124. Planetary nebulae

PLANETARY NEBULAE are the dust and gas shells ejected during the late asymptotic giant branch phase for stars of $1-8M_{\odot}$, the ejecta being ionised by the radiation from the hot, evolving central star. During the red giant phase, the He core is contracting and heating, and the outer layers are expanding and cooling, the process continuing until core temperatures reach $\sim 10^8$ K, initiating core He fusion, and leading to an inert C and O core with a He and a H burning shell.

He fusion rates are extremely temperature sensitive, leading to unstable pulsational feedback. This successively ejects more of the stellar atmosphere, progressively exposing deeper and higher temperature core regions. At exposed temperatures of $T_{\rm eff} \sim 30\,000$ K, the dense ultraviolet photon flux ionises the ejected atmosphere, illuminating the spectacular planetary nebula.

As a consequence of these complex processes, planetary nebulae provide important probes of stellar evolution, and of cosmic chemical enrichment (e.g. Stanghellini & Haywood, 2010). But determining accurate distances has always been problematic, such that Gaia's contribution was expected to be significant.

THE FIRST KNOWN, M27, was discovered by Messier in 1764. Today, some two thousand Galactic planetary nebulae are known (e.g. Acker et al., 1992; Parker et al., 2006), amongst some 20 000 estimated in our Galaxy (e.g. Bobylev & Bajkova, 2017). But the term, a misnomer, originates from William Herschel's observations that they resembled the rounded shapes of planets.

Their distances, of a few hundred parsec or more, are typically beyond reach of ground-based parallaxes, although the USNO CCD programme, at ~ 0.5 mas accuracy, measured some 20 (Harris et al., 2007).

Accordingly, other distance estimates have been used, including those based on surface brightness, interstellar Na D lines, or spectroscopic methods. Others have been based on assumptions about the nebula's physical radius (e.g., Schneider & Buckley, 1996; Frew et al., 2016), or on the hypothesis that there is a fixed value of the ionised nebula mass (Schlovsky, 1957; Daub et al., 1982; Cahn et al., 1992; Stanghellini et al., 2008).

A PRE-HIPPARCOS review by Pottasch (1997) gave parallaxes for just 9 objects with distances between 130–752 pc, and central stars with $V = 12.3 - 16.6$ mag. Acker et al. (1998) examined the properties of 19 planetary nebulae observed by Hipparcos.

Ten years later, Stanghellini et al. (2008) suggested that out of some 1800 Galactic planetary nebulae then known, only about 40 had distances determined with reasonable accuracy.

Meanwhile, many in the Large Magellanic Cloud, typically unresolved from the ground, have been observed with HST. This allows accurate measurement of their apparent radii, in turn providing one of the best pre-Gaia proxies for the planetary nebulae distance scale (Shaw et al., 2001; Stanghellini et al., 2008).

THE SPACE MOTIONS of the central stars is also of great interest. As examples, Sh 2–68 has a tail extending over 45 arcmin, formed by matter stripped off the main nebula in the course of the central star's trajectory along its Galactic orbit (Kerber et al., 2002).

Galactic orbits were used to classify GC 7293 and Sh 2–216 as thin disk objects, and IC 4593 and Sh 2–174 as thick disk objects (Kerber et al., 2004).

Indeed Sh 2–174 is an extreme velocity case with the central star located *outside* the main nebula; the proper motion of the central star's orbit is consistent with the observed displacement over 10 000 years.

Proper motion estimates for 234 planetary nebulae, based on various astrometric catalogues reduced to the Hipparcos system, were given by Kerber et al. (2008). Their vertical distribution and kinematics yield the various population scale heights (Bobylev & Bajkova, 2017).

LET ME ALSO ADD that the majority of planetary nebulae are not spherically symmetric, and the wide variety of shapes and features are variously attributed to binary central stars, stellar winds, and magnetic fields.

In addition, the role of substellar companions, and especially exoplanets, in shaping their morphology, has also been investigated (e.g. Soker, 1996; Soker, 1997; Sabach & Soker, 2018).

GAIA PARALLAXES provide the first opportunity to establish the distances of a large number of planetary nebulae, and to examine the distance scales that have been based on various proxies in the past.

With DR2, Kimeswenger & Barría (2018) identified 382 of the 728 central stars from the Stanghellini & Haywood (2010) compilation. Of these, 57 had (formally) negative parallaxes, and 39 had no astrometric solution. The others showed good agreement with the USNO parallaxes. The older statistical proxies, although reaching larger distances, showed greater systematic differences.

Schönberner & Steffen (2019) compared DR2 parallaxes of 11 central stars with previous expansion parallaxes. Good agreement for 9 was taken as confirming the underlying model, which asserts that the nebula's shell and rim are two independently expanding entities, created and driven by different processes (thermal pressure and wind interaction), both varying differently with time. The results also imply that spectroscopic methods often lead to distance overestimates, even with detailed photoionisation models of the star–nebula system.

González-Santamaría et al. (2019) identified 1571 previously known central stars in DR2, constructing a 'Golden Astrometric Sample' of 201 with good parallaxes, along with apparent sizes, radial and expansion velocities, and effective temperatures (more than 1000 were similarly identified by Chornay & Walton, 2020).

Again, DR2 parallaxes compared well with previous USNO and HST astrometry, while distances inferred from other models were generally overestimated. They calculated physical radii for a subsample used to derive 'kinematical ages' based on their published expansion velocities. Stars with small nebular radii are located in the constant luminosity region of the HR diagram, while those with the largest radii are objects at a later stage, fading on their way to become white dwarfs.

The spatial distribution suggested completeness to ~ 2.3 kpc (with others beyond 4 kpc), along with a scale-height 168^{+27}_{-62} pc, and a space density $\rho = 64^{+47}_{-18}$ kpc^{-3}. They estimated a total of 21 000 planetary nebulae in our Galaxy, with an implied birth rate 3×10^{-3} kpc^{-3} yr^{-1}.

FURTHER REFINEMENTS came with EDR3. González-Santamaría et al. (2021) constructed a catalogue of 2035 nebulae, with their central star identification and EDR3 distances for 1725. For the 405 most accurate, they derived their Galactic distribution, radius, and kinematic age, and for a subset of 74, their evolutionary state (mass and age) derived from their luminosities and effective temperatures from evolutionary models.

Chornay et al. (2021) identified 2000 sources as likely central star or compact nebula detections. Ali et al. (2022) proposed a Gaia-calibrated distance scale based on the linear relationship between the radio surface brightness temperature and nebula radius.

SOME 50 central objects are known to be binaries. Studies have pointed to a connection between binarity and morphology (including jets and low-ionisation structures), suggesting that binarity may play an important role in the nucleosynthesis processes.

There are also at least two known triple systems, NGC 246 and Sp 3, with confirmation of the latter provided by the Gaia DR2 parallax (Miszalski et al., 2019).

For wide-separation (visual) binaries, González-Santamaría et al. (2020) searched DR2 for comoving components, based on parallax and proper motion, in the vicinity of the central stars of their 'Golden Astrometric Sample' of 201 stars, finding eight wide binary components out to 15 000 au, and confirming NGC 246 as triple. They found no correlation between wide binaries and the nebular morphology.

Concerning close binaries, and in the absence of epoch photometry for most sources, Chornay et al. (2021) used the uncertainty in mean photometry in DR2 as a proxy for binarity. They recovered a large fraction of the known close binary population, also identifying a number of new binary candidates.

Ali & Mindil (2023) extended this using DR3, from which 82 central stars were classified as probable binaries, of which 24 had been previously classified as close binaries, and 58 were new candidates. A further 26 previous candidates were re-classified as symbiotic stars.

FOUR PLANETARY nebulae are known in Galactic globular clusters, and two in the Fornax dSph, their occurrence being of interest both as distance calibrators, and for the wider study of more distant populations.

Bond et al. (2020) showed that Gaia DR2 included two of the globular candidates (Ps 1 in M 15, and GJJC 1 in M 22), and that their DR2 proper motions were consistent with their suggested cluster membership. Minniti et al. (2019) identified a number of new globular cluster candidates, pointing out that future Gaia releases should provide accurate parallaxes for all.

TWENTY or more papers to date discuss individual objects based on the Gaia distances or space motions. Amongst them are the origin of the ionised halo around IC 5148 (Barría et al., 2018); the exclusion of NGC 2452 as a member of the open cluster NGC 2453 (González-Díaz et al., 2019); the post-common-envelope central star of NGC 2346 (Brown et al., 2019); and confirmation of the bipolar nebula and its central white dwarf as members of the open cluster M 37 (Fragkou et al., 2022).

THERE WAS much uncertainty, pre-Gaia, in the underlying physics of planetary nebulae due to the absence of accurate distances and space motions. More quantitative testing of models of this important phase of stellar evolution are being enabled by Gaia… and we can expect much more in the future.