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# Asymmetric Planetary Nebulae: what are we learning?

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**Summary.** This papers provides a summary of the research presented at the meeting on Asymmetric Planetary Nebulae IV, La Palma 2007.

## 1 The problem

This is the fourth meeting on asymmetrical planetary nebulae. A topic which manages to attract a large attendance four times within 15 years is clearly considered intriguing, as well as unresolved. So what are the questions that are being addressed? And from the research presented at this conference, can we find some indications towards their solutions?

The fundamental questions have not changed since the first conference of the series. What is the origin of the asymmetric structures evident in most, if not all, planetary nebulae (PNe)? When do the asymmetries first appear? And how do they evolve during the subsequent planetary nebula phase? A related question, surprisingly difficult to answer, is how common are the various types of asymmetries. Some of the proposed explanations for the asymmetries are so general that the existence of *any* symmetric PN would be unexpected!

The monologue below present a personal, and certainly biased, summary. It should not be used for original citations: reference should be made to the individual papers in the proceedings. To avoid the impression of a stand-alone scientific paper, I have avoided the use of citations all-together. The reader is referred to the entire proceedings for more general, and probably more valid, information.

## 2 Data

### 2.1 Catalogues

A major advance presented at this meeting is the number of newly discovered PNe in the galaxy. The majority of these come from the wide-field H $\alpha$  surveys of the Galactic plane. In the south, the MASH survey has been spectacularly successful. In the north, IPHAS is beginning to do the same work. Because the Galactic centre is

located in the southern hemisphere, southern surveys will be able to discover more objects. However, the extinction is more favourable in the north, so that northern surveys will be more complete. At present some 3000 PNe may be known in the Galaxy. Based on previous experiences, some fraction of these will be reclassified as different types of emission line objects at a later time. Still, given that the total number of PNe in the galaxy has been estimated as between 8000 and  $\sim 45000$ , a sizable fraction of the total is beginning to be known.

Our knowledge on the preceding evolutionary phase, represented by the post-AGB objects, is more restricted. This phase is shorter-lasting than the PN phase (although this depends on the core mass) and therefore fewer objects are expected: perhaps 1000–5000 in the Galaxy. The Torun catalogue currently contains over 200 pAGB objects. These objects are more difficult to classify than are PNe, and a larger fraction of mis-classified objects may be present.

## 2.2 Classification schemes

The most basic –and perhaps the most crucial– task is to classify the asymmetries present in the nebulae. Various schemes have been proposed, both at this meeting and in the past. No realistic study of the asymmetries can be made without such schemes. Still, the problems are major. With the current detail in the imaging data, the temptation is to classify all these details, and it may be difficult to distinguish the fundamental characteristics from the less important details. The sheer number of parameters required to describe the morphologies makes the detailed schemes difficult both to apply and to use.

Further development of the schemes should be done keeping a number of issues in mind. First, observed morphologies will appear very different (and may be more extreme) in scattered light (as in pAGB stars) from direct emission (as in PNe), and may be significantly wavelength dependent. Second, velocity structures are as important as density structures. Thirdly, the classification should ideally be based on theoretical models of the development of asymmetries.

## 2.3 Techniques

On the imaging side, advances have been spectacular. HST has been leading the push for better angular resolution, with the ACS giving the best quality images. It is however no longer the instrument giving the best resolution. Ground-based adaptive optics is still limited to the infrared and to small fields of view, but within its parameter range surpasses HST. Optical interferometry reaches resolutions of 10 mas or better, but only for simple structures and infrared-bright objects. The power of this method is shown by the discovery of solar-system-sized disks far within the much more extended pAGB objects and PNe. With the development of laser guide stars, multiconjugate AO and optical interferometry with more baselines and using shorter baselines, the quest for resolution will become more dominated by ground-based observations.

Space observatories are important for wavelength ranges where ground-based observing is not possible or too badly affected by the atmosphere. Spitzer is currently a clear example, although its imaging is affected by low spatial resolution. GALEX

is another example, with its surprising view of the Helix nebula. New ground-based facilities include the SMA, as precursor to ALMA.

On the spectroscopic side, the same observatories mentioned before have added new capabilities, where especially the Spitzer IRS should be mentioned. In the optical, the main advance is provided by integral-field spectroscopy. For extended objects, this is likely to make the traditional long-slit technique obsolete for most applications.

### 3 Results

It is not difficult to pick out important new results presented at this meeting; the difficulty lies in only picking a few!

#### 3.1 Structures

The most surprising discovery presented at this meeting may be the compact disks or flattened shells found inside PNe and related objects, with size scales of order 50 AU. Their role in shaping of the extended nebulae is not clear: they may be remnants of the shaping process, rather than originators.

Major advances have also been made in measuring the parameters of the flows. We now know much better, for instance, what the densities are within the polar flows as compared to the equatorial torii. A parallax distance to a water fountain nebula is also an important result. Velocity fields are beginning to be determined.

The role of asymmetries within AGB envelopes, as precursors to the PNe, has become more uncertain. In the past, a common feeling was that the asymmetries developed only after the AGB phase. But the discovery of asymmetric shells for some AGB stars shows that the development of the asymmetries, at least for some cases, occurs earlier than was thought a decade ago. However, an unbiased survey of AGB shells still needs to be done. The best evidence for *symmetry* during the AGB comes from the concentric shells seen around AGB and post-AGB stars. It should however be noted that these only require *velocity* symmetry: a spherically symmetric but time-variable velocity field can cause swept-up, concentric, symmetric shells to develop, even when the density field (or mass loss rate) is direction dependent. Thus, the evidence for symmetric AGB winds is much stronger for their velocity fields than for their density distributions.

#### 3.2 Evolution

The theoretical models for the evolution of the asymmetric structures are well developed and show many details which resemble those observed in reality. Some multipolar structures appear to be reproduced in models using a warped, compressible disk. The velocity fields are not always published, but are available from the model calculations. The main parameter in the models is the initial asymmetry, which becomes amplified in the subsequent evolution.

Direct evidence is now available for the evolution of the PNe structures. Expansion has been seen using images taking a few years apart: the high angular resolution now available can make such work routine for many nearby nebulae. The changes

seen in the structure of M2-9 over decades should be noted: these reflect not the evolution but the orbital motion of the illuminating star. The temporal changes provide a powerful tool with wide-ranging applicability.

The newly-named 'jet lag' can also be included in the evidence for evolution. The kinematic ages of the jets appear to be somewhat younger than those of the confining tori. This implies that the tori form first and the jets are a subsequent addition.

The importance of ISM interaction has become clear. This dominates the late evolution of PNe, and causes rebrightening of evolved nebulae. AGB envelopes are now also known to exhibit ISM sweep-up, leading to large (parsec-size) shells and/or bow shocks.

The development of the observed morphologies is best illustrated with the figure presented by Alcolea (these proceedings) based originally on work by Fong. It shows the presence of tori and jets, correlated with the position on the post-AGB tracks. This is potentially the best way to show the morphological evolution. This, and the other results, need to be compared with the theoretical models for structure evolution, providing a challenge for the coming years. The result of this will be an understanding of the initial asymmetries which drive the later evolution.

## 4 Origin

The two main models for the development of the asymmetries are both still alive. The traditional model is one where the AGB mass loss becomes equatorially enhanced, either gradually over time, or suddenly at the end of the AGB. The bipolar flows originate later in this model, when a faster wind blows into the pre-shaped ejecta.

The second model uses a secondary wind in the system. This star develops an accretion disk during the AGB, and a jet forms. The jet from the secondary star shapes the AGB ejecta, and compression from the jet may form the torus. In this model the shaping occurs earlier.

A third model invokes common envelope evolution. This model differs in that the driving mechanism for the mass loss is the common envelope, not radiation pressure.

The evidence currently does not decisively favour any of the models. The 'jet lag' found here suggests the tori may form before the jets, slightly favouring the first model. The fraction of post-common-envelope binaries among PNe is roughly 10%, and so the third mechanism is likely to present a real but minority evolutionary channel. The second mechanism operates among symbiotic systems (e.g. V Hya) but it is not proven that these evolve into PNe. It is plausible that all three mechanisms operate, hopefully not in the same objects!

Magnetic fields were given less attention at this meeting than previously. The current impression is that magnetic field by themselves are unable to cause the observed morphologies. Whether this shows a lasting change of opinion remains to be seen. The presence of magnetic fields is not in doubt, as for instance shown by the polarization measurements presented at this meeting which show a combination of toroidal and stretched dipole fields.

Angular momentum in a rotating star is of limited use in shaping a nebula, as it tends to be quickly lost as the AGB wind develops. The fact that horizontal branch stars in globular clusters rotate, but post-AGB stars do not, provides evidence for

this loss. Thus, another source of angular momentum is needed. During most of the stellar evolution, most of the angular momentum is in 'cold storage', as orbital motions of planetary or stellar companions. It can be made available either through common envelope or merger events (the 'minority' channel) or by interaction between the extended atmosphere and wind from the AGB star, and the companion. This last model has the strong point that the radius increase during the final phase of the AGB when the wind develops, explains the increased interaction—thus the angular momentum is made available at just the right moment.

A vote during the last session of the meeting showed that many people felt models should integrate both binary interaction and magnetic fields, rather than choosing between them.

## 5 Stellar evolution

An important question is which progenitors belong to which PNe. What are the initial masses, and what are the initial binary fractions and parameters?

An important constraint on the first question comes from the nebular abundances. Nitrogen enrichment is indicative of second dredge-up and indicates a progenitor mass above  $2 M_{\odot}$ . A carbon-rich nebula also indicates a more massive progenitor, although the mass range differs a lot between the Galaxy and lower metallicity systems (such as the LMC, SMC), and even between the inner and outer Galaxy. s-process elements are underexplored, but provide important tracers of the nuclear burning conditions, and can now be detected in PNe. Detailed models for the expected chemical enrichment as function of mass and metallicity are now available. The finding that carbon-rich PNe in the LMC are more likely to be bipolar is a good indication that progenitor mass is important.

The evolution following a very late thermal pulse (VLTP) is poorly understood. It leads to the ejection of a new, hydrogen-poor nebula located inside the older, first PN. It appears that the new nebula is often bipolar, while the earlier nebula is more or less round. The shaping mechanism is not known, but rotation of the stellar core may be more important during a VLTP event. The core is largely detached from the stellar envelope during the AGB. A surprising finding regarding the abundances of the VLTP ejecta is that recombination lines indicate a  $C/O \sim 0.05$ . This needs further work: if confirmed, either the mixing inside a VLTP star is very incomplete, or the ejecta predate the event.

Improved numbers on binary fractions were presented at the meeting. In a volume-limited sample, about half the objects show photometric indications for a companion, and roughly a quarter shows some evidence for close companions. Of the stars where close binaries are proven ( $\sim 15\%$ ) periods are in the range 0.2–4 days, with NGC 2346 at 16 days as the exception. The short-period objects have certainly passed through a common envelope phase.

Among post-AGB stars, our best estimate for the binary fraction is 100%. But their periods are of order 1 yr, and show essentially no overlap with the known periods among PNe, as if they trace different populations. Among early-AGB stars, about 10% are believed to be binaries but their periods are in excess of 10 yr. It is fair to conclude that we do not yet understand the observation evolutionary sequences for binaries.

Based on observed binary distributions of main sequence stars, 10-15% of stars are expected to experience common envelope evolution on the AGB, which is similar to the observed frequency of post-CE systems among PNe. Common envelope evolution is expected to lead to fast ejection of the envelope. The detailed properties of post-CE ejecta should differ of those of other PNe: no large envelope is expected, and the outflows are closer to ballistic. Observationally, PNe around such systems show rather irregular structures, with evidence for highly collimated jets. It is not clear whether dust would be expected to form in these ejecta.

Of particular interest is the case of common-atmosphere evolution. The extended atmospheres around AGB stars double the stellar radii and greatly increase the chance of interaction. Models for how such systems evolve are still being developed. Interaction between a companion and a stellar win can occur over very large distances. Mira has a companion at some 100 AU which is accreting from the wind and possible shaping the outflow as well.

The models for how the binaries evolve are impressive and make strong predictions. If we could define observational sequences of how the interactions occur and evolve, and how the binary separation evolves, it would allow immediate comparison with the models.

The AGB mass loss still presents a major uncertainty. Of relevance to this meeting is especially the effect of binarity on mass loss and mass-loss rates. Extensive models exist for mass loss rates for single AGB stars, and the expected rates are sufficient to form PNe. The PNe surrounding post-CE systems show that common-envelope ejection can also form a PN. However, we do not yet know how fast the ejection is and what mass-loss rates are reached. During the merger, the companion is strongly ablated and the material lost is a mixture of gas from both stars. It would be interesting to find evidence for this in the abundances.

We would also like to know how circumbinary disks form, and what fraction of the ejecta escapes and what fraction is caught. The fact that the disks sometimes have a different chemistry from those of the current AGB star suggests that the formation of the circumbinary disk may happen at a particular time and not afterwards.

## 6 Related objects

The physical processes acting on and causing the asymmetric PNe also occur in various types of related objects. The common theme is mass loss and mass transfer in a binary system. Mass loss occurs in evolved stars of both low and high mass, with a wealth of evolutionary sequences. Whether only the physics is related, or that asymmetric PNe fit on one or more of these sequences, is an important question which remains to be answered.

The most closely related systems are the symbiotic stars. Their binary parameters are often known (unlike for PNe), and they provide important laboratories to study the physics and the importance of accretion disks, high energy processes and mass transfer.

High-mass objects are also important. They are rare but easy to study due to their luminosity. The best known object is  $\eta$  Car. Its nebula shows a strongly asymmetric morphology, with some (perhaps superficial) similarity to Roberts 22. Strict periodicity in  $\eta$  Car provides the evidence for a binary companion. The ejecta

are much more massive than for PNe, but more important may be the interaction between different shells, possibly from different eruptions. SN1987A shows a very different circumstellar environment to  $\eta$  Car, showing that high-mass stars also show a variety of evolutionary sequences. Because high-mass systems are rare, the details of the different types of interactions are perhaps more easily studied for lower-mass stars.

The question arises whether only evolved stellar systems show these physical processes. Pre-main sequence stars also experience mass ejection, however their environment is made more complicated by the recent or on-going accretion and the invariable presence of circumstellar disks. In some cases, PNe could also show relic original disks.

## 7 The Future

The conference showed real progress in the field. What used to be viewed as the study of separate, non-representative objects showing rare evolutionary events, has over the past decade become the most important area of activity within the field of PNe. The study of a few disparate objects has become a strong and unified line of research.

So what are the main questions we would like to see answered or at least addressed over the next few years? And what are the techniques we should use?

In my opinion, the following are important questions raised at this meeting, for which only partial answers are available:

1. What are the binary parameters of the asymmetric PNe? Or can we find evidence of single stars within asymmetric PNe? The proposed binary companions have proven surprisingly elusive, and nothing is known about companions with orbits large than a few days.
2. What is the role of magnetic fields? Their presence in the circumstellar nebulae is now well established, and the field structure appears to be related to the nebular morphology. But the interaction between the field and the morphology is still uncertain.
3. What is the role of the compact disks which are being discovered? They are tiny compared to the size of the PN, but are they left over from the original shaping process? And is there any evidence for accretion from these disk?
4. What is the percentage of stars for which the mass loss rate (as opposed to the morphology) is affected by a binary companion? This will include all objects for the mass ejection followed a common envelope phase.

As to techniques, two clear points arose from the meeting. First, there is the growing importance of integral field spectroscopy. It is now possible to measure not only the morphology, but also the velocity fields. Second, theory and observations need to be used together. For the observers, it is important to obtain those data which will be important tracers of the physical processes. From the theoretical work, it is important to find those tracers. Papers based on theoretical modelling can only present a fraction of the information which is present in the models: the choice should be based on predictive power and observational testability.