White paper: the Rochester Collaborative

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1 Motivation

On June 17-19, 2009 a workshop took place in Rochester, NY, USA, to define key problem areas in the field of planetary nebulae and the evolution of intermediate mass stars. The overarching aim was to determine groups of projects that could be achieved with current and next generation of observational and computational facilities. A second aim was to seed medium and large collaborations that could develop, propose and carry out these projects. This white paper is designed to stimulate conversations in view of the forthcoming meeting on Asymmetric Planetary Nebulae, which will take place in June 2010. In this document we summarise the discussions of three panels, each involved in one of the areas of AGB, post-AGB/PPN and PN research.

2 Background and introduction

Stars between ∼1 and 10 $M_\odot$undergo two phases of expansion, one after core hydrogen runs out, called the red giant branch (RGB) and a second following core helium burning, called the AGB. At the end of the AGB phase the stellar wind (with speeds of 10-15 km s^{-1} and mass-loss rates $\sim 10^{-7}$ $M_\odot$ yr^{-1}) unexpectedly increases in intensity with mass-loss rates surging to as much as 10^{-4} $M_\odot$ yr^{-1} (Delfosse et al. 1997). This super-wind phase quickly depletes the AGB envelope till, when the envelope mass falls below 10^{-3} -10^{-4} $M_\odot$. At this point the stars structure changes as the photospheric radius shrinks and stellar effective temperature rises. The mass-loss rate of the star drops to 10^{-8} $M_\odot$ yr^{-1} while the wind speed increases to ∼200-2000 km s^{-1}. The evolving wind parameters should lead to violent circumstellar gas dynamics as fast wind plows up the material ejected during the super- wind phase. The resulting sculpted circumstellar gas distribution is then ionized by the heating central star, at which point we call it a planetary nebula (PN; Iben 1995).

The range of PN shapes are explained by the interactive wind model (IWM; Kwok et al. 1978). The super-wind is assumed to depart from spherical symmetry so that the resulting nebula should not be spherical. Later modications, known under the name of Generalized ISW (GISW; Icke 1988; Icke et al. 1989, 1992; Soker & Livio 1989; Frank 1994; Mellema 1994, 1995; Mellema & Frank 1995; Garcia-Segura et al. 1999) has achieved some success in terms of modeling PN gas density structures, kinematics and morphology (at least for the main body of the PN). However, these models assume both super-wind triggering and superwind geometry both of which are key features that a complete model would explain. We can all agree that a complete model for the evolution and shaping of PN needs to explain the surge in mass-loss rate called the super-wind, and the origin of AGB and post-AGB mass-loss geometries, rather than assume them. The question then becomes what mechanisms lead to a consistent model of both stellar and nebular evolution.

For the last two decades the community has debated whether stellar rotation and global magnetic fields can be sustained in single AGB stars and thus confer non-spherical morphologies to PN (e.g., Morris 1987; Soker & Livio 1989; Soker 1997; De Marco 2006; Zijlstra 2007, but see also Bond et al. 1978). Recently, the debate has been rekindled (Soker 2006b; Nordhaus et al. 2007) by the argument that in a large majority of cases, single AGB stars are unlikely be able to sustain large-scale magnetic fields for long enough to affect shaping. This time limit comes because the field drains the star of angular momentum on short time scales and quenches its own growth. As the models of, e.g., Garcia-Segura and collaborators have shown, magnetic fields can be an effective ingredient in shaping many PN, but in those models the magnetic field strength was assumed constant and did not include feedback of the field on the stellar envelope and envelope on the field. When one includes the feedback it appears that, without an additional source of angular momentum, the field would vanish before the post-AGB phase. An angular momentum source could effectively be provided by a stellar or sub-stellar companion. To these theoretical concerns, we add a long list of observational conundrums, which will be explained in detail in SS **??**, **??** and **??**.

An overarching issue that has plagued all research in PN and adjacent evolutionary phases has been the lack of homogeneous samples. This has in part been due to the notorious difficulty to determine distances to PN. Today, thanks to surveys such as the MASH survey, PN samples have not only been incremented and completed with fainter specimen, but a new distance method has been calibrated that can determine distances with precisions of ∼20%. This new method has allowed the creation of volume limited samples, a tremendous new asset in studying PN. In addition, the techniques used to vet PN for inclusion in the new distance scale, have allowed to generate new ways of excluding PN mimics from the sample, increasing the purity of the samples to be used in further studies.

These difficulties and the increasing competitiveness of major observational platform, dictate a need to form medium-to-large collaborative effort to tackle problems via concerted observational programs. Below we summarise the recommendations of three panels, each reviewing issues and solutions in three separate evolutionary phases: the AGB phase, the post-AGB (pAGB) or pre-PN (PPN) phase and the PN phase proper. Most of these efforts will be the most productive provided that they are executed by coordinated teams of people with a wide range of perspectives and skills. This balanced team approach is not only synergistic, it also is essential if large amount of scarce telescope time is to be obtained at key facilities and funds are to be found for capital investments in computers. Wherever possible the foundations of the research programs should be built on surveys conducted by students on smaller telescopes equipped with modern IR and optical cameras, narrow- or medium-band filters or good spectrographs, and adequate available time to take risks. The engagement of students and a multi-faceted community in research initiatives are key investments for continued vitality in this field.

3 The AGB Panel

The key mechanisms responsible for PN shapes has roots in the AGB. The key unresolved issues for AGB stars is how their super-winds are triggered and what mechanisms change their mass-loss geometries.

3.1 Major unsolved problems in the AGB phase

AGB superwinds: if AGB star progenitors are more massive than 2.5 $M_\odot$, it is possible that a simple Reimers-type mass-loss (Reimers 1975) can eject the required amount of mass in a relatively short time at the end of the AGB phase. However, on average, most PN evolve from less massive a progenitors even in the younger Galactic thin disk (Moe and De Marco 2006). As a result we are still need a mechanism that can initiate the super-wind for the bulk of the population. It is possible that the mass necessary for a single star to initiate its own super-wind might be chemistry and metallicity dependant. If so, carbon-rich AGB stars would have a greater ease in promoting the super-wind (and could do so at lower mass) than oxygen-rich ones, and Magellanic Clouds stars would always find it more difficult to promote the super-wind and would only do so at larger mass (Lagadec et al. 2008). While it is hard to imagine that binary interactions are the only way to enhance AGB mass-loss, common envelopes and other types of close binary interactions have the capability of initiating a super-wind phase and remove the AGB envelope.

AGB superwind geometry: for a long time it was thought that the AGB mass-loss geometry was spherical (Olofsson 1999 and references therein) with very few systems deviating from sphericity (e.g., V Hya, X Her; Kahane & Jura 1996, Kahane et al. 1996b). The change to axi- or multi-symmetric mass-loss happened at some point during the post-AGB evolution. Now we are finding that many AGB stars already possess a non-spherical mass-loss (Castro-Carrizo et al. 2007). Future work will reveal how many and what types of AGB stars have non spherical mass-loss and the relationship between asymmetries in mass-loss and the presence of a binary companion.

AGB Binaries. AGB star binaries of interest to the current problem are those where a companion is close enough so that Roche Lobe overflow, tidal capture or wind accretion are likely to take place upon further expansion of the stellar envelope. However, the difficulty of detecting faint companions directly in the proximity of very bright, windy and dusty AGB stars has limited the number of systems known (see also Jorissen and Frankowski (2008) for a review of how to detect binary AGB stars). RV surveys (deMedeiros & Mayor 1999) have shown that of 1500 F-K IV-II stars, 11-24% are spectroscopic binaries, while for the KII stars alone, which are more likely to be on the AGB, the fraction is 7-18%. Some AGB stars in binaries have been known for a while (most notably, Mira; Karovska et al. 1997,Wood & Karovska 2006), others are suspected from secondary indicators (e.g., BM Gem; Izumiura et al. 2008). Recently Sahai et al. (2008) has demonstrated that a large majority of AGB stars with Hipparcos astrometry containing a “multiplicity” flag, do actually contain a hot companion. It therefore appears that we are making progress on a full characterization of AGB binarity.

Homogeneous AGB samples. How can we design observing projects to answer the questions above that are free from biases? AGB stars being probed today for asymmetric structures seem to always be special: they are either the brightest or those already selected because of some other characteristic. Some techniques, such as maser detection, only work in the brightest objects. How do we select the next samples of AGB stars that can be probed for the onset of asymmetry? What new techniques will allow us to push the envelope of delectability for structures, companions, and magnetic fields in AGB stars?

3.2 Projects: AGB panel

- AGB companion detection and detection of past mergers: the determination of companions near the AGB stars down to the planetary limit is needed. What is the AGB binary fraction, period and mass ratio distribution? How many AGB stars have swallowed a companion?

  1. Can pulsations tell us about companions?
  2. Huggins et al. (2009) has shown a method to detect companions by measuring the shapes of AGB star halos.
  3. Optical spectroscopy: RV survey for companions to AGB stars.
  4. Optical photometry to detect transiting companions to AGB stars (**I do not think this can be**

done as the contrast is too high.). Can one do this with microlensing?
5. Optical astrometry: detection of companions.
6. NIR Interferometry : detection of companions and structures.
7. AO imaging and coronography: companion detection.
8. X-rays/XMM/Chandra: detection of X-rays in AGB stars as proxies for magnetic fields?
9. Radio/LOFAR: Detection of Jupiter/brown dwarf planetary magnetospheres around early AGB stars.
10. Radio/ALMA: Imaging to detect companions (can we do a large survey?) and polarization of sources with the intention of detecting structures.
11. UV spectroscopy; COS on HST: Excess UV to detect hot companions to AGB stars.

- **Detection of magnetic fields**. Those stars with fields need to be mapped at high resolution in order to determine field configurations and strengths. The link between fields detected via masers and the properties of the circumstellar environment as a whole must be detemrined. In particular are masers providing an adequate sample of the global field properties? [We should really ask Vlemmings to give 3 lines to expand on this]

  1. X-rays; XMM/Chandra: detection of X-rays in AGB stars as proxies for magnetic fields.
  2. Radio; VLA/VLBA/Merlin ALMA (archival): detect magnetic fields via mm-size grain alignment. Zeeman splitting on CN lines by the Goldreich et al. method.

- **A survey of rotation rates in AGB stars**, using modest sizes telescopes with good spectrographs, should be carried out by looking for broadening of photospheric absorption lines (as, e.g., was done for V Hya, where the equatorial rotation speed was found to be 23 km s^{-1}). A study of 67 AGB stars only found V Hya as a case of rotational broadening (probably an observational limitation as it is difficult to detect rotational broadening of $\lesssim$10 km s^{-1}).

- **The onset of axisymmetry**: catching the change. We need to detect the earliest moments of when mass loss becomes axisymmetric. What are the first structures that appear in the early transition phase (wide cones, jetlets, tori)? Early structures would be small and would typically happen in the midst of the AGB dusty envelope. What are the first signs of interaction with a companion? What are the techniques to carry out these observations?

- **Miras**. We should carry forward a particularly intensive area of study of Miras, because these objects are at the end of the AGB evolution when the super-wind takes place. In particular, objects such as V Hya, Pi Cru and AFGL3068 should have dedicated observing campaigns with matching theoretical efforts that integrate missing data/knowledge into what we know. What is the role of OH/IR stars in these studies?

- **Circular rings and arcs** (AGB and PPN): We know these rings are not explained by thermal pulses, so what is the explanation? Could they derive from shocks driven by an orbiting companion? Can MHD models generate a list of probable mechanisms? Would AO observations of the arks add critical information (asymmetric rarefaction/kinematic structures, local instability driven subarcs, arc width variations). Arc characteristics such as expansion, spacing as a function of stellar distance, statistics, lifetimes, evolution, have never been systematically probed. What is the relationship between arcs and binarity (is there a difference between arcs detected around known AGB binaries and those around other AGB stars)?

- **Dust**: the interplay of carbon and oxygen-rich dust types, or hydrogenated vs. non hydrogenated carbon dusts should be used as a way to connect to the evolution of the object. Dust evolution is unfortunately more complex and small changes in the dust environment lead to large changes in the dusts observed. Can dust type be meaningfully connected to stellar classes or to classes of other characteristics? For example, we know that some central stars of PN (mostly of the [WR] type) have dual dust chemistry. What can AGB stars tell us about this? What is the relationship between PAH and a companion presence? Why do carbon stars have silicates only sometimes and why do some carbon-rich AGB stars fail to show PAHs? Can we compare the dust chemistry of AGB stars with and without disks?

4 The post-AGB and pre-PN panel

The circumstellar envelopes (CSEs) of the vast majority of AGB stars are largely spherical and expanding slowly (5–15 km s^{-1}), whereas HST surveys have shown that the vast majority of young PN are aspherical, and likely to possess fast outflows ($\gtrsim$ 100 km s^{-1}) directed along one or more axes. Pre-planetary nebulae (PPN) are transition objects between the AGB and planetary nebula (PN) phases, and HST surveys of PPN show that these already possess, to a very large degree, the basic geometrical shapes and symmetries seen in PN. Hence, in order to understand the formation of asymmetrical PN, we must first understand the formation of asymmetrical PPN.

4.1 Major unsolved problems in the pAGB and PPN phases

Aspherical PPN Morphologies & Jets The significant changes in the circumstellar envelope (CSE) morphology during the evolutionary transition from the AGB to the post-AGB (pAGB) phase require a primary physical agent or agents which can break the spherical symmetry of the radiatively-driven, dusty mass-loss phase on the AGB. In the GISW model, a fast (>1000 km s^{-1}) isotropic wind from the PN central star expands within an equatorially-dense AGB CSE, and hydrodynamic simulations reproduce a variety of axisymmetric shapes. But the complexity, organization and frequent presence of point-symmetry in the morphologies of young PN, strongly suggests that the primary agent for breaking spherical-symmetry are jets or high-speed collimated outflows (CFW), operating during the early post-AGB or late AGB evolutionary phase. The CFWs are likely to be episodic, and either change their directionality (i.e., wobbling of axis or precession) or have multiple components operating in different directions (quasi)simultaneously.

Direct evidence for CFWs during the PPN phase has come from sensitive molecular line observations which reveal the presence of very fast (few×100 km s^{-1}) molecular outflows in PPN, with huge momentum-excesses which showed that these winds are not radiatively driven (Bujarrabal et al. 2001). In a few cases, the collimated wind is seen in stars which are bona-fide AGB stars: e.g., the extreme carbon star, V Hya, have been “caught in the act” of ejecting a very fast (250 km s^{-1}), highly collimated blobby outflow. An HST survey for such “nascent PPN” has revealed several new candidates with collimated structures.

Thus, the primary shaping of PN must begin *prior* the PN phase, and it is plausible that the variety of PN shapes and structure may be explained by variations of the properties of the CFW (direction, strength, opening angle, temporal history) interacting with a spherical AGB envelope. However, assuming this plausibility is borne out by simulations, we still have to address the question: what is the engine for producing CFW's? Can CFW's be produced by single stars or is a binary companion essential? If point-symmetric shapes result from the flow collimator precessing or becoming unstable, then what causes the destabilization? Single-star models for CFWs have invoked stellar rotation, strong magnetic fields, or both, and binary models have invoked the angular momentum and/or the gravitational influence of a companion.

Equatorial Waists & Disks: Most bipolar or multipolar PPN and PN harbor overdense, dusty equatorial waists. In PPN, the waists display convex (relative to the nebular center) sharp outer (radial) edges in absorption, with radii typically $\gtrsim$1000 AU. Very infrequently, the waist appears as a disk with a sharp outer boundary seen in emission at $few\times100$ AU. The waist region can show complex symmetries (e.g, complex (double?) torii in He2-113 and IRAS19024; point-symmetric microstructure in He2-47; central star offset by $few\times100$ AU from the symmetry-center in MyCn18).

Significantly smaller equatorially-flattened structures or disks ($\sim$50 AU) are found in a large sub-class of young pAGB stars (hereafter disk-prominent pAGB stars), many of which are RV Tauri stars, and show photospheric depletion patterns similar to that seen in the ISM. The depletion is believed to result from a poorly understood process in which the circumstellar dust is trapped in a disk, and the dust-depleted gas is accreted back onto the star. Mid-IR spectroscopy with ISO and Spitzer has shown the ubiquitous presence of abundant cystalline silicates in these objects implying the presence of dust processing in long-lived disks with composition very similar to that seen in planet-forming disks around young stars and in comet Hale-Bopp. But direct support for the disk being bound is limited to one pAGB object: the Red Rectangle (closest known PPN with a binary central star).

The origin of the small, likely Keplerian, disks and the larger, dusty waists in pAGB objects is a mystery, and the connection between these two (if any) is unknown. Compression of the AGB wind towards the equatorial plane by a fast wind with a relatively large opening angle is unlikely to work in most bipolar nebulae which appear to be highly-collimated, momentum-driven shells. Although compact ($\lesssim$1 AU) disks form readily around a companion via Bondi-Hoyle accretion of the primary AGB star's dusty wind, these simulations have so far not been able to produce the much larger circumbinary disks or the dusty waists which we observe in pAGB objects.

A large fraction of PPN and some PN show Hα emission lines with a narrow, intense emission core and very broad weak wings (extending up to few$\times$1000km s^{-1}on each side of the center); the observational evidence suggests that these arise in or around the central star. No profound explanation has yet been proposed for these very broad wings, although possible mechanisms include emission from a very high velocity outflow, Raman scattering and/or Keplerian rotation in a dense disk. Thus an improved understanding of this emission is likely to provide us new insights into the otherwise difficult to probe central regions of PPN, which are the likely launch sites of the CWFs.

Finally, a new puzzle has arisen with the discovery of large sub-millimeter excesses in both the disk-prominent pAGB objects as well as a few PPN, which imply the presence of fairly substantial masses of very large ($\sim few\times100-1000$ micron) grains. This discovery also opens up a new opportunity: namely the study of important physical processes related to dust grain evolution such as coagulation in an environment similar to, but much simpler than protostellar disks. PAGB disks will allow us to probe the very early stages of grain coagulation, i.e. on time-scales (1000 years), not possible with studies of planet-forming disks which are typically $\gtrsim10^6$ yr old.

Binarity: Mass-Loss & Evolution: Binarity can strongly influence mass-loss in evolved stars. Perhaps all asymmetric PN and PPN involve binaries, but testing such a hypothesis requires a far better knowledge of the incidence of binarity in these objects than available currently. Direct observational evidence of binarity has been very hard to come by due to observational limitations. In the case of PPN, optical radial-velocity measurements have not been successful so far due to pulsational stellar variability; new techniques are needed.

Binarity may cut short the primary's AGB evolution as appears to be the case for disk-prominent pAGB stars, where the primary and companion stars are presently not in contact, but show orbits which are too small to accommodate a full-grown AGB star, and the disk sizes are large enough that they must be circumbinary. But no theoretical models exist to explain the formation of these systems.

4.2 Projects: post-AGB and PPN panel

- **New surveys of PPN and nascent PPN** should be carried out, which will remain unsurpassed in providing large field-of-view images with very high dynamical range because of their very stable PSFs, at ∼100 mas resolution (crucial for detecting faint circumstellar structures next to bright central stars). Current surveys have provided a modest sample of resolved objects ($\lesssim$50); significantly better statistics are needed to determine the fraction of objects with morphologies which are likely to provide the strongest tests for theoretical formation and shaping models. These include objects with, e.g., multipolar shapes (e.g., IRAS19024+0044), quadrupolar shapes (e.g., IRAS19475+3119), truncated outer waists (e.g., IRAS17106-3046), haloes with circular arcs and/or searchlight beams (e.g., Egg Nebula). Optical/NIR imaging; HST/JWST.

- **Multi-epoch high-resolution images of PPN**, spaced by $\gtrsim$5-10 yr should be used to trace nebular proper motions in well-resolved PPN. Both STIS/HST and ground-based observations in the NIR with integral-field (e.g., OSIRIS/Keck) or long-slit spectrographs (e.g., NIRSPEC/Keck) behind AO should be used to probe radial velocities. Combining the radial velocity and proper motion data will enable us to map the 3-dimensional kinematics in PPN at high spatial resolution – such data are crucial for probing jet acceleration and kinematics close and far from the launch sites. Optical imaging; HST/JWST.

- **Probe the launch regions of fast collimated outflows in nascent PPN**. Near-IR and mid-IR interferometry; specially those which provide closure-phase data (VLTI/ AMBER, ISI/Mt.Wilson), low-resolution (R∼530) spectral data (VLTI/ MIDI), and real images (upcoming 6-element reconfigurable Magdalena Ridge Observatory Interferometer [MROI], New Mexico, first fringes in late 2010), with resolutions ranging from 0.1 to 100, should be used determine in particular the disk temperature, geometry and density structure.

- **Search for binaries in edge-on PPN**. It is possible that objects with optically bright central stars which have been the subjects of existing studies, are being viewed along/near an unfavorable (for detecting RV variations) polar line-of-sight. For PPN with edge-on waists where the central stars are obscured or heavily extincted in the optical, but for which the RV variation signal is maximum, a feasibility study should be carried out to see if near-IR metallic lines can be used for RV monitoring.

- **A spectroscopic survey of a distance-specific sample of pAGB objects** (i.e., in the LMC and SMC) should be carried out: high-resolution optical, near-IR and mid-IR spectra are needed (mid-IR to far-IR spectra/SEDs of some objects already available via IRS/Spitzer observations of the LMC via the SAGE Legacy and various GO programs).

- **A pilot survey of spectroscopic monitoring of the broad Hα emission lines in PPN** should be carried out - a few observations indicate that the line shapes do vary significantly. If the peak of the emission component is found to show periodic radial velocity variations, that would suggest a Keplerian disk origin for the Hα emission.

- **Studies of key objects such as the "water-fountain" PPN**, which are distinguished by the presence of very high-velocity red- and blue-shifted H_2O and/or OH maser features should be carried out at radio, millimeter and sub-millimeter wavelengths. These are arguably amongst the youngest PPN and therefore most likely to show active jet sculpting (e.g., IRAS16342 shows H_2O maser features with radial velocities separated by more than 250 km s^{-1}and the telltale "corkscrew" signature of a precessing jet in near-IR AO/Keck images). The H_2O masers in these sources lie on the opposite sides of a bipolar jet, and being very bright and compact, are unsurpassed tracers of the jet proper motions. Such proper motion measurements (together with radial velocity data) obtained with the NRAO Very Long Baseline Array (VLBA) over several epochs can a) determine the geometric parallax of sources with unparalleled accuracy to ∼10 kpc, and b) determine the high-velocity jet's 3-D motions (e.g., whether or not the jet is precessing). High spectral resolution monitoring using the Green Bank Telescope can accurately determine accelerations and decelerations in the jet radial velocity. Such measurements will greatly constrain theoretical models of how these high velocity jets sculpt the circumstellar medium in the evolution of these objects to PN.

  Upgrades to the sensitivity of the VLBA will enhance the continuum sensitivity to extragalactic sources as fiducial markers for the the measurement of proper motions, and allow geometric parallaxes to be measured to 10 or 15 kpc over a 1-year period. This improvement will not only facilitate parallax measurements for water-fountain PPN, but for optically invisible dust-obscured AGB stars as well, which harbor masers in their shells.

- **Surveys of thermal molecular gas emission in the outflows of PPN and disk-prominent pAGB** objects should be carried out in ^{12}CO and ^{13}CO J=2-1 lines with ALMA, which will provide an unprecedented dynamic range with the ability to produce 0.1 arcsec resolution images of all features above 0.1% peak intensity. Measurements of the $^{13}C/^{12}C$ ratio in the nebular material will help to distinguish between different origins – ratio would be significantly enhanced if material comes from the evolved primary, but typical of interstellar values if due to planet/main-sequence companion material. At 100 mas resolution in mm-wave molecular transitions of high-density tracers, we should see evidence for the high-velocity jet's interaction with the remnant AGB gas at ∼100 AU (or better, depending upon the distance) from the star. Such imaging is needed to separate the disk/torus and outflow components, and determine the kinematics of the former" expansive or Keplerian rotation (or a combination).

- **Surveys of high-J emission lines of CO and other molecules in PPN** with HIFI/Herschel should be carried out to probe the physical conditions (kinematics, density, temperature) of the outflows close to the central source. Such observations coupled with low-J observations from ground based telescopes can help trace the mass-loss history in PPN and nascent PPN.

- **An EVLA survey of PPN and disk-prominent pAGB objects** should be used to detect radio/millimeter/sub-millimeter continuum emission from the large grain component in these objects, which is likely to be present in the disks/torus regions.

- **Characterisation of magnetic fields in disks and outflows of well-resolved PPN** using the full polarisation measurement capability of ALMA via (a) polarisation of the sub-millimeter dust continuum resulting from aligned grains (e.g., detected via large-beam observations in a few objects), and (b) polarisation of molecular line emission resulting from the Goldreich-Kylafis effect.

- **Surveys of X-ray emission towards the central stars in PPN** can provide us with a unique probe (i) of magnetic fields in the outflow engine vicinity (dissipation of a solar analog dynamo-generated field should result in a non-thermal X-ray luminosity of 10^{32} $\mathrm{erg\,s^{-1}}$ from the central stars in very young PPN), and (ii) the shock-interaction physics which shapes these objects. In contrast to PN, only one PPN (Hen 3-1475) has been detected so far; the emission results from shocked gas. The lack of PPN detections in X-rays is most likely due to the rapid cooling of the shocked, dense regions produced by the CFWs operating during the PPN phase leading to relatively small emission measures. An increased sensitivity mini-survey, i.e., with long integration times (>50 ksec) using current facilities such as Chandra and XMM-Newton need to be carried out are needed to study the physics of the shocks interactions in PPN which are involved in the shaping. These can later be followed up by bigger surveys using the International X-ray Observatory.

5 The PN Panel

5.1 Major unsolved problems in the PN phase

The PN Panel concluded that it is time to go back to the star — i.e., a coordinated, multiwavelength observational campaign targeting the central stars of planetary nebulae (CSPN) is necessary, if we are to make further progress in our understanding of the mechanisms that shape planetary nebulae.

We need a list of three paragraphs of main problems in PN and CSPN research.

5.2 Projects: PN panel

- **A multiepoch blue/UV photometric and spectroscopic survey of a large sample of CSPN**, at moderate resolution, that will enlarge the database on physical characteristics of CSPN and their possible binarity. There is a considerable lack of high quality and consistent photometric and spectroscopic information on CSPN in the wavelength regimes where CSPN fluxes peak. A comprehensive blue/UV spectroscopic survey would provide basic stellar parameters such as luminosities, log g values, C/O abundance ratios,and reddening. Ideally these data would be obtained at multiple epochs for each object. These spectroscopic data are essential in order to better understand the photospheric and wind characteristics of WR-type , PG1159 and normal CSPN at different evolutionary stages. At the same time, dedicated programs of photometric monitoring are needed so as to establish a much larger sample of close binary central stars and thereby relate binary parameters and PN characteristics.

A key resource for the UV spectroscopic observations of CSPN is the new COS spectrograph on HST. It is a magnitude faster than STIS for point sources that arent embedded in bright nebulosity. Whether STIS or COS, HST is the only UV facility to be in routine use for the next decade or until HSTs demise, whichever is first. The next UV facility is in the early planning stages and may not be in use until 2030. Thus the next decade is a unique window of opportunity for insights into CSPN through uv observations. Telescope time will be fiercely competitive, so an expert team of observers and stellar modelers must be formed within our community with urgency.

The panel suggests that (e.g., at the APNV meeting) a request be issued for existing spectra of CSPN to be made available in a public archive. A depository and curator for this potential data archive is needed. In addition, a team with clear long-term objectives is needed to assure that stellar monitoring programs will be conducted systematically so that the archive becomes rich in key data.

- **An imaging/photometry survey to detect and characterize dusty debris or accretion disks surrounding CSPN**. The discovery of a mid-to-far-IR excess at the central star of the Helix (Su et al. 2007, ApJL, 657, L41) opens up a new means to probe for the presence of disks within PN. In the case of the Helix, the disk is most likely a residual debris disk that orbited the PN progenitor star and survived the stars post-main sequence evolution. Such a primordial debris disk may or may not have influenced the Helix PNs shaping, and would be very different in origin and structure from the accretion disks that are thought to be generated via CSPN binary interactions and are invoked to explain the formation of collimated outflows and jets in PPN and PN.

  The unprecedented mid-IR (∼10 micron) to sub-millimeter imaging photometry capabilities of the forthcoming SOFIA, JWST, and ALMA facilities loom as important tools to establish the prevalence and, eventually, the origin and evolution of such dusty disks around CSPN. A comprehensive mid-IR to submm survey of CSPN would detect dusty disks and characterize their SEDs, so as to distinguish between unresolved, lightweight, gas-poor debris disks and the larger-scale, massive and gas-rich, (perhaps) spatially extended dusty disks and tori resulting from binary interactions. Time on these facilities will be scarce, so proposals from coordinated teams of expert users and students will have distinct advantages. In addition, theoretical work on 3-dimensional radiation transfer in dusty media is necessary to connect and interpret the radio IR optical observations. Such expertise is becoming widely available around the world, and PN are an ideal application of the technology.

- **An X-ray imaging spectroscopic survey of PN:** We seek to obtain a complete, volume-limited X-ray emission survey of PNe that will sample both the thin and thick Galactic disks and therefore will represent a wide progenitor mass range. We estimate such a survey (e.g., of all PNe within ~ 2 kpc) will require an eventual total time allocation of ~ 5 Msec on contemporary X-ray observatories. The resulting suite of high-energy spectral and temporal diagnostics for a representative sample of CSPNe will provide unique constraints on circumstellar magnetic fields, accretion disks, wind shocks, and/or binary companions at PN cores, thereby relating CSPNe binaries to (potentially) related systems such as symbiotic stars and SN Ia progenitor binaries. Specifically, hard but “flickering” point-like X-ray sources would be indicative of the presence of accretion disks (Sokoloski [REF?]); soft and constant point-like X-ray sources would be indicative of shocked CSPN winds; and strongly time-variable (flaring) point sources would most likely originate in the coronae of late-type companions (Montez, De Marco, Kastner, Chu, & Soker, in prep. & Jan 2010 AAS meeting). Such detections of X-rays from the cores of the PN, in combination with future characterization of binary CSPN as described in this document, would open a new era in the study of common envelope evolution, would inform studies of magnetically active binaries in general, and would provide motivation for and constraints on future models of X-ray production from main sequence stars.

- **An HST/WFC3 snapshot survey of low ionization, very young PN** in various narrow band and broad band filters, to assess the timescales of stellar ejection and subsequent flow collimation processes. Recent morphological studies of prePN imply that the shapes of stellar ejecta morph into simpler shapes with time perhaps abetted by the onset of the disruptive shocks preceding ionization fronts and rapid local pressure changes that follows the passage of the ionization front. Theoretical models need to be generalized from one dimension using sophisticated numerical schemes for shocks and radiation transfer of stellar photons. Systematic imaging and kinematic/proper motion surveys of prePN and newly ionized PN are needed to guide and constrain the models. These efforts will require large teams that contain within them the many types of expertise needed to move the field forward, and to justify scarce time on key facilities. At the same time, small telescopes and strategic student projects can lay a firm foundation for the more challenging observations.

- **High-resolution imaging of young and compact PN** need the highest possible spatial and spectral resolution at visible wavelengths. The newly installed Wide-Field Camera 3 on HST is ideal since it has a large complement of narrow-band filters that isolate key emission lines for mapping ionization structures, such as [OI], [OII], and [OIII]. The camera also has filters that isolate key diagnostic lines such as [NII] $\lambda\lambda$5755,6583 and [SII] $\lambda\lambda$6717,6731, so that physical conditions can be mapped in detail at pressure boundaries where temperatures, densities, and streamline vectors my change precipitously. In this way the models of the origin and persistence of collimated outflows and the roles of binary-companion tidal effects can be very usefully constrained.

- **Mapping the internal kinematics of young PN** in order to identify the types and locations of forces that act on the outflowing gas. This complementary and coordinated program of ground-based, high-dispersion spectroscopy (preferably with integral field units) should go alongside the imaging campaigns.

- **Early reconnaissance surveys**. Prior ground-based spectroscopy or narrow-band photometry may be needed to uncover many more compact and low-ionization (presumably nascent) PN targets. This survey is ideal for smaller telescopes and student projects.

- **Mapping nebular interfaces**. It is clear that young PN are richer in complex symmetries than their evolved counterparts. In particular, many or possibly most are bipolar, and the bipolar lobes are associated with H_2 emission. The excitation of H_2 implies that the H_2 is found in shocks associated with photo-dissociation fronts at boundaries between the ionized nebula and a molecular medium. Thus careful studies of H_2 kinematics will reveal the nature of nebular interactions with the surrounding but largely invisible medium. Large ground-based telescopes operating at their diffraction limit are an exciting possibility for mapping H_2 flows in the next decade.

6 All panels: Theory

- **Binary population synthesis:** What can we expect from the population of PN as a whole if certain evolutionary channels prevail over others? In particular what are chemical markers of binary evolution?

- **Binary theory:** What can hydro/magneto-hydro simulations supported by analytical theory tell us about the evolution of these complex systems? What observable effects can we expect from early interaction between an AGB star and a companion? How do companions alter the rotation and mass-loss properties of AGB stars? What is the time evolution of an AGB star + close companion?

- **Central Engines & Fast Collimated Outflows:** Several observational challenges are in need of detailed simulations for their interpretation. Examples include the launching mechanisms that can account for the huge momentum excesses in molecular outflows, how mass transfer systems might provide the shears and stresses that generate strong magnetic collimators, stellar rotation might create the dusty disks that are so frequently seen in pPNe, and dynamo fields might appear briefly at the stellar surface to launch brief jets or clumps.

- **The creation of dusty disks near the AGB tip:** dusty disks, many with sharp outer edges, are so common in pPNe that a theoretical understanding of their formation and launching is urgently needed. Whether single stars can create these disks from surface rotation or field emergence is problematic and must be resolved. The binary environment offers tantalizing advantages for disk formation; however, models that can follow the growth and dynamics of AGB envelopes in a close binary environment will need to be very sophisticated. Can orbiting companion objects shape the disk after its formation?

- **Impacts of the onset of ionization on realistic pPN geometries:** GISW models have provided a firm ground for much more complex radiation hydro modeling with ionization dynamics. Ionization physics has been incorporated into 1-D hydro models by M. Steffen and his colleagues. Their models have shown that reverberating pressure waves rearrange and greatly complicate simple wind outflows. The extension of radiation hydro into 3 dimensions will permit a study of the impact of ionization fronts and the shocks that precede them on realistic pPN morphologies. Does radiation heating of the nebular interior drastically soften pPNe? What are the observable consequences of the expanding wind-heated interior bubble on the nebula shell? What happens when the hot bubble pierces the edge of he PN?