PLANETARY NEBULAE IN 2014: A REVIEW OF RESEARCH

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RESUMEN

En 2014 se celebró un doble aniversario en el campo de las nebulosas planetarias, 250 años desde su descubrimiento y 150 años desde su correcta identificación espectroscópica. En este artículo reseñamos la investigación sobre nebulosas planetarias publicada durante 2014. Se incluyen relevamientos, estrellas centrales, abundancias químicas, morfologías, campos magnéticos, poblaciones estelares y dinámica galáctica. Ha continuado la importante controversia sobre las abundancias derivadas a partir de líneas de recombinación y líneas prohibidas. Nueva es la controversia sobre la relación entre estrellas simbióticas y estrellas [WC]. La nebulosa planetaria del año es, sin duda, CRL 618, de la cual se publicaron estudios acerca de su núcleo simbiótico binario o [WC], su rápida evolución estelar, sus chorros en expansión y su campo magnético.

ABSTRACT

Planetary nebulae had a double anniversary in 2014, 250 years since their discovery and 150 years since the correct spectroscopic identification. This paper gives an overview of planetary nebula research published in 2014. Topics include surveys, central stars, abundances, morphologies, magnetic fields, stellar population and galactic dynamics. An important continuing controversy is the discrepancy between recombination-line and forbidden-line abundances. A new controversy is the relation between symbiotic stars and [WC] stars. PN of the year is undoubtedly CRL 618, with papers on its binary symbiotic/[WC] nucleus, rapid stellar evolution, expanding jets and magnetic fields.

Key Words: galaxies: stellar content — ISM: abundances — ISM: jets and outflows — planetary nebulae: general — stars: AGB and post-AGB — stars: white dwarfs

1. INTRODUCTION

2014 was an important year for the study of planetary nebulae. The first planetary nebula (PN) was discovered on 12 July, 1764 when Charles Messier stumbled across the Dumbbell Nebula, M27, making 2014 their 250th anniversary year. They were quickly recognized as the most puzzling objects in the sky. Antoine Darquier was the first to point out the similarity to the disk of a planet. William Herschel concurred. He found several, including the Saturn nebula, and wrote '*A curious nebula, or what else to call it I do not know*'. Herschel described them as seemingly a planet, but '*of the starry kind*'. The name 'planetary nebula' captured the confusion well and has been used ever since (Hoskin 2014). Coincidentally, 2014 is also an important 150th an-

niversary: the first ever spectrum of a planetary nebula (the Cat's Eye nebula) was obtained by William Huggins on August 29, 1864, and it finally revealed their true nature (Huggins & Miller 1864). Huggins wrote '*I looked into the spectroscope. No spectrum such as I expected! A single bright line only! At first I suspected some internal displacement of the prism. Then the true interpretation flashed upon me. The light of the nebula was monochromatic. The riddle of the nebulae was solved. The answer, which had come to us in the light itself, reads: not an aggregation of stars, but a luminous gas*' (reported in Moore 2007).

A double anniversary seems appropriate for objects of such dual nature.

Planetary nebulae still remain happily confusing objects, intruding into a wide range of research areas.

They trace stellar masses ranging from 1 to $\sim 6 M_\odot$. Over 90% of stellar death involves a PN phase, however short-lived. The very high luminosity, and the fact that up to 15% of the stellar luminosity can come out in a single emission line, makes PNe visible out to very large distances, and makes them ideal kinematic tracers of dark matter and of abundances of stellar populations, including areas where there is little or no young stellar population. The morphologies point to the physics of the ejection process, affected by rotation, binarity and magnetic fields.

This article will summarize PN papers published in the refereed literature in 2014, to identify the recent progress made in the field. Over 100 journal papers are covered in this review. The review should be read in conjunction with the White Paper produced by the IAU PN Working Group, which identifies future research directions (Kwitter et al. 2014).

2. SURVEYS AND DISCOVERIES

2.1. *The Galaxy*

IPHAS, a high resolution wide-area CCD Hα survey of the Northern Galactic plane, produced a catalog containing 159 new PNe (Sabin et al. 2014a), with confidence in the classification varying from 'certain' to 'possible'. Four further PNe were identified from IPHAS by Hsia & Zhang (2014), and one by Rodríguez-Flores et al. (2014) but the latter also re-classify one known PN as a D-type symbiotic, leaving zero net gain. The corresponding CCD survey of the southern galaxy, VPHAS, has commenced: the overview paper (Drew et al. 2014) shows the improvement over the photographic SHS survey which has been responsible for many of the PN discoveries in the south. The SHS was finally photometrically calibrated this year (Frew et al. 2014b), providing Hα fluxes for 88 PNe.

The Spitzer galactic plane survey MIPSGAL has found many compact, circumstellar bubbles emitting at 24μm. These bubbles (see Figure 1 for examples) have attracted much attention. They include a population of PNe, as shown by Nowak et al. (2014) based on Spitzer/LRS spectra, and by Ingallinera et al. (2014a,b) based on JVLA radio observations. The suggestion that the bubbles have peculiar central stars is an -as yet- unproven speculation which bears investigating.

A novel survey is mapping the Milky Way in the shock-sensitive line of [FeII] (Lee et al. 2014). Initial results detect 6 PNe out of 29 with this line. The second phase of the Chandra X-ray survey of nearby PNe was published (Freeman et al. 2014).

The detection rate of diffuse X-ray emission is 27% and of X-ray point sources is 36%. Diffuse emission is mainly seen in young, compact PNe with closed shells, and is rare in bipolar PNe.

One item of "It's a pity" research: the largest PN on the sky, Ou 4 with a size exceeding one degree, may no longer be a PN. It seems to originate from an HII region (Corradi et al. 2014a).

2.2. *And beyond*

Extra-galactically, the biggest advance, albeit negative, was from PHAT (Panchromatic Hubble Andromeda Treasury; the acronym is far from obvious). It re-classifies 32 nebulae in M31 as PNe, but on the other side shows that 152 previously classified PNe are not (Veyette et al. 2014). No new objects were found, implying that ground-based observations still are better at finding PNe, but HST is better at classifying them. There are now 591 PNe in the M31 PHAT survey area (not all detected in PHAT), a change of -17%. Up to 160 new PNe were found in the outer regions of M31 using SDSS data (Kniazev et al. 2014).

The Herschel Heritage project produced a catalog of far-infrared sources in the Magellanic Clouds which contains a small number of known PNe (Seale et al. 2014). The total number of PNe in the LMC is now 715 (Reid 2014).

3. CENTRAL STARS

3.1. *Binaries*

We lost one star, when the symbiotic star DT Ser was shown to be neither the central star of the much more distant PN MSC1 at this position, nor a symbiotic star (Frew et al. 2014a). This loss was compensated by discoveries of new binary companions elsewhere, so that 2014 was overall a year of stellar increase, befitting a double anniversary.

Two long period binaries with periods of 1100 days and > 1800 days were discovered by Van Winckel et al. (2014), for PN G052.7+50.7 and LoTr 5. The PN IPHASXJ211420.0+434136 (Ou 5) gained a binary companion with a period of 8.4 h (Corradi et al. 2014b), and Kn 61 may have a binary companion, with a period of 5.7 days (García-Díaz et al. 2014): its nebula is hydrogen deficient. NGC 2392 may have a 0.12 d companion, from radial velocity variations (Prinja & Urbaneja 2014); the star shows a strongly variable wind. A 0.61 d binary system was uncovered in He 2-11 (Jones et al. 2014): the post-common-envelope system is found to have ended the AGB early.
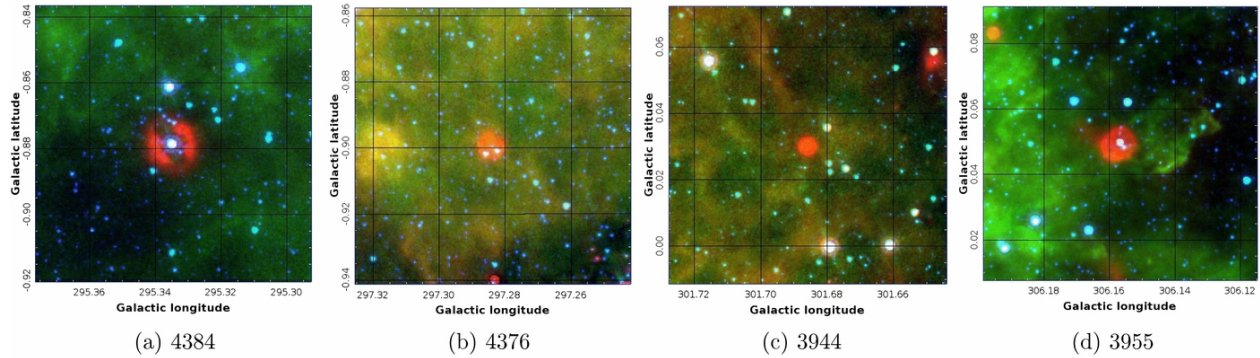
Fig. 1. Three-color images of representative Spitzer midgal bubbles. Red is MIPS 24μm, green is IRAC 8μm, and blue is IRAC 4.5μm. Each image is 5' by 5'. From Nowak et al. (2014), reproduced by permission. The color figure can be viewed online.

NGC 246 gained a star, when a tertiary companion to the binary system was found (only the second triple system found among PNe). The two main-sequence companions have masses of 0.85 and 0.1$M_\odot$ (Adam & Mugrauer 2014). The central star is evolving erratically, possibly due to the recovery from a symbiotic outburst 20 years ago. Hajduk et al. (2014a) searched for PN central stars binaries in the SMC and found 7 mimics (including one symbiotic) and one true close binary, Jacoby SMC 1. They derive a post-common-envelope fraction in the SMC of < 7%, below the 12–21% of the Galactic Bulge.

CRL 618 gained a star (Balick et al. 2014) when the central system was shown to be a symbiotic-like system with a [WC8] companion, and the central star of K 3-18, previously suspected to be a symbiotic, was found to be a [WC9] star (Miszalski & Mikołajewska 2014). The possible relation between symbiotic stars and [WC] stars deserves further investigation, for those wishing to complicate stellar evolution even further.

3.2. Emission-line stars

New stellar abundances were derived for five of the hottest [WC] stars (Keller et al. 2014), showing a wide range in the C/He ratio, high Ne abundances, and N abundances much higher than those found in previous determinations.

Six new emission line stars were discovered by Górny (2014), including two [WC] stars and one VL (or [WC11]) star, making a total of 8 new [WC] stars this year. They also discuss the issue of mimics among the emission-line stars, where a nebular line can pretend to be a stellar one. You have been warned. The PG1159 (pulsating) stars are found to

have the same frequency of dust disks as other PN central stars (Clayton et al. 2014).

The mysterious O(He) central stars (H-poor, O-rich) were investigated by Reindl et al. (2014b) who manage to both confirm and deny a merger origin. A future in politics beckons. Refreshingly honest (which may argue against their political future), they conclude that these stars exist and therefore do form, but it is not clear how. Frew et al. (2014c) argue against a relation to the [WN] stars, and propose 'exotic channels', leaving the evolution even more in darkness.

The small and equally mysterious group of [WN] stars increased its number to four (Frew et al. 2014c) or five (Stock & Barlow 2014) this year (including one LMC PN), with the double re-classification of the star of A 48 as [WN] (Stock & Barlow 2014; Frew et al. 2014c); the latter authors list 6 further possible [WN] star candidates. A 48 either shows N/O in the nebula four times above solar (Stock & Barlow 2014), three times above (Danehkar et al. 2014) or no significant N enrichment (Frew et al. 2014c), indicating either a higher-mass or lower-mass progenitor star. The difference seems to be related to the derived oxygen abundance. The nebula is highly carbon rich but the star has negligible carbon (Danehkar et al. 2014). There seems some room for further research here.

Longmore 4 is an emission-line star which has varied between PG1159-type and [WC]. The star has regular windy outbursts with high, hydrogen-poor and helium-rich, mass loss, occuring approximately every 100 days (Bond 2014). The paper finds 'no entirely satisfactory explanation' and urges people to monitor similar stars.

3.3. *Normal stars*

These lack exoticism and are not as popular. The sole relevant paper of 2014 is on 63 hot post-AGB stars in the LMC which were found by Kamath et al. (2014), as a byproduct of a survey, but they are not known to have PNe around them.

3.4. *Magnetic fields*

Magnetic fields in the central stars remain elusive. A sample of 12 stars gave three possible, weak detections (Steffen et al. 2014). The only strong detection came from the A-type companion star to NGC 1514. Another paper (Leone et al. 2014) provided 23 non-detections, giving 2-σ upper limits to the field strength of 500 G to 6 kG, whilst a different permutation of these authors (Asensio Ramos et al. 2014) analysed 13 of the same targets with the same data, but using a Bayesian approach to give 2-σ upper limits of < 400 G. A targeted, high intensity observing campaign may be needed to make progress in this area, but the evidence indicates that observers should be experienced fly-fishers as not many stars may bite. A solid detection would be a major advance, though.

3.5. *Evolutionary tracks*

The AGB and post-AGB is the most uncertain phase of the evolution of single stars. The standard Schönberner tracks need to be accelerated by a factor of 3, in order to fit central star masses (Gesicki et al. 2014). This can be achieved by reducing the remaining envelope mass at the end of the AGB: this is a free parameter in the mass-loss models.

Evolution of stars up to the PN phase is reviewed by Karakas & Lattanzio (2014), with a particular focus on nucleosynthesis. The agreement between stellar evolution models and PN abundances is generally good, but enhanced oxygen in the intershell may be needed.

4. MORPHOLOGIES

4.1. *Origin*

The origin of the morphologies of PNe remains as elusive as ever. The dominant shaping mechanism is magnetic fields, or binary motion, or stellar rotation (but see below), or a combination of these; this leaves the details to be worked out. There is progress with the growing evidence that the morphology is determined on the AGB rather than the post-AGB, with detections of disks in IRC +10°216 (Jeffers et al. 2014) and L$_2$ Pup (Kervella et al. 2014).

4.2. *Cores, jets and lobes*

HST imaging of 10 compact PNe (Hsia et al. 2014) shows that multipolar structures are common, indicating multiple phases of ejection and shaping. The paper does not state how the target sample was selected, so that rates of occurence cannot be inferred. A new member of the small class of PNe with extended shells and a compact, high density core was found (Miranda et al. 2014), joining objects such as KjPn 8, EGB 6 and M 2-29. The core of Hb 12 was studied by Clark et al. (2014) using infrared integral field spectroscopy, showing a system of bipolar lobes and equatorial arcs. A compact infrared source with precessing lobes (Blanco et al. 2014) was seen in K 3-35, one of the few PNe with water masers. Spectroastrometry with CRIRES (Blanco Cárdenas et al. 2014) has revealed structures as small as 12 mas inside SwSt 1 and IRAS 17516−2525, on par with VLTI resolution and much higher than that achievable with HST. The VLT has since removed CRIRES for two years to allow for an upgrade, slightly impeding this research. For now, high spatial resolution continues to be dominated by HST. Clyne et al. (2014) present images and spectra for MyCn 18: its asymmetries are attributed to a past explosive events, possibly an ILOT (Soker & Kashi 2012) caused by planetary accretion.

The role of magnetic fields received a boost with the finding of well-ordered fields along the polar outflow axis in CRL 618 and OH 231+04.1 (Sabin et al. 2014b), from dust polarization. Silicate dust shows higher polarization than carbon dust.

The expansion of the jets in CRL 618 was reanalyzed using HST images by Riera et al. (2014): they find a Hubble-type flow. The mirror symmetry in the lobes of CRL 618 may show indications of alternate ejection in the two polar directions (Velázquez et al. 2014), caused by one-sided heating of the accretion disk. The term 'floppy disk' comes to mind (younger readers may need to look this up). Discrete ejection events, albeit simultaneously in both polar directions, during a common envelope phase were posited by Corradi et al. (2014b).

For post-common-envelope PNe with jets, Tocknell et al. (2014) find that in 3 out of 4 cases the jets formed a few thousand years before the PN ejection occured, and in the 4th, more complex case, the jets formed a few thousand years after the PN ejection. The latter case would require very strong magnetic fields for the jet launching.

Dusty disks around some PNe have been argued to be debris disks (Su et al. 2007), or derived from binary-related post-AGB gaseous disks (Gesicki

et al. 2010). Clayton et al. (2014) compare the two options and favour post-AGB disk although debris disks cannot be ruled out.

4.3. *Models*

The highly complex structure of NGC 6302 can be explained with an isotropic wind blowing into a toroidal slow wind (Uscanga et al. 2014b). However, the observed Hubble wind requires an additional acceleration, consistent with the observational result of Szyszka et al. (2011).

Jet models also remain popular. Blackman & Lucchini (2014) investigate various accretion models for driving jets from known pre-planetary nebulae, and rule out most modes of accretion, including Bondi-Hoyle-Lyttleton wind accretion and wind Roche-lobe overflow, based on observed jet power. Roche-lobe overflow is possible, and accretion within a common envelope could also explain observed jet momenta. The result depends on the accretion time scale, which was reasonably chosen as the age of the jet. Tocknell et al. (2014) add magnetic fields to improve accretion. They do not address the jet power problem, but their jets are older (pre-dating the PN) and this may perhaps alleviate the power short-fall.

Stellar rotation seems unable to explain the shaping of bipolar PNe (García-Segura et al. 2014).

4.4. *Large scale structure*

At a time where much of the effort goes into studying small-scale structures and jets, it is good to see that the overall large-scale structure also is a rewarding research area. Schönberner et al. (2014) study the expansion velocity structure of PNe, based on 1-d radiation hydrodynamics. The paper gives a much-needed description of the sometimes confusing terminology used: 'rim' for the inner-most shell compressed by the fast wind from the star, 'shell' for the dense region outside of the rim driven by ionization pressure and surrounded by a shock, 'double shell' if both are bright, and 'halo' for the faint outer regions. The models provide very good descriptions of the line profiles. The 'rims' expand at typically 10–$20\,\mathrm{km\,s^{-1}}$, whilst the shells accelerate to up to $50\,\mathrm{km\,s^{-1}}$. The acceleration makes it difficult to derive a kinematical age, or even a single expansion velocity (the mass-averaged velocity can be useful at the 20% level). The paper also correctly stresses that the $v(r) \propto r$ Hubble wind, found in bipolar flows and jets (Uscanga et al. 2014b; Szyszka et al. 2011), cannot be used to describe the main body of the PN.

Haloes around PNe are shielded from the UV field of the star by the dense shell, and in 1-d models are often found to be recombining. But a detailed study of the halo of NGC 2348 finds that its halo, presumed to be recombining, is in fact ionized and in equilibrium, with $n_e = 10$–$30\,\mathrm{cm^{-3}}$ (Öttl et al. 2014). The ionizing radiation field may be leaking through the clumpy shell.

The interaction of the PN/AGB shell with the ISM is a continuing avenue of research. Van Marle et al. (2014) show that the interface can be shaped by the interstellar magnetic field into an elongated feature, and when seen along the direction of the field can show an 'eye' shape. This paper is a candidate for the title-of-the-year. Alignment of PNe, which remains a controversial issue, has also been attributed to interstellar magnetic fields acting on the ejecta (Falceta-Gonçalves & Monteiro 2014), as opposed to acting on the other end of stellar evolution (Rees & Zijlstra 2013).

5. ABUNDANCES

PNe allow for easy but powerful abundance measurements. A good review of PNe abundance studies and their controversies can be found in Kwitter & Henry (2012). It is an important area of study, with impact on galaxy evolution, stellar dredge-up processes, and indirectly, solid-state astrophysics.

5.1. *Theory and models*

The controversy regarding the mismatch between abundances derived from forbidden lines and those from recombination lines rumbles on, with proposed resolutions ranging from H-poor clumps to non-Maxwellian electron velocity distributions (the κ mechanism of Nicholls et al. 2012). For oxygen, the recombination lines are preferred by Peimbert et al. (2014). Storey & Sochi (2014) strongly favour a two-temperature distribution in Maxwellian equilibrium over a κ non-thermal distribution, but caution that their results may not apply to typical PNe, whilst Zhang et al. (2014) cannot decide between these two options. The war continues.

The excitation of the important forbidden 4363Å line, used for temperature measurements, was recalculated by Storey et al. (2014). They find agreement with most older work but disagreement with the recent result of Palay et al. (2012). New diagnostic diagrams and updated formulae for electron temperature and density determinations are presented by Proxauf et al. (2014): they use the now controversial calculations of Palay et al. (2012) for [O III] but

re-introduce [Ar III] $(7135\text{Å} + 7751\text{Å}) / 5192\text{Å}$ as an alternative temperature-sensitive ratio at red wavelengths.

Abundance determinations from emission lines require correction for unobserved ionization levels, through so-called ionization correction factors. A large grid of these ICFs were calculated by Delgado-Inglada et al. (2014) using Rauch stellar models: the new grid gives considerably different abundances for some elements, but also provides a quantified indication of abundance uncertainties. This could well become the highest cited paper of the year.

Oxygen is often assumed to trace the original abundances of the ISM from which the star formed. However, third dredge-up does affect oxygen abundances and can significantly increase its abundance at low metallicity. Dredge-up is reviewed in Karakas & Lattanzio (2014).

5.2. *Practice*

An extreme nitrogen enhancement was found in NGC 6302 by Rauber et al. (2014). Herschel data for NGC 6781 finds the nebula to be mildly carbon rich, with $C/O = 1.1$ (Ueta et al. 2014). Abundances were published for 53 Galactic PNe: these confirm the flattening of the [O/H] abundance gradient in the inner Galaxy (Górny 2014).

Iron is an important but difficult element. It is used for the metallicity scale, but is strongly depleted even in ionized media due to dust condensation. In PNe it is depleted by factors ranging from 2 to 500, with the highest depletions found in carbon-rich nebulae (Delgado-Inglada & Rodríguez 2014). Zinc provides an alternative (Smith et al. 2014): it forms together with iron but is much less refractory and does not suffer depletion. These authors find some evidence for subsolar zinc abundances in Bulge PNe, with some above-solar [O/Zn] values consistent with α element enhancement.

6. MOLECULES AND DUST

6.1. *Masers and molecules*

The 5th case of an H_2O maser in a PN was discovered (Uscanga et al. 2014a). Water emission can be intermittent and one post-AGB water-fountain star where the water maser disappeared, presumably due to evolution towards the PN phase, caught astronomers out by resurrecting its water maser (Vlemmings et al. 2014). Who said that evolution can't run backwards? The relation between water masers in PNe and the 22 known water fountain

sources remains to be clarified. Methanol is still undetected in PNe (Gómez et al. 2014), but the survey for it was limited to oxygen-rich objects.

An impressive list of molecules was detected in M 2-48, including SiO, CO, CN and SO, as well as their isotopologues. The $^{12}C/^{13}C$ ratio of 3 is taken as evidence for hot bottom burning (Edwards & Ziurys 2014) (however exchange reactions and selective dissociation can alter the isotopologue ratios in partly ionized regions). Molecular abundances in PNe show surprisingly little relation to the evolutionary age of the nebula (Edwards et al. 2014), at least in the five high mass bipolar nebulae which were observed. Molecules seem to be resistant to dying.

One new molecule in PNe is OH^+, so good Herschel discovered it twice (Aleman et al. 2014; Etxaluze et al. 2014).

The field of molecules in PNe suffered a great loss with the passing of Patrick Huggins. Unassuming but brilliant, always encouraging, always ahead of his time with work on CO in evolved PNe, rings around AGB stars, depletion of refractory elements, and finally jet lag in PNe: you never knew what would come next. We will miss him.

6.2. *PAHs, fullerenes, and dust*

Some PNe, especially but not exclusively in the Galactic Bulge, show both oxygen-rich dust and PAHs, indicative of mixed oxygen-rich/carbon-rich chemistry. Images show that the PAHs in these nebulae form at the outside of dense tori (Guzman-Ramirez et al. 2014). The sample of Galactic PNe containing fullerenes increased from 5 to 11 (Otsuka et al. 2014) while the number in the LMC remained 12 in 2014, thanks to a balance between the removals and additions to the sample (Sloan et al. 2014).

The PAH bands change during the PN phase (Matsuura et al. 2014), with an evolving mixture of aliphatic and aromatic features (Sloan et al. 2014), suggesting significant processing of the molecules. Dehydrogenation of PAHs by UV radiation could allow for the formation of molecular hydrogen in PNe without requiring dust (Champeaux et al. 2014). Fullerenes are seen only in PNe with cool central stars and apparently do not survive hard radiation fields well (Sloan et al. 2014).

Crystalline fosterite at $69\,\mu$m was detected in five PNe using Herschel spectroscopy (Blommaert et al. 2014). All have dense tori, cool dust, and almost Mg-pure fosterite, i.e., very little iron has entered the grains. Gas-to-dust ratios were measured in NGC 6781, with values varying from 3000 in the centre to ≈ 200 in the outer regions (Ueta et al. 2014). Sofia

images show that the dust in M 2-9 is not confined to its disk but also spread through the lobes (Werner et al. 2014).

7. DISTANCES

Distances to Galactic PNe remain an issue. Uncertainties in distance relations can be slightly reduced by using probability density functions rather than fitting linear relations (Vukotić et al. 2014), but the scatter remains dominated by the diversity in PN properties. The proposed surface brightness–radius relation (Frew 2008) may be able to reduce the scatter. In the sample of PNe with well-constrained individual distances, Majaess et al. (2014) published a new distance to the open cluster Andrews-Lindsay 1, which contains a PN. The PN He 2-86 may be a member of the cluster NGC 4463 but this requires that the extinction to the PN is partly internal (Moni Bidin et al. 2014). Accurate distances for individual PNe are awaiting GAIA.

8. EVOLUTION

PNe expand at typically 20–40 km s^{-1}: over decades this gives a detectable motion. HST has been used to detect this expansion in the hydrogen poor gas ejected by a Very Late Thermal Pulse (VLTP) in A30 and A78 (Fang et al. 2014). The expansion does not show the Hubble flow seen in bipolar PNe (however, note the discussion on PN velocity fields in Schönberner et al. 2014) but reveals a more complex pattern of local acceleration and deceleration. Sakurai's Object continues on its fast-track post-VLTP evolution. Hinkle & Joyce (2014) have resolved the ejecta into a fragmented outer region expanding at 10^3 km s^{-1} seen in shocked HeI, and a bipolar dust debris cloud expanding at $55 \,\mu\text{arcsec}\,\text{d}^{-1}$. As a by-product, this introduces a new unit into the field of PNe.

The slow increase of central star temperature in PNe should cause an increase in excitation and, in particular, in the strength of the [OIII] lines. A tendency for such an increase was found in NGC 6572 over 80 years of observations (Arkhipova et al. 2014b), and in Hen 2-260 over 28 years of data (Hajduk et al. 2014b). In the latter object, the stellar temperature is increasing by 45 K yr^{-1}. Three young PNe were found to show fading central stars, attributed to increasing temperatures since the epoch of the BD and CD catalogues, a century ago (Arkhipova et al. 2014a).

CRL 618 shows evidence for an increasing central star temperature (Balick et al. 2014), from its increasing radio flux and evolving line ratios (see Figure 2). But the increase over 40 yr is deemed to be unreasonably fast, and UV changes due to symbiotic accretion are also considered a possibility. This could move the object to Section 10.

The hot bubble inside PNe should leak between the clumps of the PN shell and depressurise. The process that stops this from happening seems to be mixing of shell (or rim) material into the hot bubble (Toalá & Arthur 2014).

9. STELLAR POPULATIONS AND EXTRA GALACTIC PN

9.1. *The Galactic Bulge*

PN abundances in the Galactic Bulge indicate progenitor stars of 3-5 $M_\odot$ (García-Hernández & Górny 2014). Such a young population would be surprising in the Bulge, although Gesicki et al. (2014) also find evidence that the PNe in the Bulge derive from a younger stellar population.

9.2. *Nearby galaxies*

PN oxygen abundances show a mass-metallicity relation of Local Group galaxies (Gonçalves et al. 2014) in agreement with other abundances, except for the lowest metallicity galaxy, Leo A, where the PN has more oxygen than expected. The authors do not discuss whether oxygen dredge-up (Karakas & Lattanzio 2014) may have an effect on their relation at low metallicity.

PNe in M81 and other spiral galaxies show a shallower oxygen abundance gradient than do the HII regions (Stanghellini et al. 2014). This indicates the effect of pre-enriched infall into the galaxies, but stellar migration may also play a role. The PNe in NGC 6822 trace the dynamics of the intermediate-age stellar population, and not that of the HI disk and its young stellar population (Flores-Durán et al. 2014).

In M31, PNe in the outer regions trace known morphological features, including the Northern Spur, the NGC 205 Loop, the G1 Clump, and And NE, and indicate that the Giant Stream, the Northern Spur, and possibly And NE are kinematically connected (Kniazev et al. 2014). The mass of the Giant Stream progenitor is estimated at 10^9 $M_\odot$ from its PNe.

Foster et al. (2014) have found 32 PNe in the Umbrella galaxy, NGC 4651, of which 10 are in the nearby stream tracing a disrupted dwarf galaxy. They show that the dwarf was on a short-period orbit and had recently passed through the disk of NGC 4651. PNe thus trace not only the death of stars, but the death of galaxies as well.
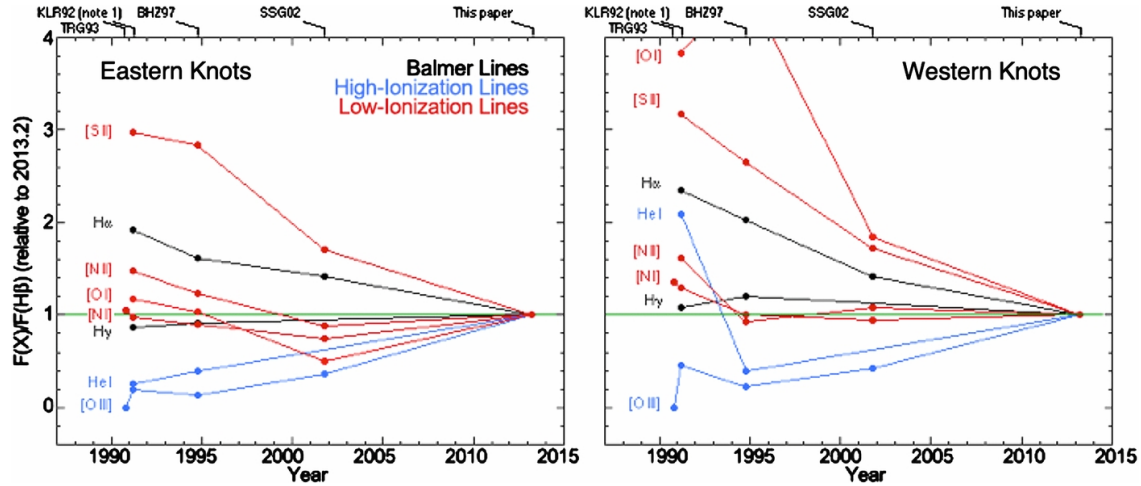
Fig. 2. Changes in line flux ratios of CRL 618 relative to the data obtained during 2013.2. Some of the scatter is measurement related. From Balick et al. (2014), reproduced by permission. The color figure can be viewed online.

10. RELATED OBJECTS

R Cor Bor stars do not produce PNe. However, they do have winds similar to those briefly shown by VLTP objects such as Sakurai's Object. Chesneau et al. (2014) show that the R Cor Bor star V854 Cen is producing a mildly flattened shell which they term 'bipolar'. (A PN with that elongation would have been 'elliptical'.) The paper was written in hospital and appeared four months after the untimely death of the first author, Olivier Chesneau. He is sorely missed. We can be proud of his achievements, and take consolation in the fact that the field of PNe attracts people as brilliant and as universally liked as Olivier.

Overly rapid and erratic evolution can be a sign of a PN mimic. The central star of the beautiful Stingray nebula was found to have increased in temperature from 38 kK to 60 kK over 14 years, with a declining luminosity (and radius), followed by a temperature decrease to 50 kK over the next 4 years. The star is classified as sdO, but it could be a post-RGB star or/and a product of common envelope evolution (Reindl et al. 2014a).

For the growing relation between symbiotic stars and PNe with [WC] central stars refer to Section 3.1.

11. MISCELLANEOUS

Planetary nebulae can make useful calibration sources, as they are compact and bright over a very wide range of wavelengths. As an example, NGC 7027 is an important calibrator at radio wavelengths (Perley & Butler 2013). The W4 filter of the Wise mission was re-calibrated using PNe (Brown et al. 2014). This made use of the strong [OIV] emission line at $25.9\,\mu$m which dominates the wavelength range of the W4 filter.

Numerical simulations often require setting an initial distribution of parameters over a grid. Hunger et al. (2014) present a method to create a 'random field' using GPUs, and apply it to defining the initial conditions for an inhomogenous, turbulent wind of a PN. Sadly this is where they stop.

Physics in the strong gravity of degenerate stars was shown to be well-behaved by Bagdonaite et al. (2014): specifically, there is no evidence that the proton-electron mass ratio depends on gravity. PNe may be as confusing in their own right as they were 250 years ago, but the laws of physics at least apply. But it remains a physics of complexity, bordering on physics of perplexity.

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