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GRB spectral turnover and the saturated Compton cooling model

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Abstract. We revisit the different physical interpretations of the spectral break in GRB continuum and the low energy turnover, especially at the beginning of pulses. We argue that optically thin synchrotron emission can be ruled out in many cases. Alternative models are discussed. We then concentrate on one paricularly attractive model: saturated Comptonization of soft photons. We summarize the various predictions of this model and highlight the critical tests of this model that may be provided by existing and future data.

Key words: gamma-rays: bursts — gamma-rays: observations — radiation mechanisms: non-thermal — techniques: spectroscopic

1. Introduction

Recent optical afterglow observations have convincingly shown that most GRBs are likely at cosmological distances (Djorgovski et al. 1997; Feroci et al. 1998). But their true nature remains a mystery. Though afterglow studies will shed important light on the energetics, progenitor and environment of GRBs, progress towards the origin of GRB itself still depends on the ultimate understanding of the gamma-ray emission mechanism. To address the physics of this early phase GRB emission we must decipher the complex information contained in the spectral and temporal evolution of the gamma-ray pulses.

Recent high-time-resolution studies of GRB spectra show that the typical hard-to-soft evolution can be characterized, using the Band et al. (1993) function, as the downward movement of the spectral break energy $E_{\rm pk}$ (Liang & Kargatis 1996), plus a softening of the low energy photon slope α (Crider et al. 1997; Crider et al. 1998). The Band et al. α often is very hard at the beginning of a pulse, with $\alpha_{\rm max} > 0$ in over 2/3 of pulses analyzed (Crider et al. 1997; Preece et al. 1998). This contradicts directly the upper limit on optically thin synchrotron ($\alpha_{\rm max} = -2/3$) (Meszaros & Rees 1993; Katz 1994). Hence a synchrotron emission model requires additional absorption mechanism to turnover the low-energy spectral slope ("X-ray deficiency problem"). Also the decay of $E_{\rm pk}$ follows the Liang-Kargatis (1996) decay law in most pulses: $E_{\rm pk} = E_{\rm o\,exp}(-\Phi/\Phi_{\rm o})$ where Φ is the running photon fluence, and $E_{\rm o}$ and $\Phi_{\rm o}$ are constants. This behavior must be satisfied by any emission and cooling model.

2. Spectral turnover interpretations

We have systematically examined all of the conventional absorption mechanisms that may lead to a spectral break at a few hundred keVs. External photoelectric absorption by a cold static ISM or CBM (circumburster medium) requires a huge column density ($> 10^{26}$ cm^{-2}) for solar abundance unless the CBM is very Fe-rich (Boettcher et al. 1999). In that case the required Fe column density would be $> 10^{21}$ cm^{-2}. But even in this case the low-energy spectral shape is inconsistent with those observed by Beppo/SAX and Ginga. However this idea merits further study in view of the recent claims of Fe-fluorescence line emission during the afterglows (Piro et al. 1999).

Internal synchrotron self-absorption up to keV energies if the bulk Lorentz factor Γ = hundreds requires very strong fields ($B > 10^7$ G) (Rybicki & Lightman 1979). Internal bremsstrahlung (Rybicki & Lightman 1979) or plasma (Razin-Tsytovich) absorption requires very high density ($> 10^{26}$ cm^{-3}) (Melrose 1980). None of these options are viable based on current relativistic fireball scenarios (Piran et al. 1993). Internal double Compton or photo-electric absorption remains to be investigated but is unlikely to produce spectral shapes that match those observed. Hence the remaining option is saturated Comptonization (Rybicki & Lightman 1979), a mechanism we have concentrated on for the last two years.

3. Saturated Compton cooling model

The saturated Compton cooling (SCC) model interprets the spectral break as the Wien peak caused by multiple Compton upscattering of soft photons. In this case $E_{\rm pk}$

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corresponds roughly to the average lepton energy $< E >$. At very high Thomson depths $\tau_{\rm T}(\gg 10)$ the Band index α is > 0. But as the Thomson depth decreases α decreases to < 0 (Rybicki & Lightman 1979; Liang et al. 1997). However for pure nonthermal power-law lepton distributions $E_{\rm pk}$ is always in the hundreds of keVs in the emitter frame. To bring it down to keVs in the emitter frame of a relativistic shell of bulk Lorentz factor $\Gamma =$ hundreds, we need to invoke a hybrid thermal-nonthermal lepton distribution with most of the particles in the thermal population with comoving $kT =$ keVs and only a few percent of the leptions in the nonthermal power-law tail. For typical magnetic fields and lepton densities discussed below, most of the soft photons are still produced by the nonthermal leptons via the synchrotron mechanism. Since the bulk of the leptons are keV thermal particles, the shock conversion efficiency from bulk kinetic energy to internal energy is likely low since the impulsive energization will be concentrated in the small number of nonthermal leptons. These and other physics issues of the SCC model need further investigation.

Since $< E > \;\; = E_{\rm pk}$ in this model the Liang-Kargatis (1996) decay law is a natural consequence of radiative cooling plus energy conservation in the comoving frame, and the LK decay constant $\Phi_{\rm o}$ is simply a measure of the total number of emitting particles modulo Ω (the solid angle filling factor of the ejecta shell) times the distance squared, independent of the bulk Lorentz factor Γ. Liang (1997) then showed that the ratio of source distance d to the relativistic shell curvature radius R becomes $d/R = 10^{12}(\tau_{\rm T}/\Phi_{\rm o})^{1/2}$. Since both $\tau_{\rm T}$ and $\Phi_{\rm o}$ are directly extractable from spectral fitting, we can deduce all relevant physical parameters of the shell once we know the distance. For example, consider a hypothetical shell at a distance of 1 Gpc, with $\Phi_{\rm o} = 10 = \tau_{\rm T}$ and a pulse rise time of 1 s. This rise time, if interpreted as the time delay caused by the curvature of the forward visible patch, limits the bulk Lorentz factor to $\Gamma \geq 224$ (Liang 1997). We find that the shell has very large aspect ratio, ($R/H \leq 4.5\ 10^3$), high density (comving lepton density $\geq 2.2\ 10^{13}$ cm^{-3}), comoving magnetic field $B = 1 - 100$ G, and is matter-dominated ($U/Nm_{\rm e}c^2 = 10^{-3}$) where U is the total internal energy. The total number of leptons $N = 10^{57}\ \Omega/(4\pi)$ and the total lepton kinetic energy $\Gamma N m_{\rm e} c^2 \geq 10^{53}\ \Omega/(4\pi)$ ergs. Due to the high comoving density such shells are likely associated with internal shocks of ejecta material (rather than external shocks).

4. The GRB - afterglow connection

We can put the above numbers in the context of a standard fireball internal shock scenario and make some rough predictions on the evolution of the shell through the different phases: from the initial free-expansion fireball phase, to the late time blast wave (snow-plow) phase, using the analytic solutions of Piran et al. (1993) and Blandford & McKee (1976). In particular, the shell parameters derived above for the GRB phase can be used to predict the subsequent evolution parameters of the optical-radio afterglows which are associated with the blast wave phase. Hence the SCC model is highly predictive in that it tightly connects the GRB spectral evolution parameters to the afterglow parameters once the ISM/CBM density and the proton loading of the ejecta shell are specified.

5. Summary

We find that the most natural explanation of the evolution of the Band photon index α is that of optical thinning. The very high initial α plus the Liang-Kargatis decay law found in many pulses are in favor of the saturated Compton cooling model. In such a model all of the physical parameters of the gamma-ray emitting ejecta shell in the comoving frame are uniquely determined or tightly constrained by the source distance d, Thomson depth $\tau_{\rm T}$, the LK decay constant $\Phi_{\rm o}$ plus the pulse rise time. These parameters then predict the afterglow behaviors from first principles once the ISM or CBM density plus proton loading is specified. Future observations should be able to test such predictions.

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References

Band D., et al., 1993, ApJ 413, 281
Blandford R., McKee C., 1976, Phys. Fluids 19, 1130
Böttcher M., Dermer C., Crider A., Liang E.P., 1999, A&A (accepted)
Crider A., Liang E.P., Preece R.D., 1998, AIP 428, 359
Crider A., et al., 1997, ApJ 479, L39
Djorgovski S.G., et al., 1997, Nat 387, 876
Feroci M., et al., 1998, A&A 352, L29
Katz J.I., 1994, ApJ 432, L107
Liang E.P., Smith I.A., Kusunose M., Crider A., 1997, ApJ 479, L35
Liang E., 1997, ApJ 491, L15
Liang E., Kargatis V., 1996, Nat 381, 49
Melrose D., 1980, Plasma Astrophysics. NY: Gordon & Breach
Piran T., Shemi A., Narayan R., 1993, MNRAS 263, 861
Piro L., et al., 1999, A&A (this volume)
Preece R.D., et al., 1998, ApJ 506, L23
Mészáros P., Rees M.J., 1993, ApJ 405, 278
Rybicki G.B., Lightman A.P., 1979, Radiative Processes in Astrophysics. New York: Wiley