The Supermassive Problem: Probing Potential Stellar Formation Pathways of Intermediate-Mass Black Holes

Abstract

Intermediate-mass black holes (IMBHs) are a key missing link in the current understanding of the formation of supermassive black holes, which are believed to have formed through the mergers of IMBHs in the early universe. While IMBHs have been detected through gravitational waves and active galactic nuclei, it remains unclear how they are formed. Since there are currently very few detections of IMBHs, the ability to shed further light on their formation has been limited. It was theorized that simulations could serve as a workaround, modeling potential circumstances that could give rise to IMBH formation. In this study, Modules for Experiments in Stellar Astrophysics (MESA), a stellar evolution code that allows for the simulation of a star's evolution from initial parameters, was used to search for a pathway by which IMBHs of ≳100 $M_\odot$ can form directly from high-mass stars. Stars were simulated at 200 $M_\odot$, the rough upper bound for a star formed from molecular cloud collapse, at various metallicities (Z). To adjust the data where MESA's physics diverges from accepted assumptions, correction algorithms were applied. The output was then plotted to illustrate the evolution of the stars' parameters and determine their properties. It was found that while solar-metallicity (Z=0.0142) and LMC-metallicity (Z=0.006) stars lose too much mass to form IMBHs, Population II (Z=0.00001) stars can form them. This finding presents a novel formation pathway for IMBHs in the early universe, offering new insight into the origins of the universe's largest black holes.

Introduction

Black Holes (BHs)

- ★ Objects so dense and massive that even light can't escape their gravity
- ★ Predicted by Albert Einstein as part of his general theory of relativity
- ★ Different size categories based on mass

Supermassive Black Holes (SMBHs)

- ★ Largest type of BH, often upwards of millions of times the mass of the Sun
- ★ Lie at the centers of galaxies, helping shape their evolution
- ★ First observed very early in the universe's history (Bañados et al., 2017)

Intermediate-Mass Black Holes (IMBHs)

- ★ Contain 100–100,000 solar masses ($M_\odot$); building blocks of SMBHs
- ★ Poorly understood, with very few observations to date (Greene, 2022)
- ★ How they form is not yet known

Stellar Formation Pathway

- ★ Massive stars often collapse into BHs when they die
- ★ Modern-universe stars typically form BHs of ≲30 $M_\odot$ (Romagnolo et al., 2024)
- ★ Massive, metal-poor stars in the early universe might have formed IMBHs

Problem: We don't know how IMBHs were formed

Research Question: Could IMBHs have come from stars?

Hypothesis: Yes, if the stars were sufficiently massive and poor in metals, as existed in the early universe

Methodology

Insufficient observational data to investigate

Stellar Evolution Simulations

- ★ Simulate a star's evolution and determine its properties over time
- ★ MESA: state-of-the-art model to run simulations (Paxton et al., 2010)

Mentor simulated stars at 200 $M_\odot$ and various metallicities (fraction of a star composed of "heavy" elements)

Plotted simulation output data to reveal how the stars' properties evolved over the course of their lives

Corrected error in output data using a formula developed by a previous study (Sander & Vink, 2020)

Analyzed plots to contextualize results and reveal the physical processes that helped shape the stars' lives

Results

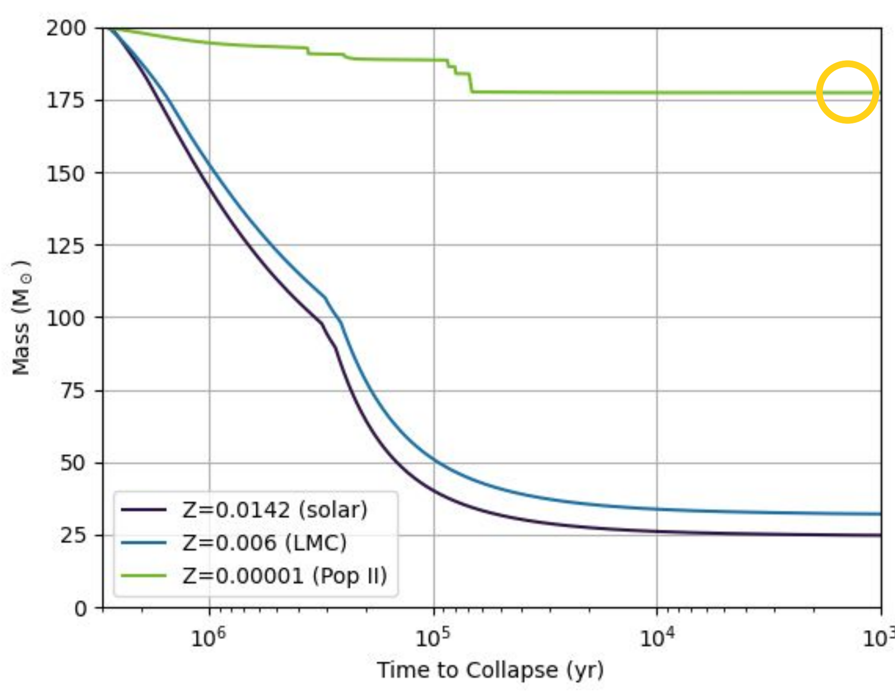

Figure 1: Star Mass over Time. Graph produced by finalist using Matplotlib, 2025.

Very-low-metallicity star (green line) retained the most mass out of the three stars

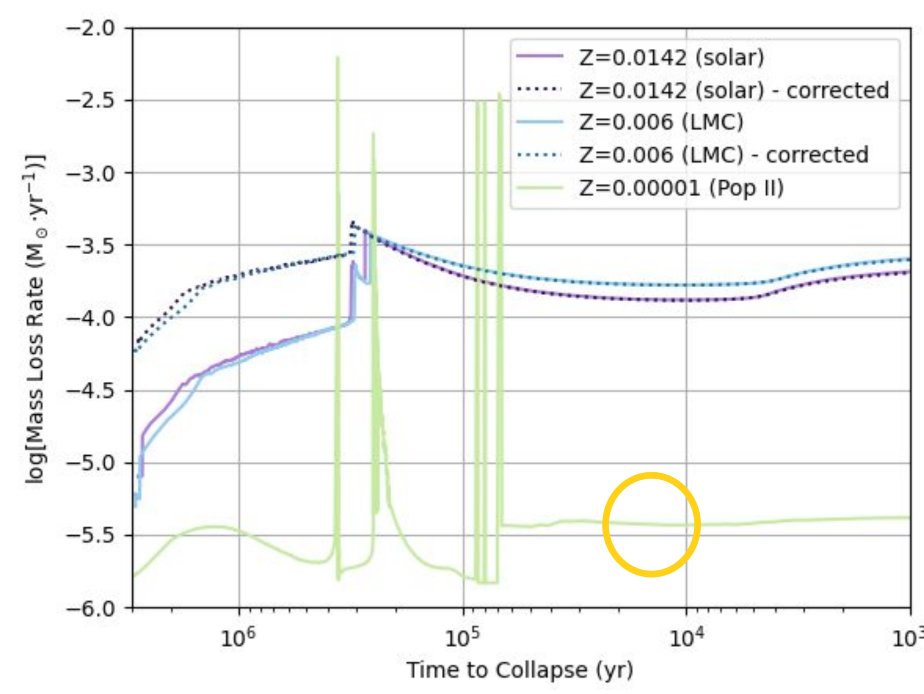

Figure 2: Wind Strength over Time. Graph produced by finalist using Matplotlib, 2025.

Very-low-metallicity star had much weaker stellar winds across its life than the other stars

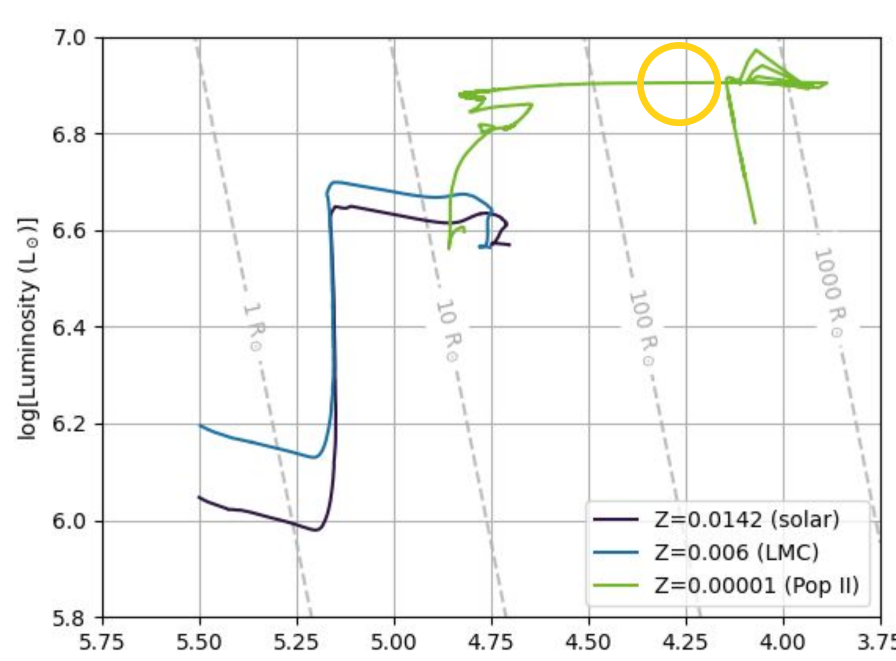

Figure 3: Hertzsprung-Russell Diagram. Graph produced by finalist using Matplotlib, 2025.

Very-low-metallicity star grew brighter, cooler, and larger as it evolved

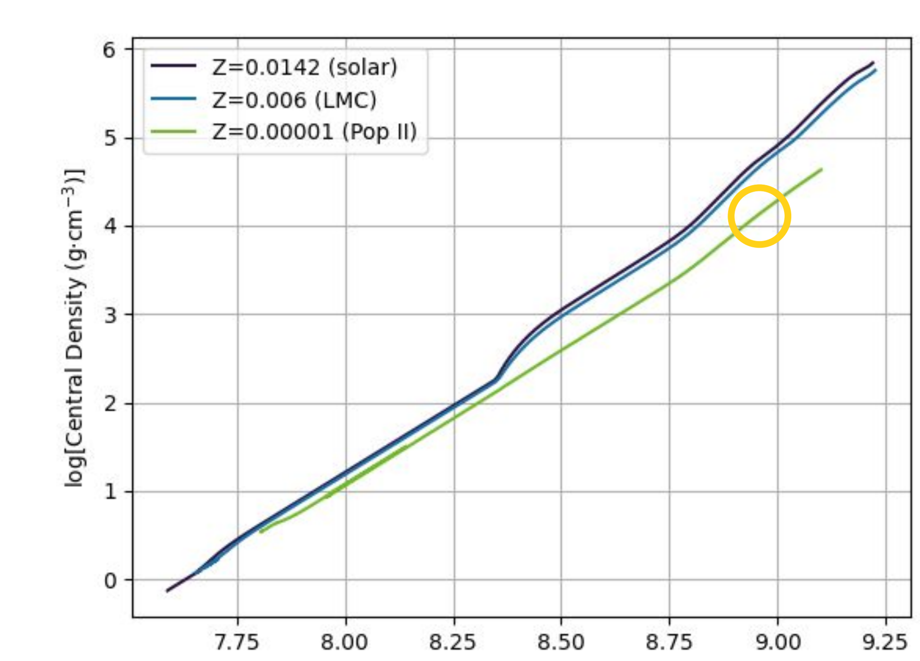

Figure 4: Core Density and Temperature. Graph produced by finalist using Matplotlib, 2025.

Very-low-metallicity star had a less dense and hot core, especially later in its evolution

Discussion

Maximum Black Hole Mass (Figure 1)

- ★ Two higher-metallicity stars formed BHs of about 30 $M_\odot$
- ★ Very-low-metallicity star formed an IMBH of ~180 $M_\odot$
- ★ IMBHs can be formed from stars

Formation Mechanisms (Figures 2 & 3)

- ★ Very-low-metallicity star lost very little mass through stellar winds over the course of its life
- ★ Because the very-low-metallicity star retained most of its mass, it evolved differently than the other stars

Viability as SMBH Seeds (Figures 3 & 4)

- ★ The extreme expansion of the very-low-metallicity star could help these IMBHs to rapidly grow into SMBHs
- ★ The less dense and less hot core means that the very-low-metallicity star is less likely to explode in a supernova and destroy itself before forming an IMBH

Limitations and Future Study

- ★ All data was from simulations, which are dependent on our current understanding of physics and the universe
- ★ Next step: search for these stars using new telescopes

Conclusions

Hypothesis: massive, metal-poor stars could form IMBHs → Hypothesis supported by data from MESA simulations → Sheds light on the origin of SMBHs in modern galaxies

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