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Supernova Physics: Probing The Dark Underworld of Black Hole Remnants

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ABSTRACT

The subject of black holes has fascinated both scientists as well as the general public. Our search for them has progressed significantly in the past decades, with the advent of LIGO, precision microlensing, powerful X-ray telescopes, and large scale sky surveys. We summarize the most recent advances in the black hole search, and connect it to our increasingly complex understanding of supernova physics. With on the order of 10s of black hole discoveries in the past decade, as well as 100s of neutron star discoveries, the compact object search is just getting started, with billions predicted to exist in the Milky Way. On the simulation side, the advent of 3D supernova simulations and more large-scale feasible 1D simulations, present promising approximations connecting our relatively strong understanding of stellar physics to the much more hidden compact object distribution. With both observation and simulation rapidly advancing in sophistication, we identify the current biggest challenges, the most promising next steps in the research area as well as the future outlook for the field.

Keywords: stars: black holes - supernovae: general - stars: neutron stars

1. INTRODUCTION

Understanding of stellar-mass black hole (BH) formation has been a longstanding challenge in the field of both theory and observation. What makes it particularly challenging is the difficulty of locating stellar-mass BHs in our galaxy, especially with remnant proof of collapse. Our best methods for observation fall into four categories: microlensing, gravitational waves, X-ray observations, and spectroscopy, each with their respective selection effects and lack of large samples (Corral-Santana et al. 2016). Furthermore, our understanding of supernova physics is in its early stages: our best models are non-analytical, requiring heavy computation and simulations. Any large scale analysis of black hole formation requires use of 1D simulations, with even 2D simulations relatively unfeasible, and lacking consensus (Raithel et al. 2018).

This complicates our understanding regarding the specific nature of these BHs. For example, are they released with natal kicks, as theorized - or do they maintain their initial motion post-collapse? Neutron Stars (NSs) are found to frequently be released with certain kicks, and these kick velocities have been found to have massive impacts on gravitational wave merger expectations (Mirabel 2016). It is predicted that BHs may have similar natal kicks, although the speeds themselves remain in question (Lam et al. 2020).

The simple picture frequently taught in introductory astrophysics is that stars with masses above $8 M_\odot$ tend to form BHs and NSs. This can happen in one of three ways: a direct collapse, a fallback collapse, and a proto-BH formation (Fryer 2013). In two of these cases, a temporary proto-neutron star is formed at the center of the star, which later accrues mass and forms a BH. Our latest theories simulate that the Zero-Age Main Sequence (ZAMS) mass for stars undergoing each of these types of collapse have multiple discontinuous ranges over which they explode differently, resulting in different final remnants produced (Sukhbold et al. 2016). These are largely functions of the complex supernova physics at these different collapsing masses.

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There are multiple unanswered questions here. Specifically, what masses of stars produce black holes and other compact remnants? What is the distribution of these compact remnants formed in the galaxy, in mass-space, and in number? How specifically, do these black holes form - as compact object mergers, from stellar accretions, or core-collapse, and in what quantities? Both supernova physics, and observational astrophysics pursue new and fascinating techniques to perform more accurate simulations, while probing further in the sky. In this paper, we delve into them, and explain the next steps to improve upon the current state of the art.

In the broader picture of astrophysics, having a large observational sample of black holes, neutron stars and white dwarfs will allow the creation of an empirical initial-final mass relation (IFMR), which can be used to accurately simulate compact objects scattered throughout the entire Milky Way galaxy (Lam et al. 2020). Not only that, but these can inform powerful simulations that are able to nearly accurately match the complexity of these supernovae, and will serve as a reality check against the best theoretical supernova models, which frequently suffer from a tough combination of high computational complexity and little empirical evidence for sanity checks (Corral-Santana et al. 2016). With accurate population estimates, understanding of compact object properties, and strongly constrained supernova simulations, we can not only recreate the "dark underworld" of the galaxy: finally including accurate populations of black holes, neutron stars and white dwarfs, but can also understand the nature of stellar cores, the frequency and distributions of supernovae, and more when combined with our current understanding of stellar populations. We will finally have a more complete understanding of our very own Milky Way galaxy.

Perhaps the biggest unsaid impact will be on our theoretical understanding of Physics. Black holes remain one of the few locations in the universe where our fundamental understanding of physics is frequently deemed incomplete. With a strong observational sample, we can investigate black holes further, perhaps leading to a renewed understanding of black hole accretion physics, electromagnetic effects, and perhaps in the far future, even investigate the feeble Hawking radiation they emit (Chisholm et al. 2003).

We structure the rest of this manuscript as follows. In Section 2 we discuss our current knowledge, the boundaries of our knowledge, the open questions, and how to improve on them. In Section 3, we summarize our conclusions with regards to the outlook of understanding BH formation.

2. DISCUSSION

2.1. *State of the art*

The progress in this field is being made on both the observational and the theoretical side. Observational astronomers are searching for various kinds of black holes from gravitational wave mergers, spectroscopic binaries, and gravitational microlensing (Mirabel 2016). Theorists are approaching this from the side of supernova physics, and the dense matter equation of state, describing not only how a star explodes, but also the boundaries between that of a neutron star and black hole remnant.

Therefore, the compact objects discovered and their mass distributions, make significant impacts on our understanding of supernova physics. They serve as a record of the explosion history of stars - and as a primary check on the supernova simulations that serve as the best theoretical models we have to date. Currently, these simulations describe that the formation of compact object remnants from supernovae, that is, a neutron star or black hole, is mainly determined by the evolution of the stellar core in the late stages of a star's life (Sukhbold et al. 2016). The masses of these compact objects are not necessarily directly correlated with the initial mass of the star during collapse either, since they can be impacted dramatically by variations in core structure, neutrino transport, and asymmetries in the 3D treatment of the supernova explosion (Raithel et al. 2018). For black holes specifically, there is uncertainty as to what fraction of the envelope of the collapsing star ends up forming the majority of the black hole - perhaps only the central He-core may collapse, or otherwise perhaps the entire stellar envelope does. In Raithel et al. (2018), they find that, on comparisons to current neutron star and black hole mass distributions, the best agreement is when the majority, or at least 90% of the stellar envelope is ejected in the supernova. There are many limitations on the theoretical side. The supernova simulations are generally unfeasible computationally to explore large regions of the parameter space, and we frequently need to resort to 1D simulations in order to derive approximate, yet meaningful results (Sukhbold et al. 2016). This is, of course, oversimplified, but on comparison with the limited sample of compact objects available, tends to capture the majority of the information in terms of the output mass distributions as well as the output velocities.

On the observation side, the mass distributions of these compact objects is still only weakly constrained, with less than 100 neutron star and black hole masses

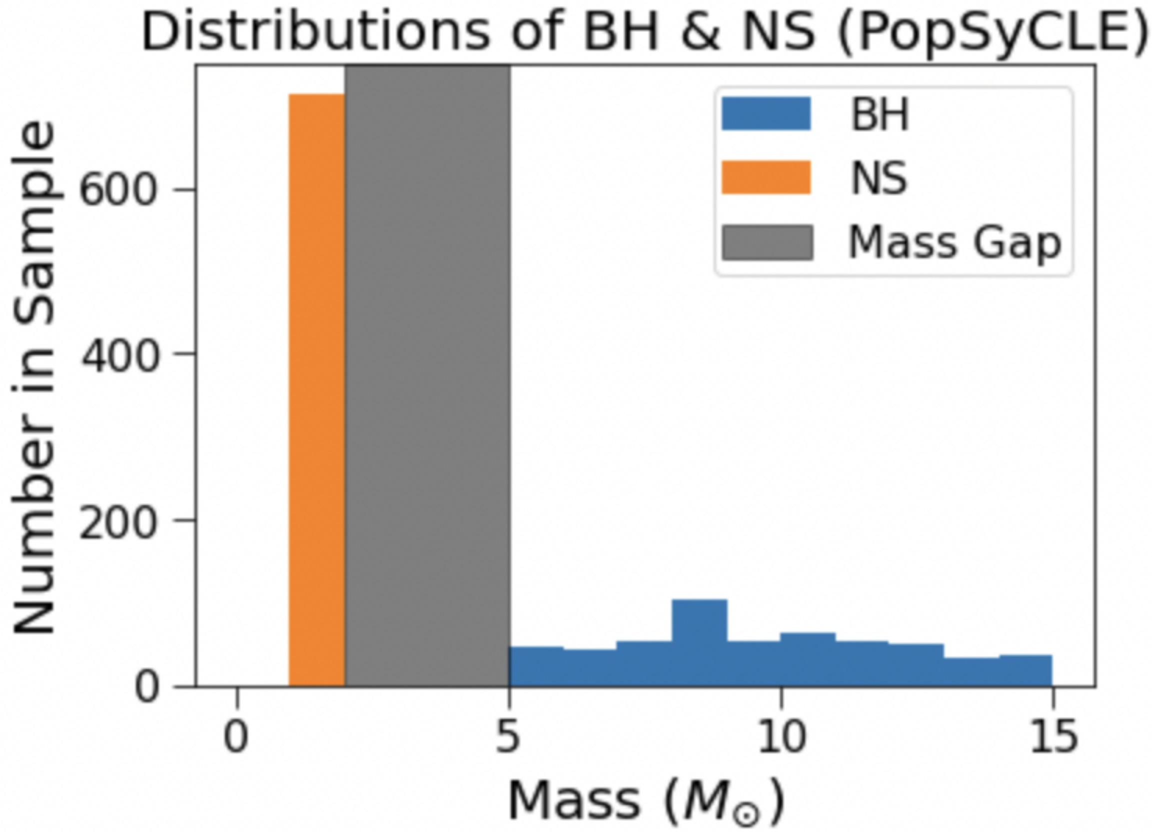

Figure 1. Taking a sample of neutron stars and black holes in a 0.34 sq. degree. area of the sky, generated by combining the current understanding of the distribution of stars in the Milky Way from Galaxia (Sharma et al. 2011) with the compact object remnants according to the Raithel et al. (2018) initial-final mass relation in PopsyCLE. The code took 3 hours to generate this by simulating entire populations of stars and injecting compact objects. We find that the Raithel IFMR indeed supports the idea of a mass-gap in the region between the heaviest neutron stars and the smallest black holes, and even points to the ratio of their frequency and distributions.

collected overall (Farr et al. 2011). With limited sampling of BHs, we know only that the distribution likely falls off exponentially as a function of mass (Özel et al. 2010), with a minimum stellar-mass black hole mass constrained at approximately 4.3 $M_\odot$ (Farr et al. 2011). This additionally may point to the existence of a mass-gap between the maximal allowed neutron star mass 3 $M_\odot$ to 4.3 $M_\odot$, and the most comprehensive 1D simulations from the supernova physics standpoint tend to agree (Raithel et al. 2018). For higher masses above 10 $M_\odot$, the limited number of observations leave little room for constraint. However, the mass of the remnant black holes can be somewhat bounded depending on the progenitor between an upper mass bound - the pre-supernova mass, and a lower mass bound - the He-core mass.

With Raithel et al. (2018) supernova simulations, there is increasing likelihood that the true distribution will be closer to the lower mass bound, where 40-50% of the ZAMS mass of the progenitor is retained in the black hole remnant. Using this as a basis, we can establish an "initial-final mass relation" (IFMR). Our understanding of statistical distributions of stars is significantly more advanced. By using the IFMR, and evolving our current samples of stellar populations, we can predict a black hole mass distribution. This is the approach taken by Lam et al. (2020) in their Galactic + Compact Object Simulation code, dubbed PopSyCLE. Injecting compact objects from stellar population evolution into the typical stellar galactic distribution in the Milky Way modeled by `Galaxia` (Sharma et al. 2011), the simulated distribution of compact object remnants can be derived. In Figure 1, I present the simulated distribution of black holes and neutron stars using PopSyCLE, with the Raithel et al. (2018) IFMR. The following distribution took over 3 hours to generate, as a large sample of the stellar population over a 0.34 squared degree area of sky was taken.

In brief, we have basic supernova simulations and a limited observed sample of compact objects. There are multiple areas of improvement in both areas. We discuss them in the following section.

2.2. *The way forward*

The supernova simulation front has significant room for improvement. Although currently somewhat in agreement with theory, the limited sampling from observation only offers a weak constraint, and so any claims of agreement with observation, for example Raithel et al. (2018), though promising, may not hold up with improved sampling. The supernova simulation models need to be improved computationally, and advanced beyond their current 1D simplifications. Furthermore, there is still a lack of consensus in the supernova simulation community regarding the accuracy of further dimensional models, and whether any can accurately represent type II supernovae (Sukhbold et al. 2016). That's not all. The best supernova models assume solar metallicities, the lack of binary companions, the effects of magnetic fields, a complete understanding of neutrino transport, and more. The Raithel et al. (2018) models in fact, cannot produce very heavy black holes of 30 $M_{\odot}$ and beyond, which are recently proven to exist by LIGO gravitational wave detections.

The observational side has significant room for improvement as well. Both observations of black holes and neutron stars will improve the understanding of supernova physics and in return our understanding of the compact object mass distributions. All three fronts of discovery can be improved upon. LIGO allows probes of the high-mass black hole population, and so must continue to improve its measurement sensitivity. Gravitational microlensing offers an ability to identify isolated black holes, which are predicted to form the majority of black holes in the Milky Way. To date, we have found no unambiguous detections. Improvements in microlensing techniques, specifically astrometric microlensing with the launch of the Rubin Observatory and Roman space telescope, will give us on the order of 1000s more black holes through astrometry (Sajadian & Poleski 2019). Lastly, spectroscopic binary detections of black holes, which have so far yielded the majority of observed detections, will improve with increased spectroscopic and astrometric precision from wide-field space-based telescopes like GAIA and Roman. The observational side of the equation is certainly promising.

3. CONCLUSIONS

There are many questions that remain in supernova physics and compact object formation. We summarize our answers to the three main questions posed in this paper at the beginning, with respect to the state of the art today, and identify the areas of improvement:

Specifically, what masses of stars produce black holes and other compact remnants?

Based on simulations from Sukhbold et al. (2016), our best current estimates are that there are multiple discontinuous ranges over which supernovae undergo collapse into black holes or neutron stars. What simulations agree on is that for ZAMS masses above $12M_{\odot}$, the supernova definitely collapses into a black hole or neutron star. For masses from 12 $M_{\odot}$ - $20M_{\odot}$, the star typically collapses into a neutron star. Beyond that, the star implodes or explodes and forms a black hole. However, there may indeed be a range from $24M_{\odot}$ - $28M_{\odot}$ where the stars once again collapse into neutron stars. There is still work to be done investigating the existence of these ranges, since these estimates are based on 1D simulations. Observationally, we have very little evidence of mass-determined stars that have collapsed into a black hole or neutron star. In the future, better simulations can confirm or improve upon these estimates, and observations determining black hole mass distributions can be used to infer these ranges with reverse modelling.

What is the distribution of these compact remnants formed in the galaxy, in mass-space, and in number?

Although we did not discuss in detail regarding the number, we ran a *PopSyCLE* simulation which injected compact objects into known stellar population distributions to find Figure 1. This gives us a good idea of the state of the art understanding of compact remnant distribution and frequencies, and in fact, does agree with (Raithel et al. 2018), after which this simulation was based, even pointing to the same neutron-star mass gap in the 3-5 $M_{\odot}$ range. The future of observation in this space is bright, with promising detections of 1000s of mass-measured black holes available during the era of the Roman and Rubin space telescopes, through astrometric microlensing. Simulations like (Raithel et al. 2018) are based on 1D supernova models and stunted by computational complexity, so future steps in the simulation space would be to improve the efficiency and accuracy of these models.

How specifically, do these black holes form - as compact object mergers, from stellar accretions, or core-collapse, and in what quantities?

Perhaps the toughest question to answer, there is significant work to be done in the area. Although there is observational evidence of each of these kinds of black holes (Corral-Santana et al. 2016; Lam et al. 2022), there are very few detected, and their detection frequency is certainly impacted by selection effects. Spectroscopic detections have a bias towards high-mass nearby binaries, and cannot detect isolated black holes. X-ray detections require accreting black holes, perhaps in close binaries. Future large scale surveys like Roman and LIGO may create a stronger sample of black hole events that allow us to better answer these questions with microlensing, but currently, the area is largely restricted to theory. Even in future surveys, the selection effects cannot be easily avoided, so the search for a true understanding of black hole formation paths currently remains out of reach.

Much work and progress has been made in answering these questions. In the coming decade, we will see an explosion of work in this area, buoyed by improved observational and computational capabilities, enhancing the black hole sample and supernova physics. With the maturation of these two fields, we will understand the distribution of objects in the dark underworld of the galaxy, as well as gain insight into the nature of supernovae, stellar cores, neutrinos, and black holes themselves.

Software: astropy, PopSyCLE (Lam et al. 2020)

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