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From Post-AGBs to white dwarfs: Exploring the fascinating evolution of intermediate mass stars (Invited contribution)

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Abstract

I will present insights from recent studies regarding the evolution of intermediate-mass stars, focusing specifically on the transition from the post-AGB phase to the white dwarf stage. These investigations provide fresh perspectives on these captivating astronomical objects. Throughout this evolutionary path, intermediate-mass stars experience intricate physical and chemical transformations, leading to notable alterations in their characteristics. I will present observational and theoretical findings crucial for enhancing our comprehension of the life cycle of intermediate-mass stars, exploring their role in enriching the Universe chemically. Additionally, I will highlight unresolved questions that warrant further investigation.

Resumen

Presentaré perspectivas provenientes de estudios recientes acerca de la evolución de estrellas de masa intermedia, centrándome específicamente en la transición desde la fase post-AGB hasta la etapa de enana blanca. Estas investigaciones ofrecen nuevas visiones sobre estos cautivadores objetos astronómicos. A lo largo de este camino evolutivo, las estrellas de masa intermedia experimentan intrincadas transformaciones físicas y químicas, lo que conlleva alteraciones notables en sus características. Presentaré hallazgos observacionales y teóricos cruciales para mejorar nuestra comprensión del ciclo de vida de las estrellas de masa intermedia, explorando su papel en enriquecer químicamente el Universo. Además, destacaré preguntas sin resolver que merecen una investigación más detallada.

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1. Introduction

In this review, I will be discussing the fate of stars with initial mass (M_{ZAMS}) comprised between ~1 and 8 $M_\odot$, after their evolution on the Main sequence, Red Giant and Asymptotic Giant Branch (AGB) sequences. Post-AGB stars (PAGBs) mark the conclusion of the AGB evolution, distinguished by relatively high mass loss events (10^{-7}–10^{-4} $M_\odot$/yr). These stars display a characteristic (mid-)IR excess and as they transition to higher effective temperatures, they maintain roughly constant luminosity. Nevertheless, they have not reached the temperature necessary to completely ionise the surrounding circumstellar material. The visibility of the central star depends on the opacity of the circumstellar shell, determining whether it is exposed or remains embedded (van Winckel, 2003). The entrance in the Planetary Nebula (PN) phase is characterised by the cessation of mass loss, a powerful and rapid stellar wind and a central star hot enough ($T_{eff} \geq 30{,}000$ K) to fully ionise the circumstellar environment. The luminous shell of ionised gas, expanding outward, will gradually diminish and disperse into the Interstellar Medium (ISM), contributing to the its enrichment (Kwitter & Henry, 2022). The central star will evolve towards a highly hot and dense electron-degenerated object, a White Dwarf (WD), which will eventually cool down (Santamaría et al., 2020a). However, our understanding of the evolutionary processes both between and within each phase remains incomplete. In Section §2, I will outline the unanswered questions that require attention. In Section §3, I will detail new findings, and in Section §4, I will also explore other intriguing evolved objects. The conclusion will be provided in Section §5.

2. Open questions

Evolved intermediate-mass stars exhibit numerous processes and mechanisms that are highly likely to be interconnected, yet each one, both individually and collectively, remains elusive to our complete understanding.
Concerning PAGBs, eight key themes demand our attention: understanding the mechanisms that drive the intense mass loss observed during the AGB phase, affecting the PAGB; exploring the chemical composition and abundance patterns in the atmospheres of these stars (insights into nucleosynthesis and mixing processes); identifying the determining factors in the diverse evolutionary paths that PAGBs follow; investigating the evolution of circumstellar environments; exploring potential connections between PAGBs and the presence of exoplanets; assessing the impact of binary interactions on the evolution of these evolved stars; studying the formation of dust grains in the outflows of PAGBs; and finally, unravelling the nature of the ultimate fate of post-AGB stars, whether they evolve into planetary nebulae, white dwarfs, or other exotic objects.
Regarding PNe (Galactic and Extragalatic), there are similar challenges to address, and I have chosen to highlight eight of them. The first pertains to understanding the processes leading to the formation of PNe from precursor stars, with a focus on mass-loss processes. Next is determining the mechanisms involved in the transition from spherical to non-spherical nebulae. Another crucial aspect is accurately determining the chemical composition of PNe and their contribution to enriching the ISM. The evolution of central stars in terms of mass-loss rates, temperature evolution, and the formation of white dwarfs is also a key concern. A precise description of the dynamics of PNe and the application of 3D visualisation are vital for comprehensive understanding. Additionally, determining the origin of collimated outflows and jets, as well as the associated formation mechanisms, is essential. The role of binary systems in the formation and shaping of PNe needs exploration, and finally, understanding the relationship between planets and PNe is an intriguing area of inquiry.
Turning to WDs (which constitute a distinct realm in itself), various questions arise, encompassing aspects such as their detection methods, binary nature (including potential planetary companions) and merging capabilities, chemical and physical properties, and ultimately their evolution as Type Ia supernovae, along with the associated generation of gravitational waves.

3. New insights into the late stage of stellar evolution

3.1. Post-AGB stars

The primary information source for PAGBs is The Torún catalogue for Galactic post-AGB (Szczerba et al., 2007), which currently documents more than 300 PAGBs. The Spectral Energy Distribution (SED) of PAGBs enables the analysis of both the central star and the external shell. The latter can be classified into two categories: PAGBs with cold, detached, expanding dust shells, referred to as "Shell-type", and PAGBs with hot dust and circumstellar discs, known as "Disk type". New data from GAIA has also allowed for a more precise analysis of the luminosity. Disks play a crucial role in the investigation of PAGBs, serving as a vital component contributing to the non-spherical symmetry observed in these objects in contrast to their AGB precursor stars. Therefore, the"recipe" involves a rotating disk, a binary system within a common envelope, an accretion disk, and the launch of jets. This theoretical framework is substantiated by several observational findings. For instance, Bujarrabal et al. (2013) detected Keplerian rotating disks around 24 PAGBs using mm-wave observations of CO lines. Kluska et al. (2019) conducted VLTI/PIONIER interferometric observations in the H-band, capturing images of circumbinary disks. As mentioned earlier, jets and outflows are pivotal components. The latter were identified by Gallardo Cava et al. (2021) using the NOEMA interferometer, employing 12CO and 13CO J = 2-1 maps for PAGB 89 Her and 12CO J = 2-1 maps for AC Her, IRAS 19125+0343, and R Sct. In a separate study, Bollen et al. (2021) detected jets in five PAGBs through high-resolution spectroscopy. The inner jet velocities span from 155 to 443 km/s and it is interesting to notice that a mechanism inferred for the launch of those jets involves magnetism. Magnetic fields ($\vec{B}$) have indeed been identified in various PAGBs through diverse methodologies.Sabin et al. (2020) utilised dust polarisation to trace $\vec{B}$ in the envelope of OH 231.8+4.2, while Huang et al. (2020) and Vlemmings & Tafoya (2023) employed the polarisation of molecules in R CrT and OH 17.7-2.0, respectively. Sabin et al. (2015) detected and measured $\vec{B}$ at the photosphere of U Mon and R Sct, and Georgiev et al. (2023) demonstrated the variability of magnetic fields in R Sct. Perez-Sanchez et al. (2013) found synchrotron emission in IRAS 15445-5449 and concluded that a magnetic launching mechanism was responsible for the bipolar morphology. Finally, Leal-Ferreira et al. (2012) detected water masers in OH 231.8+4.2 and were able to measure $\vec{B}$. Additionally, it is important to note

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that several studies have been conducted to comprehend nucleosynthesis in PAGBs. For instance, the work by Kamath & Van Winckel (2022) highlights a chemical diversity within this population. Lastly, recent studies by Kluska et al. (2022) and Martin et al. (2023) propose the presence of planets in binary PAGB binary via their observations and analysis of the disks.

3.2. Planetary nebulae

The very recent IAU Symposium 384: "Planetary Nebulae: a Universal Toolbox in the Era of Precision Astrophysics" set the main characteristics of PNe as tracers of stellar evolution, hydrodynamics event, astrochemistry laboratories, abundance decoders and as unique tools to study the structure and evolution of galaxies[1]. The HASH (Hong Kong/AAO/Strasbourg H-alpha) planetary nebulae database Parker et al. (2016) currently reports 4,623 planetary nebulae, but it is estimated that more than 20,000 exist. To address this discrepancy, various surveys have been conducted, including MASH (Parker et al., 2006; Miszalski et al., 2008), IPHAS (Sabin et al., 2014; Ritter et al., 2023), and VPHAS+ (Sun et al., 2023). These surveys utilise diverse detection techniques such as visual observations, photometry, and machine learning. The newly discovered PNe exhibit characteristics such as faintness, large size, and evolved or compact structures. It is noteworthy to mention the substantial contribution from amateur astronomers in the search for these elusive planetary nebulae[2], leading to collaborative efforts (Le Dû et al., 2022). Addressing one of the main challenges in the field—the origin of the shaping of planetary nebulae—a consensus has emerged within the PN community. The prevailing view is that the non-spherical shape of PNe is primarily linked to the presence of a close binary system that has undergone common envelope evolution (Jones, 2020). However, it is essential to recognise that not all PNe are associated with a close binary system. In fact, the majority of intermediate-mass stars in binary systems do not undergo interaction throughout their evolution (Miller Bertolami, 2022). Furthermore, MHD models propose the critical requirement for a magnetic launching mechanism (García-Segura et al., 2022). Indeed, astrophysical jets play a crucial role, and both theoretical studies and observational research have revealed their significance. These findings have been facilitated by state-of-the-art observational techniques and instrumentation, as demonstrated in works such as Rechy-García et al. (2022). On a different theme, chemical abundances are a crucial aspect of PN research, but their determination is a challenging task. To tackle this issue, sophisticated photoionisation codes are employed. The Abundance Discrepancy Factor (ADF), potentially attributed to multiple plasma components or temperature fluctuations, remains a persistent issue (Méndez-Delgado et al., 2023), although high spectral resolution observations can significantly contribute to addressing this challenge (García-Rojas et al., 2022). The ongoing challenge of distinguishing between shock excitation and photoionisation also persists in the field. The studies mentioned here represent only a fraction of the extensive researches conducted by the PN community. Not covered here are investigations into distance determinations, the PN Luminosity Function, and the study of extragalactic PNe. Additionally, there are new evolutionary models for PAGBs and PNe proposed by Miller Bertolami (2016) which predict shorter PAGB timescales. I would refer the reader to the proceedings of the IAU 384 for more information.

[1]I thank Joel Kastner for sharing his notes.

[2]Planetary Nebulae.net

3.3. White dwarfs

Weidmann et al. (2020) emphasised the extensive variety of central stars of planetary nebulae (CSPNe) and the diverse evolutionary paths they follow, a theme also explored in the work of Miller Bertolami (2022). The search for WDs is actively pursued, utilising data from GAIA EDR3 (Gentile Fusillo et al., 2021) and SDSS (Kilic et al., 2020), among other sources. Additionally, an intriguing aspect of these evolved stars lies in their connection to planets, as evidence of planetesimal objects or debris has been discovered around WDs (Vanderburg et al., 2020; Estrada-Dorado et al., 2023). In our discussion of binary systems, it's crucial to highlight the generation of Type Ia supernovae. WD J005311, known as Parker's star, and the nebula Pa 30 (discovered by an amateur astronomer!) are though to have originated from a dramatic merger involving two degenerate stars, either ONe/CO or CO/CO WDs, resulting in a Type Iax supernova. WD J005311 is so far the only known Type Iax supernova remnant in our Galaxy, providing a unique opportunity for in-depth study (Fesen et al., 2023; Schaefer, 2023; Lykou et al., 2023).

4. Peculiar and associated objects

In the realm of intermediate mass stars, there exist peculiar objects, including born-again planetary nebulae (Montoro-Molina et al., 2023), and various binary systems such as novae (Santamaría et al., 2020b), symbiotic systems (Huang et al., 2023), and cataclysmic variables (Guerrero et al., 2018). The comprehension of these objects, facilitated by high-resolution observational techniques and modelling, plays a crucial role in enhancing our understanding of (binary) evolved stars and the stellar feedback to the ISM.

5. Conclusion

I have outlined some of the open questions in the study of evolved intermediate mass stars and provided insights into how some have been addressed. Despite the substantial progress made in both theoretical models and observational techniques, there remain complex issues to explore. Fortunately, with the advent of new and upcoming instrumentation like ALMA, LMT, EELT, ngVLA, and the application of innovative techniques such as machine learning, the future looks promising for advancing our understanding of these evolved stars.

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