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THE PRESENT AND FUTURE OF PLANETARY NEBULA RESEARCH. A WHITE PAPER BY THE IAU PLANETARY NEBULA WORKING GROUP

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RESUMEN

Se presenta un resumen del estado actual de la investigación sobre las nebulosas planetarias y sus estrellas centrales, y temas relacionados como los procesos atómicos en nebulosas ionizadas, y la evolución de las estrellas de la rama gigante asintótica y post-gigante asintótica. Se discuten los avances futuros que serán necesarios para incrementar sustancialmente nuestro conocimiento en este campo.

ABSTRACT

We present a summary of current research on planetary nebulae and their central stars, and related subjects such as atomic processes in ionized nebulae, AGB and post-AGB evolution. Future advances are discussed that will be essential to substantial improvements in our knowledge in the field.

Key Words: ISM: abundances — planetary nebulae: general — stars: AGB and post-AGB — stars: evolution

1. INTRODUCTION

The field of planetary nebula (PN) research has continued to mature, incorporating a variety of new and ingenious approaches that leverage the value of PN observations to maximize astrophysical insight. PNe are the gaseous relics of the evolution of low- and intermediate-mass stars, and as such are ubiquitous in the Galaxy and beyond. They are probes of stellar evolution, populations, gas dynamics, dust and molecules. They are also extragalactic probes of metallicity and dynamics in spiral and elliptical galaxies and in the intracluster medium. Spectra of PNe are characteristic and easy to identify; their emission lines are very strong and can be used to derive C, N, O abundances that in turn characterize the stellar progenitor by comparison of the spectra with the yields from stellar evolution theory. PNe can evolve in binary systems and their morphology and chemical history reflect this type of evolution. They can survive in the intracluster medium, and are rare probes of this interesting environment. Extragalactic PNe have been studied to disclose a characteristic luminosity function whose high-luminosity cutoff appears invariant (or almost invariant) across PN populations, providing a good standard candle. After decades of searching in a variety of celestial objects, researchers have observed fullerenes in PNe, the first environment of stellar origin where these molecules have been observed.

As this brief list reveals, the modern study of PNe is extremely fruitful, with many connections to adjacent fields of research, including stellar structure and evolution, binary stars, stellar populations, radial metallicity gradients in spiral galaxies and their evolution, as well as galaxy rotation, evolution, merging, and cosmology. This White Paper by the IAU PN Working Group, represents a summary of our science activities, and is an attempt to set the stage for future developments in the field. Its aims are to raise interest and to spark discussion within the international PN community, as well as across other interested communities, and finally, to serve as preparation for the next PN Symposium several years hence.

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2. PERSPECTIVE ON PLANETARY NEBULA DETECTION AT NON-OPTICAL WAVELENGTHS

2.1. *The dawn of true multi-wavelength imaging of PNe: Discovery, refinement and characterisation*

Over the last decade Galactic PN discoveries have entered a golden age due to the emergence of high sensitivity, high resolution narrow-band surveys of the Galactic plane (e.g., Parker et al. 2005; Drew et al. 2005). These have been coupled with access to complementary, deep, multi-wavelength surveys across near-IR, mid-IR and radio regimes, in particular from both ground-based and space-based telescopes and have provided additional new powerful diagnostic and discovery capabilities.

The total number of Galactic PNe known is currently ≈3500, more than double what it was a decade ago. This is largely thanks to the ≈1200 significant PN discoveries uncovered by the two MASH[13] surveys (Parker et al. 2006; Miszalski et al. 2008) based on scrutiny of the SuperCOSMOS AAO/UKST Hα survey of the Southern Galactic plane (SHS).

Note that significant numbers of true PNe are at the very faint, highly evolved end as shown to exist in the local volume sample of Frew (2008), but they rapidly become undetectable at distances greater than a few kpc. There are also serious problems with obtaining truly representative samples of PNe across the galaxy due to variable extinction.

It is also clear that a significant population of Galactic PNe must be lurking behind the extensive clouds of gas and dust that obscure large regions of our view across the optical regime. Indeed, it is the extension of previous PN discovery techniques away from the optically dominant [O III] PN emission line in un-reddened spectra to the longer wavelength Hα emission line (that can peer at least partially through the dust), that has led to the major discoveries of the previous decade.

Consequently, as part of the mission to improve the inventory of Galactic PNe, extension of PN identification techniques to longer, more favourable wavelengths would be advantageous. This is now possible with the advent of powerful, new, multi-wavelength sky-surveys of high sensitivity and resolution. Such surveys now allow us to both find and accurately characterise the properties of PNe across a broader range evolutionary state and across a wider range of the electromagnetic spectrum than ever before, opening up new windows into their physical characteristics and dust properties in particular. Such broader perspectives have also given us the capability not only to uncover more PNe but also to refine identification of the many mimics that still lurk in existing PN catalogues. The improved identification techniques now available are briefly described below.

2.1.1. *Eliminating non-PN contaminants*

Recently Frew & Parker (2010) tested and developed criteria to more effectively eliminate contaminants using the online availability of new multi-wavelength surveys combined with emission line ratios from follow-up spectroscopy.

Applying these criteria to mid-IR samples of previously known optically detected Galactic PNe seen in GLIMPSE[14] and that overlap with the SHS ($|b| \leq 1°$ and from 210° (through 360°) to 40° in Galactic longitude) showed that 45% of previously known pre-MASH PNe in this zone are in fact H II region contaminants (Cohen et al. 2011). Independently applying these criteria to the MASH PNe revealed a contaminant fraction of 5% in the same zone, largely because similar discrimination techniques had already been applied to MASH. Furthermore, the external filaments, extended structures and/or amorphous halos that are seen in the mid-IR associated with apparently discrete emission sources in the optical generally indicate that the object is an H II region. This is an important mid-IR discriminatory diagnostic for resolved mid-IR sources.

It has also been recently demonstrated that PN mid-IR/radio flux ratios and the *Spitzer* IRAC[15] colour indices are robust attributes, invariant among PN types including those in nearby external galaxies of different metallicity such as the Large Magellanic Cloud (LMC) (Cohen et al. 2011). The median PN mid-IR/radio ratio is 4.7±1.1 and does not vary significantly with PN evolutionary phase, allowing clear separation from their major H II region contaminants, regardless of whether they are diffuse or ultra-compact. These mid-infrared colours and radio fluxes are at wavelengths minimally affected by dust obscuration.

The recent advent of the near-infrared Vista Variables in the Via Lactea (VVV) and UKIRT[16] Infrared Deep Sky surveys of the Galactic plane have ≈4 mag of improved depth and far better resolution compared to 2MASS (Two Micron All Sky Survey) and these, too, offer improved prospects for PN studies over these wavelengths. The judicious combination of the J,H,Ks bands into pseudo-colour images can offer a powerful visual aid as to nature when taken together with the individual near-infrared band photometry. The importance and prospects of the new mid-IR sky surveys to PN studies are summarised in the following section.

2.1.2. *New mid-IR sky surveys and their application to PN science*

PNe can be quite strong mid-IR emitting objects because of PAH (polycyclic aromatic hydrocarbon)

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[13] Macquarie/AAO/Strasbourg Hα Planetary Galactic Catalog.

[14] Galactic Legacy Infrared Mid-Plane Survey Extraordinaire.

[15] InfraRed Array Camera.

[16] United Kingdom Infrared Telescope.

emission, fine structure lines, high excitation mid-IR lines like [O IV] 25.89 μm, H_2 molecular lines (e.g. from the UWISH2[17] survey) and thermal dust emission within the nebulae and in circumnuclear disks. Such emissions make them a decent prospect for uncovering them as mid-IR sources.

More recently, mid-IR space-telescope images from *Spitzer* and now WISE (Wide-field Infrared Survey Explorer) potentially allow detection of very reddened PNe which may be invisible optically. Indeed preliminary recent work noted 416 compact but resolved (< 1 arcmin) ring, shell and disk-shaped sources in the Galactic plane in 24 μm *Spitzer* MIPSGAL[18] images (Mizuno et al. 2010). Some of these may well turn out to be strongly reddened, high-excitation PNe with perhaps only a minority being circumstellar nebulae around massive stars.

Newly developed mid-IR PN selection techniques have now been established using the refined photometric colour selections of known PNe as the starting point. Such selection criteria now enable efficient searches for highly obscured, previously unknown PNe present within both the photometric source catalogues of currently available Galactic plane on-line mid-IR sky surveys and the associated image data. Nevertheless the techniques have already demonstrated excellent promise with realistic prospects of being able to recognise high quality PN candidates solely using mid-IR and radio characteristics (e.g. Parker et al. 2012). This would enable efficient trawling for optically hidden PNe when heavy extinction precludes the possibility of securing optical spectra and images, alleviating the traditional reliance on such data to indicate their likely PN nature. One area of recent exploitation is in the use of combined multi-band images of PN in the mid-IR as briefly outlined below.

2.1.3. *The power of mid-IR false colour imagery*

Cohen et al. (2007) have recently shown that true PNe occur with only three colours in combined IRAC band false colour images: red, orange and violet. Similarly 2MASS J,H,Ks false colours of true PNe are violet or pink/purple when they are detected. With the advent of the VVV near infrared Y,Z,J,H,Ks photometric survey one can also trawl for such mid-IR selected PN candidates afresh. VVV overlaps with the very similar J,H,Ks pass-bands of 2MASS but the depth and resolution are far superior with the VVV J,H,Ks bands extending $\approx$4 mag deeper than 2MASS. Miszalski et al. (2011) have already used the equivalent of the VVV data for the LMC to show that many PN can be recognised in these new high quality near-IR data. Furthermore, by constructing spectral energy distributions across a broad wavelength range from all the extant wide-field sky surveys it is possible to discriminate among different astrophysical sources including PNe. The release of WISE data now enables alternative mid-IR false-colour images to be constructed for previously mid-IR selected sources. The WISE 3.4 μm and 4.6 μm bands are directly equivalent to the first two IRAC bands at 3.6 μm and 4.5 μm. The final two IRAC bands at 5.8 and 12 μm do not have any direct WISE equivalent (with the closest being the WISE 12 μm band) though the WISE 22 μm band is similar to the MIPS[19] 24 μm band. WISE can be used as a substitute for IRAC outside of the GLIMPSE regions with excellent sensitivity but poorer resolution. This has major advantages if it can be shown that the sensitivity and resolution of the WISE mid-IR bands are sufficient to provide the same diagnostic capability in revealing PNe as for IRAC. PN candidates can then be trawled for across the entire sky using essentially the same selection criteria. Examination of known PNe detected in WISE reveals strong potential in this regard.

2.1.4. *The value of the Mid-IR/radio ratio*

Cohen & Green (2001) offered the ratio of the observed flux near 8 μm to that near 1 GHz as a useful object nature discriminant. It has the merit of well separating different types of H II regions from PNe if the source is detected in both the mid-IR and radio continuum. The median ratio is 25±5 for diffuse and compact regions, and 42±5 for ultra-and hyper-compact HII regions. For PNe the ratio is 4.7±1.1.

2.2. *Summary*

The potential of the available mid-IR survey data from GLIMPSE and WISE as a tool to uncover PN candidates that would be hard or impossible to locate optically is clear. The motivation is to develop mid-IR PN candidate selection techniques that can be used to uncover the significant numbers of Galactic PNe which are believed to be hidden behind extensive curtains of dust. Recent work has also shown that examination of false-colour images of mid-IR selected PN candidates is of high diagnostic value as it enables not just the actual mid-IR photometry to be used for confirmed candidates but, crucially, the environmental context of sources to also be evaluated. Ultimately the mid-IR colour-colour techniques recently developed can be applied to the all sky coverage offered by WISE. In this way mid-IR PNe selected candidates can be compiled not only across the entire area covered by the SHS, IPHAS[20], VPHAS+[21] and the VVV but also to higher latitudes where there is no narrow-band coverage.

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[17] UKIRT Widefield Infrared Survey for H_2.

[18] Multiband Imaging Photometer for Spitzer Galactic Plane Survey.

[19] Multiband Imaging Photometer for Spitzer.

[20] The Isaac Newton Telescope Wide Field Camera Photometric Hα Survey.

[21] The VLT Survey Telescope/OmegaCam Photometric Hα Survey of the Southern Galactic Plane and Bulge.

3. EVOLUTIONARY MODELS

Progenitor masses of PNe are between $\approx 0.8\,M_\odot$ and $8\,M_\odot$, that is, stars heavy enough to ignite helium but avoid core collapse supernova. The stellar evolutionary codes used to model PN progenitors need prescriptions for dealing with highly uncertain phenomena such as convection, mass loss, rotation, and magnetic fields. Other required input physics include stellar opacities, thermonuclear reaction rates, and equations of state which introduce additional, although smaller, uncertainties.

3.1. *Convection*

The inclusion of a convective model and a treatment for dealing with convective boundaries are essential for realistic stellar evolution modeling. Convection is still the biggest uncertainty in evolutionary calculations, a situation that has persisted for more than 30 years. Only recently it has become possible to model the convection that occurs in low-mass stars using hydrodynamical simulations. Most stellar evolution codes use the mixing-length theory of convection, which depends on a number of free and uncertain parameters, notably the mixing-length parameter, α. This parameter is usually set by requiring that a $1\,M_\odot$ model of solar composition match the solar radius. There are other observables that are now being used to constrain α, e.g., giant branch temperatures for stars in clusters (Lebzelter & Wood 2007; Kamath et al. 2012). Either way, once α is set it is left constant for all masses and evolutionary stages, which is likely to be incorrect.

The persistent issue with convection means that we do not have a good description for the third dredge-up (TDU, e.g., Frost & Lattanzio 1996). Understanding the TDU is important because it determines the chemical enrichment from AGB (asymptotic giant branch) stars of the interstellar medium. Furthermore, the TDU efficiency also helps set the final H-exhausted core mass at the tip of the AGB, which is important for the initial–final mass relation. Stellar evolution models of low-mass AGB stars with near-solar metallicities still do not obtain efficient TDU without the inclusion of convective overshoot (e.g., Cristallo et al. 2009; Karakas et al. 2010). While it is now standard practice to include convective overshoot, the main improvements have come using AGB stars in clusters as a constraint on mixing in stellar evolution models (Lebzelter et al. 2008; Lederer et al. 2009; Kamath et al. 2012).

3.2. *Other theoretical issues*

Observational data have revealed that standard stellar evolutionary models of low- and intermediate-mass stars (LIMS) are missing key physics that lead to surface abundance changes during the first and asymptotic giant branches (e.g., lower ^{12}C/^{13}C ratios in giant stars than predicted by theory). This extra mixing may be driven by rotation and magnetic fields (Nordhaus et al. 2008; Lagarde et al. 2012), although other phenomena such as thermohaline mixing (Eggleton et al. 2008; Charbonnel & Zahn 2007; Stancliffe et al. 2007), and gravity waves (Denissenkov & Tout 2003; Talon & Charbonnel 2008) have been suggested. All of these phenomena occur in stars at some level, so the question is what impact they have on the stellar interior as a function of time. Recent efforts are mostly the result of hydrodynamical simulations (Stancliffe et al. 2011; Herwig et al. 2011; Viallet et al. 2012), simply because these phenomena are inherently 3D in nature. Future work should concentrate on higher resolution simulations that are evolved for longer times. However, this requires large supercomputer resources. 3D stellar evolution codes such as *DJEHUTY* are fully explicit hydrodynamics codes, and hence not suited to evolutionary calculations except over the shortest timescales (Eggleton et al. 2008). Thus stellar evolutionary sequences will still be done in 1D, but improvements in the 1D codes' physics are possible using the 3D simulations as a guide; this is starting to happen (Arnett & Meakin 2011). Improvements to our understanding of the TDU are also likely to come from this area.

Mass loss is now routinely included although there is no agreement which prescription should be used during the AGB stage. While the prescriptions used in AGB model calculations today are not new (e.g., Vassiliadis & Wood 1993; Blöcker 1995a), *Spitzer* has delivered new insights into mass loss and dust production from LIMS, which are helping to improve our understanding of these uncertain processes. Mass loss determines the final core mass at the tip of the AGB, and the circumstellar material around AGB and post-AGB stars. The final ejection of the envelope is difficult to model by theoretical calculations, and convergence difficulties often set in before all the envelope is lost. There may be some real physics behind this, as explored by Lau et al. (2012).

One recent improvement to red giant evolutionary sequences has come from the inclusion of low-temperature molecular opacity tables that follow the surface composition of the star. Low-mass stars are known to become C-rich during the AGB phase and intermediate-mass AGB stars with hot bottom burning will become N-rich. These enrichments lead to highly non-solar C/O and N/C ratios. The inclusion of molecular opacities following the surface composition leads to increases in the stellar radius, cooling of the outer layers and stronger mass loss (Marigo 2002). New tables have been published in recent years (Lederer & Aringer 2009; Marigo & Aringer 2009); the *ÆSOPUS* tables of Marigo & Aringer (2009) are the most versatile as they are available for a wide range of initial compositions and can be downloaded from the web. Recent full AGB simulations including some treatment of molecular opacities includes Cristallo et al. (2009), Weiss & Ferguson (2009), Karakas et al. (2010), Ventura & Marigo (2009), Ventura & Marigo (2010), Stancliffe (2010), and Karakas et al. (2012). The impact of low-temperature opacity tables on the stellar evolution of LIMS is still being assessed, with many more studies on this topic expected. Using accurate molecular opacity tables shortens the AGB lifetime, with great impact on PN production.

3.3. *Nucleosynthesis and Abundances*

The same stellar evolution codes are also used to calculate post-AGB evolutionary sequences (Blöcker 1995b), although stellar models calculated self-consistently from the main sequence through to the white dwarf cooling tracks are preferred (e.g., Miller Bertolami & Althaus 2007). The nucleosynthesis patterns of born-again AGB, post-AGB stars, and PNe are very useful tools for constraining the evolution and mixing of the progenitors during the AGB phase and beyond. The composition of hot, rare PG 1159 stars has been particularly illuminating as these are descendants of post-AGB evolution, forming after a late or very late TP (Blöcker 2001; Miller Bertolami & Althaus 2006). The abundances of C and O in particular have been shown to be much higher than in standard AGB models (Werner et al. 2009). The intershell compositions of PG 1159 stars have been well explained in terms of intershell convection penetrating into the C-O core (Herwig 2001), but there is still debate as to the physics that drives this (Stancliffe et al. 2011). Future work through the use of higher-resolution hydrodynamical models or from better observational constraints may help settle this. Other stars such as the born-again Sakurai's Object and FG Sagittae show real-time stellar evolution and challenge our simplistic notion of stellar convection (Herwig et al. 2011). Future hydrodynamical modeling is essential to an improved understanding of post-AGB evolution.

The abundances of elements heavier than iron are an exquisite tracer of the thermodynamic conditions in the He-burning shells of AGB stars. Heavy elements are produced by the *s*-process in the He intershell and mixed to the surface by convective processes. Unfortunately, accurate determinations of photospheric abundances from AGB stars are difficult owing to strong molecular opacities and dynamic atmospheres (e.g., Abia et al. 2008). While it has become possible to obtain constraints on, e.g., the heavy element nucleosynthesis in intermediate-mass AGB stars (García-Hernández et al. 2006, 2009; Karakas et al. 2012), uncertainties are large. It is simpler to obtain abundances from post-AGB stars (e.g., van Winckel & Reyniers 2000; De Smedt et al. 2012) but statistics are currently rather limited. Future work will expand the number of post-AGB stars with reliable abundances as a result of large-scale surveys of post-AGB stars in the Magellanic Clouds.

Abundances can be obtained from PN spectra for a number of elements such as C, N, O, S, Cl and the noble gases He, Ne, and Ar (see § 8). The abundances of noble gases and other elements (e.g., Cl, Ge, and Br) cannot be derived from the spectra of cool evolved stars, making the information that comes from PNe unique. Chemical abundances constrain the initial composition of the progenitor star and provide clues to mixing and nucleosynthesis.

The heavy element composition from PNe is a relatively new and exciting field, providing data for, e.g., Zn, Ge, Se, Kr, Xe, and Ba, some of which are difficult or impossible to observe in AGB or post-AGB star spectra (Péquignot & Baluteau 1994; Dinerstein 2001; Sterling et al. 2002; Sharpee et al. 2007; Sterling et al. 2007; Sterling & Dinerstein 2008). Thus, the chemical composition of PNe provides a unique insight into nucleosynthesis during previous phases (Karakas et al. 2009; Karakas & Lugaro 2010). One outstanding issue is that the abundances of heavy elements derived from PNe suffer from large uncertainties, driven in part by a lack of good atomic data. This is currently changing (e.g., Sterling & Witthoeft 2011; Sterling 2011), with the hope that more reliable and extensive data will be available in the near future (see § 7).

3.4. *Binarity*

It should be emphasized that all of the above deals with single star evolution. Most stars are in binary systems, where the orbital parameters and mass ratio determine the evolutionary fate of the system. Binary interactions are thought to be highly important in shaping PNe (see § 4) as well as in leading to explosive phenomena such as novae and Type Ia supernovae. Binary evolution is horrendously complicated, in particular due to the complexity of the types of stellar interactions that are possible. For example, if one star fills its Roche lobe, a common envelope can develop. We currently have a very limited understanding of common envelope evolution, a situation that is being improved through hydrodynamical simulations (Passy et al. 2012; Ricker & Taam 2012). Future work will need to address how to implement improvements from hydrodynamical simulations into stellar evolution or population synthesis models. More work is also desperately needed to address how binary evolution changes the chemical yields of single stars.

4. THE IMPACT OF BINARY INTERACTIONS ON THE PN POPULATION

Quantifying the impact of binarity on the formation and evolution of PNe needs two distinct approaches. With the first, we study individual PN harbouring binary central stars, with the aim of connecting stellar and binary parameters to PN kinematics and morphology. The second approach is to establish to what extent binary interactions have determined the characteristics of the PN population as a whole, by selecting population characteristics (such as mean central star mass) that vary depending on the frequency of interactions.

Currently, we expect that the fraction of PN that have experienced a binary interaction of their central star will be a consequence of the fraction of close binaries in the 1–8 $M_\odot$ main sequence population, which is roughly 20–30% (Raghavan et al. 2010). However, the high incidence of non spherical PNe (≈80%; Parker et al. 2006), along with the lack of a quantitative single-star theory that explains these non-spherical shapes (Soker 2006; Nordhaus et al. 2007), has prompted questions of whether the PN phenomenon is associated preferentially with binarity. If this were so, by necessity, there would be some AGB stars that never develop a PN because they do not suffer an interaction (Soker & Subag 2005; De Marco & Soker 2011). Here we consider these two sets of problems. For more complete reviews see De Marco et al. (2009) and De Marco (2011).

4.1. *Recent observational efforts to detect binary central stars of PNe and related objects*

To determine how binary interactions have played a role in the formation and shaping of PNe, newly detected binaries (e.g., Miszalski et al. 2009a; Boffin et al. 2012) need to be characterised, which may include a model of observables such as light and radial velocity curves (e.g., Hillwig et al. 2010). PN kinematics need then be related to binary parameters (e.g., Guerrero & Miranda 2012; Mitchell et al. 2007; Tocknell et al. 2013). This approach can also be carried out statistically, by examining a sample of PNe with close central stars for their PN characteristics, as done by Miszalski et al. (2009b), who concluded that bipolar PNe with filaments tend to be preferentially present around close binary central stars.

The known binaries are either the very close, post-common envelope ones (Paczynski 1976), detected by periodic photometric variability indicating ellipsoidal distortion, irradiation of eclipses, or else so wide (many thousands to tens of thousands of AU (astronomical units); Ciardullo et al. 1999) that the components have not interacted. We know of ≈40 close binaries (e.g., Bond 2000; Miszalski et al. 2009a) and the close binary fraction is ≈15%. This is expected to be a lower limit because close binaries with unfavourable inclinations, smaller companions, or cooler central stars may not be detected (the sensitive *Kepler* satellite has discovered two central star binaries, undetectable from the ground, in a sample of only six; Long et al. 2014)(see also § 5).

Central binaries with intermediate periods must exist. While at separations of a few solar radii to a few AU there will be no binary central stars because the AGB progenitor would have swept the companion into a common envelope and dramatically reduced the orbital separation. From a few AU to ≈100 stellar radii we do expect companions to exist and to have interacted with the AGB star, affecting the mass-loss geometry and possibly the mass-loss rate as well (Soker 1997). Such binaries would have no light variability and only a slight radial velocity variability. The first central star binary, with a period of ≈ 3 years was recently detected (van Winckel et al. 2014) after a long-term monitoring campaign.

In an attempt to find such elusive companions De Marco et al. (2013) and Douchin et al. (2013) carried out a survey of ≈40 central stars in the I and J bands, showing that substantially more than the 20–30% expected for the standard scenario may have companions, although only a larger sample can give a more statistically significant answer.

Finally, based on predictions from the main sequence binary fraction and period distribution we note that the central star *close* binary fraction of ≈15% (Bond 2000; Miszalski et al. 2009a) is already much higher than the few percent expected, adopting a maximum tidal capture radius of 2–3 stellar radii (Mustill & Villaver 2012).

4.1.1. *Binary AGB and post-AGB stars*

Can AGB and post-AGB binaries serve to constrain the binary fraction of PN central stars further? AGB binaries are known (e.g., Sahai et al. 2008; Mayer et al. 2013), but there is no hope for a complete census. In the Magellanic Clouds, half of the "sequence E" stars are thought to be AGB contact binaries (Nicholls & Wood 2012), the immediate precursors of post-common envelope PNe. Their numbers are consistent with a lower post-common envelope PN fraction of ≈7–9%, possibly due to the lower age of the LMC population.

One in three post-AGB stars *with no nebulosity* (naked post-AGBs) has been found to have a companion with a period in the 100-2000-day range and with a Keplerian circumbinary disk (van Winckel et al. 2009). These objects may not develop a PN, possibly because of re-accretion of material from the disk, which slows the leftward evolution on the Hertzsprung-Russell diagram. These binaries likely went through a strong binary interaction that reduced their period, but not as much as in a classic common envelope interaction. Is it then possible that all strong interactions that avoid the common envelope result in no PN at all?

Long-term monitoring of a small sample of post-AGB stars *with* a pre-PN nebulosity has revealed that at least one, and possibly two, of the monitored objects may be binaries with a decade-long period (Hrivnak et al. 2011). We could therefore conjecture that the binaries in pre-PNe all have decade-long periods. It has been proposed (Bright 2013) that it is the wide binary nature of the pre-PN central stars that allows them to have the observed pre-PNe, while the naked post-AGB stars, having suffered a closer binary interaction, experienced re-accretion, which prevented the lighting of the PN. An observational test of this scenario is the characterisation of the disks around naked post-AGB stars as well as those surrounded by a pre-PN, accompanied by a model of their formation (Bright 2013).

4.2. *Recent fundamental theoretical efforts*

Seminal work in PN shaping was carried out by García-Segura et al. (1999, see also García-Segura et al. 2005), who developed a model of how rotation and magnetic fields in AGB stars can lead to mass-loss geometries that later give rise to a range of PN shapes. However, the magnetic fields in those hydrodynamic simulations are artificially constant because gas movement does not feed back to the field strength and direction. Recently, Soker (2006) and Nordhaus & Blackman (2006) have demonstrated how such feedback would quench the field in approximately a century, eliminating the source of global mass-loss shaping that is needed to obtain non spherical PNe.

There is broad consensus that the presence of a companion can act directly on the AGB envelope gas to generate PN shapes, as well as on the stellar magnetic fields to recreate some of the conditions explored by García-Segura et al. (1999, 2005). However, binary models are few and cover random spots in parameter space with widely different techniques. García-Arredondo & Frank (2004) carried out hydrodynamic simulations of a binary system with a 10 AU separation, the parameter regime discussed analytically by Soker & Rappaport (2000), and confirmed that a "compression" disk is indeed expected when jets are present. However, they did not simulate the conditions that generate the accretion disk that launched the jets in the first place. Recently Huarte-Espinosa et al. (2013) [but see also previous work by Mastrodemos & Morris (1998, 1999) and Huarte-Espinosa et al. (2012)], carried out simulations of how the accretion disk forms, and cast doubt on wheter the accretion rates needed to blow pre-PN jets in the first place are sufficient if the orbital separation is in the 10–20 AU range. Huarte-Espinosa et al. (2012) compared their work to other papers modeling the formation of accretion disks (e.g., Mastrodemos & Morris 1998; de Val-Borro et al. 2009), but did not even mention the work of García-Arredondo & Frank (2004), because that paper does not model the accretion disk formation and only models the jets. Yet the conclusions of the two papers are at odds and leave the readers (the observers) to choose which model to follow when contemplating a unified scenario for the observations.

5. PN CENTRAL STARS

Several important questions concerning PNe are directly related to PN central star research. Examples are: distance determinations, binary fraction, distribution of binary orbital periods, fraction of H-depleted photospheres, properties of central star winds. Below we offer a list of research fields where we can expect significant progress in the near future.

5.1. *Astrometry*

The epoch of Gaia is coming soon, but it is not completely clear what kind of impact Gaia will have concerning trigonometric parallaxes of central stars. In many cases the relatively low angular resolution and observing mode may make it difficult to work with images of stars embedded in bright nebulae. (It might be useful to request, from some authoritative Gaia source, like CU4, information on what they are planning to do about PNe. *Ad hoc* simulations demonstrating performance, if not planned yet, could be suggested. Eventually our Working Group might offer a list of targets we consider particularly important for PN research; see below on "spectroscopy").

In the meantime, other trigonometric parallax measurements are steadily improving. The latest PN results are from *HST* Fine Guidance Sensor data (Benedict et al. 2009), offering distances as large as 600 pc. But especially ground-based techniques using IR adaptive optics, as in Lu et al. (2010) or Cameron et al. (2009), appear to be able to produce, at least in favourable stellar fields, trigonometric parallaxes below 1 milli-arc second, which means distances larger than 1 kpc. Central star parallax determinations using infrared adaptive optics should be encouraged, because even a few measurements would be astrophysically important.

5.2. *Photometry*

Photometric studies of central stars have two important applications: the search for (a) binary systems, and (b) surface instabilities produced by pulsations and stellar wind variations. In the near future, new sources of photometric information will become available. The *Kepler* field has already produced some evidence that a large fraction of PN central stars may show small amplitude photometric variations (Douchin et al. 2012). All-sky multi-filter surveys like Pan-STARRS[22] are being carefully calibrated to provide photometry with accuracies at or below the 1% level (Tonry et al. 2012). Systematic searches for PN central star photometric variations in these and other similar databases are being planned, and are expected to help us understand the photometric behaviour of central stars in much more detail than has yet been possible.

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[22] Panoramic Survey Telescope and Rapid Response System.

5.3. *Spectroscopy*

There are at least three excellent reasons to want central star spectra:

(1) They give information about basic stellar photospheric and wind parameters, allowing us to test radiatively-driven wind models and stellar structure and evolution models.

(2) In particular, they provide photospheric abundances, which is a good way of testing post-AGB model predictions, starting with the fraction of H-deficient central stars.

(3) They provide radial velocities, which will eventually provide an irreplaceable way of refining our knowledge of the binary orbital period distribution and binary fraction among PN central stars.

It should be clear, however, that what we need are spectrograms with high spectral resolution and the highest possible signal-to-noise ratio. Even spectral classification should be based only on high-resolution spectra, because, at low resolution, the presence of nebular Balmer emission lines does not allow us to judge whether or not the central star has an H-deficient photosphere (which is arguably the most important information we should expect a spectral type to give).

This point requires more explanation. Since low-resolution spectra are easier to obtain, many authors tried to base their spectral descriptions on such insufficient data. This resulted in the introduction of the *"wels"* (weak emission line star) description, which ignored the basic question of H-deficiency. There has been a tendency to interpret the *wels* label as a spectral type. We have even seen stars, previously classified as H-rich from high-resolution spectra, "reclassified" as *wels* from low-resolution spectra (authors and referees were equally guilty). For this reason it is necessary to emphasize that *wels* is not a spectral type, and and that its use should be restricted to mean "insufficient spectral resolution." The point has been made again by Miszalski (2012) in the context of close binary searches.

So the challenge is how to obtain the large amount of telescope time required for high-resolution spectrograms; and even more daunting, how to take many such spectrograms, in a search for radial velocity variations. Probably the best strategy is to try to join forces with other groups requiring large amounts of high-resolution spectra, in particular, exoplanet searchers. Central star spectroscopy should not be restricted to the visible range; efforts to obtain UV spectra, for example with the *HST* Cosmic Origins Spectrograph, would be very welcome.

Traditionally, only H and He photospheric central star abundances could be determined, because of complications related to the high surface temperature (requiring a non-LTE treatment of the atmosphere as a whole, and in particular of metal line opacity), and the presence of significant mass loss (requiring hydrodynamically consistent winds in an extended, expanding atmosphere). Modern model atmospheres are reaching a level of development that allows us to extend photospheric abundance determinations to several other elements, like C, N, O, Si, P and S; see, e.g., Morisset & Georgiev (2009). However, there are some difficulties. The number of physical parameters to be fitted is now larger (surface temperature, log g, abundances, mass loss rate, wind terminal velocity, velocity law, clumping filling factor). It is particularly in this respect that UV spectrograms provide essential complementary information; see, e.g. Herald & Bianchi (2011).

There is also the potential capability of deriving stellar radii, masses and luminosities from wind properties, without depending on the luminosity-core mass relation. In practice, the current state of wind models leads to an unresolved conflict: the masses of central stars derived from hydrodynamically consistent wind theory disagree with the masses we would derive from adopting the luminosity-core mass relation, as reported by Kaschinski et al. (2012). This kind of problem can only be solved by measuring reliable distances, like those from trigonometric parallaxes. The known distance then fixes the stellar radius and mass unambiguously. A few PN central star trigonometric parallaxes (in particular for those stars showing a strong wind) could have a strong impact on stellar wind theory and stellar evolution theory.

If we can grow confident in the accuracy of photospheric abundances derived from the newest generation of model atmospheres, then a new way of testing and forcing predictions from stellar evolutionary theory will become available.

6. PLANETARY NEBULA MORPHOLOGY AND KINEMATICS

6.1. *Morphology*

The study of the PN morphology has played a fundamental role in their understanding. PNe display a myriad of shapes that early observers grouped into fundamental classes. These basic morphological classes have later been related to physical properties such as the mass of the progenitor star, the chemical yields in the expelled stellar material and the galactic distribution of the population of PNe (e.g. Torres-Peimbert & Peimbert 1997).

The advent of high spatial resolution imaging, initiated with the WFPC 2[23] camera on board *HST*, followed by adaptive optics systems in large ground-based telescopes, have revealed additional complex structures and outstanding symmetries since the first stages of development of the PN phase (e.g. Sahai, Morris, & Villar 2011). The structure and substructures of a PN are related to its remnant core mass, environment and

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[23] Wide Field Planetary Camera 2.

nuclear conditions at the exit of the AGB and the subsequent mass-loss and photoionization evolution.

The presence of thick toroidal structures or equatorial mass enhancements and of symmetric structures, either compact as knots or elongated as collimated lobes, have led to the inference that the core may be often composed by a close binary system (e.g., De Marco 2009; López et al. 2011, and references therein).

6.2. *Kinematics*

Since the morphology evolution of a PN depends on the outflowing properties of the gaseous shell, the study of kinematics and morphology in PNe have developed closely in parallel (e.g. López et al. 2012a; García-Díaz et al. 2012; Pereyra et al 2013; Huarte-Espinosa et al. 2012). In addition, the mean or systemic radial velocity of each PN is a key ingredient in understanding the population distribution of PNe in the galactic context, locally and in other galaxies (e.g. Durand, Acker, & Zijlstra 1998). For the local population, spatially resolved kinematic information of the different structures that compose a PN (shell, rim, lobes, halo, etc) provides a detailed insight into the global shell dynamics (López et al. 2012b). High-speed, collimated, bipolar outflows are now known to be a relatively common occurrence in PNe and their origin has also been considered as likely originating in a binary core with magnetic fields providing collimation conditions (e.g García-Segura & López 2000).

Moreover, since the measured velocity at a certain point in the nebula corresponds to the magnitude of the radial component of the velocity vector, this information provides a good insight into the structure of the nebula along the line of sight, considering that the expansion is homologous or does not greatly depart from it. In this way a reasonably good 3D reconstruction of the nebular shape can be achieved for objects whose 2D projection on the sky (the image) is known and for which good kinematic mapping over the face of the nebula is available (Steffen & López 2006).

6.3. *Future prospects*

Current instrumentation provides access to nearly all relevant areas of the electromagnetic spectrum. Imaging at different wavelengths at high spatial resolution will provide a much better understanding of the interplay among the different contributors to the PN phenomenon throughout its evolution, from the hot plasma in the X-ray domain and the photoionized gas in the optical and radio regimes to the warm and cool dust and molecular component in the infrared and millimeter ranges.

In the optical and the infrared regimes morphology and kinematics can now be obtained simultaneously through the use of integral field spectrographs (IFS) with nearly equivalent mapping quality in both cases (only depending on the spaxel aspect ratio) and the data, morphology and kinematics can be analyzed comprehensively point to point as a function of wavelength from the data cubes. Many of the current IFS are operating on large telescopes, and they have been designed to work in the near infrared, with more expected to become operational in the near future (e.g., López et al 2007). This means that the warm and photo-dissociated regions in very young PNe will become better studied. This is a highly relevant stage to understand the early formation and development of the PN shell and one that has not been studied in the depth it deserves. IFS data lead in a natural way to a 3D reconstruction of the nebular structure and location of the stellar component(s) embedded within it. These data will surely be fruitfully complemented in the near future by the data cubes from more millimeter observations, particularly from *ALMA* (Atacama Large Millimeter/submillimeter Array) (e.g., Bujarrabal et al. 2013). Combining high spatial and spectral resolution data cubes at multiple wavelengths and deriving from them the 3D core structure and outflows that produce PNe will be the ultimate challenge in the coming years.

This information will be often complemented by the measurement of the motion of the gas or dust in the plane of the sky, thanks to the increasing time baseline for which high-resolution images of individual nebulae are becoming available (e.g., Balick & Hajian 2004; Corradi et al. 2011b; Balick et al. 2013). The combination of multiple-epoch images and Doppler shift velocities will allow to gather information on five out of the six dimensions of phase-space, and in some cases even detect acceleration (hence the forces at work), providing unique new constraints to the hydrodynamical modeling.

For quasi-spherical nebulae, it seems that a reasonable understanding of the dynamical evolution of the different observed shells has been reached (Perinotto et al. 2004, and the following articles of the series). In this respect, we stress the potential of haloes to reconstruct the mass loss history of the progenitors stars in the last 10^5 yr of the AGB (Corradi et al. 2003). The rings/arcs often observed in the inner regions of the haloes (Corradi et al. 2004) are poorly understood but potentially important, and call for further investigation.

For collimated outflows, the main goal will be to recover accurately both the mass loss history and geometry of the progenitors, providing conclusive evidence of the physical phenomena suggested so far, such as fast/collimated/precessing/intermittent winds or bullet-like ejections (e.g., Balick et al. 2013).

The dynamical properties should also be more tightly related to the physics of the central sources. As mentioned before, binarity is supposed to be a key ingredient to explain many of the observed morphologies. While the number of binary central stars is rapidly increasing (Miszalski et al. 2009a), a clear correlation with morphology has been demonstrated only for few, specific components such as extreme equatorial rings and polar outflows (Miszalski et al. 2009b; Corradi et al. 2011a; Boffin et al. 2012). A more comprehensive understanding of the most common basic geometries of the nebulae is still lacking.

The role of magnetic fields, often invoked in the modeling of the nebulae, should also be better clarified. So far no evidence exists for magnetic fields in the central stars (Asensio-Ramos et al. 2014), and little information is available for the nebular gas. Polarimetric studies from the IR to radio wavelengths, revealing dust polarization (Sabin et al. 2007), and in the optical/UV searching for fields anchored to the central stars, are needed for further progress.

7. ATOMIC PROCESSES

7.1. *Introduction*

PNe are ideal 'astrophysical laboratories' for studying atomic processes. The basic atomic processes in PNe are photoionization and recombination (including radiative and dielectronic recombination), charge-exchange reaction, collisional excitation and de-excitation, and radiative transition. Today atomic data for these processes are all available and, for some ions, have been calculated to high accuracy. Much effort is still needed to revise the old data as well as to create new data.

7.2. *Atomic data for collisionally excited lines*

The optical and far-infrared fine-structure transitions within the ground configurations of O^{2+} and N^{+} are standard tools for nebular analysis (Liu et al. 2001a; Osterbrock & Ferland 2006). Although O^{2+} has been studied extensively, recent calculations show that taking relativistic effects into account will change the collision strengths by 20% (Palay et al. 2012). Thus the calculation of O^{2+} needs careful revision. Accuracies of the N^{+} collision data are claimed to be 20% (Tayal 2011). However, using different target wave functions results in significant differences in the collision strengths. Efforts are needed to improve the atomic model.

Studies of the [O II] $\lambda3729/\lambda3726$ ratio at the high-electron-density limit suggest that large-scale electron correlations and quantum electrodynamics corrections should be considered (Han et al. 2012). Future theoretical work on O^{+} needs to use increased atomic orbitals and take into full account relativistic effects. The radiative transition rates and collision strengths of S^{+} given by Tayal & Zatsarinny (2010) are claimed to be accurate to better than 30%. Given the complexity of the e-S^{+} scattering, further investigation is desirable.

Recent theoretical work on Ne^{2+} by Landi & Bhatia (2005) shows substantial differences in transition probabilities compared with previous calculations and experiments, due to a larger number of configurations used in the new calculation. Further investigation of the Ne^{2+} atomic model is needed before a conclusion can be drawn. New collision strengths for the fine-structure transitions of S^{2+} (Hudson et al. 2012) differ significantly from an earlier calculation. More extensive study of e-S^{2+} scattering, with emphasis on the near-threshold resonances, is needed.

The transition probabilities and collision strengths of Ne^{3+} currently used are from Zeippen (1982) and Ramsbottom et al. (1998), and are out of date. For Ar^{3+}, those data are from Mendoza & Zeippen (1982) and Ramsbottom et al. (1997). More sophisticated calculations for the two ions are needed. The transition probabilities of Cl^{2+} given by Sossah & Tayal (2012) agree well with the experiments and earlier calculations, but collision strengths show significant discrepancies. Future studies of Cl^{2+} need to consider the effects of coupling to the continuum, which may be important for some transitions, but is ignored in the current work.

7.3. *The iron-peak elements*

Emission lines of Fe^{2+} and Fe^{3+} have been extensively studied (Rubin et al. 1997; Rodríguez 2003; Rodríguez & Rubin 2005). Nahar (2006) and McLaughlin et al. (2006), respectively, presented new radiative transition probabilities and collision strengths of Fe^{3+}, and varying degrees of agreement were found in transition probabilities compared with earlier calculations. The transition and collision data of Fe^{2+} currently in use are from Nahar & Pradhan (1996) and Zhang (1996). New calculations of Fe^{2+} are needed. Atomic data for other elements in the iron-peak group are still limited, with most work mainly focused on singly-ionized ions (Bautista 2006). Future investigation should extend to doubly and triply ionized ions of Sc to Co.

7.4. *Neutron-capture elements*

Since the seminal work of Péquignot & Baluteau (1994), emission lines of neutron(n)-capture elements have been identified in nearly 100 Galactic PNe. Accurate abundance analysis using those lines relies on accurate atomic data. The calculations of Sterling & Witthoeft (2011), Sterling (2011) and Sterling & Stancil (2011) enable determination of the Se and Kr abundances and investigation of the s-process enrichment in PNe. However, nebular astrophysics still lacks of atomic data for the n-capture elements. The current atomic models for heavy elements need to be revised and fully relativistic atomic codes should be developed. The sensitivity of abundance determinations to uncertainties in atomic data of the trans-iron elements also needs to be tested (Sterling et al. 2012).

7.5. *Hydrogen*

The recombination spectrum of hydrogen has been extensively used in studies of nebulae (Peimbert 1971; Barker 1978; Liu & Danziger 1993; Liu et al. 2000; Zhang et al. 2004). The most accurate calculations of H I recombination lines is by Storey & Hummer (1995). Unresolved problems related to hydrogen are: (1) Radiative transfer of Lyα photons including the effects of self-absorption, removal and collision-induced transitions between the 2s ^{2}S and 2p ^{2}P$^{\rm o}$ states (Bautista 2006); and (2) collisional excitation from the ground state to $n > 2$ states under high-$T_{\rm e}$ and high-$N_{\rm e}$ conditions, which affect primordial helium abundance determinations (Peimbert et al. 2007).

7.6. *Helium*

Theoretical He I line emissivities are now as good as 1% (Bauman et al. 2005; Benjamin et al. 1999, 2002). Plasma diagnostics based on the He I lines are established (Zhang et al. 2005a). Future work will concentrate on (1) collision cross-sections of He I; (2) optical depth effects on the He I λ3889 line; (3) self-absorption due to significant population of the 1s2s ^{3}S$_1$ meta-stable state; and (4) mechanisms that may destroy the He I resonance line photons, such as photoionization of neutral hydrogen or absorption by dust grains (Liu et al. 2001b).

7.7. *Effective recombination coefficients for heavy element optical recombination lines*

7.7.1. *The second-row elements*

Heavy element optical recombination lines (ORLs) have proved to originate from very 'cold' regions (e.g., Liu et al. 2006; McNabb et al. 2013; Fang & Liu 2013), in line with the bi-abundance nebular model (Liu et al. 2000). In order to study the properties of such 'cold' inclusions, reliable effective recombination coefficients for the C II, N II, O II and Ne II lines are needed.

The commonly used C II effective recombination coefficients of Davey et al. (2000) were calculated in *LS* coupling at a single electron density of 10^4 cm^{-3}. More extensive calculations for this ion should be carried out in intermediate coupling and should cover a broad range of temperatures and densities. Sochi (2012) presents new intermediate coupling calculations of C II, but only includes the dielectronic recombination.

New calculations of the effective recombination coefficients for the N II lines (Fang et al. 2011, 2013) and O II lines (McNabb et al. 2013) are a great improvement over previous work (Storey 1994; Liu et al. 1995; Kisielius & Storey 2002). Plasma diagnostics based on the N II and O II ORLs are constructed (McNabb et al. 2013). However, problems still exist in the calculations, e.g., compared to earlier work, the N^{2+} target state energies generated by Fang et al. (2011) agree less well with experiments; level population calculations of N II become more uncertain at very low-$T_{\rm e}$, high-$N_{\rm e}$ conditions. Future improvement includes: (1) creation of an N^{2+} target with larger configuration set; (2) a full collisional-radiative treatment among the low states; and (3) ab initio calculations extended to higher n.

The inadequacy of the currently used Ne II effective recombination coefficients calculated by Kisielius et al. (1998) was noticed through very deep spectroscopy of the Galactic PN NGC 7009 (Fang & Liu 2013). A new calculation for Ne II needs to (1) consider that relative populations of the Ne^{2+} ^{3}P$_{2,1,0}$ fine-structure levels deviate from the statistical weight ratio 5 : 3 : 1; (2) be carried out in intermediate coupling; and (3) be extended to temperatures well below 1000 K, including the effects of fine-structure dielectronic recombination.

7.7.2. *The third-row elements*

The only atomic data available for the Mg and Si ORLs are the dielectronic recombination coefficients given by Nussbaumer & Storey (1986), whose calculations were restricted to those ions for which the recombining ions have n=3 valence electrons. Thus Mg II and Si IV as well as ions with higher ionization stages were not calculated. Among all the third-row elements, the effective recombination coefficients for the Mg II and Si IV lines are the most needed (Barlow et al. 2003; Liu et al. 2004; Tsamis et al. 2004; Zhang et al. 2005b; Liu 2006; Fang & Liu 2013).

8. ABUNDANCE DETERMINATIONS

Abundances in PNe reflect both the nucleosynthesis contributions of their progenitor stars and the chemical signatures of their galactic birthplaces. Thus the abundance profiles of PNe, individually and collectively, contain valuable information about galactic chemical evolution. Over the last two decades the study of the chemical compositions of PNe has been extended beyond the abundant elements in the first two rows of the periodic table and the exclusive use of strong forbidden lines. More recently, the development of new observational capabilities and analytical techniques has highlighted the challenges and potential rewards of accurate, reliable abundance determinations. Listed below are some prospects for further advancement.

8.1. *The Forbidden-Permitted Discrepancy*

Among the most persistent problems dogging PN abundance determinations is the disagreement between abundances calculated from collisionally-excited (forbidden) lines and those from permitted recombination lines. Recombination-line abundances are systematically higher than those derived from forbidden lines, often by a large factor. Models based on fluctuations in local conditions within chemically homogeneous nebulae vie with those incorporating a bimodal abundance distribution to explain these discrepancies (see e.g., Peña 2011). Observational progress in detailing the temperature, density, and abundance structures in PNe requires spatially-resolved spectra that (1) are deep enough to unambiguously detect faint recombination lines; and (2) possess sufficient resolution to minimize the confounding effects of line blends. New capabilities in this area are represented by MEGARA[24], an IFU/MOS[25] instrument scheduled for first light on the Gran Telescopio Canarias in 2015 (Gil de Paz et al. 2012), and MUSE[26], an adaptive-optics IFU recently installed on the VLT.

Spatially-resolved maps of infrared fine-structure lines as observed with *SOFIA*[27] and *Herschel* could supply further evidence of the existence of the proposed cold, H-deficient inclusions, if these lines are found to peak in the regions exhibiting the highest abundance discrepancy (Rubin et al. 2012).

On the theoretical side, Nicholls et al. (2012) suggest that if free electron energies deviate from a Maxwell-Boltzmann distribution, and instead follow a *kappa* distribution, this may explain the abundance discrepancy. Studies such as that by Storey & Sochi (2013), who investigated the free-electron distribution from C II lines in a sample of PNe, will help to determine if this is a viable interpretation. If so, then the challenge turns to incorporating *kappa* distributions into existing modeling codes and understanding how these distributions behave as the nebula evolves.

8.2. *Neutron-capture elements*

Expanding the inventory of elements detected in PN gas augments our ability to make useful comparisons between observed abundance patterns and those predicted by theory. Of the less-abundant elements, s-process nuclei (e.g., Se, Br, Kr, Rb, Sr, Te, I, and Xe) are especially useful, as their relative abundances can provide robust constraints on computational models of AGB evolution (particularly during the late stages of the thermally-pulsing phase). Measuring s-process abundances requires echelle-level resolution of faint lines along with accurate methods for untangling blends, so studies of these elements will benefit from the availability of the instruments mentioned above. It is also possible, using large ground-based telescopes, to detect neutron-capture elements in the PNe of neighboring galaxies. Results of such investigations can illuminate the dependence of s-process enrichment factors on both metallicity and progenitor mass.

8.3. *Ionic to Total Abundances*

Without observations of lines from all populated ionization states, the derivation of total element abundances from observed ionic abundances relies on either full photoionization modeling (often with incomplete information), or the application of ionization correction factors (ICFs), or a combination of the two. Published sets of ICFs are in general use (e.g., Kingsburgh & Barlow 1994; Kwitter & Henry 2001), but the universality of a single ICF for a given element is not necessarily supported; improvements in understanding the dependencies of ICFs may point toward the need for customized formulations. For example, Peña et al. (2012) find that ICF-derived neon abundances vary with both metallicity and ionization level. Even for oxygen, the "gold standard" element in photoionized nebula abundance determinations, a universal ICF does not produce the most accurate results. Miller et al. (2012) used a grid of photoionization models to study the oxygen ICF over a broad range in central star temperature, yielding different ICFs for three stellar temperature regimes spanning 31,000 – 500,000 K. Finally, sulfur has long been troublesome (e.g., Henry et al. 2012), with ICF-derived abundances for PNe falling systematically below those of H II regions at the same metallicity, with increasing deficits at low metallicity. The difficulty in devising a suitable ICF may arise from hydrodynamical effects enhancing higher-ionization states, especially at lower metallicities, as suggested by the 1D-RHD (radiation hydrodynamics) results by Jacob et al. (2012). Such RHD models represent a powerful tool in confronting nebular observations in general, and in assessing ICF reliability, in particular. ICFs can also be affected by PN morphology, as suggested by 3D modeling results for bipolars and ellipticals (Gonçalves et al. 2012b); additional studies of sufficiently high-surface-brightness objects will help to constrain ICF behavior.

8.4. *Future Directions*

Future abundance determinations will benefit from improvements in atomic physics calculations at a wide range of physical conditions (including transition probabilities, effective collision strengths, photoionization cross sections, and rate coefficients for radiative recombination, dielectronic recombination, and charge transfer (see § 7), ideally benchmarked against experimental determinations and, importantly, including estimates of uncertainty.

Research groups involved in PN abundance determinations should be in communication, especially as new atomic data are published. A meaningful comparison of abundances derived by different groups is not always straightforward, and must include ramifications of using particular atomic data and varying techniques,

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[24] Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía.

[25] integral field unit/multi-object spectrograph.

[26] Multi Unit Spectroscopic Explorer.

[27] Stratospheric Observatory for Infrared Astronomy.

as well as an understanding of the sources of uncertainty. A recent tool addressing this last issue is the NEAT code of Wesson et al. (2012), which uses a Monte Carlo propagation of line flux uncertainties to estimate uncertainties in derived abundances.

9. THE PROPERTIES OF DUST IN PLANETARY NEBULAE

Low- and intermediate-mass ($M < 8M_\odot$), stars constitute the majority of the stars in the Universe. Many of these stars end their lives with a phase of strong mass loss and experience thermal pulses on the AGB, representing one of the main contributors to interstellar medium enrichment. As the star evolves through the last phases of the AGB, mass loss increases up to $10^{-4}M_\odot$ (Herwig 2005), forming a circumstellar envelope around the star. As this envelope expands, it eventually cools down and large numbers of molecules are formed (Olofsson 1997) along with solid-state species (Kwok 2004). Depending on the mass of the progenitor star, this envelope will be either carbon or oxygen rich. For Galactic PNe, they will be C-rich for $M < 4M_\odot$ and O-rich for $M > 4M_\odot$ (Mazzitelli et al. 1999), and for the Magellanic Cloud, C-rich for $M < 3M_\odot$ and O-rich for $M > 3M_\odot$ (Ventura et al. 2000).

9.1. *Molecular Composition*

Recent advances in infrared instrumentation (e.g. *ISO, Spitzer, Akari, Herschel*) have allowed some of the resulting species to be identified. Among the inorganic species, the most prominent are the amorphous silicates, with absorption features at 9.7 and 18 μm, and crystaline silicates, such as olivines and pyroxenes, which have absorption/emission features from 10 to 45 μm (Sylvester et al. 1999; García-Hernández et al. 2007). In addition, the broad 10–15 μm emission (centered at about 11.5 μm) and the 25–35 μm emission (the so-called 30 μm feature) are usually attributed to SiC, (e.g., Speck et al. 2009) and MgS, (e.g., Hony et al. 2002). However, these observed broad features are quite consistent with the variety of properties of hydrogenated amorphous carbon (HACs). From laboratory work, Grishko et al. (2001) showed that HACs can explain the 21, 26, and 30 μm features, while Stanghellini et al. (2012), analyzing a sample of compact PNe, classified these features as aliphatic dust. Therefore, this is an open question that should be addressed in the future.

As for organic compounds, there are a rich variety of aliphatic, aromatic and more complex molecules such as graphene, fullerenes and bucky-onions. Unidentified infrared bands (UIB) at 3.3, 6.2, 7.7, 8.6, and 11.3 μm were attributed to PAHs, (Allamandola et al. 1985). However, recently Kwok & Zhang (2011) challenged this finding, showing that the unidentified infrared emission (UIE) bands are consistent with amorphous organic solids with a mixed aromatic-aliphatic structure. They argue that this mixture is similar to organic materials found in meteorites. More recently Cataldo et al. (2013) presented new laboratory data showing that the UIE bands in the C-H stretching region (3–4 μm), can be reproduced by the petroleum fraction BQ-1, which exhibits a mixed aromatic/aliphatic and cycloaliphatic character. The far-IR bands are best reproduced by petroleum fractions made by a 'core' of two or three condensed aromatic rings which are extensively alkylated by aliphatic and cycloaliphatic fractions.

A 21 μm feature was first discovered by Kwok et al. (1989). Several attempts to identify the carrier of this feature, such as TiC clusters, have failed (e.g., Chigai et al. 2003). Cataldo et al. (2013) showed that a mixture of petroleum fraction BQ-1 with acenes PAHs (e.g. tetrahydronaphthalene, anthracene, etc.) could contribute to this 21 μm band.

Large organic molecules, graphene (García-Hernández et al. 2011), and the fullerenes C60 and C70 (Cami et al. 2010; García-Hernández et al. 2010) were recently found in PNe. García-Hernández et al. (2012) and Micelotta et al. (2012) proposed that these fullerenes are formed by UV photochemical processing of HACs.

Recently García-Hernández et al. (2013) found the largest organic molecules (bucky-onion, C60@C240 and C60@C240@C540) in the PN TC1.

Additionally, water-ice features at 3.1, 43, and 62 μm have been observed in heavily obscured post-AGB stars (Dijkstra et al. 2006; Manteiga et al. 2011).

As the envelope of the AGB star expands, it contributes to the enrichments of the ISM, and eventually contributes to star-forming regions. Trigo-Rodríguez et al. (2009) have shown from the isotopic composition of ^{26}Al, ^{41}Ca, ^{60}Fe, and ^{107}Pd in some of the remnants of the primeval solar system cloud (Calcium-Aluminum-rich inclusions (CAIs) in chondrites) that our solar system was contaminated by a massive AGB. Indeed, Pendleton, & Allamandola (2002), found the 3.4 μm aliphatic features in the Murchison meteorite. This suggests that the dust composition of our primeval solar system cloud may share similarities with the dust around PNe.

9.2. *Future perspectives*

Future research should be carried out in order to have a more complete scenario for the formation of the different species in the dust around AGB stars and PNe. In particular, how the different silicates (both amorphous and crystalline) are formed needs to be understood.

As for organic chemistry, a rich variety of molecules need to be studied. The mechanism involved in the formation of aliphatic, aromatic and more complex molecules should also be understood.

In the next decade, new laboratory work will shed fresh light on these questions and help lead to their resolution. The *Herschel* database will expand these studies to the far-IR spectral range. *ALMA* will open a unique window that will allow us to search for new species. Space probes will bring new information to our understanding of the chemical composition of our primeval solar system cloud, that could be extrapolated to the dust around PNe.

10. EXTRAGALACTIC PLANETARY NEBULAE

10.1. *Chemical abundances*

Extragalactic PNe have been searched for in galaxies of all Hubble types because their study can shed light on a series of astrophysical problems. In recent years, much work has been devoted to determining chemical abundances in these nebulae as this knowledge helps us to understand, for example, galactic chemical enrichment with time, metallicity-galactocentric distance gradients and their temporal evolution, nucleosynthesis and evolution of central stars in different environmental conditions and at different metallicities. In addition, PNe in spiral and irregular galaxies give us the opportunity to analyze the chemical behavior of the ISM at the time of PN formation (from a few Gyr up to several Gyr ago), by determining abundances of elements not affected by stellar nucleosynthesis. The comparison of these abundances with that of the present ISM (represented by H II regions, HIIs), allows us to study the chemical evolution of the ISM, and to constraint chemical evolution models of galaxies. A recent review describing several results on these subjects can be found in Magrini et al. (2012).

10.1.1. *The available data for different galaxies and their analysis*

Spectrophotometric data for extragalactic PNe, in many aspects, allows a more confident analysis than for Galactic PNe since, in distant galaxies, usually all the nebula is included in the slit, and PN distances to the galactic center are better known than they are in the Milky Way. But PNe in external galaxies are faint objects and their chemical abundances are difficult to determine with precision, as they are based on the detection of the very faint lines necessary for plasma diagnostics. Thus, although large numbers of PNe have been detected in many galaxies, abundances have been determined in only a handful of them, mostly in Local Group galaxies and only a few farther away.

Therefore, we need to substantially improve the amount and quality of the data. New surveys of PNe and deep follow-up spectroscopy (especially of the faint ones in order to define the early and late PN evolution) with large-aperture telescopes are crucial. Such deep survey work has been successfully carried out in the LMC by Reid & Parker (2006a,b, 2013), increasing the known number of spectroscopically confirmed PNe from <300 to 705. These latest discoveries have extended the luminosity function four magnitudes below what was previously achievable (Reid & Parker 2010), estimating the number of PNe at each evolutionary stage compared to the luminosity and mass of the whole galaxy. Most recently, 2MASS and Spitzer SAGE[28] data for these PNe have revealed the relative contributions from H_2, PAHs, forbidden line emission, warm dust continuum and stellar emission at various bands according to the evolutionary state of the PN (Reid 2014).

10.1.2. *PNe in dwarf galaxies*

In the Local Group and its neighbourhood, PN abundances have been determined for several irregular galaxies: the Magellanic Clouds, IC 10, NGC 6822, Sextans A and B and NGC 3109 (see Leisy & Dennefeld 2006; Magrini et al. 2012; Hernández-Martínez et al. 2011; Magrini et al. 2005; Kniazev et al. 2005; Peña et al. 2007). PNe in the dwarf spheroidals NGC 185, NGC 205, M32 and NGC 147, companions of M31, Fornax and Sagittarius galaxies have also been studied (see Gonçalves et al. 2012a; Richer & McCall 1995; Richer et al. 1999; Kniazev et al. 2008, and references therein).

PN analysis in such galaxies has been used to study the evidence and efficiency of the third dredge-up (TDU) which carries O and other elements to the stellar surface. O and Ne abundances in PNe, compared to HIIs abundances, show that TDU has occurred in many PNe at low metallicities ($\log O/H \leq 7.8$; PNe in NGC 3109 and the one in Sextans A are the best examples). This is predicted by some stellar evolution models (e.g., Karakas 2010; Marigo 2001); however, not all metal-poor PNe show evidence of TDU. Thus, the efficiency of TDU seems to depend not only on metallicity but other phenomena are apparently playing a role too. Chemical analysis of a larger sample of PNe at low metallicities should improve our knowledge of TDU and provide better constraints for stellar evolution models (which should include more complete physics) and calculations of yields.

Similarly, the chemical behavior of PNe and HIIs in dwarf galaxies has also been used to test chemical evolution models of galaxies, such as IC 10 (Yin et al. 2010) and NGC 6822 (Hernández-Martínez et al. 2011). Although a "best fit" model is obtained in each case, the results are still not satisfactory. For IC 10, Yin et al.'s best models required a selective galactic wind, stripping mainly the heavy elements, which is

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[28] Surveying the Agents of a Galaxy's Evolution.

an ad-hoc solution difficult to justify. For NGC 6822, Hernández-Martínez et al. (2011) computed models constrained by data from two different-age PN populations and from HIIs, and they found that there is not a unique model fitting the data. Different combination of parameters (standard or selective winds, a different upper mass limit of the IMF, and different yields) can reproduce the observations adequately. So, more and better observational constrains are needed to properly test the evolution models. Robust abundance ratios such as N/O, Ne/O and He/H in bright and faint PNe are crucial in determining the stellar populations giving rise to PNe. In addition, the yields provided by stellar evolution models need to be revised: for instance, no model in the literature predicts N yields in agreement with the observations.

10.1.3. *Chemical gradients in spiral galaxies*

Radial abundance gradients derived for PNe, compared to HIIs and stellar gradients for several elements (O, N, Ne, Ar and S), have been analyzed in some spirals: M31, M33, M81, and NGC 300 (see Kwitter et al. 2012; Bresolin et al. 2010; Magrini et al. 2009; Stanghellini et al. 2010; Stasińska et al. 2013). Certainly, gradients in the Milky Way have been studied by many authors, [e.g., Henry et al. (2010); Stanghellini & Haywood (2010)], although in this case the uncertainties in PN distances are too large to derive confident conclusions. The results in common for all these galaxies are:

- At a given galactocentric distance, PN abundances show a much larger dispersion than HII region values. Such a dispersion is larger than the reported uncertainties.
- A global galactic enrichment with time is apparent in the sense that central O/H abundances are higher for HII regions than for PNe.
- The gradients from HIIs are steeper than those from PNe (this is marginal in M33). That is, chemical gradients seem to be steepening with time.

But the situation is far from satisfactory, because PN abundances at given galactocentric radii exhibit a large scatter, indicating that abundances in PNe are affected by factors still poorly understood (a mixture of populations could be one of them). Besides, even when O/H(PNe) < O/H(HIIs) in the center of the analyzed galaxies, at some galactic radius PN and HIIs gradients intercept and, in the periphery the opposite is found: O/H(PNe) > O/H(HIIs), which has no good explanation so far. This occurs in M31, M81, NGC 300 and also in our Galaxy (see Rodríguez & Delgado-Inglada 2011), being marginal in M33. Then, possible migration effects and contamination by stellar nucleosynthesis in PNe, or depletion of elements in dust in HIIs, could be artificially flattening the PN gradients in comparison to the HIIs gradients. These and other possible effects have to be analyzed carefully, before extracting conclusions about PN abundance gradients.

To improve our knowledge on the subjects mentioned above, it is imperative to analyze the chemistry of larger samples of extragalactic PNe (in particular the faint ones). Obviously, spectroscopy with large-aperture telescopes (8–10 m) is required (MOS mode is the most efficient technique). Well determined abundance ratios such as He/H, O/H, N/O, Ne/O will help us to better understand the nature of stellar progenitors of extragalactic PNe, and to better constrain the chemical evolution models of stars and galaxies. Certainly these models also need improvements. A better knowledge of the extragalactic PN populations will be very useful in analyzing the chemical and structural evolution of the parent galaxies.

10.2. *Kinematics*

The initial motivation for the discovery of extragalactic PNe was to use their luminosity function (PNLF) as a distance indicator (see a recent review by Ciardullo 2012). Having detected the PNe, this opened the possibility of using them as kinematic tracers in the outskirts of early-type galaxies (Hui et al. 1995). PNe were expected to confirm the universality of dark matter halos in all types of galaxies. In recent years the motivation has changed; now the main interest has become PN kinematics and abundance studies, and a PNLF distance is more likely to be a by-product of a kinematics-oriented PN search.

10.2.1. *PNe and Dark Matter Halos*

After the classic study of PNe in NGC 5128 (Hui et al. 1995), when more efficient methods for PN radial velocity measurements were implemented, the new PN data did not always confirm the presence of dark matter halos around elliptical galaxies. To explain this, several arguments were raised. First of all, the possible existence of radial anisotropy in the velocity distributions, which could mask the presence of dark matter (Méndez et al. 2001; Dekel 2005). But there was also some concern about the reliability of the PN radial velocities, and whether or not PNe could be trusted as kinematic tracers, because of possible stellar population effects.

After more work, this confusing situation has been partially clarified. The flattened elliptical galaxy NGC 821 was observed with two different telescopes, spectrographs, and slitless velocity measurement techniques (Coccato et al. 2009; Teodorescu et al. 2010). The PN identifications and radial velocities were in good agreement, and the existence of a Keplerian decline of the PN line-of-sight velocity dispersion was confirmed.

PN kinematics in a variety of galaxies (including spirals and starburst galaxies) have always agreed with other existing tracers like HI, CO or Hα data, where available for comparison. PNe are good kinematic tracers of the stellar population they represent (see Arnaboldi et al. 2012).

Finally, consider the massive Virgo elliptical galaxy M60 (Teodorescu et al. 2011), where there is independent evidence of dark matter, through the presence of hot, X-ray emitting gas. In this case, the PN kinematics support the presence of a dark matter halo. The total mass of this halo, determined using PNe, is similar to that estimated from globular cluster, XMM-Newton, and Chandra data in M60. Therefore, where independent evidence indicates the presence of an extended dark matter halo, PNe give compatible results.

10.2.2. *Open Questions and Future Prospects*

What remains for the future is to answer the fundamental question: what is the reason for the Keplerian decline of the line-of-sight PN velocity dispersion in galaxies like NGC 4697 and NGC 821: a comparative lack of dark matter, or radial anisotropy? On the one hand, theoretical modeling (De Lorenzi et al. 2008, 2009) shows that, if we *assume* radial anisotropy, the Keplerian decline can be reproduced in the presence of a dark matter halo. On the other hand, it is fair to say that nobody has shown definitive evidence that radial anisotropy *must* be present. One example is NGC 4697 (Méndez et al. 2009). The reader will find literature claiming that the best model for NGC 821 requires a dark matter halo; but this conclusion was obtained by ignoring the PN data points.

A way of breaking the degeneracy in this problem is to construct histograms of PN radial velocities at different positions across the galaxy. At large projected distances, the predominance of radial motions should produce a peaky distribution; close to the center of the galaxy, there should be evidence of a more flattened distribution (in extreme cases, a double peak would be expected).

Observationally, this is a difficult problem. To reduce the statistical noise, a large number of PNe is required, somewhere between 500 and 1000. Since PNe follow the light, there will be a low surface density of PNe at large projected distances. The solution is to detect fainter PNe, which requires a lot of large telescope time, and is complicated by an increasing contamination by emission lines from distant galaxies redshifted into the on-band filter used for PN detection. To illustrate the magnitude of the observational problem, consider that the total number of PNe at large projected distances discovered in NGC 4697 is 48 (Méndez et al. 2009). We would need to detect somewhere between 10 and 20 times more such PNe, distributed across a large field. This is not likely to happen before we have 30 meter telescopes.

There is a possible alternative in the direction to the core of the galaxy. Such regions have always been rejected as PN searching grounds, because of the very high surface brightness, which makes PN detection very hard if we use the classic onband-offband filter technique. Another complication is that the detected PN population will be dominated by those close to the core, which may not necessarily show as much anisotropy as those few which are more distant from the core.

A better way of detecting PNe in a strong background has been recently described by Sarzi et al. (2011). They used the SAURON[29] integral field spectrograph. Breaking the anisotropy-dark matter degeneracy will require an IFU spectrograph with a larger field of view, attached to a larger telescope. Such instruments will be available soon, and we can hope that this kind of observation will be attempted. Whatever the outcome, the resulting information would strongly affect theoretical efforts to understand galaxy formation. On the dark matter side, there has already been some work exploring how a lower dark matter content in intermediate ellipticals can be reconciled with the predictions from the current cosmological paradigm (Napolitano et al. 2005, 2009). On the other hand, a solid proof of radial anisotropy would be a valuable input for groups trying to simulate the formation of elliptical galaxies. What initial conditions dictate the presence of substantial radial anisotropy? This is a field where observations can guide theory.

We are far from having exhausted the information that can be provided by PNe in different kinds of galaxies. There have been studies of PN kinematics in one S0 galaxy (NGC 1023, Noordemeer et al. 2008, Cortesi et al. 2011), others are being studied in similar detail. Studies of PNe in face-on spirals can tell how the velocity dispersion perpendicular to the galactic disk changes as a function of distance to the center (Herrman & Ciardullo 2009), giving information about the mass-to-light ratio. Studies of PNe in edge-on spirals like NGC 891 (Shih & Méndez 2010) can tell how much angular momentum is associated with populations located at large distances from the galactic plane; which may turn out to be useful in understanding how spiral halos are formed.

10.2.3. *The PNe Luminosity function*

In the words of Ciardullo (2012), the PNLF method for distance determination cannot work, but it works very well anyway. In other words, we do not understand, theoretically, why the bright end of the PNLF shows its surprising invariance. Clearly this is a problem that will require future efforts. A solution to this

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problem can potentially teach us a lot about PNe (the old question surfaces again: how many PNe are the result of binary star evolution?) and their properties in different stellar populations.

Unfortunately, in the near future (before the advent of 30 meter telescopes), any satisfactory solution will cost large amounts of telescope time. A possible way of improving our knowledge of the PNLF would be to obtain deep spectrograms of those PNe that populate the PNLF bright end. Detection of diagnostic lines like [O III] λ4363 at distances larger than 4 Mpc is too difficult, but detection of Hα and Hβ would be easier, and would provide individual values of extinction and rough limits on the oxygen abundance (e.g. Méndez et al. 2005, on NGC 4697). It would then be possible to explore, for example, if internal PN extinction plays any important role, or to what extent the distribution of intensities of [O III] λ5007 relative to Hβ should be modeled more carefully in PNLF simulations.

Another way of testing how well we understand the PNLF is to detect fainter PNe, extending our empirical knowledge of the PNLF toward its faint end in many galaxies. But again, this will require long exposures with large telescopes.

In summary, we can expect a slow increase in the number of PNLF distance determinations (which are quite good!) but it is not clear if we can expect, in the short term, any sudden progress in understanding why they are good. The solution may have to come from other areas of PN research.

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