News & views

Astronomy

Binary origins of planetary nebulae

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Planetary nebulae are the colourful remnants of a star like our Sun, following its death. These nebulae may be spherical, resembling cosmic bubbles, but often they have much more complex morphologies - likely caused by mechanisms involving binary stars.

At the end of its life, our Sun will expel the gaseous envelope surrounding its core, leaving behind a white dwarf (WD) star. For stars like the Sun, radiation from the WD can illuminate and ionise the escaping gas before it has completely dissipated. The result is a striking spectacle of colour and beauty called a planetary nebula (PN, plural PNe). This name is a misnomer, given by William Herschel who observed them as colourful, disc-like objects - hence his supposition of their "planetary nature"[1] (see Fig. 1 for examples of PNe).

The Sun's evolution into a WD is governed by the fuel which it fuses. Currently, it burns hydrogen (H) in its core, creating helium (He). Once this H reserve is depleted, fusion stops in the core, which is now entirely comprised of He. Now unable to support itself, the star's gravity compresses the hydrogen envelope surrounding the core until the temperature is sufficient for hydrogen burning to continue just above the cores surface. The energy generated pushes the gas outwards, causing the star to expand into a red giant, which loses mass due to its stellar wind and cools as its radius increases. Cooling continues until fusion again ceases; the star contracts once more, this time until the temperature in the core rises high enough that He-fusion can begin. Helium in the core fuses to form carbon along with traces of oxygen and neon. Again, the generated energy radiates outwards, forcing the envelope to expand once more. The star is now known as an asymptotic giant branch (AGB) star, characterised by its very strong stellar wind. This stellar wind strips the envelope from the star, leaving a hot, luminous WD which ionises the surrounding clouds of gas from the previous phases.[2] Fig. 2 visualises this evolution as a function of magnitude (brightness) and temperature.

One may assume from this description of stellar evolution that PN would be relatively spherical in shape, with gas expelled radially outwards from the centre, which is marked with a WD.[3] While some PN do fit this description, resembling a bubble, often they have more complex structures and features (see Fig. 1). Some attempts were made to explain these, citing stellar rotation and magnetic activity as possible causes (see Marco (2009)[4] for an overview of these arguments). However, these could not be used to definitively predict the irregular shapes of PN. Interactions between binary stars play an important role in the formation of these PN.[5]

Figure 1: Kronberger 61. Detailed images taken with the Kepler telescope reveal complex structure in the spherical gaseous cloud. Credit: Gemini Observatory/AURA

Binary stars are systems where two stars are in orbit around each other or a common centre of mass. At least half of all stars in the observable universe are believed to be in binary or multiple systems.[6] Many of these orbit close enough together to interact with each other, with some undergoing mass transfer. For two stars close enough together, the exchange of mass can be so rapid that the matter engulfs both stars, resulting in a "common envelope".[7] The stars continue to orbit each other within this common envelope.

The envelope increases drag on the stars' orbits. Angular momentum from each star is transferred to the gas, expelling it from the system. Conversely, the stars adopt closer orbits, possibly even merging. As a result, the common envelope is ejected from the system, leaving behind a single or binary central star which illuminates the emission nebula.[2] This post-common-envelope mechanism is currently the favoured theory of PN formation involving binaries.[5] The formation of a significant fraction (perhaps up to ~70%) of PN may be explained through binary interactions. Around 15% of all central stars were formed in common-envelope binaries.[8] It is also believed that weak interactions between more widely separated ("detached") binary stars contribute to PN formation through other more poorly understood mechanisms.

The aspherical shapes of PN can also be explained if an AGB star has an aspherical stellar wind.[5] Simulations have shown that wider binary stars which do not directly interact can also cause aspherical PN. Features such as spiral arms may be the consequence of wide binary stars moving through their orbits.[9] Another possible way an AGB star may develop an aspherical solar wind is due to planetary companions. It has been proposed[10] that as a star expands and engulfs surrounding planets, their impact on its winds may be enough to create the various morphologies seen in planetary nebulae.

The binary origins of planetary nebulae are still not well understood. Binary interactions can lead to an extremely wide range of outcomes, providing astronomers with an ever-expanding and unpredictable field of research to explore. As such, there will undoubtedly be developments to come, improving our understanding of the role of these systems in the formation of planetary nebulae.

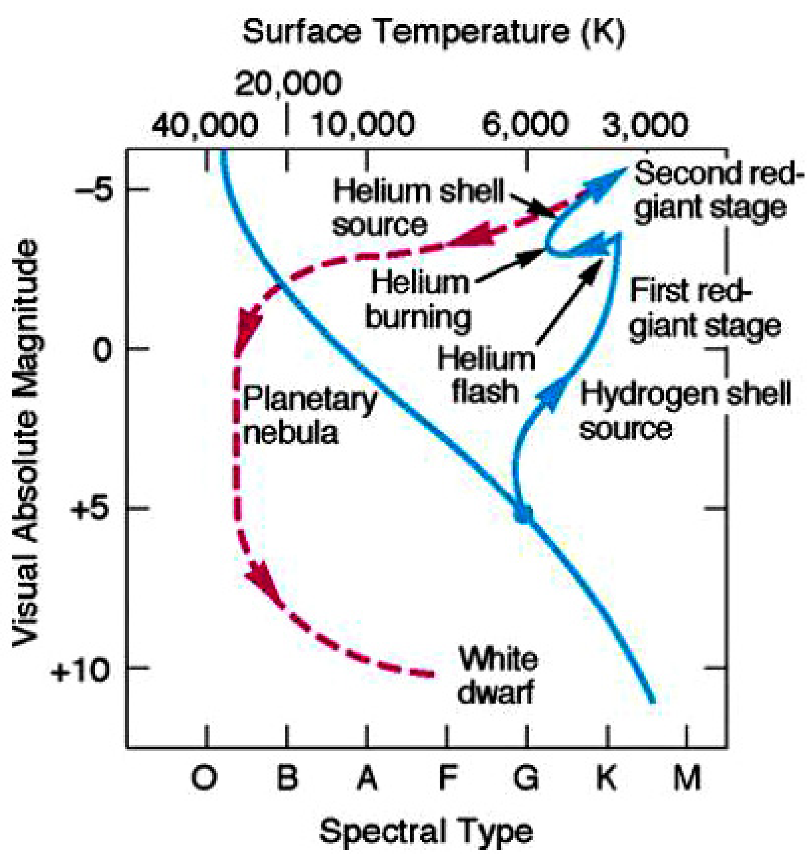

Figure 2: Hertzsprung-Russel diagram. HR diagram showing the evolutionary stages of a sun-like star. The solid-blue arrow begins at a point on the main-sequence where the Sun lies, then ascends through the red-giant stage, and the AGB stage, before expelling its envelope and becoming a planetary nebula and ultimately a white dwarf star. The dashed-red line indicates that the star is degenerate (no fusion is taking place). Credit: Chris Mihos (burro.case.edu)

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