Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
Proceedings IAU Symposium No. 323, 2016
X. Liu, L. Stanghellini & A. Karakas, eds.

doi:10.1017/S1743921317000801

Expansion parallaxes and intrinsic stellar properties for 15 simple planetary nebulae

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Abstract. We determined individual distances to a small number of rather round, quite regularly shaped planetary nebulae by combining their angular expansion in the plane of the sky with a spectroscopically measured expansion along the line of sight. For this goal, we combined up to three epochs of Hubble Space Telescope imaging data and determined the respective proper motions of rim and shell edges, and of other features as well.
Ground-based radial velocities are assigned separately to the nebular rims and shells and used to determine individual distances, thereby assuming that the expansions in the line-of-sight and in the plane of sky are equal. We employed 1D radiation-hydrodynamics simulations of planetary nebulae evolution to correct for the difference between the spectroscopically measured expansion velocities of rim and shell and the expansion speeds of their respective shock fronts.

Keywords. planetary nebulae, techniques: image processing, techniques: spectroscopic

1. Context, goals, and methodology

Accurate individual distances to planetary nebulae (PNe) are vital for determining nebular luminosities, ages, and masses of their central stars. So far, reliable distances are only available for PNe in stellar populations with well-known distances (e.g. Galactic bulge, Magellanic Clouds), but only for singular cases in the Galactic disk. Statistical distances are prone to systematic errors because they rely on assumptions whose justification is not always guaranteed.

The goals are i) to obtain accurate distances for 15 simple, bright, extended H-burning disk PNe, and ii) to use these distances to derive fundamental properties of their central stars. For this purpose, the angular expansion speeds of bright rim and/or shell boundaries, $\dot{\theta}_{\rm rim/shell}$, were measured using multi-epoch HST imaging observations. The pairs of images in the lines of [O III] an [N II] span 7.6 to 14 yr for the various PNe in this survey. Two examples (IC 418, NGC 6826) are rendered in Fig. 1.

Proper motions reflect the pattern speeds of shock or ionisation fronts that propagate through the nebula. In contrast, Doppler speeds reflect bulk motions. The ratio of the two speeds must be corrected for these differences by means of 1D radiation-hydrodynamics evolution models for PNe (Marten *et al.* 1993; Mellema 2004; Schönberner *et al.* 2005; Schönberner *et al.* 2014).

Expansion distances are derived using $D_{\rm exp} = 211 \times \dot{R}_{\rm rim/shell}/\dot{\theta}_{\rm rim/shell}$, where $\dot{R}_{\rm rim/shell}$ is the pattern velocity (km s^{-1}) corresponding to $\dot{\theta}_{\rm rim/shell}$ (mas yr^{-1}) for a rim or shell. Let F be the correction factor obtained from the models such that $\dot{R}_{\rm rim/shell} = F_{\rm rim/shell} \times V^{\rm Dopp}_{\rm rim/shell}$. For the objects in our survey, we find $F_{\rm rim} = 3 \Longrightarrow 1.5$ for $V^{\rm Dopp}_{\rm rim} \simeq 5 \Longrightarrow \simeq 20$ km s^{-1}, $F_{\rm shell} = 1.25 \pm 0.05$ for all $V^{\rm Dopp}_{\rm shell}$. We measured parallaxes using the rims

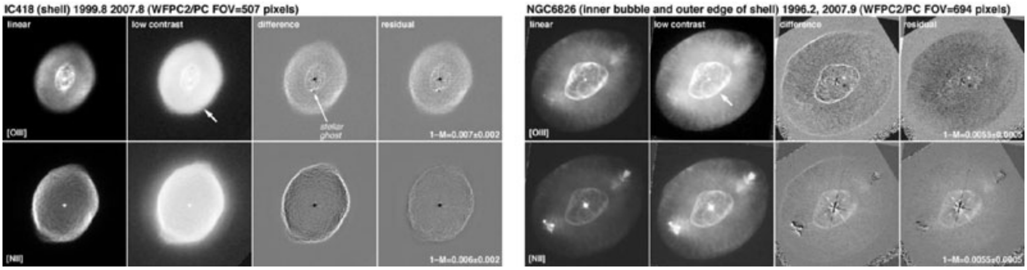

Figure 1. Examples (IC 418, NGC 6826) of the HST images, their multi-epoch changes, and post-magnification difference images. The third column shows the signal of expansion, and the fourth shows the difference after the first-epoch image was magnified by a factor M before subtraction. The angular expansion rate of a feature of angular size θ is then $\dot{\theta} = (M-1) \times \theta/\Delta t$, where Δt is the time between the epochs of the images used to measure M, ($7.6 \leqslant \Delta t \leqslant 14$ yr).

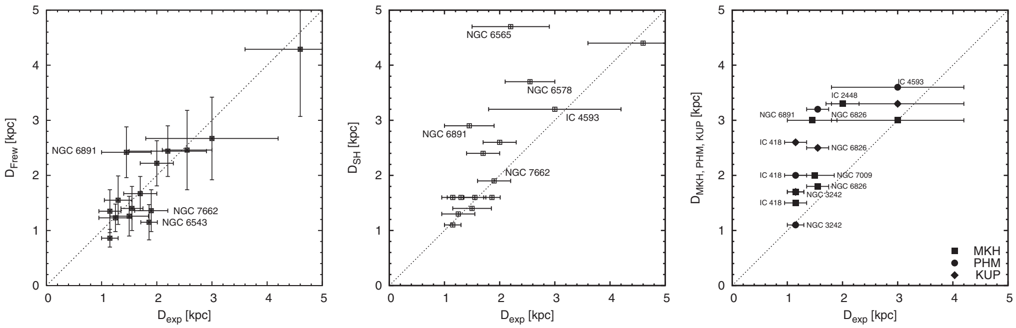

Figure 2. *Left*: distances based on the statistical calibration by Frew *et al.* (2016). *Middle*: distances based on Stanghellini & Haywood (2010). *Right*: distances derived spectroscopically.

and shells since each are independent entities with their different sources of momentum and historical motions.

2. Results and conclusion

A comprehensive presentation of the results and the conclusions drawn will be given in a forthcoming publication. Here we highlight the following (cf. Fig. 2):

1. Distances derived separately for the rims and shells agree (within the errors) after appropriate corrections for pattern speeds as explained in Sect. 1 have been applied.
2. General agreement with the statistical distances of Frew (2016) and, to a lesser degree, of Stanghellini & Haywood (2010) exists. The agreement with spectroscopic distances is poor.
3. Central-star "plateau" luminosities range from about 1500 to about 10 000 $L_{\odot}$, with a mean at about 5000 $L_{\odot}$. There is excellent agreement with the luminosities of objects from the Galactic bulge (Hultzsch *et al.* 2007) and the Magellanic Clouds (Herald & Bianchi 2004, 2007).
4. Employing the latest post-AGB evolutionary models of Miller Bertolami (2016, priv. comm.), we found a central-star mass range of about 0.53–0.60 $M_{\odot}$, with a mean of 0.55 $M_{\odot}$.

We conclude that expansion measurements of nebular edges offer, together with predictions from radiation-hydrodynamics models, a reliable method to determine distances to suited PNe.

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https://doi.org/10.1017/S1743921317000801 Published online by Cambridge University Press