High Energy Processes and Phenomena in Astrophysics
IAU Symposium, Vol. 214, 2003
X. D. Li, V. Trimble, and Z. R. Wang, eds.

Gamma-ray Burst Spectrum Influenced by the Doppler Effect of Fireballs

Yi-Ping Qin

Yunnan Observatory, National Astronomical Observatories, CAS, Kunming, Yunnan 650011, P. R. China

Abstract. The formula of the Doppler effect of fireballs, which shows how the observational flux from fireballs would be expected, is presented. It shows, when the expansion speed is very large, a weak radiation at X-ray bands would be significantly enhanced to detectable levels and shifted to much higher bands to become a gamma-ray source; at the same time, the peak of the spectrum would shift to a much higher energy band as well.

1. Introduction

Since the discovery of gamma-ray bursts (GRBs) about thirty years ago (Klebesadel, Strong, & Olson 1973), many properties of the objects have been revealed. At the same time, various models accounting for the observation have been proposed. Due to the observed great output rate of radiation, most models envision an expanding fireball (see e.g., Goodman 1986; Paczynski 1986). As the expanding motion of the outer shell of the fireball would be relativistic, the Doppler effect must be at work and in considering the effect the fireball surface itself would play a role (Meszaros & Rees 1998).

In the following, we present the basic formula of the Doppler effect in the fireball framework and study how the observational flux from the fireball would be expected.

2. The basic formula

For a fireball expanding with Lorentz factor Γ and radiating isotropically with rest frame intensity $\mathrm{I}_{0,\nu}(\mathrm{t}_0, \nu_0)$, the observational flux would be (the cosmological effect is ignored throughout this paper)

$$f_\nu(t) = \frac{2\pi}{D^2\Gamma^3}\int_{\theta_{\min}}^{\theta_{\max}} \frac{R_0^2(t_{0,\theta})I_{0,\nu}(t_{0,\theta},\nu_{0,\theta})\cos\theta\sin\theta}{(1-\beta\cos\theta)^3}d\theta, \tag{1}$$

where θ is the angle of the concerned area (say, the observer frame differential surface $\mathrm{ds}_{\theta,\varphi}$ which coincides with the rest frame differential surface $\mathrm{ds}_{0,\theta,\varphi}$ at proper time $\mathrm{t}_{0,\theta}$) to the line of sight, $\mathrm{t}_{0,\theta}$ and $\nu_{0,\theta}$ are the proper emission time and the rest frame emission frequency, respectively, of the radiation (which is detected by the observer at time t and at frequency ν) from $\mathrm{ds}_{0,\theta,\varphi}$, D is the distance of the fireball to the observer, and $R_0(t_{0,\theta})$ is the radius of the fireball at emission time $t_{0,\theta}$. Obviously, ν and $\nu_{0,\theta}$ are related by the Doppler effect. The proper time $t_{0,\theta}$ and observational time t can be well linked by considering the travelling of light from the fireball to the observer. The radius is related to θ by

$$R_0(t_{0,\theta}) = \frac{\widetilde{R}(t)}{1-\beta\cos\theta}, \tag{2}$$

where $\widetilde{R}(t)$ is a function of the observation time t. (Note that photons from different parts of the fireball, reaching the observer at the same observation time, will be emitted at different proper time which would correspond to different radii due to the expansion of the fireball.) The integration range of θ should be determined by the fireball surface itself together with the emitted ranges of $t_{0,\theta}$ and $\nu_{0,\theta}$. For a continuum, which covers the entire frequency band, radiating endless, one would get $\theta_{\min} = 0$ and $\theta_{\max} = \pi/2$. To study the Doppler effect on the spectrum, we consider in the following only those radiations lasting a sufficient interval of time so that the emitted range of $t_{0,\theta}$ does not constrain θ.

It is understood that during some period the radiation of the fireball might be dominated by a certain mechanism. Within this interval of time the radiation intensity can be expressed as: $I_{0,\nu}(t_{0,\theta},\nu_{0,\theta}) = I_0(t_{0,\theta})g_{0,\nu}(\nu_{0,\theta})$, where $g_{0,\nu}(\nu_{0,\theta})$ describes the dominant radiation mechanism while $I_0(t_{0,\theta})$ represents the development of the intensity magnitude. $I_0(t_{0,\theta})$ would be affected by many factors. But for any given mechanism, it would be directly proportional to the surface density of the corresponding radiation seeds such as electrons. If the timescale of radiation of the seeds is long enough, then for those fireballs with a very thin outer shell, as the objects grow, the density would decrease following $I_0(t_{0,\theta}) = I_1[R_1/R_0(t_{0,\theta})]^2$ (where I_1 and R_1 are constants which can be identified as the values of $I_0(t_{0,\theta})$ and $R_0(t_{0,\theta})$ for the particular time under consideration). In this case, the flux would be expressed as

$$f_\nu(t) = \frac{2\pi I_1 R_1^2}{D^2\Gamma^3}\int_{\theta_{\min}}^{\theta_{\max}} \frac{g_{0,\nu}(\nu_{0,\theta})\cos\theta\sin\theta}{(1-\beta\cos\theta)^3}d\theta. \tag{3}$$

3. The effect

It was pointed out that, after an early rearrangement phase, most of the matter and energy in a fireball is concentrated within a narrow shell (Piran et al. 1993). To illustrate how the Doppler effect in the fireball framework affects the observed burst flux, let us consider radiations from a very thin fireball with various Lorentz factors, assuming the timescale of radiation of the seeds is long enough. In this situation, equation (3) can be applied. We notice that there is no single mechanism proposed that can well represent all the observed spectra of gamma-ray bursts, which show a great diversity of forms. In practice, an empirical form called the GRB model (Band et al. 1993) was frequently, and rather successfully, employed to fit most burst spectra (Ford et al. 1995; Preece et al. 2000). In illustration, we shall adopt in our study the GRB form with typical values of the parameters (Preece et al. 1998, 2000): $\alpha_0 = -1$ and $\beta_0 = -2.25$.

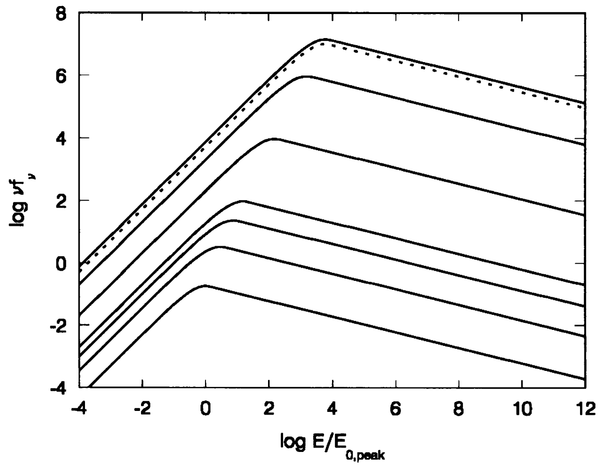

Figure 1. The expected spectrum of a fireball with its rest frame radiation being the GRB form of $\alpha_0 = -1$ and $\beta_0 = -2.25$, where the solid lines from the bottom to the top correspond to $\Gamma = 1$, 2, 5, 10, 100, 1000, and 5000, respectively, while the dotted line represents $\Gamma = 10000$.

Shown in Fig. 1 are the log (νf_ν) — log $(E/E_{0,peak})$ curves observed at time t, for fireballs with various values of Γ, assuming the adopted GRB form and taking $2\pi I_1 R_1^2 \nu_{0,peak}/D^2 = 1$.

The figure shows that the shape of the rest frame spectrum of the adopted model is not significantly affected by the expansion of fireballs. However, as the fireball expands, the peak of the spectrum shifts to higher energies and the flux over the entire energy range is amplified. Note that what we consider here is the same amount of rest frame radiation rate during the expansion of the fireball, but the enhancement of the flux occurs not only at higher, but also lower energy bands. Even if Γ is not very large (say $\Gamma = 2$), a dim and undetectable X-ray rest frame radiation would become an observable source detected both in X-ray and gamma-ray bands. It is curious that when Γ is extremely large (e.g., $\Gamma = 10000$), the flux over the entire energy range would reduce and the position of the peak spectrum, E_{peak}, would begin to shift to lower bands.

Fig. 1 suggests a correlation between E_{peak} and the output rate of energy for a wide range of Γ values. Indeed, it was discovered that the mean peak energies of gamma-ray burst spectra are correlated with intensity (Mallozzi et al. 1995). To get more detailed information about this issue, we calculate E_{peak} as well as $(\nu f_\nu)_{peak}$ for some values of Γ for the radiation considered above. We find that E_{peak} as well as $(\nu f_\nu)_{peak}$ rise with increasing Γ within a certain range (say, $\Gamma < 5000$). Beyond a certain value (say, $\Gamma = 10000$), both E_{peak} and $(\nu f_\nu)_{peak}$ would decrease. The distribution of E_{peak} was once proposed (Brainerd et al. 1998) to scale as the bulk Lorentz factor Γ. This proposal would be valid for most cases, especially when the expansion is not extremely large.

4. Discussion

From equation (3) we find that, in the case of the very thin outer shell and for the same value of Γ, the flux f_ν as well as the peak of the spectrum $(\nu f_\nu)_{peak}$ would be proportional to the square of the radius. But if the value of Γ is the same, the position of the peak of the spectrum would remain unchanged. Nevertheless, Table 1 shows that the peak of the spectrum would increase with the increasing of the Lorentz factor approximately following $(\nu f_\nu)_{peak} \propto \Gamma^2$, while the position of the peak spectrum would increase in the way $E_{peak} \propto \Gamma$. If one assumes that the rest frame positions of the peak spectrum of GRBs are almost the same, then at any frequency bands, the observed peak spectrum would be affected merely by the radius. Therefore, the distribution of $(\nu f_\nu)_{peak}$ at any frequency bands would directly reflect the distribution of the radius of the objects. Suppose the distribution of the radius is within one order of magnitude and that of the Lorentz factor is about two orders, then the distribution of the peak of the spectrum would be about six orders. We predict that the average value of $(\nu f_\nu)_{peak}$ at any frequency bands would be correlated with E_{peak} due to $E_{peak} \propto \Gamma$. At least, one can conclude that those objects with very large values of $(\nu f_\nu)_{peak}$ and E_{peak} must have large values of the Lorentz factor, while for those with very small values of $(\nu f_\nu)_{peak}$ and E_{peak} the Lorentz factor must be very small.

It should be pointed out that the situation of the development of the intensity magnitude of fireballs must be quite complicated. Some GRBs might have a rather thick outer shell, and hence the surface density might remain unchanged for some interval of time when the fireball is expanding. For a pulse, the surface density of radiation seeds might increase in its rising part but would decrease in its decay portion. Taking into account all these situations, we can expect wider distributions of $(\nu f_\nu)_{peak}$ and E_{peak}.

References

Band, D. et al. 1993, ApJ, 413, 281

Brainerd, J. J. et al. 1998, ApJ, 501, 325

Ford, L. A. et al. 1995, ApJ, 439, 307

Goodman, J. 1986, ApJ, 308, L47

Klebesadel, R., Strong, I., & Olson, R. 1973, ApJ, 182, L85

Mallozzi, R. S. et al. 1995, ApJ, 454, 597

Meszaros, P. & Rees, M. J. 1998, ApJ, 502, L105

Paczynski, B. 1986, ApJ, 308, L43

Piran, T. et al. 1993, MNRAS, 263, 861

Preece, R. D. et al. 1998, ApJ, 496, 849

Preece, R. D. et al. 2000, ApJS, 126, 19

https://doi.org/10.1017/S0074180900194690 Published online by Cambridge University Press