Black Hole Formation from Stellar Collapse

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Abstract.

I review the end-state of massive stellar evolution, following the evolution of these massive stars from the onset of collapse through the formation of a compact remnant and the possible supernova or hypernova explosion. In particular, I concentrate on the formation of black holes from stellar collapse: the fraction of stars that form black holes, the black hole mass distribution, and the velocities these black hole remnants may receive during their formation process.

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1. Supernovae, Hypernovae and Black Hole Formation

Stellar-mass black holes form during the final stages of a massive star's life, when the star implodes in on itself. To understand black hole formation, we must also understand which stars collapse and the explosions that are produced by stellar collapse. Type Ib/c and Type II supernovae (Filippenko 1997), most hypernovae (Nakamura et al. 2001), and possibly long-duration gamma-ray bursts (Woosley 1993, MacFadyen & Woosley) are all believed to be produced by the gravitational energy released when the core of a massive ($\sim$8-10 $M_\odot$ or greater) star collapses down to a neutron star or black hole. Less massive stars eject most of their material prior to core-collapse and instead form white dwarfs. Below we discuss the relation between explosion and remnant type: supernovae versus gamma-ray bursts, neutron star (NS) versus black hole (BH) remnants. These different outcomes depend not only on the star's mass, but also on its metallicity (which effects its mass-loss through winds), its rotation rate, and its binary companion.

1.1. Collapse Versus Envelope Ejection

Stars are powered by the fusion of elements in their core. Hydrogen burning into helium fuels most of a star's life. When the hydrogen fuel is used up, massive stars will contract, heat up, and ignite the ashes of hydrogen burning (helium), accessing a new store of fuel. For massive stars, this process of burning the ashes of each preceding burning stage can continue through carbon, oxygen and even silicon burning until an iron core is built up in the center of the star. Because iron is at a minimum in energy states, the fusion of iron does not produce further energy and burning halts (regardless of a star's mass). The iron core is supported by electron degeneracy and thermal pressures, but when the core reaches too large a mass, the high temperatures in the core cause the iron to dissociate into alpha particles, an endothermic reaction which reduces the thermal pressure. In addition, as the core reaches higher and higher densities, electrons begin to capture onto protons, removing electron degeneracy pressure. This loss in pressure causes the iron core to contract which accelerates the rate at which iron dissociation and electron capture occurs. Very quickly the core-collapse becomes a runaway process.

For lower mass stars, the contracting core does not heat up sufficiently to produce an iron core before shell burning above the core ejects the star's envelope, ultimately leaving behind a white dwarf. The transition from white dwarf (at lower masses) and core-collapse (at higher masses) depends sensitively on the shell burning phases and probably occurs somewhere between 8-10 $M_\odot$.

1.2. Neutron Star Versus Black Hole

For stars more massive than 8-10 $M_\odot$, a runaway collapse proceeds until the stellar core reaches nuclear densities and neutron degeneracy pressure and nuclear forces halt the collapse. The "bounce" of the core launches a shock back through the star. Although this bounce was once believed to drive the explosion, it was found that neutrino emission

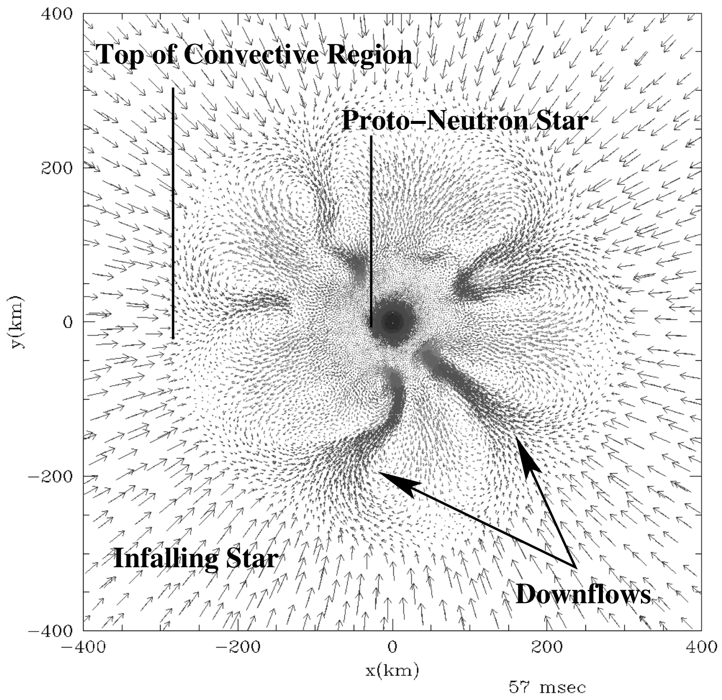

Figure 1. Slice of a 3-dimensional simulation from Fryer & Warren (2002). The infalling material crashes down on the top of the convection region and the ram pressure from this material prevents an explosion. This material builds up and accretes in discrete downflows onto the proto-neutron star. Neutrinos from the proto-neutron star and this accretion heat the material in the convective region causing it to rise. When this material can overcome the lid produced by the infalling material, this pressure cooker explodes!

from the shock causes it to stall. Plenty of energy to drive an explosion is left in the hot proto-neutron star and neutrinos emitted from this core can heat the stalled region and revive the shock. The stalled shock region, which stretches from the $\sim 30\,$km collapsed core (a.k.a. proto-neutron star) out to the furthermost edge of the shock (~ 100-$300\,$km) is convectively unstable (Fig. 1). Neutrinos from the hot proto-neutron star heat the bottom of the convective region, further driving this convection which converts the thermal energy from neutrino deposition into kinetic energy. If the convective region can overcome the ram pressure of the outer layers of the star which are crashing down on it, an explosion is launched.

Strong explosions eject most of the star, ultimately leaving behind a neutron star which we observe as pulsars or, through accretion, as X-ray binaries. If only a weak explosion is launched, some of the ejecta may fall back and accrete onto the neutron star. In some cases, this material can be sufficient to cause the neutron star to collapse and form a black hole. In still other cases, the convective region is never able to overcome the ram pressure of the shock, and the shock eventually moves in, compressing the proto-neutron star until it collapses to form a black hole.

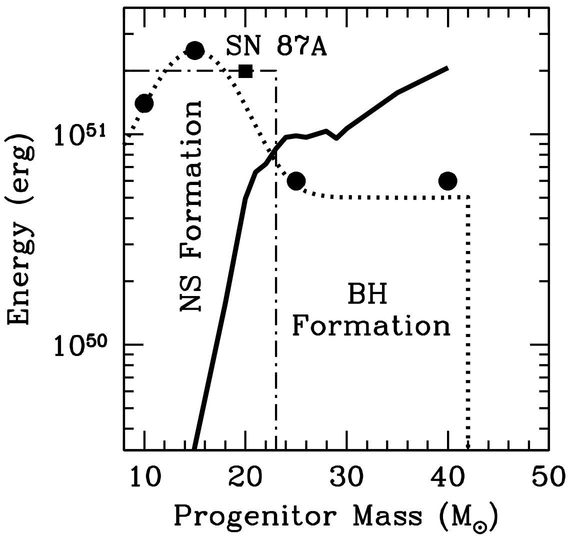

Figure 2. Binding energy (solid line)/Explosion energy (dotted,dot-dashed) line versus progenitor star mass for single star models with no mass loss. The dotted line is the fit to explosion models (circles) by Fryer (1999). The dot-dashed line refers to a step-function explosion energy used to try to fit the mass-gap in black hole masses. The square represents SN 1987A for which we truly know the progenitor mass.

Ignoring the effects of binary companions, stellar winds and rotation, the fate of a massive star depends solely upon the mass of the star. Fryer (1999) found that as a star's mass increases, its fate evolves from a strong explosion with a neutron star remnant through a weak explosion with a black hole remnant to no explosion whatsoever with a black hole remnant (Fig 2). The masses where these transitions occur are at roughly $20\,M_\odot$ and $\sim 45\,M_\odot$ respectively.

Table 1. Collapse of a $60M_\odot$ Star - Effects of Winds (Fryer et al. 2002)

Wind Multiplier	Final Mass	Explosion Energy	Remnant Mass
1	$3.132M_\odot$	1.45×10^{51} ergs	$1.35M_\odot$
1/2	$4.389M_\odot$	2.36×10^{51} ergs	$1.17M_\odot$
1/3	$6.108M_\odot$	1.60×10^{51} ergs	$2.11M_\odot$
1/4	$7.550M_\odot$	0.30×10^{51} ergs	$5.2M_\odot$
1/6	$10.746M_\odot$	0 ergs	$10.7M_\odot$

But the effects of rotation, winds, and binaries can not be neglected. Mass-loss from stellar winds can have a dramatic effect on the fate of massive stars (Table 1). A factor of 2 decrease in the mass-loss rate can change the collapse remnant from a $2.0\,M_\odot$ neutron star to a $> 10\,M_\odot$ black hole and can change a strong supernova explosion to no explosion whatsoever. Current models for massive stellar winds assume steady mass loss

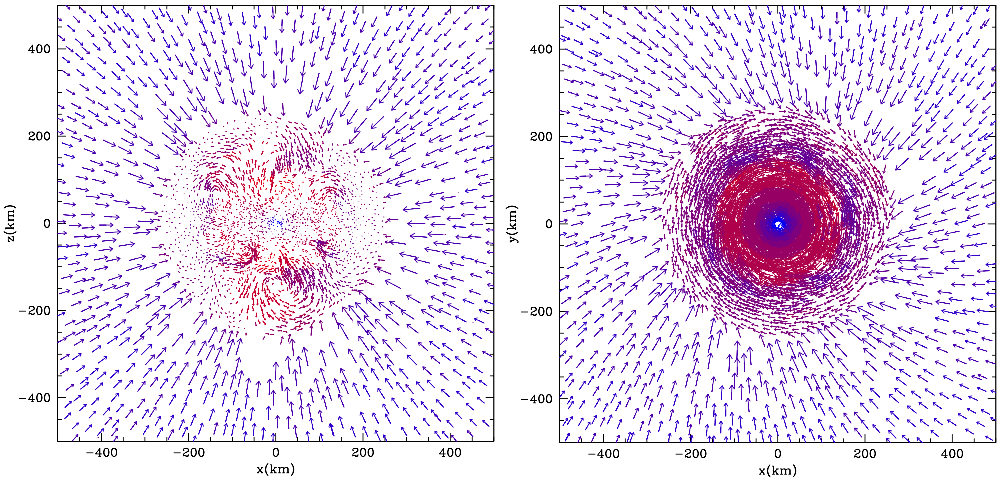

Figure 3. Slices of a 3-dimensional simulation of a rotating $15\,\mathrm{M}_{\odot}$ star (Fryer & Warren 2003) looking along the equatorial (left) and polar (right) axes. Angular momentum changes the convection dramatically, but not as much as predicted by Fryer & Heger (2000) where the angular momentum is not transported whatsoever!

and depend upon parameters that can only be determined through observations, not basic physics. Unfortunately, observations of massive, mass-losing stars have shown that mass loss is clumpy, sporadic, and difficult to predict and it is not clear that mass-loss rates used in stellar models are accurate to better than an order of magnitude.

The main effect of binaries is to help eject mass through mass transfer or common envelope episodes. When a massive star expands out of hydrogen burning onto the giant branch, it can lose mass to its companion (or even out of its entire binary system) through interactions with its companion. This can cause the star to enter a Wolf-Rayet (rapid mass losing) phase earlier and make wind mass-loss more effective. Unfortunately, roughly half of all the stars in our Galaxy are in sufficiently close binaries that these binary effects must be included.

Simulations by Fryer & Heger (2000) showed that rotating stars have weaker explosions than non-rotating stars. This occurs because the angular momentum profiles produced in the current stellar models (Heger 1998) prevent convection and the energy transport that convection affords. The collapse simulations by Fryer & Heger (2000) preserved angular momentum exactly. If convection in the core leads to angular momentum transport, such as in the latest 3-dimensional models by Fryer & Warren (2003), the convection is not damped as much (Fig. 3) and may lead to explosions on par with non-rotating counterparts. However, the angular momentum transport for the simulation in Figure 3 is likely to be higher than what actually occurs in the core, and it may be that the Fryer & Heger (2000) results are closer to nature than what is shown in Figure 3. Unfortunately, although there now exist progenitors for rotating massive stars at collapse, these simulations are missing several pieces of crucial physics (most notable being magnetic fields) and it is not clear how fast massive stellar cores are truly rotating.

Despite these uncertainties (as well as uncertainties in the initial mass function), Fryer & Kalogera (2001) showed that between 5-40% of the all collapsing stars form black holes. That means there are roughly $5 \times 10^6 - 4 \times 10^7$ black holes our Galaxy.

2. Black Hole Mass Distribution

The gravitational wave emission from black hole inspiral (either into a large black hole producing a LISA signal or into smaller black holes producing a strong LIGO signal) depends sensitively on the black hole mass (Sipior & Sigurdsson 2002). With the caveats of the uncertainties listed above, it is possible to also derive a black hole mass distribution from theory. From BH X-ray binary systems, we can also derive a black hole mass distribution, and depending upon how you analyze these results, the observational distribution may or may not be consistent with the theoretical distribution. Here we summarize the theoretical predictions for black hole mass distributions, how they constrain stellar models, and how they compare with observational data.

2.1. Theoretical Mass Distributions

Fryer & Kalogera (2001) did a systematic study of the remnants produced by stellar collapse using the explosion energies from Figure 2 as a guide. The binding energy of a star increases dramatically with mass between 15 and $25 M_\odot$ and it is likely that the explosion energy decreases in this same range, so even with the uncertainties in the supernova explosion mechanism, the transition mass from NS and BH remnants is defined within a narrow mass range. In the absence of stellar winds, the uncertainty in the binding explosions energies as a function of progenitor mass do not make large uncertainties in the black hole mass distribution. Using the fit to the supernova explosion energy and binding energies of non-mass losing stars (Fig. 2), Fryer & Kalogera constructed a mass distribution of stellar-mass black holes (Fig. 4). The slope of this distribution is fairly insensitive to the fit to the explosion energy.

However, if one includes the effects of mass loss, especially mass-loss enhanced by binary interactions, this picture can change quite dramatically. In fact, recent models of massive stars (Woosley, Langer, & Weaver 1993) predicted that massive stars above 30-40 $M_\odot$ would lose most of their mass through winds. With such strong winds, if these stars lose their hydrogen envelopes prior to helium ignition, it is likely that they will end their lives with masses less than 4-5 $M_\odot$. Such high mass-loss rates would make it difficult to form X-ray binaries with masses above 7-8 $M_\odot$. The issue of mass loss has been a point of contention between the X-ray binary community and the stellar community for over a decade. Although the stellar community is working on the theory

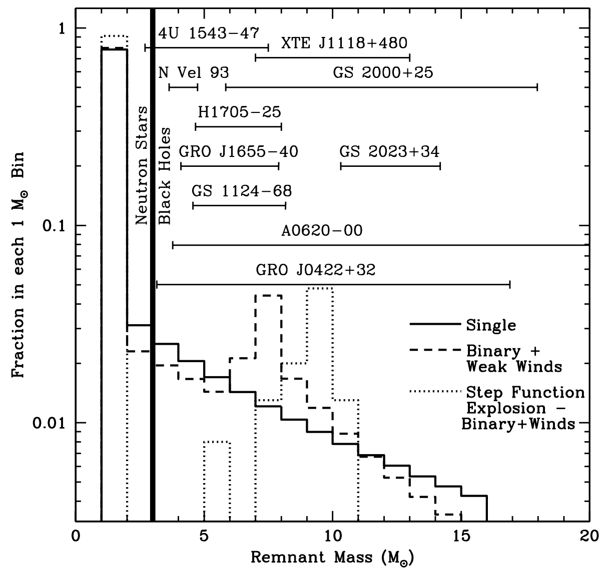

Figure 4. Mass distribution of black holes and neutron stars using the best fit to the Fryer (1999) explosion energies for single stars (solid line) and binary stars with weak winds (dashed line) along with the step-function explosion energy for binary stars and weak winds (dotted lines). The data of observed systems with their error bars are plotted as well.

of mass-loss and clearly understands the physics of stellar winds better than the X-ray binary community, the X-ray binary community has the upper hand in the fact that close binaries with $10_{\odot}$ black holes exist in the Galactic disk (the progenitor probably had a metallicity near solar). Stellar evolutionists have been forced to slowly decrease the mass-loss rate of stars. A factor of 6 decrease in mass-loss factors (Table 1) easily allows more massive BHs and mass distributions close to the binary mass distribution derived by Fryer & Kalogera (Fig. 4).

These two mass distributions predict a continuous distribution of black hole masses from the maximum neutron star mass up to $\sim 10\,\mathrm{M}_{\odot}$. However, many black hole binary observers argue strongly that there is a gap in black hole masses from 3-5$\,\mathrm{M}_{\odot}$. How must the theory change to incorporate this? Fryer & Kalogera chose a step function for the supernova explosion energy (Fig. 2) and found that they could produce a black hole mass distribution with a gap (Fig. 4). However, as we shall discuss below, the evidence for the mass gap is marginal at best, and supernova observations suggest strongly that a step function in the explosion energy is not possible.

The basic trends in the various uncertainties are summarized in Table 2. Winds are the biggest effect and can change the total number of BHs by over an order of magnitude. These effects are enhanced in close binaries. Uncertainties in the initial mass function (IMF) are also important (factors of 2 in the total black hole mass number). Uncertainties in the explosion energy make the smallest differences but can change results by 50%.

2.2. Observational Mass Distributions

Bailyn et al. (1998) argued that the observed distribution of black hole masses are consistent with a narrow range of BH masses around 7 $M_{\odot}$. Figure 4 shows the observed black hole masses with their associated error bars. Fryer & Kalogera (2001) argued that these observations are actually more consistent with a continuous mass distribution like what we would expect from theory. However, Orosz (2002) has recently argued that new data affirms the delta function mass distribution. But the masses are now clustered around 10 $M_{\odot}$, not 7 $M_{\odot}$. Creating a delta function mass distribution at 10 $M_{\odot}$ for close binary systems is difficult, if not impossible to do. It would require a step function in the explosion energy which is all but ruled out by the observed weak supernovae such as SN 1997D (Turatto et al. 1998). It also would require that the progenitor of these close binaries not lose its entire hydrogen envelope during a mass transfer phase prior to collapse.

Given that these effects are unlikely, if not impossible, it is worth discussing some of the biases that might effect the observational sample. Fryer & Kalogera (2001) did not see this gap in the data and they argued that the gap only manifests itself when some of the observations are discarded. This data is generally discarded on grounds that it "isn't reliable", but I fear that it is discarded because the error bar on the mass dips below 3 $M_{\odot}$ and hence the compact object could be a NS. But by discarding those BHs with masses which could be below 3 $M_{\odot}$, observers are biasing against low-mass BHs.

Of course, there can be other physical effects to cause the observational data set to have a gap in the 3-5 $M_{\odot}$. First of all, low-mass BHs are formed in supernova explosions that eject considerable mass which make it more difficult for the binary to remain bound. In addition, depending upon the kick mechanism for NSs, low-mass BHs might receive stronger kicks than high-mass BHs, unbinding these binaries.

2.3. Black Hole Kicks

It is now generally accepted that not only are NSs born with fast velocities as high as 1000 km s^{-1} (Cordes, Romani, & Lundgren 1993), but their "kick" distribution appears to be bimodal with roughly half of all NSs receiving velocities above 400-500 km s^{-1} and

Table 2. Trends in Black Hole Masses

Physical Property	Effect	Maximum BH Mass	Number of BH
Increasing Rotation	Decrease Energy	No Change	Increase
Increasing Wind	More Mass-Loss	Decrease	Decrease
Close Binary	Increase Wind	Decrease	Decrease
Steep IMF	Fewer Massive Stars	No Change	Decrease

the other half receiving only 100-500 $\mathrm{km\,s^{-1}}$ kicks (Cordes & Chernoff 1998). Given that BHs are formed in similar stellar collapses to those that form NSs, it is not surprising that black holes may also receive "kicks" at birth.

Unfortunately, unlike NSs which can emit quite brightly as single objects (pulsars), BHs are currently observed only in binary systems where accretion onto the black hole powers X-ray emission. So it is much harder to get a population of BHs from which to derive a kick distribution. Those black holes that are observed are in binaries. Not only must we model the entire binary to extract a kick velocity, but we must also be aware of the biases that are involved in limiting our sample to those black holes that actually remain bound.

Fryer (1999) studied the currently (at that time) known BH binary systems and found that although all but one binary system needed a kick to explain its peculiar velocities, for all systems, the BH could have received a kick as high as 50 $\mathrm{km\,s^{-1}}$ at birth and a Maxwellian kick distribution with an rms velocity of 50 $\mathrm{km\,s^{-1}}$ fits all of the binary systems much better than a 0 velocity kick distribution. Theories of kick formation are not enough developed to really say much about the neutron star kick distribution, let alone the black hole kick distribution. But assuming that kicks are produced in all stars that produce supernovae and since most black holes are produced in supernovae which have extensive fallback, it would not be surprising that the momentum of the kick imparted to NSs is the same as BHs, implying that the velocity of black hole kicks is $v_{\rm BH} = v_{\rm NS} M_{\rm NS}/M_{\rm BH}$ (Fryer 1999).

This completes our review of the current understanding of the formation of stellar-massed BHs, their mass distribution and their velocities.

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