

Black Hole Formation from Massive Star Collapse: A Review of Physical Mechanisms and Observational Evidence

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ABSTRACT

This review examines the formation of stellar-mass black holes as the endpoint of massive star evolution. As massive stars progress through successive stages of nuclear burning, they develop iron cores that can no longer be supported under typical stellar conditions by thermal pressure or electron degeneracy pressure. This ultimately leads to gravitational collapse under standard stellar evolution models. Collapse of this core can result in either a neutron star or a black hole, depending on a combination of factors such as metallicity, mass loss, rotation, binary interaction, shock revival mechanisms, and fallback accretion. Recent neutrino-driven core-collapse supernova simulations indicate that black holes do not occur above a single mass threshold, but instead along complex regions characterized by “islands of explodability” and failed-explosion pathways. This review combines theoretical and computational models of core collapse, failed explosion, fallback collapse to black holes, and direct collapse, and connects these processes to observational constraints from X-ray binaries, supernova remnants, gravitational-wave observations, and multimessenger astrophysics. Significant uncertainties remain, particularly regarding the remnant mass distribution, the importance of multidimensional effects, rotation, magnetic fields, and binary evolution. Black hole formation therefore remains a central problem linking stellar evolution, supernova theory, compact-object demographics, and strong-gravity astrophysics.

Keywords: Black holes; stellar evolution; core collapse; core-collapse supernovae; fallback accretion; neutron stars; multimessenger astrophysics

INTRODUCTION

Contrary to popular depictions as galactic predators, black holes are the final evolutionary state of massive stars. The endpoints of stellar evolution mark a final collapse under gravity. Understanding the formation of black holes not only sheds light on the life cycle of stars

but also pushes the limits of physics by intersecting with astrophysics, general relativity, and theories of extra dimensions.

Stars much more massive than our Sun live fast and die young in cosmic terms. They consume their hydrogen rapidly and evolve through heavier elements (such as helium, carbon, oxygen, and silicon) relatively quickly, ultimately ending with an iron core (1). Fusion in iron is not energetically favorable and is generally unable to provide pressure support, and the core becomes gravitationally unstable at this stage, setting the stage for core collapse.

Once the iron core exceeds the Chandrasekhar limit (~1.4 solar masses) (2), electron degeneracy pressure is

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generally unable to support itself against gravitational collapse (3). In less than a second, the core implodes to nuclear densities, releasing vast amounts of neutrinos in the process (4). Neutrinos carry away energy and play a crucial role in determining whether the stellar envelope is successfully ejected. They also influence whether fallback accretion occurs (5).

For many stars, the core bounce produces a shockwave strong enough to explode the star. If the shockwave is boosted by neutrino heating, it can launch a supernova explosion, expelling the outer layers of the star and enriching the galaxy with heavy elements (6). However, in some cases, the shockwave stalls or is too weak to unbind the envelope. In these cases, fallback instead deposits mass onto the collapsed remnant, driving it to collapse to a black hole (7).

The interplay of mass and several other parameters determines the ultimate fate of the star. The current thinking is that the star's initial mass is below ~20-25 solar masses, and the collapse leads to the formation of a neutron star (8). If it exceeds a certain threshold (dependent on other parameters), a black hole is more likely. Rotation, metallicity, and binary interactions introduce complications to this picture, shifting the threshold and creating uncertainties in predictions (9). The variance in these factors is what leads to such a wide range of final states.

After decades of theoretical and observational studies, key questions in black hole formation remain (10). We understand the overall sequence of events leading to stellar collapse. The details, such as fallback accretion, exact mass thresholds, and the role of higher-dimensional effects, are more controversial. This paper reviews both the astrophysical and theoretical aspects of black hole formation. The lifecycle of a massive star, including its core collapse, subsequent supernova explosion, and the conditions necessary to form a black hole, will be discussed. The paper will also address how higher-dimensional physics can provide insights into the formation of these enigmatic objects.

BACKGROUND

Massive stars, which have masses greater than eight solar masses, evolve over a much shorter timescale than low-mass stars due to their increased gravitational forces and higher temperatures. A massive star typically undergoes successive burning phases, from hydrogen to helium, carbon, oxygen, and silicon, with each phase burning for a shorter duration than the preceding one

due to the increasing inefficiency of the fusion reactions. The star's core will eventually start to produce iron, an element that cannot release energy via fusion. At that point, the pressure support becomes insufficient to counter gravity, and a star transitions from equilibrium to a runaway collapse. The lifetimes of each phase are influenced by metallicity, rotation rate, and mass loss from stellar winds. These factors help determine whether a massive star ends its life in a supernova or collapses directly into a black hole (1).

The iron core of a massive star will ultimately reach the Chandrasekhar limit (~1.4 M_{\odot}), at which point electron degeneracy pressure cannot support it against gravity (2). The core will collapse in less than a second, compressing the stellar material to densities higher than the nucleus of an atom. Oppenheimer and Snyder first modeled the gravitational collapse of a star, showing that a distant observer will see the infalling star appear to "freeze" and dim as its surface approaches its gravitational radius (3). At the center of the collapsing star, the protons and electrons will combine to form neutrons, releasing a massive flux of neutrinos. Fryer showed that the energy of the gravitational collapse is carried away by neutrinos (about 99% of the total energy), which play an essential role in determining whether the explosion succeeds or fails (4). If conditions are right, the infalling material bounces off the incompressible nuclear core and sets off a shockwave that travels outward through the star.

To produce an explosion, the outwardly moving shockwave needs to be strong enough to overcome the inwardly infalling material. Neutrino heating, in addition to convection and hydrodynamic instabilities, is thought to play a significant role in determining whether the explosion is successful (5). If successful, a type II supernova is produced, which is an incredibly luminous event that will expel heavy elements created during the various burning stages of the progenitor star into the surrounding interstellar medium. Metals released in supernovae will seed the next generation of stars and planets in the galaxy, affecting galactic chemical evolution (7). In the case where the explosion energy is too low, fallback accretion of the ejected material can continue to accrete onto the remnant, eventually collapsing the remnant into a black hole (4). The complexity of shock revival and fallback accretion is one of the reasons that the transition from supernova to black hole is one of the most uncertain in astrophysics.

Despite significant progress, the exact boundary between a neutron star (NS) and BH is not clearly defined. Observations show that metallicity, angular

momentum (rotation), and binary interactions influence whether a collapsing star produces a successful SN or not, leading to direct BH formation (1). Three-dimensional simulations show that factors such as neutrino heating, convection, shock revival, and fallback accretion strongly affect shock revival and the resulting compact remnant mass (10). These issues connect astrophysical modeling of stellar death with fundamental physics of nuclear-density matter and the strong-gravity limits of GR.

Taken together, these results suggest that while the general process of core collapse is well understood, the detailed outcome depends sensitively on stellar structure and the interplay of multiple physical processes rather than any single parameter.

MASSIVE STAR LIFECYCLE

The intense nuclear burning of massive stars and their short lifespans set the initial conditions for core collapse and black hole formation. The first mathematical proof that gravitational collapse leads to singularities under broad conditions was given by a theoretical model of gravitational collapse based on general relativity and the notion of a trapped surface (11). When a massive star's core collapses to a sufficiently compact region containing a closed trapped surface, it is expected to lead to the formation of a singularity under general relativity. This was the first formal mathematical demonstration that the general relativistic model of gravitational collapse leads naturally to the formation of black holes (11). This complexity is further summarized in Table 1.

Extending this theoretical work, subsequent studies connected stellar remnants to observations. Rees (11) argued that stars below the Chandrasekhar limit (~1.4 M_{\odot}) become white dwarfs, while stars that are more massive collapse further, forming neutron stars with 2-3 M_{\odot} . Above that threshold, internal pressures cannot sustain equilibrium, leading to black holes (12). Accretion onto such remnants naturally provides the extreme luminosities and fast time variability of X-ray binaries and active galactic nuclei (AGN), which therefore provide an observed connection between stellar evolution and the high-energy sky. He has also noted the historical notes and the formal support from GR for BHs as the natural consequence of gravitational collapse (12).

Further theoretical work proposed a theory of formation of black holes from supermassive stars $10^6 M_{\odot}$ with short nuclear burning scales and rapid accumulation rates ~1 M_{\odot} per year (13). Rotationally stable stars still have outer layers that are not thermally relaxed. The core

collapses, and accretion of the bloated envelope happens, eventually forming massive $\sim 10^4 - 10^5 M_{\odot}$ seed black holes. These black holes power quasars and populate the nuclei of present-day massive galaxies. Rapid continuous infall leads to high levels of entropy, and they have a more complex structure with a convective (polytropic) core surrounded by a convectively stable envelope that contains most of the mass (13).

These findings indicate that stellar evolution does not lead to a single deterministic endpoint, but instead produces a range of possible remnant outcomes depending on initial conditions and subsequent evolutionary pathways.

As discussed in Table 1, several physical factors control black hole formation outcomes, including metallicity, rotation, binary interaction and fallback accretion.

Table 1. Key factors influencing black hole formation from massive stars

Factor	Effect on BH formation
Initial mass	Higher mass can favor BH formation, but not monotonically
Metallicity	Lower metallicity reduces winds, preserves mass, can increase BH formation likelihood
Rotation	Can alter core structure and collapse dynamics
Binary Interaction	Can strip envelopes or transfer mass, changing remnant outcome
Neutrino heating	Stronger heating helps revive shock and produce NS
Fallback accretion	Can turn weak explosion remnants into BHs

These factors do not operate independently but instead shape the internal structure of the progenitor star, reinforcing the non-monotonic nature of collapse outcomes and the existence of “islands of explodability.”

CORE COLLAPSE

Massive black holes may form through direct collapse within regions of strong gravitational influence of massive black holes on short timescales of order 10^5 yr (14). The discovery of quasars, radio galaxies, and powerful X-ray emissions first detected in the 1960s led

to the finding of active galactic nuclei, where intense gravitational forces cause high rates of accretion, leading to the conversion of mass reservoir into heat and radiation, resulting in high luminosities brighter than their host galaxies. This process of direct collapse leading to the formation of a supermassive protostar or supermassive star through direct collapse of multiscale gas inflows leads to forming black holes with masses in the range $10^6 - 10^{10} M_{\odot}$ (14).

Stars with large masses face an inevitable collapse when they have exhausted their thermonuclear energy sources. Here, early theoretical models identify the forces and factors involved in the process of the continued collapse of the star (3). The four main forces listed are rotational forces, the star's radiation, the kinetic energy of the particles within the star, and the kinetic energy of the outer layers as they are stripped off. The star is expected to continue contracting under the gravitational field until it gets to its gravitational radius. As light continues to escape, making the star red, pressure within becomes increasingly negligible compared to gravitational forces, and the total time of collapse is finite. The dynamics of stellar collapse, including rotation, radiation, and kinetic energy, are expected to occur in sufficiently massive stars. However, these processes may occur on longer timescales depending on conditions (3).

Large numerical studies have examined 200 pre-SN models of size range being $9-120 M_{\odot}$, and the methods involved the KEPLER code and identical stellar physics (6). Calculations of explosion included Iron-core collapse and bounce, neutrino transport, and the propagation of the outgoing shock, along with the essential effects of neutrinos, leading to estimated nucleosynthesis. Calibrated to the characteristics of SNe: the Crab and SN 1987A, all the explosions were on the death of massive stars, $9.0-120 M_{\odot}$. There was no one cut-off size below or above which BHs formed; it was rather a random distribution of islands of explodability in the sea of BH formation. Most of the nucleosynthesis happened between 12-30; beyond 30, very few explosions were observed. In total, the nucleosynthesis would be improved if more massive stars blew up. A total of 194 SN light curves were calculated (6).

Overall, the models suggest that initial stellar mass alone is not the determining factor in whether or not a black hole will form. Rather, the structure of the progenitor, its metallicity and rotation, and the properties of the explosion itself play a role. From recent simulations, there is no distinct mass cutoff between neutron stars and black holes. Stars lie in non-monotonic

“islands of explodability”, where two progenitors of similar mass can produce different end states based on their internal structure.

However, significant uncertainties remain. Depending on assumptions made regarding dimensionality, neutrino transport, fallback accretion, some models predict successful explosions, while others of similar mass do not, producing different remnant masses. Consequently, the boundary between neutron star and black hole formation remains one of the least well-constrained in stellar astrophysics (15).

Overall, these results demonstrate that initial stellar mass alone is insufficient to predict remnant type, and that progenitor structure and explosion dynamics play a central role in determining whether collapse results in a neutron star or black hole.

SUPERNOVA EXPLOSION

Core-collapse supernova simulations through a range of progenitor masses and different input physics show that black holes are generally found to form either by prompt collapse or delayed collapse due to fallback (4). The simulations were based on the understanding that explosions are driven by neutrino-energy deposition. As the massive star collapses, a shock wave is generated. This shock can stall due to dissociation and neutrino losses, leaving behind an unstable entropy gradient. This entropy gradient continues to grow towards the proto-neutron star surface which results in forming a convective layer at the edge of the stalled shock. Neutrino absorption generating heat drives the convection further which then rises and expands leading to loss of energy via neutrino emission. As the star continues to collapse, the accretion shock binds the outer edge of the convection layer. The pressure in the convective layer must exceed the ram pressure of the shock to drive a successful explosion. It was found that a) low mass stars drive strong explosions with little fallback and produce neutron stars, b) moderately massive more than $\sim 25 M_{\odot}$ stars produce explosions, but the fallback is sufficient to form black holes, and c) high mass stars, more massive than $40 M_{\odot}$ are unable to launch shocks and collapse directly to black holes (4). The black hole mass should range from $3-15 M_{\odot}$ for progenitors less massive than $40 M_{\odot}$. Beyond $40 M_{\odot}$, the final black hole mass could be as large as its progenitor (4).

The mass distribution of compact remnants formed from core-collapse supernovae and gamma-ray bursts (8). The products of these explosions are Neutron stars and

Black holes. The mass distribution of black holes was initially thought to be very narrow around $1.35 M_{\odot}$. But recent studies show it to be widespread ranging from low masses up to the maximum NS mass limit (8). The mass of compact remnants at formation was calculated through a combination of information from stellar evolution and core-collapse calculations. A bimodal distribution was discovered in the model employed involving two extremes: fast-convection explosions and delayed-convection explosions. The remnant formation process can be split into 3 phases: stellar collapse and bounce, convective engine, and post-explosion fallback. In addition to estimating the compact remnant mass distribution, predictions were also made for the distribution of explosion energies for core-collapse supernovae. With the knowledge that minimum mass decreases with metallicity, supernovae dominate the explosions at low-metallicity, even with the relatively shallow Salpeter IMF ($\alpha = 2.35$) (8). Taken together, these models highlight that explosion success and remnant formation emerge from a balance between neutrino heating, fallback accretion, and progenitor-dependent structure, rather than from a single controlling parameter.

ASSUMPTIONS AND LIMITATIONS OF CURRENT MODELS

It should be noted that current models often rely on simplifying assumptions, such as perfect spherical symmetry, and the approximate treatment of neutrino transport, which can affect details of the predicted collapse. Additionally, the roles of magnetic fields, rotation, and binary interactions remain uncertain and are often not fully included, despite their potential importance in massive star evolution (16). Differences between one-, two-, and three-dimensional simulations, as well as uncertainty in the progenitor structure, all lead to challenges in predicting the explosion outcomes and resultant formation (10).

THRESHOLDS FOR COLLAPSE

The combination of these results suggests that no simple mass threshold exists for determining whether a massive star leaves behind a neutron star or a black hole remnant. Instead, a range of physical factors, such as metallicity, rotation, and mass loss, impact the internal structure of the progenitor, leading to differing outcomes among stars of similar mass, often referred to as “islands of explodability”. Therefore, determining the final

remnant remains one of the major uncertainties in stellar evolution and core-collapse theory (6).

OBSERVATIONAL AND MULTIMESSENGER CONSTRAINTS

Observational constraints on black hole formation have significantly improved in recent years.

Stellar-mass black holes observed in X-ray binaries show a broad mass distribution, typically in the range of $\sim 5\text{--}20 M_{\odot}$, rather than a narrow formation channel (7). In addition, gravitational-wave detections from LIGO/Virgo/KAGRA have revealed populations of merging black holes with diverse masses, including systems that are difficult to explain using conventional stellar evolution models (17).

Observations of core-collapse supernovae and supernova remnants also provide insight into explosion outcomes. In some cases, massive stars undergo “failed supernovae,” leaving behind a black hole with little to no electromagnetic signature. The detection of neutrinos from SN 1987A confirms that neutrinos are produced during core collapse (7).

Multimessenger observations are now being used more often to test these models of black hole formation. Current models reproduce general features of observationally constrained populations. However, discrepancies remain in remnant mass distributions and explosion rates. These differences suggest that important physical processes like fallback accretion, rotation, and binary evolution are not fully captured in current models (17).

These observational constraints reinforce theoretical predictions by showing that black hole formation pathways are diverse and that current models must account for a wide range of progenitor conditions and evolutionary histories.

CONCLUSION

Stellar-mass black holes are generally understood to be a natural outcome of massive star evolution, but the details of how they form are still not fully understood. While the overall path from advanced nuclear burning to iron core collapse is well understood, the final remnant is not determined by the initial mass alone. Instead, black hole formation depends on several factors, including the internal structure of the star, metallicity-dependent mass loss, rotation, binary interactions, neutrino heating, multidimensional hydrodynamic instabilities, and fallback accretion (1).

Recent studies suggest that there is no sharply defined border between neutron star and black hole formation, but rather a range of outcomes depending on the conditions of the collapse. Stars with comparable masses can still leave different remnants depending on their internal structure and details of the explosion (6). With powerful new constraints on black hole masses and formation channels now coming from X-ray binaries, supernova remnants, neutrino detectors, and gravitational-wave astronomy in particular, theoretical efforts have begun to produce results that can be directly compared to observations. However, considerable uncertainty remains in explosion properties, final remnant masses, and our treatment of multidimensional effects (17).

Looking forward, better communication between stellar evolution modelers, three-dimensional core-collapse experts, and multimessenger astronomers will be crucial. Constraints on failed supernovae, compact remnant masses, and binary star evolution will yield important insights into the collapse of massive stars into black holes. Black hole formation thus remains an important problem linking the study of stellar evolution, our understanding of gravity, matter at nuclear densities, and cosmology (18).

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CONFLICT OF INTEREST

The author(s) declares that there are no conflicts of interest related to this work.

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