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 magneto-rotational 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 a 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 re-acceleration of a stalled shock. The jet mechanism can explain the observed high polarization of Type Ib,c and Type II supernovae, pulsar kicks, very high velocity material observed in supernova remnants, indications that radioactive material was carried to the hydrogen-rich layers in SN1987A, and some others 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 gamma-ray bursts and radio outburst associated with SN 1998bw/GRB980425.

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

1. Introduction

Recent observations of core collapse supernovae provide increasing evidence that the core collapse process is intrinsically asymmetric:

The degree of polarization tend 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; Wheeler, Höflich & Wang 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 Cas 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 (Fesen 1999; Reed, Hester, & Winkler 1999).

5) High velocity “bullets” of matter have been observed in the Vela supernova remnant (Taylor et al. 1993)

Understanding the mechanism of producing supernovae explosions by core collapse is a physics problem that has challenged researchers for decades (Hoyle & Fowler 1960; Colgate & White 1966). The current most sophisticated calculations based on the neutrino energy deposition mechanism are multidimensional and involve the convection of the newly formed neutron star. These, however, but have failed to produce robust explosions (Herant et al. 1994; Burrows, Hayes & Fryxell 1995; Janka & Müller 1996; Mezzacappa et al 1997; Lichtenstadt, Khokhlov & Wheeler 1999). Even when successful, these models do not explain why SN 1998bw produced the strongest radio source 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 GRB980425 observed in the same general location in the same general time frame (Galama et al. 1998).

The discovery of pulsars led to early considerations of the role of rotating magnetized neutron stars in the explosion mechanism (LeBlanc and Wilson 1970; Ostriker & Gunn 1971; Bisnovatyi-Kogan 1971). LeBlanc and Wilson studied the magneto-rotational core collapse of a 7M\(_\odot\) star. They numerically solved the two-dimensional MHD equations coupled to the equation for neutrino transport. Their simulations showed the formation of two oppositely directed, high-density, supersonic jets of material emanating from the collapsed core. They estimated that at the surface located \(\sim 4 \times 10^8\) cm from the center, the jet carried away \(\sim 10^{52}\) g with \(\sim 1 - 2 \times 10^{51}\) ergs in \(\sim 1\) s. The magnetic field generated in this calculation was \(\sim 10^{15}\) Gauss. Evidence now exists for strongly magnetized neutron stars, “magnetars” (Duncan & Thompson 1992; Kouveliotou et al. 1998).

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 issues that arise are: how can this asymmetry propagate 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 paper, we model the explosion of a core collapse supernova assuming that the LeBlanc-Wilson mechanism has operated in the center. We take a $15M_\odot$ 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 $4.1M_\odot$ 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.

2. Numerical Simulations

Figure 1 presents a schematic of the setup of the computation. The computational domain is a cube of size $L = 1.5 \times 10^{11}$ cm with a spherical helium star of radius $R_{\text{star}} = 1.88 \times 10^{10}$ cm and mass $M_{\text{star}} \approx 4.1M_\odot$ placed in the center. The distribution of physical parameters inside the star is shown in Figure 2. The innermost part with mass $M_{\text{core}} \approx 1.6M_\odot$ and radius $R_{\text{core}} = 3.82 \times 10^8$ 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 $M_{\text{core}}$ representing the newly formed neutron star. The remaining mass, from $\approx 1.6$ to $\approx 4.1M_\odot$, 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 $R_{\text{core}}$ to $R_{\text{star}}$.

At $R_{\text{core}}$ and the outer boundary of the computational domain, we impose an outflow boundary condition assuming zero pressure, velocity, and density gradients. At two polar locations where the jets are initiated at $R_{\text{core}}$, we impose an inflow with velocity $v_j$, density $\rho_j$ and pressure $P_j$. The jet parameters are chosen to represent the results of LeBlanc & Wilson (1970). At $R_{\text{core}}$, the jet density and pressure are the same as those of the background material, $\rho_j = 6.5 \times 10^5$ g cm$^{-3}$ and $P_j = 1.0 \times 10^{23}$ ergs cm$^{-3}$, respectively. The radii of the cylindrical jets entering the computational domain are approximately $r_j = 1.2 \times 10^8$ cm.

For the first 0.5 s, the jet velocity at $R_{\text{core}}$ is kept constant at $v_j = 3.22 \times 10^9$ cm s$^{-1}$. This results in a mass flux rate of $\approx 9.5 \times 10^{34}$ g s$^{-1}$ with an energy deposition rate $dE/dt = 5 \times 10^{50}$ ergs/s for each jet. After 0.5 s, the velocity of the jets at $R_{\text{core}}$ was gradually decreased to zero at approximately 2 s. The total energy deposited by the jets is $E_j \approx 9 \times 10^{50}$ ergs and the total mass ejected is $M_j \approx 2 \times 10^{32}$ grams or $\approx 0.1M_\odot$. These parameters are consistent within, but somewhat less than, those of the LeBlanc-Wilson model. The amount of material ejected is less than that which falls through the inner boundary during the jet operation, $\approx 4 \times 10^{32}$ g. This amounts to an implicit assumption that $\approx 1/2$ of the matter accreted is channeled back out into the jets. More accurate jet parameters can only be determined by self-consistently modeling the formation of the jets in the vicinity of a neutron star.
The stellar material was described by the time-dependent, compressible, Euler equations for inviscid flow with an ideal gas equation of state \( P = E(\gamma - 1) \) with constant \( \gamma = 5/3 \). The Euler equations were integrated using an explicit, second-order accurate, Godunov type, adaptive-mesh-refinement, massively parallel, Fully-Threaded Tree (FTT) program, ALLA (Khokhlov 1998, Khokhlov & Chtchelkanova 1999). Euler fluxes were evaluated by solving a Riemann problem at cell interfaces. FTT discretization of the computational domain allowed the mesh to be refined or coarsened at the level of individual cells. Physical scales involved in the simulation range from the size of the computational domain \((1.5 \times 10^{11} \text{ cm})\) to the jet diameter \((\sim 10^8 \text{ cm})\) and span at least three orders of magnitude. We used a cartesian, nonuniformly refined FTT mesh with fine cells \( \Delta_{\text{min}} \simeq 3.7 \times 10^7 \text{ cm}\) near \( R_{\text{core}} \) to resolve the jets, and with cell size increasing towards the outer boundary of the computational domain where the cell size was \( \Delta_{\text{max}} = 2.3 \times 10^9 \text{ cm}\). This mesh was fixed from initial time 0 to 6 s of physical time. After that, the inner parts were coarsened near the center by a factor of four, and the central hole was eliminated. At this moment, the jets have exited the star and the details of the flow near \( R_{\text{core}} \) do not affect the essential features of the explosion. In this first, demonstration calculation, we did not use the time-adaptive mesh refinement capability of ALLA. It will be used to follow shocks and mixing processes with higher resolution in future simulations. We computed the entire configuration including both jets and assuming no symmetries. The total number of computational cells used in the simulation was \( \sim 2 \times 10^6 \), whereas a uniform resolution \( \Delta_{\text{min}} \) would have required \( \sim 7 \times 10^{10} \) cells.

3. Results and Discussion

Figure 3 shows the propagation of the jet inside the star. As the jets move outwards, they remain collimated and do not develop much internal structure. A bow shock forms at the head of the jet and spreads in all directions, roughly cylindrically around each jet. The sound crossing time \( \tau(r) = r/a_s(r) \) is shown as a function of stellar radius \( r \) in Figure 2, where \( a_s(r) \) is the sound speed at a given radius for the initial stellar model. It might be expected that if energy were released at the center of a star on a timescale much shorter that \( \tau(r) \), the effect of energy deposition at \( r \) would resemble that of a strong point explosion. In particular, the jet characteristic time \( \tau_j \sim 1 \text{ s} \) is much shorter than the sound crossing time of the star, \( \tau(R_{\text{star}}) \sim 10^3 \text{ s} \) (Figure 2). Nonetheless, these jets stay collimated enough to reach the surface as strong jets.

It is known that supersonic jets stay collimated for a long distance. For example, Norman et al. (1983) simulated supersonic jets with densities \( \rho_j \) both less than and greater than a uniform background, \( \rho_0 \). Jets with \( \rho_j/\rho_0 \geq 1 \) developed a bow shock and little internal structure. Our jets resemble those with \( \rho_j/\rho_0 \geq 1 \). 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 jet. The sound crossing time of the dense O-Ne-Mg mantle, \( \tau(R \sim 10^9 \text{ cm}) \approx 10 \text{ s} \), is only ten times longer than \( \tau_j \), and the jets are capable of penetrating this dense inner part of the star in \( \sim 2 \text{ s} \). 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 through the background low-density material almost ballistically. 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, $\sim 10^8$ cm, but it is still significantly less than the radius of the star.

After about 5.9 s, the bow shock reaches the edge of the star and breaks through. Figure 4 shows the subsequent evolution of the star after the breakthrough. By $\approx 20$ s, most of the material in the jets has left the star 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 laterally expanding bow shocks generated by the jets (Figure 3) move towards 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 outwards 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 $t \approx 29$ 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 $\approx 35$ s, before free expansion was attained. The stellar ejecta at this time 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 $\approx 2/1$. 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 a very high degree of asymmetry, axis ratios $\geq 2$.

4. Conclusions

We have numerically studied the explosion of a supernova caused by supersonic jets generated in the center of the supernova as a result of the core collapse 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 ahead of an oblate, highly distorted ejecta containing most of the supernova material. Below we argue that such a model explains many of the observations that are difficult or impossible to explain by the neutrino deposition explosion mechanisms.

We have assumed that the jets were generated by a magneto-rotational mechanism during core collapse and neutron star formation (LeBlanc & Wilson 1970). That collimated jets could
be a common phenomenon in core collapse supernovae and be associated with γ-ray bursts was raised recently by Wang & Wheeler (1998). A different mechanism of jet generation involving neutrino radiation during collapse of a very massive star into a black hole has been recently discussed by MacFadyen & Woosley (1999) in the context of a “failed” supernova, also to explain γ-ray bursts. Low density relativistic jets may also be produced by the intense radiation of the newly born pulsar, as discussed by Blackman & Yi (1998) and Yi et al. (1999). We found in our preliminary simulations (not presented here) that lower density and higher velocity jets than the one considered in this paper may produce similar hydrodynamical effects.

The asymmetric explosion generated in this calculation provides ejection velocities that are comparable to those observed in supernovae. For this particular calculation, an energy of $2.5 \times 10^{50}$ ergs is invested in the jet and the star of $\sim 2.5 M_\odot$ is ejected with kinetic energy of $6.5 \times 10^{50}$ ergs and average velocity $3,000 - 4,000 \ km \ s^{-1}$. Increasing the jet opening angle, jet duration, or jet velocity would result in a more powerful explosion. The density and velocity profiles of the main ejecta (excluding jets) are oblate with equator to polar ratios greater than 2/1. This structure will produce significant polarization, of order 1% or more as observed in bare-core supernovae (Höflich, Wheeler & Wang 1999).

The two polar jets move outward from the star with a speed $\sim 25,000 \ km \ s^{-1}$, much greater than the ejecta itself. They may be detected in supernova remnants and might account for the evidence of jets in Cas A (Fesen & Gunderson 1996; Reed, Hester & Winkler 1999).

The composition of the jets must reflect the composition of the innermost parts of the star, and should contain heavy and intermediate-mass elements. During the explosion, the jets would bring heavy and intermediate mass elements into the outer layers. This will influence the spectral and polarization properties of a supernova. Here we considered a bare helium core, but if the core were inside a hydrogen envelope, the explosion would remain very inhomogeneous. Radioactive elements could potentially be carried into the hydrogen envelope. This could explain the early appearance of X-rays, as in SN1987A. It is plausible that a sufficiently powerful jet could even penetrate a hydrogen envelope.

We assumed that the jets are identical which is not the general case. Any momentum imbalance might impart a kick to the neutron star. From momentum conservation, we estimate the required difference between the inflow velocities of the jets, $\Delta v_j$, be of the order of

$$\frac{\Delta v_j}{v_j} \approx \frac{M_{NS}}{M_j} \frac{v_{NS}}{v_j} \approx 1.0 \left( \frac{v_{NS}}{1,000 \ km/s} \right) \left( \frac{30,000 \ km/s}{v_j} \right),$$

where $v_{NS}$ is the kick velocity, and we have taken the neutron mass $M_{NS} = 1.5 M_\odot$, and the jet mass $M_j = 10^{32} \ g$. Although the required jet asymmetry, $\frac{\Delta v_j}{v_j} = 1$, to produce a 1,000 km/s kick may seem extreme, the parameters of jets selected for this calculations are mild. If the duration of the jets is increased by a factor of two, 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. Our resolution was not enough and the code does not have a relativistic Riemann solver incorporated to make quantitative predictions; however, a small fraction of the material at the stellar surface was observed to move with a velocity of up to \( \sim 90,000 \text{ km s}^{-1} \). This may, in principle, lead to the \( \gamma \)-ray burst and the radio outburst similar to those associated with SN 1998bw/GRB980425.

The jet-induced explosion of a supernova computed in this paper 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 shut-off of the accretion onto the neutron star by the lateral shocks that accelerate the material outwards. The explosion thus does not depend on neutrino transport or re-acceleration of the stalled shock. This work opens many issues that require further investigation. A study must be made of different input parameters, including properties of the jets and of the initial star, and the jet engine mechanisms must be studied as well. These studies are currently underway.

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REFERENCES

Bisnovatyi-Kogan 1971, Soviet Astronomy AJ, 14, 652
Iwamoto et al. 1998, Nature, 395, 672
Sunyaev et al. 1987, Nature, 330, 227

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Figure Captions

Fig. 1.— Schematic of the simulation.

Fig. 2.— Initial Conditions. The distribution of physical parameters inside the innermost 5M$_\odot$ of the 15M$_\odot$ 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 Section 2).

Fig. 3.— Jet propagation inside the star. 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 sizes of two upper frames are $\Delta x = 7.2 \times 10^9$ cm and $\Delta z = 9.0 \times 10^9$ cm. The sizes of the lower frames $\Delta x = 3.6 \times 10^{10}$ cm and $\Delta z = 4.5 \times 10^{10}$ cm.

Fig. 4.— Jet evolution after breakout. 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 sizes of frames are $\Delta x = 6.1 \times 10^{10}$ cm and $\Delta z = 1.125 \times 10^{11}$ cm.
Figure 1
Figure 2
Figure 3

log(Density, g-cc)
Figure 4

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