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Energy injection episodes in GRBs: The case of GRB 021004(*)

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Summary. — A number of GRB afterglow light curves deviate substantially from the power law decay observed in most bursts. These variations can be accounted for by including refreshed shocks in the standard fireball model previously used to interpret the overall afterglow behavior. We show that the light curves of GRB 021004 can be accounted for by four energy injection episodes in addition to the initial event. The polarization variations are shown to be a consequence of the injections.

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1. – Introduction

The standard fireball model [25] provided, with a broken powerlaw, an adequate interpretation of the data for the first GRB afterglow light curves observed. In recent years, several well observed afterglows have shown strong deviation from smooth powerlaws, *e.g.* GRB 011211 [10], GRB 021004 [3, 9] and GRB 030329 [13, 18].

It has been suggested that the cause of "bumps" and "wiggles" seen in some light curves during the first few days is due to the encounter of the fireball with density irregularities in the ambient medium [8, 11, 15]. In the case of GRB 021004, Fox *et al.* [3] suggested that the light curve variability may be due to refreshed shocks. Recently, however, some authors have argued that refreshed shock models can be rejected as they are unable to explain simultaneously the bumpy light curves and the polarization as the latter would not be affected by the freshly injected energy [12].

Here we show that several energy injection episodes may in fact be a natural explanation of the afterglow light curve re-brightenings of bursts like GRB 021004. We consider energy injections in the standard model and apply our version of the model to GRB 021004. We show that not only are the light curves readily accounted for, but also

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that their polarization properties follow directly from the model. The details of this work have been published in [1].

2. – Energy injection

We extend the standard model by applying energy and momentum conservation, as in [19], to both discrete and continuous energy injections although only discrete injections will be considered here. We assume that several discrete shells are injected simultaneously with different Lorentz factors. The shell with the highest Lorentz factor, Γ_0, drives the initial evolution of the afterglow. Once it has decelerated to a value lower than the Lorentz factor of the next shell, they will collide with a delay corresponding to the time it takes the second shell to reach the first. The collision is assumed to be instantaneous and its dynamics is neglected as is any anisotropy that may results from the shell interactions.

We assume the radiation to be of synchrotron origin, and that the local synchrotron spectra at each point in the outflow consist of power law segments, smoothly joined at the characteristic frequencies [7]. We integrate over a thin shell at the equal arrival time surface. Each shell element is assumed to be locally homogeneous, its thickness being determined by the jump conditions across the shock [2] and the conservation of particles.

We calculate the instantaneous fireball polarization as in [5] and [21]. At a given observer time, we evaluate the contribution of each surface element of the equal arrival time surface to the Stokes parameters $\mathrm{d}U = P(\theta)\mathrm{d}L\cos(2\phi)$, and $\mathrm{d}Q = P(\theta)\mathrm{d}L\sin(2\phi)$, with the angular dependence of the polarization given by $P(\theta) = P_0 \sin^2\theta'/(1+\cos^2\theta')$. Here, θ' is the angle from the line of sight in the comoving frame and $\mathrm{d}L$ is the local luminosity. As in [5], we find that for an instantaneous energy release, the polarization light curve has two extrema, bracketing the time when $\theta \approx 1/\Gamma$. At approximately that time the polarization angle rotates by 90° [5, 22]. It is important to note that the maximum degree of polarization and time at which the polarization angle changes depend strongly on the viewing angle. The polarization evolution depends mostly on the evolution of Γ.

If there are many brightening episodes, the number of model parameters can be quite large. The global parameters, the initial energy, E_0, Lorentz factor, Γ_0, half-opening angle, θ_0, ambient density, n_0 (or density profile), relative energy density in electrons, ϵ_e, and magnetic field, ϵ_B, and electron index, p, are determined, as in the standard model, from the initial afterglow evolution and the total flux level (using the burst redshift). All episode parameters are fixed by the observed time of brightenings and the increase in flux levels. Polarimetry may be the most reliable way to determine the so called jet break time as the polarization angle is predicted to change by 90° at that time.

When a relativistic shell catches up with the slower shock front propagating into the ambient medium, it increases the Γ of the forward shock [24], but the subsequent evolution of Γ continues with the same decay rate as before. The resulting rise in the flux from the fireball will not be sharply defined in time as the flux is obtained by integration over the equal arrival time surface that smooths out the transition. The net result is that the light curve is smoothly "shifted" upwards at the time of the injection, but retains its original decay rate behavior from then on. The emitting region of the relativistic outflow centered on the line of sight, also temporarily brightens up and outshines the bright emitting ring-like region around the line of sight, see, *e.g.*, [6, 16] for a detailed discussion. It is important to realize that polarization will also be affected by the energy injection, because the bright emission from the centre has no net polarization, thus decreasing the degree of polarization compared to an unperturbed evolution.

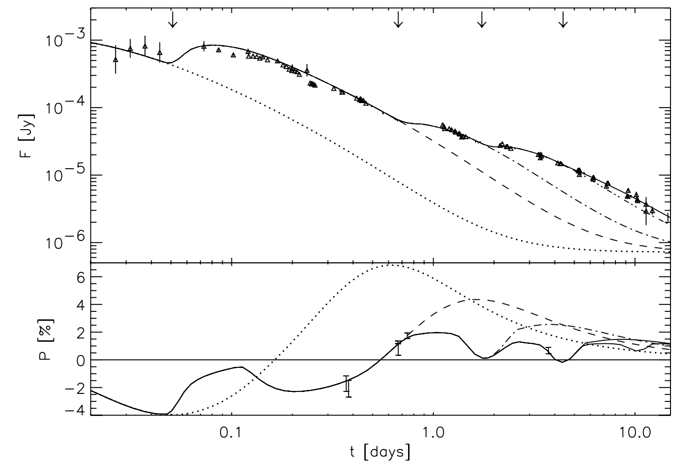

Fig. 1. – Segment of the R-band light curve of GRB 021004 (top panel). Effects of each of the energy injection events is shown. Dotted curve shows the theoretical afterglow without additional energy injections. Dashed curve shows the effect of one injection event, dot-dashed two, dash-double-dotted three and the solid curve shows the effect of all four injection events. Arrows indicate the injection times. Lower panel shows the corresponding polarization light curves. Note how each injection episode causes the polarization to deviate from the unperturbed curve (dotted). R-band data are from [9, 17, 23], polarimetry from [12, 20]. Figure from [1].

3. – GRB 021004

As an example, we consider GRB 021004. At a redshift of $z = 2.335$ (*e.g.*, [14]), it showed strong light curve variations with a best fit light curve break time of 4.74 days [9]. The afterglow also exhibited variable polarization levels and a 90° change in polarization angle at approximately 1.0 day [20]. These two time estimates should be similar, if interpreted within the standard model, but are in this case inconsistent with each other.

The light curves can be explained by 4 injection episodes, superimposed on the initial GRB event with $E_0 = 10^{50}$ ergs, $\Gamma_0 = 800$, $n_0 = 26\,\mathrm{cm}^{-3}$. A narrow opening angle $\theta_0 = 1.4°$ is obtained. Radiation parameters have typical values, $p = 2.2$, $\epsilon_e = 0.21$, $\epsilon_B = 2 \cdot 10^{-4}$. The viewing angle is $\theta_v = 0.95\theta_0$. The injections have energies 3.5, 5.6, 13.0 and 7.0 in units of E_0 and are injected at approximately 1 h, 16 h, 42 h and 105 h.

In fig. 1 we plot the R-band and polarization light curves of GRB 021004. We show the effect of each injection episode separately as well as the combined result. With this interpretation, the estimate by [9] of the late jet break time now has a simple explanation. The repeated energy injections slow the early light curve decay and delay the steepening until after the last injection. The break time, as defined by the change in polarization angle, is approximately at 0.6 days. This is just before the 2nd injection and therefore goes unnoticed in the light curves until after the last injection.

4. – Discussion

We have applied our code to GRB 021004 with a standard fireball model modified with density variations in a homogeneous medium, but without energy injections. The variations were assumed Gaussian as in [12]. The calculated flux is very sensitive to the number of radiating electrons and must be carefully counted. Only when specifically introducing the shock profile of [2], did we manage to get sufficient brightenings.

A contribution to the polarization may originate in the Galaxy or within the host. In [12] it is concluded that for GRB 021004, the host contribution can be accounted for by using spectropolarimetric data, while the Galaxy may dominate at low polarization levels. The time variation of the polarization can only originate in the source.

It is natural to assume that the central source releases energy in several discrete events, essentially simultaneously. The total energy injected into the collimated outflow inferred from our model for GRB 021004 is about $3 \cdot 10^{51}$ erg. It is of the same order as estimated in other bursts after beaming correction [4].

The strongest argument in favor of our interpretation is the fact that we are able to account for both broad band behavior as well as the polarimetry within a single model.

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