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A Retrospective: Interacting Winds Theory, Two Decades Later

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Abstract. The role of the interacting stellar winds (ISW) model in our modern understanding of planetary nebulae formation and evolution is reviewed. The physical origin of the observed morphological diversity of planetary nebulae is discussed in terms of the ISW model. The possibility that the observed morphological classes of planetary nebulae can be explained by a universal model is also considered.

1. Introduction

Since Shklovsky's (1956) suggestion that planetary nebulae (PNs) originate from red giants, a number of physical mechanisms, including dynamical, pulsational, and thermal instabilities, have been proposed as the ejection mechanism of PN. At the time of the 1977 IAU Symposium 76 in Ithaca, New York, it was clear that while these theories were qualitatively appealing, none of them were capable of ejecting the right amount of mass over the right time scale. At the same time, advances in infrared and millimeter-wave astronomy had revealed that asymptotic giant branch (AGB) stars are losing mass at a high rate, and it became apparent that the extensive circumstellar envelopes (CSE) built up by such mass loss must have an effect on the formation of PN.

However, PN have definite morphologies, and have higher densities and expansion velocites than the CSE of AGB stars. A separate mechanism was needed to compress, accelerate, and shape the CSE into a PN. The solution was found in the interacting stellar winds (ISW) model (Kwok, Purton, & FitzGerald 1978). The ISW model suggests that a PN is formed by a snow-plow process in which the remnant AGB CSE is compressed into a shell by a later-developed fast wind. 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 PN (Heap et al. 1978), 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 (e.g. *IRAS*) and millimeter-wave observations. Due to the low emission measures of the bubble, direct detection of the bubble by X-ray imaging was only marginally possible with *ROSAT*, but should be feasible with *Chandra* (Chu, these proceedings).

2. Implications of the ISW model

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 a PN therefore reflects the coupled dynamical and ionizational evolution of the nebula.

The existence of a PN requires that the nebula expansion occurs on the same time scale as the evolution of the central star. One of the difficulties faced by sudden ejection models is that if too much mass is left over after the ejection, the central star will not evolve fast enough to ionize the nebula before its dispersal. In the ISW model, the slow wind will continue to deplete the H envelope until the mass of the envelope is very low and the effective temperature of the star has begun to increase. The ejection of the nebula and the evolution of the central star are therefore naturally coupled. The existence of post-AGB mass loss in the form of a fast outflow will also speed up the central star evolution (Schönberner 1983). The fast wind is therefore not only important in the dynamical evolution of the nebula, but also in the evolution of the central star.

The time-dependent nature of PN evolution was incorporated into many of the 1-D spherically symmetric treatments of the ISW model (Giuliani 1981; Kwok 1982, 1983; Kahn 1983; Chevalier & Imamura 1983; Okorokov et al. 1985; Volk & Kwok 1985; Bedogni & d'Ercole 1986; Schmidt-Voigt & Köppen 1987a, b; Frank, Balick, & Riley 1990; Kahn & Breitschwerdt 1990; Marten & Schönberner 1991; Icke et al. 1992; Frank 1994; Mellema 1994; Frank & Mellema 1994a). These models have led to a fresh interpretation of the observed properties of PN, some of which are discussed below.

2.1. Derivation of physical parameters

Traditionally the physical properties of PN were derived from observations assuming a spherical, uniform density nebula. In the ISW model, the shell, halo, and the bubble have density and temperatures ranging over several orders of magnitude. Such differences could account for the failure of the $T_e - n_e$ curves from forbidden lines to converge to a single point (see e.g., Hyung et al. 1994).

2.2. Multiple shells

The conventional interpretation of the presence of multiple shells in PN is by multiple ejection models (Trimble & Sackman 1978; Tuchman & Barkat 1980). Since the interacting winds process erases all mass loss history on the AGB, it is unlikely that the morphology of any multiple shells ejected during the AGB will remain intact in the PN stage. On the other hand, multiple shell structures can be the natural consequences of the ISW model. As the ionization front breaks out of the shell, an envelope (or a "crown" in the terminology of Frank et al. 1990) with a linear emission profile can be created (Mellema 1994).

The fact that some outer shells of PN expand faster than the inner shells seemed difficult to explain in the ISW model (Chu 1989). However, in a 3-

wind model assuming a two-phase AGB mass loss, a second shell formed at the interface between the superwind and the AGB wind can expand faster than the main shell (Fig. 2, Schmidt-Voigt & Köppen 1997a; Fig. 4, Frank 1994).

2.3. Expansion velocities

Although we expect the dynamical ages ($t_d = R/V$ where R is the PN radius and V is the expansion velocity) of PN to be the same as the evolutionary ages (t_*) of the central stars, the observed values of t_d are found to exceed those of t_* (McCarthy et al. 1990). The expansion velocity of a PN is commonly derived from the line profiles, which give the matter velocity at the radial position with the largest emission measure. This does not necessarily correspond to the true expansion velocity, which is defined by the position of the shock front (Schönberner et al. 1997). Since the shock velocity is greater than the matter velocity, the dynamical ages of PN were estimated over in the past.

2.4. Statistical distances

The Shklovsky method of distance determination assumes a fixed mass for the nebula. In the ISW model, the mass of the nebular shell grows with age and cannot be assumed to be a constant (Kwok 1982). Observations of PN in the Magellanic Clouds have found a mass-radius relationship of the form $M \propto R^\beta$, with $\beta \simeq 1.5$. Such a relationship is in part due to the snow-plow effect, and in part due to the expansion of the ionization front (Volk & Kwok 1985; Schmidt-Voigt & Köppen 1987b; Zhang & Kwok 1993; Mellema 1994). The replacement of the constant mass assumption by the mass-radius relationship has resulted in a revision of the statistical distance scales.

3. ISW and the shaping of planetary nebulae

The possibility that asymmetric PN can be produced by the ISW process if the AGB wind has an asymmetric density profile was first discussed by Kahn & West (1985). Balick (1987) outlined a scenario in which the different morphologies of PN represent an evolutionary sequence as the result of ISW shaping. This idea stimulated much numerical work, including Icke (1988), Soker & Livio (1989), Icke (1991), Icke et al. (1992), Frank et al. (1993), Frank & Mellema (1994b), Mellema & Frank (1995), Mellema (1995), Dwarkadas et al. (1996), Mellema (1997), Dwarkadas & Balick (1998), and Garcia-Segura et al. (1999).

4. Interacting winds in other astrophysical problems

The concept of interacting winds has also been successfully applied to other fields, including ring nebulae around massive stars (WR stars, LBV, etc; D'Ercole 1992, Garcia-Segura & MacLow 1995), supernovae (Lou & McCray 1991), young stellar outflows (Frank & Noriega-Crespo 1994), relativistic jets in AGN (Eulderink & Mellema 1994), and galactic superbubbles (MacLow et al. 1989). The 3-ring structure observed in SN 1987A gives a strong confirmation of interacting winds at work in that system (Gaensler, these proceedings).

Of particular interest to the study of PN are the interacting winds in symbiotic stars. Rather than both winds originating from the same star as in the case of PN, the slow and fast winds originate, respectively, from the cool and hot (compact) components of the symbiotic system. The evidence for interacting winds is particularly strong in symbiotic novae (e.g. V1016 Cyg, HM Sge), which show many similarities in observational properties to PN (Kwok 1988).

Since the hot component of a symbiotic system is likely to have gone through a PN phase before it is reignited by mass transfer, and the cool component, a mass-losing AGB star, will also evolve to a PN on its own in a million years, the symbiotic novae could represent an interlude between two PN phases! Furthermore, in the second PN phase, the nebula will be seen to have two central stars: one more luminous (the core of the present AGB star) and one a WD on the cooling track.

5. 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, 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 (Dayal & Bieging 1995), suggesting the AGB mass loss over the dynamical lifetime ($\sim 10^4$ yr) is approximately spherical. Figure 1 shows the HST V-band image of the inner regions of IRC+10216. Although the CSE of IRC+10216 is spherical on an arcmin scale, the central 5 arcsec reveals a bipolar reflection nebula. This could imply that the mass loss has become aspherical as the star approaches the end of the AGB, or that a collimated fast outflow has cleared the polar regions, allowing the scattered light to escape and be seen as a reflection nebula.

6. Morphological classification of planetary nebulae

Beginning with the work of Curtis (1918), there have been many attempts in classifying the morphologies of PN. However, all classification schemes suffer from the following problems:

- Sensitivity dependence: a deeper exposure can reveal fainter structures which change the classification of the PN. For example, the waist of a bipolar nebula could be classified as elliptical if the bipolar lobes are too faint to be detected.
- Species dependence: The morphology of PN 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 PN.

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 nec-

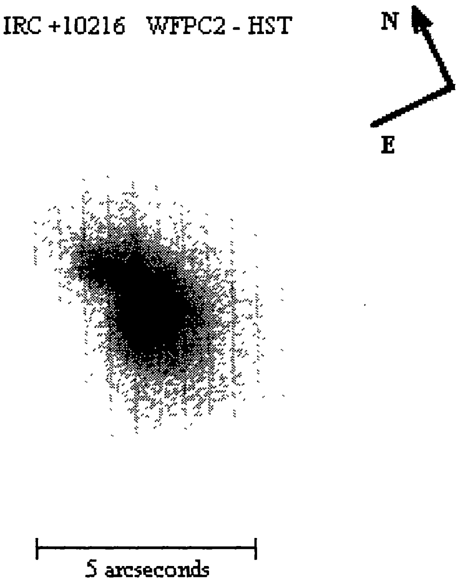

Figure 1. HST WFPC2 F606W drizzled image (4700 s exposure) of IRC+10216. Processed from HST data archive (program 6856, PI: J. T. Trauger).

essary to separate various components projected on the same positions in the sky. This is clearly illustrated by the case of NGC 3132, which has an obvious elliptical shape, but kinematic data suggest that it is a bipolar nebula (Monteiro et al., these proceedings).

7. A universal model 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 an open-ended cylinder projected onto the sky, and Masson (1989, 1990) and Aaquist & Kwok (1996) employed an ellipsoidal shell (EPS) 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 EPS model.

The success of the EPS model suggests that ionization plays a role in creating the different morphologies of PN. As discussed above in section 2, PN evolution is a combination of photoionization and the ISW process. Based on this principle, we can consider the following universal model of PN:

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

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. When viewed near edge on, the PN will appear to have a bipolar or butterfly shape.

8. Problems

Recent observations, in particular high-resolution images obtained with the HST, have discovered new microstructures which were not predicted by the ISW model.

- FLIERS and jets: FLIERS are pairs of small, bright knots of low excitation gas found along the major axes of PN. 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.
- Rings and arcs: concentric rings and arcs have been observed in both PN (e.g. Hb 5, NGC 6543, NGC 7027) and PPN (e.g. AFGL 2688, IRAS 17150-3224). These arcs are of almost perfectly circular 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 is a difficult problem to resolve.
- Point-symmetric structures: point-symmetric pairs of knots in an S-shape structure, or sometimes referred to as bipolar, rotating, episodic jets (BRETs), have been seen in a number of PN (López et al. 1995, Sahai & Trauger 1998) and PPN (Hrivnak et al. 1999). Some PN have been found to have more than one polar axis, suggesting that the outflow direction has changed with time (López et al. 1998).
- Collimated outflows: some PN (e.g. M2-9, Schwarz et al. 1997) and PPN (e.g. Hen 401, Sahai et al. 1999) have extreme bipolar (cylindrical) shapes, suggesting that their morphology is shaped by a collimated outflow.

Qualitatively speaking, we can identify the rings and arcs as manifestations of the slow wind, and the point symmetric structures as reflections of the properties of the fast wind. FLIERS, on the other hand, are likely to be the consequence of wind interactions and photoionization (Dyson, these proceedings).

9. The ISW model in the next decade

The discovery of bipolar PPN suggests that the shaping mechanism is already active several hundred years after the AGB (Kwok et al. 1996). Since the central star is still cool during the PPN stage, the fast wind cannot be explained by radiation pressure on resonance lines, which is the commonly accepted mechanism for fast winds seen in central stars of PN. The only direct evidence for the fast outflows in PPN are in the high-velocity line wings of CO. These wings need to be mapped by millimeter interferometry so that we can have direct information on the structures of the outflows. The possibility that these outflows are episodic instead of continuous, as suggested by the observed point symmetric structures, needs to be investigated.

While wind interaction remains the main driving force in the formation of PN, the possibility of angle or time dependence of either or both of the outflows can create richer and more varied morphologies. The identification of the physical origin of such asymmetric outflows will be the next major challenge in our understanding of the PN phenomenon.

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