Failed Supernovae Explain the Compact Remnant Mass Function

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ABSTRACT

One explanation for the absence of higher mass red supergiants ($16.5 M_\odot \lesssim M \lesssim 25 M_\odot$) as the progenitors of Type IIP supernovae (SNe) is that they die in failed SNe creating black holes. Simulations show that such failed SNe still eject their hydrogen envelopes in a weak transient, leaving a black hole with the mass of the star’s helium core ($5–8 M_\odot$). Here we show that this naturally explains the typical masses of observed black holes and the gap between neutron star and black hole masses without any fine-tuning of stellar mass loss, binary mass transfer, or the SN mechanism, beyond having it fail in a mass range where many progenitor models have density structures that make the explosions more likely to fail. There is no difficulty including this $\sim$20% population of failed SNe in any accounting of SN types over the progenitor mass function. And, other than patience, there is no observational barrier to either detecting these black hole formation events or limiting their rates to be well below this prediction.

Key words: stars: evolution – stars: massive – supergiants – supernovae: general

1. INTRODUCTION

All massive $M \gtrsim 8 M_\odot$ stars undergo core collapse, but only some must explode as core collapse supernovae (ccSNe). All collapses leading to the formation of a neutron star must have a ccSN to eject mass and avoid collapsing into a black hole. Core collapse can lead to the formation of a black hole either through a failed SN, where the stalled accretion shock never revives, or in a successful ccSN, where sufficient mass falls back onto the proto-neutron star, which causes a collapse to a black hole. Little is observationally known about the balance between these scenarios. The diffuse SN neutrino background sets an upper limit on the failed SN rate at roughly 50%–75% of the observed SN rate (Lien et al. 2010; Lunardini 2009), and there is some evidence for a mismatch between massive star formation and SN rates, which suggests a significant failed SN rate (Horiuchi et al. 2011; but see Botticella et al. 2012). However, theoretical studies generally favor low rates of failed SNe (e.g., $\sim$10% of ccSN rate) at solar metallicity (e.g., Woosley et al. 2002). We know nothing observationally about the formation of black holes in successful ccSNes, but it is a relatively common outcome in simulated explosions (e.g., Zhang et al. 2008; Fryer et al. 2012; Dessart et al. 2010).

While not directly motivated by understanding the formation of black holes, surveys attempting to provide a census of the progenitor stars to successful SNe can reveal the existence of failed SNe. In particular, there appears to be a deficit of high mass progenitor stars compared to standard initial mass functions (IMF; Kochanek et al. 2008). This is best quantified for the deficit of higher mass ($\sim 20 M_\odot$) red supergiant progenitors (Smartt et al. 2009). Perhaps this deficit can be explained by observational biases, such as stronger dusty winds around more massive stars (Walmswell & Eldridge 2012; but see Kochanek et al. 2012), or by having stars in this mass range evolve away from being red supergiants before exploding (see the discussion in Smartt et al. 2009, with the enormously increased mass loss for stars of these masses in the rotating stellar models of Groh et al. 2013 as a further example). However, the problem is unlikely to be explained by the uncertainties associated with estimating progenitor masses.

Individual progenitor mass estimates drift with the availability of data and changes in analysis methods (e.g., Maund et al. 2014), but none of these reassessments have changed the fundamental conclusions. Models of SN explosion phenomenology also disfavor these higher mass progenitors for Type IIP SNe (Dessart et al. 2010; Jerkstrand et al. 2013).

It is interesting to note that this mass range also corresponds to stars with internal structures that make it more difficult for them to explode (e.g., O’Connor & Ott 2011; Ugliano et al. 2012). Thus, one very simple explanation for the absence of higher mass Type IIP SN progenitors is that in the mass range $16.5 M_\odot \lesssim M \lesssim 25 M_\odot$ form black holes without an SN. The lower limit is set by the upper mass limit Smartt et al. (2009) found for Type IIP progenitors and $25 M_\odot$ is a reasonable estimate for the maximum mass of stars that undergo core collapse as red supergiants (see the discussion in Smartt et al. 2009). This mass range corresponds to $\sim 20\%$ of core collapses.

In principle, neutrino (e.g., Abbasi et al. 2011; Alexeyev & Alexeyeva 2002; Ikeda et al. 2007), or gravitational wave detection (e.g., Ott 2009) of a core collapse leading to black hole formation, combined with external astronomical observations of any resulting transient, would be the cleanest probe of this phenomenon. Unfortunately, such observations are only feasible in our Galaxy and its very nearest neighbors (e.g., Ando et al. 2005; Scholberg 2012). Thus the event rates are very unpleasantly low if the failed SN rate is $\sim 20\%$ of the SN rate. While any associated visible transient would be more easily observed in a nearby galaxy, almost all events in the Galaxy would be observable in the near-IR, despite the high extinction in the Galactic plane (see Adams et al. 2013).

After pointing out the deficit of higher mass SN progenitors in Kochanek et al. (2008), we also outlined an approach to identifying black hole formation events without accompanying SN, which was independent of the nature of any intervening transient. By carrying out a “disappearance” experiment, it is possible to monitor a large number of evolved massive stars to see if any “vanish.” We advocated this approach because the nature of the phenomenology that occurs between presence and absence was unclear and little studied. Some stars have density
Figure 1. Observed masses of neutron stars (filled triangles) and black holes (filled squares) from Özel et al. (2010, 2012). The thick solid line at 2.25 $M_\odot$ roughly marks the maximum mass of a neutron star. The relative numbers of neutron stars and black holes cannot be quantitatively compared.

Figure 2. Remnant mass distributions for the explosion models of Zhang et al. (2008; solid) and Fryer et al. (2012), where dotted lines show the distribution for rapid explosions and dashed lines show the distribution for delayed explosions. The distributions are normalized by the average number of remnants between 5 $M_\odot$ and 10 $M_\odot$. The models predict distributions dominated by low mass ($<5 M_\odot$) black holes and lack any clear gap between the masses of neutron stars and black holes. The thick solid line at 2.25 $M_\odot$ roughly marks the maximum mass of a neutron star.

This would naturally cause a gap in mass, with neutron stars having a mass $\lesssim 1.4 M_\odot$ and black holes having the final stellar mass. The problem is that almost all stars at death are more massive than the typical mass of the observed black holes. In standard models (e.g., Zhang et al. 2008; Dessart et al. 2010; Fryer et al. 2012) this forces black holes to be made in the course of successful ccSNe explosions so that mass can be ejected. The explosion is initiated in the core and the initial mass of the proto-neutron star is similar to an explosion in which a neutron star is formed, however this is followed by significant “fall back” of material onto the neutron star, which leads to the formation of a black hole. This allows for the formation of black holes that are less massive than their progenitor stars, but it requires fine tuning of stellar mass loss and explosion energies. In particular, it is difficult to avoid a continuous distribution of remnant masses without the observed gap between neutron stars and black holes. These problems are illustrated in Figure 2, where we show the remnant mass distributions predicted by Zhang et al. (2008) and Fryer et al. (2012). We fully explain the construction of Figure 2 in Section 2. The Zhang et al. (2008) models have no gap, whereas the Fryer et al. (2012) models partially create one by changing the explosion energetics with progenitor mass (also see Belczynski et al. 2012). One practical difference between these models is that the Fryer et al. (2012) models were constructed in part to explain the remnant mass distribution, while the Zhang et al. (2008) models were not. It is possible that the lack of similarity between the observed (Figure 1) and model (Figure 2) distributions is purely observational, but it could also be evidence that fall back is not a good mechanism for explaining the masses of black holes.

Binary interactions offer an alternate route to addressing this problem. Most massive stars are in binaries and a large fraction...
of them will interact (e.g., Sana et al. 2012; de Mink et al. 2014). Mass transfer, like mass loss, can strip a star of mass, and there are strong arguments that significant fractions of the stripped SN classes originate in mass transfer binaries (e.g., Eldridge et al. 2008; Smith et al. 2011). It is not clear, however, whether mass transfer provides any natural mechanism to produce a gap or minimum between the masses of neutron stars and black holes. The relative timing of stellar evolution for the two stars and the separation determines the mass transfer and no natural mass scale emerges, as evidenced by the continuum of SN properties from IIP (a massive hydrogen envelope) to IIL (limited hydrogen envelope) to IIb (very little hydrogen) to Ib (no hydrogen) to Ic (not much helium). Furthermore, since most mass transfer occurs once stars evolve, any mass range producing low-mass black holes by mass transfer will likely produce comparable numbers of high mass (> 10 M☉) black holes from the stars that do not undergo significant mass transfer, because black hole formation is likely controlled by the properties of the unstripped core, rather than the total mass. Fryer et al. (2012) include estimates for the effects of binaries on the compact remnant mass function, finding that it improves the match to the observed distribution but still lacks a pronounced minimum.

An alternate solution is suggested by simply accepting the evidence from progenitor studies that red supergiant stars with masses of 16.5 M☉ ≤ M ≤ 25 M☉ suffer failed SN explosions and form black holes. This provides a new and very natural explanation for both the existence of the gap and the typical masses of black holes. The key is the observation by Nadezhin (1980) that the envelopes of red supergiants are so weakly bound that the weakening of the gravitational potential created by the mass lost in neutrinos during core collapse is sufficient to unbind the hydrogen envelope of the star. Lovegrove & Woosley (2013) carried out detailed radiation-hydrodynamic simulations of this mechanism for 15 M☉ and 25 M☉ red supergiants and found that the adjustment of the envelope to the neutrino mass loss triggers a weak shock that unbinds the envelope as Nadezhin (1980) predicted. The result is a low luminosity (∼ 10⁶ L☉), cool (∼ 3000 K) transient lasting roughly one year and largely powered by the recombination energy of the envelope. Piro (2013) notes that there is also a shock break out pulse that is 10–30 times brighter and hotter (∼ 10⁴ K), which lasts roughly a week.

The key point for the remnant mass distribution is that the natural mass scale of the resulting black hole is the mass of the helium core of the progenitor star, thereby reproducing both the gap between neutron star and black hole masses, and the characteristic minimum masses of black holes, with no need for fine tuning stellar mass loss, the explosion mechanism, amount of fall back, or binary evolution. In Section 2 we show some simple models of mass functions based on this idea and how to fit a significant population of failed SNe into this overall accounting for the deaths of massive stars. In Section 3 we discuss some additional implications and strategies for identifying these events.

2. RESULTS

We generated Figure 2 using the following assumptions. We drew the progenitor masses from a Salpeter IMF over the mass range 8.5 M☉ < M < 100 M☉, although the upper mass limit is quantitatively unimportant. We then assigned masses either by interpolating over the Zhang et al. (2008) models or using the analytic approximations in Fryer et al. (2012). We used the solar metallicity SA model from Zhang et al. (2008), corresponding to an energy of 1.2 Bethe and a piston located at a fixed entropy per particle of S/k = 4. Above and below the tabulated range, from 12 to 100 M☉, we simply used the results for the appropriate limiting mass. For the Fryer et al. (2012) models, we assigned 1.4 M☉ remnant masses to progenitors with M < 11 M☉. As noted in Section 1, the results predict a continuum of black hole and neutron star masses and lack a clear peak in the observed mass range of black holes. When comparing Figures 1 and 2, do not compare the relative numbers of black holes and neutron stars, but only the two classes separately. In Pejcha et al. (2012) we modeled the masses of binary neutron stars from Özel et al. (2012) and found that they strongly disfavored models in which there was any fall back mass, however all the models used in Figure 2 must include fall back because it was the only way they can produce any low mass black holes.

In the Nadezhin (1980) mechanism, as confirmed by the simulations of Lovegrove & Woosley (2013), the remnant mass from the failed SN of a red supergiant is set by the mass of the helium core of the star. There may be some hydrogen fall back contribution, but in the Lovegrove & Woosley (2013) simulations it is small. Figure 3 shows the pre-SN mass, helium core mass, and the mass of the Ye core for the pre-SN stellar models of Woosley et al. (2002). The Ye core mass is a good proxy for neutron star masses in the absence of fall back and is defined by the point in the core where there is a significant jump in the electron abundance Ye. In Pejcha et al. (2012) we found that the mass of the Ye core with no fall back was one of the better models for the mass distribution of binary neutron stars. In this model sequence, mass loss becomes increasingly important above 20 M☉. Stars in the mass range corresponding to the missing red supergiant progenitors have helium core masses between 5 M☉ and 8 M☉, which almost exactly corresponds to the observed mass range of black holes.

Figure 3. Pre-supernova structure of massive stars from Woosley et al. (2002). The dashed line shows the final mass of the star. The solid lines show the mass of the Ye core, which will roughly correspond to the mass of any resulting neutron star, and the mass of the helium core. Note the enormous mass loss associated with the higher mass stars. The shaded region encompasses the mass range from 16.5 M☉ to 25 M☉ that we associate with failed supernovae.
Rather than being evidence against failed SNe, this is really evidence for the importance of binaries, which was discussed by Smith et al. (2011) in other contexts. Because we lack a fully quantitative understanding of either mass loss by individual stars or mass transfer in binaries, we only consider three classes of objects. We attribute Type IIP SN to lower mass stars \((M_0 \approx 8.5M_\odot < M < M_1 \approx 16.5M_\odot)\). These limits are chosen to match the mass range associated with Type IIP SNe by Smartt et al. (2009). Non-IIP SN are a combination of high mass stars \((M > M_2 \approx 25M_\odot)\), which have lost mass due to either stellar evolution or binary mass transfer, and a fraction \(b\) of the IIP mass range, where binary interactions lead to a non-IIP SN. For the present purposes, the relative fractions of the higher \(M > M_2\) mass stars that are stripped by mass loss or binary interactions do not matter. The mass scale \(M_2 \approx 25M_\odot\) is roughly the highest mass at which stars both undergo core collapse as red supergiants and the range of progenitor masses that can be more difficult to explode (e.g., O’Connor & Ott 2011 and Ugliano et al. 2012). Finally, the mass range \(M_1 < M < M_2\) leads to a failed SN. The interacting binary fraction is expected to be very high. For example, Sana et al. (2012) estimate that of all O stars at birth, roughly 30\% are effectively single, 24\% merge, 33\% undergo some envelope stripping, and 14\% have some accretion, which means it is perfectly plausible that \(b = 30\%–50\%\) of stars in the IIP mass range become non-IIP SNe due to interactions. In the IIP mass range, the donor star explodes as a non-IIP SN because of the mass transfer, and the recipient can explode as a non-IIP SN because it evolves as a more massive star with greater mass loss. We discuss the potential effects of this binary fraction on the phenomenology of the failed SNe in Section 3.

Under these assumptions, we can simply solve for the binary fraction required to leave a 48\% Type IIP fraction for successful SNe. For \(M_0 = 8.5M_\odot, M_1 = 16.5M_\odot\), and \(M_2 = 25M_\odot\) this results in a binary fraction of \(b = 0.33\), which is quite reasonable. Raising the upper mass limit for a failed SNe to \(M_2 = 30M_\odot\) only requires raising the binary fraction to \(b = 0.37\). For \(M_2 = 25M_\odot\) and the higher Type IIP fraction of 59\% found by Smartt et al. (2009) the binary fraction need only be \(b = 0.18\). Given all the other uncertainties, the main point is simply that given a reasonable fraction of binary-induced SN type transformations (from IIP to not IIP), there is no difficulty accommodating a significant rate of failed SNe in an accounting of SN types over the IMF. Figure 5 illustrates this graphically, following the similar figures by Smith et al. (2011).

3. DISCUSSION

Assuming that high-mass red supergiants die as failed SNe naturally solves two observational puzzles: (1) the failure to find progenitors in this mass range (e.g., Kochanek et al. 2008; Smartt et al. 2009), and (2) the peculiar mass distribution of compact remnants (e.g., Bailyn et al. 1998; Özel et al. 2010, 2012; Farr et al. 2011). While we lack a fully predictive theory of core collapse events, it is also true that many stellar models in this mass range have density structures that render them more difficult to explode (e.g., O’Connor & Ott 2011; Ugliano et al. 2012). Models of successful SNe can form black holes with masses of 5–10\(M_\odot\) by carefully tuning the stellar mass loss or mass transfer and the explosion energetics to achieve the correct amount of mass fall back. We used the examples of Zhang et al. (2008), which poorly matches the observed black hole mass distribution, and Fryer et al. (2012), which does better.

Figure 4. Remnant mass distributions if the core collapse of stars, in the mass range from 16.5\(M_\odot\) to 25\(M_\odot\), leads to the formation of black holes with the helium core mass from the models of Woosley et al. (2002; Figure 3). Outside this mass range we continue to use the results from Zhang et al. (2008; solid) and Fryer et al. (2012), where dotted lines show the distribution for rapid explosions and dashed lines show the distribution for delayed explosions. The distributions are normalized by the average number of remnants between 5\(M_\odot\) and 10\(M_\odot\). The black hole mass distributions now have a distinct peak in the observed mass range and far fewer low mass black holes. These low mass black holes could be completely eliminated by adopting higher energy explosion models from Zhang et al. (2008) or Dessart et al. (2010) with negligible fall back. The thick, solid line at 2.25\(M_\odot\) roughly marks the maximum mass of a neutron star.

We can now examine the remnant mass distribution if the more massive red supergiants undergo failed SN but eject their hydrogen envelopes based on the Nadezhin (1980) mechanism. Figure 4 shows the remnant mass distributions after we replace the remnant masses from the underlying models (for the mass range 16.5\(M_\odot\) < \(M < 25M_\odot\)) with the helium core mass shown in Figure 3. For all three cases, there is now a far more distinct peak at the observed masses of black holes, and the production of unobserved low mass black holes is greatly reduced. The effect is most dramatic for the Zhang et al. (2008) model, where the fraction of black holes (remnant masses > 2\(M_\odot\)) with masses between 5 and 10\(M_\odot\) rises from 6\% to 46\%. Even for the Fryer et al. (2012) models, where the parameters were, in part, tuned to better reproduce the mass function of binary black holes, the fractions rise from ~40\% to ~70\%.

Smith et al. (2011) argue that adding such a population of failed SNe is difficult to reconcile with attempts to distribute SN types over the IMF. The essence of the argument is that the Type IIP fraction of (48 ± 6\%) found by Li et al. (2011) is so low that the proposed failed SN mass range of 16.5\(M_\odot\) < \(M < 25M_\odot\) needs to produce non-Type IIP SNe in order to match the observed SN type fractions. For example, in the absence of binaries, assigning the mass range from \(M_0 = 9.4M_\odot\) to \(M_1 = 15.3M_\odot\) to producing Type IIP SNe, and \(M > M_1\) to producing non-Type IIP SNe has a 48\% Type IIP fraction and is consistent \((\chi^2 = 1.5\) for 1 dof) with the estimates of \(M_0 = 8.5^{+1.0}_{-1.5}M_\odot\) and \(M_1 = (16.5 \pm 1.5)M_\odot\) by Smartt et al. (2009). However, this leaves no room to allot a mass range containing ~20\% of progenitors to failed SNe.
Interactions, stars from 16 $M_{\odot}$ to 25 $M_{\odot}$ (Smith et al. 2011), and this helps. While the existing models do not reproduce the observed remnant mass function well, it is certainly possible given the uncertainties in the remnant mass function (e.g., Kreidberg et al. 2012) that the solution lies in the combined uncertainties of mass loss, mass transfer, and explosion physics.

However, if we simply excise the mass range from 16.5 $M_{\odot}$ to 25 $M_{\odot}$ from these models and instead make them fail SNe in which the hydrogen envelope is ejected by the Nadezhin (1980) mechanism, then we necessarily create large numbers of black holes in the observed mass range. The mass scale comes naturally from the mechanism because only the weakly bound hydrogen envelope can be ejected. The black hole mass scale is simply the mass of the helium cores of the stars ending their lives as failed SNe. Because there is no longer any need to tune the amount of fall back mass to produce low mass black holes in successful SNe, we could allow all successful SNe to form neutron stars with no fall back, which would eliminate the residual problem that other progenitor mass ranges also produce low mass black holes in the Zhang et al. (2008) or Fryer et al. (2012) models. Having no fall back would also better match the neutron star mass distribution (Pejcha et al. 2012) or the shock break out pulse from the (Euclidean) dependence of the survey volume on transient luminosity. For the extended, cool transient, the expected numbers are very low, $\sim 10^{-3}$ to $10^{-4} f_{\text{NIP}}$, depending on the survey band pass. This phase of the transient does not stand out significantly from other slow variations in high luminosity stars. Hence, as suggested by Piro (2013), normal SN surveys should focus on the shock break out pulse from these events where the expected number would be $\sim 0.03 f_{\text{NIP}}$. Such a search will require cadences closer to daily than weekly, in order to sample the transient well-enough to have confidence in the detection and to motivate a search for the longer duration, a fainter transient with larger telescopes. Fortunately, the break out peak and duration appear to occupy a region of transient space without significant, known backgrounds, as they should be significantly more luminous than classical novae of the same duration. Achieving a 90% confidence limit of $f < 0.1$ requires a survey where the expectation value is 2.3 events, so surveys containing $10^3$ Type IIP SNe that could have detected the break out peaks of these transients at high efficiency will begin to provide strong constraints on the existence of this mechanism. As presently designed, however, most field surveys for SN have cadences that will make it difficult to achieve a high efficiency for detection of these transients, since they will sample the events poorly (e.g., cadences of five, seven, and three days for Palomar Transient Factory (PTF), Pan-STARRS1, and LSST, respectively; see Rau et al. 2009 for a summary of surveys).

A targeted survey focused on nearby galaxies, such as our more general search for failed SNe (Kochanek et al. 2008), has little prospect of detecting the break out pulse because of its low cadence (>monthly), but would have no difficulty following the longer transient because it was already designed to search for the disappearance of far less luminous stars. Here, the rate is limited simply by the rarity of the SNe, as $N_{\text{IP}} \approx 1$ yr$^{-1}$ when summed over all local ($\lesssim 10$ Mpc) galaxies, which leads to an expected rate of $\approx f_{\text{IP}}$/year for this class of failed SNe. Thus, achieving a 90% confidence limit that $f < 0.1$ requires two decades of monitoring nearby galaxies, which is painfully long but entirely feasible. Of course, if $f \approx 0.2$, the probability of finding such an event in a decade is quite high (86%) and it is only for these nearby events that we are guaranteed to be able to say convincingly that the progenitor star has vanished.

Finally, we should not expect all these events to have the luminous counterparts predicted by Lovegrove & Woosley (2013). First, as noted by Lovegrove & Woosley (2013), the neutrino mass loss may not be large enough to trigger envelope
ejection in all cases. Second, like the stars that eventually have successful SNe, a significant fraction of the stars that will become failed SNe will be in binaries and will have part or all of their hydrogen envelopes stripped before death. To the extent that the interior structure that leads to a failed SNe is not significantly altered by the mass loss, these stars will still end as failed SNe. If there is remaining hydrogen and it is still in an extended, low binding energy envelope, then we would still expect a transient associated with core collapse, but it would be weaker. In some senses, these would be the failed SN equivalents of Type IIL or IIb SNe. If the mass loss leads the envelope to collapse, or if all the hydrogen is stripped, then there would likely be no luminous transient. Because we are unable to predict the outcome of core collapse from first principles, it is difficult to address these scenarios quantitatively. However, if \( \sim 1/3 \) of stars that would otherwise become IIP SNe do not do so because of binary interactions, we might expect a similar fraction of failed SNe to be modified.

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