Part 1. Invited Reviews and Contributed Presentations

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Session 1: A census of the PostAGB stars and PN populations
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Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
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Some Historical Notes

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Abstract. The study of planetary nebulae started more than a century ago. Since then the understanding of these exciting objects has advanced extraordinarily. I present a personal selection of topics to reflect on some developments of PNe research.

Keywords. planetary nebulae: general

1. More than a century ago

Firstly I will present some historical events that took place more than a hundred years ago, for us to ponder on the changes that we have attained on this very exciting topic.

First identifications and images. We are all aware that the first PNe (M27, M57, M76 and M97) were catalogued in 1764 by Charles Messier. I also found of interest to comment on the first drawings of what we now know as PNe by William Parsons, 3rd Earl of Rosse (Rosse 1844). From what was at the time the world largest telescope, he observed and sketched by hand the appearance of M57, M97, NGC 2438, NGC 7662 and NGC 7009. It required more than 70 years for Curtis (1918) to present photographic plates of a large number of PNe obtained with the 0.9 m Crossley Telescope at Lick Observatory at a scale of $30''$/mm.

Optical Spectroscopy and radial velocities. One of the first spectra of planetary nebulae reported is from the photographic plate of NGC 6543 by Huggins & Miller (1864) who recorded 3 nebular emission lines (Hβ, 4959 and 5007 Å) with no continuum; the last two lines are from [O III], of which their origin was not known at the time. Following this work, the first radial velocities of Orion and a dozen PNe, previous to the identification of the [O III] 5007 feature, were obtained by Keeler (1894) at Lick Observatory with the 36-in equatorial telescope. He determined very accurately at 5007.07 Åthe rest wavelength of the strong emission line; from this measurement he could derive the velocities of a dozen objects, with uncertanties of a few miles/sec and concluded that "...The observations show that the nebulae are moving in space with velocities comparable with those of the stars...". At the time it was of great importance to determine whether the nebulous objects had the same kinematical properties as the stars to decide whether they were Galactic or extragalactic.

2. PNe Symposia

As we all know this meeting is part of a series of 11 symposia that have taken place, at intervals of approximately five years where we have witnessed the development of the field. Ten of these symposia have been held as IAU activities (the exception was the symposium held in Liege in 1972). These meetings have not been the only scientific events dedicated to PNe; since 1984 a series of conferences on Asymmetrical Planetary Nebulae was started, which have attracted an important number of participants in the field. In addition, there have been several other conferences dedicated to specific aspects of PNe. The proceedings of these meetings allow us to glimpse at a snapshot of our knowledge on this topic at a given time.

From IAU Symposium 34. In particular, I would like to mention some highlights of the meeting held in Czechoslovakia in 1967. The program included the different topics that we continue to address: space distributions, observational data (some of the first photoelectric data, and infrared emission from bolometers that were able to record up to 15 μm), model predictions for UV emission lines, free-free radio data, updates on physical processes, determinations of chemical compositions, data on central stars and studies on the origin and evolution of these objects. It was clear that the recently published Catalogue of Planetary Nebulae by Perek & Kohoutek (1967) gave a new perspective to PNe research: there were 1067 galactic objects uniformly catalogued, with as many characteristics as were available, as well as overall properties like Galactic distribution, kinematics, etc. For his part, Terzian (1968) presented observations at radio wavelengths of about 80 PNe which were then compared to the Hβ flux. These results confirmed the recombination theory of emission and thus established PNe as thermal sources. Osterbrock (1968) considered that "...we have the theoretical tools we need to investigate planetary nebulae...collision strengths, transition probabilities, recombination coefficients and photo-ionization cross-sections..."; according to Feast (1968) the "...major problem in discussion on the distribution and kinematics of the planetaries is the problem of distance determination...". Gurzadian (1968) listed several questions of particular interest: (a) internal motions, (b) two-envelope nebulae, (c) magnetic fields, (d) gas dynamics, and (d) condensations of NGC 7293. Savedoff (1968) reflected that the ancestor for the planetary nebulae are the Red giants; but at that meeting there was also the concern about the large amount of energy required to lift the envelope material from a degenerate core. In the field of extragalactic nebulae, Westerlund (1968) indicated that there were 30 true planetary nebulae identified in the SMC and about 45 in the LMC to the limiting magnitude $M_{pg} = -3.0$.

3. From Early Discoveries to the Present

Now returning to more modern studies, I would now like to call attention to the great leaps achieved on several topics.

Radio observations of PNe. Heckathorn (1971) in a very interesting review noted that in the first radio survey of PNe by Lynds (1961) at NRAO with the 85 ft dish, only 5 PNe were detected. Later, Menon & Terzian (1965) measured the flux density of 10 PNe with the 300 ft transit dish at NRAO; these observations were used to check the recombination theory of emission by comparison with Hβ fluxes. In Heckathorn catalogue there were about 150 PNe with radio observations at 2 wavelengths (750 & 1410 MHz) and the main concern was the difference between recombination theory and the validity of the models. We can compare these early efforts with the recent work by Chhetri *et al.* (2015) who provided radio properties at high frequencies up to 20 GHz, for 65 PNe which comprise a complete radio flux limited sample of planetary nebulae in the Galactic plane at $|b| < 1.5°$ in the southern hemisphere.

Ultraviolet observations. The pioneer rocket observation of NGC 7027 by Bohlin *et al.* (1975) was the precursor of the PNe ultraviolet observations. They were followed by Copernicus data and very shortly by the IUE mission which provided extensive studies of a large sample of PNe yielding the very important C abundance in the nebulae and mass loss determinations from central stars. Furthermore the IUE database set up a precedent regarding uniformly secured spectra that could be retrieved and analyzed. This facility was used widely by a large number of investigators. HST allowed new opportunities for observations to observe UV spectra. The FUSE mission again opened up the access for extensive studies of PNe (see Guerrero *et al.* 2010) who analized P-Cygni profiles of 60 central stars.

X-ray observations. Among the first data on PNe were the results by Tarafdar & Apparao (1988) who searched the archival observations of the Einstein Observatory for 19 central stars of PNe for X-ray emission. They found detections in X-rays in four of them (NGC 246, NGC 1360, NGC 6853 and NGC 7293); NGC 246 had also been observed by the high-resolution imaging instrument, from which they concluded that this object is a point source.

More sensitive observations from the Chandra X-ray Observatory and the XMMNewton missions revealed the presence of difuse X-ray emission within PNe, lending strong support to the interacting stellar winds model of PN formation (e.g., Kastner *et al.* 2000). Chandra has been particularly successful in the detection of point-sources at CSPNe (Ruiz *et al.* 2013).

The review by Guerrero (2015) emphasize that two types of X-ray sources are mostly found in planetary nebulae (PNe): point sources at their central stars and diffuse emission inside hot bubbles. The available data on these hot bubbles have been displayed in conjunction with the optical observations and the match for the inner regions is outstanding.

At present there are very complete surveys at different energies (see Kastner *et al.* 2012). Building over multiple programs for X-ray observation of individual sources, the PN community has joined efforts into the Chandra Planetary Nebulae Survey, ChanPlaNS, aiming at the X-ray study of a volume-limited sample of PNe within 1.5 kpc of the Sun. In this survey, they find an overall X-ray detection rate of 70% for a sample of 35 objects, and 50% of the PNe observed by Chandra present X-ray-luminous CSPNe, while soft, diffuse X-ray emission tracing shocks (in most cases hot bubbles, formed by energetic wind collisions) is detected in 30% of them; five objects display both diffuse and point-like emission components. Further results of this same project have been presented by Montez *et al.* 2015 who carried out X-ray spectral analysis of 20 point-like X-ray sources detected in the solar neighborhood. Most of these detections are associated with luminous central stars within relatively young, compact nebulae.

Proto-planetary nebulae. A new class of stellar objects, called proto-planetary nebulae, PPNe, were discovered on the data acquired by the IRAS satellite. They are objects in transition between the asymptotic giant branch, AGB, and planetary nebula phases in the evolution of intermediate- and low- mass stars. As such, they are characterized by a central star of spectral type B - G surrounded by an expanding envelope of gas and dust. Selecting PPNe candidates is difficult using only visible light observations, but the excess mid-infrared emission produced by their cool dust affords a good means to identify PPN candidates. PPNe have been studied widely in the IR and now there are extensive identifications and a significant number of them have been imaged in the IR.

Thus, following the IRAS mission, it became possible to identify a number of candidates and to confirm them with ground-based observations, followed up with Hubble Space Telescope imaging and ISO and Spitzer mid- infrared spectroscopy. It was seen that most PPNe could be characterized as oxygen-rich ($C/O < 1$) or carbon-rich ($C/O > 1$) based on mid-infrared spectral features. Hu *et al.* (1993) from a sample of PPNe candidates based on the IRAS colors, were able to secure photometry, spectroscopy and molecular line observations which led to the confirmation of their nature as PPNe.

At the same time theoretical calculations through the AGB phase with the inclusion of mass loss, and also through the following evolutionary stages down to the white dwarf

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stage have become available (e. g. Vassiliadis & Wood 1994; Bloecker 1995) to compare with observations. These calculations predict for a typical remnant of 0.6 M$\odot$, evolutionary lifetimes of several 1000 yr in the transition region between the tip of the AGB and the planetary-nebulae region. Thus it became possible to compare theory and observations in the very early phase of the post-AGB evolution. However, recent post-AGB evolutionary sequences computed by Miller Bertolami (2016) for the same stellar mass are at least three to ten times faster than those previously published. These results will allow a better comparison between studies of post-AGB stars and planetary nebulae.

Extragalactic Planetary Nebulae. The number of catalogued extragalactic PNe has increased significantly from the early works on point source emission line objects in the Magellanic Clouds which comprised less than a hundred. From high sensitivity, high resolution narrow-band surveys very deep catalogues have been produced to study planetary nebulae in nearby galaxies. These studies have been coupled with access to complimentary, deep, multi-wavelength surveys across near-IR, mid-IR and radio regimes in particular from both ground-based and spaceborne telescopes. Planetary nebulae have been identified not only in Local Group Galaxies, but also at larger distances including the nearby Virgo and Fornax galaxy clusters and even there are planetary candidates in the distant Coma Cluster (Gerhard 2007). They are being used not only as standard candles to determine distance scales to galaxies (starting with the seminal work by Jacoby 1989), but also to determine kinematics and metallicity gradients in local universe galaxies (e. g. Magrini *et al.* 2016).

Abundance determinations. The study of abundance determinations has advanced considerably, not only from forbidden lines from but also from permitted lines. Altogether the abundance determination of 17 elements had been obtained by 1990. Later neutron capture elements in Galactic planetary nebulae, undertaken to study enrichments from s-process nucleosynthesis in their progenitor stars were identified for the first time in NGC 7027 by Pequignot & Baluteau (1994).

These results have been achieved due to the increasing observational capabilities, the far UV and far IR observations and to the possibility of line identifications and atomic parameter determinations. Even in the optical and near infrared observations it is possible to derive abundances of a significant number of elements. For example, in the near infrared Sterling, *et al.* (2016) discovered Rb, Ca & Ge in the near infrared spectra and García-Rojas *et al.* (2015) based on deep, high-resolution spectrophotometric data obtained with a high resolution echelle spectrograph, from 3100 - 10500 Å, identified and measured more than 750 emission lines of NGC 3918 and from them determined the abundances of 16 elements (He, C, N, O, Ne, Na, S, Cl, Ar, K, Ca, Fe, Se, Kr, Rb, Xe). Delgado-Inglada (2017) indicate that also P, F, and Br have been determined in several PNe.

The ionization structure model determinations that started in late 1960s (e. g. Flower 1968; Williams 1968) have acquired more complete representations and options through codes such as CLOUDY (Ferland *et al.* 2013) and with codes by other authors that allow a better understanding of the ionization structure within the nebulae.

Nevertheless there is a standing problem due to the difference in abundance determinations between the forbidden lines and the recombination lines. The recombination lines systematically yield higher ionic abundances than the forbidden line determinations. This difference has been called the Abundance Discrepancy Factor, ADF, and great efforts have been devoted to explain this discrepancy. An explanation of this problem has been proposed being due to temperature inhomogeneities in the nebula (Peimbert 1967). Recently Peimbert *et al.* (2014) found that in a group of 20 well observed PNe, at least 16 of them are chemically homogeneous and present large temperature fluctuations. On the other hand, Corradi *et al.* (2015) and Jones *et al.* (2016) have found several chemically inhomogeneous PN with binary central stars.

4. Conclusions

I have presented just a few samples of the great advances that have taken place on the study of planetary nebulae. Many of the topics of interest have not been included, and will be discussed in this meeting and in several meetings to come.

The increase in our understanding of the origin, development and status of PNe has been remarkable. This has been possible through the concerted efforts of more extended and deeper observations coupled to great efforts in theoretical and computational progress. There are still many pending issues that we have not yet been able to solve, and we are looking forward for many more future meetings on PNe.

References

Bloecker, T. 1995, *A&A*, 299, 755

Bohlin, R. C., Stecher, T. P., & Marionni, P. A. 1975, *ApJ*, 202, 415

Chhetri, R., Ekers, R. D., Kimball, A., *et al.* 2015, *MNRAS*, 451, 3228

Corradi, R. L. M., García-Rojas, J., Jones, D., & Rodríguez-Gil, P. 2015, *ApJ*, 803, 99

Curtis, H. D. 1918, *Pub. Lick Obs.*, 13, 9

Delgado-Inglada, G. 2017, in IAU Symp. 323: Planetary nebulae: Multi-wavelength probes of stellar and galactic evolution, eds. X.-W. Liu, L. Stanghellini & A. Karakas

Dinerstein, H. & Stirling, E. 1993, *ApJ*, 28, 490

Feast, M. W. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 445

Ferland, G. J., Porter, R. L., van Hoof, P. A. M., *et al.* 2013, *RMxAA* 49, 137

Flower, D. R. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 205

García-Rojas, J., Madonna, S., Luridiana, V., *et al.* 2015, *MNRAS*, 452, 2606

Gerhard, O., Arnaboldi, M., Freeman, K. C., Okamura, S., Kashikawa, N., & Yasuda, N. 2007, *A&A*, 468, 815

Guerrero, M. A., Ramos-Larios, G., & Massa, D. 2010, *PASA*, 27, 2, 210

Guerrero, M. A. 2015, in *Wolf-Rayet Stars* eds. W-R Hamann, A. Sander, & H. Todt (Potsdam: Univ-Verlag), 263

Gurzadian, G. A. 1968, in IAU Symp. 34: Planetary Nebulae: ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 448

Heckathorn, J. 1971, *Ap&SS*, 11, 309

Hu, J. Y., Jiang B. W., de Jong, T., & Slijkuis, S. 1993, in IAU Symp 155: Planetary nebulae: ed. R. Weinberger & A. Acker (Dordrecht, Kluwer), 333

Huggins, W. & Miller, W. A. 1864, *Proc. R. Soc. Lond.*, 13, 491

Jacoby G. H. 1989, *ApJ*, 339, 39

Jones, D., Wesson, R., García-Rojas, J., Corradi, R. L. M., & Boffin, H. M. J. 2016, *MNRAS*, 455, 3263

Kastner, J. H., Soker, N., Vrtilek, Saeqa D., & Dgani, R. 2000, *ApJ*, 545, L5

Kastner, J. H., Montez, R., Jr, Balick, B., *et al.* 2012, *AJ*, 144, 58

Keeler, J. E. 1894, *Pub. Lick Obs*, III, 161

Lynds, C. R. 1961, *Pub. NRAO*, 1. No. 5

Magrini, L., Coccato, L., Stanghellini, L., Casasola, V., & Galli, D. 2016, *A&A*, 588, A91

Menon T K. & Terzian Y. 1965, *ApJ*, 141, 745

Miller Bertolami, M. M. 2016, *A&A*, 588, 25

Montez, R., Jr., Kastner, J. H., Balick, B., *et al.* 2015, *ApJ*, 800, 8

Osterbrock, D. E. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 441

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Peimbert, M. 1967, *ApJ*, 150, 825
Peimbert, A., Peimbert, M., Delgado-Inglada, G.,García-Rojas, J., & Peña, M. 2014, *RMxAA*, 50, 329
Pequignot, D. & Baluteau, J.-P. 1994, *A&A*, 283, 593
Perek, L. & Kohoutek, L. 1967, Catalogue of Galactic Planetary Nebulae (Prague: Academia)
Rosse, Earl of 1844, *Phil. Trans. R. Soc. London*, 134, 321
Ruiz, N., Chu, Y.-H., Gruendl, R. A., *et al.* 2013, *ApJ*, 767, 35
Savedoff, M. P. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 463
Sterling, N. C., Dinerstein, H. L., Kaplan, K. F., & Bautista, M. A. 2016, *ApJ* (Letters), 819, L9
Tarafdar, S. P. & Apparao, K. M. V. 1988, *ApJ*, 327, 342
Terzian, Y. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 87
Vassiliadis, E. & Wood, P. R. 1994, *ApJS*, 92, 125
Westerlund, B. E. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 23
Williams, R. E. 1968, in IAU Symp. 34, Planetary Nebulae, ed. D. E. Osterbrock & C. R. O'Dell (New York, Springer-Verlag), 190

Discussion

ARNABOLDI: Important most developments is to establish the properties of PNe with respect to the late phase of stellar evolutions and relation with AGB and metallicity of the parent stellar population.