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JET-INDUCED EXPLOSIONS OF CORE COLLAPSE SUPERNOVAE

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ABSTRACT

We numerically studied the explosion of a supernova caused by supersonic jets present in its center. The jets are assumed to be generated by a magnetorotational mechanism when a stellar core collapses into a neutron star. We simulated the process of the jet propagation through the star, jet breakthrough, and the ejection of the supernova envelope by the lateral shocks generated during jet propagation. The end result of the interaction is a highly nonspherical supernova explosion with two high-velocity jets of material moving in polar directions and slower moving, oblate, highly distorted ejecta containing most of the supernova material. The jet-induced explosion is entirely due to the action of the jets on the surrounding star and does not depend on neutrino transport or reacceleration of a stalled shock. The jet mechanism can explain the observed high polarization of Types Ib, Ic, and IIsupernovae, pulsar kicks, very high velocity material observed in supernova remnants, indications that radioactive material was carried to the hydrogen-rich layers in SN 1987A, and other observations that are very difficult or impossible to explain by the neutrino energy deposition mechanism. The breakout of the jet from a compact, hydrogen-deficient core may account for the γ-ray burst and radio outburst associated with SN 1998bw/GRB 980425.

Subject headings: gamma rays: bursts — ISM: jets and outflows — pulsars: general — supernovae: general — supernovae: individual (SN 1998bw)

1. INTRODUCTION

Recent observations of core collapse supernovae provide increasing evidence that the core collapse process is intrinsically asymmetric: (1) The spectra of these supernovae are significantly polarized, indicating asymmetric envelopes (Méndez et al. 1988; Jeffrey 1991; Trammel, Hines, & Wheeler 1993; Tran et al. 1997). The degree of polarization tends to vary inversely with the mass of the hydrogen envelope, being maximum for Type Ib/c events with no hydrogen (Wang et al. 1996; Wang, Wheeler, & Höflich 1999). (2) After the explosion, neutron stars are observed with high velocities, up to 1000 km s^{-1} (Strom et al. 1995). (3) Observations of SN 1987A showed that radioactive material was brought to the hydrogen-rich layers of the ejecta very quickly during the explosion (Lucy 1988; Sunyaev et al. 1987; Tueller et al. 1991). (4) The remnant of the Cassiopeia A supernova shows rapidly moving oxygen-rich matter outside the nominal boundary of the remnant (Fesen & Gunderson 1996) and evidence for two oppositely directed jets of high-velocity material (R. A. Fesen 1999, private communication; Reed, Hester, & Winkler 1999). (5) High-velocity "bullets" of matter have been observed in the Vela supernova remnant (Taylor, Manchester, & Lyne 1993).

The mechanism of producing supernovae explosions by core collapse is a physics problem that has challenged researchers for decades. The current models based on the neutrino energy deposition mechanism fail to produce robust explosions (Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996; Mezzacappa et al. 1998). Even when successful, they do not explain why SN 1998bw produced one of the strongest radio sources ever associated with a supernova, probably requiring a relativistic blast wave (Kulkarni et al. 1998), or account for a probable link between SN 1998bw and the γ-ray burst GRB 980425 (Galama et al. 1998).

Another mechanism of core collapse supernova explosion is the magnetorotational mechanism (LeBlanc & Wilson 1970; Ostriker & Gunn 1971; Bisnovatyi-Kogan 1971). LeBlanc & Wilson computed the magnetorotational core collapse of a 7 $M_\odot$ star by numerically solving the two-dimensional MHD equations coupled to the equation for neutrino transport. The simulations showed the formation of two oppositely directed, high-density, supersonic jets of material emanating from the collapsed core. LeBlanc & Wilson estimated that at the surface located $\sim 4 \times 10^8$ cm from the center, the jet carried away $\sim 10^{32}$ g with $\sim(1–2) \times 10^{51}$ ergs in ~ 1 s. The magnetic field generated in this calculation was $\sim 10^{15}$ G. Evidence now exists for strongly magnetized neutron stars, "magnetars" (Duncan & Thompson 1992; Kouveliotou et al. 1999).

The LeBlanc-Wilson mechanism is extremely asymmetric and contains jets. Their calculations only followed the jet to a distance of $\sim 10^8$ cm, whereas a stellar core has a radius of 10^{10} cm or more. The issue that arises is how this asymmetry propagates to much larger distances inside the star. Can these jets induce asymmetry at distances comparable to the stellar radius or even push through the entire star and exit?

In this Letter, we model the explosion of a core collapse supernova assuming that the LeBlanc-Wilson mechanism has operated in the center. We take a 15 $M_\odot$ main-sequence star evolved to the point of the explosion (Straniero, Chieffi, & Limongi 1999) and assume that the star has lost all of its hydrogen envelope before the explosion. The resulting 4.1 $M_\odot$ model of a helium star corresponds to the explosion of a Type Ib or Ic supernova. The simulations show that the jets cause a very asymmetric explosion of the star. Most of the observations of asymmetries listed above can be explained by this process.

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2. NUMERICAL SIMULATIONS

The computational domain is a cube of size $L = 1.5 \times 10^{11}$ cm with a spherical helium star of radius $R_{star} = 1.88 \times 10^{10}$ cm and mass $M_{star} \simeq 4.1\ M_\odot$ placed in the center. The distribution of physical parameters inside the star is shown in Figure 1. The innermost part with mass $M_{core} \simeq 1.6\ M_\odot$ and radius $R_{core} = 3.82 \times 10^8$ cm, consisting of Fe and Si, is assumed to have collapsed on a timescale much faster than the outer, lower density material. It is removed and replaced by a point gravitational source with mass M_{core} representing the newly formed neutron star. The remaining mass, from $\simeq$1.6 to $\simeq$4.1 $M_\odot$, consists of an O-Ne-Mg inner layer surrounded by the C-O and He envelopes. This structure is mapped onto the computational domain from R_{core} to R_{star}.

At R_{core} and the outer boundary of the computational domain, we impose an outflow boundary condition. Jets are initiated at two polar locations at R_{core} with an inflow velocity $v_j = 3.22 \times 10^9$ cm s^{-1}, density $\rho_j = 6.5 \times 10^5$ g cm^{-3}, and pressure $P_j = 1.0 \times 10^{23}$ ergs cm^{-3}. The parameters are chosen to represent the results of LeBlanc & Wilson (1970). At R_{core}, the jet density and pressure are the same as those of the background material. The radii of the cylindrical jets entering the computational domain are $r_j \simeq 1.2 \times 10^8$ cm. The jet inflow velocity is kept constant for the first 0.5 s and gradually decreased to zero at $\simeq$2 s. The total energy deposited by the jets is $E_j \simeq 9 \times 10^{50}$ ergs, and the total mass ejected is $M_j \simeq 2 \times 10^{32}$ g ($\simeq$0.1 $M_\odot$).

The evolution of this system is described by the time-dependent, compressible, Euler equations for inviscid flow with an ideal gas equation of state and constant $\gamma = 5/3$. The Euler equations were integrated using an explicit, second-order accurate, Godunov-type, adaptive-mesh-refinement, fully threaded tree (FTT) program, ALLA (Khokhlov 1998). Euler fluxes were evaluated by solving a Riemann problem at cell interfaces. A three-dimensional Cartesian FTT mesh was nonuniformly refined with fine cells $\Delta_{min} \simeq 3.7 \times 10^7$ cm near R_{core} to resolve the jets and with cell size increasing toward the outer boundary of the computational domain where the cell size was $\Delta_{max} = 2.3 \times 10^9$ cm. This mesh was fixed from 0 to 6 s of physical time. After that, the inner part of the mesh was coarsened near the center by a factor of 4 and the central hole was eliminated. At 6 s, the jets have exited the star and the details of the flow near R_{core} do not affect the essential features of the explosion. The self-gravity of the star was turned off. The explosion energy delivered by the jets is much larger than the binding energy of the star and is released on a timescale much shorter than the stellar sound crossing time. We computed the entire configuration including both jets and assuming no symmetries, which required $\sim 2 \times 10^6$ computational cells. A uniform resolution Δ_{min} would have required $\sim 7 \times 10^{10}$ cells.

3. RESULTS AND DISCUSSION

Figure 2 shows the explosion of the star. As the jets move outward, they remain collimated and do not develop much internal structure. A bow shock forms at the head of each jet and spreads in all directions, roughly cylindrically around the jets (Fig. 2*a*). The stellar matter is shocked by the bow shock and then flows out and acts as a high-pressure confining medium by forming a cocoon around the jets. Although the jet characteristic time $\tau_j \sim 1$ s is much shorter than the sound crossing time of the star, $\tau(R_{star}) \sim 10^3$ s (Fig. 1), the jets stay collimated enough to reach the surface as strong jets. The sound crossing time of the dense O-Ne-Mg mantle, $\tau(R \sim 10^9$ cm$) \simeq 10$ s, is only 10 times longer than τ_j, and the jets are capable of penetrating this dense inner part of the star in $\sim$2 s. By the time the jets penetrate into the less dense C-O and He layers, the inflow of material into the jets has been turned off. By this time, however, the jets have become long bullets of high-density material moving almost ballistically through the background low-density material. The higher pressures in these jets cause them to spread laterally. This spreading is limited by a secondary shock that forms around each jet between the jet and the material already shocked by the bow shock. The radius of the jets, $\sim 3 \times 10^9$ cm as they emerge from the star, is larger than the initial radius of $\sim 10^8$ cm, but it is still significantly less than the radius of the star.

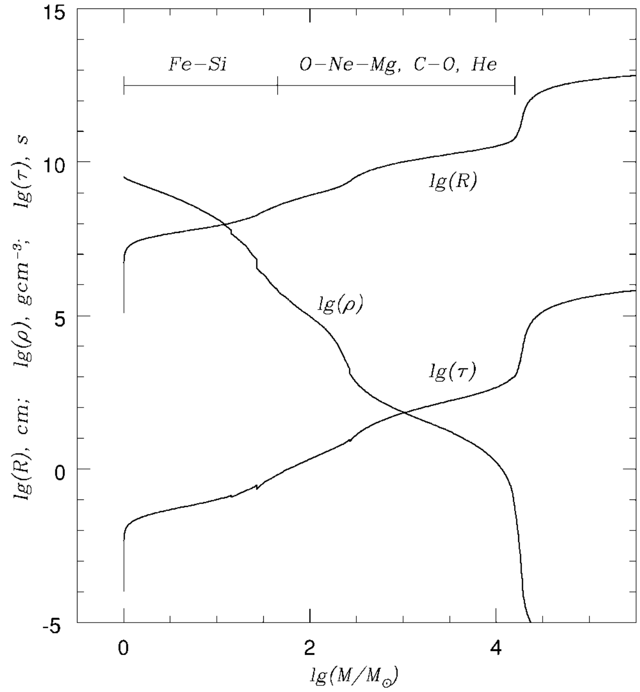

FIG. 1.—Initial conditions. The distribution of physical parameters inside the innermost 5 $M_\odot$ of the 15 $M_\odot$ stellar model of Straniero et al. (1999). The Fe-Si inner part is assumed to collapse into a neutron star. The O-Ne-Mg, C-O, and He layers are mapped onto the computational domain (see § 2).

After about 5.5 s, the bow shock reaches the edge of the star and breaks through (Fig. 2*b*). The laterally expanding bow shocks generated by the jets move toward the equator, where they collide with each other. The collision of the shocks first produces a regular reflection that then becomes a Mach reflection. The Mach stem moves outward along the equatorial plane. The result is that the material in the equatorial plane is compressed and accelerated more than material in other directions (excluding the jet material). At $t \simeq 29$ s, the Mach stem reaches the outer edge of the star, and the star begins to settle into the free expansion regime. The computation was terminated at $\simeq$35 s, before free expansion was attained (Fig. 2*c*). At this time, most of the material in the jets has left the star and propagates into the interstellar medium ballistically. We estimate the total mass in these two jets as $M_j \approx 0.05\ M_\odot$ and the total kinetic energy $E_j \approx 2.5 \times 10^{50}$ ergs. The average velocity of the jet is about 25,000 km s^{-1}. The stellar ejecta is highly asymmetric. The density contour of 50 g cm^{-3}, which is the average density of the ejecta at this time, forms an oblate configuration with the equator-to-polar velocity ratio $\simeq 2:1$.

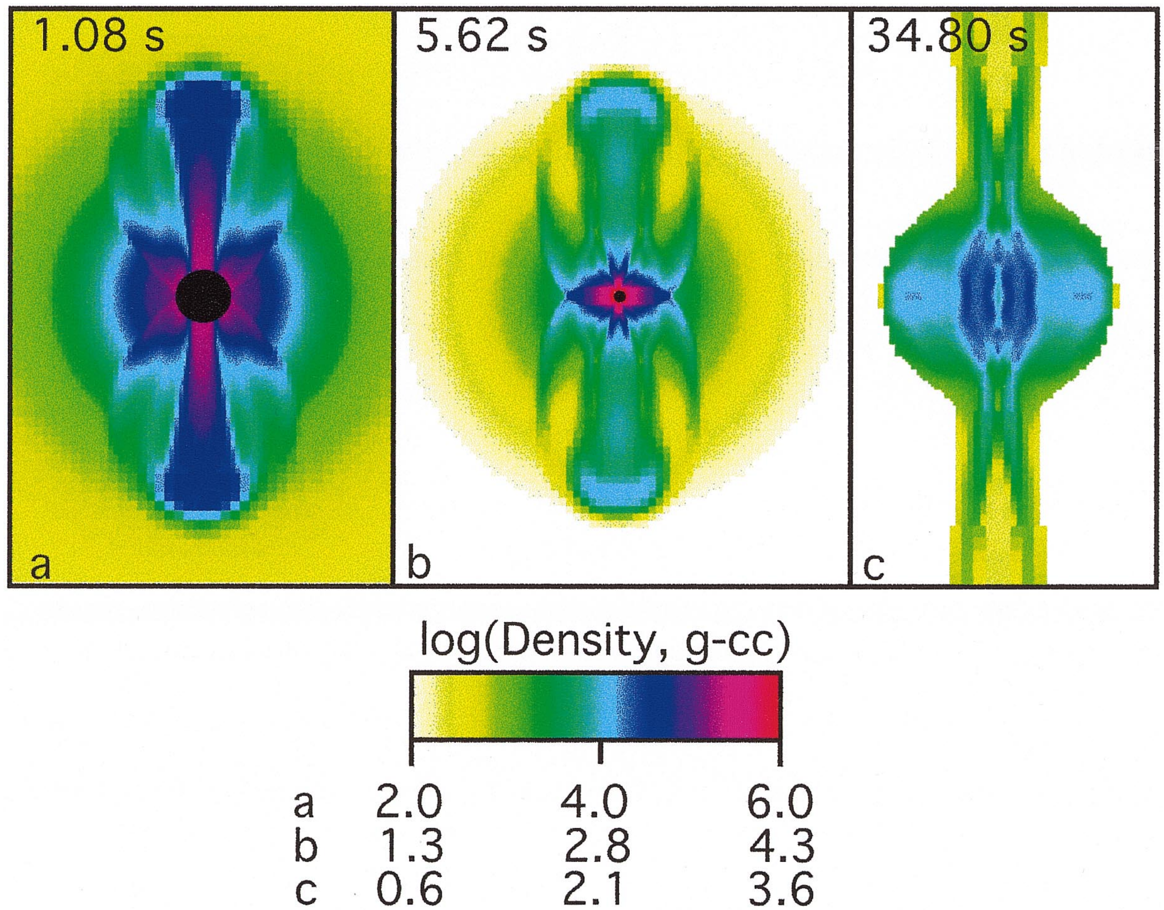

FIG. 2.—Jet-induced explosion. The frames show the density in the *x-z* plane passing through the center of computational domain. Time since the beginning of the simulation is given in the upper left corner of each frame. The size of panel *a* is $\Delta x = 6 \times 10^9$ cm and $\Delta z = 9.0 \times 10^9$ cm. The size of panel *b* is $\Delta x = 3.6 \times 10^{10}$ cm and $\Delta z = 4.5 \times 10^{10}$ cm. The size of panel *c* is $\Delta x = 6.0 \times 10^{10}$ cm and $\Delta z = 1.125 \times 10^{11}$ cm.

Complex shock and rarefaction interactions inside the expanding envelope will continue to change the distribution of the parameters inside the ejecta. Nonetheless, we expect that the resulting configuration will resemble an oblate ellipsoid with an axis ratios ≥ 2, which is a very high degree of asymmetry.

4. CONCLUSIONS

The result of the explosion is a nonspherical supernova with two high-velocity jets of material moving in polar directions ahead of an oblate, highly distorted ejecta containing most of the stellar material. The explosion provides ejection velocities that are comparable to those observed in supernovae. For this demonstration calculation, an energy of 2.5×10^{50} ergs is invested in the jets and a mass of $\simeq 2.5\ M_\odot$ is ejected with kinetic energy of 6.5×10^{50} ergs and average velocity 3000−4000 km s^{-1}. Increasing the jet opening angle, jet duration, or jet velocity would result in a more powerful explosion. Such a model explains many of the observations that are difficult or impossible to explain by the neutrino deposition explosion mechanisms.

Oblate density and velocity profiles of the main ejecta (excluding the jets) with equator-to-polar ratios greater than 2 : 1 will produce significant polarization, of order 1% or more as observed in bare-core supernovae (Höflich, Wheeler & Wang 1999). The two high-velocity polar jets moving ahead of the main ejecta may be detected in supernova remnants and might account for the evidence of jets in Cas A. The composition of the jets must reflect the composition of the innermost parts of the star and should contain heavy and intermediate-mass elements. If the helium star is actually a core inside a hydrogen envelope, radioactive elements will be carried into the hydrogen envelope. This could explain the early appearance of X-rays, as in SN 1987A. It is plausible that a sufficiently powerful jet could even penetrate a hydrogen envelope.

If the two jets are not identical, the momentum imbalance might impart a kick to the neutron star, $v_{\rm NS}$. The required difference between the inflow velocities of the jets Δv_j is

$$\frac{\Delta v_j}{v_j} \simeq \left(\frac{M_{\rm NS}}{M_j}\right)\left(\frac{v_{\rm NS}}{v_j}\right) \simeq 1.0\left(\frac{v_{\rm NS}}{1000\ {\rm km\ s^{-1}}}\right)\left(\frac{30{,}000\ {\rm km\ s^{-1}}}{v_j}\right),$$

where we have taken the neutron star mass to be $M_{\rm NS} = 1.5\ M_\odot$ and the jet mass to be $M_j = 10^{32}$ g. Although the required jet asymmetry, $\Delta v_j/v_j \sim 1$, to produce a 1000 km s^{-1} kick may seem extreme, the parameters of the jets selected for this calculation are mild. If the duration of the jets is increased by a factor of 2, an asymmetry of only 0.5 would be required.

When the jets break through the stellar photosphere, a small amount of mass will be accelerated through the density gradient to very high velocities. In our simulation, a small fraction of the material at the stellar surface was observed to move with a velocity of up to ∼90,000 km s^{-1}. This may, in principle, lead to a γ-ray burst and a radio outburst similar to those associated with SN 1998bw/GRB 980425.

Collimated jets could be a common phenomenon in core collapse supernovae and be associated with γ-ray bursts (Wang & Wheeler 1998). Here, we have assumed that jets were generated by a magnetorotational mechanism. A different mechanism of jet generation to explain γ-ray bursts involves neutrino radiation in the context of a collapsar model (MacFadyen & Woosley 1999). Low-density relativistic jets may also be produced by the intense radiation of the newly born pulsar (Blackman & Yi 1998). Preliminary simulations (not presented here) show that lower density and higher velocity jets than the ones considered in this Letter may produce similar effects.

The jet-induced explosion of a supernova computed in this Letter is entirely due to the action of the jet on the surrounding star. The mechanism that determines the energy of such an explosion must be related to the stopping of the accretion onto the neutron star by the lateral shocks that accelerate the material outward. The explosion thus does not depend on neutrino transport or reacceleration of the stalled shock. However, a combination of the jet and neutrino explosion mechanisms is also possible.

This work raises many questions that require further investigation. A study must be made of the effects of different input parameters, including properties of the jets and of the initial star, and the jet engine mechanisms. These studies are currently underway.

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