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Planetary Nebulae: Emerging Directions and Critical Research

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Abstract. The number and significance of the contributions presented at this meeting – the third in a series focusing on the asymmetrical structure of planetary nebulae and the origin of that asymmetry – shows the fruitfulness of this line on inquiry.

1. Introduction

This is a "sampler" of the large amount of interesting work presented at this meeting. I have restricted my attention to planetary nebulae (PNe) and have excluded, for the most part, proto-planetaries and AGB stars. Even so, I can hardly do more than present a list of what caught my attention.

Some areas where interesting advances have been reported:

- Morphology & Dynamics
- Spectroscopy
- X-rays
- Photoionization Modeling
- Central Stars
- Hydrodynamic Modeling
- The Role of Binaries

2. Morphology & Dynamics

The complex symmetries revealed by morphological studies were a key impetus for the whole line of investigation which the APN conference series has explored. A number of new morphological studies were presented here. When combined with velocity data, the value of the results is greatly increased, as this strongly restricts the hydrodynamic origin scenarios. These studies have revealed ever more elaborate "point symmetry" (Icke: mathematicians call it antisymmetry). For example, Corradi showed "Hubble-like" flows in some PNe. A study of IC 4634 by Guerrero shows elaborate symmetries reminiscent of NGC 6543.

Astrometric measurements with the HST have also revealed complex and puzzling motions. Balick mentioned the (surprising!) result that in NGC 6543, the equatorial ring is the most rapidly expanding feature.

The faint circular rings which have been found around some bright PNe now appear to be **common** features, and seem to appear around many PNe if we can take deep enough images (Su; Corradi). In IRC+10216, a younger object, they are seen in CO velocity slices to be true expanding spherical shells (Feng). These rings are important features because they show that a spherical mass-loss phase has preceded the later, asymmetric main ejection. The mechanism to produce the observed periodicity (spacing) remains uncertain. Suggestions include: (a) some form of stellar wind instability, or (b) H-burning (as opposed to He-burning) shell flashes.

3. Spectroscopy

One of the surprising spectroscopic results was the detection of lines of rare s-process elements. Two lines in the infrared are due to Krypton (Kr) (2.2 μm) and Selenium (Se) (2.3 μm) (Sterling). In the UV, the FUSE satellite has detected lines of Germanium (Ge) (Dinerstein). These new lines may be important if they allow the determination of abundances, since this will put constraints on s-process nucleosynthesis in the progenitor stars.

4. X-Rays in PNe

An image that is both beautiful and suggestive is the now familiar composite of NGC 6543 which combines Hubble WFPC data with the Chandra X-ray data. The X-rays are seen to fill the inner bubble and extend into secondary bubbles that grow from the ends of the main bubble. The temperature of the X-ray emitting gas is well determined at 2×10^6 K (Chu).

Observations of extended X-ray emission from PNe are important because they give us direct evidence of the high temperature phase. They are a validation of the two-wind model in the broadest sense: we see the shocked stellar wind filling the wind-blown inner bubble. But beyond this, questions arise: why is this hot gas non-uniform, and why is it much cooler that naive theory would predict? Suggestions include the adiabatic cooling due to the expansion of the bubble or the possibility that the stellar wind velocity was lower while most of the shocked wind was accumulating. Another possibility is to invoke some interaction of the multi-million degree shocked wind and the nebular gas, either through conduction at the bubble edge, or through mass-loading during the growth of the bubble.

With regard to conduction at the interface, Chu reported FUSE observations of O VI lines from the (100,000 K) transition layer. If this leads to a determination of the energy loss from this layer, we could then see if there is significant heat conduction from the shocked wind. Observations of this transition layer should be pursued, for there is a lot of interesting and complex physics here.

5. Photoionization Modeling

There seems to be less developmental work in this area than is the past, but photoionization modeling remains an indispensable tool. There is widespread use of CLOUDY, which is up to date, well tested and well documented. CLOUDY continues to evolve; the new dust physics was discussed in a poster (van Hoof).

A notable new entry is the 3D code MOCASSIN, which features a Monte Carlo radiative transfer algorithm (Ercolano). This makes it possible to treat all sorts of complex geometries, such as dense knots within nebulae and their shadows (Morisset). An interesting application of the code has been made to the H-poor knots in Abell 30, which have extremely strong heavy element recombination lines. Observations could be matched after the inclusion of heating by dust photoelectrons, and knot abundances were derived (Ercolano).

Knots (globules) are important. Where we have the resolution to see them, we find they make up a large fraction of the nebula (Huggins; Meixner poster on the Helix). They cannot be ignored in interpreting the spectra of planetaries. It has been argued that globules form after the initial AGB outflow.

6. Central Stars

Advances continue in modeling the atmospheres of the central stars of PNe. The challenges are significant, as the stars often have winds – optically thick in the case of the Wolf-Rayet stars – and non-LTE treatment of the lines is essential. In addition, we can only observe a small fraction of the star's flux, most of which is in the unobservable far UV. At this meeting, a poster by Koesterke presented a fit to the UV observations of NGC 1535. An important approach, which is more demanding, is to model the nebula simultaneously, so that the far UV radiation is constrained as well.

7. Hydrodynamic (& MHD) Modeling

Good progress is being made with hydro codes as modelers try to meet the challenge of the increasingly complex structures presented by the observers. But the focus has now shifted to the **proto-**PN stage as the origin of complex structures. Some results presented at this conference:

- Icke stressed the importance of cooling in generating complex structures. Cooling of shocked gas will be more likely in earlier stages where the densities are higher and stellar winds may have lower velocities. A poster by Rijkhorst showed that the introduction of a warped disk can produce point symmetric structures.
- MHD disk winds seem able to power the flows seen in proto-PNe (which *cannot* be driven by radiation pressure) (Frank). Are these disks only present in the proto-PNe stage or do such winds ever persist into *mature* PNe?
- More observational material has been obtained on interactions of PNe with the ISM (Kerber). Villaver reported on 2D hydrodynamic models of such PN-ISM interactions made with the ZEUS code.

8. The Role of Binary Central Stars

The role of binary central stars in the formation of PNe and in the production of asymmetry remains the big question. In the first place, the basic structure of most PNe displays an overall axial symmetry which is not easily explained by mass ejection from an isolated isolated, slowly-rotating AGB star. Secondly, we also observe phenomena such as complex point symmetries, bipolar outflows, and jets. These features all seem to point to the existence, at some time during the formation of the nebulae, of accretion disks.

The only obvious way to spin up a slowly-rotating AGB star is with a companion – stellar or perhaps sub-stellar. And accretion disks in evolved stellar systems invariably arise as a result of mass transfer in close binary systems. Is this the case with PNe as well?

We know from the very existence of short period eclipsing binary nuclei and photometrically variable nuclei that strong interactions between these stars had to occur during the ejection of the nebula: the present separation – less than the size of the AGB star – could only arise this way. As of a few years ago, attempts to extrapolate the number of known close binaries to the general population indicated that about 10% of all PNe could fall into this category (Bond). So this did not seen to provide a *general* solution to the asymmetry problem.

But could the fraction of PNe with the companions be higher? The direct search for binary nuclei is difficult, but is extremely important. This search goes on and more nuclei with companions are being found (Pollacco). It now appears that *most PN nuclei are binaries.*

A number of years ago, the suggestion that the ejection of essentially all observed PNe was the result of the interaction of the central star with a companion seemed more provocative than serious. It has now become a serious proposition. For if we can appeal to companions only half the time, that does not solve the asymmetry problem. But if companions are almost always involved – except for those rare, perfectly round PNe – then what happens to single stars? Could it be that they die so quietly that we don't even notice their mass loss?

The question remains, and it's still the big question.

References

Since all the names referred to in the text indicate contributions to this volume, a formal reference list seems unnecessary.