Mass Limits For Black Hole Formation

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ABSTRACT

We present a series of two-dimensional core-collapse supernova simulations for a range of progenitor masses and different input physics. These models predict a range of supernova energies and compact remnant masses. In particular, we study two mechanisms for black hole formation: prompt collapsed and delayed collapse due to fallback. For massive progenitors (>20 M⊙), after a hydrodynamic time for the helium core (a few minutes to a few hours, fallback drives the compact object beyond the maximum neutron star mass causing it to collapse into a black hole. With the current accuracy of the models, progenitors more massive than 40 M⊙ form black holes directly with no supernova explosion (if rotating, these black holes may be the progenitors of gamma-ray bursts). We calculate the mass distribution of black holes formed, and compare these predictions to the observations, which represent a small biased subset of the black hole population. Uncertainties in these estimates are discussed.

Subject headings: black hole physics - stars: evolution - supernova: general

1. Introduction

As the number of massive compact accretors in X-ray binaries increases (McClintock & Remillard 1986; Casares, Charles, & Naylor 1992; Remillard, McClintock, & Bailyn 1992; Bailyn et al. 1995; Filippenko, Matheson, & Barth 1995; Remillard et al. 1996), so does the importance of understanding the formation of these stellar-mass black holes. Although it
has long been known that stellar-mass black holes could form from the collapse of massive stars (Oppenheimer & Snyder 1939), theorists have yet to explain any details of black hole formation: e.g. the number or mass distribution of the black holes formed.

This lack of progress in understanding black hole formation is a result of the difficulty in modeling the core collapse of massive stars. Pursuit of the relevant physics of core-collapse supernovae has occupied theorists for three decades (see Bethe 1990). The evidence suggesting that black holes form from stars with mass above 25 M\(_\odot\) continues to grow and includes: nucleosynthetic constraints (Maeder 1992; Kobulnicky & Skillman 1997) and the formation of black hole X-ray binaries (Portegies Zwart, Verbunt, & Ergma 1992; Ergma & van den Heuvel 1998). Not until the last decade, with the acceptance (and the successful 2D simulations) of the delayed neutrino-driven supernova mechanism (Wilson & Mayle 1988; Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996; Fryer 1998), has it become possible for simulations of core collapse to make predictions on black hole formation. Unlike the constraints from nucleosynthesis and from X-ray binary formation, core-collapse simulations provide direct evidence for black hole formation. Black holes can form in core collapse either by direct collapse of a massive star or through fallback after a supernova explosion. In this paper, we outline the conditions required to produce black holes and apply these conditions to the results of core-collapse simulations. From these simulations we can determine the number and mass distribution of black holes.

2. Black Hole Formation

To understand black hole formation, one must first understand the mechanism behind core-collapse supernovae. The current paradigm is based upon an explosion driven by neutrino-energy deposition. A shock is produced as the inner core of a massive star collapses and bounces. The shock stalls due to dissociation and neutrino losses but leaves behind an unstable entropy gradient. This entropy gradient initiates a convective layer at the edge of the stalled shock which grows down to the proto-neutron star surface. Neutrino heating drives the convection further as cool material flows down to the proto-neutron star, heats via neutrino absorption and rises and expands before it can lose its energy through neutrino emission. The outer edge of the convection layer is bounded by an accretion shock as the star continues to collapse on itself. The ram pressure of the shock is given by:

\[
P_{\text{shock}} = \frac{1}{2} \rho_S v_{\text{ff}}^2 = \frac{\sqrt{2GM_{\text{encl}}\dot{M}_S}}{8\pi R_S^{5.5}} \tag{1}
\]

where \( G \) is the gravitational constant, \( v_{\text{ff}} = \sqrt{2GM_{\text{encl}}/R_S} \), \( \rho_S \), \( \dot{M}_S \), and \( M_{\text{encl}} \) are, respectively, the free-fall velocity, density, mass infall rate and enclosed mass just above the
shock radius ($R_S$). The pressure in the convective layer must overcome this ram pressure to drive a successful explosion.

Once the convective layer begins to push the shock radius outward, the pressure from the shock ($P_{\text{shock}}$) decreases, and an explosion is virtually inevitable (Bethe 1997). However, if the shock pressure overcomes the pressure in the convective layer, its radius decreases, and it becomes even more difficult for the convective layer to overcome the ram pressure. In these cases, the star collapses directly into a black hole\footnote{This does not preclude such a collapse from being observed. If the star is rotating rapidly enough, it will form an accretion disk which can power a gamma-ray burst (Woosley 1993; MacFadyen & Woosley 1999).}. Unfortunately for supernova theorists, the most recent simulations find that massive cores straddle the fine line between explosion and collapse (Wilson & Mayle 1988; Miller, Wilson, & Mayle 1993; Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996; Mezzacappa et al. 1998; Messer et al. 1998; Fryer 1998). Because core-collapses straddle this line, their ultimate outcome depends sensitively upon the implementation of the physics (e.g. equation of state, neutrino transport, general relativity) as well as upon the progenitor (e.g. progenitor mass or rotation). Burrows & Goshy (1993) stressed the importance of the mass infall rate for the success or failure of a supernova explosion. This is directly related to the progenitor mass, because, at any given time after collapse, the infall rate increases with increasing progenitor mass (Fig. 1). As the mass infall rate increases, the shock pressure increases (Eq. \[\equiv\]), and the convective layer must have more energy to explode. The large difference between 15 and 25 M$_\odot$ progenitors is due to differences in the iron core mass of these models (Weaver & Woosley 1993, 1996; Timmes, Woosley, & Weaver 1996). Above some progenitor star mass, all stars will directly collapse to black holes, forming black holes of mass equal to their progenitor.

But even those stars which explode may form black holes. As the supernova shock travels outward, it decelerates (Sedov 1959):

$$v_{\text{shock}} \propto t^{\frac{5}{15}}$$

where $\omega$ is given by the density structure of the medium through which the shock travels ($\rho \propto r^{-\omega}$). Some of the expanding material may decelerate below the escape velocity and fall back onto the neutron star (Herant & Woosley 1994, Woosley & Weaver 1995). If this material pushes the neutron star above the maximum neutron star mass limit, a black hole is formed. In this manner, the core-collapse of a massive star can produce both a supernova and a black hole. The mass of these black holes depends upon the amount of fallback and ultimately produce a range of black hole masses.
Thus, for core collapse models, we can define three regimes of compact object formation: 
a) low mass, core-collapse stars drive strong explosions with little fallback and produce 
neutron stars, b) moderate mass stars produce explosions, but the fallback is sufficient to 
form black holes, and c) high mass stars are unable to launch shocks and collapse directly 
to black holes. The question for core-collapse theorists, then, is to determine the limits for 
these regimes.

3. Core-Collapse Simulations

For our simulations, we use a code originally described in Herant et al. (1994). This 
code models the core collapse continuously from collapse through bounce and ultimately 
to explosion. The neutrino transport is mediated by a crude, single energy flux-limiter. 
Beyond a critical radius, $\tau < 0.3$, a simple “light-bulb” approximation for the neutrinos 
is invoked which assumes that any material beyond that radius is bathed by an isotropic 
flux equal to the neutrino flux escaping that radius. For our simulations, we have raised 
this radius to $\tau < 0.1$ (which modified the kinetic energies by 10%), and we also removed 
the neutrino/electron scattering opacity\(^2\). The angular resolution has been improved to 
roughly 1°. To this code, we have added spherically symmetric general relativity and a more 
sophisticated flux limiter (Fryer et al. 1999). The advantage of this code is that it models 
the supernova explosion from collapse through bounce without the need to set up a new 
grid. In addition, all but the inner 0.001 – 0.004 $M_\odot$ is modeled in 2-dimensions, avoiding 
any problems that might arise from constructing an inner boundary. The drawback of this 
code is its single-energy flux-limited neutrino transport. Because the massive cores straddle 
the line between a supernova explosion and a direct collapse into black hole, the details of 
all the input physics (e.g. equation of state, general relativity) are important, including the 
algorithm for neutrino transport (Janka & Müller 1996, Mezzacappa et al. 1998, Messer et 
al. 1998). We will come back to the uncertainties in the physics in the next section.

First, however, let’s review the results of our simulations. Table 1 summarizes the 
entire set of simulations, using 3 progenitor masses ($15 M_\odot, 25 M_\odot, 40 M_\odot$) both with and 
without the effects of general relativity. The “standard” models\(^3\) are given in bold-face.
In addition, because Mezzacappa et al. (1998) found that their more detailed neutrino 
transport lead to lower neutrino energies and luminosities (by roughly 10%), we have run

\(^2\)This can have large effects. See Swesty (1998)

\(^3\)These models are the most physical of our models. We do not artificially alter the neutrino flux and 
include the effects of general relativity.
a set of models where the neutrino energies are artificially lowered by 20%. This lowers the luminosity by 20%. Since the neutrino opacity is proportional to the square of the neutrino energy, it lowers the amount of neutrino heating by an additional 40%. This lowered neutrino run leads to energies and luminosities which are lower than those of Mezzacappa et al. (1998) and, combined with our “standard” runs, brackets their results. If the differences in the models are simply caused by differences the neutrino energy, by lowering the neutrino energies by 20%, our 15 M$_\odot$ model should have fizzled along with the 15 M$_\odot$ models of Mezzacappa et al. (1998). In figure 2, note that our mean neutrino energies and luminosities are indeed lower than those of Mezzacappa et al. (1998), yet from Table 1, we see that we still get an explosion. Clearly, the differences in the mean neutrino energies can not explain all the differences in the simulation. However, our low neutrino run allows us to estimate the sensitivity of the core-collapse simulations on the neutrino transport.

The trends in the compact remnant masses and explosion energies can be understood by comparing the shock pressure to the pressure in the convective region. By lowering the neutrino energies, there is less heating and the convective layer has less pressure. It therefore takes longer for the convective layer to overcome the ram pressure. The collapsed core accumulates more mass, and generates less energetic explosions. Although the increased effective mass using general relativistic gravity leads to a faster (by 10 ms) bounce, the lower heating rate (due to both the time dilation and the redshift of the neutrinos) leads to weaker convection, and a later explosion.

The differences in the ram pressure for different progenitors also explains the varying results for the massive progenitors. For the 15 M$_\odot$, the mass infall rate (Fig. 1), and hence ram pressure, is 5 times lower just 100 ms past bounce. It is not surprising, then, that the 15 M$_\odot$ model explodes much faster than its more massive counterparts. Figure 3 shows the evolution of the 15 M$_\odot$ and 25 M$_\odot$ models with time (in the standard models). The convective layer in the 15 M$_\odot$ model quickly overcomes the ram pressure and launches an explosion 140 ms past bounce. The 25 M$_\odot$ model takes nearly 100 ms longer to explode. Since the infall rate of the 25 M$_\odot$ and 40 M$_\odot$ progenitors do not differ significantly until 300 ms past bounce, it is not surprising that these simulations give similar answers. However, the 40 M$_\odot$ model teeters on the edge of direct collapse (lowering the neutrino energy produces no explosion, and at the end of the simulation, the accretion shock radius is decreasing). For our simulations, the 40 M$_\odot$ progenitor roughly marks the dividing line between supernova explosion and direct collapse.

But what about the lower progenitor mass-limit for black hole formation due to fallback? In calculating our explosion energy, we only considered the binding energy of the material in our simulation (the inner 3-4 M$_\odot$). But the rest of the star must also be
ejected. We can roughly estimate the fallback by assuming that only the outer layers with total binding energy less than the explosion energy are actually ejected (Table 1). From the models of Woosley & Weaver (1995), we can calculate the energy required to eject all but the inner $3 \,\text{M}_\odot$ core (Fig. 4). If the explosion energy is less than this amount, the compact remnant will accrete beyond $3 \,\text{M}_\odot$ and will collapse to a black hole. Note that our explosion energies decrease with increasing progenitor mass, whereas the binding energy of the star increases with increasing mass. These two effects limit the “neutron star-fallback black hole” transition mass to a narrow range (18-25 M$_\odot$).

However, one must be careful about the definitions of these energies. The explosion energy given here is computed by calculating the difference (before and after the explosion) between the sum of kinetic + internal - potential energies of the material beyond the core mass. As a lower limit, this energy must overcome the binding energy of the star to avoid the formation of a black hole. But, in fact, it must be greater to actually produce an energetic supernova. In practice, some of the energy from our simulations goes into the kinetic energy of the explosion ($\text{KE}_\infty$ of Woosley & Weaver 1995), and the amount of fallback predicted in Table 1 is a lower limit. Note that, especially in observational papers, the term “explosion” energy is used to mean $\text{KE}_\infty$. To extract $\text{KE}_\infty$ from the explosion energies given in Table 1, one must subtract the binding energy of the material which is ejected.

For example, the mass of the progenitor of supernova 1987A is thought to be $\sim 20 \,\text{M}_\odot$, and yet its energy at infinity was roughly $10^{51}$ ergs (Woosley 1988) which corresponds to over $2 \times 10^{51}$ ergs of core-collapse explosion energy (Table 1). The low Nickel yield and low kinetic energy of supernova 1997D (Turatto et al. 1997) suggests that its total explosion energy was lower than that of supernova 1987A. Turatto et al. (1997) estimate its progenitor mass was at least $26 \,\text{M}_\odot$. However, Turatto et al.’s model used much more energy than our $25 \,\text{M}_\odot$ model predicts: to eject all but the inner $\sim 2.1 \,\text{M}_\odot$ with an energy at infinity of $0.4 \times 10^{51}$ ergs requires roughly $1.4 \times 10^{51}$ ergs explosion energy, twice the value for our $25 \,\text{M}_\odot$ model (Table 1). Clearly, the details of the core-collapse model must be understood better.

4. Implications

Core-collapse simulations can now place rough limits on black hole formation: stars more massive than $\sim 25 \,\text{M}_\odot$ will eventually collapse to form a black hole, and those more massive than $40 \,\text{M}_\odot$ will not produce a supernova explosion. Assuming a Scalo (1986) initial mass function ($\alpha_{\text{IMF}} = 2.7$), the ratio of black holes to neutron stars in the Galaxy is 1.5%
(1.2% from fallback, 0.3% from direct collapse). This number does not include those black holes formed from hypercritical accretion onto neutron stars in binaries (Bethe & Brown 1998; Fryer & Woosley 1998; Fryer, Woosley, & Hartmann 1999) which may double this number.

From Table 1, we see that the black hole mass should range from 3-15 M\(_\odot\) for progenitors less massive than 40 M\(_\odot\). Beyond 40 M\(_\odot\), the final black hole mass could be as large as its progenitor. But the progenitor mass depends sensitively on the implementation of winds and binary effects. Bailyn et al. (1998) have suggested that the masses of black holes cluster around \(\sim 7\) M\(_\odot\). The black holes that have been measured are all in X-ray binaries. It is likely that the progenitors of these black holes lost most of their hydrogen envelope in a common envelope evolution. The loss of this hydrogen envelope will not change the core, nor the results of the core-collapse simulations dramatically, but it will change the amount of material which can fall back onto the core. 26 M\(_\odot\) and 45 M\(_\odot\) stars have helium cores of mass 10 M\(_\odot\), 20 M\(_\odot\) respectively. Given that some of the helium core mass will be lost to winds, and further mass will be ejected in the supernova explosion, these black holes should, on the average, be less massive than their single-star counterparts, but in any case, it these black holes should have a range of masses: 3-15 M\(_\odot\). With the current data, this range fits the data as well as the Bailyn et al. (1998) single mass value. If the data improves and exhibits no range whatsoever, an important piece of the black hole puzzle is still missing. However, a range of black hole masses will support our outline of black hole formation.

However, the sensitivity of the core-collapse simulations upon the implementation of the physics, both in the core collapse and the progenitor models, strongly argues for caution in any of these claims. Simply by lowering the mean neutrino energy by 20% decreases the resultant explosion energy by over a factor of 2. This lowers the fallback black hole mass limit to roughly 15 M\(_\odot\), increasing the fraction of black holes from 1.5% to 24%! Neutrino transport is not the only uncertainty in core-collapse models which will affect the results, and these details must be studied before a final answer can be determined. However, the good agreement of the general picture of black hole formation does, however, imply that the solution has indeed moved to a study of the details. As the uncertainties of the physics are better understood, the reliability of the core-collapse predictions of black hole formation will increase.

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Table 1. Core Masses, Explosion Energies, and Ejecta Masses

| Model             | $M_{\text{Core}}$ | $M_{\text{Remnant}}$ | Energy | $M_{\text{ejected}}$ |
|-------------------|-------------------|-----------------------|--------|----------------------|
|                   | (M$_{\odot}$)     | (M$_{\odot}$)        | (10$^{51}$ Erg) | $Y_e < 0.4$ | $Y_e < 0.45$ | $Y_e < 0.49$ |
| 15 M$_{\odot}$ Newtonian | 1.1              | 1.1                   | 3.0         | 0.15     | 0.19    | 0.24    |
| 15 M$_{\odot}$ GR$^d$ | 1.2              | 1.4                   | 2.5         | 0.07     | 0.13    | 0.17    |
| 15 M$_{\odot}$ GR-low $\nu$ | 1.4              | 2.2                   | 0.1         | -$^e$    | -       | -       |
| 25 M$_{\odot}$ Newtonian | 1.3              | 1.3                   | 2.2         | 0.25     | 0.30    | 0.54    |
| 25 M$_{\odot}$ GR     | 1.4              | 5.2                   | 0.6         | -$^e$    | -       | -       |
| 25 M$_{\odot}$ GR-low $\nu$ | 1.6              | 25                    | 0.0        | -        | -       | -       |
| 40 M$_{\odot}$ GR     | 1.6              | 12.9                  | -$^e$      | -        | -       | -       |
| 40 M$_{\odot}$ GR-low $\nu$ | >1.6             | 40                    | 0.0        | -        | -       | -       |

$^a$The core mass assumes no fallback. All masses are the baryonic mass.

$^b$The remnant mass after fallback estimated by assuming only material with binding energy less than the supernova energy is actually ejected and that no mass is lost from winds.

$^c$The explosion energy is computed by calculating the difference (before and after the explosion) between the sum of kinetic + internal - potential energies of the material beyond the core mass. This energy must overcome the binding energy of the star to avoid the formation of a black hole.

$^d$The results in bold-faced are the “most-likely” given the current sophistication of the models. The different variations in the results, however, give some idea of the range in these results.

$^e$The low energy 15 M$_{\odot}$, 25 M$_{\odot}$ runs as well as the 40 M$_{\odot}$ “standard” run will not eject significant amounts of neutron rich material unless it is carried out by convection.
Fig. 1.— Mass infall rates for a 3 separate progenitor masses: 15, 25, 40 $M_\odot$. The mass infall rate for the 15 $M_\odot$ progenitor drops to 1/5th that of the 25 and 40 $M_\odot$ models in 100 ms. This allows it to explode sooner, leaving behind a smaller core. The infall rates of the 25 and 40 $M_\odot$ progenitors stay roughly the same for 300 ms past bounce, and hence their explosion energies are similar.
Fig. 2.— (a) Electron neutrino and anti-electron neutrino luminosities and (b) energies for our 15 M_⊙ run with lowered neutrino energy and the 15 M_⊙ simulation of Mezzacappa et al. (1998). Note that our luminosity and energy is less than or equal to theirs, yet our simulation explodes and theirs collapses directly to a black hole. We have also plotted the lowest neutrino luminosity from Janka & Müller (1996) which leads to a supernova explosion in 2-dimensions. Their luminosity is also lower than that of Mezzacappa et al. (1998).
Fig. 3.— Snapshots of the evolution of both a 15 and 25 M$_\odot$ core collapse (top to bottom: 50, 90, 140, 240 ms). The 15 M$_\odot$ model has launched a strong explosion after 140 ms. It takes the 25 M$_\odot$ progenitor nearly 100 ms longer to develop such an explosion. The color codes entropy with blue and red indicating limiting entropies of roughly 1.10 k$_B$ per nucleon respectively. The vectors indicate the strength and direction of the velocities.
Fig. 4.— Binding energy (solid line) and explosion energy (dots) vs. mass of progenitor. This binding energy includes all but the inner 3 $M_\odot$ core of the star. If the explosion energy is less than the binding energy, the compact remnant will exceed 3 $M_\odot$ and collapse to form a black hole. The explosion energy drops and the binding energy rises with increasing progenitor mass, their net effect is to create a fairly narrow range of uncertainty in the transition mass from neutron star formation and black hole formation from fallback. For reference, supernovae 1987A and 1997D are placed on this graph (squares).