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Gamma-Ray Bursts From Neutron Star Phase Transitions

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ABSTRACT

The phase-transition induced collapse of a neutron star to a more compact configuration (typically a "strange" star) and the subsequent core bounce is often invoked as a model for gamma-ray bursts. We present the results of numerical simulations of this kind of event using realistic neutrino physics and a high density equation of state. The nature of the collapse itself is represented by the arbitrary motion of a piston deep within the star, but if any shock is to develop, the transition, or at least its final stages, must occur in less than a sonic time. Fine surface zoning is employed to adequately represent the acceleration of the shock to relativistic speeds and to determine the amount and energy of the ejecta. We find that these explosions are far too baryon-rich ($M_{\rm ejecta} \sim 0.01 M_\odot$) and have much too low an energy to explain gamma-ray bursts. The total energy of the ejecta having relativistic $\Gamma \gtrsim 40$ is less than 10^{46}erg even in our most optimistic models (deep bounce, no neutrino losses or photodisintegration). However, the total energy of all the ejecta, mostly mildly relativistic, is $\sim 10^{51}$erg and, if they occur, these events might be observed. They would also contribute to Galactic nucleosynthesis, especially the r-process, even though the most energetic layers are composed of helium and nucleons, not heavy elements.

Subject headings: gamma rays: bursts — stars: neutron

1. Introduction

A major goal in modern model building for cosmological gamma-ray bursts is finding a source which provides both the high energies ($\gtrsim 10^{51}$erg for symmetric explosions) and high Lorentz factors ($\Gamma \gtrsim 100$) required to explain the observations (e.g., Mészáros & Rees 1993). One often proposed source for this energy is an explosion resulting from the phase transition of a neutron star to a "strange" or "hybrid" star (Ramaty et al. 1980; Ramaty, Lingenfelter & Bussard 1981; Brecher 1982; Ellison & Kazanas 1983; Bonazzola 1986; Michel 1988; Haensel, Paczynski & Amsterdaamski 1991; Ma & Xie 1996; Ma & Luo 1996; Shaviv & Dar 1996, Qin et al. 1997). Though there is some variation in the models - sometimes a critical mass is achieved for an accreting neutron star, sometimes only a single star is involved - all take note of the large gravitational binding energy of a neutron star and speculate that some fraction of this can be tapped and converted into an outgoing shock wave when the inner core abruptly makes the transition to a more compact state. Because the density is so high, neutrino losses are small, except very near the surface; similarly photodisintegration losses are negligible, so the "prompt shock" mechanism that fails to give mass ejection in standard supernova models (e.g. Bethe 1990), might, in this case, deliver large amounts of momentum to the surface layers. Models for strange or "hybrid" stars predict central core densities nearly 5 times greater and radii 10-20% smaller than neutron stars of the same mass (Rosenhauer, Staubo, & Csernai 1991). A rough estimate of the potential energy released, $E \sim \frac{GM^2}{R}\frac{\Delta R}{R}$, predicts energies on the order of 10^{52}erg, easily sufficient for gamma-ray burst models (e.g., Ma & Xie 1996).

However, to get the required high Lorentz factors (Γ), this energy must be concentrated into a thin layer near the neutron star surface so that only a small amount of mass is ejected.[1] Competing with this sink for the gravitational energy is an increase in the internal energy that occurs when matter moves to higher gravitational potential, so the shock does not carry an energy equal to the entire change in gravitational potential. And of course the matter ejected will have a distribution of kinetic energies with most of the mass concentrated at low energies. In this paper, we show that while the phase-transitions of neutron stars can indeed impart total energies to their ejecta in excess of 10^{50}erg, they fail to deposit enough energy at high Γs to explain gamma-ray bursts. The phase-transition induced collapse of neutron stars is therefore *not* a viable gamma-ray burst mechanism.

[1]To reach a mean Γ of 100, a 2×10^{51}erg explosion must eject less than $10^{-5} M_{\odot}$.

2. Simulations

To simulate the collapse and subsequent explosion of neutron stars, we use two separate hydrodynamic codes, one for the bounce and shock formation in the inner core and another to study shock propagation in the outer 0.001 to $0.01 M_\odot$ where very fine zoning must be employed. For the collapse and bounce phase of the simulation, we use the relativistic supernova code described in Herant et al. (1994) and Fryer et al. (1998) which includes the equation of state for high density matter developed by Lattimer & Swesty (1991), neutrino processes and transport, general-relativistic effects and nuclear burning assuming nuclear statistical equilibrium in a Lagrangian hydrodynamics code. We base our calculations on a $1.4 M_\odot$ neutron star initial model provided by Keil(1997). The inner 50% of the mass is removed from the neutron star and replaced by an inner boundary. After the star has recovered from this remapping (the stable radius using our code is within 5% of the initial radius of Keil's model), we move the inner boundary quickly, but not instantly to a smaller radius to artificially simulate the phase transition.[2] The outer zones in this calculation are resolved down to $10^{-4} M_\odot$ at the edge of the neutron star using over 450 variably massed zones. The ultimate results of this calculation are an accurate estimate of the total mass ejected and a history of the inner boundary of this ejecta ($r(t)$), which we can use as a piston for the high resolution models of the shock progression through the neutron star crust.

To model the shock progression through this outer crust, we use the hydrodynamical code KEPLER (Weaver, Zimmerman, and Woosley 1978). Densities are sufficiently low ($\lesssim 10^{12}$ g cm^{-3}) in this material that an ordinary equation of state (ions, radiation, electrons and pairs of arbitrary relativicity and degeneracy) can be used. Although the code is Newtonian, not relativistic, it has the advantage that very fine mass zoning can be employed while conserving momentum and energy to high accuracy. The code also has the ability to compute approximate nucleosynthesis using a network of 19 isotopes.

¿From our bounce simulations, we derive a piston velocity for the outer $0.01 - 0.001 M_\odot$ of ejecta (depending upon the model) which is then placed at the inner boundary of the KEPLER simulation. Using ~ 200 logarithmically binned zones, we are able to compute shock velocities and nucleosynthetic yields with an outer resolution of $10^{-11} M_\odot$. Later in the paper we shall discuss the validity of our Newtonian results for a problem where the motion is trans-relativistic.

[2]We vary both the depth of the final inner radius and the speed at which it drops.

2.1. Bounce Results

Table 1 summarizes the results of a series of simulations in which we varied the depth and speed at which the inner boundary was lowered. We assume that the inner boundary in these simulations moves in rapidly (with its free-fall velocity) and have varied the strength of the bounce. If the material collapses much more slowly, the bounce will be much weaker and explosions may not occur at all.

A common misconception in gamma-ray burst work is that all of the potential energy gained during the compression of a compact object is immediately injected into the exploding material. From the mass-point trajectories of our most energetic explosion (Figure 1)[3] we see that, although there may be a great deal of potential energy released as the neutron star converts to a strange star, only a small fraction of this potential energy appears in the ejecta. The kinetic energy of the inner boundary is almost entirely reprocessed into potential energy as the outer 40% of the neutron star expands (see Figure 1). This energy slowly leaks out of the neutron star as it re-experiences Kelvin-Helmholtz evolution. This effect is akin to the process in core-collapse supernovae where, during the explosion, the proto-neutron star collapses down to 50km, driving an explosion with only 20% of the gravitational energy that it will ultimately lose in becoming a cold 10km neutron star. Hence, simple estimates of the energy, and nucleosynthetic yield of these explosions. such as those by Ma & Xie (1996), begin by overestimating the available energy by a factor of 5-10.

A more crucial misconception is the assumption that the explosion ejects only a tiny fraction of the collapsing object. In table 1, we see that the mass ejected ranges from $0.001 - 0.2 M_{\odot}$ (corresponding to 10-100 zones in our bounce simulations), much larger than gamma-ray burst models require. Although we can increase the explosion energy by altering the depth at which we lower the inner boundary, we do not change the shock velocity significantly, but rather eject more material. Note that if the neutron star collapses to a black hole, no matter is ejected, the neutrinos are trapped in the collapse and no energy is ejected. Thus, the collapse model proposed by Qin et al. (1997) fails to produce any explosion, let alone a gamma-ray burst.

Neutrinos play a minor role in the mass ejection in these objects simply because, by the time the ejecta begins to get optically thin, 90% of the energy has already been converted to kinetic energy. The opacity for neutrinos due to absorption onto free nucleons is (Herant

[3]In this model, the inner boundary falls inward from 7.5km to 4.5km. The inner boundary is then given a kinetic energy per gram equivalent to the potential energy released and it drives the shock through the infalling zones.

et al. 1994):

$$\kappa = 8.5 \times 10^{-18} \left(\frac{\epsilon_\nu}{12.5\mathrm{MeV}}\right)^2 \ \mathrm{cm}^2/\mathrm{g}, \tag{1}$$

where ϵ_ν is the neutrino energy. The optical depth ($\tau = \kappa\rho\Delta R$) becomes one when the shock has reached 50 km and the density is $\sim 10^{10}\mathrm{g/cm}^3$.

After the initial ejection of matter, neutrinos will continue to deposit energy outside the neutrinosphere due to neutrino/anti-neutrino pair annihilation. We reiterate the fact that neutrino/anti-neutrino annihilation requires nearly head-on neutrino collisions (Janka 1991) and will not be effective in driving a gamma-ray burst for our spherically symmetric explosions[4]. The energy deposition near the neutrinosphere drives a wind which is far too baryon rich to be a gamma-ray burst model (Duncan et al. 1986). This effect has been seen in simulations for neutron star mergers (Janka & Ruffert 1996) and the accretion induced collapse of white dwarfs (Woosley & Baron 1992, Fryer et al. 1998) and the resultant winds are non-relativistic. However, these winds are likely to eject an additional $0.01M_\odot$ of possibly neutron-rich material.

2.2. Shock Progression Through The Crust

As the shock progresses through the outer crust of the neutron star, it accelerates. For non-relativistic shocks, the shock velocity is given by (Sedov 1959):

$$v_{shock} \propto t^{\frac{\omega-3}{5-\omega}}, \tag{2}$$

where ω is given by the density structure of the medium through which the shock travels ($\rho \propto r^{-\omega}$). Shocks propogating through density profiles where $\omega > 3$ accelerate. As the shock propogates through the exponentially decreasing density profile of the neutron star crust, it accelerates and quickly becomes relativistic. Analytic solutions of ultra-relativistic shocks and semi-analytic solutions of mildly relativistic shocks also exist (Johnson & McKee 1971; McKee & Colgate 1973; Gnatyk 1985). For an exponentially falling density profile (to high accuracy, the structure of the outer crust of a neutron star is an exponential atmosphere) the product of the Lorentz factor (Γ) and the velocity of the shock ($\beta = v/c$ where c is the speed of light) is given by (Gnatyk 1985):

$$\Gamma\beta \propto (\rho r^{N+1})^{-\alpha}, \tag{3}$$

[4]Angular momentum does not alter our results. The outer crust of the neutron star does not collapse significantly before being ejected and their trajectories are not significantly effected by angular momentum. Likewise, the explosion is too rapid to allow the development of convection and it will also not effect the results.

where N is a geometric factor set to 2 for spherical symmetry, and α is determined, via simulations, to be ∼0.20.

Unfortunately, this solution does not apply to the velocity of the material after the shock has passed through the material and the internal energy of the material begins to convert back to kinetic energy[5]. Therefore, we are forced to simulate, to high spatial resolution, the velocity of the ejecta. For this purpose, we use the code KEPLER. Although KEPLER is not a relativistic code, we can determine the effective Lorentz factor of the expanding material by setting $\Gamma = E_{tot}/(Mc^2)$ where E_{tot} is the total energy from the simulation and M is the mass of the ejecta. Figure 2 plots the energy output of our explosions as a function of material ejected with Lorentz factors greater than Γ_0. Comparing our simulations just after shock breakout with the analytic solutions shows that this conversion holds quite well at this point in the simulation (see Figure 2).

However, the material continues to accelerate after the shock breaks out of the neutron star as internal energy is converted to kinetic energy. Although energy is conserved globally, our conversion for Γ places more energy than the relativistic solution at high Lorentz factors, overestimating the amount of highly relativistic material at late times (see appendix). The exact energy output of these explosions, then, is bounded by the energy distribution given at shock breakout and our overestimate of the *final* energy output. A more accurate distribution requires relativistic simulations. Assuming the upper limit given by our simulations, there is still very little energy ($< 10^{46} erg$) ejected atΓ's greater than 40 (see Figure 2). Thus, even in our most energetic explosion (which is probably much stronger than reality), there is insufficient energy at high Lorentz factors to explain gamma-ray bursts.

3. Observational Properties

The primary result of this work is simply that the energies produced via the phase-transition of neutron stars at high Lorentz factors ($\Gamma > 40$) is at least 4-5 orders of magnitude too low to explain cosmological gamma-ray bursts, and these explosions can not explain the gamma-ray burst observations. Although the explosion resulting from a phase-transition of a neutron star into a strange star is not sufficiently relativistic to be a gamma-ray burst source, it does have a lot of energy ($\sim 10^{51}$erg) at mildly relativistic velocities. To estimate the luminosity profile of these explosions, we assume the ejecta loses

[5]The final velocity depends upon the equation of state and the effects of gravity, effects not modeled by the semi-analytic solution

its energy over its deceleration timescale (Rees & Mészáros 1992):

$$L = E(\Gamma)/t_{\rm dec}(\Gamma) \tag{4}$$

where the deceleration timescale ($t_{\rm dec}$) is given by:

$$t_{\rm dec}(\Gamma) = \frac{r_{\rm dec}(\Gamma)}{2\Gamma^2 c} \tag{5}$$

and the deceleration radius ($r_{\rm dec}$) is:

$$r_{\rm dec}(\Gamma) = \left(\frac{E(\Gamma)}{4/3\pi\rho_{\rm ext}\Gamma^2}\right)^{1/3}. \tag{6}$$

In these equations, Γ is the Lorentz factor, $E(\Gamma)$ is the explosion energy at that Lorentz factor, and $\rho_{\rm ext}$ is the density of the interstellar medium (for our purposes, we assume a number density of 1 cm^{-3}). Under these assumptions, we can estimate the luminosity of phase-transition induced explosions of neutron stars (see Figure 3). There is a small peak at early times, but the luminosity "burst" quickly levels off at luminosities as high as 10^{45}erg/s and persists for roughly 30 days. Note that this luminosity is brighter than a typical galaxy, but 6 orders of magnitude less than a supernova. Even if we assumed that the all neutron stars undergo such phase transitions ($\sim 1/100$yr^{-1} per L_* galaxy), these objects would make only a fraction (10^{-9}) of any magnitude limited supernova survey due to their lower luminosity. If instead, only those neutron stars which accrete a sizable amount of material ($\gtrsim 0.1 M_\odot$) undergo this phase transition, the rate falls to roughly the X-ray binary formation rate: $\lesssim 10^{-5}$yr^{-1} per L_* galaxy (Kalogera & Webbink 1998). We must rely on nucleosynthetic constraints to place limits on these transitions.

We follow nuclear processes throughout the explosion, assuming the electron fraction is roughly 0.5 (Our bounce models predict that the neutrinos will reset the electron fraction to this value) and assuming that the triple-α process dominates the helium burning. The bulk of the ejecta from these simulations is helium (see Figure 4). Some iron and r-process elements are produced, but only in the interior zones where the expansion is only mildly relativistic. This result is an additional counter argument against those models that require high iron fractions in the ejecta (Shaviv & Dar 1996).

The amount of r-process ejecta is difficult to estimate without a detailed calculation. In the outer layers the expansion time scale is too short and the entropy too high to reassemble alpha particles to iron group isotopes and above. In most of the ejected mass, as in Figure 4 around 10^{30}g, elements just above the iron group will be ejected in a strong α-rich freeze out from nuclear statistical equilibrium (Woosley & Hoffman 1992). There may be rare species here such as ^{88}Sr, ^{89}Y, and ^{90}Zr that limit the occurrences of these events (see also

Woosley & Baron 1992; Woosley et al. 1994). For an amount of material of order 10^{27} - 10^{28}g (Figure 4), a classical r-process may occur (Hoffman, Woosley, & Qian 1997), though the ejecta would still be chiefly helium. Given a rate for neutron star phase-transitions comparable to the X-ray binary formation rate ($\lesssim 10^{-5}$/yr), the small amount of r-process ejecta ($\lesssim 10^{-5} M_{\odot}$) contributes roughly 0.1% of the galactic r-process nucleosynthesis. Only if nearly every neutron star formed in the galaxy experienced this phase transition would the resultant ejecta dominate the r-process nucleosynthesis. At these rates, the contribution to cosmic rays might also be appreciable.

We are grateful to Wolfgang Keil for providing us with a neutron star model and many useful discussions. Also, we would like to thank Thomas Janka and Ewald Müller for their helpful insight on this problem. We would like to thank the hospitality of the Max-Planck Institut für Astrophysik for hosting us over the duration of this project. This work was supported by the NSF (AST 94-17161) and by NASA (NAG5 2843 and MIT SC A 292701). SEW also acknowledges the support of an award from the A. V. Humboldt Foundation that covered his research expenses while at the MPA in Garching.

A. Comparison of Newtonian and Special Relativistic Equations

In this paper we have used a Newtonian code to simulate relativistic motion. While we compared the results of our code with analytic derivations for the shock progression and found good agreement after the shock breaks out of the neutron star, we have assumed without equal justification, that our Newtonian code remains accurate during the post-shock expansion. Here we show that our results for $\Gamma \gg 1$ ejecta are an upper limit (i.e., even less material will be ejected at high Γ's than in Figure 2).

After the shock has traversed the neutron star, matter continues to accelerate as internal energy is converted to kinetic energy. Assuming no energy is lost via neutrino radiation, the energy conservation equation can be written as the relativistically correct expression (e.g. Marti and Müller 1994):

$$\frac{\partial(\rho h \Gamma^2 - P - \rho \Gamma c^2)}{\partial t} + \bigtriangledown(\rho h \Gamma^2 v - \rho c^2 \Gamma v) = 0 \tag{A1}$$

where ρ is the density, P, the pressure, v, the velocity, c, the speed of light, t, the time, $\Gamma \equiv 1/\sqrt{1-(v/c)^2}$, $h \equiv c^2 + \epsilon + P/\rho$ is the enthalpy, and ϵ, the internal energy per unit mass. By using the special relativistic formula for mass conservation:

$$\frac{\partial(\rho \Gamma)}{\partial t} + \bigtriangledown(\rho \Gamma v) = 0, \tag{A2}$$

we derive a reduced form of the energy conservation equation:

$$\frac{\partial(\rho\epsilon)}{\partial t} + (1-\Gamma^{-2})\frac{\partial P}{\partial t} + \bigtriangledown(\rho\epsilon v) + \bigtriangledown(Pv) + (2\Gamma(\rho h) - \rho c^2)\Gamma^{-2}\frac{d\Gamma}{dt} = 0. \tag{A3}$$

The first and third term in this equation correspond to changes in internal energy, the second and fourth terms correspond to changes in pressure, and the final term is associated with changes in kinetic energy. This equation can be compared to its Newtonian counterpart:

$$\frac{\partial(1/2\rho v^2 + \rho\epsilon)}{\partial t} + \bigtriangledown[v(1/2\rho v^2 + \rho\epsilon + P)] = 0, \tag{A4}$$

which, with a similar reduction using mass conservation becomes:

$$\frac{\partial(\rho\epsilon)}{\partial t} + \bigtriangledown(\rho\epsilon v) + \bigtriangledown(Pv) + \rho v\frac{dv}{dt} = 0. \tag{A5}$$

In the limit as $\Gamma, h/c^2 \Rightarrow 1$, the $\partial P/\partial t$ term in A3 disappears, and the last term in both A3 and A5 become equal. As the material expands, internal energy is converted to kinetic energy. To check our estimation of Γ $(= E_{tot}/(Mc^2))$ during this phase, we compare the dependence of the rate of change of Γ on the rate of internal energy change for the case of special relativity (A3):

$$\left.\frac{d\Gamma}{dt}\right)_{\rm SR} = \frac{\Gamma[\partial(\rho\epsilon)/\partial t + \bigtriangledown(\rho\epsilon v)]}{2(\rho c^2 + \rho\epsilon + P) - \rho c^2/\Gamma} \tag{A6}$$

with its Newtonian counterpart (A5):

$$\frac{\partial v}{\partial t} = \frac{[\partial(\rho\epsilon)/\partial t + \bigtriangledown(\rho\epsilon v)]}{\rho v}. \tag{A7}$$

Using our conversion assuming all the energy has been converted to kinetic energy $(\Gamma = E_{tot}/(Mc^2) \Rightarrow v^2/(2c^2))$, we get the following transformation:

$$\frac{d\Gamma}{dt_{\rm SR}} = \frac{c^{-2}d(v^2/2)}{\Gamma^{-1}dt_{\rm Newt}} = \frac{\Gamma v}{c^2}\frac{dv}{dt_{\rm Newt}} \tag{A8}$$

and equation (A7) becomes:

$$\left.\frac{d\Gamma}{dt}\right)_{\rm Newt} = \frac{\Gamma[\partial(\rho\epsilon)/\partial t + \bigtriangledown(\rho\epsilon v)]}{\rho c^2}. \tag{A9}$$

Comparing A6 and A9, it is evident that although our conversion works well for low Γ material where the internal energy and pressure our negligible, we will *overestimate* the increase in Γ when $\Gamma >> 1$ or when the internal energy and pressure become important. This implies that we are overestimating the amount of mass at high Γ's, making it even less likely that these explosions are gamma-ray bursts. However, this simple comparison does not give an exact value for Γ. We will provide piston velocities for anyone who would like to simulate this explosion using a relativistic code.

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Table 1. Neutron Star Collapse Simulations

Collapse Model	Ejected Mass	Kinetic Energy	Energy ($\Gamma > 40$)
Strong Explosion[a]	$0.017 M_\odot$	$\sim 5 \times 10^{51}$	10^{46}erg
Weak Explosion[b]	$0.001 M_\odot$	$\sim 3 \times 10^{50}$	10^{45}erg
Black Hole[c]	0	0	0

[a]In this simulation, the inner boundary falls inward from 7.5km to 4.5km assuming free-fall conditions. It then rebounds with a kinetic energy per gram equal to the potential energy (10^{53}erg/$0.6 M_\odot$). This is an overestimate of the energy released as some of the energy certainly goes into internal energy. The inner boundary slowly decelerates as it expands (from gravity) until it reaches 6km, where it stops and is held fixed for the duration of the simulation.

[b]In this simulation, the inner boundary falls inward from 7.5km to 5.0km assuming free-fall conditions. It is then held fixed.

[c]In this simulation, the inner boundary falls inward from 7.5km to 4.5km assuming free-fall conditions. It is then held fixed but the infalling cells are accreted when they reach densities above 5×10^{14}g/cm^3.

Fig. 1.— Mass-point trajectories of our most energetic collapse simulation. In this simulation, the inner boundary falls inward from 7.5km to 4.5km assuming free-fall conditions. It then rebounds with a kinetic energy per gram equal to the potential energy (10^{53}erg/$0.6M_{\odot}$). This is an overestimate of the energy released as some of the energy certainly goes into internal energy. The inner boundary slowly decelerates as it expands (from gravity) until it reaches 6km, where it stops and remains constant for the duration of the simulation. This simulation is almost certainly more energetic than we would expect from a true phase-transition induce collapse. Note that almost $0.02M_{\odot}$ is ejected with nearly 10^{51}erg, but that nearly the entire star beyond the inner boundary expands beyond its initial radius (Figure 1b). In fact, the ejecta contains less the 10% of the potential energy released.

Fig. 2.— Energy of ejected material with $\Gamma\beta$ greater than $\Gamma_0\beta_0$. Both the analytic derivation and our simulation are compared at a time prior to shock break-out and the conversion of internal energy to kinetic energy. The two curves lie nearly directly on top of each other, confirming our method to convert from the total energy in the simulations to the value for Γ. Note that even for the most energetic explosion less than 10^{46} erg is ejected at Γ's greater than 40. The strong and weak explosions correspond to the strong and weak explosions in Table 1.

Fig. 3.— Luminosity vs. time for our explosions. The luminosity remains above 10^{45}erg/s for up to 30 days for our most energetic explosion. We use the output from the simulations, summing the contribution of each zone of material to the luminosity. The highly relativistic material decelerates quickly and dominates the luminosity at short timescales whereas the massive ejecta at low velocities dominates the lightcurve at late times. Again, the strong and weak explosions correspond to the strong and weak explosions in Table 1.

Fig. 4.— Nucleosynthetic yield for our most energetic explosion. We have assumed here that the initial electron fraction is roughly 0.5 (our bounce simulations predict that the absorbed neutrino flux resets the electron fraction to this value) and that the triple-α process is the dominant helium burning mechanism. Most of the ejecta, especially the highly relativistic ejecta, is helium, but some r-process nucleosynthesis can occur.

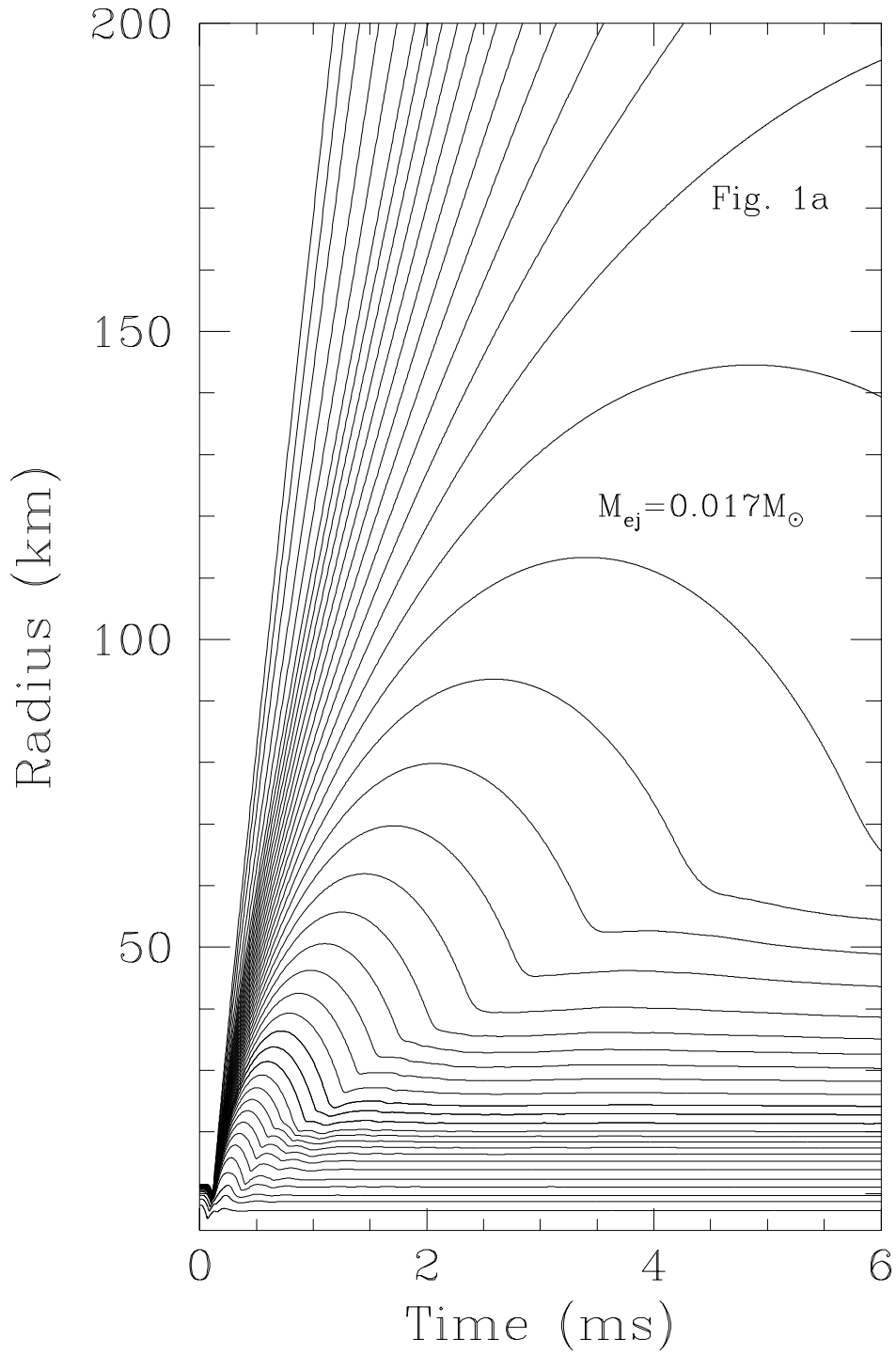


Fig. 1a
$M_{ej}=0.017M_\odot$
Radius (km)
Time (ms)
200
150
100
50
0
2
4
6

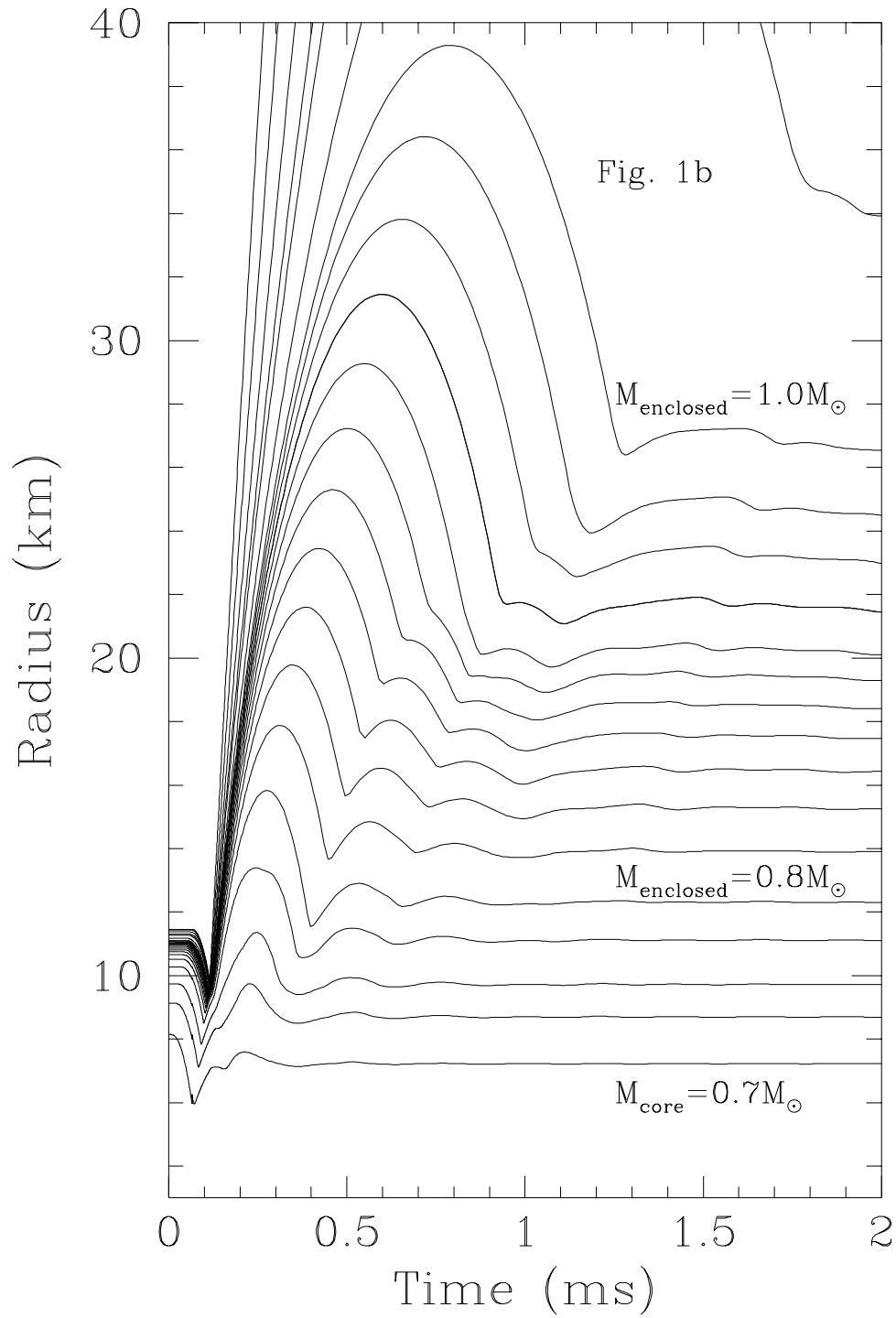
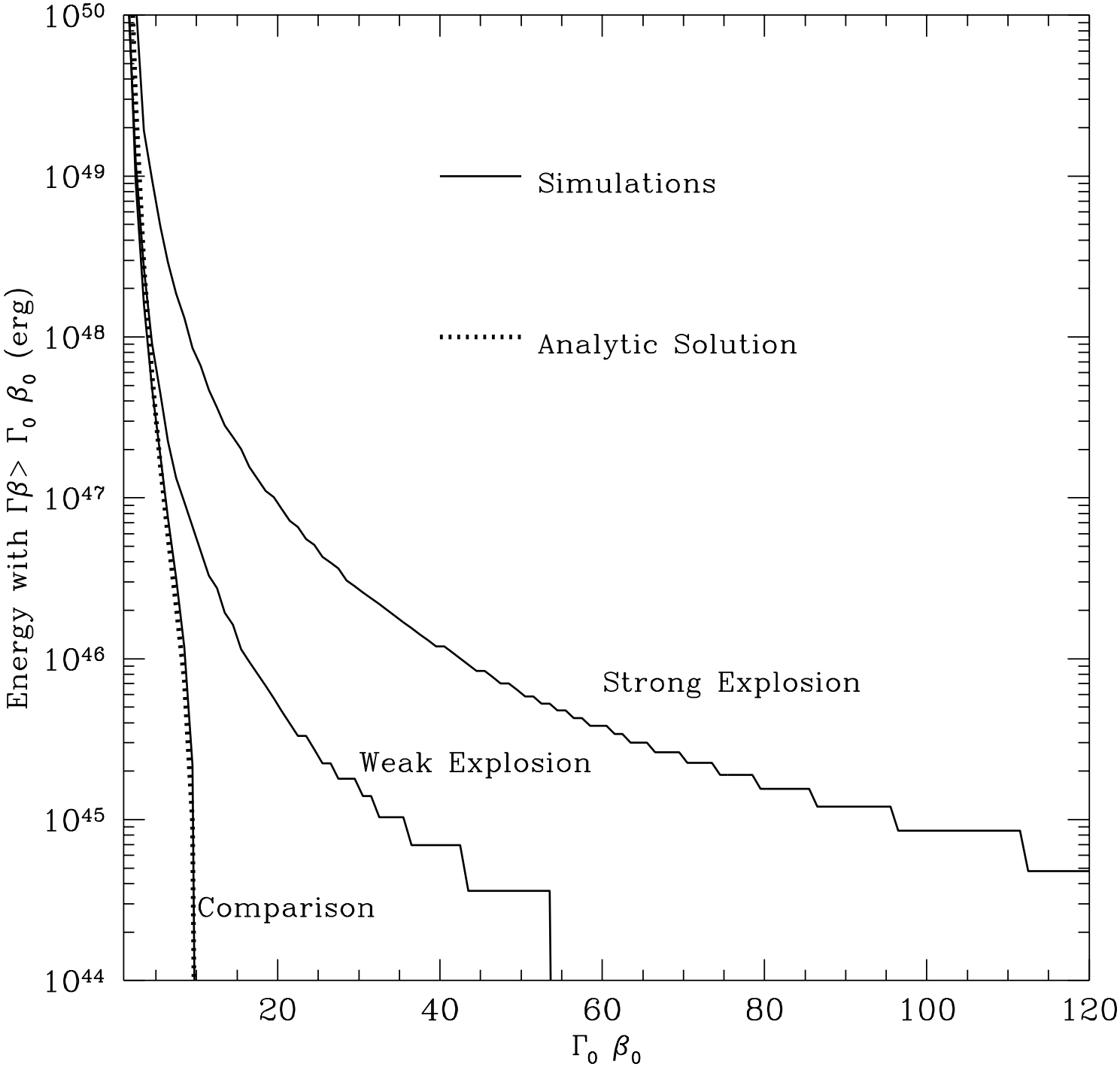
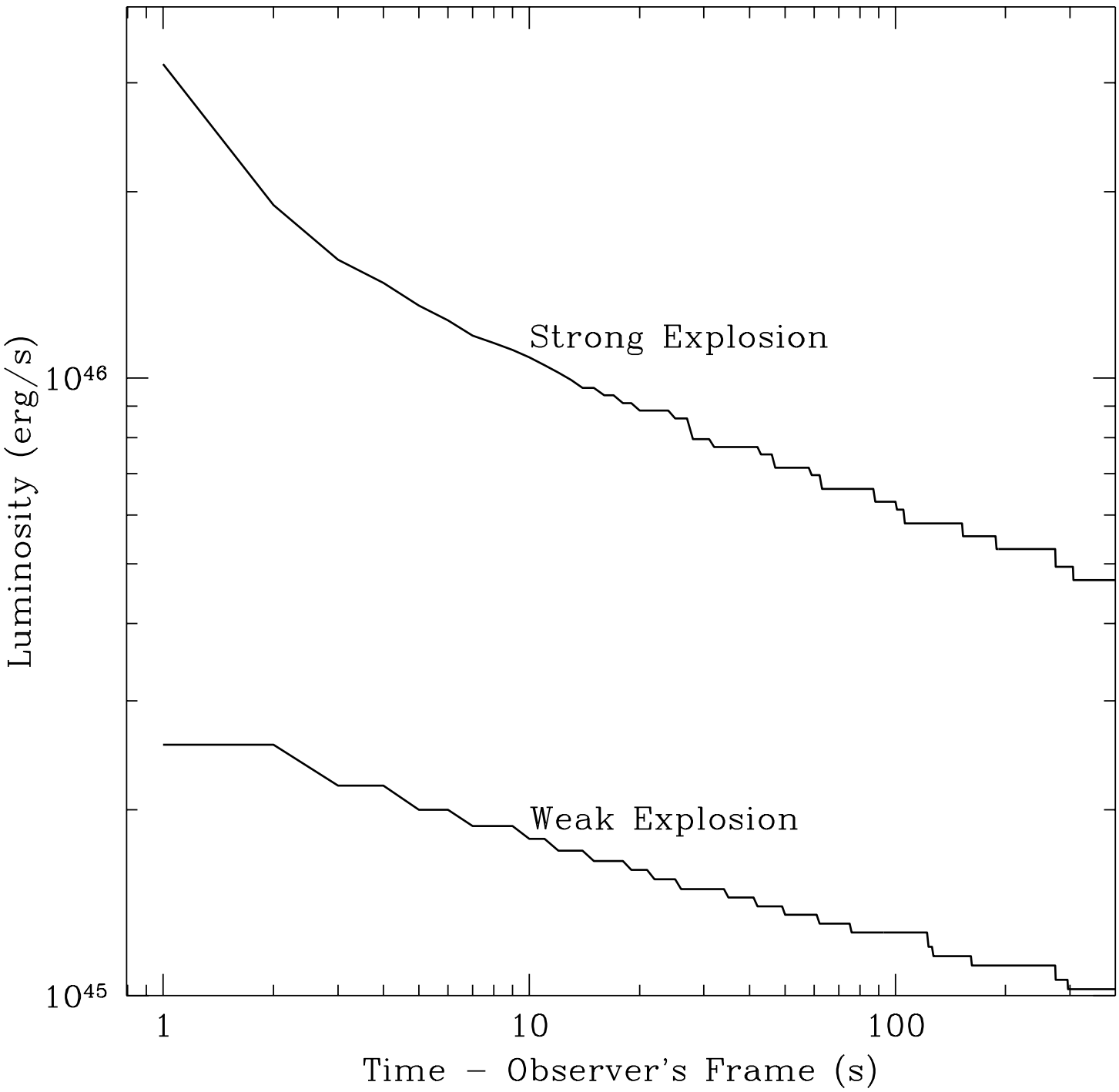
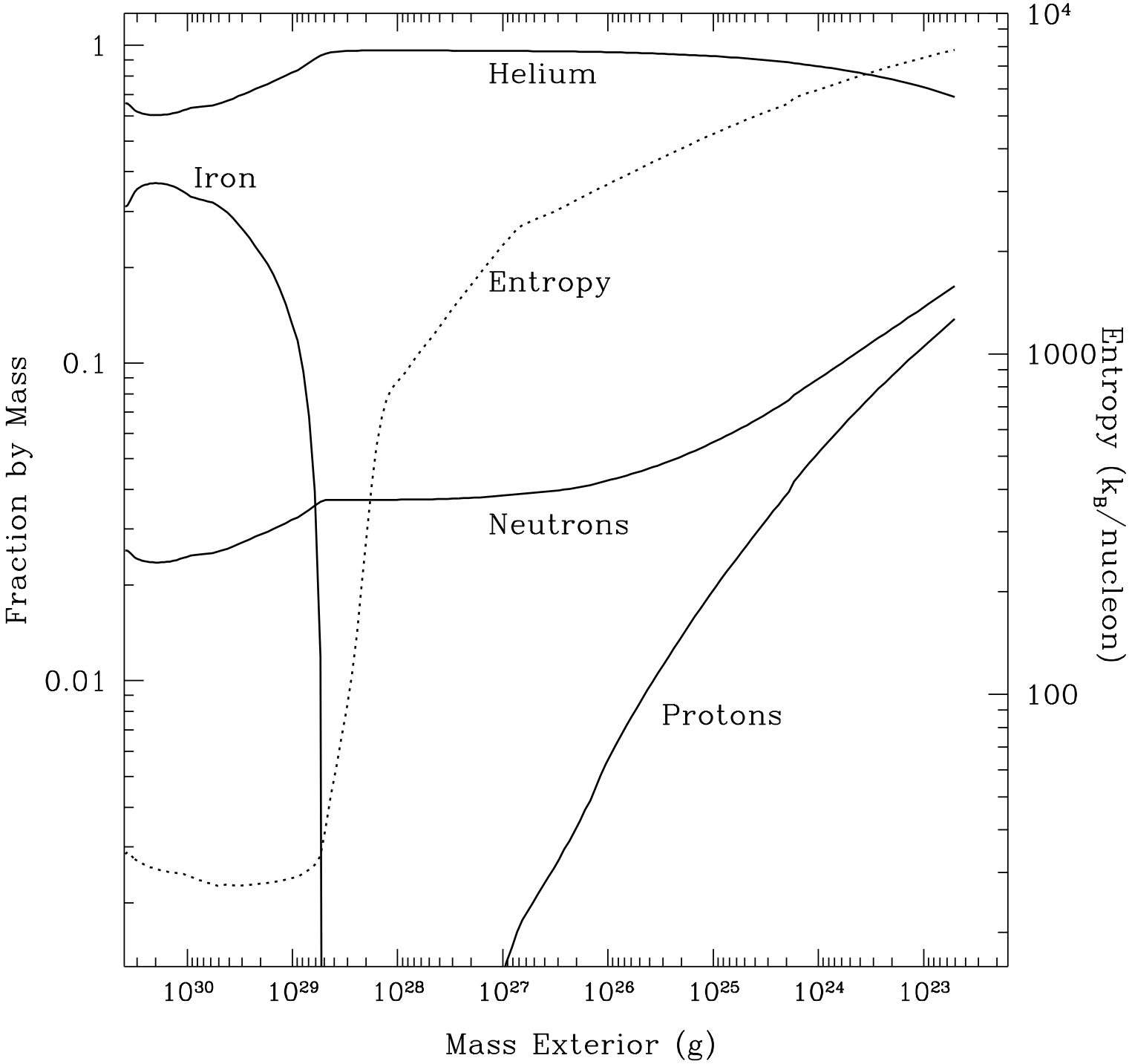


Fig. 1b
$M_{enclosed}=1.0M_\odot$
$M_{enclosed}=0.8M_\odot$
$M_{core}=0.7M_\odot$
Radius (km)
Time (ms)
40
30
20
10
0
0.5
1
1.5
2


Simulations
Analytic Solution
Strong Explosion
Weak Explosion
Comparison
Energy with Γβ> Γ0 β0 (erg)
Γ0 β0
10^50
10^49
10^48
10^47
10^46
10^45
10^44
20
40
60
80
100
120


Strong Explosion
Weak Explosion
Luminosity (erg/s)
10^{46}
10^{45}
1
10
100
Time – Observer's Frame (s)


Helium
Iron
Entropy
Neutrons
Protons
Fraction by Mass
Entropy (k_B/nucleon)
Mass Exterior (g)
1
0.1
0.01
10^4
1000
100
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}