Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
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Conference Summary

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Abstract. The progress in planetary nebulae (PN) research reported in this symposium is reviewed in the context of our current understanding of the PN phenomenon.

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1. Evolution of the subject

Research in planetary nebulae (PN) has undergone significant evolution over the years. Before the IAU PN Symposium in Ithaca in 1977, observational studies of PN were primarily focused on optical spectroscopy of atomic lines resulting from recombination and collisional excitation, and the determination of elemental abundance from these observations. After 1977, it was realized that PN consist of more than ionized gas, and observations have extended to infrared observations of continuum emissions from dust and millimeter-wave observations of line emissions from molecules. After the introduction of CCD detectors and the availability of observation platforms from space, detailed morphological structures of PN as well as exterior haloes were discovered through high-dynamic-range imaging (Jewitt *et al.* 1986, Corradi *et al.* 2003).

On the theoretical side, we knew that PN are progenitors of white dwarfs and descendents of red giants (Shklovsky 1956) and the PN shells are ejected outer envelopes of red giant stars (Abell and Goldreich 1966). However, the details of central star evolution and shell ejection mechanism were not understood. The identification of H-shell burning on an electronic-degenerate core as the energy source of central stars of PN (Paczyński 1971) made possible the construction of realistic evolutionary tracks (Schönberner 1979). This also put PN as a post-asymptotic-giant-branch (post-AGB) phenomenon. The realization that PN are formed through an interacting winds process solved many of the problems faced by sudden-ejection models (Kwok *et al.* 1978). New interacting-winds dynamical models coupled with time-dependent photoionization models opened new ways to interpret the complex morphological structures observed (Schönberner *et al.* 2014).

The ability to observe PN in extragalactic systems by large telescopes has also allowed PN to be used as kinematic tracers (Meatheringham *et al.* 1988) and standard candles for distance determination (Jacoby 1989). A summary of our modern understanding of PN is given by Kwok (2000).

2. Interaction with other fields

The field of PN research did not develop in isolation. This discipline of research has benefited from developments in other fields and progress in the field has influenced many

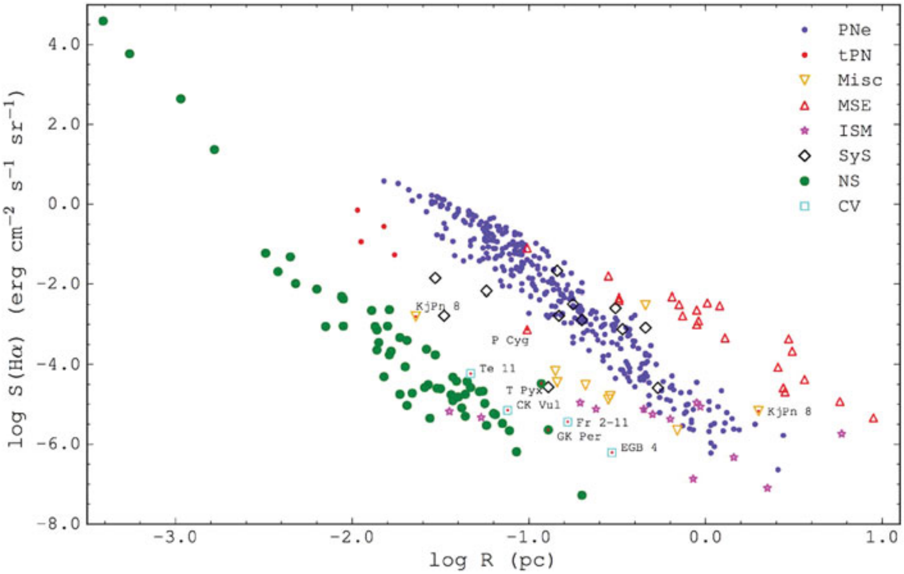

Figure 1. The Hα−radius plot as a diagnostic for ionized nebulae. Figure by David Frew.

other related areas. As photoionized regions, PN share many similar physics and diagnostic tools as HII regions and active galactic nuclei. As descendents of AGB stars and precursors of white dwarfs, research on PN rely on work on nucleosynthesis and mass loss of AGB stars and stellar atmosphere models of white dwarfs. Massive OB stars have fast stellar winds and Wolf-Rayet stars have Wolf-Rayet nebulae which have similar dynamical structures as PN. Studies of mass transfer and common envelope evolution in binary systems such as novae, cataclysmic variables and symbiotic stars have relevant lessons for PN. Some of the physical mechanisms in PN are similar to star formation regions as both have directional outflows collimated by dense equatorial tori. PN can serve as tracers of history of star formation and chemical enrichment in the Galaxy. Beyond the Galaxy, extragalatic PN can be used to map the distribution of dark matter and to establish the cosmological distance scale. Since PN are formation sites of molecules and complex organics, they play a role in the emerging new disciplines of astrochemistry and astrobiology.

It is in this context that I review the progress observed in this Symposium.

3. Surveys and catalogs

The classification and cataloging of objects is the first step to every field of research. The progress since the *Catalog of Galactic Planetary Nebulae* by Perek and Kohoutek (1967) and the *Strasbourg-ESO Catalog of Galactic Planetary Nebulae* of Acker *et al.* (1992) was reviewed by Frew (these proceedings). Narrow-band surveys have increased the number of PNs in the Galaxy to 3,300. Parker (these proceedings) describes the Hong Kong–AAO–Strasbourg Hα (HASH) database and the comprehensive functions that it offers. It is possible that many PN are not detected in optical surveys because of dust extinction and a survey in the near infrared may reveal many hidden PNs. The UWISH2 survey of the northern Galactic plane has identified 285 candidates using narrow-band imaging centered on the H_2 line (Gledhill, these proceedings). The search for

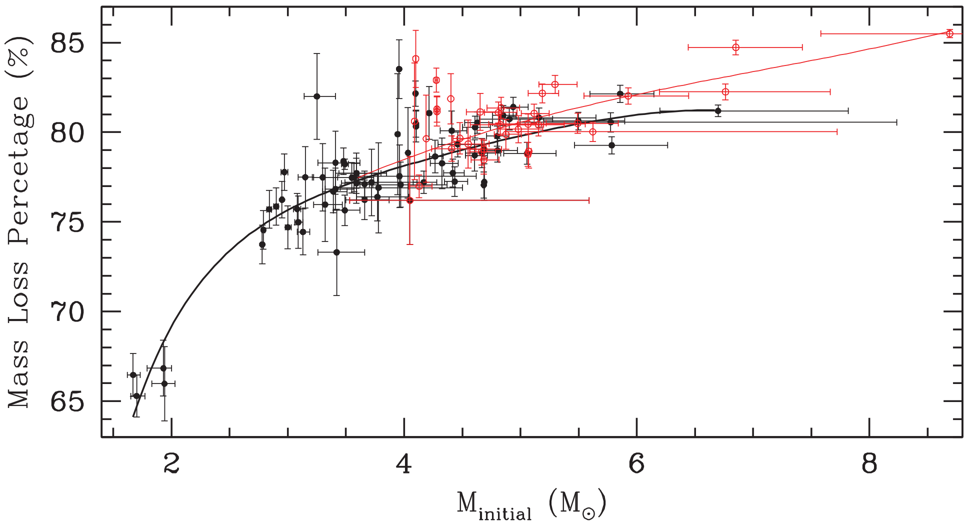

Figure 2. Percentage of total mass lost as a function of initial mass. Figure by Jeff Cummings.

proto-PN using infrared colors was reported by Szczerba (these proceedings) and Suh (these proceedings).

Since spectral and morphological properties of PN are also shared by other astrophysical objects such as symbiotic stars and compact HII regions, significant confusion problems still remain in existing catalogs. Various techniques on separating mimics from true PNs were discussed by Frew (these proceedings). A Hα surface brightness vs. radius plot was suggested to be an effective tool for this purpose (Figure 1). It is clear that we cannot embark on a meaningful discussion on the nature of PN if we do not have a consistently homogeneous group of member objects.

4. Distances

An accurate distance scale for PN is important as distances affect the luminosity determination and the distribution of PN on the Herztsprung-Russell (H-R) diagram. Statistical distances are known to have serious problems. Inaccurate distances, together with missing fluxes in the UV and infrared and poor estimates of central-star temperatures, led to the erroneous Herman-Seaton Sequence which misled a whole generation of theoreticians trying to produce evolutionary tracks of PN. Modern high-angular-resolution imaging offers hope in the use of expansion parallax (Schönberner, these proceedings). *GAIA* promises to provide accurate parallaxes to a large number of PNs, which may finally solve our long-standing problem with distances (Stanghellini, these proceedings).

5. Central stars and their evolution

The central stars of PN interact with the nebulae both radiatively and dynamically. Central stars of PN have a wide range of temperatures, emit photons of different energies, and are undergoing rapidly changing mass loss. Their time-dependent radiative and mechanical outputs determine the ionization and dynamical structures of the nebulae. The physical properties (temperature, surface gravity) of central stars can be studied by high-spectral-resolution spectroscopy and interpreted by non-LTE stellar atmosphere models. An accurate determination of these properties are essential in their accurate

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placement on the H-R diagram. Some central stars show X-ray emission or evidence of accretion. Some are found to be close or wide binaries.

While most central stars of PN are H-rich, the existence of H-deficient central stars requires explanation. For example, early [WC] stars are considered as products of a late thermal pulse but late [WC] central stars are not so well understood. The detection of [WN] stars and their origins were discussed by Todt (these proceedings).

PN containing binary or multiple central stars are important in determining the role of binary evolution in the formation of PN. However, correct identification of the central stars of PN is critical. A number of central stars of PN are found to be main-sequence field stars and there stars clearly are not responsible for the ionization of the nebula (Jones, these proceedings).

The existence of PN depends on the coupled evolution between the central star and the nebula. The nebular dynamical age is defined by the time that the nebular surface brightness falls below the observational limit (Jacob *et al.* 2013), whereas the evolutionary age is defined by the speed of the central star evolution. If a central star evolves too slowly, then the nebula would have dispersed before it is ionized. The consistency between the theoretical evolutionary age and the observed kinematic age is therefore a serious issue (Pereyra, these proceedings). Using different starting points, the new evolutionary tracks of Miller Bertolami (these proceedings) evolve much faster than previous tracks, resulting in much shorter lifetimes of tracks of the same mass. These new tracks have considerable effects on the initial-mass−final-mass relationship and the PN luminosity function (PNLF). These new tracks are found to be more consistent with the observed PN in the bulge, which predominantly come from an 8-12 Gyr population (Zijlstra, these proceedings). These new tracks are also found to be able to explain the rapid evolution of the central star of the Stingray Nebula (Reindl, these proceedings).

A good initial-mass−final-mass relation provides important constraints to PN evolution. Recent results from Cummings (these proceedings) show that intermediate-stars lose 60-80% of their mass during the AGB (Figure 2). This suggests that the observed ionized mass of PN ($\sim 10^{-1}$ $M_\odot$) represents only a small fraction of the total mass of the circumstellar envelope.

6. Physical structure and morphology

Planetary nebulae are interesting astrophysical objects because they contain all states of matter, from ions, neutral atoms, molecules, and solid-state dust particles. High-dynamic-range imaging of PN has revealed that PN have very complex internal structures even in the optical. Various features such as shell, rim, crown, and halo can be found in the ionized-gas component of PN (Frank *et al.* 1990). These multi-layered structures are formed as the result of interactions between consecutive stages of mass loss from the central star and their subsequent ionization by the evolving central star.

The hot bubble is formed by the shocked fast wind and the temperature structure and abundance ratios of the bubble can be studied by observing the ratios of X-ray lines (Schönberner, these proceedings). The mixing layer between the hot bubble and the optical shell has intermediate (10^5 K) temperatures and can be studied with UV spectroscopy (Guerrero, these proceedings). X-ray imaging of the hot bubble can be used to test dynamical models (Montez, these proceedings).

The observed changing abundance of molecular species with evolution provides constraints to circumstellar chemical synthesis models (Zhang, these proceedings). Molecular hydrogen is an effective tracer of the shock region in PNs (Manchado, these proceedings).

From the observed spectral energy distributions of PN, we learn that a significant fraction of the total energy output of PN is from dust emission (van de Steene, these proceedings).

Since a great deal of mass is in the neutral component, infrared mapping of the dust component is important to determine the true mass distribution of PN. We should note that the bright optical nebulae are the low-density cavities carved out by high-speed outflows and optical brightness does not translate into matter distribution (Kwok 2010). The equatorial torus, which focus the bipolar outflow, can be mapped in the mid-infrared and compared to the optical image of the lobes (Lagadec, these proceedings). The outer dust envelope can be mapped in the far infrared with space-based telescopes such as *Herschel* (van de Steene, these proceedings).

7. Complex molecules

One of the most exciting development in recent years is the detection of complex molecules and organic solids in PN. Fullerene (C_{60}) molecules are now widely detected in PN (Cami, these proceedings; Díaz-Luis, these proceedings; Otsuka, these proceedings). It is possible that hydrogenated fullerenes are also present (Zhang, these proceedings). The crucial question of the chemical structure of the carrier of the unidentified infrared emission (UIE) bands was discussed by Sloan (these proceedings). PN are the only astronomical sources where we can observe the UIE bands emerge. The short ($\sim 10^3$ yr) time scale of formation of the UIE bands provides useful clues to the pathway of synthesizing complex molecules in space. The C_{60} and UIE phenomena are linked by the presence of the 8, 12, and 17 μm plateau features, leading to the discussion of whether C_{60} is formed by a top-down or bottom-up pathway.

8. Nucleosynthesis

The elemental abundance discrepancy (AD) between determinations from optical recombination lines (ORL) and collisionally excited lines (CEL) has been with us for decades. Recently obtained high-quality spectra have been able to determine the AD factors much more accurately (Delgado Inglada, these proceedings). If the discrepancy is due to ORL and CEL being emitted in different regions, a kinematic study may reveal differences (Pena, these proceedings). Some of the most extreme discrepancy cases are found in binary systems, in particular among post-red-giant-branch objects (Wesson, these proceedings; Garcia-Rojas, these proceedings).

An accurate photoionization model is needed to properly interpret emission-line spectra. Improvements in photoionization models include taking into account stellar atmosphere models as input and 3D nebular models (Morisset, these proceedings). Incorporation of dust continuum transfer into photoionization models was discussed by Otsuka (these proceedings).

On the theoretical side, AGB nucleosynthesis models are continuously being refined. Extended nuclear networks have been developed to include reactions involving intermediate neutron processes (Doherty, these proceedings). García-Hernández (these proceedings) reminds us that O is not always a good indicator of original ISM metallicity.

One of the most interesting new results is the detection of new neutron-capture elements through lines of Rb IV, Cd IV, Se III, and Kr VI (Sterling, these proceedings; Dinerstein, these proceedings). Through nucleosynthesis models, one can use rubidium as signature of the initial mass of the star (Lugaro, these proceedings).

Pre-solar grains such as SiC represent an important link between AGB stars and the solar system. The isotopic ratios of noble gases in pre-solar grains can be actually measured in the laboratory, giving a precise test of nucleosynthesis models (Lugaro, these proceedings).

9. Binary evolution

An increasing number of AGB and PN are found to have binary central stars and there is a great deal of interest to tie the binary nature to the nebular morphology. *ALMA* offers great enhancements to sensitivity and angular resolution in molecular mapping of circumstellar envelopes. Kim (these proceedings) has found evidence for spiral structures in the circumstellar envelope of the carbon star AFGL 3068. These spirals are probably created by stellar winds of the orbiting central star, with the orbital plane of the binary system lying on the plane of the sky.

A long-term study to put limits on binaries in proto-PN through radial velocity monitoring was reported by Hrivnak (these proceedings). Since proto-PN are loosely labeled as such from objects showing infrared excesses, some proto-PN candidates were found to be circum-binary disc systems and therefore are un-related to the PN phenomenon (van Winckel, these proceedings). Dusty disks around red giant stars can also cause confusion, causing these objects wrongly labeled as post-AGB objects (Kamath, these proceedings).

Recent observations have found that planets are common around stars, so the effects of planets in AGB and post-AGB evolution is an interesting topic to investigate. Do planets play any role in morphological shaping of PN (Villaver, these proceedings; Boyle, these proceedings)?

It has been known for over 40 years that close binary systems can develop common envelopes, resulting in common-envelope ejections (Paczyński 1976). The possible relevance of common envelope ejection with PN was investigated by many authors, with numerous possible variations and scenarios possible (Iben and Tutukov 1989, de Kool 1990). In order to assess the relevance of common envelope evolution with the PN phenomenon, it would be useful to compare the fraction of common envelope objects in the PN population to the theoretical expectation from population synthesis (De Marco, these proceedings). If PN are products of binary evolution, one needs to specify which one out of several hundred possible channels (Tutukov & Yungelson 2002) that PN emerge from. Since post-ejection evolution is heavily dependent on the remnant H-envelope mass, we need to know whether the post-common-envelope-ejection object will evolve. If it does not evolve on thousand-year timescales due to too large a remnant envelope mass, do we still call it a PN?

Recognition of PN as a post-AGB phenomenon only happened in 1970, 200 years after the first discovery of PN. So we know that fundamental paradigm shift can happen. However, to challenge the current paradigm, one has to present a self-consistent alternative model which can explain evolution, morphology, abundances, kinematics, and other physical properties of PN.

10. PN as probes and tracers

The bright and narrow emission lines of PNs allow for their use as tracers of chemical and dynamical evolution of galaxies. The observed elemental abundance gradients reflect different stellar yields, infall rate laws, and star formation history (Molla, these proceedings) as well as external influence such as accretion or merger (Bresolin, these proceedings). New large-telescope observations have given accurate elemental abundances of M31, including the outer regions. The oxygen abundance from the inner regions of M31 to beyond 100 kpc is almost constant with near solar values (Fang, these proceedings).

As dynamical tracers, PN extend the coverage of rotation curves and trace stellar content in the outer regions (Coccato, these proceedings; Söldner-Rembold, these proceedings). Modern wide-field narrow-band surveys make possible the observations of PN in haloes of galaxies in the Virgo cluster. The homogeneous sample allows the determination of production rates of PN (Hartke, these proceedings). The potential effects of triaxiality was discussed by Arnaboldi (these proceedings). A key question is whether the Keplerian decline of line-of-sight velocity dispersion observed in several elliptical galaxies can be mostly attributed to a relative lack of dark matter or to the effects of radial anisotropy.

The effects of the new evolutionary tracks of Miller Bertolami on the PNLF was reviewed by Mendez (these proceedings). The possibility that PNLF can be a function of galactic location was discussed by Balick (these proceedings).

11. What is the future of PN research?

Progress in PN research has benefited greatly from technological advances such as CCD, infrared, millimeter-wave, and X-ray observational techniques. Many of the new observing facilities (*ALMA, GAIA, JWST, SOFIA*) can further extend the observational frontiers and we should try to take advantage of these facilities. It has been amply demonstrated in the past that knolwedge gained in PN research can be applied to other fields and it is important that we continue to stay relevant in the view of other disciplines.

As for the field itself, we still have many unsolved problems, in part because PN are complex objects and in part because we have so much high quality data across all wavebands to test theoretical models. We know that the ionized component does not contain most of the mass in PN, but the exact ratio of ionized to molecular mass of PN is not known. Future high-angular-resolution mappings of the ionized, molecular, and dust components can resolve this issue. Although we have detailed images of PN showing the various morphological components, the physical mechanisms for various wind components leading to the shaping of PN are yet to be identified.

In order to have a model for chemical synthesis, we need a detailed time sequence of the synthesis, including the exact relationship between the C_{60} and UIE emitters. An accurate determination of the chemical structure of organic compounds synthesized during the PN stage will be an important step in solving the mysteries of unidentified spectral phenomena such as diffuse interstellar bands, 220 nm feature, 21 and 30 μm features, and the extended red emission.

Scientific fashions come and go, but PN research has remained resilient after over 200 years. This field of research is still important as a laboratory to study physical and chemical processes and has proven useful as a diagnostic tool for other areas of research. Tremendous progress on the understanding of the nature of PN was made in the last 40 years. Whether this pace of advance can be maintained will depend on the continued injection of new talents.

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