair content. So far, only observations of 3C 279 provided sufficiently good data to allow to search for such precursor (Wehrle et al. 1998;

Lawson, McHardy & Marscher 1999). Detailed analyses of the X–ray spectral index evolution before and during the flare show possible presence of precursor: the modest flux detected from this flare excludes high pair content in this object. We also note that studies of Comptonization of external radiation by cold electrons in a jet were performed previously (see, e.g., Begelman & Sikora 1987 and Sikora, Madejski, Moderski, & Poutanen (1997), but those considered only stationary jets. Consideration of such stationary case makes it difficult to distinguish the contribution of precursors originating from the bulk Compton radiation described above from other sources of soft X–rays.

4. Acknowledgements

5. References

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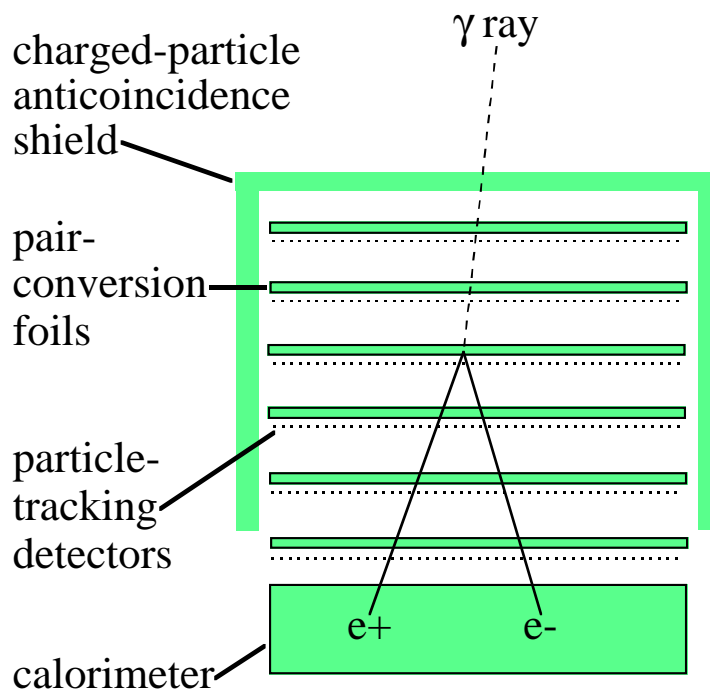
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Fig. 2. Schematic illustration and the principle of operation of the GLAST Large Area Telescope (LAT). Entering γ–ray converts into an e^+ / e^- pair in the conversion foil. The resultant e^+ and e^- charges deposit energy and are detected in the particle-tracking detectors, which are made of position-sensitive silicon strips. Recording of the locations where the charges interacted with the silicon strips allows a reconstruction of their "tracks." This in turn permits the determination of the direction of arrival of the incident γ–ray. The calorimeter, located beneath the tracker, is a scintillator, capable of measuring the total energy deposited by the particles produced by the incident γ–ray. The LAT detector is modular: it consists of a 4×4 array of identical towers. The entire detector system is enclosed by an anti-coincidence shield, designed to reject the charged particle background.
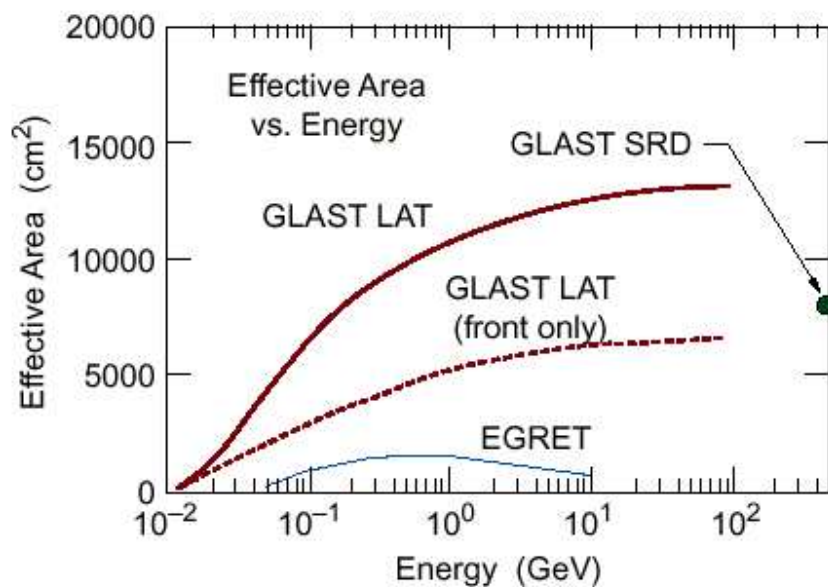

Fig. 3. Effective area of the GLAST LAT instrument as a function of energy. The instrument has some sensitivity at 20 MeV; its effective area is greatest between ~ 0.1 and 100 GeV. One of the design criteria of the instrument was to extend the energy bandpass to at least 100 GeV, to allow some overlap with ground-based TeV Cerenkov air shower array detectors. Current plans for GLAST have the sensitivity extending to the point marked as "GLAST SRD," where even the current TeV detectors have a reasonably good sensitivity.