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Images, light curves and spectra of GRB afterglow

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Abstract. We calculate the light curve and spectra near the peak and the self absorption break, for an adiabatic blast wave described by the Blandford-McKee solution, considering the emission from the whole region behind the shock front. The expected light curve and spectra are flat near the peak. This rules out the interpretation of the sharp peak observed in the optical afterglow of GRB 970508 as the expected peak of the light curve. The observed image of an afterglow is calculated for a broad range of frequencies. We show that for frequencies below the self absorption frequency the image is rather homogeneous, as opposed to the bright ring at the outer edge and dim center, which appear at higher frequencies. We fit the observed spectra of GRB 970508 to the detailed theory and obtain estimates of its physical parameters.

Key words: gamma-rays: bursts — gamma-rays: theory — magnetic fields — hydrodynamics — shock waves

1. The physical model

We consider emission from the whole volume behind an adiabatic highly relativistic spherical blast wave expanding into a cold and uniform medium. The hydrodynamics is described by the Blandford-McKee (1976 denoted BM hereafter) self similar solution. For typical parameters, the evolution becomes adiabatic fairly early, about an hour after the initial burst (Sari et al. 1998; Granot et al. 1999 and 1998, hereafter GPSa and GPSb, respectively). The BM solution is valid from this time, and as long as $\gamma \gtrsim 2$ (Kobayashi et al. 1998), typically a few months after the burst.

We assume that $\nu_{\rm a} \ll \nu_{\rm m}$, where $\nu_{\rm m}$ is the peak frequency and $\nu_{\rm a}$ is the self absorption frequency, which is reasonable for the first few months. The dominant radiation emission mechanism is assumed to be synchrotron radiation, while Compton scattering and electron cooling are ignored. We denote quantities measured in the local

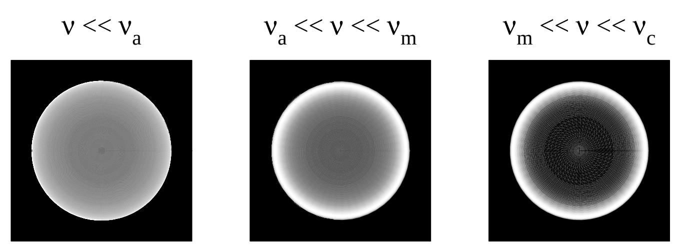

Fig. 1. The observed image of a GRB afterglow at a given observed time, for different frequencies

rest frame of the matter with a prime, while quantities without a prime are measured in the observer frame.

We assume that the energy of the electrons is everywhere a constant fraction of the internal energy: $e'_{\rm el} = \epsilon_{\rm e} e'$, and consider a power law electron distribution: $N(\gamma_{\rm e}) \propto \gamma_{\rm e}^{-p}$ for $\gamma_{\rm e} \geq \gamma_{\rm min}$. The magnetic field is also assumed to hold a constant fraction of the internal energy: $e'_{\rm B} = \epsilon_{\rm B} e'$, where $e_{\rm B} = B^2/8\pi$ is the energy density of the magnetic field. Alternative magnetic field models were considered in GPSa and GPSb, and we obtained that our results are not sensitive to the assumptions on the magnetic field.

2. The observed image

The observed images, at various frequencies, are shown in Fig. 1 (GPSa, GPSb). For $\nu \gg \nu_{\rm m}$ a thin bright ring appears on the outer edge of the image, while the center is much dimmer (only a few percent of the maximal surface brightness). For $\nu_{\rm a} \ll \nu \ll \nu_{\rm m}$ the surface brightness at the center is 34% of the maximal surface brightness, and 58% of the average surface brightness. For $\nu \ll \nu_{\rm a}$ the surface brightness at the center of the image is 77% of its average value, resulting in an almost uniform disk.

3. Light curve, spectra & the burst parameters

The light curve and spectra of an afterglow are flat near the peak. The exact shape, and the value of the peak frequency and peak flux depend on the values of the physical

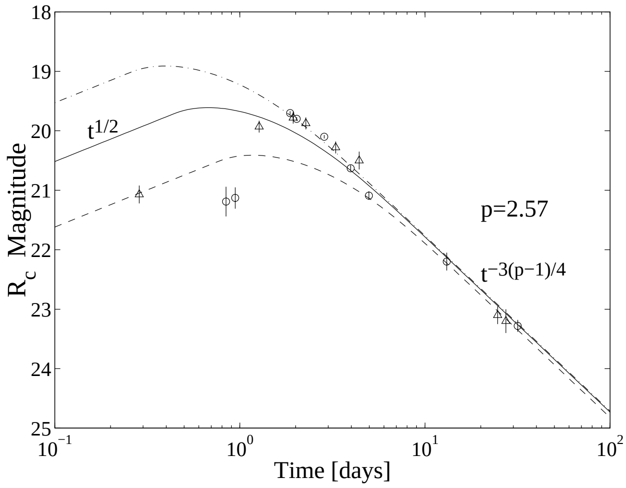

Fig. 2. Optical observations of GRB 970508, made by Sokolov et al. (1997, circles) and Metzger et al. (1997, triangles). The three curves are three possible theoretical light curves

parameters of the burst (see GPSa). In Fig. 2 we see the peak in the optical light curve of GRB 970508 (Sokolov et al. 1997; Metzger et al. 1997), with three theoretical light curves. These light curves are for $p = 2.57$, which corresponds to the power law decay that follows the peak, and differ by the values of the remaining parameters (GPSa).

It is quite evident from Fig. 2 that the shape of the optical peak displayed by GRB 970508 is not accounted for by the theoretical light curve arising from the model we used, and a different explanation should be considered.

The observed flux density near the self absorption frequency (i.e., $\nu \ll \nu_{\rm m}$) can be approximated, with an accuracy better than 3%, by the following simple expression:

$$F_\nu = F_{\nu_{\rm a,ext}} \psi^2 \left(1 - \exp[-\psi^{-5/3}]\right), \quad \psi \equiv \nu/\nu_{\rm a}. \quad (1)$$

Where $F_{\nu_{\rm a,ext}}$ and $\nu_{\rm a}$ are defined in Fig. 3 and depend on the values of the physical parameters (GPSb).

In Fig. 3 we show a fit of our theoretical spectra near $\nu_{\rm a}$ to radio afterglow observations of GRB 970508 (Shepherd et al. 1998), which were made about one week after the burst. Extracting the values of $F_{\nu_{\rm a,ext}}$ and $\nu_{\rm a}$ from this fit and comparing them to the theoretical values results in two constraints on the parameters of the burst (GPSb).

Using the values of $\nu_{\rm a}, \nu_{\rm m}, F_{\nu_{\rm m}}$ and the cooling break frequency $\nu_{\rm c}$ extracted from the broad band spectra of GRB 970508, and comparing them to their theoretical values, Wijers & Galama (1998) calculated the parameters of this burst, using a simple broken power law theoretical spectrum (Sari et al. 1998). Making a similar calculation, using the more detailed description of the self absorption break and of the spectral peak, we obtained the following values for the physical parameters of GRB 970508:

$$E = 5.3\ 10^{51}\ {\rm ergs} \qquad \epsilon_{\rm e} = 0.59 \quad (2)$$
$$n_0 = 3.0\ {\rm cm}^{-3} \qquad \epsilon_{\rm B} = 0.014,$$

where E is the total energy of the shell and n_0 is the ambient number density.

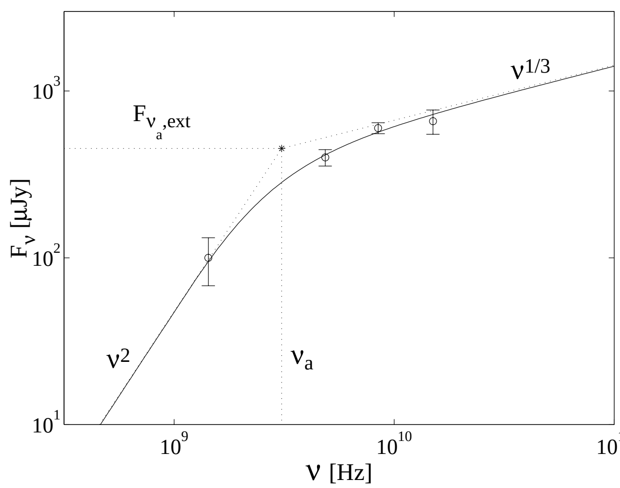

Fig. 3. A fit of our calculated spectra to radio afterglow observations of GRB 970508, made about one week after the burst

4. Discussion

We have calculated the light curve and spectra due to synchrotron emission from an ultra-relativistic adiabatic blast wave, which is described by the Blandford-McKee (1976) self similar solution. We obtained a flat peak for the light curve, which rules out the interpretation of the sharp optical peak of GRB 970508 as the expected peak of the light curve. The observed image of an afterglow has been calculated over a wide range of frequencies. The image at $\nu < \nu_{\rm a}$ is quite homogeneous, while at higher frequencies there is a bright ring at the outer edge and the center is dim.

We have calculated the physical parameters of GRB 970508 based on detailed calculations of the spectra near $\nu_{\rm a}$ and $\nu_{\rm m}$. The values we have obtained are different by up to two orders of magnitude from the values obtained using a simple broken power law theoretical spectrum (Wijers & Galama 1998). This stresses the sensitivity of this method to the exact details of the theoretical model.

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