MISSING BLACK HOLES UNVEIL THE SUPERNova EXPLOSION MECHANISM

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\begin{abstract}
It is firmly established that the stellar mass distribution is smooth, covering the range 0.1–100 $M_{\odot}$. It is to be expected that the masses of the ensuing compact remnants correlate with the masses of their progenitor stars, and thus it is generally thought that the remnant masses should be smoothly distributed from the lightest white dwarfs to the heaviest black holes (BHs). However, this intuitive prediction is not borne out by observed data. In the rapidly growing population of remnants with observationally determined masses, a striking mass gap has emerged at the boundary between neutron stars (NSs) and BHs. The heaviest NSs reach a maximum of two solar masses, while the lightest BHs are at least five solar masses. Over a decade after the discovery, the gap has become a significant challenge to our understanding of compact object formation. We offer new insights into the physical processes that bifurcate the formation of remnants into lower-mass NSs and heavier BHs. Combining the results of stellar modeling with hydrodynamic simulations of supernovae, we both explain the existence of the gap and also put stringent constraints on the inner workings of the supernova explosion mechanism. In particular, we show that core-collapse supernovae are launched within 100–200 ms of the initial stellar collapse, implying that the explosions are driven by instabilities with a rapid (10–20 ms) growth time. Alternatively, if future observations fill in the gap, this will be an indication that these instabilities develop over a longer (>200 ms) timescale.

\textit{Key words:} stars: neutron – X-rays: binaries

\textit{Online-only material:} color figure
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1. INTRODUCTION

Our universe is littered with black holes (BHs), ranging from ones roughly the mass of our Sun to behemoths many million times more massive. Understanding how these BHs are formed, and how many there are over the course of the universe’s history, is one of the defining challenges of modern astrophysics. The formation of BHs is related to the life and death of stars, involving stellar evolution, accretion, stellar explosions, binary formation, galaxy feedback, and a host of other important physical processes. In the past decade, advances have occurred both in the observation of BH systems and in the theory underlying them. Although the formation of the supermassive BHs remains poorly understood, there is a growing consensus on the formation and evolution mechanisms for BHs born out of dying stars. Our focus is on these stellar mass BHs.

A total of about 50 stellar-mass BH systems (Ziolkowski 2010) and about 1000 neutron stars (NSs) have been observed in the local universe (Liu et al. 2006). Of these systems, we have mass determinations for about 20 BHs and 50 NSs. The most striking feature of the mass distribution of these compact objects is the observed gap in remnant masses between NSs and BHs. As first noted by Bailyn et al. (1998), there are no observed compact remnants in the mass range 2–5 $M_{\odot}$. The most recent measurements and independent sophisticated statistical analyses have further established this “mass gap” (Ozel et al. 2010; Farr et al. 2011). Exploring this mass range is critical to understanding the equation of state of dense nuclear matter that is otherwise inaccessible, as well as BH formation and the supernova engine. We investigate the formation of NSs and BHs to show that the mass gap can be naturally explained and that its existence puts strong constraints on the underlying supernova engine.

2. SUPERNOVA EXPLOSIONS

There is general agreement that the supernova engine is powered by the collapse of a massive star. To produce an explosion, the star must eject its outer layers. Although there exist a number of physical processes for initiating the explosion, there is consensus among supernova modelers that instabilities play an important role in increasing the efficiency with which the gravitational energy from the collapsing star is tapped to drive an explosion. Stars in the mass range $\sim$10–20 $M_{\odot}$ experience strong supernova explosions and produce low-mass NSs. Most massive stars (\geq 40 $M_{\odot}$) fail to explode and instead form massive BHs. It is generally accepted that stars with masses in-between undergo weak supernovae, producing both higher-mass NSs and lower-mass BHs. This would produce a continuous distribution of remnant masses, including some within the mass gap, and is therefore in tension with current observations. Although differing models of instability introduce different mass distributions within the gap region, none adequately reproduce the observed gap. In the current work we show that, by positing a sufficiently rapid growth of turbulence in the supernova explosion engine, combined with a detailed binary star evolution model, the observations can be fully explained.

NSs and BHs are thought to form from core-collapse supernovae. Initial core collapse is halted when a proto-NS forms, the infalling material “bounces” off of the suddenly rigid core,
and the outgoing shock runs into the rapidly infalling outer layers of the star, and eventually stalls. Some fraction of a strong flux of neutrinos from proto-NS is absorbed and heats the “turbulent atmosphere,” the layer between the proto-NS and the stalled shock. A supernova engine is successful only if this energy can be utilized to revive the shock, allowing it to overcome the pressure from the infalling material. For sufficiently strong convective motions, the infalling layers may be pushed out and the explosion may be restarted. However, an initial jolt is required to start convection. In the past two decades, it has been realized that the turbulent region plays a crucial role in accumulating the energy from collapse, and that an instability must then trigger the convective engine leading to the supernova explosion (Herant et al. 1994; Fryer & Warren 2004; Blondin et al. 2003; Burrows et al. 2006; Fryer & Young 2007; Scheck et al. 2008; Bruenn et al. 2009; Marek & Janka 2009; Nordhaus et al. 2010; Takiwaki et al. 2011). At present the physical nature of the force initiating the explosion is poorly understood, and the precise mechanism for the instability and shock revitalization are under active study. As we discuss below, the differing models can be broadly characterized by their growth times. Two models that demonstrate the differences in the growth times are the Rayleigh-Taylor and standing accretion shock instabilities, the former having a growth time of nearly a factor of 10 shorter than the latter. In this paper, we seek to distinguish between these growth times by studying two extreme models: a rapid instability model assuming a 10–20 ms growth time and a delayed instability model assuming a 100–150 ms growth time. For simplicity, we dub these models as rapid and delayed, respectively.

In a collapsing star, the Rayleigh–Taylor is encountered just above the surface of the proto-NS. Neutrinos heat the turbulent atmosphere from below creating a temperature gradient, while the infalling gas from above creates a density gradient. As a result, low entropy gas finds itself on top of high entropy material, and a violent displacement of layers follows. Once the movement of the plasma is initiated, it turns into a convective engine. For the conditions of the post-shock stall region, Fryer & Young (2007) found that the Rayleigh–Taylor instability may appear very early, at ∼20 ms after the initial bounce. However, the convective engine needs additional time (≥100 ms) to build up sufficient strength to fully move the medium above and launch the explosion. If this engine is strong enough to drive an explosion, the explosion will happen rapidly. In simulations, if this instability does not launch the explosion within the first 200–300 ms, it means that the mechanism has failed, and the star will not explode. We note, however, that not all supernova models lead to explosions through the development of the Rayleigh–Taylor instability at early times. The differences in model outcomes may be due to differing treatments of neutrino transport and/or hydrodynamics (e.g., numerical viscosity).

The standing accretion shock appears where the initial bounce stalls and gives rise to additional instabilities. One example is the vortical-acoustic instability that arises and is amplified by the standing shock. Some of the outer stellar material is essentially in free fall as the star collapses. These blobs of infalling matter can acquire significant momentum by the time they hit the standing shock, and the resulting “pounding” causes the underlying plasma to entrapped in the turbulent atmosphere to vibrate and create pressure waves. The interference of these waves transfers momentum to the plasma, which in turn starts the convective engine. This is a heuristic description; the full numerical “discovery” and inner workings of these instabilities are reviewed by Foglizzo (2009). Note that in the case of standing accretion shock instabilities, the initial perturbation that triggers the convective engine comes from above (as opposed to being sourced just above proto-NS surface in the Rayleigh–Taylor instability). Blondin et al. (2003) estimate the growth time of this “acoustic” instability to be considerably longer than the Rayleigh–Taylor case; strong standing accretion shock instabilities require ∼500 ms to develop, and may result in supernova explosion as late as 1000 ms after the bounce.

With time the proto-NS cools off, and the deposition of energy into the turbulent region declines. The turbulent atmosphere is also subject to cooling, and eventually the energy stored in this region begins to decline. The amount of energy that can be extracted from this region is therefore dependent on how long it takes before the convective engine turns on. The Rayleigh–Taylor is the first instability to appear. If it is strong enough to start the convection and if there is enough energy accumulated in the turbulent region by that time to eject the outer layers of the star, a rapid explosion follows (within ∼200–300 ms). If these conditions are not met, then the infall continues, leading to the development of standing accretion shock instabilities. If these instabilities are strong enough a delayed explosion follows (after ∼500–1000 ms). If neither scenario comes to pass, the star fails to explode, and infall continues until the proto-NS collapses into a BH.

Supernova modelers debate the precise emergence times and energy outputs of the different instabilities, in an effort to identify which are strong enough to trigger the convective engine. The answer depends on detailed numerical treatment of the turbulent region, as well as on highly uncertain physics of extremely dense and hot plasma (convection, neutrino transport, radiation–matter interactions). Obviously, this is the key issue in a quest to understand supernova explosions. As the appropriate underlying physics, and ensuing instabilities, continue to be contested, we have decided to subsume our ignorance of the detailed physical mechanism, and instead parameterize the appropriate physics through the turbulent growth time. We find that this growth time directly relates to the masses of compact remnants. Comparing the predicted mass distributions for both short and long growth times with the observed masses of Galactic NSs and BHs, we find that only an instability that develops within the first ∼10–20 ms after the bounce and leads to a rapid explosion (∼100–200 ms) can account for the data. Any mechanism that can grow and drive the explosion on this timescale can be consistent with the observed mass gap.

The nature of the infalling stellar material depends upon the density structure of the star prior collapse. Just before collapse, the center, which determines the fate of the star, is composed of iron covered by silicon and oxygen layers. The extent of these layers depends sensitively on the mode of energy transport while these layers were being formed. For relatively low temperatures (lower-mass stars) the energy output from nuclear fusion is modest, and the energy is transported radiatively; for high temperatures (high-mass stars) the energy output is sufficiently high that convection turns on. The convective mixing drags additional fuel into the burning zones, extending the lifetime of the star and producing more massive silicon and oxygen layers of high density. Although the exact limit depends sensitively on details of nuclear burning and is poorly established, the transition from radiative to convective burning is very abrupt in terms of star mass of about 20–25 M⊙ (Woosley et al. 2002).

The inner part of the stellar core collapses to a ~1 M⊙ proto-NS. After the bounce this dense object accretes from the turbulent region at extremely high rates (as high as ~1 M⊙ s⁻¹).
Depending on the delay before the explosion, the mass of the proto-NS may increase via post-bounce accretion by up to $\sim1 M_{\odot}$. After the explosion, accretion via fallback is encountered. Even for strong explosions some amount of fallback is expected ($\sim0.1–0.2 M_{\odot}$). For weaker explosions the ejected material has less kinetic energy, and more fallback is noted.

In the initial mass regime for core collapse supernovae ($M \sim 8–14 M_{\odot}$), the density of the star falls off steeply outside the very center. In addition, the early energy deposition is very efficient, and the energy accumulated in the turbulent region increases rapidly. For these stars the convective engine is not necessary, as the strong flux of neutrinos heats the material above the proto-NS, and the resulting pressure is able to drive the explosion. The convective engine is initiated early by the Rayleigh–Taylor instability and may enhance the explosion energy, resulting in strong to moderately strong explosions. As there is little time for post-bounce accretion and additionally very little fallback is expected, low-mass NSs are formed: $\sim1–1.5 M_{\odot}$. For higher-mass stars the compact remnant formation process is different for the delayed and rapid models, as we detail below.

For stars in the low-mass regime ($M \sim 14–20 M_{\odot}$) the supernova explosions are very strong, owing to the moderate density of infalling material. The infalling material can hold off the explosion for long enough to allow significant energy build up in the turbulent region, and yet this pressure lid is not strong enough to delay the explosion to the point that the energy in the turbulent region starts to decline. Because the pressure of the infalling material decreases with time, the explosions in the rapid model are more energetic than in the delayed model. As a consequence, high-mass NSs are formed in the rapid model: $\sim1.5–2 M_{\odot}$ with significant post-bounce accretion and rather weak fallback. In the delayed model, fallback becomes more pronounced and compact objects with mass extending to higher values $\sim1.5–3 M_{\odot}$ are predicted.

In the intermediate-mass regime ($M \sim 20–40 M_{\odot}$) extended layers of high density are present. In the rapid model, the infalling silicon/oxygen layers prevent the convective engine to launch the explosion. There is no (or almost no) explosion, and the entire star collapses onto the proto-NS, followed by the formation of a BH. Depending on the mass of the exploding star (mostly a function of initial stellar mass and the strength of stellar winds) BHs with mass $5–10 M_{\odot}$ are formed. In the case of the delayed model, however, by the time the standing shock instabilities arise to drive the convective engine, the high density layers are finishing their infall. Since the infalling layers are now lower density, the pressure lid is weak, and any resulting explosion is similarly weak. Depending on the extent of the silicon/oxygen layers, compact objects within the mass range $3–5 M_{\odot}$ are formed. The range results from more massive presupernova stars leading to weaker explosions and increased fallback.

For the most massive stars ($M > 40 M_{\odot}$) the outcome of core collapse is independent of the supernova model. These stars have very extended high density layers in their centers. In the case of either the early or delayed instabilities, the convective engine releases insufficient energy to overcome the high pressure of the infalling material. Even if a weak explosion manages to occur, all of the ejected material is subject to fallback, and the entire star is accreted onto a compact object followed by the formation of a massive BH ($5–15 M_{\odot}$).

For the delayed supernova model, the explosions range from weak to strong, resulting in a wide spectrum of compact object masses. In particular, no gap in mass is predicted. In the rapid supernova model, on the other hand, the explosions are either strong or fail. The break in stellar evolution, from radiative to convective burning, coupled with the rapid rise of the supernova engine, leads to a commensurate break in the masses of the compact remnants. In practice, the mass gap in the rapid model is not as dramatic as presented in our simplified arguments above. For example, some of the rapid explosion models predict a small number of compact objects within the range $2–5 M_{\odot}$ (e.g., Fryer et al. 2012). These compact objects would be born out of the weakest of the rapid explosions, launched just as the Rayleigh–Taylor instability fizzles out (at 200–300 ms after the bounce). Guided by the observed mass gap, in our models we have limited the time of explosion to 100–200 ms, which precludes any compact object remnants in the $2–5 M_{\odot}$ mass range. This condition was imposed in the rapid model version of our description of single stellar evolution, and then further employed in our binary star analysis. The (very few) objects within the mass gap found in the rapid model are the result of accretion onto compact objects from their binary companions. Since all known BHs are found in binary systems, we now turn to binary evolution to test whether the mass gap predicted for single stars prevails in binary populations.

3. Binary evolution

We have employed a Monte Carlo “population synthesis” method to follow the evolution of several million binary stars from their birth in the gravitational collapse of gas clouds, through 10 billion years of Galactic history until the present. Specifically, we have implemented two major supernova explosion scenarios in the StarTrack population synthesis code developed by Belczynski et al. (2002). The two scenarios provide strikingly different mass distribution for massive remnants in the case of single star evolution. In particular, Fryer et al. (2012) find that the rapid explosion model is depleted of remnants in the mass range $2–5 M_{\odot}$, while the delayed model, utilizing explosions sourced by the standing accretion shock instability, delivers a continuous mass distribution from NSs through BHs, with no gap in mass. However, since all the known BHs are found in X-ray binary systems, we ask whether the results of Fryer et al. (2012) are sustained in binary populations. Various binary interactions involving mass transfer episodes between binary component stars may increase the mass of NSs in the rapid model, and thereby may wash out the gap. Alternatively, other evolutionary processes may severely deplete the number of binaries that host low-mass BHs and produce a gap in the delayed model. An example would be a selective increased disruption of binaries with low-mass BHs via natal kicks caused by supernova asymmetries (e.g., Hobbs et al. 2005).

Our code incorporates the major physical processes to be expected in the evolution of binaries with NSs and BHs. In particular, various modes of mass transfer/loss are followed in detail (Belczynski et al. 2008a), the spin evolution and accretion onto compact objects are accounted for (Belczynski et al. 2008b), and recent estimates for stellar mass loss rates (Belczynski et al. 2010) and natal kicks were also included (Fryer et al. 2012). The StarTrack remnant mass distribution was based on standard stellar models (Hurley et al. 2000) interposed with previous generation supernova simulations (Timmes et al. 1996), and accounts for a range of explosion energies and fallback estimates (Fryer & Kalogera 2001).

We find that the major features of both models in the single star case are preserved in binary populations. Figure 1 shows...
the current Galactic population of X-ray binaries found in our evolutionary Monte Carlo simulations. As expected, both the rapid and delayed models are dominated by NS X-ray binaries (remnants with mass smaller than 2 $M_\odot$), as stars forming these remnants are more abundant than the more massive progenitors of BHs (e.g., Kroupa & Weidner 2003). For massive remnants the models make distinct predictions. In the rapid supernova scenario, we find few to no Galactic X-ray binaries with remnants in the mass range 2–5 $M_\odot$. By contrast, the delayed model allows for a significant population of X-ray binaries in this mass range. Both models provide X-ray binaries with BHs more massive than 5 $M_\odot$, extending to about 15 $M_\odot$, and coinciding with the most massive BHs observed in the Galaxy: Cyg X-1 (14.8 $M_\odot$, ± 1.0; Orosz et al. 2011) and GRS 1915 (14 $M_\odot$ ± 4; Casares 2007).

A continuous compact object mass distribution is to be expected from the delayed model, since a decreasing supernova energy results in larger fallback and larger compact object mass with increasing progenitor mass. The emergence of a gap in the rapid model occurs at compact object mass of $\sim 2 M_\odot$ for the evolution of a single star (Fryer et al. 2012). A compact object of such a mass is formed out of an $M_{\text{zams}} \sim 20–25 M_\odot$ progenitor (see, e.g., Belczynski et al. 2008a). As seen from Figure 1, the lower-mass gap boundary starts at $\sim 3 M_\odot$ if the effects of binary evolution are included. It is still a subject of debate whether compact objects with mass in the range 2–3 $M_\odot$ are NSs or BHs. The only known system with a dynamical mass estimate in this range is 4U 1700–37 ($M = 2.44 \pm 0.27$; Clark et al. 2002; $M = 2.58 \pm 0.23$; Rude et al. 2010; J. Orosz 2011, private communication). The nature of the compact object in 4U 1700–37 is not yet established, although recent detection of quasi-periodic oscillations (Dolan 2011) indicates a low-mass BH as originally suggested by Brown et al. (1996). For initial progenitor masses higher than $M_{\text{zams}} \sim 20–25 M_\odot$, the supernova models based on Rayleigh–Taylor instability fail to explode (e.g., Fryer et al. 2012). More massive progenitors collapse to form heavy BHs. For example, $M_{\text{zams}} = 30 M_\odot$ single progenitor collapses to a $\sim 10 M_\odot$ BH (the rest of the progenitor mass is lost during its nuclear evolution via stellar winds). At $M_{\text{zams}} \gtrsim 35 M_\odot$ single progenitors are subject to enhanced mass loss via Luminous Blue Variable (LBV) winds (e.g., Vink & de Koter 2002). As a result, the high-mass progenitors at core collapse may be less massive than the initially lighter stars. For example, an $M_{\text{zams}} \sim 40 M_\odot$ progenitor collapses to a 5–6 $M_\odot$ BH. For the most massive single progenitors $M_{\text{zams}} \gtrsim 80 M_\odot$ the combined effect of the very high progenitor mass and the shortness of the LBV phase (stars at this mass rapidly evolve into a W-R stage that is not a subject to the LBV-type mass loss) allows for the formation of BHs with mass 10–15 $M_\odot$. The onset of the LBV phase marks the formation of the lightest BHs in the rapid model and terminates the mass gap at the compact object mass of 5–6 $M_\odot$ in the case of single stellar evolution. In binary evolution, the lowest mass BHs are formed either through onset of the LBV phase (non-interacting binaries) or via combination of the LBV phase and the common envelope evolution (close binaries; e.g., Webbink 1984). Both processes, although very different in their nature, generate the same outcome: H-rich envelope removal that leads to the formation of the lowest mass BHs in the rapid model at 5–6 $M_\odot$.

The gap, or lack thereof, is the primary signature that distinguishes the two supernova models, and it originates directly from the physics outlined earlier in the text and based on the evolutionary and supernova models compiled by Fryer et al. (2012). From the binary evolution perspective, mass accretion onto NSs is insufficient to wash out the gap in the rapid model, nor does it produce a gap in the delayed model (e.g., from natal kicks) where none was present before.

In the case of low-mass X-ray binaries, although prolonged mass transfer episodes may be expected, a low-mass companion ($\lesssim 1 M_\odot$) does not provide enough of a mass reservoir to increase the NS mass significantly over 2 $M_\odot$. For high-mass X-ray binaries, there are enormous amounts of mass in the massive companion stars. However, since in these cases the mass ratio of both components is extreme (typically a 1.4 $M_\odot$ NS and a $\gtrsim 5–10 M_\odot$ bright companion star) the mass transfer via Roche lobe overflow is sufficiently fast and violent that most of the mass is ejected from the binary instead of being accreted onto the NS (e.g., Tauris & Savonije 1999; Dewi & Pols 2003). This follows from the Eddington limit, where photon emission generates a strong countervailing wind and inhibits further accretion. In both of these cases the accretion from the companion’s stellar wind does not become a significant factor in increasing a NS’s mass, although it may drive a significant X-ray luminosity, as observed in some wind-fed X-ray binaries (e.g., Liu et al. 2006).

On the other hand, the formation channels providing X-ray binaries do not selectively prevent the formation of systems with low-mass BHs. Natal kicks are believed to be highest for NSs; the progenitors are almost fully disrupted in supernova explosions and thus are characterized by significant asymmetries. With increasing mass of the progenitor, the supernova energetics drop and the matter initially ejected falls back onto
the proto-compact object, forming a BH. In this case, moderate asymmetry is expected. Finally, for the most massive stars the entire star collapses to form a BH, and little asymmetry (and thus kicks) is expected (e.g., Fryer & Kalogera 2001; Mirabel & Rodrigues 2003). For remnant masses in the mass range 2–5 $M_\odot$ (most likely light BHs if they exist), the predicted fallback is significant. We find that the resulting kicks are therefore insufficient to deplete the X-ray binary population and they cannot create the mass gap in the delayed model.

We note that Figure 1 only includes Galactic stellar population models assuming solar metallicity ($Z_\odot = 0.02$). Due to rather high wind mass loss rates from stars at this metallicity (e.g., Vink et al. 2001) the maximum BH mass, both observed and predicted in our models, is only $\sim 15 M_\odot$. However, if the metallicity is decreased the mass loss rates drop as well, and the maximum BH mass can extend to $\sim 80 M_\odot$ in our models for $Z = 0.01 Z_\odot$ (Belczynski et al. 2010). In particular, the most massive known BH of stellar origin BH IC10 X-1 with mass of $\sim 30 M_\odot$ (Prestwich et al. 2007) is naturally explained by our models (Buil et al. 2011). The high end of the compact object mass spectrum is insensitive to the supernova explosion engine, as the most massive stars go through very weak explosions and the entire (or almost entire) immediate progenitors end up as compact object. This is why the rapid and delayed models look virtually identical for compact object masses higher than 6 $M_\odot$ (see Figure 1). The major limiting factor on the maximum BH mass, for a given metallicity, is the efficiency of stellar winds in removing mass from the progenitor star. The winds, in turn, are coupled to the driving radiative force and thus are set by stellar evolution (luminosity and temperature of BH progenitor stars). Since empirical estimates of stellar wind rates and the knowledge of stellar evolution are incomplete, the maximum mass of stellar BH remains at present an open issue. This, along with uncertainties in accretion physics, has led to a controversy over whether the ultraluminous X-ray sources are powered by stellar origin or instead are dynamically formed (intermediate-mass) BHs (e.g., Farrell et al. 2009; Sutton et al. 2012).

4. DISCUSSION

The existence of the mass gap, with an absence of NSs and BHs in the mass range 2–5 $M_\odot$ in the current observations is fairly well established. At the moment, it cannot be excluded that the gap arises from some potential observational biases that may hide low-mass BHs from the current observed sample. An example of such a bias is that, in the case of low-mass X-ray binaries powered by Roche lobe overflow, BH mass measurements are enabled only when the host X-ray binary exhibits transient behavior; transient behavior is thought to be suppressed when the mass ratio is closer to unity, and therefore it is conceivable that low-mass BHs are biased against in the current sample (Fryer & Kalogera 2001; Ozel et al. 2010). However, in the case of wind-fed high-mass X-ray binaries, low-mass BHs would not suffer the same bias.

In a recent study, Ugliano et al. (2012) have calculated remnant birth masses for neutrino driven supernova explosions. They have performed one-dimensional spherically symmetric hydrodynamical simulations with analytical approximation on a central proto-NS and artificially driven explosions. Their study was focused on solar metallicity stars within initial mass range $M_{\text{zams}} = 10–40 M_\odot$. They have found that the explosions can develop in a broad range of time (0.1–1.1 s post-bounce) and they have estimated compact object mass spectrum. They found that (1) NSs form with broad maximum 1.4–1.7 $M_\odot$ baryonic mass (that corresponds to 1.3–1.6 $M_\odot$ gravitational mass) and that (2) BHs form above 6 $M_\odot$ with vast majority of them found in 12–15 $M_\odot$ (baryonic) mass range (see their Figure 6). Apparently, their findings stand in stark contrast with observational data on Galactic compact objects (solar metallicity). First, the majority of Galactic BHs are found with mass 5–12 $M_\odot$ (with just two outliers at about $\sim 15 M_\odot$; Cyg X-1 and GRS 1915; see our Figure 1) while Ugliano et al. (2012) found almost all BHs are in the range 12–15 $M_\odot$. Second, the prediction by Ugliano et al. (2012) of mass gap starts over 6 $M_\odot$ which again is in clear contradiction with mass measurement of some BHs with masses below that value (e.g., $\sim 5.1 M_\odot$ for a BH in XTE J1650–500; Slany & Stuchlik 2008). Third, NS mass distribution is sharply peaked at $\sim 1.35 M_\odot$ (e.g., Lorimer & McLaughlin 2009), although Ugliano et al. (2012) found NS mass evenly distributed over the range 1.3–1.6 $M_\odot$. Overall, it appears that results obtained by Ugliano et al. (2012) are based on too simple of a model (e.g., one-dimensional simulations, spherical symmetry, not-self consistent but artificially driven explosions) to provide meaningful comparison with observations. Ugliano et al. (2012) major result of wide range of explosion times noted to be in contrast with our conclusion (only short timescale explosions allowed by current observations) is further deprecated by recent three-dimensional physically self-consistent supernova simulations (e.g., Nordhaus et al. 2010; Murphy et al. 2012).

An early premise was that BHs tend to harbor massive companions (e.g., the massive O star in Cyg X-1; recently estimated at 19.2 $M_\odot$ by J. Orosz 2011, private communication). Brown et al. (1996) estimated that the formation rate of X-ray binaries with low- and high-mass BHs is similar. It was claimed that for low-mass BHs the ensuing Roche lobe overflow would be very short (thermal timescale due to extreme mass ratio) and therefore it poses an observational bias against detection. On the other hand, for binaries with massive BHs, the accretion proceeds on much longer (e.g., nuclear) timescales and hence the X-ray phase lasts longer. However, at present the Galactic sample of known BH binaries consists mostly of transient X-ray sources with low-mass donors (e.g., Ziółkowski 2010), and hence the premise that the majority of BH binaries harbors massive companions is no longer supported.

In recent work, Kreidberg et al. (2012) have analyzed in detail the elements entering the BH mass determination and have identified an important source of a systematic error that can potentially lead to the masses being overestimated. Ellipsoidal light curve variations are typically used to establish the inclination of a given binary. Most known binaries harboring BHs are interacting systems with Roche lobe overflow, and therefore emission from an accretion disk and a hot spot are present in the measured flux, even during what is assumed to be quiescent phases. These extra contributions of light are often either not accounted for or misinterpreted in BH binary light curve analyses. According to Kreidberg et al. (2012), this leads to a systematic bias in the inclination measurements and hence the BH masses, and may mistakenly push low-mass BHs out of the mass gap. Their analysis is based on the high-quality data for A0620–00, which they use and extend the analysis for the full sample of BH X-ray binaries with low-mass donors. For two of the systems in the sample, GRO J0422+32 and 4U1543–47, the corrected BH masses turn out to lie within the mass gap. They repeat the statistical analysis...
of Farr et al. (2011) for the corrected values and find that the statistical significance of a mass gap is eliminated, if the corrected BH mass for GRO 0422+32 is indeed correct (the BH mass for 4U1543−47 is burdened with large errors due to limited observations and hence does not affect the result in a statistically significant way). Kreidberg et al. (2012) note that higher quality observations are needed for both of these systems to conclusively assess the existence of a BH mass gap in the current sample.

Nevertheless, we have shown that the observed gap in compact remnant mass could arise naturally, depending solely on the growth timescale of the instabilities driving the explosion of massive stars. In fact the observed gap places strong constraints on the development of stellar collapse, with a rapid explosion model being strongly preferred. This model predicts two distinct fates for a massive star: either a violent outburst which ejects most of the star and leads to NS formation or a failed supernova wherein the entire star collapses to a BH. For a gap to be present, very few stars can lie in the intermediate regime where weak explosions occur. An explosive mechanism that only succeeds within the first ∼100–200 ms produces a remnant mass gap in accordance with observations. For slower-growing turbulent instabilities we are unable to match the observed gap. For the delayed standing accretion shock instabilities to reproduce the observed mass gap, an extra source of energy is required in the supernova models (e.g., a magnetar phase) to inhibit the fallback that produces low-mass BHs in weak explosions. Alternatively, if in the future the mass gap is found to be an observational artifact, and compact remnants are found to populate the gap, this will indicate that long growth time, delayed instabilities occur in supernova explosions. Thus, the presence or absence of a mass gap is a critical clue in unveiling the engine behind supernova explosions.

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