Part I

Introduction

PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Introductory Review

Sun Kwok

Department of Physics and Astronomy, University of Calgary, Calgary, Canada T2N 1N4

Abstract. Our current state of understanding of the planetary nebulae (PNe) phenomenon is reviewed in the context of modern stellar evolution and dynamical models. Also discussed are a number of new problems that have emerged as the result of recent space (x-ray, UV, optical, and infrared) observations. The roles of PNe in the chemical (atomic, molecular, and solid-state) enrichment of the galaxy and as tracers of the large scale structure of the Universe are also discussed.

1. Planetary nebulae as a phase of stellar evolution

Planetary nebulae (PNe) represent a short ($\sim 10^4$ yr) phase of stellar evolution between the asymptotic giant branch (AGB) and white dwarfs. The central stars of PNe are remnants of the electron-degenerate C-O cores of their AGB progenitors, having lost most of their H envelopes due to mass loss on the AGB. They maintain their energy output through H-shell burning and evolve with constant luminosity from low to high temperature across the H-R diagram. When their entire H envelope is consumed by a combination of nuclear burning and mass loss, their luminosities begin to decrease and the central star gradually cool to become white dwarfs. This basic scenario was outlined by Paczyński (1971), followed by detailed evolutionary tracks calculations by Schönberner (1979), Iben (1984), and Wood & Faulkner (1986).

1.1. What stars will become PNe?

Due to strong mass loss on the AGB, stars with main-sequence masses as high as 8 $M_\odot$ can lose their entire H envelope before the core mass reaches the Chandrasekhar limit of 1.4 $M_\odot$. From the initial mass function, one can estimate that 95% of all stars will end their lives as white dwarfs. Since the existence of a PN requires the presence of an ionized nebula, not all stars that evolve past the AGB will become PNe. The transition time between the AGB and PN stage is highly dependent on the core mass. While a high-mass star will evolve so fast that it only illuminates the nebula for a very short time, a star with low core mass will evolve too slowly to ionize the circumstellar nebula before it dissipates into the ISM. From evolutionary models, the minimum core mass required for PNe is 0.58 $M_\odot$. This translates to a main-sequence mass of 1.5 $M_\odot$ based on current initial mass-final mass relationship (Weidemann 2000). Although these values are still uncertain, we believe that all Popoulation I stars with initial masses between 1.5 and 8 $M_\odot$ will become PNe.

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1.2. PN in different galactic environments

The current number of known PNe in the Galaxy is approximately 2000 (Parker, these proceedings). Due to galactic extinction and incompleteness of surveys, the total PNe population is much higher. Based on the observed local density of PNe and an assumed scale height, the total population in the Galaxy is estimated to be about 14,000. However, this number is highly uncertain due to the inaccurate distances of local PNe. Dividing this total population by the lifetime of PNe, one can estimate that the birth rate in the Galaxy is ~ 1 PN per year.

Since PNe are the result of AGB mass loss, the birth rate of PNe could be a function of metallicity and may differ in different galactic environments. Narrow-band imaging in the [OIII] line has identified PNe in galaxies as far away as the Virgo cluster, and spectroscopic observations have shown that PNe in external galaxies (e.g. Cen A) are similar to Galactic PNe (Walsh et al. 1999). High-resolution imaging by the *HST* of PNe in the Magellenic Clouds found that they have the same kinds of morphology as Galactic PNe (Stanghellini, these proceedings), suggesting that the PNe have undergone similar shaping processes.

Extensive surveys of globular clusters have revealed only 4 PNe in globular clusters. This is not unexpected because globular clusters are old and consist of mainly low mass stars. The question why PNe (e.g. K648 in M15) are present at all has led to the suggestion that they are the result of merged binaries (Bond & Alves 2001). Since almost all of our theoretical understanding of PN evolution is based on a single star scenario, the role of binaries play in PN evolution is still under developed.

1.3. He burning central stars

Since post-AGB stars and central stars of PNe are expected to undergo periodic thermal pulses, the existence of He-burning PNe has long been theoretically anticipated. The most likely candidates for such objects are PNe with H-deficient central stars. Many such stars show WR-like spectra and ~50 [WC] central stars are known. An evolutionary scenario linking these [WC] stars to PG 1159 stars and eventually to non-DA white dwarfs has been proposed (see Hamann, these proceedings). A late thermal pulse leading to the formation of born-again central star (e.g. Sakurai's object) offers the possibility of observing stellar evolution in real time.

The nature of [WC] stars is complicated by the observations of mixed chemistry in their dust envelopes. CPD-56 8032, e.g., has been observed to show oxygen and carbon chemistry in its infrared spectrum (Cohen et al. 1999). There are still many discrepancies between the observation H-deficient stars and the theoretical properties of He-burning stars. The fraction of He-burning stars among PNe is still highly uncertain.

2. Interacting winds and the dynamical evolution of PNs

While an impulsive ejection appears intuitively obvious for the formation of PNe, the discovery of large-scale mass loss on the AGB led to the realization of the importance of AGB mass loss on the origin of PNe and the formulation of the interacting stellar winds model (Kwok et al. 1978, Kwok 1982). In addition to the well-observed shell, the ISW model predicts the following components: a fast wind from the central star, a low-density halo representing the unshocked AGB wind, and a high-temperature bubble representing the shocked fast wind. With the launch of the *IUE* satellite in 1978, P Cygni profiles implying wind velocities of several thousands km s^{-1} were found in many central stars of PNe, confirming that fast winds are indeed common in PN. Evidence for the existence of haloes outside the PN shells were found by CCD imaging, and by the detections of dust and molecular envelopes by infrared and millimeter-wave observations. Extended diffuse X-ray emission from the hot bubble was detected by *ROSAT* (Leahy et al. 2000) and by *CHANDRA* observations (Kastner et al. 2001, Chu et al. 2001).

The ISW model suggests that a PN can no longer be viewed as a static entity. The central star of a PN is not only radiatively interacting with the nebula, but dynamically interacting as well. A PN is a dynamical system whose evolution is tightly coupled to the evolution of the central star through a changing rate of stellar Lyman continuum output and photoionization, and by a changing mass loss rate and wind velocity from the central star and wind interaction. The appearance and the structure of PN therefore reflect the coupled dynamical and ionizational evolution of the nebula. The time-dependent nature of PN evolution was incorporated into many of the 1-D spherically symmetric treatments of the ISW model (e.g., Schmidt-Voigt & Köppen 1987a, b; Marten & Schönberner 1991; Frank 1994; Mellema 1994). These models reveal a complex structure of density, velocity, and temperature as the nebula evolves, leading to fresh interpretations of the observed properties of PNe, including mass, kinematics age, and abundances (Perinotto et al. 1998).

3. Morphology of PN

High dynamical range imaging observations of PN with CCD detectors have revealed a much more complicated structure of PN than the classical picture of a shell plus central star. In addition to a bright shell, low surface brightness outer structures can be seen. These structures were labelled "Type I" and "Type II" outer shells by Chu et al. (1987), and "inner shell", intermediate shell", and "halo" by Guerrero et al. (2000). The most comprehensive description of PNe was given by Frank et al. (1990), who used terms "inner core", "bright rim", "shell", "crown", "edge", "halo", and "limb-brightened halo" to describe the morphological features observed (Fig. 1). While such multiple shell structures are difficult to understand in the classical model, they can be reproduced when the evolution of the central star is incorporated in the interacting winds model (Mellema 1994, Steffen et al. 1998, Corradi et al. 2000). In a 1-D model, the "rim" can be identified as the high-density shell compressed by the hot bubble, the "shell" as the extent of the ionization front, and the halo as the remnant of the AGB wind (Schönberner, these proceedings). It is important to note that these structures can change with time as the star evolves. For example, "recombination haloes" can emerge as the stellar luminosity begins to decline (Tylenda 1983).

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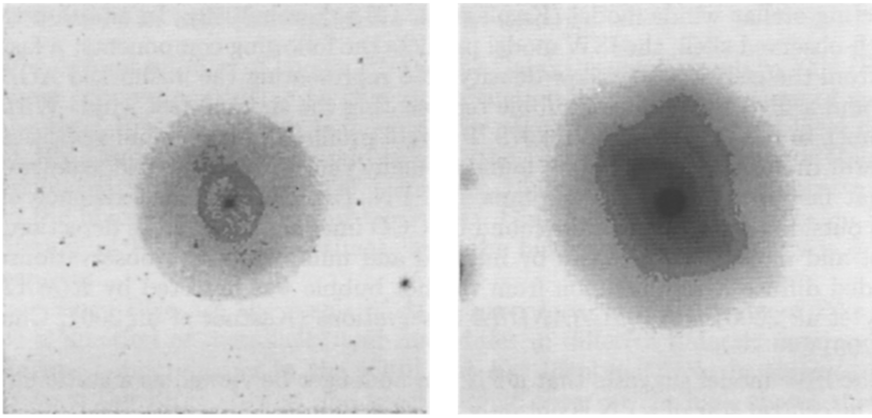

Figure 1. (a) Left: *HST* V-band image of NGC 6629 showing the multiple shell structure commonly observed in PNe. (b) right: this [NII] image of NGC 6891 shows a three-shell structure. The kinematics of the shells is consistent with the predictions of the ISW model (Guerrero et al. 2000).

3.1. Morphological classification of planetary nebulae

Beginning with the work of Curtis (1918), there have been many attempts in classifying the morphologies of PNe (e.g. Stanghellini et al. 1993, Manchado et al. 1996). However, all classification schemes suffer from the following problems:

- Sensitivity dependence: a deeper exposure can reveal fainter structures which change the classification of the PNe. For example, the waist of a bipolar nebula could be classified as elliptical if the bipolar lobes are too faint to be detected. NGC 650-1, Sh 1-89, and SaWe 3 are some of the cases where their bipolar nature were discovered as the result of deep CCD imaging (Hua, 1997; Hua et al. 1998).

- Species dependence: the morphology of PNe observed in lines of different ions is not necessarily the same, as the result of ionization structures and stratification effects.

- Projection effects: morphology classifications describe the two-dimensional apparent structures, not the intrinsic structures of the PNe.

It is clear that the examination of the apparent morphology alone is not sufficient to obtain the true intrinsic structure of PN. Kinematic data are necessary to separate various components projected on the same positions in the sky.

3.2. The intrinsic structure of planetary nebulae

There have been several efforts to account for the variety of PN morphologies by different views of a single, unified, basic three-dimensional structure. Khromov

& Kohoutek (1968) explained the morphology of PN in terms of a open-ended cylinder projected onto the sky, and Masson (1989, 1990) and Aaquist & Kwok (1996) employed an ellipsoidal shell (ES) model in which the PN morphology is determined by an ellipsoidal shell with both radial and angular density gradients ionized by a central star to different depths in different directions. Simulated images for 110 PN were produced by Zhang & Kwok (1998) using the ES model.

In the first order, the 2-D structure of a PN consists of the following components:

- A low-density spherical halo representing a remnant of the AGB wind.
- An ionization-bounded, dust-obscured torus representing an equatorial outflow during the late stages of AGB evolution.
- Two density-bounded polar lobes representing cavities created by fast outflows and the subsequent photoionization of the circumstellar material.

Under this model, a PN viewed near pole on will appear elliptical, with the torus seen as a shell and the lobes seen as envelopes surrounding the shell. Detailed kinematic studies have shown that several of the well-observed ring-like PN are in fact bipolar (NGC 6720, Bryce et al. 1994; NGC 7027, Latter et al. 2000; NGC 3132, Monteiro et al. 2000). When viewed near edge on, the PN will appear to have a bipolar or butterfly shape. Although the fraction of bipolar PNe based on apparent morphology is relatively small (~15%), the true fraction could be much higher.

3.3. Microstructures

Recent observations, in particular high-resolution images obtained with the *HST*, have discovered a number of microstructures beyond the basic bipolar structure.

- FLIERS and jets: FLIERS are pairs of small, bright knots of low excitation gas found along the major axes of PNe (Balick et al. 1998). Linear structures (jets) can be seen in two of the corners of the [NII] image of NGC 6543. The existence of these features suggests that the fast outflow could be collimated rather than spherical.
- Point-symmetric structures: point-symmetric pairs of knots in an S-shape structure, or sometimes referred to as bipolar, rotating, episodic jets (BRET), have been seen in a number of PNe (e.g. KjPn8, López et al. 1995; NGC 6884, Miranda et al. 1999). Some PNe have been found to have more than one polar axis, suggesting that the outflow direction has changed with time (e.g. NGC 2440, López et al. 1998; M1-37 and He2-47, Sahai 2000).
- Collimated outflows: some PNe (e.g. M2-9, Schwarz et al. 1997) and PPNe (e.g. Hen 3-401, Sahai et al. 1999) have extreme bipolar (cylindrical) shapes, suggesting that their morphology is shaped by a collimated outflow. The direct imaging of bipolar lobes emerging from a circumstellar disk in the PPN IRAS 17106−3046 (Kwok et al. 2000) suggests that disks could play a role in the collimation of the bipolar flows.

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- Rings and arcs: concentric circular arcs have been observed in both PNe (e.g. Hb 5, NGC 6543, NGC 7027) and PPNe (e.g. AFGL 2688, IRAS 17150−3224). These arcs are of almost perfectly circular in shape, and have relatively uniform separations of $\sim 10^2$ yr. Similar arcs have been detected in the carbon star IRC+10216, suggesting that these features originate in the AGB phase. The coexistence of these perfectly circular features with bipolar lobes suggests that the arcs are projections of undisturbed spherical shells on the sky. Possible mechanisms for the creation of such arcs include dynamical instability in the gas-dust coupling in the AGB outflow (Deguchi 1997), perturbation by a binary companion (Mastrodemos & Morris 1999), and magnetic cycle (Soker 2000, Garia-Segura et al. 2001).

  Two-dimensional rings perpendicular to the bipolar axis have been found in several PNe, including MyCn18 (Sahai et al. 1999) and NGC 6881 (Kwok, Su, & Sahai, these proceedings). The origin of these rings is not understood.

3.4. Shaping of PNe and the origin of the asymmetry

While the ISW model has been shown to be able to amplify the asymmetry of the AGB wind to create the variety of morphologies of PN (Kahn & West 1985, Balick 1987, Mellema & Frank 1995), the origin of the asymmetry remains to be identified. Millimeter interferometric observations of the molecular envelopes of AGB stars have always found the envelopes to be spherically symmetric, suggesting the AGB mass loss over the dynamical lifetime ($\sim 10^4$ yr) is approximately spherical. Recent imaging of proto-planetary nebulae (PPNe) have found many PPNe to possess bipolar morphology, implying that the shaping process occurs during the PPN phase, before the photoionization of the nebulae (Hrivnak, these proceedings). Observations of PPNe therefore hold the key of understanding of the shaping process.

Some PPNe and young PNe have highly focused lobes (Fig. 2), suggesting that the fast wind is being collimated by a disk. Spectroscopic monitoring has found a number of post-AGB stars to possess binary central stars (van Winckel et al. 1999). To what extent binary central stars play a role in the shaping and collimation process is one of the most difficult questions we face (Soker, these proceedings).

Hydrodynamic models have shown that FLIERs and BRETs could be naturally produced by the ISW process if the mass loss rate and velocity of the fast wind are functions of both time and direction (Steffen et al. 2001). The change in outflow direction could be the result of binary interaction and magnetic fields (Garcia-Segura, these proceedings).

4. Chemical Enrichment of the ISM

Since PNe are descendents of thermal-pulsing AGB stars, they are long known to play a major role in the chemical enrichment of the ISM. As emission-line objects, PNe serve a natural laboratory for the observations of C, N, and many s-process elements (see reviews by Herwig, Lattanzio and van Winckel, these proceedings). The recent avialability of ultraviolet and infrared spectroscopic

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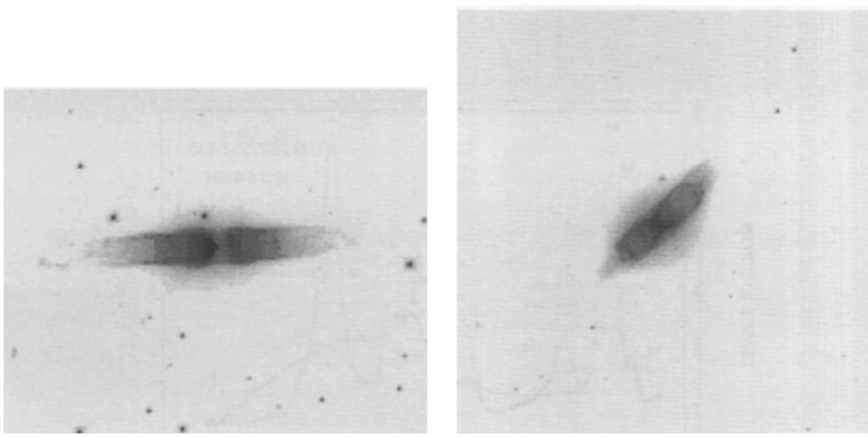

Figure 2. Two PNe with highly collimated lobes. left: He3-401, right: He2-320.

observations through the *FUSE* and *ISO* missions has resulted in an increasing degree of sophistication and accuracy in the determination of the abundance of these elements (Liu, these proceedings). The development of millimeter-wave spectroscopy has led to the detection of rotational transitions of over 50 molecules (including carbon chains as large as HC_9N and cyclic molecules such as C_3H_2) in the circumstellar envelopes of AGB stars and PNe, suggesting that these objects are also major sources of molecular enrichment of the ISM. The detection of HCO^+ in PNe demonstrates the importance of photo-chemistry and shows that gas-phase chemistry is still actively ongoing in the molecular envelopes of PNe (see Hasegawa, these proceedings). Infrared spectroscopy from *ISO* has made possible the observation of stretching and bending modes of non-linear molecules, leading to the detection a variety of new species including di-acetylene, triacetylene and benzene in PPNe (Cernicharo et al. 2001a,b). These results clearly show that the synthesis of organic molecules are occuring through the AGB-PN transition.

Solid-state compounds in the form of amorphous silicates and silicon carbides are commonly found in AGB stars, and these grains are expected to survive through the PNe stage (Kwok 1982). However, recent infrared observations have revealed that, in addition to these species, the dust envelopes of PPNe and PNe contain other inorganic and organic compounds. The infrared spectra of PNe show strong emission features at 3.3, 6.2, 7.7, and 11.3 μm due to aromatic hydrocarbons, and aliphatic features at 3.4 and 6.9 μm are seen in the spectra of PPNe. The broad emission plateaus at 8 and 12 μm have also been identified as due to a variety of aliphatic sidegroups attached to aromatic rings (Kwok et al. 2001) (Figs. 3 and 4). There are also emission features at 21 and 30 μm which origins are yet to be identified (Volk, these proceedings). These discoveries, together with the detection of crystalline silicates and carbonates in PNe (Molster, these proceedings), suggests that the solid-state component is also under change in the PNe environment.

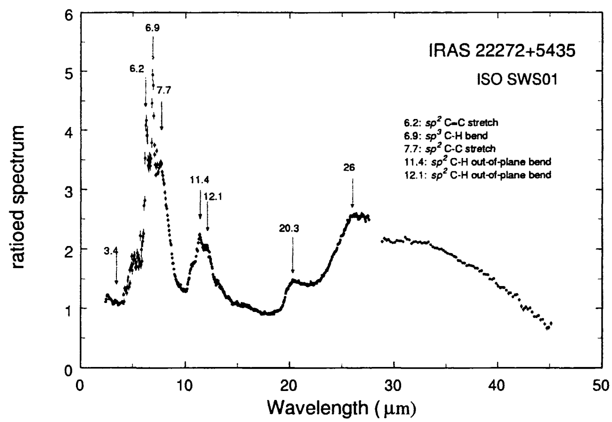

Figure 3. The ISO SWS01 spectrum (after removal of continuum) of the PPN IRAS 22272+5435 showing narrow and broad emission features due to a variety of aromatic, aliphatic, as well as unidentified compounds.

There is now strong evidence that meteorites contain grains of presolar origin. The detection of silicon carbide in meteorites (Bernatowicz et al. 1987) clearly suggests that solid state materials made in AGB stars can pass through the ISM and survive the formation of the solar system. This was followed by the detection of presolar grains of corundum and spinels (Nittler et al. 1997), which probably originate from oxygen-rich AGB stars. The similarity between the 3.4 μm features seen in meteorites and galactic dust also suggests a common origin due to CH_2 and CH_3 side groups (Pendleton 1999). The fact that many organic compounds including alipahatic and aromatic hydrocarbons, alcohols, amines, amides, and carbonyl compounds are found in meteorites raises the question what fraction of these organic compounds is stellar in origin.

5. PN as galaxy probes

The technique of PN luminosity function (PNLF) pioneered by Jacoby (1989) and Ciardullo et al. (1989) has turned out to be one of the most robust method to determine extragalactic distances. Comparison with Cepheid distances shows that the two techniques yield excellent agreement, at least for large, metal-rich galaxies. Interestingly, the success of the PNLF imposes useful constraints on our understanding of the PN evolution, initial mass-final mass relationship, and the initial mass function of PN progenitors.

The utility of PNe as tracer of dark matter distirbution in elliptical galaxies is now firmly established since the early work of Hui et al. (1995). Even for

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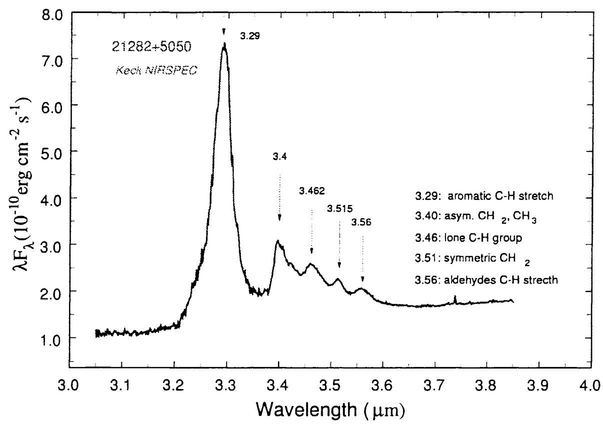

Figure 4. The spectrum of IRAS 21282+5050 taken with the NIR-SPEC instrument at Keck showing the stretching modes of CH_2 and CH_3 sidegroups, as well as the 3.56 μm feature due to aldehydes.

spiral galaxies where the existence of dark matter halo can be inferred from HI rotational curves, PNe can separate the mass contributions from the bulge, disk, and haloes.

The detection of intracluster PN (IPN, Arnaboldi et al. 1996) opened the possibility of using PNe to infer the dynamical history of the cluster. The detection of IPN also allows us to estimate the total intracluster stellar population. Since the fraction of matter in baryonic form is a significant parameter in any cosmological model, the observations of IPN has obvious implications on the origin of the Universe.

6. Summary

In spite of the long history of PNe as objects of astronomical observations, we are just beginning to understand their origin, structures, and evolution. As a short phase of stellar evolution linking the AGB and white dwarf stages, PNe (and PPNe) evolve over a factor of 10-100 in temperature and a factor a 100 in luminosity. PNe are unique among astrophysical objects in the richness of physical and chemical processes present. These processes lead to radiations throughout the electromagnetic spectrum, from radio to x-ray. They also serve as the ideal laboratory for the study of radiative, mechanical, and chemical interactions between stars and their environment.

The high-dynamic range images of PNe have revealed new details in the structures of PNe. The lessons we learn in the interpretation of these features by dynamical models will have significant implications in our understandings

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of Wolf-Rayet nebulae, supernovae, young stellar objects, and active galactic nuclei.

The chemical abundances in PNe reflect the history of nucleosynthesis on the AGB, as well as the galactic environment from which they are born. The study of PNe therefore provides important clues on both stellar and galactic evolution. As standard candles and dynamical tracers, PNe serve as useful tools for the determination of the large scale structure of the universe, the distribution of dark matter, and the measure of the total bayronic mass in the universe. The possibility that the organic content of meteorites may be linked to PNe ejecta suggests that PNe are relevant from the largest structure of the universe to the smallest bodies in the solar system.

As we gather here in Australia for the seventh IAU symposia on planetary nebulae, we are riding on the heights of tremendous successes we had in the last 5 years. At the same time, we face new challanges not forseen in the last symposium. I look forward to five days of vigorous discussions and debates, and I am certain that the results to emerge from this meeting will have significant implications not only to our field, but also to other fields of astronomy, and even to other disciplines of scientific research.

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From left to right: Lucy and Bruce Hrivnak, Maria and Detlef Schönberner.

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