Mon. Not. R. Astron. Soc. **337,** 1349–1356 (2002)

Events in the life of a cocoon surrounding a light, collapsar jet

Enrico Ramirez-Ruiz,[1★] Annalisa Celotti[1,2] and Martin J. Rees[1]
[1]*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2]*SISSA, Via Beirut 2-4, I-34014 Trieste, Italy*

Accepted 2002 August 16. Received 2002 August 16; in original form 2002 April 26

ABSTRACT

According to the collapsar model, γ-ray bursts are thought to be produced in shocks that occur after the relativistic jet has broken free from the stellar envelope. If the mass density of the collimated outflow is less than that of the stellar envelope, the jet will then be surrounded by a cocoon of relativistic plasma. This material would itself be able to escape along the direction of least resistance, which is likely to be the rotation axis of the stellar progenitor, and to accelerate in approximately the same way as an impulsive fireball. We discuss how the properties of the stellar envelope have a decisive effect on the appearance of a cocoon propagating through it. The relativistic material that accumulated in the cocoon would have enough kinetic energy to substantially alter the structure of the relativistic outflow, if not in fact provide much of the observed explosive power. Shock waves within this plasma can produce γ-ray and X-ray transients, in addition to the standard afterglow emission that would arise from the deceleration shock of the cocoon fireball.

Key words: hydrodynamics – supernovae: general – gamma-rays: bursts – X-rays: bursts.

1 INTRODUCTION

Collimated flows of plasma with velocities close to the speed of light, commonly referred to as relativistic jets, have been discovered in a number of astronomical systems. Objects known or suspected to produce them include: extragalactic radio sources (Begelman, Blandford & Rees 1984); microquasars (Mirabel & Rodriguez 1999); supernovae (Khokhlov et al. 1999); and γ-ray bursts (GRBs). While extragalactic radio sources produce by far the largest and most energetic jets in the Universe, GRBs provide perhaps the most extreme example of relativistic flow that may be collimated, exhibiting speeds of $\Gamma \approx 100$ or more; see, for example, Waxman, Frail & Kulkarni (1998), Wang, Dai & Lu (2000), Panaitescu & Kumar (2002) and Soderberg & Ramirez-Ruiz (2002).

Given the twin requirements of enormous energy $\approx 10^{53}$ erg and association with star-forming regions [see Mészáros (2001) for a recent review], the currently favoured models all involve massive, collapsing stars and their byproducts, especially black holes. A 'collapsar' forms when the evolved core of a massive star collapses to a black hole, either by fallback or because the iron core fails to produce an outgoing shock (Woosley 1993; MacFadyen & Woosley 1999). The shocks responsible for producing the γ-rays must arise after the relativistic jet has broken free from the stellar progenitor, whose density is reduced along the rotation axis as a result of an early phase of accretion[1] (MacFadyen & Woosley 1999; Aloy et al. 2000; Wheeler et al. 2000; MacFadyen, Woosley & Heger 2001; Wheeler, Meier & Wilson 2002). While the light, relativistic jet (i.e. light compared to the stellar density) makes its way out of the progenitor star, its rate of advance is slowed down and most of the energy output during that period is deposited into a cocoon or 'wastebasket' surrounding it. The jet head propagates at mildly relativistic velocity until it emerges from the edge of the He core into the low density H envelope at $r_* \approx 10^{11}$ cm (MacFadyen & Woosley 1999; Mészáros & Rees 2001; Matzner 2002). At this stage (and provided that the density of the H envelope varies steeply with radius; see Section 3), the head of the jet will advance relativistically, and the cocoon plasma could escape swiftly from the stellar cavity and accelerate in approximately the same way as an impulsive fireball – its energy will be converted via adiabatic expansion into bulk kinetic energy.

Here we describe the evolution and collimation of such cocoon fireballs. We argue that an understanding of the structure and time dependence of the cocoon plasma can come only through a knowledge of the properties of the stellar material through which it propagates. A cocoon fireball may be stalled while propagating through an extended or a high mass envelope, but could expand freely beyond the stellar cavity of a helium post-Wolf–Rayet star. We show that even if only a small fraction of the energy in the jet ($\approx$1 per cent) is deposited into the cocoon, it would have enough kinetic energy to substantially alter the structure of the expanding outflow, if not in fact provide much of the observed power. The latter may be true

★E-mail: enrico@ast.cam.ac.uk

[1] The majority of stellar progenitors, with the exception of some very compact stars, will not collapse entirely during the typical duration of a GRB. A stellar envelope will thus remain to impede the advance of the jet; see Matzner (2002).

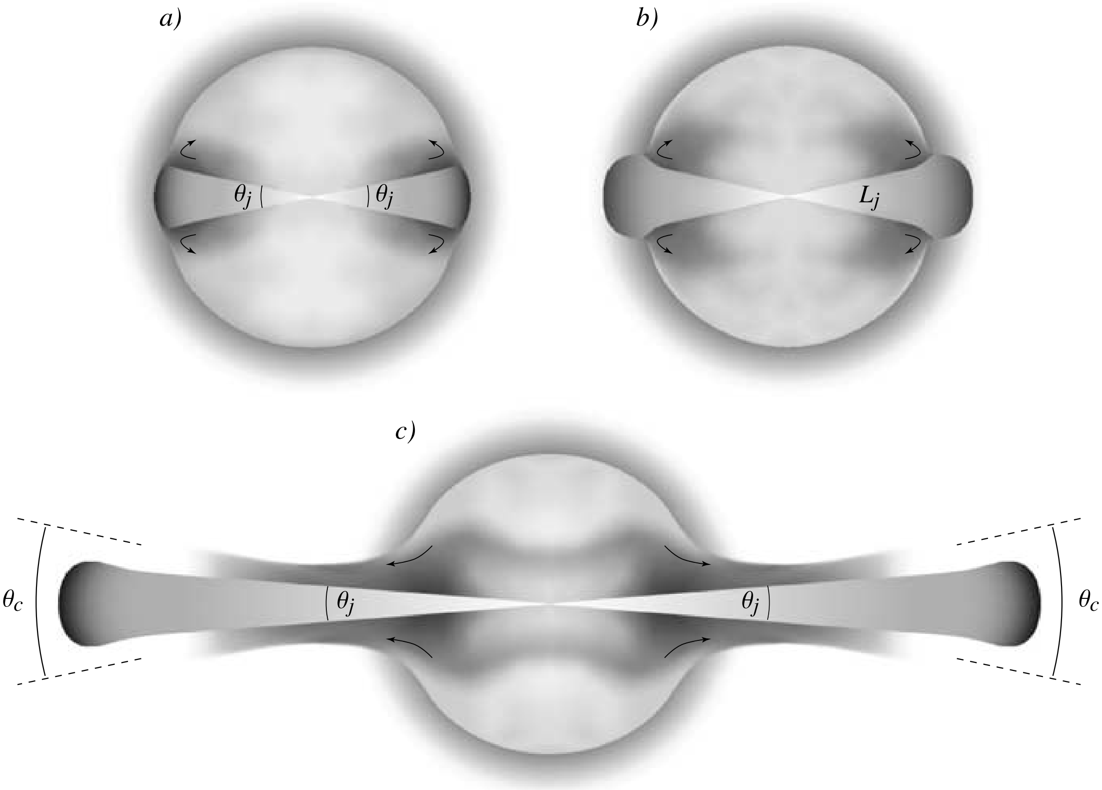

Figure 1. Schematic diagram illustrating the propagation of a relativistic jet through the stellar envelope. Initially, the jet is unable to move the envelope material to a speed comparable to its own and thus is abruptly decelerated (a). Most of the energy output during that period is deposited into a cocoon or 'wastebasket' surrounding the jet (b). After the jet head advances relativistically, the cocoon plasma would itself be able to escape swiftly from the stellar cavity and accelerate in approximately the same way as an impulsive fireball (c).

for an observer that lies off-axis to the jet or at early times when the initial jet contribution to the emission is negligible. We examine the physical conditions within the cocoon plasma – namely its confinement, collimation and initial entropy – to determine whether or not this delayed fireball will become matter dominated before it becomes optically thin. We discuss the possible role of cocoon fireballs in producing γ-ray and X-ray transients (both thermal and non-thermal), along with the standard afterglow emission that would originate from the deceleration shock. We suggest that detailed observations of this prompt burst and afterglow emission may provide a potential tool for diagnosing the size of the cocoon cavity and the initial energy to mass ratio $\eta = (E/Mc^2)$. It also provides a means for probing the state of the stellar medium through which both the initial jet and cocoon propagate.

2 COCOONS: 'WASTEBASKETS' OF RELATIVISTIC PLASMA

The properties of the stellar envelope have a decisive effect on the appearance of a jet propagating through it. The characteristic stellar progenitor structure is that of an evolved massive star, with $\approx 2\ \mathrm{M}_\odot$ Fe core of radius $\approx 10^9$ cm and a $\approx 8\ \mathrm{M}_\odot$ He core extending out to $r_* \approx 10^{11}$ cm (MacFadyen et al. 2001). In some cases, a cool H envelope reaches out to $\geqslant 10^{13}$ cm, while in others the envelope has been largely lost. The post-collapse (radiation-dominated) pressure profile out to the edge of the He core drops roughly as $p_{\mathrm{He}} \propto \rho_{\mathrm{He}}^{4/3} \propto r^{-2}$ over some two decades in radius (Mészáros & Rees 2001). Beyond the He core, it drops drastically as $p_{\mathrm{H}} \propto r^{\approx -4}$ because at these distances the pressure profile is still the pre-collapse one. The pre-collapse density of the pre-supernova model A25 of MacFadyen et al. (2001) scales roughly as $\rho \propto r^{-3}$, so that the radiation-dominated pressure is $p \propto r^{-4}$; see Mészáros & Rees (2001).

Suppose that a collimated beam has been established. If all the particles in the beam are ultrarelativistic, then $p_{\mathrm{j}} = \frac{1}{3}\rho_{\mathrm{j}} c^2$ and the sound speed is $c_{\mathrm{s}} \approx c/\sqrt{3}$. At a given time, the beam will have evacuated a channel out to some location where it impinges on the stellar envelope[2] at a 'working surface' which itself advances out at speed V_{h}; see Fig. 1(a). If the power in the jet, L_{j}, is roughly conserved and stationary, then approximating the channel as a cylinder of radius r, we balance momentum fluxes at the 'working surface' to obtain

$$\frac{L_{\mathrm{j}}}{\theta_{\mathrm{j}}^2 r^2 c} \approx \rho_{\mathrm{env}} V_{\mathrm{h}}^2 \quad v \gtrapprox V_{\mathrm{h}} \gtrapprox c_{\mathrm{s}}, \tag{1}$$

where v is the speed of the beam, ρ_{env} is the stellar envelope density, and θ_{j} is the jet opening angle. If the beam consists of relativistic plasma then $v \approx c$, and relativistic fluid mechanics must be used (the reader is referred for further details to the generalized formalism developed by Matzner 2002). During propagation in the iron and He cores, the head of the jet will propagate with subrelativistic velocities. The energy supplied by the jet exceeds that imparted to the swept-up stellar material by a factor $\sim c/V_{\mathrm{h}} \gg 1$. The surplus (or waste) energy must then not accumulate near the 'working surface'

[2]Reconversion into random energy occurs at the end of the channel, which is a natural site for particle acceleration (Colgate 1974; Chevalier 1982; Mészáros & Waxman 2001; Ramirez-Ruiz, MacFadyen & Lazzati 2002).

but be deposited within a cocoon surrounding the jet (Fig. 1); slightly resembling the cocoons that envelop jets of radio sources (Begelman et al. 1984; Begelman & Cioffi 1992).

After the jet emerges into the H envelope, the sudden and drastic density drop at the outer edges permits the jet head to accelerate to velocities close to the speed of light ($V_{\rm h} \approx c$). Thus, if it is a general property that the jet becomes relativistic near the boundary of the He core, the outer edge of the H envelope is reached in a crossing time $\approx r_{\rm H}/2c\Gamma_{\rm h}^2$ as measured by an observer along the line of sight. For an H envelope density varying as $\rho_{\rm H} \propto r^{-\beta}$ with $\beta \geqslant 3$ (see Section 3), the outer edge of the star is reached in a crossing time that may matter little when compare to the He-core traversal time.[3] The fraction of relativistic plasma injected into the cocoon after $V_{\rm h} \approx c$ will be much reduced (Mészáros & Rees 2001). The amount of energy that accumulated in the cocoon while the jet was advancing subrelativistically is then[4]

$$E_{\rm c} = \int_0^{t_{\rm He}} L_{\rm j}(t)\,{\rm d}t \approx \frac{r_* L_{\rm j}}{\bar{V}_{\rm h}} \approx 5 \times 10^{50}\,\bar{V}_{\rm h,10}^{-1}\,r_{*,11}\,L_{\rm j,50}\,{\rm erg}, \qquad (2)$$

where $t_{\rm He} \approx r_*/\bar{V}_{\rm h}$ is the He-core traversal time, $\bar{V}_{\rm h}$ is the average speed of the jet head – which is about $c/2$, see Aloy et al. (2000) – and we adopt the convention $Q = 10^x\,Q_x$, using cgs units. The cocoon expands in the transverse direction with a velocity given by $V_{\rm c} \approx (p_{\rm c}/\rho_{\rm env})^{1/2}$. The forces driving the cocoon expansion will be effective so long as $p_{\rm c} > p_{\rm env}$ (Matzner 2002). The cocoon material could in principle reach pressure equilibrium with the external stellar gas, but this generally would not occur before the jet head has reached the outer layers of the progenitor star. The length of the cocoon region is similar to that of the jet, but its breadth is determined by its transverse velocity. A wide jet would create a near-spherical cavity, but a narrow jet would advance much faster than the transverse expansion of the cocoon (Matzner 2002), so that the cocoon would be 'cigar-shaped' – or maybe more like an 'hourglass' in the case when the external pressure is a steep function of radius; see Fig. 1(c).

At the radii $\approx r_*$ (probably the radius of the He core) where the head of the jet starts to advance relativistically, the volume of the material deposited into the cocoon, $\Lambda_{\rm cav}$, is related to both jet and cocoon expansion velocities by $\Lambda_{\rm cav} \approx (\pi/3) r_*^3 (V_{\rm c}/V_{\rm h})^2$ (Matzner 2002). At that point in time, the cocoon plasma would itself be able to break out and accelerate. Unlike the jet, this cocoon material does not have a relativistic outward motion, although it has a relativistic internal sound speed (i.e. similar energy to mass ratio). At first, an asymmetric bubble (because pressure balance may never be reached if the external pressure falls off more steeply than r^{-3}) will be inflated which can expand most rapidly along the rotation axis [Fig. 1(c)] and may eventually escape the stellar progenitor. But it may never expand freely unless it escapes into an exponentially decreasing atmosphere with $\beta \gtrapprox 5$ (i.e. bare He star; see Section 3).

2.1 Trapping and collimation

In so far as the cocoon material and the lower-entropy stellar envelope can be treated as two separate fluids (i.e. diffusion and viscosity can be neglected), it is feasible to estimate the cone angle, $\theta_{\rm c}$, of the expanding plasma. The stellar envelope, which contains the outflow along the axis, has a sufficiently large optical depth $\tau_{\rm env} \sim 10^{11}$ that most of the radiation released is trapped, and transported into the cavity by bulk flow rather than diffusing outwards. The optical depth across the cavity is enormous, even if η is so high that the baryon density is low, because of the thermal pair density ($T \geqslant 20$ keV), and the radiation is then well enough trapped to justify a fluid treatment. Collective plasma effects and magnetic fields may also reduce the effective mean free path. Unless there is violent entrainment, there would not be much mixing of baryons from the envelope into the cocoon, so that during the build-up its ratio of energy to baryon-rest-mass will be given approximately by η. If the magnetic field contributes significantly to the total energy density [i.e. magnetohydrodynamics (MHD) jet] and has a preferred orientation, then the pressure and magnetosonic velocities are of course anisotropic, but the dynamics would be essentially the same as for pure radiation. When the pressure at the outer edges of the cocoon cavity has halved, the flow becomes transonic and the cross-sectional area is minimized. In this way, a directed nozzle can be established. The channel cross-section is proportional to the total power discharge and varies inversely with the pressure at the outer edges of the cocoon cavity (Blandford & Rees 1974). Unfortunately neither the jet thrusts nor the pressures at the outer edges of the cocoon are known well enough to quantitatively predict the dimensions of the nozzle. Beyond the nozzle, however, the external pressure drops steeply, and the cocoon material expands freely in the transverse direction. The flow spreads out over an angle $\sim \gamma_{\rm c}^{-1}$. If its free expansion starts just outside the nozzle, where the Lorentz factor of the cocoon material $\gamma_{\rm c}$ is only $\sim$2, then it will spread over a wide angle and will develop into a roughly semi-spherical blast wave. The cocoon fireball will then expand with $\gamma_{\rm c} \propto r/r_{\rm cav}$, where $r_{\rm cav} \sim \theta_{\rm c} r_*$ is the typical, initial dimension that the fireball would have if it started out spherically.

3 THE STATE OF COCOON FIREBALLS

3.1 A brief overview of the fireball model

Before turning to the question of how the kinetic energy of the cocoon plasma is converted to radiation, it is worthwhile to summarize now the essential features of the generic fireball scenario.

In the so-called standard fireball model [see Piran (1999) for a recent review], it is conjectured that the fireball wind, expelled by a central source of dimension $r_0 \approx 10^5$–10^6 cm (notice than in the case of the cocoon fireball, the relativistic plasma is confined to a much extended cavity), accelerates at small radii such that its Lorentz factor grows linearly with radius until the entire fireball energy is converted into kinetic energy at ηr_0 (Cavallo & Rees 1978; Goodman 1986; Paczyński 1986; Shemi & Piran 1990). This energy must be converted to radiation in an optically-thin region, as the observed bursts are non-thermal. The radius of transparency of the ejecta is

$$r_\tau = \left(\frac{\sigma_{\rm T} E_{4\pi}}{4\pi m_{\rm p} c^2 \eta}\right)^{1/2}, \qquad (3)$$

where $E_{4\pi}$ is the isotropic equivalent energy generated by the central site. The inertia of the swept-up external matter decelerates the shell ejecta significantly by the time it reaches the deceleration radius (Mészáros & Rees 1997; Chevalier & Li 1999):

[3] Many pre-supernova stars, on the other hand, have density profiles with $\beta \sim 2$ (Chevalier 1989). For these stellar progenitors, the jet may be unable to punch through the stellar envelope (Matzner 2002).

[4] A more rigorous estimate of the cocoon energy content, which accounts for both relativistic and non-relativistic jet propagation, can be found in equation (10) of Matzner (2002).

$$r_\gamma = \left(\frac{(3-s)E_{4\pi}}{m_\mathrm{p} A c^2 \eta^2}\right)^{1/(3-s)}, \quad (4)$$

where the external medium particle density is $n(r) = Ar^{-s}$, with $s = 0$ for a homogeneous medium $n(r) = n_\mathrm{ism}$, and $s = 2$ for a wind ejected by the stellar progenitor at a constant speed. Given a certain external baryon density $n(r)$, the initial Lorentz factor η then strongly determines where both internal and external shocks develop; see, for example, figure 3 of Ramirez-Ruiz, Merloni & Rees (2001). Changes in η will modify the dynamics of the shock deceleration and the manifestations of the afterglow emission.

3.2 The propagation of cocoon fireballs

The above summary describes the qualitative features of the generic fireball model. While similar scaling laws are also expected for the evolution of the cocoon material, the physical conditions within and around this plasma are different, and so appreciable deviations from the 'standard' evolution are thus likely to occur. This variety of propagation effects can substantially modify the emergent radiation, so that important constraints on the nature of the source producing them can be obtained simply by detecting these changes. For this reason, we now turn to consider the cocoon properties in more detail.

Consider a homogeneous fireball of energy E_c, total mass M_c initially confined to a cocoon cavity. Clearly, because $\tau > 1$, the initial fireball will be an opaque sphere in thermal equilibrium, characterized by a single temperature: $T_\mathrm{c} \approx 400 g E_{\mathrm{c},52}^{1/4} r_{\mathrm{cav},9}^{-3/4}$ keV in a spherical cocoon cavity, or $T_\mathrm{c} \approx 100 g E_{\mathrm{c},52}^{1/4} \Lambda_{\mathrm{cav},30}^{-1/4}$ keV in a 'hourglass' cocoon. $g = 11/4$ for $T_\mathrm{c} > m_\mathrm{e}c^2$ (photons and pairs), and it drops to 1 when $T_\mathrm{c} \ll m_\mathrm{e}c^2$ (only photons).

When the radiation energy dominates the evolution (i.e. $\eta \gg 1$), the fluid expands under its own pressure such that its Lorentz factor grows linearly with radius, $\gamma_\mathrm{c} \propto r/r_\mathrm{cav}$. When the fireball has a size of $r_{\eta_\mathrm{c}} = \eta r_\mathrm{cav}$, all the internal energy has been converted into bulk kinetic energy and the matter coasts asymptotically with a constant Lorentz factor η. This is perhaps true for a cocoon propagating into the exponentially decreasing atmosphere of a carbon–oxygen or helium post-Wolf–Rayet star and into the circumstellar environment beyond it, as in curve a of Fig. 2. When there is a remaining H envelope (with $\rho_\mathrm{H} \propto r^{-\beta}$) beyond the He core, the deceleration radius of the cocoon fireball may well be inside the star. The energy required to sweep up an external stellar mass of m_env is $\gamma_\mathrm{c}^2 m_\mathrm{env} c^2$, where $\gamma_\mathrm{c} \propto r$ and $m_\mathrm{env} \propto \rho(r) r^3 \propto r^{-\beta+3}$. Thus, the cocoon blast wave is undecelerated for $\beta \gtrsim 5$. By the same token, the initial relativistic jet will expand freely provided $\beta \gtrsim 3$. For a moderately dense H envelope, the cocoon fireball, which starts being decelerated by the stellar matter at $r < r_\eta$ (see curve b of Fig. 2), emerges from the H envelope with a Lorentz factor $\gamma_\mathrm{c} < \eta$. For an extended or denser H envelope, corresponding to curve c in Fig. 2, the cocoon of relativistic material would be stalled before emerging. However, even in this case, the cocoon may have more energy than the binding energy of the envelope, and could give rise to a 'hypernova' (Iwamoto et al. 1998; Paczyński 1998; Wang & Wheeler 1998). An accompanying GRB will be present depending on whether or not the jet is also choked.

3.3 The role of η

The baryon load build-up in the cocoon reservoir, $M_\mathrm{c} \approx E_\mathrm{c}/\eta c^2$, influences the fireball evolution by increasing the opacity and thus delaying the escape of radiation. The $e^\pm$ pair opacity, τ_p, decreases exponentially with decreasing local temperature, and falls to unity

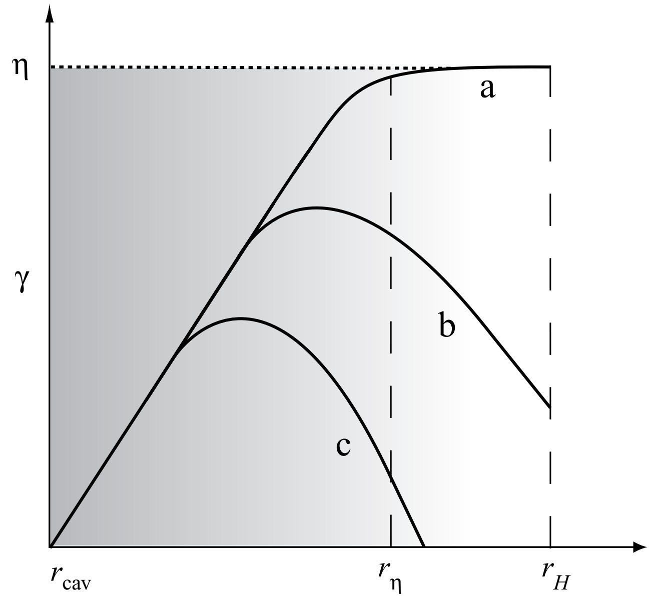

Figure 2. This diagram shows, for three illustrative cases, how the cocoon expansion would be affected by the properties of the stellar envelope through which it propagates. The axes (logarithmic) are γ_c versus r, where r is $r_\mathrm{cav} \approx r_* \theta_\mathrm{c}$ when the cocoon is observed to start its expansion. Three illustrative cases are depicted. In case a, the stellar matter has a low density (i.e. exponentially decreasing atmosphere of a carbon–oxygen or helium post-Wolf–Rayet star), and the cocoon blast wave sweeps up all the envelope's matter before it has been decelerated. When the fireball has a size of $r_{\eta_\mathrm{c}} = \eta r_\mathrm{cav}$, all the internal energy has been converted into bulk kinetic energy and the matter coasts asymptotically with a constant Lorentz factor η. In case b, with higher stellar density, deceleration occurs at radii $< r_{\eta_\mathrm{c}}$, and the blast wave is still moving through the H envelope material during the afterglow. After that, the cocoon escapes into the circumstellar environment beyond the stellar envelope, where it escapes freely with $\gamma_\mathrm{c} < \eta$. For a very dense (or extended) H envelope, corresponding to case c, the cocoon material would be unable to break free from the stellar envelope. However, even in this case, the cocoon material has more energy than the binding energy of the envelope.

when $T_\mathrm{p} \approx 20$ keV. The matter opacity, τ_b, on the other hand, drops as r^{-2}, and thus the escape temperature may drop far below T_p if $\tau_\mathrm{b} > \tau_\mathrm{p} = 1$ (Shemi & Piran 1990; Piran 1999). Two critical values for η determine the order of these transitions:

$$\eta_\mathrm{p} = \left(\frac{3\sigma_\mathrm{T}^2 E_\mathrm{c} \sigma T_\mathrm{p}^4}{\theta_\mathrm{c}^2 m_\mathrm{p}^2 c^4 r_\mathrm{cav}}\right)^{1/2} \approx 10^{10} E_{\mathrm{c},52}^{1/2} r_{\mathrm{cav},9}^{-1/2} \theta_{\mathrm{c},0}^{-1} \quad (5)$$

and

$$\eta_\mathrm{b} = \left(\frac{3\sigma_\mathrm{T} E_\mathrm{c}}{2\theta_\mathrm{c}^2 m_\mathrm{p} c^2 r_\mathrm{cav}^2}\right)^{1/3} \approx 5 \times 10^3 E_{\mathrm{c},52}^{1/3} r_{\mathrm{cav},9}^{-2/3} \theta_{\mathrm{c},0}^{-2/3}. \quad (6)$$

The effect of the baryons is only negligible when $\eta > \eta_\mathrm{p}$ and the evolution is that of a pure photon–lepton fireball ($\tau_\mathrm{p} = 1 > \tau_\mathrm{b}$). If η is less extreme, there are two qualitative changes in the fireball's mode of propagation. First, the matter opacity becomes important when $\eta_\mathrm{p} > \eta > \eta_\mathrm{b} \approx 5 \times 10^3\, E_{\mathrm{c},52}^{1/3} r_{\mathrm{cav},9}^{-2/3} \theta_{\mathrm{c},0}^{-2/3}$. The comoving temperature, in this case, decreases far below T_p before $\tau = \tau_\mathrm{b}$ reaches unity, yet the fireball continues to be radiation dominated and most of the energy still escapes as radiation. Secondly, for η smaller than η_b, the fireball becomes matter dominated before it becomes optically thin, and most of the initial energy its converted into bulk kinetic energy (this is likely to be the common situation for the initial jet fireball;

see Section 3.1). These two modes of propagation will be referred to in the following as radiation dominated and matter dominated, respectively.

4 MASSIVE PROGENITORS, STALLED COCOONS AND FE LINES

The properties of the stellar envelope determined in the previous section have an important effect on the appearance of a jet propagating through it. While the details remain uncertain, preliminary calculations suggest that a relativistic jet can be launched along the progenitor rotation axis (MacFadyen & Woosley 1999; Aloy et al. 2000; MacFadyen et al. 2001). We would expect baryon contamination to be the lowest near this axis, because angular momentum flings material away from it and material with low-angular momentum falls into the black hole (Fryer & Heger 2000). The jet would be expected to break free of the H envelope, and in principle to lead to a successful GRB, provided the central engine feeding time exceeds the He-core crossing time and that the stellar pressure continues to drops at least as fast as $p_{\rm H} \propto r^{-4}$. In addition to the stellar pressure required to stall the initial jet, there is another, smaller pressure which can prevent the cocoon material from expanding freely. The cocoon fireball will, in general, be easier to confine than the initial jet, for two reasons: first, the fraction of matter with a clear line of sight along the rotation axis will be much reduced (i.e. $\Omega_{\rm c} > \Omega_{\rm funnel} \gtrapprox \Omega_{\rm j}$); and, secondly, the cocoon blast wave may never expand freely for an H envelope density varying as $\rho_{\rm H} \propto r^{-\beta}$ with $\beta < 5$.

The energy of the relativistic material that accumulated in the cocoon while the jet was advancing subrelativistically is nevertheless much larger than the binding energy of the H envelope. As soon as the jet penetrates into the low-density envelope beyond r_*, the cocoon plasma would itself be able to ‘break out’ and expand through the envelope along the direction of least resistance, which is likely to be the rotation axis of the stellar progenitor (perhaps further channelled as the jet penetrates further into the envelope). The cocoon fireball, in this scenario, may start to decelerate before it becomes matter dominated. It starts being relativistic during the acceleration stage, but a self-similar phase could then begin after enough external material has been collected. In the interim, the Lorentz factor will drop faster than would that of a cold fireball propagating through a similar density profile (Fig. 2). If the H envelope did not exist, then the cocoon fireball would reach the outer edge of this envelope after a few seconds, corresponding to case a in Fig. 2, where $t_{\rm c,H} \approx r_{\rm cav}/c + r_{\rm H}/(2c\eta^2)$. However, for very extended or slow rotating stars (i.e. denser cores), the cocoon material would generally carry less energy and inertia than the stellar envelope; it would then take up to a few hours for it to reach the outer surface of the star as it expands subrelativistically with a velocity of the order of $V_{\rm c} \approx c(E_{\rm c}/M_{\rm env}c^2)^{1/2} \approx 10^9 (M_{\rm env}/{\rm M}_\odot)^{-1/2}$ cm s^{-1} (the case of an ultimately choked cocoon).

As it expands relativistically (but notice that, as argued above, for very extended or slow rotating stars the cocoon material may be stalled prior to the acceleration of the fireball to relativistic velocities), the cocoon fluid cools with $T \propto (r/r_{\rm cav})^{-1}$. The coasting photons, whose local energy is T, are blueshifted. An observer detects them with a temperature of $T_{\rm obs} \propto \gamma_{\rm c}(r)T(r)$. Seeing that $T \propto r^{-1}$ and $\gamma_{\rm c} \propto r$, we find that during the acceleration stage $T_{\rm obs} \approx T_{\rm c}$, where

$$T_{\rm c} \approx \begin{cases} 70\, r_{*,11}^{-5/8} L_{\rm j,50}^{1/8} \left(\frac{M_{\rm env}}{{\rm M}_\odot}\right)^{-1/4} \text{ keV} & \text{(spherical)} \\ 34\, r_{*,11}^{-1/2} L_{\rm j,50}^{1/4} V_{\rm c,9}^{-1/2} \text{ keV} & \text{(hourglass)} \end{cases} \qquad (7)$$

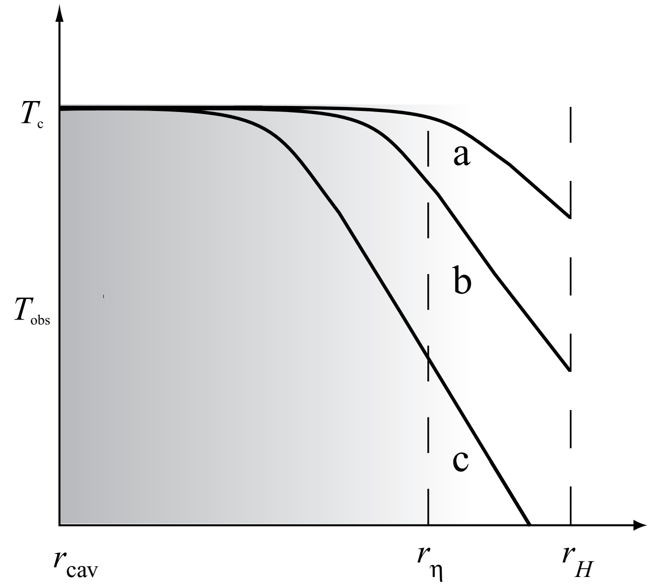

Figure 3. Schematic plot of the escape temperature $T_{\rm obs}$ as a function of radius for the three, qualitatively different cases depicted in Fig. 2. As it expands, the cocoon fluid cools with $T \propto (r/r_{\rm cav})^{-1}$. The coasting photons, whose local energy is T, are blueshifted. An observer would detect them with a temperature of $T_{\rm obs} \propto \gamma_{\rm c}(r)T(r)$. These photons would escape freely after the expanding fireball becomes optically thin, which is likely to occur at some distance from $r_{\rm H}$.

is the initial blackbody temperature of the opaque, cocoon cavity. These photons would escape freely after the expanding fireball becomes optically thin, which is likely to occur at some distance from the stellar surface and thus $T_{\rm obs} \leqslant T_{\rm c}$. The escape temperature may drop far below $\gamma_{\rm c}(r)T_{\rm p}$ if condition $\eta > \eta_{\rm b}$ is not satisfied or if the deceleration of the fireball takes place before the radius of transparency (but it is always $\geqslant 4000\gamma_{\rm c}(r)$ K, the recombination temperature). A similar diagram to Fig. 2 can be drawn for $T_{\rm obs}$ as a function of radius (see Fig. 3).

In the case of a successful breakthrough of the jet, a strongly decelerated, cocoon fireball could result in a potentially interesting and observable phenomenon. Not only would a conventional ‘long’ GRB be detectable, followed by a standard afterglow, but also there would be, after some seconds or up to a day, a secondary, almost thermal [see Goodman (1986)] brightening, caused by the cocoon photospheric emission containing $\geqslant 10^{50}$ erg. The observed duration of this emission would be of the order of $r_{\tau_{\rm c}}/(c\gamma_{\rm c}^2) \sim$ a few hours for a cocoon expanding at mildly relativistic velocities (case b in Fig. 3). A choked cocoon will, however, expand more or less isotropically through the rest of the envelope, causing its disruption. This would then appear, after the disrupted envelope becomes optically thin, as a type II supernova (or a type Ib/c if there is a significant injection of radioactive material). Some evidence for supernova-type emission has been found in: GRB 980 326 (Bloom et al. 1999); GRB 970 228 (Reichart 1999); GRB 990 712 (Björnsson et al. 2001); GRB 000 911 (Lazzati et al. 2001); GRB 011 121 (Bloom et al. 2002; Dado, Dar & De Rújula 2002; Garnavich et al. 2002). The decelerating external shock of a cocoon fireball may produce a significant absorption edge in the cooled shocked ejecta, so long as cooling is faster than adiabatic losses and protons are well coupled to the electrons. Absorption edges can also arise from cooler, denser material or filaments in pressure equilibrium with the shocked envelope ejecta (Mészáros & Rees 1998).

It is, of course, possible that the initial jet is a magnetically confined configuration, whose collimation properties are unaffected by the distribution of the external matter. In this case, the cocoon cavity would still have a dynamically-important magnetic field strength. If the field were tangled, continuing reconnection processes may lead to acceleration of non-thermal electrons. It is therefore plausible that a substantial fraction of the energy stored in the cocoon cavity could be released, via magnetic dissipation, in a non-thermal ∼ UV/X-ray continuum with $L \approx E_c/t_{c,H} \sim 10^{47}$ erg s^{-1}. A magnetic field of 10^5 G could confine clumps of gas with densities up to $n \geqslant 10^{17}$ cm^{-3}, even at keV temperatures. Such clumps would be optically thick and could reprocess a non-thermal UV/X-ray continuum arising from within the dilute plasma between them – as envisaged by Mészáros & Rees (2001) – and (in the absence of both entrainment and substantial $e^{\pm}$ pair production) may also excite Fe line emission. If the UV/X-ray continuum can maintain an ionization parameter $\xi = L_x/(nr^2)$ of the order of 10^3–10^4, a modestly supersolar Fe mass fraction could yield a recombination line luminosity comparable to that observed in GRB 991 216 (Piro et al. 2000; Ballantyne & Ramirez-Ruiz 2001; Rees & Mészáros 2000; Vietri et al. 2001; McLaughlin et al. 2002; Ballantyne et al. 2002; Kallman, Mészáros & Rees 2002).

5 COMPACT PROGENITORS, GRB PRECURSORS, AND AFTERGLOW SIGNATURES

A relativistic cocoon fireball is likely to escape if the star loses its hydrogen envelope before collapsing (MacFadyen & Woosley 1999; Aloy et al. 2000; Wheeler et al. 2000; MacFadyen et al. 2001; Matzner 2002). This is expected, for example, in stars with high radiative mass loss; see, for example, Ramirez-Ruiz et al. (2001). The fireball cocoon will then emerge from the He core into an exponentially decreasing atmosphere and into the rarefied circumstellar environment beyond it, where it acquires the limiting bulk Lorentz factor $\gamma_c \approx \eta$, unless of course $\eta > \eta_b$. In this latter case, the cocoon plasma continues to be radiation dominated when it becomes optical thin. At this stage, the baryons will switch immediately to a coasting phase with $\gamma_c \approx r_{\tau_c}/r_{cav}$ (where $r_{\tau_c} < r_\eta$) and most of the energy escapes as photons. As follows from the previous discussion, an observer will detect them with a temperature of $T_{obs} \propto \gamma_c T$. Thus, the observed thermal peak frequency would be in the BATSE [20–600] keV spectral window [see equation (7)] for compact He envelopes $r_* \approx 10^{11}$ cm; the outer edge of the He core varies with initial mass, roughly as $r_* \sim 10^{11}(M_i/35M_\odot)^{-2}$ (Woosley, Langer & Weaver 1993). For extended He envelopes ($r_* \geqslant 10^{12}$ cm), however, the thermal emission could be detectable with instruments such as *Ginga* and the *BeppoSAX* wide field cameras. The time delay between the cocoon photospheric emission and the start of the main burst is given by $\Delta t_\gamma \approx r_{cav}/(2c) + r_{\tau_c}/(2c\eta^2) - \max[r_{\tau_j}, r_{int}]/(2c\eta^2)$, where r_{int} is the radius of internal shocks in the jet fireball. The thermal signal emerging from a cocoon fireball with $\eta_p > \eta > \eta_b$ will most likely appear as a transient signal at the beginning of the main burst because $|\Delta t_\gamma| \leqslant 0.1$ s. In contrast to the main burst, this signal would only last for $r_{cav}/c \approx 0.1$ s. Such thermal precursors may have indeed been observed by *Ginga* (Murakami et al. 1991). For compact stellar cocoons ($r_{cav} < 10^{10}$ cm), however, this thermal signal could be very short-lived and may be difficult to disentangle from the internal shock emission.

The cocoon fireball will strongly modify the usual properties of the standard internal shocks and the afterglow emission when $\eta < \eta_b$ (i.e. the cocoon fireball becomes matter dominated). The total energy available in the cocoon afterglow is essentially, the kinetic energy of the relativistic wind deposited during the He-core traversal time, here estimated to be $\approx 7r_{*,11}$ s, minus the fraction dissipated (and converted into prompt γ-rays) in internal shocks. The size of the stellar cavity and the initial Lorentz factor η, along with the jet lifetime, strongly determine whether or not the cocoon fireball would carry less energy and inertia than the relativistic jet itself. For $E_{4\pi,c} > E_{4\pi,j}$, the main afterglow will be dominated by the deceleration of the cocoon fireball (this scenario is likely to occur when the source lifetime is of the order of the He-core traversal time, so that the energy carried by the initial jet is much less than that accumulated in the cocoon). An interesting consequence of this scenario is that if the observer lies off-axis to the jet, there could be a large fraction of detectable afterglows for which no γ-ray event is detected – commonly referred to as 'burstless' or 'orphan' afterglows; see Mészáros, Rees & Wijers (1998). The initial jet starts being decelerated by the external medium at a smaller radius, so that the cocoon material always overtakes it and sweeps the jet material. This collision would be an important contribution to the observed afterglow at early times ($\approx \frac{r_{\gamma_j}}{2c\eta^2} < \frac{r_{\gamma_c}}{2c\eta^2}$), when the afterglow emission produced by the jet fireball dominates. The afterglow shock may experience, after starting out in the canonical manner, a 'resurgence' similar to the shock refreshment produced by the delayed energy injection of a long-lived central engine; see Panaitescu, Mészáros & Rees (1998) for the case of GRB 970 508.

If the jet produced by the accretion maintains its energy for much longer than it takes the jet to reach the surface of the H envelope, or is very highly collimated, the initial jet is likely to be more energetic than the cocoon material (i.e. $E_j > E_c$, and because entrainment may dominate in the initial fireball $E_{4\pi,j} = \frac{4\pi E_j}{\Omega_j} > E_{4\pi,c} = \frac{4\pi E_c}{\Omega_c}$). Fig. 4 shows the evolution of both jet and cocoon fireballs for this matter-dominated case. The adiabatic fireball evolution (thick solid line) was computed using a similar numerical method to that developed by Kobayashi, Piran & Sari (1999). The main afterglow will be produced by the slowing down of the jet as in the usual case, however, the emission at early stages would be caused by the deceleration of the cocoon fireball. Fig. 5 shows the contribution of the cocoon afterglow radiation at low frequency and at early times when the initial jet contribution to the emission is negligible. If the external medium is homogeneous the submillimetre afterglow produced by the jet should rise slowly at times between a few hours and one day, while for the cocoon material the emission should fall steeply after this. Therefore, observations made at submillimetre frequencies with the SCUBA (James Clerk Maxwell Telescope) or with MAMBO (IRAM telescope) instruments would be very powerful in determining if the early afterglow is dominated by the cocoon fireball emission.

There could also be additional precursor signatures, which are not associated with the ejecta blast wave, but with the dynamics of the fireball at the coasting phase. The γ-ray (i.e. internal shocks) signal emerging from the cocoon fireball would precede, by $\Delta t_\Gamma \approx \frac{r_{\tau_j}}{2c\eta^2} \approx$ a few seconds, that produced by the initial relativistic wind (provided that $E_{4\pi,j} > E_{4\pi,c}$ and $\frac{r_{\tau_j}}{2c\eta^2} > r_{cav}/c$). The observed variability time-scale of this prompt γ-ray emission is related to the typical size of the shocked plasma region containing the photon field: $\Delta \approx r_{cav}$ or $\Delta \approx r/\gamma^2$ for $r > \Delta\gamma^2$. For compact stellar cocoons (i.e. $r_* < 10^{11}$ cm), the expected delay between the cocoon precursor and the main pulse, Δt_Γ, would be proportional to the total initial jet energy: $E_{4\pi,j}$. It will then simply reflect a correlation between the burst strength and the time elapsed since the previous emission episode,

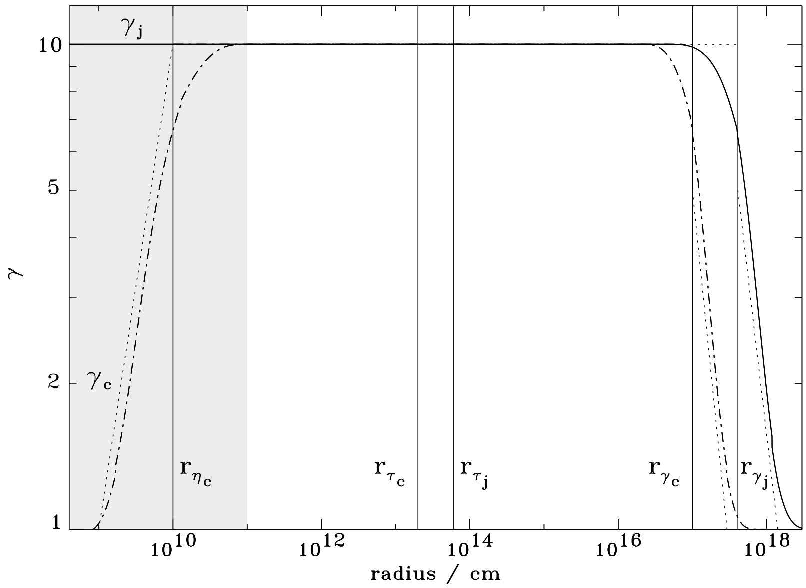

Figure 4. Evolution of a matter-dominated cocoon fireball from its initial formation at rest to its final stage. Both the initial jet (solid line) and the cocoon fireball (dashed-dotted line) propagate into the exponentially decreasing H atmosphere and into the circumstellar environment beyond it, where they will both accelerate while expanding and then coast freely until the surrounding matter will eventually influence their coasting expansion. The energy dissipation is a result of interaction with the interstellar medium (ISM) via a relativistic forward shock and a Newtonian reverse shock. The parameters for this computation are: $\eta = 10$, $r_{\rm cav} \sim 10^9$ cm, $L_{\rm j} = 10^{50}$ erg s^{-1}, $n_{\rm ism} = 1$ cm^{-3}, $\theta_{\rm j} = 0.1$ and $\theta_{\rm c} = 1.0$. The numerical value of the average Lorentz factor (solid and dashed lines) and its analytical estimate (dotted line) are shown.

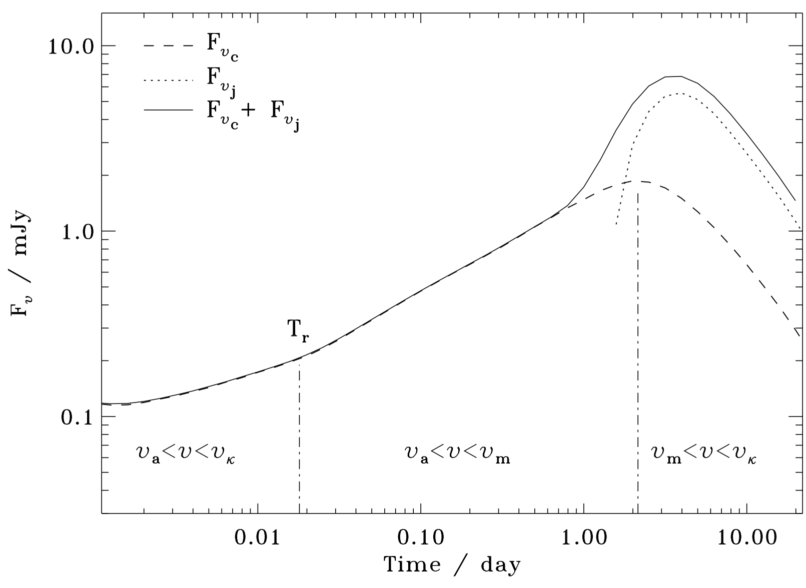

Figure 5. Comparison between the initial jet and the cocoon afterglow light curves at early times and at observing frequency $\nu = 10^{12}$ Hz. The afterglow brightness depends on the relationship between this frequency and those of the injection ($\upsilon_{\rm m}$), cooling (υ_κ) and absorption ($\upsilon_{\rm a}$) breaks; see, for example, Panaitescu & Kumar (2000). The dotted and dashed lines represent the jet and cocoon afterglow contributions corresponding to the parameters of the calculations shown in Fig. 4.

similar to what is observed in GRB light curves (Ramirez-Ruiz & Merloni 2001).

6 DISCUSSION

We have discussed, in the context of a collapsar model of γ-ray bursts (which are normally assumed to occur in shocks taking effect after the relativistic jet has broken free from the stellar envelope), the dynamics and evolution of the relativistic plasma surrounding a light, relativistic jet. As the jet makes its way out of the stellar envelope, most of its energy output during that period goes into a cocoon of relativistic plasma. This material subsequently escapes along the direction of least resistance. Provided that the density along the H envelope varies monotonically with radius as $\rho_{\rm H} \propto r^{-\beta}$, the properties of the cocoon plasma would be similar to those argued in Section 3. A collimated cocoon moving into a region with $\beta \approx 5$ (i.e. no H envelope) will become overpressured relative to its surroundings, and thereafter expands freely. If the relativistic jet carries less energy and inertia than the cocoon plasma itself ($\frac{4\pi E_c}{\Omega_c} > \frac{4\pi E_j}{\Omega_j}$), it will start to decelerate at a smaller radius than the collimated cocoon fireball, so that the latter would overtake it. In this case, the afterglow would be dominated by the emission of the cocoon material, which is likely to be ejected at larger angles relative to the observer than those from the jet itself. On the other hand, if the jet produced by the accretion maintains its energy for much longer than it takes the jet head to reach the surface of the He envelope, the relativistic jet is likely to contain substantially more energy than the off-axis cocoon material (because $\Omega_j \ll \Omega_c$), so that it dominates the flux after expanding for a longer time than the initially observed off-axis region.

Additional effects are expected when the cocoon fireball material becomes optically thin. Shock waves within the plasma can contribute with a short-lived ($\approx$ a few seconds) non-thermal γ/X-ray transient for a cocoon propagating inside a compact post-Wolf–Rayet star (and so long as $\eta < \eta_b \approx 5 \times 10^3 E_{c,52}^{1/3} r_{cav,9}^{-2/3} \theta_{c,0}^{-2/3}$; see Section 3). For very extended or slow rotating stars, a long lasting (a few hours to a day) UV/X-ray (almost) thermal pulse, whose total energy may be a few per cent of the total burst energy, is likely to appear. If magnetic dissipation within this plasma is important, it is also possible that a substantial fraction of the energy stored in the cocoon can contribute a non-thermal UV/X-ray afterglow, and also excite Fe line emission from the envelope gas. The detection of these prompt multi-wavelength signatures would be a test of the collapsar model; and the precise measurement of the time delay between emissions may help constrain the dimensions and properties of the H envelope, the size of the cocoon cavity, the initial dimensionless entropy of the jet, η, and the radius of the emitting region. The processes discussed here suggest that if GRBs are the outcome of the collapse of massive stars involving a relativistic fireball jet, bursts and afterglows may have a more complex spectra and time structure than those alluded to the 'standard' model.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge many helpful conversations with Roger Blandford and Peter Mésza ́ros. We thank the referee, Chris Matzner, for numerous insightful comments and suggestions. This research has been supported by CONACYT, SEP, ORS foundation, the Royal Society, and the Italian MUIR.

REFERENCES

Aloy M. A., Ibanez J. M., Marti J. M., Muller E., MacFadyen A. I., 2000, ApJ, 531, L119
Ballantyne D., Ramirez-Ruiz E., 2001, ApJ, 559, L83
Ballantyne D., Ramirez-Ruiz E., Lazzati D., Piro L., 2002, A&A, 389, L74
Begelman M. C., Cioffi D. F., 1992, ApJ, 345, L21
Begelman M. C., Blandford R. D., Rees M. J., 1984, Rev. Mod. Phy., 56, 255
Björnsson G., Hjorth J., Jakobsson P., Christensen L., Holland S., 2001, ApJ, 552, L121
Blandford R. D., Rees M. J., 1974, MNRAS, 169, 395
Bloom J. S. et al., 1999, Nat, 401, 453
Bloom J. S. et al., 2002, ApJ, 572, L45
Cavallo G., Rees M. J., 1978, MNRAS, 183, 359
Chevalier R. A., 1982, ApJ, 259, 302
Chevalier R. A., 1989, ApJ, 346, 847
Chevalier R. A., Li Z., 1999, ApJ, 520, L29
Colgate S. A., 1974, ApJ, 163, 221
Dado S., Dar A., De Rújula A., 2002, ApJ, 572, L143
Fryer C., Heger A., 2000, ApJ, 541, 1033
Garnavich P. M. et al., 2002, ApJ, submitted (astro-ph/0204234)
Goodman J., 1986, ApJ, 308, L47
Iwamoto K. et al., 1998, Nat, 395, 672
Kallman T. R., Mészáros P., Rees M. J., 2002, submitted (astro-ph/0110654)
Khokhlov A. M., Huflich P. A., Oran E. S., Wheeler J. C., Wang L., Chtchelkanova A. Y., 1999, ApJ, 529, L107
Kobayashi S., Piran T., Sari R., 1999, ApJ, 513, 669
Lazzati D. et al., 2001, A&A, 378, 996
MacFadyen A. I., Woosley S. E., 1999, ApJ, 524, 262
MacFadyen A. I., Woosley S. E., Heger A., 2001, ApJ, 550, 410
McLaughlin G. C., Wijers R. A. M. J., Brown G. E., Bethe H. A., 2002, ApJ, 567, 454
Matzner C. D., 2002, MNRAS, submitted (astro-ph/0203085)
Mészáros P., 2001, Sci., 291, 79
Mészáros P., Rees M. J., 1997, ApJ, 476, 232
Mészáros P., Rees M. J., 1998, MNRAS, 299, L10
Mészáros P., Rees M. J., 2001, ApJ, 2001, ApJ, 556, L37
Mészáros P., Waxman E., 2001, Phys. Rev. Lett., 87, 1102
Mészáros P., Rees M. J., Wijers R. A. M. J., 1998, New Astron., 4, 301
Mirabel I. F., Rodriguez L. F., 1999, ARA&A, 37, 409
Murakami T., Inoue H., Nishimura J., van Paradijs J., Fenimore E. E., 1991, Nat, 350, 592
Paczyński B., 1986, ApJ, 308, L43
Paczyński B., 1998, ApJ, 494, L45
Panaitescu A., Kumar P., 2000, ApJ, 543, 66
Panaitescu A., Kumar P., 2002, ApJ, 571, 779
Panaitescu A., Mészáros P., Rees M. J., 1998, ApJ, 503, 314
Piran T., 1999, Phys. Rep., 314, 575
Piro L. et al., 2000, Sci., 290, 955
Ramirez-Ruiz E., Merloni A., 2001, MNRAS, 320, L25
Ramirez-Ruiz E., Merloni A., Rees M. J., 2001, MNRAS, 324, 1147
Ramirez-Ruiz E., Dray L., Madau P., Tout C. A., 2001, MNRAS, 327, 829
Ramirez-Ruiz E., MacFadyen A. I., Lazzati D., 2002, MNRAS, 313, 197
Rees M. J., Mészáros P., 2000, ApJ, 545, L73
Reichart D. E., 1999, ApJ, 521, L111
Shemi A., Piran T., 1990, ApJ, 365, L55
Soderberg A. M., Ramirez-Ruiz E., 2002, MNRAS, 330, L24
Vietri M., Ghisellini G., Lazzati D., Fiore F., Stella L., 2001, ApJ, 550, L43
Wang L., Wheeler J. C., 1998, ApJ, 507, L87
Wang X. Y., Dai Z. G., Lu T., 2000, MNRAS, 319, 1159
Waxman E., Frail D., Kulkarni S., 1998, ApJ, 497, 288
Wheeler J. G., Yi I., Hoflich P., Wang L., 2000, ApJ, 537, 810
Wheeler J. C., Meier D. L., Wilson J. R., 2002, ApJ, 568, 807
Woosley S. E., 1993, ApJ, 405, 273
Woosley S. E., Langer N., Weaver T., 1993, ApJ, 411, 823

This paper has been typeset from a TEX/LATEX file prepared by the author.