●マクニール ルーシー オリビア 特定助教

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研究課題： 高解像度観測の時代に向けた超新星前質量損失の理論的更新
（Generational theoretical updates to pre-supernova mass loss in the era of high resolution observations and all-sky surveys）

専門分野： 天体物理学（Astrophysics）

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Most massive stars, those heavier than 8 solar masses, end their lives in a spectacularly energetic and violent explosion known as a core-collapse supernova.

While these stars produce chemical elements as heavy as iron during their lifetimes through successive nuclear burning phases, it is only during a supernova explosion that many heavier elements in the universe can be created.

These bright cosmic explosions have been observed in our night sky for millennia. Despite advances in stellar evolution theory and numerical simulations, it remains challenging to connect the properties of the explosion—such as luminosity, explosion geometry, and chemical element production—with the properties of both the massive star progenitor (e.g., mass, structure, rotation) and the compact neutron star or black hole remnant (e.g., mass, spin) left behind.

Since 2019, astronomers have been able to observe mass ejections at the stellar surface during the final months before a core-collapse supernova. This critical time corresponds to the fast and violent oxygen and silicon shell burning phases, during which mechanisms in the central burning regions of the star can, for instance, partially eject the outer stellar envelope.

At the same time, it is now possible to model these final burning phases on supercomputers with three-dimensional stellar evolution simulations. For my Hakubi project, I will develop new analytic theory guided by such simulations to explore possible explanations for the upcoming observational dataset on pre-supernova mass loss.

Mass loss in supernova progenitors

The precise chemical element production and the appearance of a supernova depend on the shell structure at the time of explosion. Massive stars typically lose a large fraction of their total mass (10% to over half) over roughly 1,000-year timescales, either through winds at their surface or stripping by a close companion star. The pre-explosion structures are grouped into three broad categories based on the outermost envelope:

Observations of mass loss during the final months

Signatures of violent mass loss, corresponding to up to a few solar masses per year during the final oxygen and silicon shell burning phases, have been observed across all supernova classes as of 2024 (Type Ic: Maeda et al., 2021, Type II: Jacobson-Galán et al., 2022, Type Ib: Brennan et al., 2024). This “late-time” mass loss occurs in the final year to days before supernova explosion.

Supernovae are grouped into three broad categories: II, Ib or Ic. This depends on their chemical structure at the time of explosion, due to mass loss history

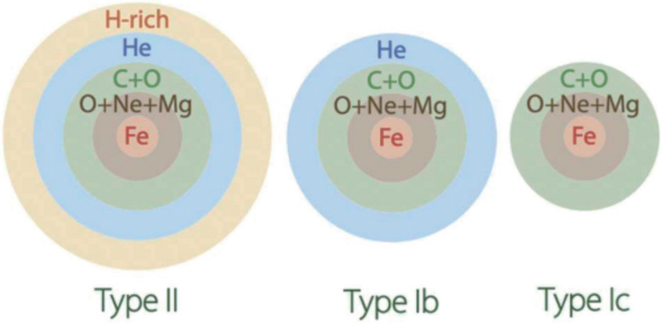

Figure 1. The three main supernova classification types, based on pre-explosion chemical shell structure (*Figure credit: Takashi Moriya*).

Observing this late-time mass loss at the surface offers insights into the uncertain physical processes in the innermost regions of the star, which are otherwise impossible to observe. These include understanding, for example, nuclear reaction rates and the mass and angular momentum enclosed in the region that will form the spinning compact neutron star or black hole remnant.

While the current sample of observations is somewhat serendipitous, the launch of the Vera C. Rubin telescope will clarify how common late-time mass ejections are in the intrinsic supernova population over the next decade.

Theoretical explanations for late-time mass loss at the progenitor surface

For mass loss in Type II supernovae, Woosley and Heger (2015) predicted that in some mass ranges, silicon burning becomes unstable, possibly ejecting the hydrogen envelope months before the actual core-collapse supernova.

Shiode and Quataert (2014) proposed that the violent inner oxygen or silicon convective burning layers can produce buoyancy waves so strong that when they eventually reach the outer envelope, they heat it, causing mass ejections from the surface in Type I or Type II supernovae.

Comparing current theoretical framework with observations

These mechanisms, based on simplified one-dimensional theory and numerical stellar evolution models, predict mass loss and surface heating levels that are too low compared to current observations. Preliminary results from 3D simulations suggest faster nuclear burning (Muller et al., 2016) and a preference for differential rotation (McNeill and Muller, 2022), both of which imply enhanced mass loss compared to one-dimensional predictions.

Hakubi project: theoretical framework guided by 3D hydrodynamics and nuclear burning simulations

Using state-of-the-art three-dimensional stellar evolution codes (PROMETHEUS: Fryxell et al., 1991, MAESTRO: Nonaka et al., 2012), we will examine the qualitative behavior and derive basic quantitative relationships related to late-time mass loss mechanisms in 3D. This covers wave generation and transport, as well as unstable nuclear burning "flashes." These insights will guide accompanying analytic theory for various mechanisms, which will then be applied to a diverse range of Type I and Type II progenitors in simplified 1D stellar models.

With a generalised framework for the physical processes that cause mass loss ejections at the stellar surface in the months before a supernova explosion, consistent with more realistic full three-dimensional simulations, the detection (or absence) of a pre-supernova mass ejection event could constrain properties like the progenitor's mass or rotation, and the remnant neutron star's or black hole's mass or spin-rate.

Such theoretical work is critical in this emerging observational paradigm for pre-supernova mass loss.

References

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* Figure 1: taken from the PhD dissertation of Takashi J. Moriya (https://sci.nao.ac.jp/MEMBER/takashi.moriya/PhDMoriya.pdf)

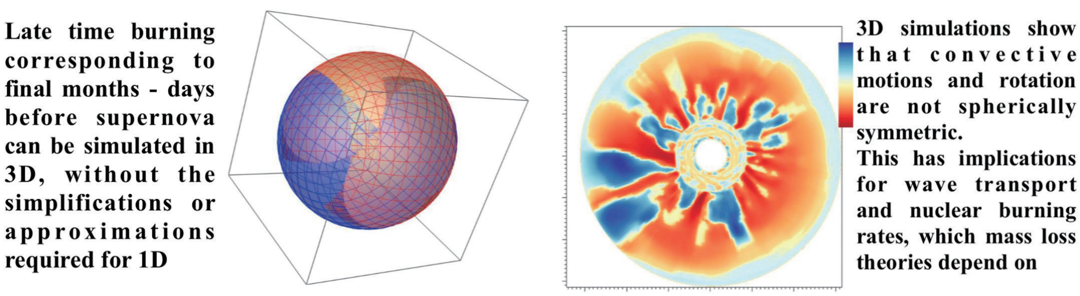

Figure 2. (Left) Geometry of a 3D grid-based stellar evolution model using the PROMETHEUS code. (Right) Cross-sectional slice through the middle of a 3D simulation of a Type Ic supernova progenitor during oxygen shell burning, showing convective up-drafts (blue) and down-drafts (red). Various results from 3D hydrodynamics, such as these large-scale convective burning asymmetries, enhance pre-supernova mass loss estimates.