Planetary Nebulae in the Era of *Gaia*

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Introduction: Planetary Nebulae (PNe)

- Brief end stage of life for 1 - 8 solar mass stars between AGB and white dwarf.
- Nebula of gas ejected during AGB is ionised by hot central star and becomes visible over large distances, making PNe valuable chemical probes of not only the Milky Way but also nearby galaxies.
- Rare objects: only 3500 PNe are known in the Milky Way (versus billions of stars).
- Still many open questions: distances, sizes, lifetimes, central star evolution, population size, explanation of morphologies, role of central star binarity…

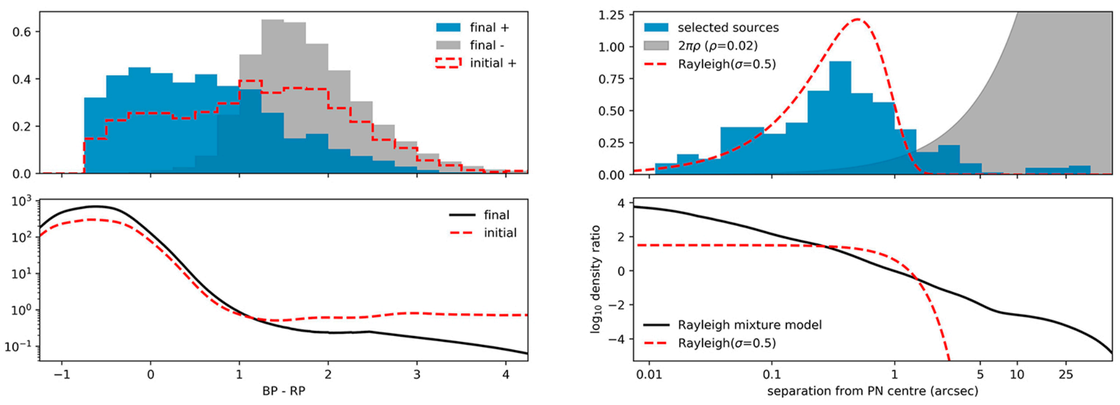
Automated Matching of Central Stars of PNe in *Gaia* DR2

Background

- Accurate distances critical for astrophysical characterisation of PNe but difficult to come by (in part because of rapid central star evolution), with most distance estimates modelling-based and highly uncertain.
- Trigonometric parallaxes of central stars are most direct measurement technique but were only available for a few PNe before *Gaia* DR2; the first step towards using them is accurately matching central stars in *Gaia* data.

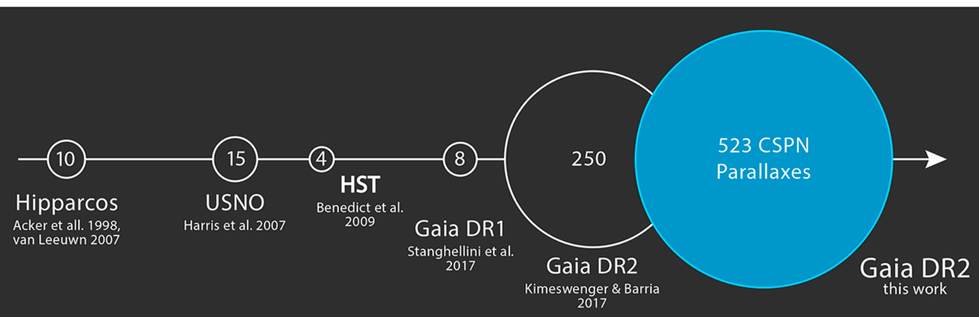
Method

- Apply the likelihood ratio method commonly used for catalogue matching (Sutherland & Saunders 1992) to match *Gaia* DR2 sources to PNe in the HASH PN catalogue (Parker et al. 2016).
- Method compares two hypotheses: that a pair of sources in different catalogues are in fact the same object versus a coincidence; depends on separation, uncertainties, local source density, and other features such as brightness.

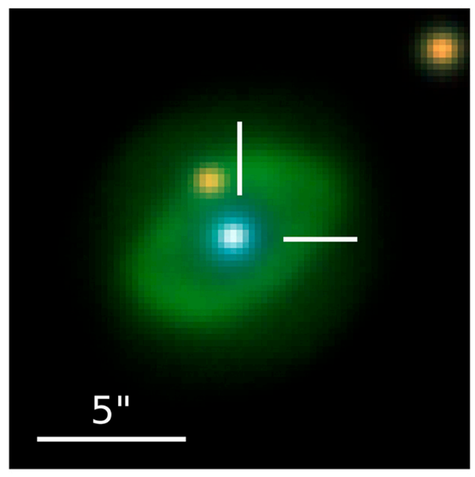


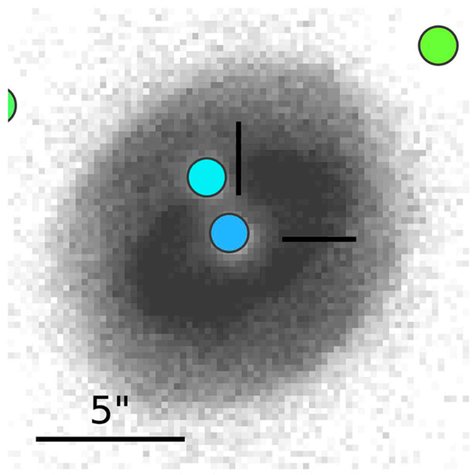
- Consider the positions of *Gaia* DR2 sources and BP - RP colours: expect blue stars near nebula centres but may not always be the case (reddening, binarity).
- Infer unknown positional uncertainties and colour distribution from data using high-confidence matches from position or colour alone to derive a prior distribution for the other feature (related to co-training method in semi-supervised learning).

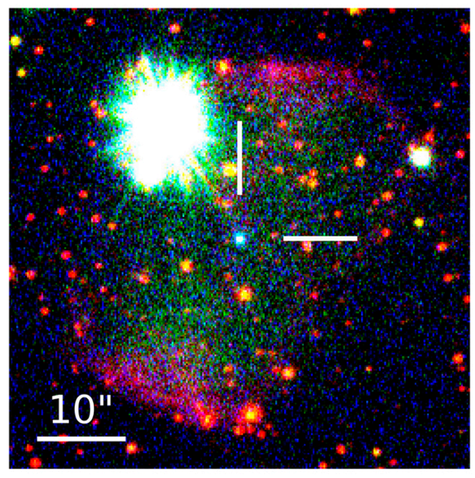
Results

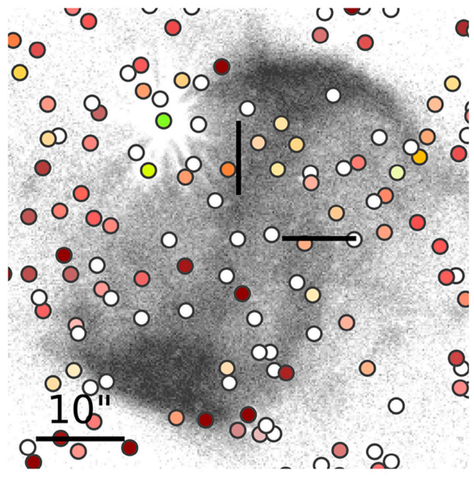


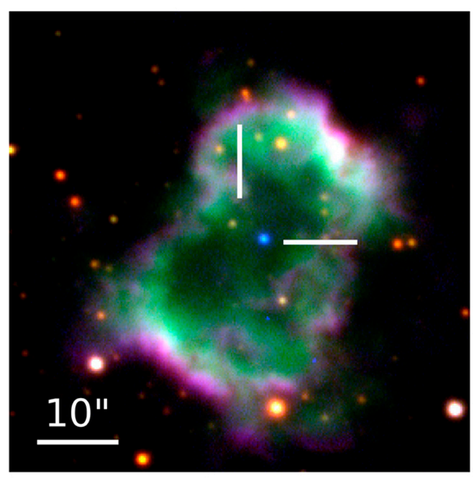
- Double the count of central star matches from previous works with fast search.

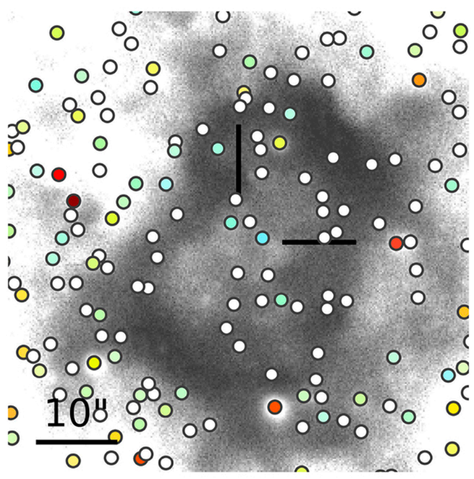


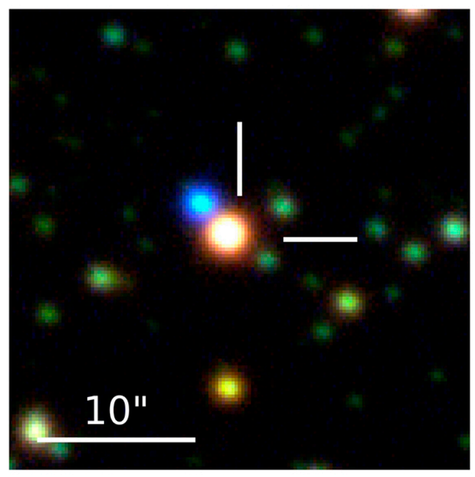


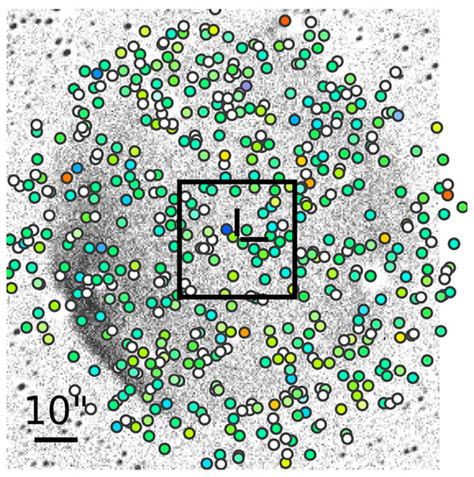




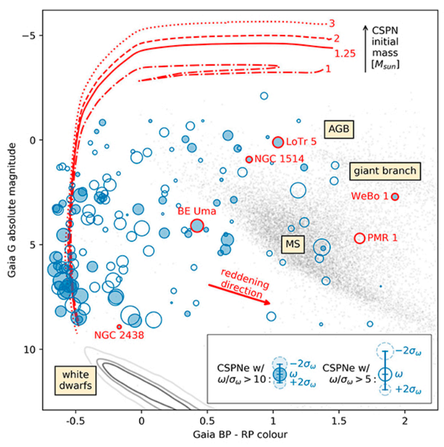






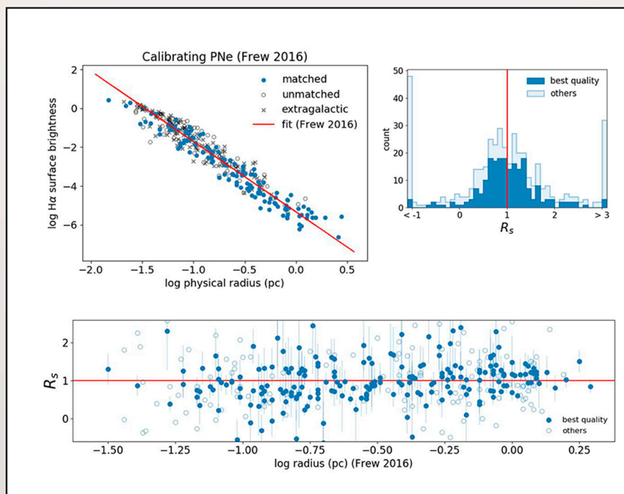


False colour (u′g′r′) and quota (r′ - Hα) images from VPHAS+ of example PNe in the HASH PN catalogue for which we matched central stars. The broadband colours highlight the blue central stars, while the quota images capture the the nebula. Coloured dots in the quota images are *Gaia* DR2 sources, coloured according to BP - RP (with white meaning no colour).



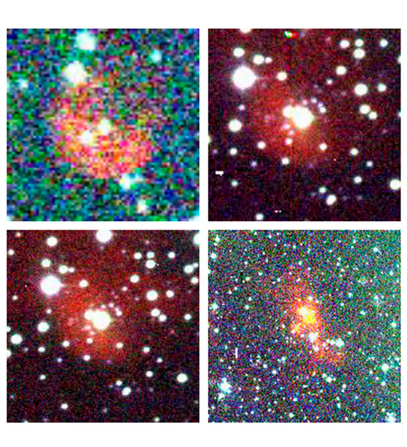
Tracing Central Star and PN Evolution

Plotting matched PN central stars with best parallaxes on an HR diagram shows how their observed properties fit with theoretical models, and highlights binary systems and other interesting outliers.



Recalibrating Statistical Distances

- Recent statistical distance scale of Frew et al. (2016) related Hα surface brightness to PN physical radius, calibrated by around 300 PNe with known distances.
- Overall accuracy can be directly evaluated using distance ratio technique from Smith (2015); we plan to re-calibrate the distance scale incorporating the new *Gaia* parallaxes with a fully Bayesian approach.



Searching for New PNe

- Large narrowband imaging surveys such as SHS and IPHAS discovered many new PNe, but known galactic PNe still a fraction of what is expected.
- Upcoming data from VPHAS+ (images), WEAVE (spectra), and *Gaia* offer new discovery possibilities, particularly with automated techniques.

Acknowledgements

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Further details at https://zendo.org/record/2798016

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