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The Case for Anisotropic Afterglow Efficiency within Gamma-Ray Burst Jets

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ABSTRACT

Early X-ray afterglows recently detected by *Swift* frequently show a phase of very shallow flux decay lasting from a few hundred seconds up to $\sim 10^4$ s, followed by a steeper, more familiar decay. We suggest that the flat early part of the light curve may be a combination of the decaying tail of the prompt emission and the delayed onset of the afterglow emission observed from viewing angles slightly outside the edge of the jet, as predicted previously. This would imply that a significant fraction of viewers have a very small external shock energy along their line of sight and a very high γ-ray to kinetic energy ratio. The early flat phase in the afterglow light curve implies, according to this or other interpretations, a very large γ-ray efficiency, typically $\gtrsim 90\%$, which is very difficult to produce by internal shocks.

Subject headings: γ-rays: bursts — γ-rays: theory— blast waves

1. Introduction

Although early models of fireballs (Goodman 1986) did not postulate baryons within, the existence of baryons in γ-ray burst (GRB) fireballs was anticipated because the highly super-Eddington luminosities suggest that baryons are expelled. In fact, the baryonic component that is expected to accompany such an outflow would quench the γ-ray emission. This realization led to the popularization of a model for GRBs in which baryonic kinetic energy was reclaimed at large radii by internal shocks to be used for making high energy particles (Levinson & Eichler 1993) and γ-rays (Mészáros & Rees 1994). This model postulated fewer baryons than expected from a-priori estimates of the super-Eddington flux-driven mass

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outflow, but it did invoke baryons, or in any case matter that survived annihilation in the compact regions closer to the central engine.

The above models should be contrasted with internal shock models in which there are few baryons (Eichler 1994) where the role of the internal shocks, presumably near the photosphere, is simply to non-thermalize the spectrum of γ-rays that dominate the energy content. In particular, the reclamation of baryonic kinetic energy by internal shocks for the purposes of making the prompt γ-radiation of the GRB itself (Mészáros & Rees 1994) led to the prediction that there should be a blast wave in the circumburst medium that would generate afterglow. The discovery of afterglow was therefore an enormous boost to the internal shocks model of Mészáros & Rees (1994), who had predicted such an afterglow.

On the other hand, it has never been proven that the γ-rays and the ejecta are made by the same components of the outflow. More generally, the ratio of γ-ray to baryonic energy densities may vary considerably within the outflow in a way that would have significant consequences both for observations and for theories of GRB origin. One consequence of GRB baryon anisotropy would be lines of sight that are more favored than others for GRB detection while others might be more favorable for seeing early afterglow. In this *Letter*, we argue in favor of this hypothesis. In §2 we present arguments in favor of baryon anisotropy. In §3 we show that the combination of the decaying tail of the prompt emission and the flat early afterglow light curve from viewing angles slightly outside the edge of the jet can produce the early flat decay phase of the X-ray afterglows recently observed by *Swift*. Our conclusions are discussed in §4.

2. Arguments in Favor of Baryon Anisotropy within the Jet

Several arguments have been put forth that the baryon richness of a GRB fireball relative to the γ-ray intensity varies with the viewing angle for a given fireball. Levinson & Eichler (1993) argued theoretically that the anatomy of a GRB is likely to be Poynting flux or γ-rays emerging from horizon-threading magnetic field lines, while the baryons might flow out predominantly near the periphery of the above, along field lines that thread the interface of the inner accretion disk and the event horizon. On field lines that thread the accretion disk, which should also have a super-Eddington power output, there ought to be a "slow sheath" of baryons that, while being too baryon rich to yield a detectable GRB, would yield a contribution to the afterglow and possibly a "dirty fireball". Several observations have also been interpreted in the context of a dichotomy between the baryon poor flow lines and the baryon rich ones. Scattering of γ-rays from baryon poor regions off more slowly moving baryons could yield a weak spray of γ-rays at large angles. Such scattered emission would be a very small fraction ($\sim 10^{-5}$) of the total, and would thus be detectable only for very nearby GRBs. Nevertheless, they would be detectable over a much larger solid angle, and would be manifested as soft GRBs (no photons well above an MeV), with smooth light curves from nearby sources. GRB 980425 was a good example of such a GRB and was interpreted in this light (Nakamura 1998; Eichler & Levinson 1999).

Another intriguing result of baryon anisotropy of the GRB fireball could be that the γ-ray emission itself - not just the baryonic content - could have a non-trivial angular profile. Here the details have not been worked out yet. It could be, e.g., that most of the emission in the interior of the outflow is virgin Poynting flux, and that the γ-rays themselves are generated preferentially at the periphery of the fireball where the Poynting flux is somehow tapped by interaction with the slower baryonic sheath. It is also not yet established under what conditions virgin Poynting flux creates afterglow. If a necessary condition for afterglow is that external protons can execute at least one gyroradius in the comoving frame within a proper hydrodynamic timescale, $\sim R/\Gamma c$, then the condition can be expressed (Eichler 2003) as

$$\Gamma \leq \Sigma^{1/3} , \tag{1}$$

where Σ is the electric potential energy drop, eBR, across the ejecta in units of $m_p c^2$, and B is the magnetic field in the lab frame. Typically, this would imply that $\Gamma \lesssim 10^4$ for GRBs. However, there are still several additional conditions that could enter into the picture.

If the γ-rays have an angular structure that is more complicated than a solid cone, then the fraction of the total solid angle from which the γ-rays are detectable that corresponds to off-beam viewing angles increases, thus making such lines of sight more probable. In this regard, the Amati relation (Amati et al. 2002) and Ghirlanda relation (Ghirlanda et al. 2004), which correlate spectral peak photon energy, $E_{\rm peak}$, and the apparent isotropic equivalent energy, $E_{\gamma,{\rm iso}}$, can both be explained as viewing angle effects (Eichler & Levinson 2004; Levinson & Eichler 2005). GRBs with $E_{\rm peak} \ll 1$ MeV are interpreted as viewed off-beam at angles $\theta > \Gamma^{-1}$ from the edge of the jet.[1] This lowers both the observed $E_{\gamma,{\rm iso}}$ and $E_{\rm peak}$ in a way that conforms to the Amati relation (Eichler & Levinson 2004). Furthermore, the value of the jet opening angle that is inferred from the observed break time in the afterglow and the observed $E_{\gamma,{\rm iso}}$ is then slightly overestimated relative to its true value, because the observed $E_{\gamma,{\rm iso}}$ is underestimated relative to its true value. When this slight overestimate is accounted for, the Ghirlanda relation becomes equivalent to the Amati relation (Levinson & Eichler 2005).[2]

[1]In this case the observed photons are directed backwards in the comoving frame of the emitting plasma.

[2]Note that the Amati relation applies only if *most* (or in any case, a fixed fraction) of the total GRB

Another recent piece of evidence for baryon anisotropy comes from the 27 December 2004 giant flare from SGR 1806−20. The radio afterglow (Gaensler et al. 2005) that followed this event has been interpreted as being powered by a baryonic mass outflow of $\sim 10^{25}$ g (Gelfand et al. 2005) that is probably driven from the neutron star surface. This tentative conclusion is based on the fact that if the required mass was, instead, dominated by swept up external medium, this would require a highly contrived and unrealistic external density profile in order to explain the observed evolution of the source size, motion, and flux (Granot et al. 2005). Furthermore, this outflow should have been only mildly relativistic, with $\Gamma\beta \sim 1$, close to the escape velocity from the surface of the neutron star (Granot et al. 2005). On the other hand, such a large and mildly relativistic baryonic outflow would have (at least partly) obscured the prompt γ-rays from the flare had they been expelled in our direction. The data can be reconciled, however, by the assumption that the baryons are ejected in some directions and not others.

The idea that many GRBs are viewed slightly off the main intensity peak by a finite offset angle, θ, was used (Eichler 2005) to interpret delayed onset of X-ray afterglow that was reported by Piro et al. (2005). The delay is simply the time needed for the flow to decelerate to a Lorentz factor $\Gamma < 1/\theta$, beyond which time the afterglow beam encompasses our line of sight. This predicts, under the assumption that the afterglow-generating blast wave and the γ-ray beam coincide, that the lower the spectral peak, the longer it will take for the afterglow to assume its full on-beam value (Granot et al. 2002; Granot 2005).

Eichler & Jontof-Hutter (2005) reconsidered the issue of blast efficiency, making the assumption that $E_{\rm peak}$ is determined mostly by the viewing angle effect. It was found that when the ratio of blast energy to apparent γ-ray energy is tabulated for GRBs with known redshifts, the ratio is of order unity but with a great deal of scatter. This scatter, however, is considerably reduced when the ratio of "viewing angle corrected" γ-ray energy,[3] $\propto E_\gamma/E_{\rm peak}^{3/2}$, is compared with blast wave energy, and the characteristic value of the γ-ray to kinetic energy ratio seems to be ~ 7. That is, nearly 90% of the energy goes into radiation (γ-rays) and only about $10\% - 15\%$ goes into the blast wave. This raises serious problems for the internal shocks model, in which the γ-ray energy is powered by whatever fraction of the baryonic

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energy is emitted more or less isotropically in a high Lorentz factor frame. In cases such as GRB 980425, where only a small fraction, $f \sim \Omega_o/\Omega_f$, (where Ω_o and Ω_f are the original and final opening angles of the scattered radiation) is presumed to be scattered by slowly moving (say non-relativistic) material to large angles, then the observed $E_{\gamma,\rm iso}$ is lowered by an additional factor f with no further change in $E_{\rm peak}$, and such sources should be highly distinct outliers to the Amati relation, as they are observed to be.

[3]The form of this correction assumes that the Ghirlanda relation is due to viewing angle effects so that the factor $E_{\rm peak}^{3/2}$ is taken to be a measure of the Doppler factor that corresponds to the viewing offset angle.

kinetic energy can be radiated away by the internal shocks. In particular, it would require the internal shocks to consistently radiate away nearly 90% of the total energy within the observed photon energy range and consistently leave the same small fraction. It is hard to see how internal shocks, which are by nature erratic, could perform so efficiently and so consistently. Moreover, even if internal shocks could consistently convert more than 90% of the kinetic energy into internal energy, they would still need to put more than 90% of the internal energy into electrons (and therefore $< 10\%$ into ions) which could radiate this energy within the dynamical (i.e. expansion) time. Although there in no definitive model for supercritical ultrarelativistic shocks, this requirement would run contrary to theoretical expectations.

Very recently, Nousek et al. (2005) arrived at a similar conclusion using early X-ray afterglow data taken by *Swift*. The early X-ray afterglows frequently show an intermediate phase ($t_1 < t < t_2$) of very flat flux decay at early times (between a few 10^2 s and $\sim 10^4$ s) that is deficient relative to expectations from a uniform adiabatic blast wave. Among this subset of GRBs, it typically takes the X-ray afterglow a few hours to attain the values inferred from *BeppoSax* data. They note that for $t \ll t_2$, the $\gamma-$ray efficiency, ϵ_γ, is typically much higher than previously inferred (Panaitescu & Kumar 2001; Lloyd-Ronning & Zhang 2004), yet at $t \gtrsim t_2$, the distribution in these efficiencies converges to the narrow range of values inferred previously.[4]

Yet another possible effect produced by offset viewing is the spectral evolution of spikes in the prompt GRB emission, which scale as $E_{\rm peak} \propto t^{-2/3}$ (Ryde 2004). This can be interpreted as the spike being due to an accelerating blob of matter that scatters primary radiation into our line of sight. Assuming that the blob is being accelerated to high Γ by an extremely super-Eddington radiation flux in the direction of the local radiation flux, the Lorentz factor of the blob scales as $\Gamma \propto R^{1/3}$ (Eichler 2004). A spectral peak photon energy which is E_* in the source frame, is E_*/Γ in the blob frame, and $E_{\rm peak} = E_*/\Gamma^2(1-\beta\cos\theta)$ in the observer's frame. Once the blob has accelerated to $\Gamma \gg 1/\theta$, then the observed time scales linearly with radius, $t \propto R$, and $(1-\beta\cos\theta)$ is asymptotically constant ($\approx \theta^2/2$) so that $E_{\rm peak} \propto \Gamma^{-2} \propto R^{-2/3} \propto t^{-2/3}$. The general picture of matter being accelerated by radiation is consistent with the inference argued above that the matter draws its kinetic energy from the radiation rather than the other way around.

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[4]Actually, the better terminology is the blast efficiency, $\epsilon_b = 1 - \epsilon_\gamma$. In this class of bursts $\epsilon_\gamma \sim 90\%$ and the blast efficiencies $\epsilon_b \sim 10\%$ have greater relative scatter due to their smaller values.

3. Delayed Afterglow Onset and Flat Early Light Curves

The explanation favored by Nousek et al. (2005) for the early flat part of the X-ray afterglow light curves that were observed by *Swift* is energy injection into the afterglow shock (see also Zhang et al. 2005; Panaitescu et al. 2005). Here we suggest an alternative explanation for this early flat phase, namely the flat early afterglow light curve for viewing angles slightly outside the (rather sharp) edge of the jet (i.e. outside the regions where the energy per solid angle in the external shock is large enough to produce bright afterglow emission).

For such "off-beam" lines of sight, the afterglow flux initially rises, at early times, as the beaming of the radiation away from the line of sight gradually decreases with time, then rounds off as the afterglow beaming cone expands enough to include the line of sight, and finally gradually joins the decaying "on-beam" light curve (seen by observers within the jet). For a point source, the fluxes seen by off-beam and on-beam observers are related by

$$F_\nu(\theta, t) \approx a^3 F_{\nu/a}(0, at) = a^{3+\beta_X-\alpha_X} F_\nu(0, t) \tag{2}$$

(Granot et al. 2002), where θ is the angle between the source's velocity and the direction to the observer in the lab frame, t is the observed time, $a = (1-\beta)/(1-\beta\cos\theta) \approx (1+\Gamma^2\theta^2)^{-1}$ is the ratio of the off-beam (at θ) and on-beam ($\theta = 0$) Doppler factors, and the last equality is valid when $F_\nu(0,t) \propto t^{-\alpha_X}\nu^{-\beta_X}$. Thus, the off-beam flux is suppressed relative to the on-beam flux by a factor $\eta = a^{3+\beta_X-\alpha_X}$. For early times, when $\Gamma\theta \gg 1$, we have $a \approx (\Gamma\theta)^{-2}$ and $\Gamma \propto t^{-(3-k)/2}$ where $\rho_{\rm ext} \propto R^{-k}$, so that $a \propto t^{3-k}$, $\eta \propto t^{(3-k)(3+\beta_X-\alpha_X)}$ and $F_\nu(\theta,t) \propto \eta(t)t^{-\alpha_X} \propto t^{(3-k)(3+\beta_X)-(4-k)\beta_X}$. The point source limit is valid when the angle θ from the closest point along the edge of the jet is larger that the typical angular extent of the jet, $\theta_{\rm jet}$. However, more often the opposite is true, i.e. $\theta < \theta_{\rm jet}$ (or $\Gamma_0^{-1} \ll \theta \ll \theta_{\rm jet}$ where Γ_0 is the initial Lorentz factor of the jet), in which case the dependence of η on a decreases by one power (Eichler & Levinson 2004; Levinson & Eichler 2005) to $\eta = a^{2+\beta_X-\alpha_X}$. This implies $\eta \propto t^{(3-k)(2+\beta_X-\alpha_X)}$ and $F_\nu(\theta,t) \propto \eta(t)t^{-\alpha_X} \propto t^{(3-k)(2+\beta_X)-(4-k)\beta_X}$ at very early times.

Fig. 1 shows afterglow light curves from a jet with a cross section in the shape of a thick ring, for different viewing angles, calculated using the model developed in Granot (2005). The light curves were calculated by integrating over the surface of equal arrival time of photons to the observer, while the jet dynamics are simplified. The simplified jet dynamics, which features an abrupt hydrodynamic transition at the deceleration radius, $R_{\rm dec}$, ($\Gamma = \Gamma_0$ at $R < R_{\rm dec}$ and $\Gamma \propto R^{-(3-k)/2}$ at $R > R_{\rm dec}$) causes an unrealistically sharp break in the predicted afterglow light curve at the deceleration time ($t_{\rm dec} \approx 10^{-2.5}$ days for on-beam observers). As derived analytically in the previous paragraph, Fig. 1 also shows a rather sharp rise in the flux at very early times, for off-beam viewing angles.

Fig. 2 is the same as Fig. 1 but with the addition of a typical contribution from the tail emission of the prompt GRB, $\propto t^{-3}$ (Kumar & Panaitescu 2000). This figure demonstrates that the combination of the decaying tail emission of the prompt GRB and the gently rising or rounding off afterglow emission from slightly off-beam viewing angles can produce a flat early phase in the afterglow light curves, similar to those seen by *Swift* in the X-rays (Nousek et al. 2005). In some cases we expect to even see a gentle rise at very early times.

Fig. 3 demonstrates the dependence of the early rise in the afterglow light curves, for off-beam viewing angles, on the jet structure and dynamics. The three bottom panels are taken from Granot, Ramirez-Ruiz & Perna (2005) and are calculated using model 1 of Granot & Kumar (2003), where lateral expansion is neglected, the jet dynamics is calculated according to a simplified semi-analytic formulation of the energy conservation equation, and the light curve is calculated by integrating over the equal arrival time surface of photons to the observer, assuming a simple piece-wise power law synchrotron (and synchrotron self-Compton) spectrum in comoving frame. The second panel shows afterglow light curves from a uniform jet with sharp edges for different viewing angles $\theta_{\rm obs}$ from the jet symmetry axis. The light curves are similar to those for a wide ring jet (Fig. 1) for similar off-beam viewing angles. The two bottom panels in Fig. 3 are for a Gaussian jet, and show that the smoother the edges of the jet (both in terms of energy per solid angle and in terms of the initial Lorentz factor Γ_0), the shallower the initial rise in the flux for off-beam viewing angles.

The upper panel in Fig. 3 shows the afterglow light curves for an initially sharp edged jet whose dynamics were calculated using a hydrodynamic simulation (Granot et al. 2001). The initial conditions were a cone of half-opening angle θ_0 taken out of the spherical self-similar solution of Blandford & McKee (1976). The light curves for off-beam viewing angles, and especially for $1 \lesssim \theta_{\rm obs}/\theta_0 \lesssim 2$, are much flatter at early times compared to those calculated using semi-analytic models for the jet dynamics, since the shocked external medium at the sides of the jet has a significantly smaller Lorentz factor than that near the head of the jet, and therefore its emission is not so strongly beamed away from off-beam lines of sight. Thus we conclude that very flat (either a very shallow rise or a very shallow decay) early afterglow light curves are expected for a realistic jet structure and dynamics. Combined with the rapidly decaying tail of the prompt GRB emission, this can nicely reproduce the observed early flat parts of the X-ray afterglow light curve observed by *Swift*.

4. Discussion

We have shown that the early flat phase in the X-ray afterglow light curves observed by *Swift* is broadly consistent with earlier predictions that afterglow onset might appear delayed to an "offset viewer" - an observer who is outside of the directed beam of baryons. Granot et al. (2002) predicted that this would be the case for orphan afterglows, and Granot, Ramirez-Ruiz & Perna (2005) argued that this is expected for X-ray flashes (and nicely agrees with their pre-*Swift* optical and X-ray early afterglows), assuming that the softening or non-appearance of prompt γ-rays in these instances is due to offset viewing. Eichler & Levinson (2004) and Eichler & Jontof-Hutter (2005) predicted that this could also be the case for "normal" γ-ray bursts with a bright prompt emission if a) the Amati relation for normal GRBs is due to offset viewing and/or, as was conjectured might be the case, b) the outliers to the Amati relation are cases of baryon poor lines of sight. Delays of several minutes in some afterglows whose onsets were serendipitously caught by the wide field camera of *BeppoSAX* (Piro et al. 2005) led Eichler (2005) to conjecture that, over a scale of several hours, an even larger fraction of afterglow onsets would appear delayed. We have argued here that the stage of flat decay, often seen within the first few hours of afterglow, can be attributed to the delayed onset discussed in these earlier papers.

It would be interesting to see whether there is any correlation between the duration or flatness of the flat decay stage (i.e. its temporal index α_2 where $F_\nu \propto t^{-\alpha_2}$), which we posit are measures of the afterglow delay, and the spectral peak photon energy, $E_{\rm peak}$, or isotropic equivalent energy in γ-rays, $E_{\gamma,{\rm iso}}$, as this would check the hypothesis that the latter is indeed due to viewing angle effects. Tables 1 and 2 of Nousek et al. (2005) show no obvious apparent correlation between α_2 and $E_{\gamma,{\rm iso}}$. On the other hand, some of the GRBs recorded by *Swift*, such as GRB 050315, have a rather large $E_{\gamma,{\rm iso}}$ *as well as* long stages of very flat decay, and could be interpreted in our view as being due to lines of sight along which the afterglow emission was intrinsically weak. Such a weak afterglow emission can easily be attributed to a paucity of baryons relative to γ-rays in the outflow along our line of sight.

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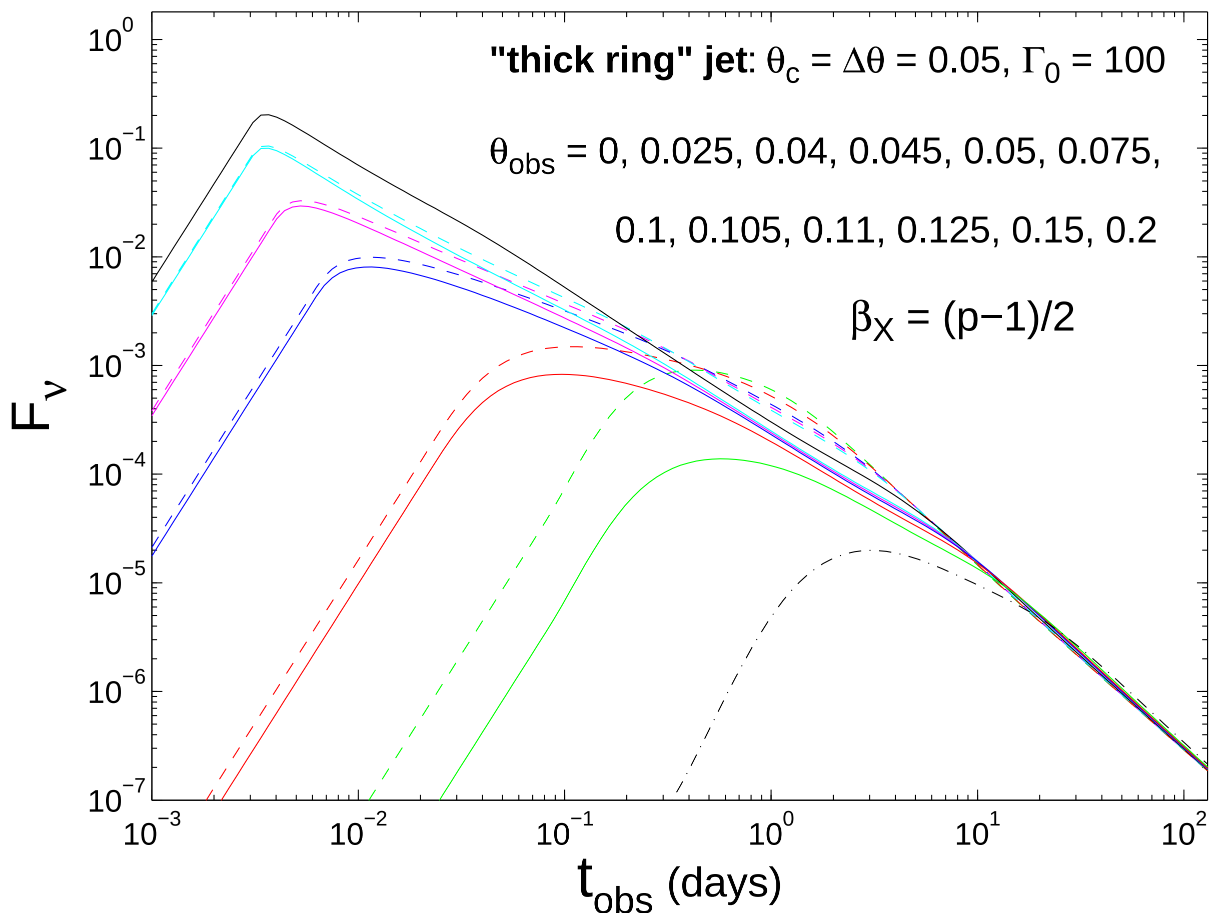

Fig. 1.— Afterglow light curves from a jet in the shape of a thick ring (uniform within $\theta_c < \theta < \theta_c + \Delta\theta$), for different viewing angles $\theta_{\rm obs}$ relative to the jet symmetry axis. The light curve is calculated using the model described in Granot (2005), for $E = 10^{51}$ erg, $n = 1\ {\rm cm}^{-3}$ and $\beta_X = (p-1)/2$.

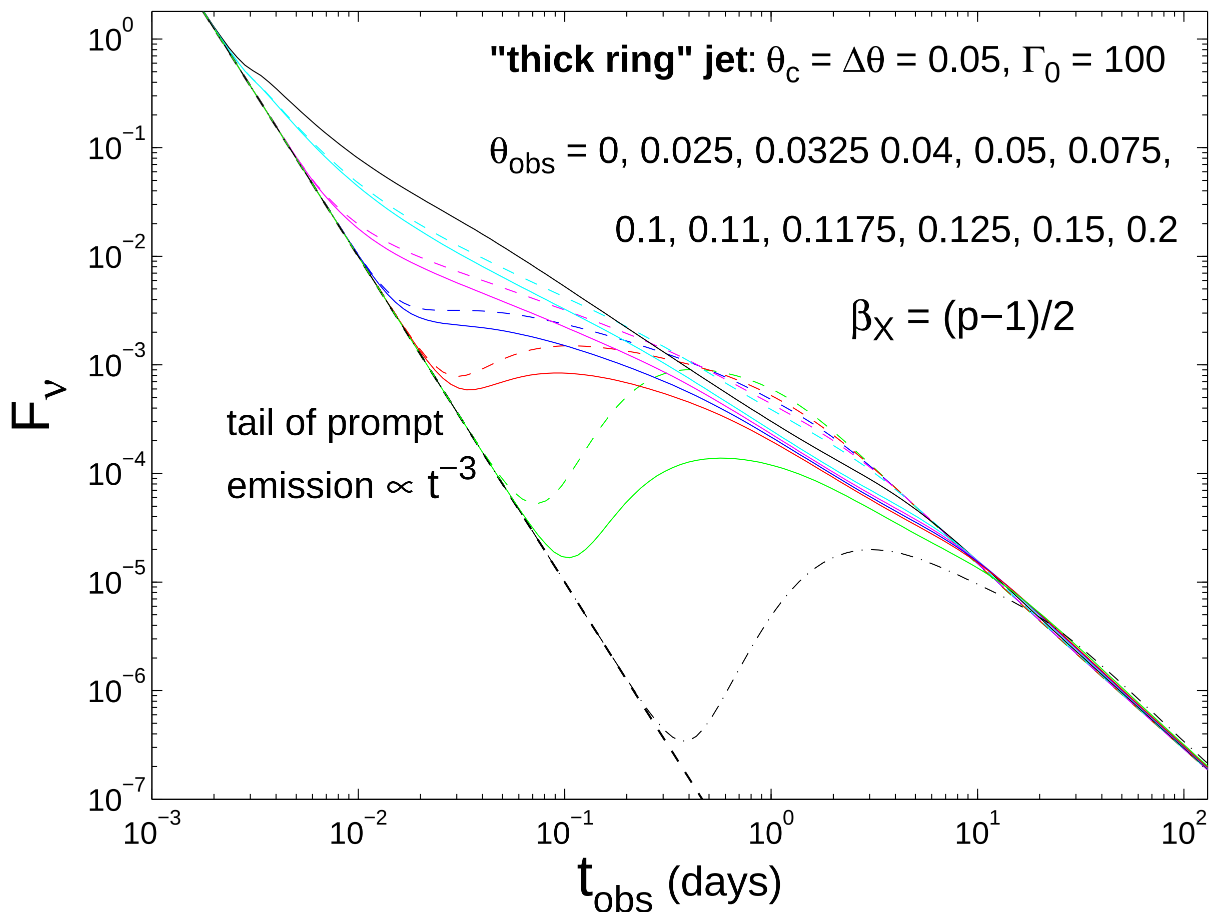

Fig. 2.— Similar to Figure 1, but with the added contribution from the tail of the prompt emission (Kumar & Panaitescu 2000) in the form of a rapidly decaying flux $\propto t^{-3}$.

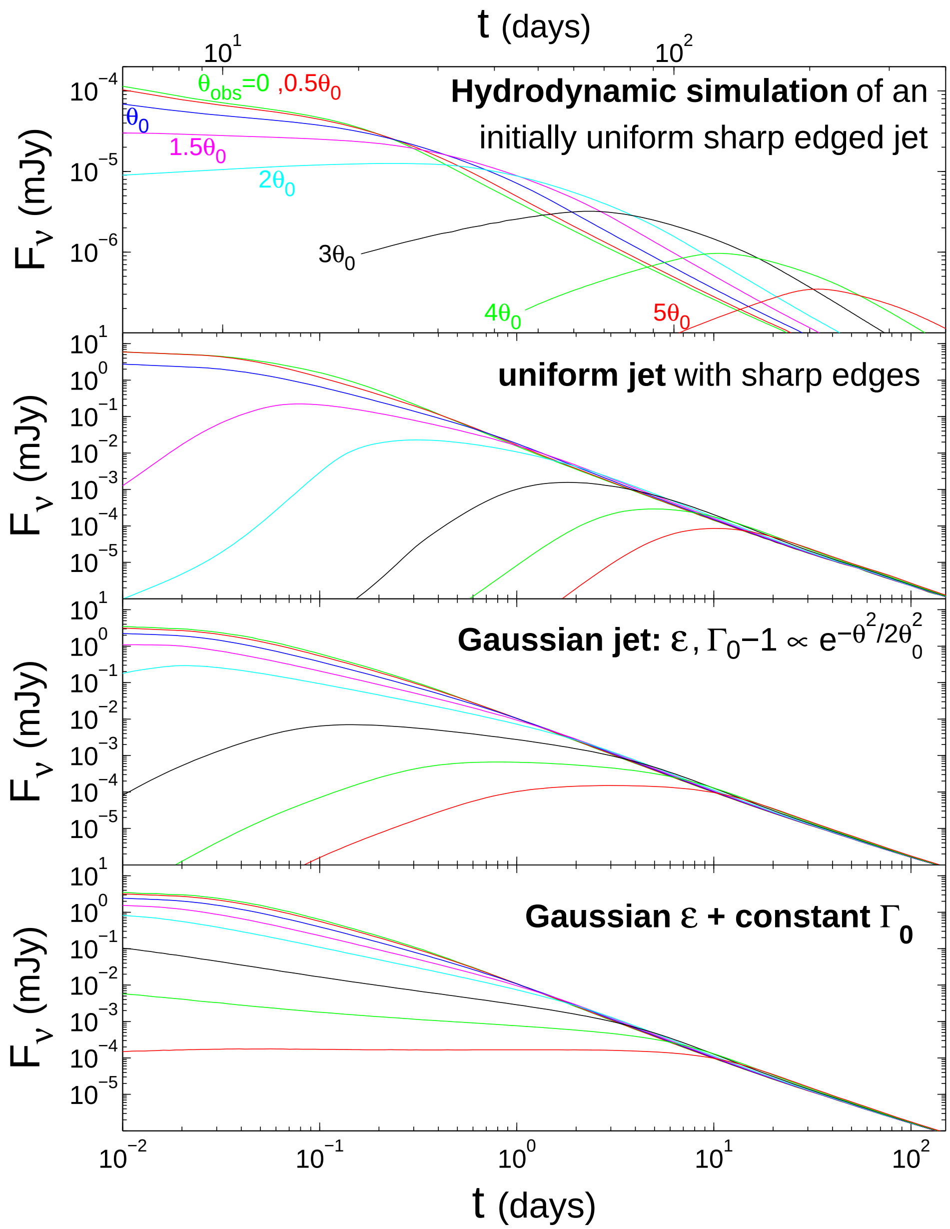

Fig. 3.— Light curves for different jet structures, dynamics and viewing angles. The upper panel is from an initially uniform jet with sharp edges whose evolution is calculated using a hydrodynamic simulation (taken from Fig. 2 of Granot et al. 2002). The remaining three panels are taken from Fig. 5 of Granot, Ramirez-Ruiz & Perna (2005), where a simplified jet dynamics with no lateral expansion is used. The middle two panels are for a Gaussian jet, in energy per solid angle, and either a Gaussian or a uniform initial Lorentz factor, while the bottom panel is for a uniform jet. The viewing angles are $\theta_{\rm obs}/\theta_0 = 0$, 0.5, 1, 1.5, 2, 3, 4, 5 where θ_0 is the (initial) half-opening angle for the uniform jet (two upper panels) and the core angle for the Gaussian jet (lower two panels).