Planetary Nebulae: A Universal Toolbox in the Era of Precision Astrophysics
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EXPLORE: The wide binary companions to the two Ring nebulae

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Abstract. Two planetary nebulae have sofar been observed with JWST. Both show stellar companions. The paper discusses how and what we can learn from the companions.

Keywords. Catalogs, Surveys, stars: binaries, planetary nebulae

1. Introduction

EXPLORE (https://explore-platform.eu) is an EU-funded project to develop tools to located and analyze on-line archival data, without the need to download these data. The philosophy is to bring the software to the data. EXPLORE is developing a set of scientific data applications (SDAs) on topics as diverse as Lunar crater classification, galactic archaeology, and 3-d extinction models.

We are developing an SDA called SPHOT which retrieves photometry for individual stars from a large number of surveys, with GAIA distances, and uses these to fit stellar atmosphere models. It is based on work in McDonald, Zijlstra, & Watson (2017).

The SDA can also be run off-line by installing the underlying `pyssed` package. It has two main modes, one for individual stars and one for fields. The package obtains an accurate position and proper motion for each star, and uses this to find the correct counterpart in various surveys, e.g. Sloan and IPHAS. The filter curves for each survey are retrieved and the stellar atmosphere models (BT-Settle by default) convolved with these. Extinction is obtained from 3-d extinction cubes in EXPLORE.

2. The two Ring Nebulae

We have used the SDA for stars associated with planetary nebulae. Two planetary nebulae have been observed with JWST: the Southern Ring (NGC 3132; De Marco et al. 2022) and the Ring Nebula (NGC 6720; Wesson et al. 2023). The central star of the Southern Ring has a bright A-type companion located at 1300 au from the central star. The pyssed fitting confirmed the temperature of 9200 K, from GAIA DR3 spectroscopy and was used to calibrate the photometry of the central star in these early JWST data. The companion star has evolved off the main sequence, allowing us to determine both the mass and age fron PARSEC isochrones: $2.4 \pm 0.15\,M_\odot$ and 530 Myr. Extrapolating the isochrone gives the progenitor mass of the PN central star: $2.86 \pm 0.05\,M_\odot$. Dartmouth isochrones yield masses lower by $0.15\,M_\odot$.

JWST shows that the central star has a resolved dust disk which is aligned with the companion star. The disk extends from 50 to 140 au from the star with an inner disk at 3 to 8 au seen in a hot dust excess (De Marco et al. 2022). Multiple arcs visible in the JWST images show evidence for an unseen close companion star, at ~ 50 au, around the inner edge of the disk. The close companion must be no more than $0.2\,M_\odot$ if Main Sequence or it would have been detected in pyssed.

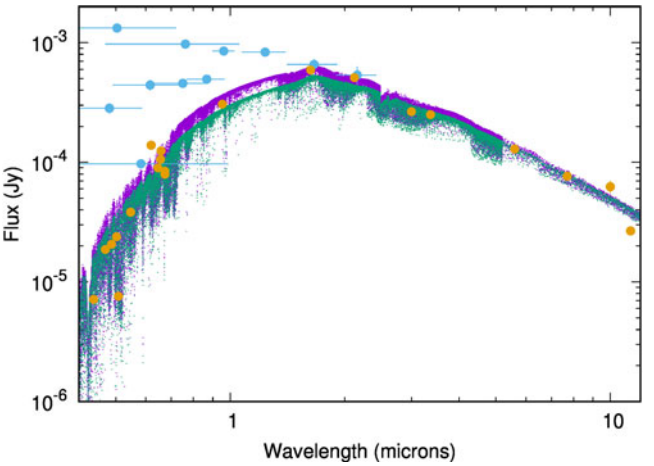

Figure 1. SED of the Ring Nebula companion star with BT-Settl models. The blue circles falling above the fit are affected by nebular emission and were excluded from the fitting.

A distant proper motion companion to the central star of the Ring Nebula (González-Santamaría et al. 2021) lies 18.5 arcsec from the central star, or a projected distance of 0.07 pc. It was proposed to be a white dwarf, based on the *Gaia* DR3 photometry. However, this photometry is badly affected by nebular emission lines. The pyssed fit (Fig. 1) gives $T_{\rm eff} = 3300$–3400 K. This indicates a main sequence star of approximate spectral type M2–M4 with a mass of 0.3–0.5 $M_\odot$.

The distant companion has remained bound to the central star over its life time. By estimating time scales for stellar encounters, we find that the mean survival time would 1 Gyr. This suggest a progenitor mass for the central star of $\sim 2\,M_\odot$.

JWST images show ~ 10 concentric arcs, interpreted as due to a companion star at 50 au. The star is not detected in photometry. Both ring nebulae therefore contain triple stellar systems with both closer and more distant companions. The more massive progenitors of 2–3 $M_\odot$ may have a higher chance of companions.

Companion stars can be important tools in deriving properties of the central stars. It is not clear how much tripe systems affect the structure of the nebulae. Angular momentum exchange between the outer and inner companions might amplify the angular momentum available to the wind of the mass losing star. However, this is speculative.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921323004878

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