Collapsar Jets, Bubbles and Fe Lines

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ABSTRACT

In the collapsar scenario, gamma ray bursts are caused by relativistic jets expelled along the rotation axis of a collapsing stellar core. We discuss how the structure and time-dependence of such jets depends on the stellar envelope and central engine properties, assuming a steady jet injection. It takes a few seconds for the jet to bore its way through the stellar core; most of the energy output during that period goes into a cocoon of relativistic plasma surrounding the jet. This material subsequently forms a bubble of magnetized plasma that takes several hours to expand, subrelativistically, through the envelope of a high-mass supergiant. Jet break-through and a conventional burst would be expected not only in He stars but possibly also in blue supergiants. Shock waves and magnetic dissipation in the escaping bubble can contribute a non-thermal UV/X-ray afterglow, and also excite Fe line emission from thermal gas, in addition to the standard jet deceleration power-law afterglow.

Subject headings: Gamma-rays: Bursts - Stars: early type - Hydrodynamics - X-rays: general - Line: formation

1. Initial Model

Collapsars seem a good model for the ‘long’ (Beppo SAX) gamma-ray bursts (GRB), though not for the short ones (e.g. Paczynski, 1998; Woosley, 1999). Numerical simulations of the progenitor collapse have been made, e.g. by MacFadyen, Woosley & Heger (2001) and references therein. We will use as an example their progenitor model A25, a pre-supernova star of initial mass $M_i = 25M_\odot$, reduced to $14.6M_\odot$ by mass loss, with restricted semi-convection and rotation. This has a red supergiant structure, with a $\sim 2M_\odot$ Fe core of radius $r_{Fe} \sim 7 \times 10^8$ cm, an $8.4M_\odot$ He core extending out to $r_{He} \sim 10^{11}$ cm, and a hydrogen envelope out to $r_{H} \sim 10^{13}$ cm. The average specific angular momentum within the He core is $j \sim 5 \times 10^{16}$ cm$^{-2}$s$^{-1}$, with values $\sim 50\%$ higher in the equator. However, the results we shall discuss also apply qualitatively to other cases,
e.g. models with larger initial masses, which may have lost more or all of their H envelope and whose outer radii are $\sim r_{He} \sim 10^{11}$ cm.

A central black hole (BH) of several $M_{\odot}$ forms after collapse of the Fe core, in a free-fall $t_{ff,Fe} \sim 1$ s, and the subsequent jet evolution was calculated numerically, non-relativistically by MacFadyen et al. 2001, and relativistically by Aloy et al., 2000. These calculations assume that thermal energy generated by the accreting BH is deposited in a conical region between 200-600 Km out along the rotation axis. In Aloy et al.’s calculation, using a star similar to A25 but without an H envelope, the jet bulk Lorentz factor reaches intermittently values $\bar{\Gamma}_j \lesssim 5-30$ in rarefied portions of the flow not near the head of the jet, while throughout most of the star the average jet advance speed is $\lesssim 10^{10}$ cm$^{-1}$. This would have interesting implications for the ability of the collapsar to make a GRB: jets fed by a central engine whose duration (say, $t_j \lesssim 10-100$ s) is shorter than a crossing time would not break through, and would not produce a GRB (MacFadyen et al., 2001).

Some aspects of the dynamics may, however, modify the development of the jet in a rapidly rotating collapse, particularly if there is a delay between the formation of a collapsed core and the initiation of a jet. The effect of rotation is to create a funnel of a determined shape along the rotation axis, within which the density becomes substantially lower than the equatorial. This is because, within this funnel, material drains into the hole on a free-fall timescale, rather than being centrifugally supported. Jets that propagate out after this funnel has developed would, at least at small $r$, develop differently from those studied by Aloy et al. (2000) and MacFadyen et al., 2001.

The pre-collapse central density of the pre-SN model A25 is $\rho \approx 10^{12}$ cm$^{-3}$, and out to the edge of the He core $r_{He} \sim 1.5 \times 10^{11}$ cm it scales roughly as $\rho \propto r^{-3}$, while the (radiation dominated) pressure is $p \propto \rho^{4/3} \propto r^{-4}$. Loss of pressure support leads in a few seconds (the free-fall time from the radius enclosing the innermost few solar masses) to a BH, girded by a centrifugally supported torus, which heats up to virial temperatures and cools through neutrino losses. Mass infall proceeds freely along the rotation axis, leading via the continuity equation to $\rho \propto r^{-3/2}$. Thus, a few seconds after collapse, the gas density inside the funnel near $r_0 \gtrsim 10^6$ cm may be approximated by the pre-collapse density at the edge of the Fe core at $r_{Fe} \sim 7 \times 10^8$ cm multiplied by the free fall compression ratio, $\rho_{i,0} \approx \rho_{Fe}(r_{Fe}/r_0)^{3/2} \approx 5 \times 10^{10} K_i r_{Fe}^{3/2} r_0^{-3/2}$ g cm$^{-3}$. The gas outside the funnel, which takes a free-fall time to form, initially was in approximately radial free-fall, until it starts to pile up near the equatorial plane. A jet, fed near $r_0$ by a strong Poynting flux from the inner disc or the hole itself, will then be channeled along the rotation axis. In reality, the jet power may fluctuate; so also may its baryon content, due to entrainment, or to unsteadiness in the acceleration process at the base of the jet. In the following section, however, we treat the jet as being steady.
2. Jet Dynamics

The dynamics of the collapsing rotating stellar gas with a BH at the bottom implies that there is a critical specific angular momentum \( J_0 \sim 10^{16} \text{cm}^{-2} \text{s}^{-1} \). Since the transverse velocity at radius \( r \) cannot exceed the escape velocity (\( \propto r^{-1/2} \)) this implies (Fishbone & Moncrief, 1976) that, after the BH forms, there is a funnel around the rotation axis, within which there can be no axisymmetric equilibrium. For \( r \gg r_0 \) the funnel opening angle has a paraboloid shape,

\[
\theta_s \sim \theta_0 (r/r_0)^{-1/2}.
\]

Matter falling in from the outer edge of the Fe core at \( r \sim 10^9 r_{Fe,9} \) cm will, in a few seconds, result in a considerably lower density within the funnel near the BH horizon, creating the conditions for the launching of a jet. As inferred GRB and afterglow observational fits, the jet must be injected with a dimensionless entropy per baryon \( \eta = (L_j/\dot{M}c^2) \sim 10^2 \eta_2 \), where \( L_j \) is kinetic luminosity, \( \dot{M} \) is mass loss rate, \( c = 3 \times 10^{10} \text{cm} \text{s}^{-1} \). This implies a low density, highly relativistic jet, injected by the central engine at the base of the outflow. For the purposes of calculation we take an initial Lorentz factor \( \Gamma_0 \sim 1 \) and an initial jet opening angle \( \theta_0 \sim 1 \) (in radians; e.g. Aloy, et al., 2000). We assume a steady, adiabatic jet (internal shocks would occur, if at all, at radii \( \gtrsim 10^{12} - 10^{13} \) cm, while small scale, Thomson-thick dissipation results in trapped radiation which is effectively adiabatic). From the relativistic Bernoulli equation (e.g. Begelman et al., 1984), the jet, of opening angle \( \theta_j \), gradually converts at \( r > r_0 \) its internal energy into bulk kinetic energy with \( \Gamma_j > 1 \),

\[
\Gamma_j \propto (r\theta_j) = \begin{cases} 
\Gamma_0(r/r_0)^{1/2} & (\theta_j \propto r^{-1/2}, \ r \lesssim r_f); \\
\Gamma_0(r_f/r_0)^{1/2}(r/r_f) & (\theta_j = \text{const.}, \ r \gtrsim r_f),
\end{cases}
\]

where \( r_f \) is defined in equation (4). Thus the jet internal Lorentz factor increases as \( \Gamma_j \propto r^{1/2} \), until the jet opening angle behavior changes or until a maximum saturation value \( \Gamma_j \sim \eta = 10^2 \eta_2 = \text{constant} \). The funnel behavior \( \theta_j \propto r^{-1/2} \) can be maintained only so long as transverse balance holds between the jet pressure (assumed isotropic) and the stellar pressure outside the funnel. The radius where this occurs depends on specific assumptions about jet production. (Note that ours differ from Aloy et al., 2000; we assume that jet propagation starts after a parabolic funnel has developed; and we postulate a jet injection with high internal energy to rest mass ratio, constant throughout the central energy life).

A key aspect is that the \( \Gamma_j \gg 1 \) jet slows down abruptly in a narrow layer near the head of the jet, which advances into the star with an initially sub-relativistic velocity. The jet head velocity \( V_h < c \) is given by the longitudinal balance between the jet thrust per unit area \( p_{j\|} \sim (L_j/2\pi \theta^2 cr^2) \) and the ram pressure of the funnel material ahead of it, \( p_e \sim \rho_i(r)V_h^2 \). This gives at \( r_0 \) a fiducial jet head velocity

\[
V_{h0} = V_h(r_0) \sim 10^8 L_{50}^{1/2} K_i^{-1/2} \theta_0^{-1/4} \rho_{10,6}^{-1/4} r_{Fe,9}^{-3/4} \text{cm}.
\]

(This is a crude approximation of the dynamics near \( r_0 \), because of the possible rapid infall of the gas, and the complexities of jet formation; however, it sets the scale for the values of \( V_h \) at \( r \gg r_0 \) where the approximations are likely to be better).
In front of the contact discontinuity between the jet and the stellar gas there is a thin layer of shocked stellar gas moving ahead with velocity \( \sim V_h \) into the star. Behind the contact discontinuity there is a shock where the relativistic jet material, with \( \Gamma_j \gg 1 \), is slowed to a velocity of order \( V_h \). Between this inner shock and the contact discontinuity is a layer of shocked relativistic plasma which also moves with velocity \( \sim V_h \). Both the unshocked \( \Gamma_j \gg 1 \) jet gas and the (higher pressure) shocked relativistic gas remain, at low radii, trapped in the transverse direction by the paraboloidal funnel \( \theta_j \propto r^{-1/2} \), sideways expansion being prevented by the much higher external pressure (and inertial confinement, beyond \( r_f \) given by equation \( 3 \)). The shocked jet gas would have such a high electron density (augmented by pairs) that radiation would be trapped, so that it behaves adiabatically even for short radiative cooling times. The shocked material occupies a volume \((c/V_h)\) larger than the jet material itself, so the relativistic shock would be located \((c/V_h)^{1/2}\) closer in than the head of the jet (since the volume within a thin paraboloid goes as \( r^2 \)). In the stellar frame, the pressure of the unshocked relativistic jet in the transverse direction is, from the relativistic Bernoulli equation, \( p_{j\perp} \sim (1/3) L_j/(2\pi r^2 \theta^2 c \Gamma_j^2) \sim 4 \times 10^{25} L_5 \theta_0^{-2} \Gamma_j^{-2} (r/r_0)^{-2} \) cgs, as long as \( \theta_j \propto r^{-1/2} \). At \( r \ll r_{Fe} \sim 10^9 r_{Fe,9} \) cm a few seconds after the collapse, we can approximate the stellar gas density profile outside the funnel as given by free-fall, \( \rho \propto r^{-3/2} \), with a (radiation dominated) pressure \( p \propto \rho^{4/3} \propto r^{-2} \). Using MacFadyen et al.’s 2000 pressure at \( r_{Fe} \), the value near \( r_0 \) is \( p_{e,0} \sim p_{Fe}(r_{Fe}/r_0)^2 \sim 4 \times 10^{29} K_o^{4/3} r_{Fe,9}^2 \rho_0^{2/3} \) dyne cm\(^{-2}\), where \( K_o \sim 1 \), and \( p_e = p_{e,0}(r/r_0)^{-2} \sim 4 \times 10^{29} K_o^{4/3} \rho_0^{2/3} r_{Fe,9}^2 \) cgs. The external pressure at low radii is much larger than that of the unshocked \( \Gamma_j \gg 1 \) jet. The shocked jet gas pressure is larger than that of the unshocked jet gas, since it moves with \( V_h < c \) and is not affected by the \( \Gamma_j^{-2} \) factor. The value of \( p_{h\perp} \sim (1/3) L_j/(2\pi r^2 \theta^2 c) \sim p_{h||} \) is comparable to the external ram pressure \( p_{e} V_h^2 \), and decays as \( p_{h\perp} \sim 5 \times 10^{20} L_5 \theta_0^{-2} r_0^{-2} (r/r_0)^{-1} \) cgs, whereas the (initially higher) external pressure is \( \propto r^{-2} \). They become equal at a radius \( r_f/r_0 \sim 10^3 L_5^{-1} K_o^{4/3} \theta_0^2 r_{Fe,9} \) or

\[
r_f \sim 10^9 L_5^{-1} K_o^{4/3} \theta_0^2 r_{Fe,9} \rho_0^{2/3} \text{ cm},
\]

which is close to the radius \( r_{Fe} \). (The exact details of the external pressure profile below \( r_{Fe} \) are not crucial, as long as it depends on \( r \) more steeply than the shocked-jet gas pressure \( 1/r \)). At the radius \( r_f \), the funnel opening angle is then

\[
\theta_f = (r_f/r_0)^{-1/2} \sim 3 \times 10^{-2} L_5^{1/2} K_o^{-2/3} \theta_0^{-1} r_{Fe,9}. \]

For \( r > r_f \) the transverse pressure of the shocked jet material exceeds the external stellar pressure, and it can no longer be confined inside the paraboloidal funnel \( \theta_j \propto r^{-1/2} \). It spills out sideways and trails behind the jet, creating a sheath of low density, relativistic material resembling the cocoons (cf Scheuer 1974) that surround the relativistic jets of radio sources. In Aloy et al. 2000, based on different initial assumptions, a cocoon appears at smaller radii. Cocoons are generally over-pressured, whenever their boundary moves faster than the sound speed in the surrounding stellar gas. The cocoon expands in the transverse direction until it reaches pressure equilibrium with the external stellar gas. The jet head advances subrelativistically with \( V_h < c \).
But the shocked jet material has an internal sound speed \( \sim c/3 \), so the pressure in the cocoon is equalized almost instantaneously throughout its entire volume. The unshocked jet gas moving with \( \Gamma_j \gg 1 \) is now constrained in the transverse direction by the pressure of the cocoon bubble, which in turn is in equilibrium with the external stellar pressure, \( p_b \sim p_e \propto r^{-n} \) (where for \( r \gg r_{Fe} \) we take the approximate pre-collapse pressure profile \( n \sim 4 \), e.g. §1). The relativistic jet opening angle \( \theta_j \) adjusts itself to satisfy \( p_{j\perp} \propto L_j/(r^2\theta_j^2\Gamma_j^2) \propto p_b \propto p_e \propto r^{-n} \), and \( \Gamma_j \propto (r\theta_j) \), so

\[
\theta_j \propto r^{(n-4)/4} \propto \begin{cases} r^{-1/2} & \text{for } r \lesssim r_{Fe}; \\ \text{constant} & \text{for } r \gtrsim r_{Fe}. \end{cases}
\]

Thus, above \( r_f \sim r_{Fe} \), the jet becomes ballistic, with \( \theta_j \sim \theta_f \sim \text{constant} \), which from equation (3) is a few degrees. From \( p_{j\parallel} \propto L_j/(r^2\theta_j^2) \propto p_eV_h^2 \), the jet head advance velocity is

\[
V_h \propto r^{n/8} \propto \begin{cases} r^{1/4} & \text{for } r \lesssim r_{Fe}; \\ r^{1/2} & \text{for } r \gtrsim r_{Fe}. \end{cases}
\]

The head reaches \( r_f \sim r_{Fe} \) in approximately a second, with \( V_h(r_f) \sim 10^9L_{50}^{1/2}K_i^{-1/2}\theta_0^{-1}r_{0.6}^{-1/2}r_{Fe,9}^{-1/2} \text{ cm/s}. \) The bubble surrounding the jet would be cigar-shaped (cf Scheuer 1974) in a uniform pressure external medium. However, a stellar pressure \( p_e \propto r^{-n} \) will result in a bottom-up pear shape (also in Aloy et al.2000). Balancing the bubble pressure \( p_b \sim L_j t/(\pi r^2 \theta_j^2 V_h t) \) and the external pressure \( p_e \propto r^{-n} \), the bubble opening angle \( \theta_b \) is

\[
\theta_b \propto r^{(n-2)/2}V_h^{-1/2} \propto r^{(7n-16)/16} \propto \begin{cases} r^{-1/8} & \text{for } r \lesssim r_{Fe}; \\ r^{3/4} & \text{for } r \gtrsim r_{Fe}. \end{cases}
\]

For the model used here the second line is applicable, since the external pressure equals the jet pressure at \( r_f \sim r_{Fe} \), and it is only beyond this equality radius that the shocked relativistic plasma can expand sideways to form a cocoon.

At \( r > r_f \sim r_{Fe} \sim 10^9r_{Fe,9} \text{ cm} \), for the timescales of a few seconds of interest here, the pre-collapse profile \( p_e \propto r^{-n} \) applies with \( n \sim 4 \). From equation (7) the jet head velocity \( V_h \propto r^{1/2} \to c \) by the time it reaches \( r_{He} \sim 10^{11}r_{He,11} \text{ cm} \), approximately 10 seconds after jet is launched. For \( r > r_f \) the jet opening angle remains constant, \( \theta_j \sim \theta_f \sim 0.03 \). From equation (2), the internal Lorentz factor \( \Gamma_j \sim \Gamma_0(r_f/r_0)^{1/2}(r/r_f) \propto r \), and, in the absence of strong internal dissipation, it reaches its maximum saturation value \( \Gamma_j \sim 10^2\eta_2 \) (where \( \eta = \dot{L}_j/Mc^2 \)) at a radius \( r_\eta \) where \( r_{Fe} < r_\eta < r_{He} \).

If the external pressure changes gradually, causal contact can be maintained across the jet with the exterior (ensuring that the jet is able to bend smoothly along the funnel) when \( \theta_j, \Gamma_j \lesssim 1 \) for \( \Gamma_j < \eta \), and \( \theta_j, \Gamma_j \lesssim (v_{th}/c)^2 \) for \( \Gamma_j = \eta \). Here \( v_{th} \) is sound speed, and \( (v_{th}/c)^2 \propto r^{-2/3} \) accounts for adiabatic cooling after the Lorentz factor saturates. The first case is approximately satisfied for \( r < r_f \), since \( \Gamma_j \sim \theta_0\Gamma_0 \sim 1 \sim \text{constant} \).

The energy concentration in the bubble is not of course as extreme as in the inner jet itself, but it is still exceedingly high: even at \( r \sim 10^{11} \text{ cm} \), the energy density would be \( \sim 10^{20} \text{ erg cm}^{-3} \), corresponding to field strengths more than \( 10^{10} \text{ G} \).
At the edge of the He core $r_{He} \sim 10^{11}r_{He,11}$ cm, which has not had time to collapse before the jet reaches it (at $t \sim 10$ s after the jet is launched), the density suddenly drops by a large factor, from about $\rho_{He} \sim 1$ g cm$^{-3}$ to $\rho_{H} \sim 10^{-8}\rho_{H,-8}$ g cm$^{-3}$. These values are for the stellar model A25 of MacFadyen et al., 2001, but the behavior is typical of massive stars (Woosley, Langer & Weaver, 1993), e.g. supergiants and Wolf-Rayet stars. When there is a remaining H envelope beyond the He core, as in model A25, it has a drastically lower density, out to an outer radius $r_{H} \gtrsim 10^{13}r_{H,13}$ cm. The sudden, large density drop at the boundary of the He core gives a large boost to the jet head Lorentz factor, from $\Gamma_{h} \sim 1$ to a highly relativistic value. Whether the jet head is relativistic or sub-relativistic upon arrival at $r_{He}$, beyond this radius the jet head Lorentz factor is given by balancing the jet thrust to the external ram pressure in the (much) reduced density H envelope, using the final jet opening angle $\Theta_{o}$. Thus, the head of the jet emerges from the He core into the H envelope with a Lorentz factor

$$\Gamma_{h,He} \simeq 50K_{\rho}^{1/3}\theta_{0}^{1/2}r_{0}^{1/4}r_{He,9}^{1/4}r_{He,11}^{1/4}\rho_{H,-8},$$

(9)

not far below the limiting value $\eta = 10^{2}\eta_{2}$. For a slowly varying H-envelope density $\rho_{H} \propto r^{-m}$ (where $m \lesssim 1/2$ approximately fits the typical stellar models), the head Lorentz factor varies as $\Gamma_{h} \propto r^{-1/2-m} \propto r^{-3/8}$ for $m = 1/2$. Near the outer edge of the H envelope, its value is $\Gamma_{h,H} \sim 10K_{\rho}^{1/3}\theta_{0}^{1/2}r_{0}^{1/4}r_{He,9}\rho_{H,-8}^{1/4}r_{He,11}^{1/4}$. This is reached in a crossing time $t_{H} \sim r_{H}/2c\Gamma_{h,H}^{2} \sim 2K_{\rho}^{2/3}\theta_{0}^{-1}r_{He,9}\rho_{He,9}^{-1/2}r_{He,11}^{-1/2}$. After that, the jet escapes through an exponentially decreasing atmosphere into the circumstellar environment, where it would acquire the limiting bulk Lorentz factor, $\Gamma_{hf} \sim \Gamma_{j} \sim \eta = 10^{2}\eta_{2}$.

3. Cocoon and Bubble Dynamics and X-ray Lines

After emerging into the low density H envelope at $r > r_{He} \sim 10^{11}r_{He,11}$, the jet head advances ultrarelativistically. It then no longer produces a cocoon, for two reasons: (i) the energy/momentum ratio of the swept-up material is such that there is no ‘waste energy’ (whereas when $V_{h}$ is subrelativistic only a fraction ($V_{h}/c$) of the jet energy is used up in pushing the jet head outwards); (ii) causality constraints would in any case prevent shocked material from expanding sideways through a significant angle. However, the relativistic material that accumulated in the cocoon while the jet was advancing inside $r_{He}$ would, for a jet crossing time $t_{He} \sim 10$ s ($\Theta_{o}$), amount to $E_{b} \sim L_{J,He} \sim 10^{51}E_{b,51}$ ergs. This is much larger than the binding energy of the H envelope.

The (highly relativistic) jet head crosses the H envelope in a time of order $r_{H}/c$. An observer along the line of sight would see this speeded up by the square of the bulk Lorentz factor – so that, unless $M_{env} \gtrsim 5M_{\odot}$ or $r_{H} \gtrsim 10^{13}$ cm, a gamma-ray burst could be detected beyond $r_{H}$ within a few seconds of the jet head reaching $r_{He}$. The cocoon material would itself be able to ‘break out’ and accelerate as soon as the jet penetrated into the low-density envelope beyond $r_{He}$. It has a relativistic internal sound speed; however, unlike the jet, it does not have a relativistic outward
motion. It therefore, on reaching $r_{He}$, spreads out over a wide angle, and expands through the envelope as a bubble, in approximately the same way as an impulsive fireball in a tenuous external medium.

The bubble breaks out of the H-envelope with a velocity $V_{b,H} \sim c(E_b/M_{env,\odot})^{1/2} \sim 10^9(E_{b,51}/M_{env,\odot})^{1/2}$ cm/s, at a time $t_{b,H} \sim r_H/V_{b,H} \sim 10^4r_{H,13}(M_{env,\odot}/E_{b,51})^{1/2}$ s after the burst. The black-body temperature of the bubble is $T_b \sim 10^5 E_{b,51}^{1/4} r_{H,13}^{-3/4}$ K, so pairs are no longer in equilibrium. However, at $r \sim 10^{13} r_{H,13}$ cm the bubble is still Thomson thick, since during its build-up as a relativistic spill-over reservoir it acquired a baryon load $M_b \sim E_b/\eta c^2 \sim 10^{28} E_{b,51}^{-1}$ g, hence its average particle density is $n_{b,H} \sim 10^{13} E_{b,51}^{-1} r_{H,13}^{-3}$ cm$^{-3}$, and its average mass column density is $y \sim M_b/r_H^2 \sim 10^2 E_{b,51}^{-1} r_{H,13}^{-2}$ g cm$^{-2}$. This is a lower limit to the bubble mass: during the production of the cocoon, stellar core material could have been mixed in and entrained (Aloy et al.2000); and there would be further mixing with the envelope during the later bubble-expansion. Moreover, if the jet which supplied the original material was magnetically-driven, the bubble would still have a dynamically-important (and perhaps dominant) magnetic field: its strength would then be $B \sim 10^5$ G even after expansion to $10^{13}$ cm.

If the field were tangled, continuing reconnection would lead to acceleration of non-thermal electrons. There would also be subrelativistic shocks at the bubble boundary, which compress the envelope gas, probably inducing further clumpiness, and a reverse shock that moves into the bubble. The minimum electron random Lorentz factor in equipartition with shocked relativistic protons is $\gamma_m \gtrsim 6 \times 10^2$, which in an equipartition magnetic field $B \sim 10^5$ G will produce a synchrotron UV/X-ray continuum. The lifetime of electrons in such strong fields is of course very short. However, the dissipation by shocks and reconnection would provide a continuous supply of fresh electrons. It is therefore plausible that a substantial fraction of the energy stored in the bubble (i.e. at least $10^{51} - 10^{52}$ ergs) could be released in the few hours after the burst. A magnetic field of $10^5$ G could confine clumps or filaments of gas with densities up to $n \gtrsim 10^{17}$ cm$^{-3}$, even at keV temperatures. Such filaments would be individually optically thick, and could reprocess a non-thermal UV/X-ray continuum $L_x \sim E_b/t_{b,H} \sim 10^{47}$ erg s$^{-1}$ arising in the dilute plasma between them.

The UV/X-ray continuum would maintain a clump ionization parameter $\xi = L_x/nr^2 \sim 10^3 - 10^4$, and the $Fe^{26}$ recombination time is $t_{rec} \sim 10^{-6} T_7^{1/2} n_{17}^{-1}$ s. For a mass fraction of Fe advected from the core $x_{Fe}$, the number of Fe nuclei in the outer Thomson depth unity layer of the bubble (of average depth $\tau_T \sim 10^2$) is $N_{Fe} \sim x_{Fe} M_b/(\tau_T 56 m_p) \sim 4 \times 10^{49} x_{Fe}$. The Fe line luminosity is $(N_{Fe}.7 \text{ keV}/t_{rec})(1+z)^{-1}$, or

$$L_{Fe} \sim 10^{47} M_{h28} x_{Fe}(2/[1+z]) \text{ erg s}^{-1},$$

where $10^{28} M_{h28}$ g is the bubble mass in the absence of entrainment. A modestly supersolar Fe mass fraction $x_{Fe} \sim 10^{-2}$ (or less, if $M_{h28} > 1$ due to entrainment) yields a recombination Fe line luminosity comparable to the typical observed value $L_{Fe} \sim 10^{45} \text{erg s}^{-1}$ (e.g. Piro, et al., 2001), the mass of Fe involved being $\lesssim 10^{-5} M_\odot$. More detailed radiative transfer calculations are under
way (Kallman, Mészáros & Rees, 2001).

4. Implications for Progenitors and Fe Lines

The He core dimensions do not vary greatly among the different types of massive evolved stars, whether they have lost their envelopes or not. The exact values depend on uncertain details of wind mass loss, rotation rate, binary mass exchange, common envelope evolution, etc. (e.g. Heger, et al., 2001). Similarly, the density and pressure profiles are roughly $\rho \propto r^{-3}$ and $p \propto r^{-4}$, with the density suddenly dropping at the outer edge of the He core to $1 - 10^2 \text{g cm}^{-3}$. Provided that the pressure and density near the center of the precollapse star vary more slowly than linearly with the initial total stellar mass, the initial properties of the jet injected near the BH horizon would be approximately similar to those discussed in §2.

Thus, if it is a general property that the jet becomes relativistic near the outer radius $r_{\text{He}} \sim 10^{11} \text{ cm}$ of the He core, even for a substantially extended envelope outside of this, its lab-frame crossing time $r_{\text{He}} / c \Gamma^2_h$ adds little to the previously incurred He-core crossing time $t_{\text{He}} \sim 10 - 20 \text{ s}$. Thus, provided the central engine (jet) feeding time exceeds $t_{\text{He}}$, the jet would be expected to break free of the envelope, and in principle lead to a successful GRB. This could increase the range of potential GRB progenitors, including (besides the He-star merger and Wolf-Rayet candidates, e.g. MacFadyen et al., 2000) also blue supergiants, unless the advancing jet (depending also on $\theta_f$) sweeps up so much envelope mass that $\Gamma_h$ drops drastically.

Unsuccessful GRB, where the jet is choked before emerging, would occur for central engine lifetimes $t_j \lesssim t_{\text{He}} \sim 10 \left( r_{\text{He}} / 10^{11} \text{ cm} \right) \left( V_{\text{h}} / c \right)^{-1} \text{ s}$. The TeV neutrino signatures of bursts discussed by Mészáros & Waxman (2001) would thus have a characteristic duration $t_{\text{He}} \sim 10 \text{ s}$, which in successful GRB would precede the $\gamma$-rays by about $t_{\text{He}}$ s, while in $\gamma$-ray dark (failed) GRB they might be the only immediate observable manifestation of a choked collapsar jet. However, the cocoon of relativistic matter created during the sub-relativistic jet passage through the star would, in the choked case, not have a ready-made escape route, yet still have more energy than the envelope binding energy; it could expand more or less isotropically through the envelope, and (as also envisaged by Woosley et al., 2000 and Aloy et al.2000) violently disrupt it. For jets which start out with $V_{\text{h},0} \ll 10^8 \text{ cm/s}$ the He core crossing time could substantially exceed 10 s, and the total energy in the cocoon might be $\gtrsim 10^{52} \text{ ergs}$, giving rise to a “hypernova” (Paczynski, 1998, Iwamoto, et al., 1998, Wang & Wheeler, 1998), without, however, an accompanying GRB. This would appear, after the disrupted envelope becomes optically thin, as a peculiar SN Ib/c, of greater than usual brightness.

In a successful jet break-through, not only would a conventional “long” ($\gtrsim 10 \text{ s}$) GRB be detectable, followed by a “standard” non-thermal power-law decay afterglow from the decelerating jet blast wave, but also there would be, after hours to a day, a secondary brightening in the light curve, caused by the emergence of a bubble with $\sim 10^{51} \text{ erg}$. A reliable estimate of the amount
of Fe entrained in the bubble would require numerical calculations. However, under plausible conditions, the bubble can produce a Fe K-α X-ray line with $l_{Fe} \sim 10^{45}$ erg s$^{-1}$.

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