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

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ABSTRACT

According to the collapsar model, -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 could itself be able to escape along the direction of least resistance, which is likely to be the rotation axis of the stellar progenitor, and accelerate in approximately the same way as an impulsive reball. 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 accumulates 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 -ray and X-ray transients, in addition to the standard afterglow emission that would arise from the deceleration shock of the cocoon reball.

Key words: gamma-rays: bursts \ stars: supernovae \ X-rays: sources \ Hydrodynamics

1 INTRODUCTION

Collimated outflows 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 (Beelen et al., Blandford & Rees 1984); microquasars (Mirabel & Rodríguez 1999); supernovae (Khokhlov et al. 1999);...
and X-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 outflow that may be collimated, exhibiting speeds of \(100\) or more (e.g. Waxman, Frail & Kulkarni 1998; Wang, Dai & Lu 2000; Panaitescu & Kumar 2002; Soderberg & Ramirez-Ruiz 2002).

Given the twin requirements of enormous energy \(10^{53}\) erg and association with star forming regions (see Meszaros 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 \(\gamma\)-rays must arise after the relativistic jet has broken free from the stellar progenitor, whose density is reduced along the rotation axis due to an early phase of accretion (MacFadyen & Woosley 1999; Lovelace et al. 2000; Heeger et al. 2000; MacFadyen, Woosley & Heeger 2001; Heeger, 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 He envelope at \(r \sim 10^{11}\) cm (MacFadyen & Woosley 1999; Meszaros & Rees 2001; Matzner 2002). At this stage (and provided that the density of the He envelope varies steeply with radius; see x3), 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 reball (its energy will be converted via adiabatic expansion into bulk kinetic energy.

Here we describe the evolution and collimation of such cocoon reballs. 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 reball 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-W olfrayet star. We show that even if only a small fraction of the energy in the jet (\(\leq 1\%\)) is deposited...
into the cocoon, it would have enough kinetic energy to substantially alter the structure of the expanding out ow, if not in fact provide much of the observed power. The latter may be true for an observer that lies o -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 composition, collimation and initial entropy) to determine whether or not this delayed reball will become matter dominated before it becomes optically thin. We discuss the possible role of cocoon reballs in producing -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 $\frac{E}{M} = M c^2$. It also provides a means for probing the state of the stellar medium through which both the initial jet and cocoon propagate.

2 C O C O O N S: "W A S T E B A S K E T S" O F R E L AT I V I S T I C P L A S M A

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 a 2M Fe core of radius $10^9$ cm and an 8M He core extending out to $r = 10^{13}$ cm (MacFadyen et al. 2001). In some cases, a cool H envelope reaches out to $>10^{13}$ 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 $p_{\text{He}} / r^4$ over some two decades in radius (Meszaros & Rees 2001). Beyond the He core, it drops drastically as $p_{\text{He}} / r^4$ since at these distances the pressure profile is still the pre-collapse one. The precollapse density of the presupernova model A25 of MacFadyen et al. (2001) scales roughly as $n_{\text{He}} / r^3$, so that the radiation-dominated pressure is $p / r^4$ (see Meszaros & Rees 2001).

Suppose that a collimated beam has been established. If all the particles in the beam are ultra-relativistic, then $p_j = \frac{1}{3}j c^2$ and the sound speed is $c_s = \frac{c}{\sqrt{3}}$. At a given time, the beam will have evacuated a channel out to some location where it impinges on the stellar
envelope[4] at a \textquotedblleft working surface\textquotedblright{} which itself advances out at speed \( V_h \) (see Fig. 1a). 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 \textquotedblleft working surface\textquotedblright{} to obtain

\[
\frac{L_j}{j^2c^2c} \quad \text{env} V_h^2 \quad v > V_h > c_j; \quad (1)
\]

where \( v \) is the speed of the beam, \( \text{env} \), the stellar envelope density, and \( c_j \) 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 generalised form alism 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 \( c = V_h \) \( \approx 1 \). The surplus (or waste) energy must then not accumulate near the \textquotedblleft working surface\textquotedblright{} but be deposited within a cocoon surrounding the jet (Fig. 1; slightly resembling the cocoons that envelop jets of radio sources: see Begelman et al. 1984 and Begelman & Ciolfi 1992).

After the jet emerges into the He 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 (\( V_h \approx c \)). Thus, if it is a general property that the jet becomes relativistic near the boundary of the He core, the outer edge of the He envelope is reached in a crossing time \( \tau = 2c^2 \frac{r}{V_h} \) as measured by an observer along the line of sight. For an He envelope density varying as \( \text{He} / r \), with \( r > 3 \) (see x3), the outer edge of the star is reached in a crossing time that may matter little when compared to the He-core traversal time[2]. The fraction of relativistic plasma injected into the cocoon after \( V_h \approx c \) will be much reduced (Meszaros & Rees 2001). The amount of energy that accumulated in the cocoon while the jet was advancing subrelativistically is then[3]

\[
E_c = \int_0^{\tau_{\text{He}}} L_j(t) \, \frac{r \, L_j}{V_h} \quad 5 \times 10^5 V_{h,10} \approx 10^{50} \text{ erg}; \quad (2)
\]

where \( \tau_{\text{He}} \) \( = V_h \) is the He-core traversal time, \( V_h \), the average speed of the jet head (which is about \( c/2 \); Aloy et al. 2000), and we adopt the convention \( Q = 10^8 \, Q_x \), using cgs units. The cocoon expands in the transverse direction with a velocity given by \( V_c \equiv Q \approx \text{env} \), \( (2) \approx (1) \).

The forces driving the cocoon expansion will be effective so long as \( p_c > p_{\text{env}} \) (Matzner 2002).

\[\text{References:}\]

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

3 Many presupernova stars, on the other hand, have density profiles with \( r \approx c \), and we adopt the convention \( Q = 10^8 \, Q_x \), using cgs units. 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).
The cocoon material could in principle reach pressure equilibrium with the external stellar gas, but this generally would not happen 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. 1c).

At the radius \( r \) (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, \( \text{cav} \), is related to both jet and cocoon expansion velocities by \( \text{cav} \propto (r^3V_c=V_{\text{th}})^2 \) (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 (since pressure balance may never be reached if the external pressure falls off much steeper than \( r^{-3} \)) will be inated which can expand most rapidly along the rotation axis (Fig. 1c) and may eventually escape the stellar progenitor. But it may never expand freely unless it escapes into an exponentially decreasing atmosphere with \( r > 5 \) (i.e. bare He star; see x3).

### 2.1 Trapping and collimation

Insofar 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, \( \theta \), of the expanding plasma. The stellar envelope, which contains the outflow along the axis, has a sufficiently large optical depth \( \text{env} \approx 10^1 \) that most of the radiation released is trapped, and transported into the cavity by bulk flow rather than diusing outwards. The optical depth across the cavity is enormous, even if it is so high that the baryon density is low, because of theThemal pair density (\( T > 20 \) 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 \( \sim T^2 \). If the magnetic
eld contributes significant to the total energy density (i.e. 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 (Blundford & 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 \( c \). If its free expansion starts just outside the nozzle, where the Lorentz factor of the cocoon material \( c \) is only \( 2 \), then it will spread over a wide angle and will develop into a roughly semi-spherical blast wave. The cocoon reball will then expand with \( c / r = r_{\text{cav}} \), where \( r_{\text{cav}} \) is the typical, initial dimension that the reball would have if it started out spherically.

3 THE STATE OF COCOON FIREBALLS

3.1 A brief overview of the reball model

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

In the so-called standard reball model (see Piran 1999 for a recent review), it is conjectured that the reball wind, expelled by a central source of dimension \( r_0 \sim 10^6 \) cm (notice than in the case of the cocoon reball, 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 reball energy is converted into kinetic energy at \( r_0 \) (Cavallo & Rees 1978; Goodwin 1986; Paczynski 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

\[
r = \frac{r E_4}{4 m_p c^2}^{1/2} ;
\]

where \( E_4 \) is the isotropic equivalent energy generated by the central site. The inertia of the
swept-up external material decelerates the shell ejecta signally by the time it reaches the
deceleration radius (Meszaros & Rees 1997; Chevalier & Li 1999):
\[ r = \frac{(3s)E_4}{m_pA c^2} \times \left( 1 - \left( \frac{3s}{E_4} \right) \right) \]
where the external medium particle density is \( n(r) = \frac{n}{r^s} \), with \( s = 0 \) for a homogeneously
medium \( n(r) = n_{\text{im}}, \) 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 then strongly
determines where both internal and external shocks develop (see e.g. Fig. 3 of Ramirez-Ruiz,
Merloni & Rees 2001). Changes in \( n \) will modify the dynamics of the shock deceleration and
the manifestations of the afterglow emission.

3.2 The propagation of cocoon rebolls

The above summary describes the qualitative features of the generic reball 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 reball of energy \( E_c \), total mass \( M_c \) initially con ned to a
cocoon cavity. Clearly, since \( c > 1 \), the initial reball will be an opaque sphere in them al
equilibrium, characterised by a single temperature: \( T_c = \frac{400gE_{c14}^{1-4} r_{cav}^{3-4}}{2} \) keV in a spherical
cocoon cavity, or \( T_c = \frac{100gE_{c14}^{1-4} r_{cav}^{1-4}}{2} \) keV in a "hourglass" cocoon. \( g = 11/4 \) for \( T_c > m_e c^2 \)
(photons and pairs), and it drops to 1 when \( T_c \) \( m_e c^2 \) (only photons).

When the radiation energy dominates the evolution (i.e., \( c = 1 \)), the shell expands
under its own pressure such that its Lorentz factor grows linearly with radius, \( c / r = r_{cav} \).
When the reball has a size of \( r_c = r_{cav} \), all the internal energy has been converted into
bulk kinetic energy and the matter coasts asymptotically with a constant Lorentz factor. 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 Figure 2. When there is a remaining H envelope (with \( H / r \))
beyond the He core, the deceleration radius of the cocoon reball may well be inside the star.
The energy required to sweep up an external stellar mass of \( M_{\text{env}} \) is \( \frac{2}{3} m_{\text{env}} c^2 \), where \( c / r \)
and $m_{\text{env}} / (r/r^3) \rightarrow 3$. Thus, the cocoon blast wave is undecelerated for $r > 5$. By the same token, the initial relativistic jet will expand freely provided $r > 3$. For a moderately dense H envelope, the cocoon rebball, which starts being decelerated by the stellar matter at $r < r_0$ (see curve (a) of Fig. 2), emerges from the H envelope with a Lorentz factor $c_\gamma < 1$. For an extended or denser H envelope, corresponding to curve (c) in Figure 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; Paczynski 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

The baryon load build-up in the cocoon reservoir, $M_c = E_c = c^2$, influences the rebball evolution by increasing the opacity and thus delaying the escape of radiation. The electron pair opacity, $\rho_e$, decreases exponentially with decreasing local temperature, and falls to unity when $T_p = 20$ keV. The matter opacity, $\rho_m$, on the other hand, drops as $r^{-2}$, and thus the escape temperature may drop far below $T_p$ if $\rho_e > \rho_m > 1$ (Shemi & Piran 1990; Piran 1999). Two critical values for $\rho_e$ determine the order of these transitions:

$$p = \frac{3 \frac{2}{c^2 m_{\text{p}} c^2 r_c^2}}{E_c T_p^4} 10^{10} E_c^{1-2} \rho_{\text{env}}^{1-2} c_\gamma^{1}$$

and

$$b = \frac{3 \frac{2}{c^2 m_{\text{p}} c^2 r_c^2}}{5} 10^{10} E_c^{1-3} \rho_{\text{env}}^{2-3} c_\gamma^{2-3}$$

The effect of the baryons is only negligible when $p > 1 > b$. If $p$ is less extreme, there are two qualitative changes in the rebball's mode of propagation. First, the matter opacity becomes important when $p > b = 5 10^{10} E_c^{1-3} \rho_{\text{env}}^{2-3} c_\gamma^{2-3}$. The comoving temperature, in this case, decreases far below $T_p$ before it reaches unity, yet the rebball continues to be radiation-dominated and most of the energy still escapes as radiation. Second, for smaller than $b$, the rebball becomes matter-dominated before it becomes optically thin, and most of the initial energy is converted into bulk kinetic energy (this is likely to be the common situation for the initial jet rebball; see x3.1). 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, Woosley & Heger 2001). One would expect baryon contamination to be the lowest near this axis, because angular momentum is 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 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 $p_H / r^4$. In addition to the stellar pressure required to stall the initial jet, there is another, smaller pressure which can prevent the cocoon material to expand freely. The cocoon reball will, in general, be easier to conne than the initial jet, for two reasons: first, the fraction of material with a clear line of sight along the rotation axis will be much reduced (i.e., $c / \sin \theta > 1$), and second, the cocoon blast wave may never expand freely for an H envelope density varying as $H / r$ with $< 5$.

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

reball, 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 that of a cold reball propagating through a similar density profile would (Fig. 2). If the H envelope did not exist, then the cocoon reball would reach the outer edge of this envelope after a few seconds, corresponding to case (a) in Fig. 2, where $t_{\text{eff}} = \tau_{\text{col}} = (2c^2) r_H / c$. 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 \( V_c \approx c (\beta = M_{\text{env}} c^2)^{1/2} \) \( \times 10^6 (M_{\text{env}} = M) \)^{1/2} \( \text{cm s}^{-1} \) (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 reball to relativistic velocities), the cocoon shell cools with \( T \sim (r/r_{\text{cov}})^{1/4} \). The coating photons, whose local energy is \( T \), are blue shifted. An observer detects them with a temperature of \( T_{\text{obs}} \approx c(r) T(r) \). Seeing that \( T \sim r^{-1} \) and \( c \sim r \), we find that during the acceleration stage \( T_{\text{obs}} < T_c \), where

\[
T_c \sim 34 r^{-2/3} V_{\text{cosp}}^{-1/2} \text{keV} \quad \text{(hourglass)}
\]

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

In the case of a successful break-through of the jet, a strongly decelerated, cocoon reball 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 \( > 10^{50} \) erg. The observed duration of this emission would be of the order of \( r_c = (c_\beta^2) \) 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 980326 (Bloom et al. 1999); GRB 970228 (Reichart 1999); GRB 990712 (Bjornsson et al. 2001); GRB 000911 (Lazzati et al. 2001); GRB 011211 (Bloom et al. 2002; Dado et al. 2002; Gamavič et al. 2002). The decelerating external shock of a cocoon reball 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 lam ents in pressure equilibrium with the shocked envelope ejecta (Meszaros & Rees 1998).

It is, of course possible that the initial jet is a magnetically con ned 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 $L_{E}=t_{\text{eff}} 10^7 \text{ erg s}^{-1}$. A magnetic field of $10^5 \text{ G}$ could confine clumps of gas with densities up to $n > 10^{17} \text{ cm}^{-3}$, 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 Meszaros & Rees 2001) and (in the absence of both entrainment and substantial pair production) may also excite Fe-line emission. If the UV/X-ray continuum can maintain a ionization parameter $\ionpar = L_x/\av$ of the order of $10^3 10^7$, a modestly supersolar Fe mass fraction could yield a recombination line luminosity comparable to the one observed in GRB 991216 (Piro et al. 2000; Ballantyne & Ramirez-Ruiz 2001; Vietri et al. 2001; McLaughlin et al. 2002; Ballantyne et al. 2002; Kallman, Meszaros & Rees 2002).

5 COMPACT PROGENITORS, GRB PRECURSORS, AND AFTERGLOW SIGNATURES

A relativistic cocoon reball is likely to escape if the star loses its hydrogen envelope before collapsing (MacFadyen & Woosley 1999; Aloy et al. 2000; Heefer et al. 2000; MacFadyen et al. 2001; Matzner 2002). This is expected for example in stars with high radiative mass-loss (e.g. Ramirez-Ruiz et al. 2001). The reball cocoon will then emerge from the He core into an exponentially decreasing atmosphere and into the radiated circumbinary environment beyond it, where it acquires the limiting bulk Lorentz factor $\gamma_b$, unless of course, $\gamma_b > 1$. 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 $r_c = r_{\text{cav}}$ (where $r_c < r$) and most of the energy escapes as photons. As follows from
the previous discussion, an observer will detect them with a temperature of $T_{\text{obs}} / c T$.
Thus the observed off-peak frequency would be in the BATSE [20-600] keV spectral window (see equation 7) for compact He envelopes $r < 10^1$ cm (the outer edge of the He core varies with initial mass, roughly as $r < 10^1 (M_\odot = 35 M_\odot)^2$; Woosley, Langer & Weaver 1993). For extended He envelopes ($r > 10^{12}$ cm), however, the therm al emission could be detectable with instruments like 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
\[ t = \frac{2c}{r_c} + \frac{2c}{r_c} \max (r_j, r_{\text{int}}) = \frac{2c}{r_c}, \]
where $r_{\text{int}}$ is the radius of internal shocks in the jet reball. The thermal signal emerging from a cocoon reball with $p > b$ will most likely appear as a transient signal at the beginning of the main burst since $t_j < 6$ s. In contrast to the main burst, this signal would only last for $r_{\text{cav}} = c 01$ s. In contrast to the main burst, this signal would only last for $r_{\text{cav}} = c 01$ s.

The cocoon reball will strongly modify the usual properties of the standard internal shocks and the afterglow emission when $p < b$ (i.e., the cocoon reball 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 $7 r_{\mu_1}$ seconds, minus the fraction dissipated (and converted into prompt -rays) in internal shocks. The size of the stellar cavity and the initial Lorentz factor, along with the jet lifetime, strongly determine whether or not the cocoon reball would carry less energy and inertia than the relativistic jet itself. For $E_\pi \geq E_\pi j$, the main afterglow will be dominated by the deceleration of the cocoon reball (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 o-axis to the jet, there could be a large fraction of detectable afterglows for which no -ray event is detected (commonly referred to as\textquotedblleft burstless\textquotedblright or \textquotedblleft orphan\textquotedblright 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 ($t < \frac{r_j}{2c}$), when the afterglow emission produced by the jet reball dominates. The afterglow shock may experience, after starting out in the canonical manner, a \textquotedblleft resurgence\textquotedblright similar to the shock
refreshment produced by the delayed energy injection of a long-lived central engine (see Panaitescu, Meszaros & Rees 1998 for the case of GRB 970508).

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 since entrainment may dominate in the initial reball $E_{4, j} = \frac{4E_j}{E_j} > E_{4, c} = \frac{4E_c}{E_c}$). Figure 4 shows the evolution of both jet and cocoon reballs for this matter-dominated case. The adiabatic reball evolution (thick solid line) was computed using a similar numerical method to the one developed by Kobayashi, Sari & Piran (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 reball. Figure 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 sub-mm illiter 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 sub-mm illiter 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 reball emission.

There could also be additional precursor signatures which are not associated with the ejecta blast wave, but with the dynamics of the reball at the coasting phase. The -ray (i.e. internal shocks) signal emerging from the cocoon reball would precede by $\frac{r_j^3}{2c^2}$ a few seconds that produced by the initial relativistic wind (provided that $E_{4, j} > E_{4, c}$ and $\frac{r_j}{2c} > r_{\text{cav}}$). The observed variability time scale of this prompt -ray emission is related to the typical size of the shocked plasma region containing the photon field: $r_{\text{cav}}$ or $r = 2$ for $r > r_{\text{cav}}$. For compact stellar cocoons (i.e. $r < 10^{11}$ cm), the expected delay between the cocoon precursor and the main pulse, $t$, would be proportional to the total initial jet energy: $E_{4, j}$. It will then simply reflect a correlation between the burst strength and the time elapsed since the previous emission episode, similar to what is observed in GRB lightcurves (Ramirez-Ruiz & Merloni 2001).
We have discussed, in the context of a collapsar model of gamma-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 vary monotonically with radius as \( \frac{H}{r} \), the properties of the cocoon plasma would be similar to those argued in \( x_3 \). A collimated cocoon moving into a region with \( 5 \) (i.e. no H envelope) will become overpressed relative to its surroundings, and thereafter expands freely. If the relativistic jet carries less energy and inertia than the cocoon plasma itself \( \left( \frac{E_j}{E_c} > \frac{E_j}{E_c} \right) \), it will start to decelerate at a smaller radius than the collimated cocoon ball, 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 o-axis cocoon material (since \( j \)), so that it dominates the ux after expanding for a longer time than the initially observed o-axis region.

Additional effects are expected when the cocoon reball material becomes optically thin. Shock waves within the plasma can contribute with a short-lived (few seconds) non-thermal /X-ray transient for a cocoon propagating inside a compact post-W olfrayet star (and so long as \( b 5 10^{13} \frac{E_{cp}^2}{r_{cav}} < 0.5 \); see \( x_3 \)). For very extended or slow rotating stars, a long lasting (few hours to a day) UV/X-ray (almost) thermal pulse, whose total energy may be a few percent 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 ULV/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, 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 reball jet, bursts and afterglows may have a more complex spectra and time-structure than those alluded to the "standard" model.

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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 reball (c).
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 (logarithmically) are $\eta$ versus $r$, where $r = r_{\text{cav}}$ 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), and the cocoon blast wave sweeps up all the envelope's matter before it has been decelerated. When the remnant has a size of $r_{\text{f}} = r_{\text{cav}}$, all the internal energy has been converted into bulk kinetic energy and the matter coasts asymptotically with a constant Lorentz factor. In case (b), with higher stellar density, deceleration occurs at radii $< r_{\text{f}}$, 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 $c < $ . 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.
Figure 3. Schematic plot of the escape temperature $T_{\text{obs}}$ as a function of radius for the three, qualitatively different cases depicted in Figure 2. As it expands, the cocoon will cool with $T \propto (r-r_{\text{cav}})^{-1}$. The coasting photons, whose local energy is $T$ are blue shifted. An observer would detect them with a temperature of $T_{\text{obs}} \propto c (r) T (c)$. These photons would escape freely after the expanding remnant becomes optically thin, which is likely to occur at some distance from $r_{\text{H}}$. 
Figure 4. Evolution of a matter dominated, cocoon rebal from its initial formation at rest to its final stage. Both the initial jet (solid line) and the cocoon rebal (dashed dotted line) propagate into the exponentially decreasing H atom sphere 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 due to interaction with the ISM via a relativistic forward shock and a Newtonian reverse shock. The parameters for this computation are: \( \gamma = 10 \), \( r_{\text{cav}} = 10^9 \) cm, \( L_j = 10^{52} \) erg s\(^{-1}\), \( n_{\text{ISM}} = 1 \) cm\(^{-3}\), \( j = 0.1 \) and \( c = 1.0 \). Shown are the numerical value of the average Lorentz factor (solid and dashed lines) and its analytical estimate (dotted line).
Figure 5. Comparison between the initial jet and the cocoon afterglow lightcurves at early times and at observing frequency $= 10^{12}$ Hz. The afterglow brightness depends on the relationship between this frequency and those of the injection ($m$), cooling ($\gamma$), and absorption ($\alpha$) breaks (e.g., Panaitescu & Kumar 2000). The dotted and dash lines represent the jet and cocoon afterglow contributions corresponding to the parameters of the calculations shown in Figure 4.