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Area of Ignorance in Stellar Physics: Stellar Mass Black Hole Distribution; Lowest Initial Progenitor Mass Limit for Black Hole Evolution

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ABSTRACT

The creation and evolution of black holes have been the subject of ongoing debate and investigation due to their elusive nature, specifically in the mass distribution of stellar mass black holes. Using data and observations of changes in the remnant mass of stars, a mass distribution function for black hole formation was created. Coupled with an analysis of heavy element production, there is discussion of the mass minimum needed by a single-star stellar system to form a black hole. It can be concluded at the end of this paper that stellar progenitor systems of 20 or more solar masses with helium cores experience a fallback that propels the compact object past the maximum mass of a neutron star. This instigates its collapse into a black hole. According to current models, it can also be shown that progenitors surpassing$_\odot$ 40M give rise to black holes without a preceding supernova explosion.

Introduction

Unknown in the world of black holes (BHs) is the mass distribution of their preceding stellar structures. When a star is hot enough, having a core temperature exceeding 107 K, hydrogen fusion can begin to form other elements. The hydrogen-to-helium fusion process emits a massive amount of energy and prevents stellar collapse. With more heat and pressure in the core, more elements are fused to form heavier ones; helium can be further fused to form carbon, carbon to neon, neon to oxygen, oxygen to silicon, and finally silicon to iron. When iron is fused, the energy released is not enough to counter the inward gravitational force; this imbalance between the radiation pressure and gravitational force causes the star system to collapse under its own gravity (Iben Jr, 1967). The star undergoes a supernova explosion and the remnants leftover result in either a neutron star or, if the star is massive enough, a black hole (BH). BH evolution can also occur through additional paths that aren't from stellar collapse. Intermediate BHs are caused by merging binary neutron stars that can overcome the neutron degeneracy pressure, and supermassive BHs are hypothesized to be formed from galaxy mergings (Chakraborty et al., 2023). Focusing on stellar mass BHs, it is hypothesized that the stars born on the main sequence with a mass of 8-10 $M_\odot$ will evolve into BHs, but that range is debated and the exact minimum and range for stellar mass BH evolution are unknown. This is primarily debated because the mass distribution of BH progenitors is also highly unknown. This break is due to a lack of understanding of the core collapse of massive stellar systems.

There is an understanding, brought into the astronomy community by Maeder (1992), that nucleosynthetic production and metallicity, which is the number of elements in a star that are larger than hydrogen and helium, are the main reasons why there is a mass distribution for BH formation. The massive stars that are able to trigger Type II Supernovae, and further related, can offer insight into the stellar mass of BHs, which differs for stars with different metallicities. First-generation stars compared to younger-generation stars have greatly varying ratios of the mass of elements heavier than hydrogen and helium to the total mass of the stellar object. This is directly due to the chemical composition of the gas cloud from which they were formed. However, these variances have major implications in the mass distribution for BH formation, assuming a negligible amount of mass is lost with stellar winds, pre-explosion bursts, and minor binary interactions. Multiple differing values for the lower limit of BH progenitor masses are given if heavier elements create more massive stars, but not by a noteworthy amount since the metallicity of stellar objects is so low compared to other factors of a star's final stage evolution.

However, according to Maeder (1992), there seems to be a correlation between the amount of heavy metal produced and the lowest initial mass limit for BH formation. More specifically, when the mass limit for BH formation decreases, the production of heavy elements also decreases because a larger proportion of the heavy elements is being captured by the BHs rather than being released into the surrounding space. This makes the relationship between the lowest initial mass limit for BH formation and the yields of heavy elements

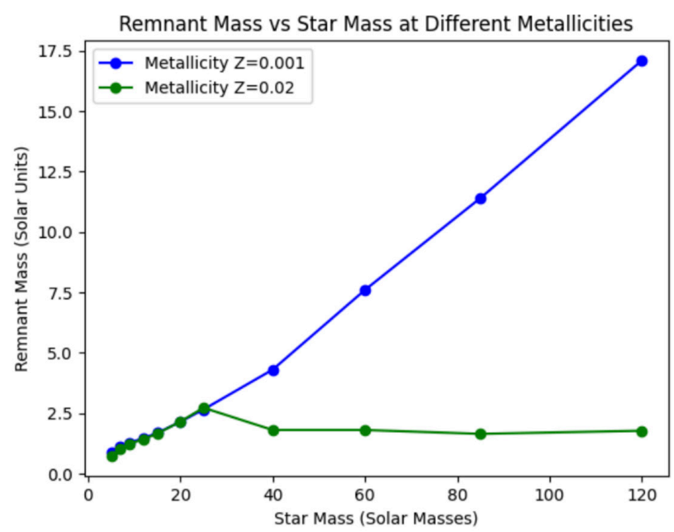

Figure 1: Remnant Mass Compared to Metalticity Levels. A range of stellar masses, from 5 to 120 $M_\odot$, is considered. Not depicted are stars with a mass less than 2$M_\odot$, stars that experience a helium flash. (Maeder, 1992) and references therein. The table gives the masses of the remnants obtained along with their heavy element component. There is continuity between the remnant masses above and the ones derived for higher masses.

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inversely proportional, except at high levels of metallicity when mas$_{\odot}$ is blown away by stellar winds.

As the results find, the theoretical models of stellar evolution start differing from the observational estimates of the amounts of heavy elements produced during supernova explosions. The comparison with the observations rejects a scenario in which all the layers of a star, leading up to its supernova explosion, are completely ejected from stars, regardless of the star's initial masses.

The observational comparisons lead to the suggestion that, after a supernova produces a BH, it is formed with the lowest initial mass limit for BH formation of 20 to 25 times the mass of the Sun. It is emphasized that when the metallicity reaches Z = 0.02, even stars with very large initial masses may not likely result in the formation of a BH because these stars lose a significant amount of mass during their evolution and the remaining mass may not be sufficient to form a BH, as seen in Figure 1. Again, according to current models, it is shown that progenitors surpassing 40M$_{\odot}$ give rise to BHs without a preceding supernova explosion. However, under the analysis of mass remnants with differing metallicities, it could also be concluded that the lowest initial mass limit for BH formation is a stellar system of 20M$_{\odot}$.

Discussion

Low-mass stars don't have a likelihood of turning into BHs because, unlike massive stars, they cross the threshold from classical to degenerate. These don't lead to big explosions because radiation pressure starts to dominate the star's energy production and this leads to degenerate electrons and unstable systems. On the flip side, as a massive star burns through its fuel, it begins to drop in temperature because it is unable to produce as much energy as it had during its initial Hydrogen core burning. The outward pressure force begins to drop and is unable to counter the gravitational force, leading to collapse.

The pressure eventually reduces low enough that the gravitational force immediately dominates and causes the star to collapse on a dynamical timescale:

$$\tau_{dyn} = \tau_{ff} = \frac{1}{\sqrt{G\rho}}$$

Institute (2020). Where ρ is the mean density of the stellar object, G is the gravitational constant at any point in this universe,

$$G = 6.6740810^{-11} Nm^2/kg^2$$

For this process, we make the assumption that BH formation comes from massive star collapse, though there is evidence to see the formation of BHs through neutron star collapse if aligned with hypercritical accretion. But this is still limiting to lower mass stars by a factor of 10-100 (Fryer et al., 1999), so we will continue to only look at BH formation through massive star collapse.

We are also able to attribute the range in the upper mass limit to mass loss through stellar winds as the lower mass star collapses miss this gap. (Fryer et al., 1999) Massive stars experience an envelope expansion from their internal contraction of the core as heavier and denser material is burnt for nuclear energy. The decreasing density in the shell that happens from the envelope expansion also causes a decrease in pressure in the shell to balance the energies throughout the system. If a star is not massive enough, it will cross the line of complete degeneracy, subsequently forming a white dwarf that either cools or

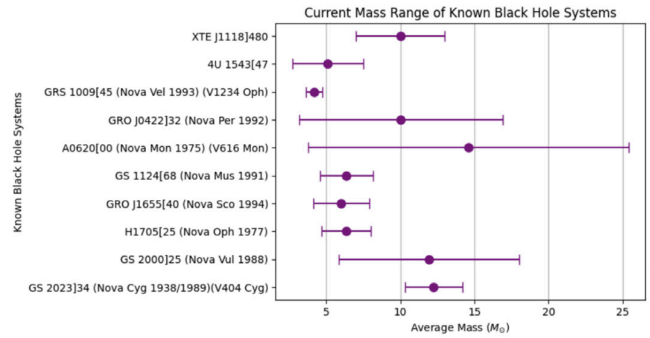

Figure 2: Mass Distributions of Black Hole Systems. These systems and ranges have masses that are more certain than those that weren't found using X-ray transients because of the non-Gaussian nature of the probability distributions. Data taken from Bailyn et al. 1998. Lower limit; analysis from Phillips et al. 1999. Upper limit; revised mass function, Shahbaz et al. 1999. The upper limit of these ranges is still disputed. (Fryer & Kalogera, 2001) and references therein.

explodes into a Type 1A Supernovae if in a binary system.

The calculations of the mass distributions of the BH systems shown in the figure are found from a series of steps that include deriving the remnant mass function of the initial mass of the BH system's progenitor (in this instance, progenitor refers to the mass of the star system). The progenitor's mass was found from taking the necessary energy required to unbind the star system's envelope and weakening the tie to the mass and density structure of the progenitor, and the energy of a core-collapsed explosion given as a function of progenitor mass studied from computer simulations in Python. The simulation is from a Bayesian analysis performed to study the parent distribution of BH masses.

The energy from the explosion was found by taking the energy before the hydrogen or helium star collapse and finding the difference in energy for the total energy found after the extremely short collapse. For stars that are burning carbon and oxygen in their cores, they experience enough of a mass loss to the point where their stellar core is affected, so the mass of the core is used instead of the entire system before and at the end of the collapse. The process of mass loss during a star's evolution has a significant impact on the core of the star, only for a relatively small population of stars with initial masses greater than ~40M$_{\odot}$. This suggests that for stars with masses less than ~40M$_{\odot}$, the mass loss doesn't have a substantial effect on its stellar core, and these stars are less likely to evolve into BHs through core collapse. However, for stars with masses greater than ~40M$_{\odot}$, the effects of mass loss become significant and affect the core enough to likely invoke black holes through core collapse.

In my analysis of the decaying exponential trend used to model the low-mass X-ray samples observed from the theoretical model proposed by Fryer & Kalogera (2001), the results of the model selection process and analysis do not support the theoretical model proposed. A viable alternative to better suit low-mass systems would be a power-law distribution, with a Gaussian distribution. This is the second model explored by Özel et al. (2010). Additionally, the reasoning for the mass gap happens to do with how using the power-law as the best-fit model for low-mass systems is over the theoretical maximum neutron star mass. This was concluded by Farr et al. (2011) that systems that are not massive show strong evidence of a mass gap, but for the most part, the presence of a mass gap remains theoretically unexplained.

It should also be noted that to accurately find the BH system's lower limit, and therefore, a more accurate mass, the angle of the system relative to observation (inclination, i) and the relative masses (mass ratio, q) must be measured in an ideal form. This would be done by analyzing and modeling the variations in the observed brightness caused by the ellipsoidal shape of the system. Additionally, studying the rotation of the secondary star results in the broadening of the spectral lines observed from the secondary star, making them appear wider and more diffuse than they would be if the star was not rotating. Large differences also prevent confidence in inclination measurements in the part of determining the upper limits of the BH masses as well. Since the inclination is tied to where there is a missing section of eclipses in the light curve, to get a better measurement of these calculations, intricate system-by-system studying and analysis would find more accurate values for q and i.

Methods

3.1. Mass Distribution Representations and Models

The BH mass distributions were met by combining the initial progenitor mass function with the mass relationship of remnant-progenitor, respectively, but also when entwined with the stellar mass function for supernova progenitors, suggests a representation through exponential decay with a mass minimum:

$$\begin{Bmatrix} e^{\frac{M_{\min}}{M_0}} \cdot M_0 \cdot \exp\left(-\frac{M}{M_0}\right), & M \geq M_{\min} \\ 0, & \text{otherwise} \end{Bmatrix} = \rho(M, \theta)$$

Where M_{min} was shown beforehand to be $0M_\odot \leq M \leq 40M_\odot$, this also makes sure that most of the probability of the masses lies between this inequality. M_0 is chosen by adding an additional factor of $2M_\odot$ to M_{min} to ensure the cutoff of $40M_\odot$ is not dipped below. (Farr et al. (2011)) In this context, the units of the term $\rho(M, \theta)$ are probabilities. Specifically, they represent the probability distribution function of the parameters based on model parameters and data retrieved. It also signifies the likelihood that the prior expresses a probability estimation, without using given data, but by using the associated model parameters. The values themselves are unitless, and the total probability across all possible events or parameter values sums to 1 within this statistical framework. For each of the respective systems, the use of spectroscopy to analyze and study the properties of the secondary star yields essential parameters such as the orbital period of the system and the semi-amplitude of the secondary star's velocity curve. The full process is in Farr et al. (2011), but the integration of those measurements can be used to calculate the mass function.

$$\mathrm{f(M)} = \frac{PK^3}{2G\pi} = \frac{M \sin^3 i}{(1+q^2)}$$

Where P and K are parameters in the context of binary star systems (P is the orbital period, K is the secondary's velocity semi-amplitude), M is the mass of the BH, i is the angle at which the system is observed relative to an observer's line of sight, and q is the ratio of the mass of the secondary star to the mass of the primary star. This then defined the mass function and lower limit of the BH mass distribution as $f(M)<M$.

By employing both the power-law and Gaussian models from above to create a confident BH mass distribution, we establish that the 90% confidence interval for the minimum mass a BH can range is $2.9M_\odot$ and $4.3M_\odot$ shown in Figure 1.

Conclusions

Simulations depicting core-collapse supernovae from black hole progenitor mass ranges also depict supernova energy ranges when combined with remnant mass observations from years prior (Fryer et al., 1999). Immediate collapse and delayed collapse resulting from fallback are the two main routes that lead to the formation of black holes. On a dynamical timescale (a timescale of around a few seconds to a few hours), helium cores in the case of massive progenitors exceeding $20M_\odot$ experience a fallback that propels the compact object past the maximum mass of a neutron star. This instigates its collapse into a black hole. And, according to current model precision, progenitors surpassing $40M_\odot$ give rise to black holes without a preceding supernova explosion. After computing the distribution of black hole masses resulting from these processes and juxtaposing these projections with observations, acknowledging that the observed sample represents a limited, and potentially biased, subset of the overall black hole population, it can be concluded that the lowest initial mass of a black hole progenitor lies in 20 solar masses.

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References

1. Chakraborty, S., Sadler, B., Hoeflich, P., et al. 2023, arXiv preprint arXiv:2311.03473
2. Farr, W. M., Sravan, N., Cantrell, A., et al. 2011, The Astrophysical Journal, 741, 103
3. Fryer, C. L., & Kalogera, V. 2001, The Astrophysical Journal, 554, 548
4. Fryer, C. L., Woosley, S., & Hartmann, D. H. 1999, The Astrophysical Journal, 526, 152
5. Iben Jr, I. 1967, Annual Review of Astronomy and Astrophysics, 5, 571
6. Institute, J. R. 2020, Timescales of Stellar Evolution, Lecture-15. https://jila.colorado.edu/~pja/astr3730/lecture15.pdf Maeder, A. 1992, Astronomy and Astrophysics (ISSN 0004-6361), vol. 264, no. 1, p. 105-120., 264, 105 Özel, F., Psaltis, D., Narayan, R., & McClintock, J. E. 2010, The Astrophysical Journal, 725, 1918