Precessing jets interacting with interstellar material as the origin for the light curves of gamma-ray bursts.

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ABSTRACT
We present an internal shock model with external characteristics for explaining the complicated light curves of gamma-ray bursts. Shocks produce gamma-rays in the interaction between a precessing beam of relativistic particles and the interstellar medium. Each time the particle beam passes the same line of sight with the observer the interstellar medium is pushed outward. Subsequent interactions between the medium and the beam are delayed by the extra distance to be traveled for the particles before the shock can form. This results in a natural retardation and leads to an intrinsic asymmetry in the produced light curves for gamma-ray bursts. In addition we account for the cooling of the electron-proton plasma in the shocked region, which gives rise to an exponential decay in the gamma-ray flux. The combination of these effects and the precessing jet of ultra relativistic particles produces light curves which can be directly compared with observed gamma-ray burst light curves. We illustrate the model by fitting a number of observed gamma-ray bursts which are hard to explain with only a precessing jet. With a genetic algorithm we are able to fit several observed gamma-ray bursts with remarkable accuracy. We find that for different bursts the observed fluence, assuming isotropic emission, easily varies over four orders of magnitude from the energy generated intrinsically.

1 INTRODUCTION

Gamma-ray bursts (GRBs) are possibly among the most energetic event in the Universe, emitting $10^{51} - 10^{54}$ erg in soft gamma rays in an energy range of $\sim 100$ keV–1 MeV if the radiation is isotropic (see e.g., Piran 1999 for a review). They occur in galaxies, at cosmological distances, and various theoreticians suggest that the phenomenon is related to the death of massive stars, the formation of compact objects or the coalescence between compact objects.

The temporal structure of GRBs is characterized by a high variability and durations vary from (possibly sub) millisecond to minutes (e.g., Norris et al. 1996), the origin of which is not yet understood. Explanations range from multiple shock fronts running into an ambient medium (Sari et al. 1996), expanding shells with brighter patches and dimmer regions (Fenimore et al. 1996) to repeated series of pulses with Gaussian or power-law profiles (Norris et al. 1996). However, a clear physical explanation lacks and the geometry in these scenarios is not at all clear; combinations of hydrodynamic, deteriation, expansion and dilation time scales are introduced without a clear physical explanation or understanding. The light curves of GRBs can possibly be explained by a beamed emission from a precessing accretion disk of compact stars (see Portegies Zwart et al 1999; but also Roland et al. 1994; Fargion 1998, 1999). Such a model provides a rather simple physical explanation for the complex temporal structure of GRBs. Gamma-rays are emitted in a collimated cone or beam, and precession of the jet produce multiple peaks in GRB light curves when it passes the line of sight from an observer to the central engine. Portegies Zwart, Lee & Lee (1999, hereafter PZLL) investigated this scenario in detail assuming that GRBs are produced by a particle emitting precessing jet from the gamma-ray binary; a binary in which a neutron star fills its Roche-lobe and transfers its mass to a black hole (Portegies Zwart 1998).
PZLL show that the precessing jet scenario can roughly reproduce the observed GRB light-curves by selecting reasonable precession parameters and a distribution of the internal energy production within the jet. There are, however, some difficulties with the physical picture of the precessing jet as well as with fitting the model light-curves to the observed GRBs. A precessing jet tends to produce light curves in which subsequent peaks appear at periodic intervals. The peaks themselves may be slightly asymmetric but clearly lack the observed strong asymmetries; individual peaks show a fast rise and a slow decay. Observed gamma-ray bursts also show no evidence for periodicities at any time scale and Ramirez-Ruiz & Fenimore (1999) show that the width of the pulses in GRBs time histories remain remarkably constant throughout the classic GRB phase.

The central engine cannot directly emit gamma-rays into a collimated jet, owing to the well-known compactness problem (see e.g. Piran 1999). The high opacity of $e^\pm$-pair creation reaction prevents the free escape of the gamma-rays from such a compact region near the central engine. To overcome this difficulty, it is generally believed that gamma-rays are emitted from shocked regions far from the central engine, which are generated by ultra-relativistic outflows from the GRB central engine with a Lorentz factor of typically $\Gamma \sim 100$–1000. This problem could be solved if the jet carries relativistic particles which shock the interstellar medium, far from the central source.

We present a model for GRB light curves in which the above problems are solved. The model reproduces observed GRB light-curves even better than the older models of PZLL. In this model gamma-rays are emitted from outer shocked regions formed by interaction between the material ejected ultra-relativistically in the precessing jet and ambient interstellar medium. The compactness problem is then resolved identically as in ordinary fireball models. We also introduce a retardation effect in the emission time and the moment the energy is released in the form of gamma-rays. This effect originates from the finite velocity $< c$ of the relativistic particles and the slow cooling of the shocked matter.

In section 2, we briefly review the GRB light-curves predicted by the precessing jet scenario, and then present a detailed physical picture and simple model of interaction between an ultra-relativistic jet and the interstellar matter. In §3 we describe the genetic fitting procedure of the model to the observed GRB light-curves, and present results for some GRB light-curves observed by the BATSE experiment. We summarize in section 4.

2 THEORY

2.1 Precessing jet

The model of the precessing jet was discussed in detail by PZLL (see their section 3). For clarity we summarize the model and list its parameters. For details concerning the energy generation process and the origin of the precession we refer to PZLL.

The beam of relativistic particles emitted from the central object precesses. As discussed by PZLL the direction in which the locus of the precessing jet points is described by the precession angles $\theta_{\mathrm{jet}}$ (the polar angle) and $\phi_{\mathrm{jet}}$ (the azimuth angle, both are defined in a spherical polar coordinate system). These angles are obtained at any time $t$ from the initial direction in which the jet points ($\theta_{\mathrm{jet}}^0$) and the precession and nutation periods ($\tau_{\mathrm{pre}}, \tau_{\mathrm{nun}}$; see PZLL).

The direction from which an observer looks into the jet (two angles $\theta_{\mathrm{obs}}$ and $\phi_{\mathrm{obs}}$) now fixes the line of sight between the observer and the central object.

The jet itself has a finite width. The intensity in the jet is assumed to be a function of the distance to the central locus, as given by the Blandford-Znajek (1977) mechanism. The intensity distribution within the beam and the width of the jet can be described with three dimension less parameters $\alpha$, $\beta$, and $\delta$. Portegies Zwart, Lee & Lee (1999) give a few examples of the shape of the jet as a function of $\alpha$, $\beta$ and $\gamma$ in their figure 2. In these examples the width of the jet at half maximum varies between $5^\circ$ (for $\alpha = 0.5, \beta = 6$ and $\gamma = 0.4$) and $10^\circ$ ($\alpha = 0.6, \beta = 6$ and $\gamma = 0.3$) with the maximum near $5^\circ$ in both cases. More extreme values for $\alpha$, $\beta$ and $\gamma$ have a stronger effect on the location of the maximum and the width at half maximum but the general shape remains very similar. In the fitting performed by PZLL $\alpha$, $\beta$ and $\gamma$ were taken to be constant, 0.5, 6 and 0.3, respectively. Here they may vary.

With these parameters the width of the beam is of the order of $\Gamma^{-1}$. And even if the initial width of the beam is smaller than $\Gamma^{-1}$ sideways pressure guarantees an expansion of the beam to approximately $\Gamma^{-1}$. The curvature of the jet front should have an important effect on the observed shape of the GRB pulse profile. The photons from a region off the line-of-sight are delayed compared with those just on the line-of-sight, and this effect makes the pulse profile as 'fast rise and slow decay', as generally observed for GRB pulses (Fenimore et al. 1996). For the simplicity we do not include this effect in our calculation, but it should be noted that this effect is similar to the effect of cooling of gamma-ray emitting electrons, which is included in our model. Therefore, it can be argued that the curvature effect is implicitly taken into account in our model.

Here we must make an important assumption that the intrinsic time variation of the relativistic energy output from the central engine is much weaker than that caused by the precessing jet. The purpose of this paper is to investigate whether the light curve of GRBs can be understood mainly by the precessing jet effect, and it implicitly assumes that the intrinsic time variability of the central engine is rather smooth. However, this assumption may not be true, and if the central engine activity is also highly variable, our model does not have strong predictability just like other stochastic explanations of GRB light curves. The intrinsic time variation of the relativistic particle beam at its opening angle are chosen identical to the curve adopted by PZLL, who con-
struct time profiles for the central engine from three components: an exponential rise with characteristic time scale $\tau_{\text{rise}}$, a plateau phase with time scale $\tau_{\text{plat}}$ and a stiff decay with time scale $\tau_{\text{decay}}$ (see their Eq. 11). This results in the following expression for the emitted flux of relativistic particles in the direction of the observer as a function of time:

$$L_{\text{part}}(t) = I(t, t_{\text{rise}}, t_{\text{plat}}, t_{\text{decay}})J(\psi(\theta_{\text{obs}}, \phi_{\text{jet}}), \alpha, \beta, \delta)(1)$$

where the angle $\psi$ between the observer $\hat{r}_{\text{obs}}(\theta_{\text{obs}}, \phi_{\text{obs}})$ and the central locus of the jet $\hat{r}_{\text{jet}}(\theta_{\text{jet}}, \phi_{\text{jet}})$ is given by $\psi = \cos^{-1}(\hat{r}_{\text{obs}} \cdot \hat{r}_{\text{jet}})$.

2.2 Production of gamma-rays

Two possible scenarios are known to generate the ultrarelativistic shock required to explain GRBs: the external shock generated by the collision between relativistic outflow with the ambient interstellar matter, and internal shocks generated by collisions between relativistic shells due to a relative velocity difference. If the relative velocity difference between internal shocks would be stochastic, the complex time structure of GRB light curves is also stochastic. This would make a detailed comparison between the light curves of individual bursts with model calculations useless. However, we investigate the possibility that the light curves are determined by precessing jets, which are deterministic; our model is not stochastic and the energy generation by the central engine follows uniquely from the provided parameters.

The precessing jet emits relativistic particles (it is not clear whether the beam consists of an electron-positron or an electron-proton plasma). The interaction between these and the interstellar medium results in a deceleration of the particles and their kinetic energy is transformed into gammarays. This picture is somewhat different than the external shock scenario, as in our case the same region is shocked each time the precessing jet happens to beam in the same direction. The relativistic beaming makes gamma-rays visible only from the shocked region on the line of sight to the central engine.

The short precession and nutation times cause the precessing jet to pass many times the line of sight, and hence jet energy is injected with a complex and different time structure in each direction. A relativistic flow injected into one direction collides with other flows which have been ejected earlier and slowed down by the interaction with the interstellar medium. This picture is therefore somewhat intermediate between internal and external shock models.

We introduce two new effects to the light curves for the precessing jet scenario discussed in PZLL: 1.) the time retardation caused by the wake created by subsequent beam passages of relativistic particles and 2.) the cooling of the shocked interstellar medium. The point 2 may also be regarded as the pulse asymmetry generated by the curvature effect, as discussed in the previous section.

The speed of the relativistic jet must be close to, but smaller than, the speed of light to solve the compactness problem. This results in a time delay between the moment the particles leave the central engine and the moment they collide with the interstellar medium. While the gamma-ray burst is active the location of the shocked region is pushed farther away from the central engine by the relativistic particles. The time delay will therefore build up in time. This effect causes a deviation from a periodic light curve produced by a precessing jet and it extends the duration of the burst. The effect itself, however, does not necessarily lead to a gradient in the pulse shape as a function of time.

Gamma-rays are produced by some radiation process such as synchrotron or inverse-Compton processes, as in the ordinary fireball model. Colliding electrons in such processes have typical cooling tails, which also affect the shape of the observable light curve.

The interaction of a precessing jet with the interstellar matter is a complicated process and hard to model without detailed hydrodynamical simulations with relativistic correction. For our qualitative analysis we rely on a simple prescription of the two discussed effects, which may be sufficient.

2.3 Implementation of the retardation time

The kinetic-energy luminosity emitted by the precessing jet in relativistic particles per steradian in the direction to the observer is given by Eq. 1.

$$\frac{\partial L_{\text{part}}(t)}{\partial t} = \int_0^t L_{\text{part}}(t) dt .$$

The deceleration radius $r_d$ is the distance from the central engine at which the shock and thus the radiation are generated. We assume that $r_d$ is determined by the energy balance between $E(t)$ and the energy carried by the mass of the interstellar matter which has been swept up. This condition can be written as:

$$4\pi E_{\text{part}}(t) = \frac{4\pi}{3} r_d n_1 m_p \Gamma^2$$

$$r_d = 1.3 \times 10^{17} \left( \frac{E_{\text{part}}(t)}{10^{52} \text{erg}} \right)^{1/3} n_1^{-1/3} \Gamma^{-2/3} \text{cm}^3$$

where $n = n_1 \text{ cm}^{-3}$ is the interstellar matter density, $\Gamma_{100} = \Gamma/100$ and $m_p$ is the proton mass. As the total energy $E(t)$ increases with time the deceleration radius increases.

It takes time $r_d/(1 - \Gamma^{-2})^{1/2}$, for the ejecta from the jet to reach the shocked region at $r = r_d$. (We use $c = 1$.) The emission from the shocked region is then delayed by a

$$\Delta t \sim r_d \Gamma^{-2/2}$$

$$= 2.1 \times 10^2 \left( \frac{E_{\text{part}}(t)}{10^{52} \text{erg}} \right)^{1/3} n_1^{-1/3} \Gamma^{-8/3} \text{sec} .$$

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If $t'$ is the time for the observer then $L_{\text{part,obs}}(t')$ is the observed light curve. The relation between $L_{\text{part,obs}}(t')$ and the light curve generated by the central engine $L_{\text{part}}(t)$ is then given by

$$t' = t + \Delta t(t),$$

$$L_{\text{part,obs}}(t')dt' = L_{\text{part}}(t)dt.$$

Substitution of Eq. 4 results in

$$\frac{dt'}{dt} = 1 + 70n_1^{-1/3}\Gamma^{-8/3}E_{\text{part,52}}^{-2/3}(t)L_{\text{part,52}}(t),$$

where $E_{\text{part,52}} = E_{\text{part}}/(10^{52}\text{erg})$ and $L_{\text{part,52}} = L_{\text{part}}/(10^{52}\text{erg s}^{-1})$.

### 2.4 Implementation of the cooling time

In order to predict the gamma-ray light curve from the particle light curve defined above, we have to make several assumptions regarding the gamma-ray production efficiency in the shocked region. It is a standard view that electrons are accelerated efficiently in the shocked region to radiate high energy gamma-rays. The efficiency of electron acceleration, i.e., the fraction of energy used to accelerate electrons in the total energy injected into the shock, is not well known quantitatively, and here we assume that it is constant during the GRB phenomenon. Then the light curve of gamma-rays should be determined by taking into account the cooling time scale of such accelerated electrons by gamma-ray production.

We consider the cooling time of electrons assuming that the emission process originates from electron-synchrotron radiation. The energy density of the shock heated matter in the rest frame of the shock is $4\pi m_e\Gamma^2$ ($m_p$ and $m_e$ are the proton and electron masses). Here we assume the magnetic field to be $B = (32\pi\xi_{\text{B}}nm_p\Gamma^2)^{1/2}$, where $\xi_{\text{B}}$ is the equipartition parameter for the magnetic field and the energy density of the shocked matter (Blandford & McKee, 1976).

The photon energy $\varepsilon_\gamma$ of the electron synchrotron radiation in the rest frame of the observer is given by $\varepsilon_\gamma = \Gamma\gamma_\text{e}^2eB/m_e$, where $\gamma_\text{e}$ is the Lorentz factor of the electrons measured in the rest frame of the shock and $e$ is the electron charge. Hence, we can estimate the Lorentz factor of the electrons relevant to the synchrotron photons in the BATSE range, as

$$\frac{\gamma_\text{e}}{\Gamma} = 4700\Gamma^{-2}\xi_{\text{B}}^{1/4}n_1^{-1/4}\left(\frac{\varepsilon_\gamma}{100\text{keV}}\right)^{1/2}.$$

A typical value of $\gamma_\text{e}/\Gamma$ is 1 when the energy transfer from protons into electrons is inefficient, while $\gamma_\text{e}/\Gamma \sim m_p/m_e \sim 2000$ for efficient transfer.

What determines the typical photon energy range of GRBs is still a difficult problem. We do not discuss this and only use the above estimate for the electron Lorentz factor to calculate the electron cooling time. In the rest frame of the shock the cooling time is given by $t_{\text{cool}} = 6\pi m_e/(\sigma T B^2 \gamma_\text{e})$.

### Table 1. Model parameters which may vary per burst.

| Parameter | Description |
|-----------|-------------|
| $\tau_{\text{dead}}$ | initial epoch without signal |
| $\tau_{\text{rise}}$ | start-up time of the central engine |
| $\tau_{\text{plat}}$ | central engine plateau time |
| $\tau_{\text{decay}}$ | central engine decay time |
| $\tau_{\text{pre}}$ | precession period |
| $\tau_{\text{nu}}$ | nutation period |
| $\theta_{\text{jet}}^0$ | precession angle |
| $\theta_{\text{obs}}$ | observer angle |
| $\phi_{\text{obs}}$ | observer angle |
| $L_{\text{cool,obs}}$ | cooling time |
| $n_1$ | interstellar density |
| $\alpha$ | internal jet parameter |
| $\beta$ | internal jet parameter |
| $\delta$ | internal jet parameter |

and the cooling time for the observer is then

$$t_{\text{cool,obs}} = \frac{t_{\text{cool}}}{2\Gamma} = 5.5 \times 10^{-2} \left(\frac{\varepsilon_\gamma}{100\text{keV}}\right)^{1/2}\Gamma_\text{100}^{-2}\xi_{\text{B}}^{-3/4}n_1^{-3/4}\text{sec}.$$

This cooling time is convolved with the particle luminosity curve to get the observed photon light curve, i.e.,

$$L_{\gamma,\text{obs}}(t) = \int_0^t dt' L_{\text{part,obs}}(t') f_t(t,t'),$$

where $f_t(t,t')$ is a transfer function:

$$f_t(t,t') = \frac{\exp \left( -\frac{t-t'}{t_{\text{cool,obs}}} \right)}{t_{\text{cool,obs}}}.$$

### 3 Fitting of Observed Light Curves

The retardation effect and the cooling time increase the number of free parameter to the model with the retardation time (Eq. 3) and the characteristic cooling time scale $t_{\text{cool}}$ (Eq. 8). These parameters are functions of $E(t)$, $\Gamma_{\text{100}}$ and $n_1$, which are not independent. For clarity we assume $E = 10^{52} \text{erg}$ and $\Gamma_{\text{100}}$ is a few.

The model contains then a total of fourteen parameters (Tab. 1) which are more or less free to be chosen within the theoretical framework. For practical reasons we introduced the dead time $\tau_{\text{dead}}$ which is the initial time between the BATSE trigger and the start-up of the real burst (see PZLL). The intrinsic parameters for the $\Psi$-dependence of the intrinsic luminosity within the cone ($\alpha$, $\beta$, and $\delta$) are not treated as fixed parameters, in contrast to PZLL, who assumed the intrinsic luminosity distribution within the cone to be static between bursts.

The fits of PZLL are not all of the same high quality. Their lightcurves still show symmetries, as could be expected from their simple prescription of a precessing jet. Possibly their fitting algorithm was not robust enough to elude all the local minima in the complex parameter space of the burst.
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### Table 2. Parameters for gamma-ray bursts BATSE 999, 1425, and 2067

| BATSE # | 999  | 1425 | 2067 |
|---------|------|------|------|
| Parameter | Note |      |      |
| $\chi^2$  | 1.4 | 5.1 | 2.5 |
| $\tau_{\text{rise}}$ | 1.00 | 0.883 | 1.328 |
| $\tau_{\text{plateau}}$ | 1.35 | 13.1 | 12.5 |
| $\tau_{\text{decay}}$ | 7.50 | 7.36 | 0.860 |
| $\tau_{\text{pre}}$ | 0.705 | 0.25 | 3.63 |
| $\tau_{\text{rise}}$ | 0.920 | 0.0452 | 0.214 |
| $\phi$ | 0.0047 | 0.193 | 0.216 |
| $\theta_{\text{jet}}$ | 0.134 | 0.0259 | 0.221 |
| $\theta_{\text{obs}}$ | 0.726 | 0.436 | 1.798 |
| $\phi_{\text{obs}}$ | 3.23 | 0.0353 | 2.985 |
| $t_{\text{cool}}$ | 0.242 | 0.150 | 1.390 |
| $n_1$ | 1.60 | 0.050 | 0.107 |
| $\alpha$ | 0.25 | 0.207 | 0.530 |
| $\beta$ | 0.78 | 0.180 | 0.973 |
| $\delta$ | 0.0045 | 0.416 | 0.130 |

We therefore decided to use a completely different fitting technique.

#### 3.1 The fitting procedure

The first step in the fitting procedure is to determine the background. This is done on the initial, ~ 1800, time bins of 64 ms in the data stream of each observed burst. The average count rate in this part is used as background.

We developed a genetic algorithm to elude the local minimum in the optimization of the fitting process. This method performs considerably better than the annealing technique adopted by PZLL, in finding the global minimum and requires less iterations.

The array of parameters (see table 1) can be identified with a chromosome in which each individual parameter (allele) is identified as a gene. Each chromosome has a mean for the precession period $\tau_{\text{pre}}$ the nutation period $\tau_{\text{nu}}$ etc. (see table 1). Since the relative effect of one parameter to the quality of the fit and the cross correlation between the parameters is hard to determine we treat all parameters independently.

The fitting process is started by selecting the allele for each gene for the first chromosome, which may contain a reasonable first guess to the bursts profile. This chromosome is copied $N_{\text{chrom}}$ times, with $N_{\text{chrom}} = N_{\text{gene}} + 1$ if $N_{\text{gene}}$ is uneven and $N_{\text{chrom}} = N_{\text{gene}} + 2$ times otherwise. The initially selected chromosome is stored as potentially best fit. All other chromosomes are mutated to produce the genotype for the new populations.

The iterative process starts with a loop over the following steps, which we call a generation:

1. Mutate a chromosome each gene has a probability $P_{\text{mutate}}$ of changing its value ($P_{\text{mutate}} \sim 5\%$). The selected gene is then incremented with $0.5\sqrt{2} (g_i / (X_1 + X_2 - X_3 - X_4))$, where $\langle g_i \rangle$ is the mean value for gene $i$ of the allele in all genotype, and $X_1$ to $X_4$ are four random numbers between zero and unity.
2. The genotype are evaluated by calculating the $\chi^2$ of the models with the observed gamma-ray burst. For this purpose we calculate the light curves associated with the selected chromosome and compare that with the observed burst. The $\chi^2$ is then calculated. (Note that a 10 seconds gamma-ray bursts has more than 150 degrees of freedom.)
3. The fitness for each genotype $f_i$ is then calculated by rescaling the $\chi^2$ for each burst via

\[
f_i = c_f + m_f \nu_i,
\]

where

\[
\nu_i = \exp \left( \frac{a\chi^2}{\langle \chi^2 \rangle} \right),
\]

\[
m_f = (b - 1) \frac{\nu_{\text{max}} - \nu_{\langle \nu \rangle}}{\nu_{\langle \nu \rangle}}.
\]

Here $a \sim -20$ and $b = 2$ or 3 are constants, $\langle \nu \rangle$ and $\nu_{\text{max}}$ are the mean and maximum value of $\nu_i$ in the parental pool. From the available genotype we randomly select $N_{\text{chrom}}$ parents. The probability for parent selection is proportional to its fitness: $f_i / \langle f \rangle$, where $\langle f \rangle$ is the mean fitness in the parental pool. The genotype which are fitter than average may be selected more than once and the less fitter parents may stay unselected.

Each time two parents are selected they produce two offspring, which populate the new phenotype. Parents, however, are not allowed to be identical: this would lead to two identical children. Each gene from one of the parents has a fifty-fifty chance to become part of one of the two children. In this way it is possible that two parents result in two children with identical chromosomes as the parents, in which case both children mutate (via Eq. (12)).

If the chromosome with the lowest $\chi^2$ in the population appears fitter than the potentially best fit, they are exchanged. After $N_{\text{gen}}$ generations the chromosome with the lowest $\chi^2$ is selected as the best fit.

#### 3.2 The fitting results

The model and fitting algorithm are tested on a number of observed gamma-ray bursts. The result of the fits are presented in the figures 1 to 3.

Most parameters in the model should be the same in different energy bands of the same burst. The intrinsic precession and nutation parameters, observers angles, the density of the interstellar medium and the strength of the magnetic field should all be identical for the same burst at different energy channels. Only the cooling time of the interstellar medium and possibly the structure parameters of the jet may differ between energy bands within the same burst.

Figures 1 to 3 illustrate how the same jet parameters...
Figure 1. (a) Result of the genetic fitting to BATSE trigger number 999 (second energy channel: 50 – 100 keV). Upper panel shows the real burst profile (solid line) and the fit (dashed line) of isotropic luminosity assuming isotropic radiation, where the lower panel shows the same but for isotropic fluence. Here the isotropic luminosity and fluence are given in units of the true luminosity and fluence of the jet from the central engine integrated over all directions. Small numbers of isotropic fluence indicate that we observe only a small fraction of the true energy emitted as the jet. Fit parameters are as in Tab. 2. (b) Fit to third energy channel of GRB 999 (100 – 300 keV). The obtained $\chi^2 = 1.29$, $t_{\text{cool}} = 0.105$ (see Tab. 2 for other parameters). (c) Fit to fourth energy channel of GRB 999 (> 300 keV). The obtained $\chi^2 = 1.29$, $\delta$ as in Fig. 1, $t_{\text{cool}} = 0.05$ (see Tab. 2 for other parameters).

Figure 2. (a) Example to fit to second energy channel (50 – 100 keV) of GRB 2067. The obtained $\chi^2 = 2.5$, $t_{\text{cool}} = 1.39$ (see Tab. 2 for other parameters). (b) Fit to third energy channel of GRB 2067. The obtained $\chi^2 = 14.4$, $t_{\text{cool}} = 0.15$ (see Tab. 2 for other parameters).

Figure 3. Fit to second energy channel of GRB 1425 (parameters are in Tab. 2).
fit the different energy channels of an observed gamma-ray burst. Only the cooling time for the interstellar medium and one of the structure parameters of the jet are varied. The tail of the main pulse of this burst becomes shorter in higher photon energy bands, and this trend is well explained by the effect of the cooling. It should also be noted that the similar trend is also expected by the curvature effect, since the photons from regions off the line-of-sight are softened by an effectively smaller Lorentz factor.

The $Y$-axis in these figures represents the fluence measured by an observer assuming that the burst radiated isotropically, in units of the true energy output from the central engine. Note that this number may be larger as well as smaller than unity and shows a wide spread in our fits.

Another example is presented in the figures 2a and 2b, where we attempted to fit GRB trigger number 2067 in two energy bands. The other energy bands are satisfactory fitted by changing the cooling time and the internal structure of the jet.

Figure 3 illustrates how the fit to GRB 1425 produces an asymmetric burst due to the discussed effects, where PZLL had difficulties explaining the increase in the time intervals between peaks in GRB 1425.

4 Discussion and Conclusion

The extension of the simple model (by Portegies Zwart et al. 1999) in which a precessing jet is the cause of the complicated light curves of gamma-ray bursts fits observed light curves with higher quality. The increase in the model complexity causes an increase in the required computer time per burst and makes the fitting much harder.

We have obtained remarkable fits to the light curves of some real gamma-ray bursts, by using a physical model of the precessing jet and its interaction with the interstellar medium. Of course, there are quite a few gamma-ray bursts for which we tried our fitting algorithm but were unable to obtain satisfactory fits. However, it may be due to the difficulty of the fitting and does not mean that the precession jet scenario cannot explain all of the GRB light curves. Currently the precession jet scenario is almost the only ‘physical’ or ‘deterministic’ explanation for the GRB light curves, and it deserves further investigation. For clarity we assumed a simple and smooth light curve for the intrinsic luminosity of outflow from the central engine, characterized by three time scales (initial rize, plateau, and decay). The variation in the observed output is in these cases caused by variations in the other model parameters and the angle from which the source is observed. Note, however, that this choice is not a requirement and that the energy output of each burst may well vary intrinsically.

We mainly consider the cooling of electrons as the origin of the asymmetric shape of peaks in GRB light curves, but some other explanations for the asymmetry are also possible. One of these is the delayed emission from shocked region off the line-of-sight to the central engine (Fenimore et al. 1996). In the external shock model of GRBs, such an asymmetry is expected because gamma-rays emitted from off-axis region will be delayed and softened compared with the emission from the on-axis region, because of a geometric effect and lower effective Lorentz factor of relativistic motion. A similar effect is also expected in our model; when a precessing jet passes the line-of-sight from an observer to the central engine, the emission from on-axis region is promptly observed by us, but emission before and after the passing beam should be delayed and softened because it is from off-axis shocked regions generated by the precessing jet. The intrinsic curvature of the jet front may also be important, since the width of the jet in our model is comparable with the visible size of the emission region ($\theta \sim \Gamma^{-1}$). Although this effect is difficult to include exactly in our calculation, we note that it is taken into account, at least qualitatively. We have fitted the GRB light-curves with the cooling time as a free parameter, and this is not necessarily to be the cooling time for electrons. Off-axis emission is expected to show a qualitatively similar effect, and it is possible that the cooling time which we obtained in the fits may be the effect of off-axis emission.

It is known that the observed total energy emitted from GRBs assuming isotropic radiation shows a wide dispersion by about 2-3 orders of magnitudes. Our fitting results also show a wide dispersion in the isotropic energy by more than 3 orders of magnitudes, with a constant true energy emission as a jet from the central engine. (See isotropic fluences in Figs. 1, 2, and 3.) The model therefore provides a possible explanation for the observed wide dispersion in the isotropic total GRB energies.

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