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COMMISSION H3 PLANETARY NEBULAE (Parent divisions H and G)

TRIENNIAL REPORT 2021-2023

1. Background

An IAU working group on planetary nebulae (PN) has existed since 1967, in charge of organising regular symposia in the field. The IAU Commission on planetary nebulae (H3) started in August 2015 under the leadership of Letizia Stanghellini. In 2018 Albert Zijlstra took over as commission president, and in 2021 Orsola De Marco took over with Magda Arnaboldi (Germany) as vice-president. The other commission members are Isabel Aleman (Brazil), Bruce Balick (USA), David Jones (Spain) and Toshiya Ueta (USA). Albert Zijlstra (UK) has served as a very active immediate past president. The commission currently has 84 members.

PN trace the end phase of the life of low-mass and intermediate-mass stars. These stars evolve up the giant branches, and eject their envelopes at the tip of the asymptotic giant branch (AGB). The star, now reduced to the C/O or Ne/O core, quickly evolves to higher temperatures, before nuclear burning ceases and the remnant joins the white dwarf cooling track. The expanding ejecta become ionised by the hot star, and the ionised ejecta forms the PN. PNe are short lived ($\sim$50 000 years), are very bright, and can be detected out to very large distances where the original star would have been undetectable. The emission comes out in the form of strong forbidden lines, which further aids the visibility.

PNe provide excellent tools for several important scientific problems, in stellar astrophysics, the interstellar medium and galaxies. The Commission supports research in PNe with particular emphasis on its applications in other fields.

(*a*) The ejection mechanism on the AGB stellar envelope is still very poorly understood. PNe provide a unique record of the mass-loss history of the progenitor star.

(*b*) The shaping of the ejecta is a topic of high scientific interest. PNe show a large variety in shapes, and in their structures can combine tori, disks, jets (sometimes with precession), globules, clumps and tails, halos and asterospheres. PNe are used to study the evolution of the structures, both using observations and hydrodynamic models. The origins of the asymmetries are studied, with a main focus on binary interaction, angular momentum, and magnetic fields.

(*c*) Common-envelope evolution plays an important in some PNe. A fraction of PNe contain short-period binaries with periods of order 1 day, which have passed through a common-envelope phase. The mass ejection during a common envelope is still very uncertain, and PNe are the best tracers of the end phase of their evolution, in terms of the final orbit and the ejecta.

(*d*) Abundances of light elements can be readily measured using both forbidden and recombination lines. These trace the abundances of the progenitor star, and any nuclear processing. PNe provide accurate abundances tracers also for older stellar populations, and can be used in galaxies where HII regions are absent.

(*e*) PNe are strong dust emitters, and they show many dust components including some not seen elsewhere.

(*f*) PN also contain large polycyclic aromatic hydrocarbons (PAH) molecules and fullerenes. The dust and molecules are known to have formed in situ. PNe can thus be used to study their formation and evolution.

(*g*) The bright lines allow for accurate velocity determination to within a few km/s. PNe are used to measure velocity distributions of stellar populations in distant galaxies, to measure galaxy potentials and dynamics.

2. Developments within the past triennium

2.1. *JWST early release observation and a Commission H3 Nature Astronomy paper*

In August 2022 JSWT's first images were unveiled in a press event. Several members of the PN community were pleased that one of the first light images was PN NGC 3132. However when the stunning images were presented, all PN scientists would have noticed an anomaly: the central star of PN NGC 3132 is a visual binary, where the A-type companion is very bright and the white dwarf central star is extremely dim and blue (as previously revealed by HST). The anomaly was that in the JWST multi-colour images the white dwarf appeared as brighter than its A-type companion and very red. Clearly there had to be a dust component to the white dwarf. This started a conversation among commission H3 members on whether we should do a press release. Soon it was decided this would be a small paper and we extended an invitation to the entire community to participate. To cut a long story short, the paper ended up being written for (and accepted by) Nature Astronomy and the author tally, by the end of the paper development was 70. The full story can be found in a Nature Astronomy Blog article authored by Orsola De Marco†. The paper raised a lot of media interest in many of the countries where press released were issued, with several paper and radio interviews.

Two additional papers on JWST data of PN have since been published by Roger Wesson and collaborators on the Ring Nebula‡ and by Jones et al. (2023) on SMP LMC 058. A few proposals have been approved in the recent JWST round.

2.2. *IAU Symposium 384; September 2024, Krakow*

The IAU Symposium on PN, with the title "Planetary nebulae, a universal toolbox in the era of precision astrophysics", took place in Krakow, Poland, on 4-8 September 2023. There were 104 participants from 27 countries. A total of 18 invited talks/reviews were presented, 9 by people identifying as women. An additional 50 contributed talk completed the programme. Twenty participants received travel grants for a total of 20 000 Euros. The SOC was composed of 16 researchers: Krzystof Gesicki (Poland), Denise Goncalves (Brazil), Amanda Karakas (Australia), Xiao-Wei Liu (China), Lynn Matthew (USA), Mirima Pena (Mexico), Laurence Sabin (Mexico), Carmen Sánchez Contreras (Spain), Ryszard Szczerba (Poland, co-chair), Albert Zijlstra (UK, co-chair), plus the 5 members of the OC and myself as chair.

The topics discussed were (i) PN are tools in the extra galactic distance scale and

† The article can be found here.
‡ Wesson et al. 2023, highlighted by NASA and ESA press releases, e.g., here.

in galaxy chemical evolution and kinematics. (ii) Chemistry in PN environments, from molecules to dust, particularly in the era of ALMA and JWST, with emphasis on yields and organic chemistry. (iii) Atomic abundance determination, including the challenges and discrepancies presented by different methods, as ways to assess the complexity of stellar evolution on the asymptotic giant branch, including mass loss. (iv) PN formation, including morphology in light of different energetic engines: from single star mass loss to binary mechanisms. (v) Synergies between PN and their central stars and other classes of stars, such as symbiotic binaries, white dwarfs and, importantly, transients. In the Section below the conference highlights are presented.

3. Planetary nebulae, some science highlights

In order to present a summary of where the field is at today, we report below, only slightly abridged, the excellent and colourful summary of IAU 384 by Joel Kastner. Talks and posters referred therein in italics are all going to be published in the upcoming proceedings of the conference.

"**Spectral multiplexing is driving the PN field forward.** Integral field unit (IFU) and multi-object spectrometers (MOSs) are enabling studies of extragalactic PN kinematics and abundances aimed at connecting and enhancing cosmic abundance evolution and extragalactic stellar population studies. Our present-day workhorses in this domain are PN.S, MUSE, GTC/OSIRIS, and (soon) SITELLE (talks by *Cortesi, Ennis, Bureau, Fang, Hartke, Arnaboldi*). The future of PNe as extragalactic probes undoubtedly lies in the coming generation of 30-meter-class Extremely Large (optical/IR) Telescopes (ELTs), equipped with even more powerful IFUs and MOSs, that will enable higher-z studies (*Stanghellini*). A selfish aside here: the dependence of extinction on progenitor mass seen in M31 (*Bhattacharya*) ties in nicely with what we know about Galactic PNe; solar neighborhood studies have long shown that the dustiest, most molecule-rich PNe are descended from higher-mass progenitors (e.g., Kastner et al. 1996).

ESA's *Gaia* Mission is (still) changing everything. In addition to providing parallaxes for a growing number of planetary nebula central stars, the exquisite precision of *Gaia* data impacts studies of the PN luminosity function (PNLF; more on that later) and Local Group stellar populations (*Hernandez-Juarez, Chornay, Manteiga*). Even with the new Gaia-imposed constraints, the properties of PN central stars remain intriguing and (often) elusive (*Souropanis, Montoro Molina*), although there is potential to unlock the mystery of the ultra-high-excitation (UHE) lines that are detected both in certain white dwarfs and in certain PN central stars (*Reindl*).

Nature still likes to confound us with PN mysteries. There appears to be a statistically significant alignment of the symmetry axes of bipolar PNe in the Galactic Bulge. What physical mechanism could possibly accomplish such an effect, if real? Unclear. (*Parker*)

The PNLF: it's baaaack! Like a venerable old rock band, the PN [O III] luminosity function (PNLF) seems to be embarking on a (Universal) Reunion Tour. First described and proposed as a potential rung on the extragalactic distance ladder in the late 1980's by George Jacoby & Robin Cardiullo (e.g., Ciardullo et al. 1989), the aforementioned IFUs and MOSs are now reviving and refining the PNLF, presenting new opportunities for its application as a secondary external galaxy distance calibrator (*Chornay, Roth, Adhyaqsa Soemitro, Schlagenhauf, Jacoby*). But the apparent invariance of the PNLF from galaxy to galaxy remains somewhat mysterious — if not quite as mysterious as the possible alignment of bipolar PNe in the Bulge — and so clearly could stand some additional, firmer theoretical underpinnings.

We learned about some new steps in that direction at this meeting (*Valenzuela*) — including, during discussion time, what I have dubbed "Jacoby's Law" (with apologies to George): *there exists a delicate balance between a stellar population's peak PN [O III] luminosities and the extinction caused by the copious dust production of these most [O III]-luminous PNe.* The "poster child" for Jacoby's Law is NGC 7027, which is the most [O III]-luminous known PN in the Galaxy and is also certainly among its dustiest. But NGC 7027's dizzyingly complex structure and rapid structural evolution should give even PNLF "true believers" pause. NGC 7027 makes clear how much more remains to work out theoretically, before we can understand why the PNLF appears to work as well as it does — and before it is even more widely applied, once ELT MOSs come on line.

PN abundance determinations are so essential, yet so tricky. As photoionization codes become increasingly sophisticated, even more care is required in interpretation of the results of such modeling (*Stasińska, Monteiro*). Extinction can be highly position-dependent, introducing additional complications (*Ueta*); NGC 7027 is again a case in point here. And in this same vein...

The ADF: after all these years, it's still haunting us. The abundance discrepancy factor (ADF) parameterizes the systematic discrepancies between elemental abundances as determined from collisionally excited lines vs. recombination lines. Like the PNLF, the physical origin of ADFs continues to defy easy explanation, but — given PNe serve as exemplars of the determination of elemental abundances in the Universe — the ADF is more like a zombie coming to eat us than an aging rock band on a reunion tour. Models invoking strong plasma temperature inhomogeneities appear to mitigate ADFs, but the devil remains in the details (*Méndez Delgado, Morisset*).

High spectral resolution can reveal details that are in fact not details. Examples of the diagnostic power and discovery potential of high-resolution spectroscopy presented at the meeting included s-process nucleosynthesis, line broadening due to turbulence, 3D structural modeling of PNe, and dynamics in the atmospheres of post-AGB stars (*Sterling, Richer, Derlopa, Pukitis*).

We now know everything we need to know about AGB stars necessary to model the AGB/post-AGB/PN transition. Well, just kidding. But single-star AGB evolutionary models have become remarkably sophisticated and predictive, thanks to five decades of excellent, hard work in this particular area (*Ventura, Mendez*).

We are still struggling to disentangle shock excitation and photoionization within PNe. Case in point: low-ionization structures (LISs). Newly revealed connections between "classical" LIS tracers (such as [O I] and [S II]) and both more highly ionized and neutral (molecular) gas in PNe might help distinguish between the effects of shocks vs. central star UV in LISs; but, even in these regions, it remains difficult to assess whether and where one process dominates over the other (*Belén Mari, Akras, Gonçalves*). And speaking of shocks: nearly ten years after completion of the Chandra Planetary Nebula Survey (ChanPlaNS; Freeman et al. 2014), the ChanPlaNS X-ray data are still providing useful insight into PN shocks and, in particular, the shock-temperature-regulating effects of heat conduction (*Montez*).

Ring Nebulae Rule! Or should I say: two rings, NGC 6720 (the Ring) and NGC 3132 (the Southern Ring), now seem to rule the (PN) world, thanks in large part to dramatic new JWST infrared imaging of both nebulae (De Marco et al. 2022; Wesson et al. 2023). Despite (or perhaps because of) the fresh JWST-enabled insight into the morphologies and compositions of these two nebulae, the 3D structures of both PNe were the subject of much discussion and debate at the meeting (*Monteiro, Wesson*). It is worth pointing out that, in the case of the Ring Nebula, this debate has been raging since at least the end of the 19th century. Fortunately, both NGC 6720 and NGC 3132 harbour large masses of cold molecular gas, such that mm-wave interferometric molecular line mapping — with its km s^{-1} radial velocity precision — likely offers our best hope of obtaining the detailed gas kinematics necessary to break the present morphological degeneracies between structural models for these two iconic Rings. Please read on...

Molecular line observations of PNe, especially by ALMA, are highly revealing. ALMA mm-wave molecular line and dust emission mapping is completely transforming the study of protoplanetary nebulae, PNe, and the AGB-PN connection. ALMA is dissecting "familiar" objects like M 1–92, M 2–9, AFGL 618, the Red Rectangle, and nearby bipolar nebulae (e.g., NGC 6445) to reveal their detailed kinematics and their molecular gas and dust structures and compositions (*Santander-García, Alcolea, Sánchez Contreras, Moraga Baez*). ALMA data is also further solidifying the connection between binary-induced spirals and detached envelopes in AGB ejecta, on the one hand, and spiral/arc/ring systems in PNe, on the other (*Kim, Toala*). More generally, molecular emission and absorption spectroscopy of PNe can shed light on UV- and X-ray-driven chemistry, making PNe excellent case studies through which to better understand photon-dominated regions and X-ray-dominated regions (*Ziurys, Black*).

PN remain essential laboratories for understanding the formation and survival of dust and complex organic molecules. PNe give us our last look at AGB-generated dust and simple molecules before these materials are incorporated into the interstellar medium (ISM) — and they offer our *only* look at the complex inventory of organics that is likely generated during the post-AGB/PN transition, and which then promptly seeds the ISM (*Dell'Agli, Huertas Roldán, Kwok, Cami, García Hernández, Matsuura, Bermúdez-Bustamante*).

Novae and supernovae can teach us a lot about PNe — and vice versa. We (still) stand to learn a great deal about PNe from efforts to observe and model these closely related objects, as well as stellar merger candidates (*Guerrero, Siebert, Quintana-Lacaci, Kamiński, Ritter, Hajduk*).

Oh yes, and jets. [...] all of these objects — novae, SN remnants, PNe — show evidence for jet activity (*Suzett, Soker, Planquart*) and so serve as potential touchstones to understand a wide variety of astrophysical jet sources, from young stellar objects to active galactic nuclei. New HST and ALMA results presented at IAUS 384 (*Balick, Sahai*) made clear that while such fast, collimated outflows are essentially a defining characteristic of bipolar/multipolar pre-PNe and PNe, the physics underlying the systems of "scattershot," episodic jets that shape these objects still remain to be worked out.

I close by posing what I believe are some key open questions in our field of PN research, and speculating about potential future studies and directions that might address these questions†.

What can PNe tell us about the evolution of light-element and s-process element abundances over cosmic time? IAUS 384 demonstrated that the time is ripe for comprehensive molecular line studies aimed at elucidating PN molecular chemistry. Such work can inform a disparate range of studies, from the effects of irradiation on molecular chemistry to tracing the origin and evolution of C, N, and O isotopic ratios. Clearly, the field of cosmochemistry also stands to benefit greatly from ambitious programs of spectroscopy of PNe in external galaxies on the forthcoming generation of

† The only thing of which I'm certain, in writing down these questions and speculations, is that this list is woefully incomplete.

thirty-meter-class telescopes. In the meantime, we'd best continue to try to understand the origin(s) of the PN ADF "anomaly" and its implications for tracing the chemical evolution of the Universe, as well as the physical basis for the apparent wide applicability of the PNLF.

How long do jet-tracing, PN-shaping shocks persist? Improved constraints on the timescales and "duty cycles" of PN-shaping jets will require concerted campaigns of contemporaneous JWST+HST imaging and spectroscopy of multiple shock tracers (e.g., [S II], [N II], [Fe II]) in PNe, as well as JWST+HST nebular feature proper motion studies spanning long temporal baselines. In addition, forthcoming eROSITA all-sky survey X-ray data should be mined for PN X-ray detections/nondetections, to ascertain the lifetimes of shock-generated hot bubbles that reveal interactions between active fast PN central star winds and slower-moving pre-PN (AGB star) ejecta.

How do binary companions affect late AGB and post-AGB evolution? In the Gaia era, we can and should now revisit (ZA)MS star binary statistics — mass ratios, separations — to understand whether and when binary companions influence mass loss processes as intermediate-mass stars climb the RGB and then AGB. In parallel, we will need families of models invoking truncated AGB evolution and/or binary-assisted mass loss, and detailed simulations of AGB mass loss in interacting multiple star systems.

How can we distinguish between common envelope (CE) vs. detached companion PN shaping scenarios? We need CE evolution and jet interaction simulations spanning larger ranges of size scales and timescales. In parallel, we need multiwavelength studies at high spatial and spectral resolution (e.g., HST, MUSE, JWST, ALMA) that can establish, among other things, the masses of ionized gas, molecular gas, and dust in polar lobe vs. equatorial plane regions of bipolar and multipolar pre-PNe and PNe.

Is there a logarithmic relationship between the number of stars required to explain a given PN's complex shape and the number of coauthors on the paper invoking that multiple star system? This is one key question it seems we *can* answer at present — in the affirmative — given the extant data (i.e., De Marco et al. 2022). But perhaps this important issue is nonetheless worth revisiting, at the next IAU PN Symposium. "

Excerpts from the talk by Joel Kastner, to summarise the recent IAU Symposium 834 on PN.

4. Planetary nebulae, commission H3 and the future

During IAU Symposium 384, Jan Cami, a delegate from the Canada, stated that "PN can solve any problem in Astrophysics". While this may have been an overstatement, it is certainly true that PN are a versatile tool in a surprising range of astrophysical domains. It is clear therefore that the way forward is an increase in the connections made to other fields both outwards (by ensuring representation of PN community members in non-traditional (for those members) meetings, soliciting invitations as well as holding PN meetings with mixed communities. This is easier said than done and testament to the difficulty of cross pollinating fields is that attempts have been made already for a while with only marginal results. Commission H3 should therefore actively determine how to enact this cross pollination.

Students and young researchers are the lifeblood of any field. In the field of PN they are doing tremendously exciting and transformative work. We need to encourage these junior researchers to speak at IAU meetings by actively seeking them out via their more senior mentors. We should continue to encourage their incisive questions concerning PN models, observations, and results and the myriad connections of PNe to other domains of astrophysics — and, indeed, we should invite junior researchers from adjacent fields to IAU PN meetings, so they can experience the excitement.

There is also an opportunity for H3 to take over the preparation of the monthly AGB Newsletter - taking over from the University of Keele.

Orsola De Marco
President of the Commission

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