On the "canonical behaviour" of the X-ray afterglows of the Gamma Ray Bursts observed with Swift's XRT

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ABSTRACT

The "canonical behaviour" of the early X-ray afterglows of long-duration Gamma-Ray Bursts (GRBs) —observed by the X-Ray Telescope of the SWIFT satellite— is precisely the one predicted by the Cannonball model of GRBs.

Subject headings: gamma ray burst

1. Introduction

Within a year of its launch on 20 November, 2004, SWIFT accomplished most of its goals (Gehrels et al. 2004): it saw and localized short-duration GRBs and discovered their X-ray afterglow (e.g. Gehrels et al. 2005; Covino et al. 2005; Retter et al. 2005), heralding the discovery of their host galaxies in ground-based follow-up observations (e.g. Bloom et al. 2005a, 2005b; Hjorth et al. 2005; Antonelli et al. 2005). SWIFT has detected GRBs at large redshifts (Jakobsson et al. 2005), with a record $z = 6.29$ (Haislip et al. 2005; Cusumano et al. 2005; Tagliaferri et al. 2005a). Its X-ray telescope (XRT) measured well the X-ray afterglows (AGs) of long-duration GRBs in the first hours after burst (e.g. Chincarini 2005). The latter observations have been claimed to provide two *major surprises:*

(a) The 0.2–10 keV light curves of the X-ray AGs exhibit a "canonical behaviour", to wit: (i) an initial very steep decay ($t^{-\alpha}$ with $3 < \alpha < 5$), followed by (ii) a shallow decay ($0.2 < \alpha < 0.8$), which finally evolves into (iii) a steeper decay ($1 < \alpha < 1.5$). These power-law segments are separated by the corresponding "ankle" and "break" at times 300 s $< t_{\rm ankle} <$ 500 s and 10^3 s $< t_{\rm break} < 10^5$ s (Chincarini et al. 2005; Nousek et al. 2005; Cusumano et al. 2005; Hill et al. 2005; Vaughan et al. 2005; Tagliaferri et al. 2005b; Barthelmy et al. 2005). This is illustrated in Figs. 1a,b for GRB 050315 and GRB 050319.

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(b) While most of the early AG light curves decline smoothly, a substantial fraction has large X-ray flares on short time scales (see, e.g. Burrows et al. 2005a, 2005b; Nousek et al. 2005).

It has also been claimed (e.g. Chincarini et al. 2005; Nousek et al. 2005; Zhang 2005) that the "canonical behaviour" and the flares cannot easily be explained by current models. This may be true of the popular fireball (FB) models (for a general review, see e.g. Zhang & Mészáros 2004). It is not true of the "Cannonball" (CB) model (Dar & De Rújula 2000, 2004 and references therein). In the CB model the observed canonical behaviour and the flares are *predictions* (Dado, Dar & De Rújula 2002, hereafter DDD2002). This is discussed in this letter for two recent representative SWIFT-XRT observations: GRB 050315 (Vaughan et al. 2005) and GRB 050319 (Cusumano et al. 2005).

2. The Cannonball model of GRBs

In the CB model *long-duration* GRBs and their AGs are produced by bipolar jets of CBs ejected in *ordinary core-collapse* supernova explosions. An accretion disk or torus is hypothesized to be produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (De Rújula 1987). As observed in microquasars (e.g. Rodriguez & Mirabel 1999), each time part of the accretion disk falls abruptly onto the compact object, a pair of CBs made of *ordinary matter* are emitted with large bulk-motion Lorentz factors γ, in the polar directions wherefrom matter has already fallen back owing to the lack of rotational support.

The γ-rays of a single pulse in a GRB are produced as a CB coasts through the SN "Glory" —the SN light scattered by the SN and pre-SN ejecta. The electrons enclosed in the CB Compton up-scatter to GRB energies the photons of the Glory (Dar & De Rújula 2004). As the CBs escape the SN environment, the ambient-light distribution becomes increasingly thin and radial. No longer can the Glory's photons be efficiently up-scattered. The γ-ray emission is taken over by thermal bremsstrahlung (TB) and line emission (LE) from the rapidly expanding CBs. Their rapid expansion stops (DDD2002) within a few minutes of the ejection (of near-axis observer's time) by their interaction with the interstellar medium (ISM). The fast-declining TB and LE is subsequently taken over by synchrotron radiation from swept-in ISM electrons spiraling in the CBs' enclosed magnetic field (DDD2002). The CB radiation is a sum of these mechanisms which produce a continuous X-ray AG light curve as the dominant CB radiation mechanism evolves according to: **Inverse Compton Scattering → Bremsstrahlung + Line Emission → Synchrotron Radiation.**

In the CB model, the typical parameters of CBs are not predicted but can be extracted from the analysis of optical and radio AGs (DDD2002, Dado, Dar & De Rújula 2003a). Their values can then be used to predict the properties of the γ-rays of GRBs (Dar & De Rújula 2004). They also agree with the characteristic "canonical" timing and flux of the above sequence, and the corresponding power-law and spectral changes (DDD2002). The surprise (a) of the Introduction was already visible in the X-ray data of GRBs 970508, 970828, 990510 and 010222, and compatible with less-precise data on six other GRBs, including 980425. As for surprise (b), late-time bumps and flares have been detected before in the X-ray AG of GRB 970508, in the radio AG of GRB 030329 and in the optical AG of e.g. GRBs 000301c and 030329. Their CB-model interpretation is straightforward (DDD2002, Dado et al. 2004b).

3. Radiation from expanding CBs

During the CB expansion phase, the emission from a CB is dominated by TB and LE. In the rest frame of a CB, interactions of the ISM particles and photons with the CB's constituency produce a quasi-thermal electron population with a power-law tail ($\propto E^{-p}$) of Fermi-accelerated ($p\sim 2.2$) and "Bethe-Block" ($p\sim 2.0$) knocked-on CB electrons (Dar & De Rújula 2001). Thus, a CB emits a TB spectrum with a power-law tail, Doppler-boosted by the CB's motion. The spectral shape (Dar & De Rújula 2004) is:

$$\frac{dN_\gamma}{dE} \propto \left(\frac{T_{\rm eff}}{E}\right)^\alpha \, e^{-E/T_{\rm eff}} + b\,(1-e^{-E/T_{\rm eff}})\left(\frac{T_{\rm eff}}{E}\right)^\beta , \tag{1}$$

where $\alpha \approx 1$, $\beta = (p+2)/2 \approx 2.1$, b is a dimensionless parameter and $T_{\rm eff} = \delta\, T/(1+z)$, with T the CB's plasma temperature and $\delta \equiv 1/[\gamma\,(1-\beta\,\cos\theta)] \approx 2\,\gamma/(1+\gamma^2\,\theta^2)$ the Doppler factor of a CB with a bulk Lorentz factor $\gamma \gg 1$, observed from an angle $\theta \ll 1$ relative to its motion. The indexes α and β may deviate from the central predictions, as the radiation becomes dominated by LE. Also the power-law index of the radiating electrons (after cooling) may be larger than $p+1 \simeq 3.2$ (Dar & De Rújula 2004).

The observed energy flux from a CB at a luminosity distance D_L is:

$$\frac{dF}{dt} \approx \frac{3\,\Lambda(T)\,N_b^2\,\delta^4}{16\,\pi^2\,R^3\,D_L^2}\,, \tag{2}$$

where N_b is the CB's baryon number, R its radius and $\Lambda(T)$ its "cooling function". If the loss-rate of the CB's internal energy is mainly adiabatic, $T\propto 1/R^2$. At a CB's transparency time, τ, $T\sim 10^4$–10^5 K (DDD2002), and $\Lambda(T)$ oscillates and depends on composition in this T-range. A rough description of the results of Sutherland & Dopita (1993) is: $\Lambda(T)\sim T^a$, with $a\sim 2$ for zero metallicity, and $a\sim 0$ for high metallicity. During the short TB+LE phase, δ stays put and R increases approximately linearly with time. The observer time t is related to the CB's rest-frame time t' through $dt = (1+z)\, dt'/\delta$. Thus, $dF/dt \propto (t+\tau)^{-(3+2\,a)}$ and the expected powers are $\sim t^{-3}$ to $\sim t^{-7}$ (O'Brein et al. 2006 report $\sim t^{-1}$ cases, but they were not "caught" early enough). Here we adopt an intermediate metallicity, $a \sim 1$, for which $dF/dt \propto (t+\tau)^{-5}$. The CB-model predictions for the identity of the LE-phase lines and the time-evolution of their energy are quite remarkable (Dado, Dar & De Rújula 2003b) —and perhaps worth testing.

4. Synchrotron AG from decelerating CBs

A CB is assumed to contain a tangled magnetic field in equipartition with the ISM protons that enter it. As it ploughs through the ionized ISM, it gathers and scatters its constituent protons. The re-emitted protons exert an inward pressure on the CB, countering its expansion. In the approximation of isotropic and complete re-emission in the CB's rest frame and a constant ISM density n, one finds that within minutes of observer's time t, a CB reaches an asymptotic radius $R(\gamma_0)$, with γ_0 its initial γ. Subsequently, $\gamma(t)$ obeys:

$$[(\gamma_0/\gamma)^{3+\kappa} - 1] + (3-\kappa)\,\theta^2\,\gamma_0^2\,[(\gamma_0/\gamma)^{1+\kappa} - 1] = t/t_0; \quad t_0 \equiv \frac{(1+z)\,N_b}{(6+2\kappa)\,c\,n\,\pi\,R^2\,\gamma_0^3}\,,$$

$$t_0 \sim (1.8\times 10^3\,\mathrm{s})\,(1+z)\left[\frac{\gamma_0}{10^3}\right]^{-3}\left[\frac{n}{10^{-2}\,\mathrm{cm}^{-3}}\right]^{-1}\left[\frac{R}{10^{14}\,\mathrm{cm}}\right]^{-2}\left[\frac{N_b}{10^{50}}\right], \tag{3}$$

with $\kappa = 0$. If the re-emitted ISM particles are a small fraction of the intercepted ones $\kappa = 1$ in Eq. (3). In both cases γ and δ change little as long as $t < t_{\rm break} \approx [1+(3-\kappa)\,\theta^2\,\gamma_0^2)]\,t_0$.

In the CB model, the ISM electrons that a CB gathers are Fermi-accelerated in the CB's enclosed magnetic maze and cooled by synchrotron radiation to a broken power-law distribution with an *injection "bend"* at the energy $E_b = m_e\,c^2\,\gamma(t)$ at which they enter the CB. Their emitted synchrotron radiation has a broken power-law form with a bend frequency, $\nu_b \simeq (1.87\times 10^3\,\mathrm{Hz})\,[\gamma(t)]^3\,\delta(t)\,[n/(10^{-3}\ \mathrm{cm}^{-3})]^{1/2}/(1+z)$, corresponding to E_b. In the observer frame, before absorption corrections (DDD2002):

$$F_\nu \equiv \nu\,(dn_\gamma/d\,\nu) \propto n\,R^2\,[\gamma(t)]^{3\alpha-1}\,[\delta(t)]^{3+\alpha}\,\nu^{-\alpha}\,, \tag{4}$$

where $\alpha \approx 1.1$ for $\nu \gg \nu_b$, as in the X-ray domain. The initial slow decline of $\gamma(t)$ and $\delta(t)$ results in the shallow decay of the early X-ray synchrotron AG, which is smooth if the intercepted ISM density and the extinction along the line of sight are constant. The sum of TB and synchrotron emissions produces the canonical X-ray light curve with an early fast TB decay, overtaken at the "ankle" by an initially much flatter synchrotron emission, which becomes steeper around the "break", as demonstrated in Figs. 1a,b.

5. Comparison with recent representative observations

The 0.2–10 keV X-ray AG light curves of GRB 050315 (Vaughan et al. 2005) and GRB 050319 (Cusumano et al. 2005) —which exhibit the “canonical behaviour”— are compared in Figs. 1a,b, with the sum of the TB+LE and synchrotron radiations, Eqs. (2) and (4); with use of $\gamma(t)$ as in Eq. (3) with $\kappa = 1$. The two normalizations were best-fit, along with the CB model parameters, $\gamma_0 = 1162$, $\theta = 0.83$ mrad, $\tau = 110$ s and $t_0 = 0.14$ days for GRB 050315 at $z = 1.949$, and $\gamma_0 = 710$, $\theta = 0.39$ mrad, $\tau = 20$ s and $t_0 = 0.17$ days for GRB 050319 at $z = 3.24$, all within their usual range (DDD2002). The parameters n, N_b and R occur only in the combination t_0 of Eq. (3) and in the fit normalization of Eq. (4). The remaining parameter –the normalization of $\Lambda(T)$ in Eq. (2)– occurs only in the corresponding flux normalization. Similarly good fits are obtained with $\gamma(t)$ as in Eq. (3) with $\kappa = 0$. More accurate late-time data are required to tell apart the $\kappa = 0, 1$ deceleration laws.

6. Bumps and flares in the AG

A fraction of early X-ray AGs have flares on short time scales (see, e.g. Burrows et al. 2005a, 2005b). In the CB model, such early time X-ray flares may be part of a long GRB due to late time accretion episodes of the fall-back material on the compact central object, and/or if a significant precession of the jet axis occurs prior to these episodes, an X-ray flare may be a GRB pulse viewed more off-axis, with the corresponding time-dilation and energy-softening. Another possible source of flares is density jumps along the CB trajectory (e.g. DDD2002; Dado et al. 2004b). In the CB model, the AG is a direct and *quasi-local* tracer of the density of the ISM through which a CB travels; see Eq. (4). Such density jumps are produced in the circumburst environment by the SN and pre-SN ejecta, by the “winds” inside the superbubbles (SBs) where most core-collapse SNe take place and, in particular, at the complex SB boundaries created by stellar winds and previous SNe within the SB. This is demonstrated in Fig. 2a (Dado et al. 2004b) for a density profile shown in Fig. 2b. Fitting bumps to density profiles is not over-informative, unless they are seen at various frequencies, as the CB model predicts the energy-dependence of the bump widths (Dado et al. 2003a). The oscillations of $\Lambda(T)$ in the relevant T-range may also induce X-ray flares.

7. Discussion

The early-time X-ray afterglows of GRBs measured with SWIFT-XRT provide an excellent test for two contenders: the FB and CB models. We have shown that the CB model passes this test with flying colours: the observed "canonical" behaviour was correctly predicted (DDD2002) long before the launch of SWIFT. To the best of our knowledge, no satisfactory FB model explanation of this behaviour has been found, though certain correlations have been proposed. Let the early X-ray flux be described as $F_\nu(t) \propto \nu^{-\beta_x}\, t^{-\alpha_1}$. The FB-model prediction is $\alpha_1 - \beta_x = 2$, as recently discussed by Kumar et al. (2006). The CB-model prediction is $\beta_x \simeq 1.1$ at all times, so that $\alpha_1 - \beta_x \approx \alpha_1 - 1.1$. The models are compared with the data of O'Brein et al. (2006) in Fig. (3). While the prediction of the CB model agrees with the data, the prediction of the FB model is in clear contradiction with the observations.

A celebrated prediction of "conical fireball" models is a break in the AGs when the beaming angle of radiation from a decelerating cone increases beyond the opening angle of the jet, $\gamma(t)^{-1} \sim \theta_j$, and the observer begins to see the full cone (e.g. Rhoads 1999; Sari et al. 1999). If the observer happens to be nearly on the cone's axis, the break time (Sari et al. 1999) is:

$$t_{\rm break} \sim 2.23\,(1+z)\left[\frac{\theta_j}{0.1}\right]^{8/3}\left[\frac{n}{0.1\,{\rm cm}^{-3}}\right]^{-1/3}\left[\frac{\eta_\gamma}{0.2}\right]^{-1/3}\left[\frac{E_\gamma^{\rm iso}}{10^{53}\,{\rm ergs}}\right]^{1/3}\ {\rm day}\,, \tag{5}$$

with η_γ the conversion efficiency of the ejecta's energy into γ rays. Frail et al. (2001) suggested that the γ-ray energy of conical GRBs is a θ_j-independent standard candle. Consequently $E_\gamma^{\rm iso} \approx E_\gamma\, \theta_j^2/4$: the Frail Relation[1]. From 16 GRBs of known z, Bloom et al. (2003) found $E_\gamma \approx 1.3 \times 10^{51}$ ergs. Insert this and $\theta_j^2 = 4\, E_\gamma / E_\gamma^{\rm iso}$ into Eq. (5), to obtain:

$$t_{\rm break} \sim 4.33\,(1+z)\left[\frac{n}{0.1\,{\rm cm}^{-3}}\right]^{-1/3}\left[\frac{\eta_\gamma}{0.2}\right]^{-1/3}\left[\frac{E_\gamma^{\rm iso}}{10^{53}\,{\rm ergs}}\right]^{-1}\ {\rm day}\,. \tag{6}$$

All published attempts to use Eq. (6) to predict $t_{\rm break}$ —before it was measured— from the observed $E_\gamma^{\rm iso}$, failed[2]. In fact, in many GRBs the AG is not achromatic as expected in the jetted FB model, and the break in the X-ray AG is not matched by a similar break in the optical AG (e.g. Panaitescu et al. 2006). This further questions the FB-model interpretation of the AG break (Rhoads 1997, 1999; Sari, Piran and Halpern 1999) and the proclaimed success of the "Frail Relation". These suggest that the success of the Frail relation is an artefact resulting from an a-posteriori adjustment of free parameters. Moreover, $E_\gamma^{\rm iso}$ for all XRFs with known z is much smaller than the "standard-candle" value of Frail et al. 2001,

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[1]The fraction of the sky illuminated by a conical GRB is $f_b = (1-\cos\theta_j)/2 \approx \theta_j^2/4$ and not $(1-\cos\theta_j) \approx \theta_j^2/2$, used by Frail et al. (2001) and many other authors. Bipolar GRBs do light a fraction $\theta_j^2/2$.

[2]For instance, Rhoads et al. 2003 predicted $t_{\rm break} > 10.8$ days for GRB 030226, while Greiner et al. 2003, shortly after, observed $t_{\rm break} \sim 0.8$ day.

implying that XRFs and GRBs cannot be the same phenomenon viewed from different angles, contrary to indications (e.g. Dado et al. 2004a). Many other more successful relations, such as the one between the equivalent isotropic energy and the "peak" γ-ray energy of GRB pulses (the "Amati Relation") are predictions of the CB model (Dar & De Rújula 2004; Dado & Dar 2005) but not of the FB model.

In the CB model, AG flares follow either from CB encounters with density inhomogeneities (DDD2002; Dado et al. 2004b) or from late accretion episodes on the compact central object. In the FB model, late-time flares result from late central activity (e.g. Granot, Nakar and Piran 2003). Although such an activity can neither be predicted nor ruled out, it is not clear why the ensuing ejecta do not also produce γ-ray pulses and why the duration and magnitude of the AG flares scale roughly with the time and magnitude of the declining AG.

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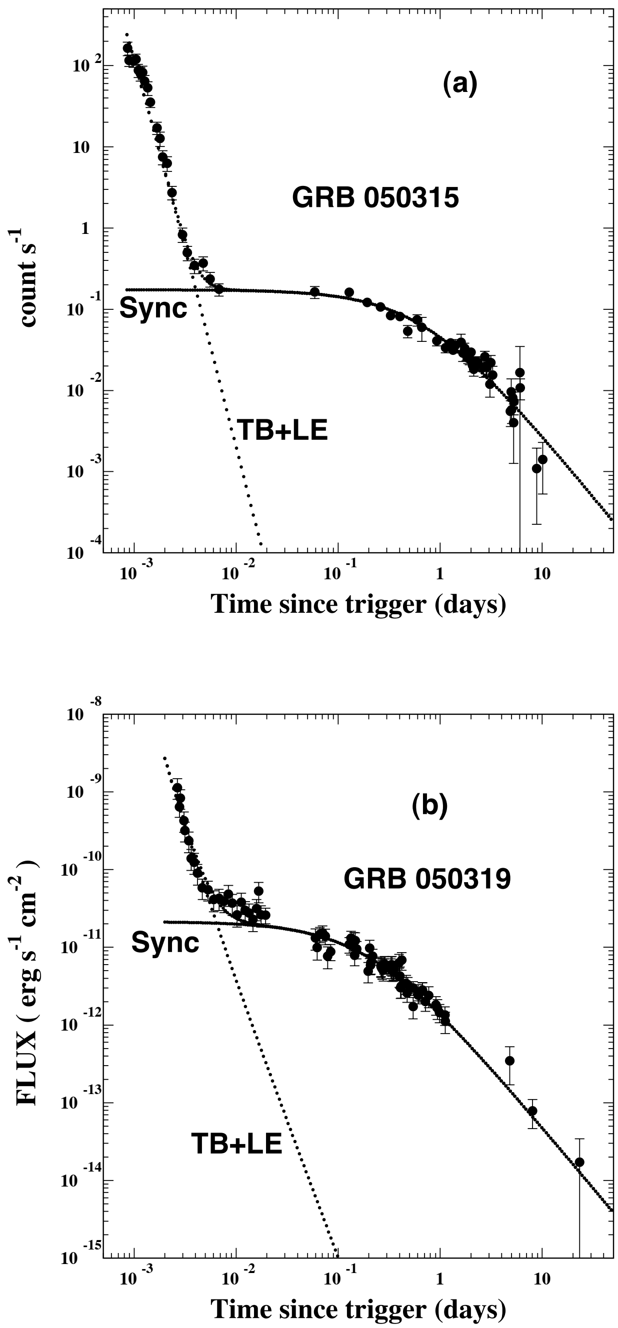

Fig. 1.— (a) Comparison between the X-ray afterglow (0.2–10 keV) of GRB 050315 measured with XRT on board SWIFT (Vaughan et al. 2005) and the CB model fit. (b) The same comparison for GRB 050319 (Cusumano et al. 2005).

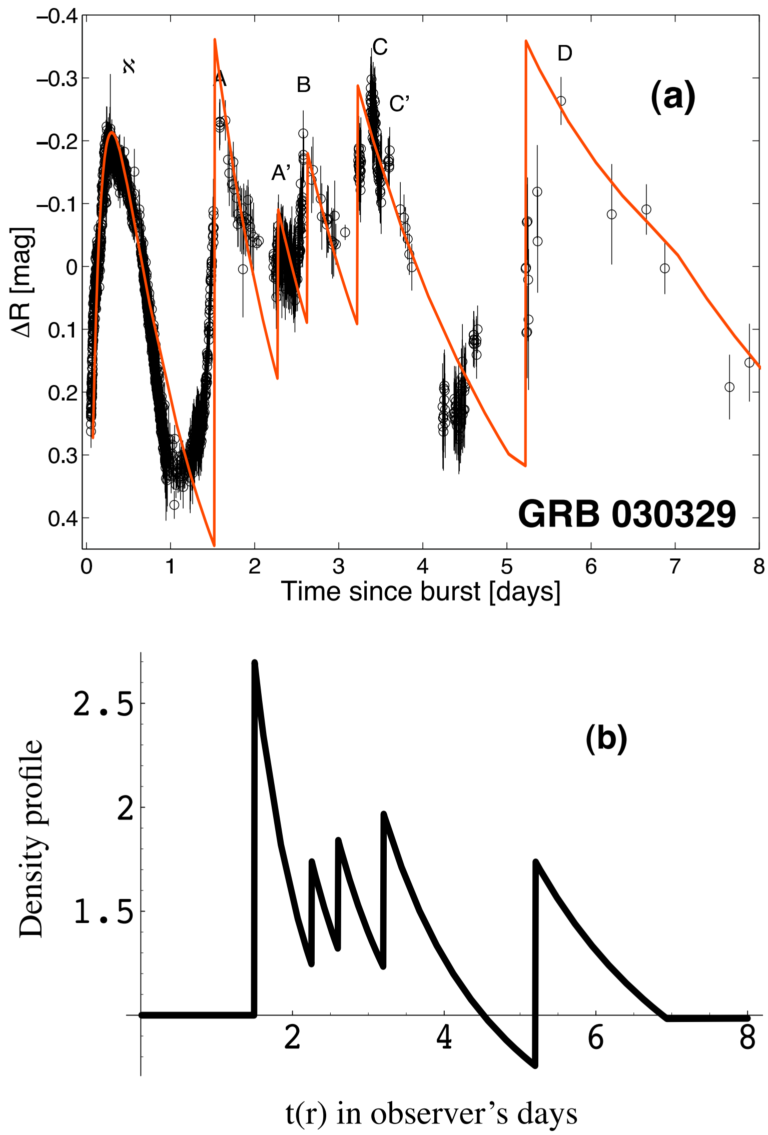

Fig. 2.— (a) Comparison between the R-band AG of GRB 030329, shown as "residua" ΔR of the data relative to a broken power law of index $-\alpha$ jumping from ~ 1.1 to ~ 2 at $t \sim 5$ days (Lipkin et al. 2004), and the residua, relative to the same broken power law, calculated from the CB model (red line) for the input density profile shown in Fig. 2b. The $\aleph$ feature is a prediction (Dado et al. 2004b). (b) The density profile (relative to a smooth ISM density —a constant plus a "wind" contribution decreasing as $1/r^2$). The density is $n = \Sigma_j n_j\,(r_j/r)^2\,\Theta(r - r_j)$, with Θ Heaviside's function.

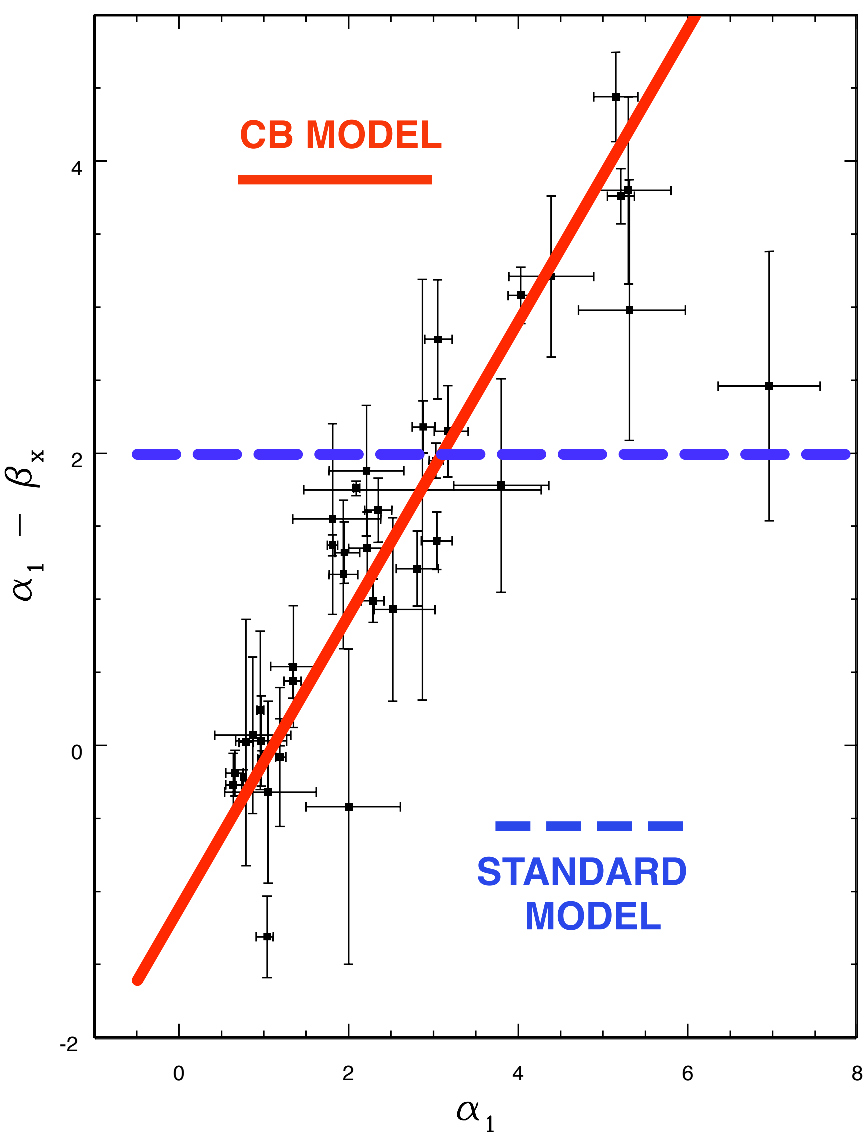

Fig. 3.— The CB- and standard (FB-) model predictions for the relation between the indices of a simple description of the early X-ray AG flux: $F_\nu(t) \propto \nu^{-\beta_x}\, t^{-\alpha_1}$. Data analysis from O'Brein et al. (2006).