A Grand Challenge for PNe

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Summary. The field of PN studies has been confronting a growing list of dilemmas which have yet to find coherent resolution. These issues are both observational and theoretical and can be stated as a series of "facts" which can not, as of yet, be accounted for via a single framework. We review these facts and propose a skeleton framework for developing a new understanding post-AGB stars, PPN and PN. Our framework represents an attempt to articulate a a global perspective on the late stages of stellar evolution that can embrace both the nature of the central engine and the outflows they produce. Our framework focuses on interacting binary central stars which drive collimated outflows through MHD processes. We propose that the field of AGB/PN studies now faces a "Grand Challenge" in articulating the observational systematics of these objects in a way that can address issues related to binarity and magnetic shaping. A theoretical Grand Challenge is also faced in the form of integrated studies which can explicate the highly non-linear processes associated with MHD outflows driven by interacting binaries. These issues include the generation of magnetic fields via dynamo processes, the creation of accretion disks, the dynamics of Common Envelope ejection and the creation of magnetized jets.

1 Method

Since the onset of high resolution observational platforms, such as the Hubble Space Telescope, the field of planetary nebula (PN) studies has confronted a growing list of paradoxes or dilemmas which have yet to find coherent resolution. The dominant paradigm of single star evolution (Iben 1995) coupled with hydrodynamic interacting wind scenarios (e.g., Icke, Balick, Frank 1990, Frank & Mellema 1994) is only able to explain a subset of the total mature PN population and fails entirely to explain the properties of pPNe (Sahai & Trauger 1998). This is an exciting time in PN studies as the new mechanisms being explored speak directly to some of the most important unsolved problems in astrophysics such as the nature of dynamo generated magnetic fields, accretion disk formation processes, collimated stellar explosions, stellar evolution in the context of binary stars and the interaction of jets and outflows with surrounding environments.

Progress forward requires systematic exploration of both observational and theoretical issues. The purpose of this contribution is to provide an outline, in terms of justification, for a new framework for PN studies. We first provide a list of observational results or "facts" which have not, as of yet, been fully accounted for within traditional models. Next we provide a list of theoretical results or "facts" which point to the need for development of a new global framework for studying PN systems outside of traditional single-star, radiation driven models. In the final section we link observation and theory and propose a series of postulates that can serve as a straw-man for developing a paradigm for understanding PN and their related phenomena in a global evolutionary context.

Observational Facts

1. **PPN Momentum Excess:** The linear momentum observed in the majority of PPN outflows is higher than can be accounted for by radiation driving from the central star even when multiple scattering is included. These momentum excesses are typically of order 1000 or higher (Bujarrabal et al. 2001).
2. **Nebular Bipolarity:** All PPN and all very young PNe appear bipolar or multipolar (Sahai & Trauger 1998) even though all PN halos are spherical or mildly elliptical (Corradi et al. 2003).
3. **PPN and PN collimated structures:** Highly collimated structures, possibly jets exist in many PPN and PN (Balick & Frank 2002 and references therein.
4. **Post-AGB Binarity:** Virtually all post-AGB stars with dust tori (which may be disks) have a binary companion. Typical periods are short enough to infer some form of interaction $100 < P < 1500$ days (van Winckel 2003).
5. **CSPN Binarity:** $> 10\%$ of central stars of PN have close companions and $> 10\%$ have wide, non interacting companions, one system is a triple (Bond 2000; Ciardullo et al. 1999).
6. **Magnetic Field Detections:** Magnetic field measurements, while difficult, have been made in both nebular systems and their central engines. Fields have been observed in 4 central stars as well as in a variety of AGB, pAGB/PPN and PN (Jordan et al. 2005; Vlemmings et al. 2006; Sabin et al. 2007).
7. **H-deficient central stars:** $15 - 20\%$ of all central stars are H-deficient. Most of these exhibit O and C dual dust chemistry.
8. **The PN Luminosity Function:** There is a ubiquitous population of bright PNe that have the same brightness (the bright edge of the PNLF). This is in glaring conflict with predictions from population syntheses and stellar evolution models which predict older galaxies to have overall fainter PNe (Marigo et al. 2004). Theory therefore predicts the PNLF should not to be a distance indicator, but practice demonstrates the PNLF to actually be an accurate distance predictor.
9. **Bipolar PNe Scale Height:** Bipolar PNe tend to have a lower scale height and tend to be Type I. This is interpreted as meaning that more massive starts produce bipolar PNe (although this well known observation is in doubt in the LMC).
10. **PN Abundances:** There is a discrepancy between PN abundances from optical recombination vs. forbidden lines. This discrepancy is alleviated by allowing small H-deficient clumps in the PN, however a physical reason for the existence of such clumps has yet to be found.

Theoretical Facts

1. **MHD Shaping:** The shapes of many bipolar PN and PPN can not be accounted for with the classic hydrodynamic Generalized Stellar Wind model. MHD models, even those invoking weak magnetic fields, can produce a wide range of PN shapes (Garcia-Segura et al. 1997, 1999).
2. **Magnetic Fields and Momentum Excess:** Magneto-centrifugal launch (MCL) processes invoke a rotating central source and magnetic field (Pudritz 2004). These models can recover the high outflow momentum and energy observed in PN systems. Thus MCL models can both launch and collimate PPN/PN outflows (Blackman et al 2001a,b, Frank & Blackman 2004).
3. **Magnetic Fields and Short Acceleration Timescale:** The short acceleration timescales implied for many PPN flows can be accounted for via MCL models in which differential rotation in the central source produces strong toroidal field gradients which drive a "magnetic explosion" (Matt, Frank & Blackman 2006). The fragmentation of the expanding shell produced in such an explosion may provide a reasonable account for some multi-polar outflows (Dennis et al 2007).
4. **Magnetic Fields and Angular Momentum:** MCL models require relatively strong magnetic fields. These fields will require the action of a dynamo (Blackman et al 2001). Theoretical models show that it is likely that such fields cannot survive across the AGB unless a binary companion acts to provide the angular momentum lost in each dynamo cycle (Soker 2006, Nordhaus, Blackman & Frank 2006).
5. **Binaries and Disks:** Circumbinary disks in PPN systems, now observed in a variety of cases, can form in a variety of ways including common envelope evolution (Nordhaus & Blackman 2006) and Bondi accretion of the AGB wind (Soker & Rappaport 2000).

2 Towards a New Paradigm

Below we provide postulates that follow from consideration of both the observational and theoretical facts.

1. **Almost all PN form from binary interactions including common envelopes:** *Required observations:* Systematic photometric variability (see D. Shaw's contribution) and radial velocity studies (see O. De Marco's contribution) of central stars of PPN and PN. Goal: determine the frequency and period distribution of binaries. Systematic spectro-photometric monitoring study. Goal: determine the properties of all known binaries (companion masses, orbital parameters, secondary irradiation characteristics) as well as those of their PNe (see B. Hrijvnak's and D. Frew's contributions).
2. **Accretion disks will determine structure of many PPN:** *Required observations:* Systematic search for accretion disks in PN and PPN (by small scale photometric variability, X-ray detections [H emission lines likely contaminated by PN]).
3. **Binary interactions (avoiding common envelope) = binary pAGBs with circumbinary excretion discs:** *Required theoretical program:* Determine

how intermediate separation binaries result in a massive, circumbinary disk. How do disks evolve in time? *Required observations:* Use systematic modeling of IR observations of systems known to have circumbinary dusty disks to determine properties.

4. **Binary interactions provide initial conditions for MHD launching:** *Required theoretical program:* A multi-dimensional numerical study of common envelope evolution and disk formation via a variety of mechanisms including mass transfer and wind capture and tracking energy deposition within the common envelope.
5. **Dynamo generated stellar fields will dominate evolution of PPN/PN:** *Required theoretical program:* Related to the point above this postulate requires systematic study of dynamo processes in AGB stars in both single stars and binary stars. The potential for single stars to maintain strong fields via recirculation must be ascertained. Include development of multi-dimensional numerical simulations appropriate to stellar interiors.
6. **Magnetocentrifual launching accounts for PPN/PN morphologies:** *Proposed theoretical program:* A systematic study of MCL models in the context of PPN/PN central source configurations must be carried forward. The generation of outflows from transient MCL driven magnetic explosions as well as more continuous outflow produced by accretion disks must be explored.

Conclusion: Our proposal that the majority of PN are shaped by binary stars and MHD processes holds promise for uniting the disparate observational and theoretical results cite above. We note that many individual facets our proposal has been discussed before by other workers. Our goal is to draw these together in a new synthesis which provide a direction for future coordinated work. We make this proposal with the understanding that much of the heavy lifting to prove, or disprove, our proposal has yet to be done. However it is noteworthy that the investigation of this paradigm will shed light not only on PN but also on other phenomena (YSOs, AGN, micro-Quasars, GRBs) currently at the forefront of astrophysical research.

References

1. Bujarrabal, V., Castro-Carrizo, A., Alcolea, J. & Sánchez Contreras, C., A&A, **377**, 868 (2001)
2. Bond, H.E. 2000. ed. JH Kastner, N Soker, S Rappaport, 199:115. San Francisco: Astron. Soc. Pac.
3. B. Balick, & A. Frank, ARAA, **40**, 439 (2002)
4. E.G. Blackman, A. Frank,& C. Welch, ApJ, **546**, 288 (2001)
5. Blackman, E. G., Frank, A., Markiel, J. A., Thomas, J. H., & Van Horn, H. M. 2001, Nature, 409, 485
6. Ciardullo, R., Bond, H. E., Sipior, M. S., Fullton, L. K., Zhang, C.-Y., & Schaefer, K. G. 1999, AJ, 118, 488
7. Corradi, R. L. M., Schönberner, D., Steffen, M., & Perinotto, M. 2003, MNRAS, 340, 417
8. T.J. Dennis, A.J. Cunningham, A. Frank, B. Balick, E.G. Blackman, & S. Mitran arXiv:0707.1641 submitted to ApJ (2007)
9. Frank, A., & Blackman, E. G. 2004, ApJ, 614, 737

10. G. García-Segura, J.A. López, & J. Franco, ApJ, **618**, 919 (2005)
11. Jordan, S., Werner, K., & O'Toole, S. J. 2005, A&A, 432, 273
12. S. Matt, A. Frank & E.G. Blackman, ApJl, **647**, L45 (2006)
13. M. Moe & O. De Marco, ApJ, **650**, 916 (2006)
14. Marigo, P., Girardi, L., Weiss, A., Groenewegen, M. A. T., & Chiosi, C. 2004, A&A, 423, 995
15. J. Nordhaus & E.G. Blackman, MNRAS, **370**, (2006)
16. J. Nordhaus, E.G. Blackman, & A. Frank, MNRAS, **376**, 599 (2007)
17. R.E. Pudritz, *Accretion discs, jets and high energy phenomena in astrophysics.* Eds. V. Beskin, G. Henri, F Menard, et al, Les Houches Summer School, **78**, 187. (2004)
18. Sahai. R., Trauger, J.T. 1998. AJ 116:1357
19. Sabin, L., Zijlstra, A. A., & Greaves, J. S. 2007, MNRAS, 376, 378
20. Soker, N. 2006, PASP, 118, 260
21. Soker, N., & Rappaport, S. 2000, ApJ, 538, 241
22. W.H.T. Vlemmings, P.J. Diamond, & H. Imai, Nature, 440, **58** (2006)
23. van Winckel, H. 2003, ARA&A, 41, 391