JET BREAKS AND MISSING BREAKS IN THE X-RAY AFTERGLOW OF GAMMA-RAY BURSTS

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ABSTRACT

The X-ray afterglows (AGs) of gamma-ray bursts (GRBs) and X-ray flashes (XRFs) have, after the fast-decline phase of their prompt emission, a temporal behavior varying between two extremes. A large fraction of these AGs has a canonical light curve which, after an initial shallow-decay plateau phase, breaks smoothly into a fast power-law decline. Very energetic GRBs, contrariwise, appear to not have a break: their AGs decline like a power law from the start of the observations. Breaks and “missing breaks” are intimately related to the geometry and deceleration of the jets responsible for GRBs. In the frame of the cannonball (CB) model of GRBs and XRFs, we analyze the cited extreme behaviors (canonical and pure power law) and intermediate cases spanning the observed range of X-ray AG shapes. We show that the entire panoply of X-ray light-curve shapes—measured with Swift and other satellites—are as anticipated in the CB model. We test the expected correlations between the AG’s shape and the peak and isotropic energies of the prompt radiation, strengthening a simple conclusion of the analysis of AG shapes: in energetic GRBs the break is not truly missing, it is hidden under the tail of the prompt emission, or it occurs too early to be recorded. We also verify that the spectral index of the unabsorbed AGs and the temporal indexes of their late power-law decline differ by half a unit, as predicted.

Subject headings: gamma rays: bursts — gamma rays: theory
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1. INTRODUCTION AND RÉSUMÉ

The isotropic distribution of gamma-ray bursts (GRBs) in the sky and their number distribution as a function of intensity, measured with the BATSE instrument aboard the Compton Gamma Ray Observatory, provided the first observational evidence that GRBs originate at large cosmological distances (Meegan et al. 1992). Moreover, the rapid variation of their light curves (Bhat 1997) of their optical afterglows (AGs) and their host galaxies (Sahu et al. 1997), which were used to extract their cosmological redshifts (Metzger et al. 1997). The AGs seemed to follow an achromatic power-law decline, as expected from a highly relativistic expanding fireball that drives a blast wave into the circum-burst environment (e.g., Mészáros & Rees 1997). This prediction of the spherical fireball model (see, e.g., Piran 1999) being independent of the assumption of spherical symmetry, it was also argued that the AGs, like the GRBs themselves, are produced by narrowly collimated jets (Dar 1997, 1998).

The concept of jets was incorporated into the FB model by the substitution of its spherical shells by conical sections thereof, the mechanism for the γ-ray emission still being synchrotron radiation from shock-accelerated e⁺, e⁻ pairs in a baryon-poor material (see, e.g., Piran 1999; Mészáros 2002 and references therein), in spite of the difficulties that such a radiation mechanism encounters (Ghisellini et al. 2000).

An elegant and simple way to distinguish between a conical jet and a spherical fireball was suggested by Rhoads (1997): the AG of a decelerating conical jet will show an achromatic steepening—a jet break—in its power-law decline when the relativistic beaming angle of its radiation becomes larger than the opening angle of the jet. Soon afterward, better sampled data on the optical AG of GRBs showed the existence of what appeared to be such achromatic jet breaks (Harrison et al. 1999; Stanek et al. 1999), and the spherical FB model was modified into a collimated fireball model (e.g., Piran et al. 1999). In this model GRB pulses are produced by synchrotron radiation from the collision between conical sections of shells. The collision of the ensemble of shells with the interstellar matter (ISM) generates the AG by synchrotron radiation from the forward shock propagating in the ISM, and/or from the backward shock within the merged shells. Rhoads (1999) and Sari et al. (1999) derived a relation between the opening angle of the conical jet and the time of the jet break. This relation has been applied extensively to the pre-Swift data to infer the opening angle of the conical jet and to determine the “true” energy of GRBs, posited to be an approximate standard candle (Frail et al. 2001).
Since the launch of Swift, the above generally accepted “standard” paradigm has been challenged, due to the absence of breaks in the AGs of many GRBs (Panaitecu et al. 2006; Burrows & Racusin 2007), to the chromatic behavior of the AG of other GRBs having the alleged jet break (Stanek et al. 1999; Harrison et al. 1999), and to the failure of the Frail relation (Frail et al. 2001) in many Swift GRBs (Kocevski & Butler 2008). In the FB model, the jet breaks need not be sharp; they are often parameterized with a varying smoothness (Stanek et al. 1999). Allowing for such breaks, Covino et al. (2006) could not identify a Swift GRB with a fully achromatic break. Liang et al. (2006) have extended this study, and analyzed the Swift X-ray data for the 179 GRBs detected between 2005 January and 2007 January and the optical AGs of 57 pre- and post-Swift GRBs. They found that not a single burst satisfies all the criteria of a jet break. This brings us fully into the question of the nature and properties of the jets responsible for GRBs and their AGs and, more specifically in this paper, to the understanding of breaks and “missing breaks.”

An alternative to the fireball scenario is offered by the cannonball (CB) model of GRBs (Dar & De Rújula 2000a, 2004; Dado et al. 2002; for a recent review see De Rújula 2007). In this model long-duration GRBs and their AGs are produced by bipolar jets of CBs (Shaviv & Dar 1995; Dar & Plaga 1999), ejected in ordinary core-collapse supernova (SN) explosions as matter is accreted onto the newly formed compact object (De Rújula 1987). The “cannonballs” are made of ordinary-matter plasma. The γ-rays of a single pulse of a GRB are produced as a CB coasts through the SN glory—the initial SN light, scattered away from the radial direction by the wind: the ejecta puffed by the progenitor star in a succession of pre-SN flares. The electrons enclosed in the CB raise the glory’s photons to GRB energies by inverse Compton scattering (ICS). As a CB coasts through the glory, the distribution of the glory’s light becomes increasingly radial and its density decreases rapidly. Consequently, the energy of the up-scattered photons is continuously shifted to lower energies and their number decreases swiftly, resulting in a fast softening and decline of the prompt emission (Dar & De Rújula 2004; Dado et al. 2007a, 2007b). In the CB model, the AG of a GRB is due to synchrotron radiation (SR) from swept-in ISM electrons spiraling in the CB’s enclosed turbulent magnetic field, generated by the intercepted ISM nuclei and electrons (Dado et al. 2002). At X-ray energies, the SR afterglow begins to dominate the ICS prompt emission only during the fast-decay phase of the latter (Dado et al. 2006).

In the CB model, the beau rôle in the understanding of GRBs is played by the Doppler factor, δ(t), relating times, energies, and fluxes in a CB’s rest system to those in the observer’s system. Its form in terms of the observer’s angle θ (relative to the CB’s direction of motion) and the time-dependent Lorentz factor γ(t) of a CB is

\[
\delta(t) = \frac{1}{\gamma(t)[1 - \beta(t) \cos \theta]} \approx \frac{2\gamma(t)}{1 + [\gamma(t)\theta]^2},
\]

where the approximation is excellent for γ ≫ 1 and θ ≪ 1. The decrease of γ(t) with time, as a CB encounters the particles of the ISM, is calculable on grounds of energy-momentum conservation (Dado et al. 2002; Dar & De Rújula 2006). The energy-integrated energy flux of the AG of a GRB is ∝ δ. Let γ₀ ≡ γ(0). Consider a CB that is observed almost on-axis, so that θγ₀ < 1: the observer is ab initio within the opening cone of the relativistically beamed radiation. As γ(t) decreases, δ(t) monotonically decreases and so does the observed AG. Consider the same CB, viewed by an observer at a much larger angle, so that θγ₀ is a few. As γ(t) decreases, δ(t) in equation (1) increases, reflecting the fact that the characteristic opening angle of the radiation, 1/γ(t), is reaching the observer’s direction. Past the point γθ = 1, the decrease of δ(t) is monotonic, as in the first case we considered. The AG radiation again parallels the behavior of δ(t). For observers of the same GRB from different angles, as θ increases at fixed γ(t), the AG’s flux decreases. All these simple facts, supported by the corresponding explicit derivations, are reflected in Figure 1a, which we have copied from Dado et al. (2002), as it foretells the progressive variety of AG shapes to be studied here.

There is more to Figure 1a than what we said. The Lorentz factor γ(t) of a CB only begins to change significantly, in a calculable manner, when the increase in its mass—induced by the energy influx of the swept-in ISM particles—becomes comparable to the CB’s initial mass. This happens, as we shall review, at a time \( t_b \approx (1 + 2\gamma_0^2\delta_0^2)\gamma_0^2 \). At fixed γ(t), as reflected in Figure 1a, a larger θ entails a larger \( t_b \). This achromatic “deceleration bend” at \( t = t_b \), we believe, was often interpreted in FB models as a putative jet break.

Naturally, the values of γ₀ and δ₀ of a given CB also affect the properties of its prompt ICS-dominated radiation (we are presenting this introductory discussion as if there were a single CB generating the prompt and AG radiations, a simplification to be undone when needed). In the CB model the ICS-dictated (θ, γ₀) dependences of a CB’s isotropic energy, peak energy, and peak luminosity are \( E_{\text{iso}} \propto \delta_0^2, E_p \propto \gamma_0\delta_0, \) and \( L_p \propto \delta_0^3 \) (Dar & De Rújula 2000b). The conditions for these quantities to be relatively large (a relatively small θ or a large γ₀) are the ones leading to a luminous AG with a small \( t_b \). The basis for one of these expected correlations, studied before in detail in Dado et al. (2007c), is illustrated in Figure 1b.

If the deceleration bend at time \( t_b \) takes place after the fast-decline phase of the prompt emission, it is observable, and the unabsorbed X-ray light curve is canonical (Dado et al. 2002). In these cases, there is a break. If \( t_b \) takes place earlier, it is hidden under the prompt emission, and only the tail of the canonical behavior, namely, the late power-law decline of the unabsorbed synchrotron AG, is observable. In these cases, the break is missing. The transition from long-plauteau, clearly broken AGs to power-law-like unbroken AGs should be anticorrelated with the trend from underenergetic to overenergetic GRBs.

In the CB model the late-time spectral energy density \( F_\nu \) of the X-ray and optical AG tends to a time and energy dependence \( \propto t^{-\nu}\nu^{-p-2} \), with \( p \) the spectral index of the electrons accelerated within a CB and cooled by the emission of the very SR seen as the AG. A prediction that we have not emphasized before is that the temporal power decline should be, for GRB by GRB, half a unit steeper than the spectral decline.

In Dado et al. (2006, 2007a) we have demonstrated that the most common light curves of the X-ray AG of GRBs are well described by the CB model. We have also explained there the various origins of the chromatic behaviors of AGs. In Dado et al. (2007b) we have focused on the fast-decline phase of the prompt emission and have demonstrated that the rapid spectral evolution observed during this phase is also as expected in the CB model. In Dado et al. (2007c) we have shown, for large ensembles of GRBs, how the observed correlations between \( E_{\text{iso}}, E_p \) (Dar & De Rújula 2000b; Amati et al. 2002), \( E_p \), and other prompt observables (pulse rise time, lag time, and variability) follow
mainly from the same simple geometrical considerations—reviewed above—on the case-by-case variability of the Doppler factor. In the CB model, XRFs are simply GRBs seen at relatively large \( \theta \) (Dado et al. 2004); even the particularly interesting XRF 060218 is in no way exceptional (Dado et al. 2007a).

In this paper we focus on the shape of the light curves of the X-ray AG of GRBs, with and without breaks, measured with the X-Ray Telescope (XRT) aboard Swift. We show that the shapes of the X-ray light curves of GRBs and XRFs predicted in Figure 1a, and the correlation between \( t_b \) and \( E_{\text{iso}} \) illustrated in Figure 1b (and the consequent apparent presence or absence of breaks in the AG), agree with the CB model’s expectations. We also analyze the \( (t_b, E_p) \) correlation in the same light. Finally, we investigate the relation between the temporal power-law index of the postbreak decline and the photon spectral index, reaching satisfactory results. To do all this, we investigate 16 GRBs chosen to reflect the full span of the question of the presence or absence of breaks. The selected GRBs range from the faintest known GRB (980425, of supernova association fame), which also has the most pronounced plateau and the latest break time, to the brightest Swift GRB 061007, with the most luminous and longest observed unbroken power-law X-ray AG.

2. THE AFTERGLOW OF A DECELERATING CB

In the CB model, the mechanism for the emission of the prompt radiation of GRBs and XRFs is ICS. The temporal and spectral properties of the prompt phase, including its fast decline, are summarized in a “master formula” (Dar & De Rújula 2004) that we have already contrasted with Swift data (Dado et al. 2006, 2007a, 2007b, 2007c, 2007d). We do not repeat it here—as our emphasis in the current study is on breaks in the X-ray light curves of GRB AGs—although we do use it to describe the fading of the prompt emission until the takeover by the synchrotron AG emission, and the occasional late X-ray flare. Neither do we discuss here the optical AGs (Dado et al. 2007a). The extinction in the optical—and, more so, in the radio—domain (within the CBs, in the circum-burst environment, in the ISM of the host galaxy and ours, and in the intergalactic medium) are difficult to model as reliably as the X-ray extinction. We see once again that the X-ray light curves (corrected for extinction) carry clear and direct information on the radiation mechanisms that dominate the prompt emission and the AG phase (ICS and SR, respectively, in the CB model).

During the initial phase of \( \gamma \)-ray emission in a GRB, the Lorentz factor \( \gamma \) of a CB stays put at its initial value \( \gamma_0 = O(10^3) \), for the deceleration induced by the interactions with the ISM has not yet had a significant effect. The Doppler factor by which the light emitted by a CB is boosted in energy is given by equation (1). Since the emitted light is forward-collimated into a cone of characteristic opening angle \( 1/\gamma_0 \), the boosted energetic radiation is easiest to detect for \( \theta = O(1/\gamma_0) \). Thus, typically, \( \theta_0 = O(10^5) \).

As a CB plows through the ISM, fully ionized by the preceding \( \gamma \)-radiation, it gathers and scatters the ISM ions, mainly protons. These encounters are collisionless, since, at about the time it becomes transparent to radiation, a CB also becomes transparent to hadronic interactions. As a consequence of momentum conservation, the scattered and reemitted protons inevitably exert an inward pressure on the CB. We have assumed that the main effect of this pressure is to slow the CB’s expansion, posited to be relativistic at the emission time. In the approximation of isotropic reemission in the CB’s rest frame and a constant ISM density \( n \), one then finds that, typically within minutes of the observer’s time \( t \), a CB reaches a roughly “coasting” radius, \( R = O(10^{14}) \) cm, which increases slowly until the CB finally stops and blows up.
where $\kappa = 1$ if the ISM particles reemitted fast by the CB are a small fraction of the flux of the intercepted ones. In the opposite limit, $\kappa = 0$. In the CB model of cosmic rays (Dar & De Rújula 2006), the observed spectrum strongly favors $\kappa = 1$, used here in our fits. We have also concluded from previous analysis of Swift X-ray data that $\kappa \approx 1$ is the right choice.

As indicated by first-principle calculations of the relativistic merger of two plasmas (Frederiksen et al. 2004), the ISM ions continuously impinging on a CB generate within it turbulent magnetic fields, which we assume to be in approximate energy equipartition with the energy of the intercepted ISM, $B \approx (2\pi m_n n e)^{1/2}$. In this field, the intercepted electrons emit synchrotron radiation. The SR, isotropic in the CB’s rest frame, has a characteristic frequency $\nu_0(t)$, the typical frequency radiated by the electrons that enter a CB at time $t$ with a relative Lorentz factor $\gamma(t)$. In the observer’s frame

$$\nu_\nu(t) \approx \nu_0 \left(\frac{\gamma(t)}{1 + z}\right)^{3/2}\left(\frac{n}{10^{-10} \text{ cm}^{-3}}\right)^{1/2} \text{Hz},$$

where $\nu_0 \approx 8.5 \times 10^{16}$ Hz $\approx 354$ eV. The spectral energy density of the SR from a single CB at a luminosity distance $D_L$ is given by (Dado et al. 2003a)

$$F_\nu \approx \eta \pi R^2 n_m e^3 \gamma^3(t)^2 \delta(t)^4 A(\nu, t) p - 2 \left(\frac{A(\nu, t)}{\nu_0^2}\right) \frac{1}{p - 1} \left[\frac{\nu}{\nu_0}\right]^{-1/2} \left[1 + \frac{\nu}{\nu_0}\right]^{-(p-1)/2},$$

where $p \approx 2.2$ is the typical spectral index of the Fermi accelerated electrons, $\eta = 1$ is the fraction of the impinging ISM electron energy that is synchrotron reradiated by the CB, and $A(\nu, t)$ is the attenuation of photons of observed frequency $\nu$ along the line of sight through the CB, the host galaxy (HG), the intergalactic medium (IGM), and the Milky Way (MW):

$$A(\nu, t) = \exp[-\tau_\nu(CB) - \tau_\nu(HG) - \tau_\nu(IGM) - \tau_\nu(MW)].$$

The opacity $\tau_\nu(CB)$ at very early times, during the fast expansion phase of the CB, may strongly depend on time and frequency. The opacity of the circumburst medium $\tau_\nu(HG$ at early times) is affected by the GRB and could also be $t$- and $\nu$-dependent. The opacities $\tau_\nu(HG)$ and $\tau_\nu(IGM)$ should be functions of $t$ and $\nu$, for the line of sight to the CBs varies during the AG observations, due to the hyperluminal motion of CBs. These facts, the different $t$, $\nu$ dependences of the ICS and SR emissions, and the dependence of the synchrotron AG on $\nu_0(t)$, are responsible for the complex observed chromatic behavior of the AGs. To a fair approximation, however, the deceleration bend, if occurring late enough, is achromatic from X-ray energies to the optical domain (Dado et al. 2002) but not as far as radio (Dado et al. 2003a).

The Swift X-ray bands are above the characteristic frequency $\nu_0$ in equation (3) at all times. It then follows from equation (4) that the unabsorbed X-ray spectral energy density has the form

$$F_\nu \propto R^2 n(t)^{p+2}/(3p-2)(p+6)/2 \nu^{-p/2}$$

$$= R^2 n^{1/2} T_\nu^{-1} \delta^{1/2} \nu^{-1},$$

where we have used the customary notation $dN_\nu/dE \approx E^{-1}$. 3. BREAKS, MISSING BREAKS, AND THE ASYMPTOTIC POWER DECLINE OF THE AG

The functions $\delta(t)/\delta_0$ and $\gamma(t)/\gamma_0$ of equations (1) and (2) evolve slowly, up until a time

$$t_b = (1 + 2\theta_0^2 z_0^2) t_0$$

$$\approx (130 \; \text{ s})(1 + 2\theta_0^2 z_0^2)(1 + z)\left(\frac{\gamma_0}{10^3}\right)^3\left(\frac{n}{10^{-11} \text{ cm}^{-3}}\right)^{-1} \left(\frac{R}{10^{14} \text{ cm}}\right)^{-2} \left(\frac{N_B}{10^{50}}\right),$$

where we scaled the result to typical CB model values of $R$ and a CB’s baryon number, $N_B$. The combination of the parameters $n$, $R$, and $N_B$ appearing in equation (7) is best constrained by the excellent X-ray observations discussed here. Our previous results on optical and radio AGs (for fixed $R$ and $N_B$) favored a 10 times smaller $n$ at the much larger sampled times; this is not an inconsistency, since a CB travels for $\sim \delta$ light days in 1 day of GRB data. We have chosen to normalize $n$ as in equation (7), rather than to reproduce long discussions on the distributions of CB model parameters (e.g., De Rújula 2007).

The quantity $t_b$ in equation (7) characterizes the deceleration bend time of the CB model: equation (2) for $\gamma(t, t_0, 0, \gamma_0)$ describes the gradual character of this break. At later times equation (2) implies that $\gamma \rightarrow \gamma_0/(t/t_0)^{1/4}$, and equation (1) that $\delta \rightarrow 2\gamma$. Thus, at $t \gg t_b$, equation (6) yields

$$F_\nu(t) \propto \nu^{1/2-p/2} \nu^{-p/2} = \nu^{1/2-p/2} \nu^{-2},$$

$$p = 2(\Gamma - 1),$$

with, as announced, a power decay in time half a unit steeper than in frequency.

4. THE PROMPT OBSERVABLES

In the CB model, the peak energy of GRBs satisfies

$$E_p \approx \frac{1}{2} \gamma_0 \delta_0^2 \frac{1}{1 + z} \epsilon_0,$$

where $\epsilon_0 \sim 1$ eV is the typical energy of the glory’s photons, that of the associated supernova early light just prior to the ejection of CBs. The isotropic (or spherical equivalent) energy of a GRB is (Dar & De Rújula 2004)

$$E_{iso} \approx \frac{\delta_0^2}{6c} L_{SN} N_{CB} 2^{\beta_2} 4\pi \nu_0^2 \left(\frac{\sigma_T N_{CB}}{4\pi}\right)^{1/2} \sim (1.2 \times 10^{53} \text{ erg}) V_E,$$

$$V_E = \delta_0^2 L_{SN} N_{CB} 2^{\beta_2} 4\pi \nu_0^2 \left(\frac{N_{CB}}{10^{50}}\right)^{1/2},$$

where $\epsilon_0$ is the energy of the glory’s photons.
where $L_{SN}$ is the mean supernova early optical luminosity, $N_{CB}$ is the number of CBs in the jet, $\beta_0$ is the co-moving early expansion velocity of a CB (in units of $c/\sqrt{3}$), and $\sigma_T$ is the Thomson cross section. For $(N_{CB}) = 6$ (Schafer 2007), the early SN luminosity required to produce the mean isotropic energy, $E_{iso} \sim 4 \times 10^{53}$ erg, of ordinary long GRBs is $L_{SN} \sim 5 \times 10^{42}$ erg s$^{-1}$, the estimated early luminosity of SN 1998bw. All quantities in equation (10) are normalized to their typical CB model values. We have normalized to $N_{CB} = 2$, an adequate mean number of prominent X-ray pulses in the subset of GRBs analyzed here.

The results in equations (9) and (10) are based on the assumption that ICS is the mechanism generating the prompt radiation. They depend on $\gamma_0$ and $h_0$, two parameters also appearing in the description of the SR afterglow. That is why we are able to test the implied correlations, GRB by GRB, between the shape of the AG and the energetics of the prompt radiation, the very strong dependence of the $\delta$ on $\theta$ once more playing the major role.

According to equations (1), (9), and (10), CBs with large $\gamma_0$ and, more so, small $\theta$ produce the largest values of $E_P$ and $E_{iso}$: they generate the brightest GRBs. According to equation (7), such $(\gamma_0, \theta)$ values entail a small $r_0$, an expectation that our analysis validates. In such cases, the deceleration bend or break of the synchrotron AG may take place before the beginning of the XRT observations and/or be hidden under the prompt Compton emission. According to equation (6), these AGs must be very luminous at early times, and according to equation (8), they must be well approximated from the start by the asymptotic power-law behavior given by equation (8). Our analysis verifies all these predictions.

5. COMPARISON WITH OBSERVATIONS

To date, Swift has detected and localized nearly 300 long GRBs, and for most of them it followed their X-ray emission until it faded into the background. Incapable of discussing all of them, we analyze the light curves of the X-ray AG of a set of GRBs with and without jet breaks, which represent fairly well the entire spectrum of canonical and noncanonical X-ray AGs of GRBs. They include the most extreme cases of canonical and noncanonical behavior (GRB 09080425 and GRB 061126, respectively), the longest measured canonical and noncanonical X-ray light curves (GRB 060729 and GRB 061007), and a variety of light curves with and without breaks, with and without superposed X-ray flares. Since many CB model fits to canonical light curves of X-ray AGs with breaks were included in previous publications (Dado et al. 2002, 2006, 2007a, 2007b, 2007d), we discuss in this paper more cases of GRBs with an approximate power-law AG than of GRBs with a canonical AG.

We start the fits to the X-ray light curves during the transition between the rapid decline phase of the ICS-dominated prompt emission to the SR-dominated AG phase. It suffices to include the ICS contribution of the last prompt emission pulse (or the last two), because of an exponential factor in the pulse shape that suppresses very quickly the relative contribution of the earlier pulses by the time the data sample the later ones (Dado et al. 2007a, 2007b). For the synchrotron contribution, it usually suffices to consider a common emission angle $\theta$ and an average initial Lorentz factor $\gamma_0$ for the ensemble of CBs. The ISM density along the CBs’ trajectories is approximated by a constant. We then fit the entire observations of the X-ray AG of the selected GRBs by using the master formula (Dar & De Rújula 2004; eq. [11] of Dado et al. 2007a) for the tail of the ICS prompt emission contribution, and equation (6) for the SR. Many GRBs have late X-ray flares, which we interpret as dying pangs of the engine; that is, the emission of CBs in late episodes of accretion into the recently collapsed central compact object. These CBs, whose ICS-generated flares can only be seen on the weak background of a decaying SR “afterglow” (in quotes because the “AG” is observable before the late prompt flares), are also modeled with the same master formula.

The calculated shape of the energy-integrated X-ray AG, equation (6), depends only on three fit parameters. Two of them are the product $\gamma_0 \theta$ and the deceleration bend time, $t_b$, for an on-axis observer, as given in the first line of equation (2). They determine the deceleration bend time, $t_b$, observed at a viewing angle $\theta$; see equation (7). The third fit parameter is the index $p$ in the $\gamma$ and $\delta$ time-dependent factors of equation (6). Unlike in previous analyses, we let $p$ be a free parameter, unrelated to the spectral index $\Gamma$, independently extracted by the observers from the shape of the X-ray spectrum. This way we are able to test explicitly the CB model prediction implied by equation (6), $p = (1 - 1)$, or by its more readable asymptotic form, equation (8). In all the cases we study but two (GRBs 071020 and 050416A), a single CB or an average CB suffice to describe the AG. The occasional need for two CBs in the AG light-curve description is not a novelty. The most notable instance is that of GRB 030329 (Dado et al. 2003b).

A comparison between the observed and predicted light curves of the 16 selected GRBs is shown in Figures 2–5. When well measured, the break time, $t_b$, is indicated in the figure by an arrow. The best-fit values of $p$, $\gamma_0 \theta$, and $t_b$ are listed in Table 1, along with additional observational information on these GRBs (redshift, peak energy, equivalent isotropic energy, the start time of the Swift XRT observations, the spectral index of the unabsorbed AG, and the $\chi^2$ per degree of freedom [dof] of the fits). AGs which exhibit nearly a pure power-law decline have a $t_b$ smaller than $t_e$, the time after trigger when the XRT started its observations of the AG, or a $t_b$ smaller than the time when the AG became brighter than the tail of the prompt emission. Such AGs have a nearly power law shape, $F_\nu \approx \nu^{-p}$. Their fits, however, return upper limits for $\gamma_0 \theta$ and $t_b$, above which the shape of the AG deviates from the data. These limiting values are also reported in Table 1, but the corresponding limit-$t_b$ location is shown in the figures in the case-by-case analysis, as it generally falls off limits.

In most cases (including many Swift AGs studied in Dado et al. [2006, 2007a, 2007b]), but not shown here), the CB model produces good fits with reduced $\chi^2$ values close to unity. Even if the $\chi^2$ figures are good, we generally have refrained in the past from reporting them. One reason is that it is easy to obtain an excellent $\chi^2$ for a fit that has many data points, but misses some that clearly reflect a significant structure (such as a supernova; see Dado et al. 2002), or is, even within errors, systematically above the data in one region and below it in another. For that reason, and the occasional local scatter of the data, we consider the eye to be a better judge than any statistical measure. We comment on the $\chi^2$ values when they are bad.

The values of $\gamma_0 \theta$, $t_b$ (or $t_0$), and $p$ returned by our fits and reported in Table 1 have formal errors of a few percent. The error correlation matrix has relatively small off-diagonal elements. The reduced-$\chi^2$ values are very close to unity, once the occasional flares are taken into account, to reveal the presence of a smoother SR background. One reason for this is that $t_0$ sets the overall timescale, $\gamma_0 \theta$ determines the shape of the bend, and $p$ is sensitive to the whole SR light curve, playing a major role in its power-law tail. This means that when a light curve is well sampled (over orders of magnitude in flux and time), the fit is very sensitive to its parameters. Naturally, the results depend also on the deceleration law, equation (2), meant to be an approximation. Therefore, the
extracted parameters have systematic errors reflecting the approximate nature of equation (2). We can argue explicitly why the approximation should be better than it looks at first sight, even case by case (on average, and independently, it leads to the correct spectrum of cosmic rays from nonrelativistic energies up to the “knee” at some $2 \times 10^6$ GeV; Dar & De Rújula 2006). The continuation of this rather formal argument on errors would take us well beyond the scope of this paper.

5.1. Case Studies

In this section we comment one by one on the 16 GRBs or XRFs whose X-ray light curves we discuss. The results of the CB model fits are shown in Figures 2–5, and the parameters relevant to our discussion are listed in Table 1. The first eight GRBs are shown in the order of decreasing $t_b$. For the next four, only an upper limit on $t_b$ can be extracted from the fits. The last four have very complex AGs.

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Fig. 2a

GRB 980425

Fig. 2b

GRB 060729

(0.3-10 keV)

Fig. 2c

GRB 050505

(0.3-10 keV)

Fig. 2d

GRB 050401

(0.3-10 keV)

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Fig. 2.—Comparison between the observed X-ray light curves of selected GRBs and their CB model fit. (a) GRB 980425. The last point was measured 1285 days after burst (Kouveliotou et al. 2004); the dotted line is for Dado et al. (2002), and the solid line is fit here as all other light curves. (b) GRB 060729. (c) GRB 050505. (d) GRB 050401. All light-curve data, except for GRB 980425, are from the Swift XRT light-curve repository (Evans et al. 2007). [See the electronic edition of the Journal for a color version of this figure.]
The presence or absence of visible breaks in X-ray light curves and their different “look”—the panoply of possibilities that we illustrate with our GRB choices—depend not only on $t_b$, but on its value relative to $t_s$ (the start time of XRT observations) and relative to the duration of the initial period of prompt radiation dominance over the synchrotron AG. For this reason, it is easier to compare the plethora of looks of our GRBs in an order slightly different from that of a decreasing $t_b$. This we do (only) in the next paragraph.

GRBs 980425 and 060729 have light curves with a complete and simple canonical shape: one or two very clear prompt X-ray flares, a pronounced fast decay, a long plateau, and a very visible break smoothly bending at $t_b$ to become a power-law decay. In GRBs 050401, 060105, 060418, 061007, and 050717, the plateaus becomes less and less pronounced, so that the AG’s $t_b$ is hiding better and better under the prompt signal, to the point that the last two are close to a pure power-law tail. In GRBs 060813, 070508, and 050505, the prompt radiation ended early enough
not to be caught by *Swift* XRT (in the last case the follow-up started very late), but this trio display very canonical AGs, with their neat plateaus softly bending into a late power law. GRBs 071025, 061126, and 070125 are again approximate power-law tails, in which neither the early X-ray flares nor the putative bend are seen. GRBs 071020, 050416A, and certainly 060607A are very complex. The first two require contributions to the AG from two distinct CBs, 050416A having also a late flare. The unsightly X-ray light curve of GRB 060607A can be described by the CB model without any new ingredients, but not much is learned from fitting it.

**GRB 980425.**—The light curve of this memorable single-peak GRB, as observed by *BeppoSAX* (Pian et al. 2000), is shown in Figure 2a. The dotted line is the fit in Dado et al. (2002), showing what we called a pronounced plateau. We have added to it the last (predicted) data point, measured with *Chandra* by Kouveliotou.
et al. (2004), some 1285 days after burst! To be consistent with the analysis here, we have refit the ensemble of data in the same manner as for all the other GRBs to be discussed. The result is the continuous curve in the figure. This GRB has, so far, the record large values $\gamma_0 \theta \approx 9.2$ and $t_b \approx 1.4 \times 10^5$ s, resulting in a light curve that rises before it falls, as explained in the introduction and illustrated in Figure 1a. This is the behavior expected for far-off-axis GRBs (Dar & De Rújula 2000a). This one barely missed official classification as an XRF: its $E_p$ is $\sim 56$ keV, as opposed to $E_p < 50$ keV (see Dado & Dar 2005 for further comment on this point).

**GRB 060729.**—This GRB and its X-ray light curve were studied in detail by Grupe et al. (2007). It has a canonical shape, the longest follow-up observations with *Swift* XRT, and the record high $t_b \sim 8300$ s among the *Swift* GRBs. In Figure 2b we show its CB model description with, superposed on its prompt decline phase, four ICS X-ray flares included in the fit, as discussed in detail in Dado et al. (2007a). This GRB, being canonical and...
having a very clear break—as do several others also discussed in Dado et al. (2007a)—is included here to illustrate the start of the transition from breaks to missing breaks. Although the best fit to the X-ray AG appears to be excellent, it yields a large \(\chi^2/\text{dof} = 635/140 = 4.5\), mostly due to many far-flung isolated data points in the Swift data. More accurate data from XMM-Newton (Grupe et al. 2007) do not show such outliers. Eliminating their contribution yields the \(\chi^2\) value reported in Table 1.

**GRB 070508.**—Swift XRT started to measure the X-ray light curve of this GRB 82 s after the GRB trigger. Even at this early time, it already displays the shallow-decay plateau phase of a canonical AG, which later bends into a power-law decline, as shown in Figure 3a.

**GRB 060813.**—This GRB, shown in Figure 3b, is a case in which the prompt radiation is not seen by the XRT, and the AG has no obvious flares. In spite of some evidence for local variability, the smoothly bending AG is well described by the CB model (\(\chi^2/\text{dof} = 1.07\) for 254 dof). Had the break happened a bit earlier, as in other cases, the X-ray AG would look like a power law. The last data point lies below the fit; it could be due to an overestimated background.

**GRB 060418.**—This GRB’s achromatic AG was studied in detail by Molinari et al. (2007). Its X-ray AG evolves fast into a power-law decline; see Figure 3c. The CB model fit returns an early break at \(t_b = 123\) s, well hidden under the flaring activity during the fast-decline phase of the prompt emission. The transition from an ICS-dominated regime to one in which \(S\) is prevalent is corroborated by the fast spectral softening of the tail of the flare from around \(t \sim 130\) s (Evans et al. 2007), which suddenly turns, at \(t \sim 165\) s, into the much harder time-independent power-law spectrum characteristic of the synchrotron AG (Dado et al. 2007b). We have checked that the reasonable \(\chi^2/\text{dof} = 1.21\) for 295 dof of the fit shown in the figure can be reduced to \(\chi^2/\text{dof} \sim 1\) by including X-ray flares between 5 and 10 ks, or by replacing the fluctuating data points by average values.

**GRB 050717.**—This GRB was studied in detail by Krimm et al. (2006). It had the largest inferred peak energy of all Swift GRBs, \(E_p = 2401^{+234}_{-156}\) keV, despite its estimated large redshift, \(z > 2.7\). At this \(z\)-limit, \(E_{\text{iso}} \sim 1.1 \times 10^{54}\) erg, and the local peak energy is \((1 + z)E_p \sim 8840\) keV. It also had an initially very bright X-ray AG, after the fast-declining prompt emission, with a power-law decline from \(t \sim 200\) s onward. The fit in Figure 3d returns an early break-time limit, \(t_b < 55\) s, well hidden under the prompt emission tail. The CB model interpretation of the transition from a prompt ICS radiation to a synchrotron AG is supported by the...
observed rapid spectral softening of the tail of the prompt emission and its sudden change at $t \approx 200$ s into the harder time-independent power-law spectrum of the synchrotron AG (Dado et al. 2007b). In the case of this GRB the best-fit value, $p = 1.67$, does not satisfy equation (8), with $\Gamma = 1.61 \pm 0.10$, as inferred from the X-ray spectrum with a fixed column density limited to the Galactic one (Krimm et al. 2006). However, $p = 1.67$ is consistent with $\Gamma = 1.88 \pm 0.15$ of the AG for $t > 200$ s, the spectral index reported in Zhang et al. (2007) after inclusion of host galaxy and IGM absorption.

GRB 061126.—This GRB, studied in detail by Perley et al. (2007), had two major prompt pulses. Due to an Earth-limb constraint, Swift slewed to the burst’s direction only 23 minutes after its localization by its Burst Alert Telescope (BAT). Its light curve, measured by the XRT between 1.6 ks and 1.88 Ms, is shown in Figure 4a. The X-ray light curve was reported to be well fit by a power law in time with index $1.29 \pm 0.08$ (Barufatti et al. 2006). A CB model fit, with $p = 1.89$ and $t_b < 104$ s, is shown in Figure 4a. There is a possible indication in the data of a steeper decay between 1.6 and 3.6 ks, which might belong to the tail of another CB with a smaller $t_b$. Cases of AGs clearly requiring two CBs will be discussed anon.

GRB 071025.—Swift XRT started observations of the X-ray light curve 146 s after the BAT trigger. The initial relatively hard spectrum ($\Gamma = 1.4$) softened beyond 300 s and the light curve declined like a single power law, consistent with the CB model’s asymptotic power-law decline with a power-law index $\Gamma \approx 1.6$, as shown in Figure 4b. The data suggest a flaring activity between 4 and 40 ks. The effect of such flares on the CB model X-ray light curve is illustrated in the figure by adding an ICS flare around 40 ks with parameters (peak time, width, and normalization) chosen, as in all other cases with clear flares, to best fit the data. GRB 070125.—This GRB was studied in detail by Bellm et al. (2007). It was detected by Mars Odyssey, Suzaku, INTEGRAL, and RHESSI. It is one of the Swift-era GRBs with the largest measured values of $E_{\text{iso}} \approx 1 \times 10^{54}$ erg, $L_p \approx 3 \times 10^{53}$ erg s$^{-1}$, and source-frame $(1+z)E_p \approx 1100$ keV. The initial detection of this GRB occurred while it was not in the BAT field of view during the beginning of the prompt emission, and its XRT light curve starts at 46 ks after the burst. As shown in Figure 4c its power-law decline is well described by the CB model. The feature at $\sim 110$ ks can be interpreted as an X-ray flare, as in the figure.

GRB 061007.—This GRB, whose AG was studied in detail by Schady et al. (2007) and Mundell et al. (2007), was the brightest GRB detected by Swift and was accompanied by an exceptionally luminous X-ray and UV/optical AG, which decayed as a power law with an index $1.65 \pm 0.02$. It had the largest values of $E_{\text{iso}} \approx 1 \times 10^{54}$ erg, $L_p \approx 2 \times 10^{53}$ erg s$^{-1}$, and emission-point peak energy $(1+z)E_p \approx 1000$ keV (Golenetskii et al. 2006). This GRB is the best example to date of a bright X-ray AG, well sampled from the start of the XRT observations (86 s after the BAT trigger) to $10^6$ s. The AG, shown in Figure 4d, behaves as a power law right after the tail of the prompt emission. The CB model fit returns $t_b < 89$ s, below which the $\chi^2$/dof (a reasonable 1.13 for 1030 dof) stays put.

GRB 071020.—This GRB was measured by Swift XRT between 68 s and 1.7 Ms after trigger, and is shown in Figure 5b. Holland et al. (2007) fitted the data with a broken power law with an initial decay index of $\approx 0.5$, a break at $t_b = 160$ s, and a late-time decay index of 1.14 \pm 0.02. The fit is poor between 1.5 ks and 1.5 Ms. A CB model fit with a single CB is also unsatisfactory. The addition of a second CB to the AG’s description, as in the fit shown in Figure 5a, greatly improves the fit to $\chi^2$/dof = 1.52 for 174 dof, acceptable in view of what appears to be evidence for flaring activity, from 1.5 to 15 ks, which we have not endeavored to describe, given the scarcity of data.

GRB 050416A.—The complex X-ray light curve of this XRF was monitored up to 74 days after the burst (Mangano et al. 2007). The late decline rate of the light curve is significantly slower than expected in the CB model from the observed photon spectral index $\Gamma$, namely, $t^{-1.5 \pm 0.10}$. The prompt signal of XRF 050416A had two clear pulses which, in the CB model, correspond to two separate CBs. The X-ray light curve, modeled with two CBs and shown in Figure 5b, has a SR component late power decay that—although it is not readable by eye due to the late-occurring ICS flare—is compatible with the predicted one.

GRB 060105.—This GRB’s X-ray light curve was studied in detail by Tashiro et al. (2007). Following the prompt emission, which ended with a very steep decay, the light curve is canonical; it has a shallow decay after 180 s and steepens at around 500 s to a fast power-law decline, with a weak flaring activity superposed on it.

The deviations from a smooth X-ray light curve may be caused by the flaring activity, not included in this particular fit, whose $\chi^2$/dof = 1.36 for 854 dof is not adequate.

5.2. The Afterglow as a Function of Time and Frequency

We have summarized in equation (4) the predicted form of the spectral energy density of the AG of a GRB, in which the time dependence and the energy dependence are explicitly concatenated. In the large-frequency limit of the X-ray domain, the expression simplifies to that of equation (6), implying a predicted relation between the temporal index $p$ (which we fit to the XRT light curve of the X-ray AG) and the spectral index $\Gamma$, independently fitted by the Swift team to the X-ray AG spectrum after correcting for attenuation, and reported in Zhang et al. (2007). The prediction is particularly simple, and is most transparently readable in the limit of the AGs’ dependence on $t$ and $\nu$, equation (8), in which both the time and the frequency functional forms are separate power laws.

The values of $p$ and $\Gamma$ are listed in Table 1. Notice that $\Gamma$ varies over a significant range of central values, 1.61–2.25, and that the measurements are not compatible within errors with a common value. To illustrate the prediction in equations (6) and (8), we have plotted in Figure 6 the ratio $r = p/(2\Gamma - 2)$ (predicted to be unity) for the various GRBs analyzed in this paper, and added a few other analyzed in the same fashion. The results are quite satisfactory. The mean value of $r$, for instance, is 0.999 ± 0.025 for the GRBs analyzed here, and 1.000 ± 0.019 for the ensemble plotted in Figure 6.

5.3. The $(t_b, E_{\text{iso}})$ and $(t_b, E_p)$ Correlations

In the CB model, the functional dependence on $\theta$ and $\gamma_0$ of the deceleration bend time of the synchrotron AG, $t_b$, as well as its
normalization, are specified by equation (7). This is also the case for the parameters, $E_p$ and $E_{\text{iso}}$ of equations (9) and (10), of the prompt ICS signal. As we saw in the introduction, this implies explicit correlations between $t_b$ and the prompt observables. The $(t_b, E_{\text{iso}})$ correlation is illustrated in Figure 1b for various choices of $\theta$ and $\gamma_0$, with the rest of the parameters in $t_b$ and $E_{\text{iso}}$ fixed to reference values in equations (7) and (10).

In Figure 7 we plot, in the $[t_b/(1+z), E_{\text{iso}}]$ plane, the values returned by our analysis of the GRBs we have discussed; see Table 1. The GRBs represented by arrows reflect the fact that some data are just upper limits. The large shaded contour plot in the figure is the boundary of the domain covered by letting $\gamma_0$ vary from 500 to 1500, and $\theta$ from 0 to 8 mrad, typical ranges encountered in the CB model analysis of GRBs. Moreover, the normalization of $t_b$ in equation (7) was varied from its central value in equation (7) to 1/2 an order of magnitude above it, and the normalization of $E_{\text{iso}}$ in equation (10) from its central value to 1/2 an order of magnitude below and above it. The variability in these normalizations is best ascertained by the current analysis; it has been chosen to make Figure 7 “look good.” We have added to the figure the results for a few GRBs which we have previously analyzed along the same lines in Dado et al. (2007a, 2007b).

There is no reason to expect the data to populate uniformly the region bounded by the contour in Figure 7. On the contrary, the relativistically beamed radiation from a point in a CB initially subdents an angle $1/\gamma_0$. Observers at an angle $\theta$ from the axial direction have a chance $\propto \theta d\theta$ of being illuminated. At $\theta > 1/\gamma_0$ this chance decreases abruptly, given the fast fall of the Doppler factor. All in all, $\theta \sim 1/\gamma_0$ is the optimal observation angle, for any $\gamma_0$. Most GRBs, then, should be seen at $\theta = \gamma_0 = O(1)$. The thick straight line in Figure 7 is $t_b(E_{\text{iso}})$ at fixed $\theta = \gamma_0$, for which $t_b/(1+z) \propto \gamma_0^{-3}$ and $E_{\text{iso}} \propto \gamma_0^3 \propto \gamma_0^{-3}$. Thus,

$$t_b/(1+z) \propto E_{\text{iso}}^{-1}. \quad (11)$$

The data follow this trend well, but at the high-$E_{\text{iso}}$ end, at which they bend as in Figure 1b.

In Figure 8 we plot, in the $[t_b/(1+z), (1+z)E_p]$ plane, the corresponding results of our analysis. The shaded domain is obtained with the same ranges in $\gamma_0$ and $\theta$—and in the normalization of

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**Fig. 6.**—Test of the prediction $r = p/(2\Gamma^2 - 2) = 1$, of eq. (8), relating the temporal index, $p$, to the spectral one, $\Gamma$, of the AGs of GRBs. The GRBs discussed in this paper are the outlined ones. We have extended this test to other GRBs analyzed in the same fashion. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 7.**—The $[t_b/(1+z), E_{\text{iso}}]$ correlation. The circles are the GRBs of known $E_{\text{iso}}$ analyzed in this paper, most of which have comparatively small $t_b$. The arrows reflect results for which only an upper limit is available. The stars are GRBs, mainly with canonical X-ray light curves, analyzed in Dado et al. (2007a). The large shaded domain is the contour of a region obtained by letting the parameters vary as specified in the text. The shaded straight line is the expectation for GRBs viewed close to the most probable angle of observation, $\theta = 1$. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 8.**—The $[t_b/(1+z), E_p]$ correlation. The circles are the GRBs of known $E_p$ analyzed in this paper, most of which have comparatively small $t_b$. The arrows reflect results for which only an upper limit is available. The ellipses are for GRBs, mainly with canonical X-ray light curves, analyzed in Dado et al. (2007a). The large shaded domain is the contour of a region obtained by letting the parameters vary as specified in the text. The shaded straight line is the expectation for GRBs viewed close to the most probable angle of observation, $\theta = 1$. [See the electronic edition of the Journal for a color version of this figure.]

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The energy of the radiation is predicted to decrease during the pulse’s duration: $E_p(t) = E_p(\tau_0)(1 - \tau/\tau_0)^{-3/2}$, with $\Delta$ the width parameter (the full width at half-maximum, FWHM, is $\sim 1.8\Delta$). Observers usually report $E_p$ at the peak’s maximum, expected to be $E_p(t_{\text{iso}}) \approx 0.23E_p(0)$, or its pulse-averaged value: $(E_p) \approx 0.18E_p(0)$ over the FWHM. We have not corrected for these facts, which may explain the choice of the “best” domain.

$^5$ The $E_p$ of eq. (9) is the peak energy at the start of a pulse; we set it to $t = 0$. The energy of the radiation is predicted to decrease during the pulse’s duration: $E_p(t) = E_p(\tau_0)(1 - \tau/\tau_0)^{-3/2}$, with $\Delta$ the width parameter (the full width at half-maximum, FWHM, is $\sim 1.8\Delta$). Observers usually report $E_p$ at the peak’s maximum, expected to be $E_p(t_{\text{iso}}) \approx 0.23E_p(0)$, or its pulse-averaged value: $(E_p) \approx 0.18E_p(0)$ over the FWHM. We have not corrected for these facts, which may explain the choice of the “best” domain.

$^6$ See http://www.mpe.mpg.de/~jcg/grbgen.html.
under the prompt ICS radiation, or occur too early to be seen. This sounds like a trivial and model-independent excuse. It is not. It is supported by our case-by-case analysis of AG shapes. Moreover, a crucial ingredient—the angle of observation of the jet, compared to the beaming angle of its Doppler-boosted radiation—is validated by the correlations, e.g., the luminous AGs are the ones with early or even undetectable breaks, as in Figure 1a, and in many of the examples we discussed here (the correlation between $t_b$ and the energy in the X-ray AG was studied in Dado et al. 2007d). Our conclusions are also supported by the correlations between the CBs’ deceleration bend break times, $t_b$, (in the synchrotron AGs), and the values of $E_{iso}$ and $E_p$ (in the prompt Compton signal). These correlations, shown in Figures 7 and 8, reconfirm the consistency of the overall picture.

We have given no comment in the conclusions to our fits to the GRBs and XRFs that we have studied. This is because the point we would like to make is not that the CB model can be used to fit the data very well. The main issue, in our view, is how a model, preferably in a predictive manner and in terms of very few concrete concepts—like its radiation mechanisms, the aperture of its jets and the angle from which they are viewed—can be used to understand the ensemble of long-duration GRBs, and XRFs. After all, phenomena that require ever increasingly complex explanations are of limited scientific interest.  

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