Stellar Populations in the Milky Way and Beyond
Proceedings IAU Symposium No. 395, 2026
J. Meléndez, C. Chiappini, R. Schiavon & M. Trevisan, eds.
doi:10.1017/S1743921325001139

Underlying the Importance of Galactic Star Clusters in Low-to-Intermediate Mass Stellar Evolution Studies

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Abstract. Stellar evolution studies of low-to-intermediate mass stars are hindered by the lack of a solid link that connects their initial and final properties. This problem can be resolved for stars that are members of star clusters and at the final stages of their evolution. In such cases, we can estimate their final properties from direct measurements and obtain the necessary information for the properties of their progenitors from independent cluster studies. Here, we focus on the study of planetary nebulae that are confirmed members of Galactic open star clusters. These rare instances provide us with a new additional sample of data, which contributes to the fundamental initial-to-final mass relation (IFMR). We examine the quality of this contribution and assess the efficacy of our method, showing that our approach is very promising with already significant initial results. Our data generally confirm the latest IFMR trends, filling important gaps in the process.

Keywords. Star Clusters, Planetary Nebulae

1. Planetary Nebulae (PNe) in Galactic Star Clusters

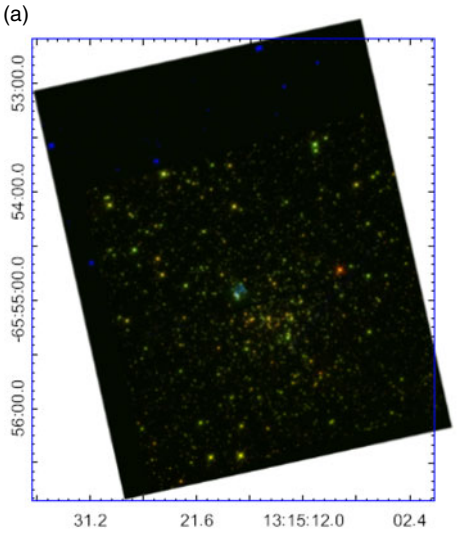
In the case of PNe that are physical members of star clusters, multiple of their properties (e.g. distance, environment, progenitor star's initial mass and age) can be determined independently from cluster color-magnitude diagrams (CMDs) and theoretical cluster isochrones (Bressan et al. 2012). These rare instances allow the study of the link between initial stellar mass and the PN's chemical enrichment, and also provide additional, independent data for the, currently poorly constrained, IFMR (e.g., Cummings et al. 2018). This relation connects the central star's (CS) mass with that of its progenitor and is crucial for stellar evolution studies. Only four PNe have been confirmed to be physically associated with globular clusters (e.g., Jacoby et al. 1997), and another four with open clusters (OCs; Parker et al. 2011; Fragkou et al. 2019a,b, 2022a,b, In preparation) in our Galaxy. Such confirmations require good agreement in terms of angular proximity, distance, reddening, and most importantly radial velocities (since cluster velocity dispersions are typically very low) between the PN and the cluster.

2. PNe in Open Clusters

The four confirmed OC-PNe pairs are: the PN PHR1315-6555 in the OC Andrews Lindsay (AL) 1, the PN BMPJ1613-5406 in the OC NGC 6067, the PN IPHASX J055226.2+32372 in the OC M37 and the PN NGC 2818 in the OC NGC 2818A (see Figure 1).

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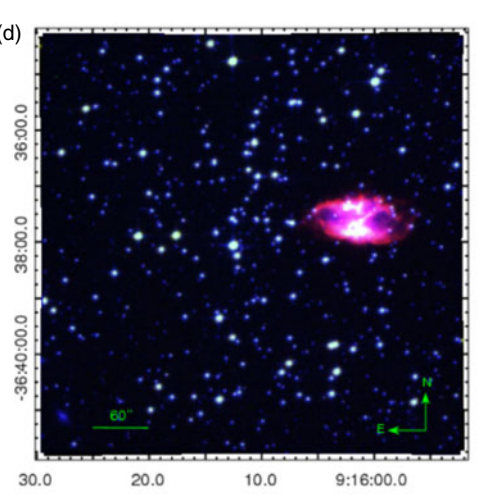
PN PHR1315-6555 - OC Andrews Lindsay (AL) 1. A WFC3 HST color-composite (F814W = red, F555W = green, F502N = blue) image depicting the first confirmed cluster-PN pair [Figure from Fragkou et al. (2019a)].



PN BMPJ1613-5406 - OC NGC 6067. A 30' x 30' SHS (Parker et al. 2005) RGB (Hα, short-red, blue) image (north is on the top, east on the left) showing the cluster NGC 6067 and its PN member north of its apparent center [Figure from Fragkou et al. (2019b)]. The PN progenitor mass is estimated around 5.6 $M_{\odot}$ making it the most massive PN progenitor confirmed empirically to evolve to a PN.



PN IPHASX J055226.2+32372 - OC NGC M37. A color-composite image (frame height=25', Hα = red, [OIII] 5007 Å = green, broadband filters= red, green, blue) centered on the cluster M37. North is on the top, east on the left. Its PN member is clearly shown in red, right on the north-east of its geometrical center. [Figure from imagingdeepspace.com, https://www.imagingdeepspace.com/iphasx-j0552262323724.html]. The PN's estimated kinematic age of 78 kyr is the largest ever found for a PN, indicating that cluster PN do not dissipate as fast as their counterparts in the field.



PN NGC 2818 - OC NGC 2818A. An SHS (Parker et al. 2005) RGB (Hα, short-red, blue) image centered on the apparent center of the cluster NGC 2818A. Its PN member, NGC 2818 that has a very complex structure, is clearly visible on its west side [Figure adapted from the HASH database (Parker et al. 2016)].

Figure 1. The four confirmed open cluster-PNe pairs.

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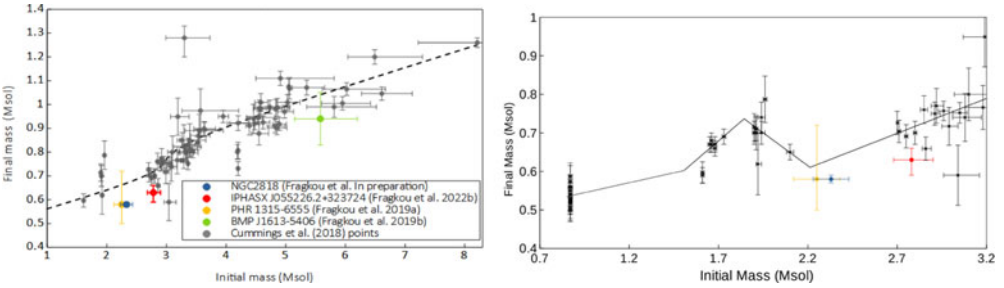


Figure 2. The open cluster-PNe data points over-plotted on the Cummings et al. (2018) white dwarf IFMR trend and points (left panel) and on the Marigo *et al.* (2020) IFMR estimates (right panel). [Figures adapted from Fragkou et al. (2022a)].

3. Initial Results and General Remarks on PNe in Open Clusters

All four open cluster PNe confirmed so far are bipolar with enhanced nitrogen (Peimbert & Torres-Peimbert 1983) and relatively high-mass progenitors. Their estimated initial and final masses have been overplotted along the latest IFMR estimates (see Figure 2). The open cluster PNe generally represent well the previous trends estimated from cluster white dwarfs and fill important gaps. Our points confirm and even deepen the 'kink' found at $M_i \approx 1.6$-$1.9\ M_\odot$ (Marigo *et al.* 2020). The PN in NGC 6067 has the largest PN progenitor mass ($\approx 5.6\ M_\odot$) ever determined empirically. In the case of the PN in M37, its kinematical age was found to be 78 kyr (or even larger according to Werner et al. (2023))- the oldest ever found for a PN. This suggests that PNe in clusters have a larger observable lifetime than field PNe since they do not dissipate as fast due to the low-velocity dispersion between cluster stars and the surrounding interstellar medium. In general, the extreme characteristics of PNe in open clusters are rare PNe properties that deserve further study.

4. Future Work

A detailed study of all confirmed cluster PNe is currently underway. The detection of more such rare instances is essential. Two more candidate open cluster-PN pairs are already identified, pending confirmation with the help of newly obtained high-resolution PN data.

Acknowledgments

VF acknowledges support from Brazilian research funding agency CAPES (grant: 88887.838401/2023-00).

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