

Dynamical PN Evolution with Magnetic Fields

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Abstract. Hydrodynamical simulations played an important role in understanding the dynamics and shaping of planetary nebulae in the past century. However, hydrodynamical simulations were just a first order approach. The new millennium arrived with the generalized understanding that the effects of magnetic fields were necessary to study the dynamics of planetary nebulae. Thus, B-fields introduced a whole new number of physical possibilities for the modeling. In this paper, we review observational work done in the last 5 years and several works on the magnetohydrodynamics of proto-planetary nebulae, since all the effort has been focused on that stage, and discuss different scenarios for the origin of magnetized winds, and the binary-bipolarity relation.

Keywords. MHD—Stars: AGB and Post-AGB—Planetary Nebulae: general

1. Introduction

The origin and evolution of proto-planetary nebulae (PPNs) and planetary nebulae (PNs) represents one of the key questions in our understanding of stellar physics. Modeling the fascinating features displayed by these objects requires not only a better knowledge of stellar structure at the AGB stage (and beyond) but also a proper consideration of the driving mechanisms for mass ejection. The transition from AGB to Post-AGB to PN central stars involves drastically different conditions at every stage. Whereas radiation pressure on dust grains is the most likely mechanism at the AGB phase, as are line-driven winds in the case of PN central stars, for Post-AGB stars the details of the driving force has been relatively unexplored.

To begin this review, it is interesting to mention the increasing number of articles related to magnetic fields in PNs during the last years. Before IAU Symp. 180 (Groningen 1996), the average number of papers per year was 0.41 (base line of 39 years). Over the next 5 years until IAU Symp. 209 (Canberra 2001) the number increased to 6.2 per year. Over the last 5 years this number had grown to 11.8 per year by the present Symposium (Hawaii 2006). What is even more interesting is that, in the last five years, 75% of all the papers were observational. Finally, **measurements of magnetic field intensities and their orientations have been made!!** This fact will be important in the next five years, since theoretical models have something robust to start with.

All the theoretical work done on PNs up to 2001 was focused on the line-driven wind theory, including weak or moderate magnetic fields frozen in the winds (see review by García-Segura 2003). However, since the paper by Bujarrabal *et al.* (2001), in which it is stated that PPNs could not be explained by radiation forces on the winds, most of the work done in the last five years has focused on PPNs and the winds from post-AGBs stars.

In this paper, we first make a short review of the observations done in the last five years, and then proceed with the MHD work.

2. Magnetic field measurements

2.1. SiO, H₂O and OH masers: Zeeman

15 objects with circularly polarized masers due to the Zeeman effect have been detected so far: S Per (Vlemmings *et al.* 2001, 2002, 2005); K 3–35 (Miranda *et al.* 2001, Gómez *et al.* 2003, 2005); RT Vir, RCrT, W Hya (Szymczak *et al.* 2001); VY CMa, NML Cyg, U Her (Vlemmings *et al.* 2002, 2005); W43A (Imai *et al.* 2002, Vlemmings *et al.* 2006); OH 17.7-2.0 (Bains *et al.* 2003, Szymczak & Gérard 2004); U Ori, VX Sgr (Vlemmings *et al.* 2005); IRAS 20406+2953 (Bains *et al.* 2004); IRAS 07331+0021, IRAS 18266-1239 (Szymczak & Gérard 2004). The measurements for the magnetic fields intensities go from 10^{-2} gauss for OH masers up to several tens of gauss for SiO masers (Vlemmings *et al.* 2005, 2006). The most exciting object is W43A, which presents a precessing, magnetically collimated jet (Vlemmings *et al.* 2006), showing also how the field is oriented in the flow. These measurements will constrain future MHD models of winds in late AGB stars, and disk-wind models from interacting binaries and common envelope phases.

2.2. Nebulae with toroidal fields: dust grain alignments

The alignment of dust grains under the influence of a magnetic field can be observed in linear polarization in the submillimetre regime. The following nebulae show toroidal field configurations: NGC 7027 and CRL 2688 (Greaves 2002, Sabin *et al.* this volume); NGC 6537 and NGC 6302 (Sabin *et al.* this volume).

2.3. Central stars of PNs: Zeeman

Magnetic fields of the order of kilogauss have been finally detected in central stars of PNs. The detected objects are NGC 1360, EGB 5, LSS 1362 and Abell 36 (Jordan *et al.* 2004, 2005). Those central stars are hot and evolved; thus, these measurements will constrain MHD models with line-driven, magnetized winds.

2.4. Large scale fields: Faraday rotation in PNs

The discovery of a Faraday screen feature associated with a known astronomical object, the PN S216, has been reported by Uyaniker (2004). This detection is extremely interesting for two reasons, the first one is that it is the first Faraday screen in which the distance is known ($d \sim 80$ pc), and the second one is that it proves the existence of large scale magnetic fields associated with a PN (S216 is 3×3 pc, 1° in the sky).

3. The PPN-wind problem: radiation ruled out

Winds from AGB stars are thought to be driven by radiation pressure on dust grains (see review by Habing 1996), although an alternative physical mechanism has been proposed by Pascoli (1997) based on magnetic pressure that is transported out from the stellar interior to the stellar surface. On the other hand, it is widely accepted that planetary nebulae are powered by line-driven winds emerging from their central stars, and they are formed from a two-wind dynamic interaction (i.e., Kwok, Purton & Fitzgerald 1978). Evidence for this scenario includes the large number of P-Cygni line profiles detected in their central objects (Perinotto 1983).

Post-AGB stars with their associated Proto-planetary nebulae (PPNs) are short-lived transition objects between AGB stars and white dwarfs. Their wind energy source, although unclear, has been usually assumed to be radiation pressure. However, recent observations of PPNs (Alcolea *et al.* 2001; Bujarrabal *et al.* 2001 and references therein) have revealed that the linear momenta and kinetic energies associated with these objects are in excess to what can be provided by radiation pressure alone, in some cases by up to three orders of magnitude. These large amounts of momentum and energy, as discussed in detail by Bujarrabal *et al.* (2001), cannot be accounted for by either radiation pressure on dust grains, line-driven winds or continuum-driven winds.

4. Magnetic-driven winds: a possible solution

Four scenarios with different types of wind driving mechanisms have been suggested in the literature:

A. Accretion disk wind solutions

The theory of magneto-centrifugal launched winds from an accretion disk, where toroidal magnetic fields become finally dominant (e.g. Contopoulos 1995) is applied in this scenario. Several solutions differ in the accretion mode: accretion of the primary wind onto the secondary (e.g. Morris 1987, Mastrodemos & Morris 1998); Roche lobe overflow (e.g. Livio, Salzman & Shaviv 1979; Livio & Soker 1988); accretion on the primary after common envelope evolution (in this case, the disk is formed around the primary star). Recent works on this scenario are Reyes-Ruiz & López (1998), Blackman *et al.* (2001b), Frank & Blackman 2004, and Frank (this volume).

B. Stellar (Post-AGB) solutions

The results discussed by Pascoli (1997), based on surface magnetic pressure as the main driver of the large mass-loss rates in AGB stars, are an alternative to generate the required mechanical power in the winds of Post-AGB stars (García-Segura *et al.* 2005), provided that the generation of magnetic fields can be efficient in post-AGB stars, as suggested by Blackman *et al.* (2001). There is not yet a clear model of how a single star can achieve this. One plausible scheme is that the rotation rate and the field strength at the stellar core increase during the formation of the white dwarf. Thus, the inner magnetic field becomes stronger as the core contracts and becomes exposed at the stellar surface when the envelope is peeled-off during the PN formation. Thus, a strong and dominant toroidal component develops at the interface between the core and the envelope, where some dynamo action is expected and which may be responsible for launching a magnetically driven wind. Actually, Blackman *et al.* (2001), Matt, Frank & Blackman (2004) and Miyaji *et al.* (this volume) have proposed that the post-AGB wind is produced by magneto-centrifugal processes, when dynamo activity increases the internal field (see Blackman 2004) and the AGB star sheds its outer layers, exposing the rotating and magnetized core. Obviously, more detailed stellar interior studies with rotation and B -fields are needed to understand the details of this issue. In addition, some authors have suggested that this may also occur in binary systems and, for instance, Soker (1997) proposed that the Post-AGB stellar core can be spun-up by a secondary, increasing the shear between the core and the envelope.

C. Stellar + disk solutions

This scenario combines the two solutions above, for the case in which the disk is formed around the primary star (Blackman *et al.* 2001; Frank, this volume).

D. Dynamo during common envelope phase

The spiral-in process of a secondary star, or a giant planet, may also be able to produce a large shear in the stellar envelope, and raise the magnetic field strength by dynamo activity (Tout & Regös 2003). These cases link the large mass-loss rates in the post-AGB stages with a common envelope phase. Unfortunately, there are very few detailed studies of post-common envelope systems (e.g. Exter, Pollaco & Bell 2003).

5. Magneto-centrifugal core-envelope launching

A promising avenue, using dynamo amplification at these late evolutionary stages, has been discussed by Matt *et al.* (2004). They use a simplified model in which the interface between the (rotating and magnetized) stellar core and envelope stores a large amount of magnetic energy due to the twisting of an originally poloidal magnetic field. The magnetic energy is extracted from the stellar rotational energy, causing a rapid spin-down of the proto white dwarf, and is able to drive a strong and short outburst (this is somehow similar to the “magnetic bubble” mechanism proposed by Draine (1983), to generate molecular outflows in star-forming clouds). The outflow can expel the envelope and is termed “magnetic explosion” by Matt *et al.* (2004; see also the work by Miyaji *et al.* in this volume).

6. Proto-Planetary Nebula MHD Models

García-Segura *et al.* (2005) have followed magnetic-driven wind expansion and nebula formation for six models. Three of them, models A, B and C have a spherically symmetric initial atmosphere (their Figure 1), while models D, E and F (their Figure 2) have an equatorial density enhancement.

The numerical solutions show that collimation is well established at the very early phases of evolution, creating jet-like outflows at locations close to the star. The inclusion of the density enhancement (their Figure 2) produces, as expected, a narrow equatorial waist without any apparent direct impact at the polar regions. The polar expansion velocities are similar for all models with the same input magnetic field; models A and D have $v_{exp} \sim 30 \text{ km s}^{-1}$, models B and E have $v_{exp} \sim 150 \text{ km s}^{-1}$, while models C and F have $v_{exp} \sim 390 \text{ km s}^{-1}$.

As a comparative example, their Figure 3 compares the result of one of the models with 1 gauss (model E) at 1,000 yr, with two well known, extremely collimated PPNs, He 3-401 (Sahai 2002) and M 2-9 (Schwarz *et al.* 1997). It is apparent in this figure that the solution is able to reproduce convincingly the extreme collimated shapes, along with the sizes and kinematics of these nebulae. Similar results also have been computed by Washimi *et al.* (this volume).

We now turn our attention to the kinetic energy and linear momentum contained in the outflows from these models. Bujarrabal *et al.* (2001), as mentioned earlier, have pointed out that radiation pressure is insufficient to provide the observed mechanical power in the outflows of PPNs. Figure 6 of García-Segura *et al.* (2005) gives the results for three different values of the surface magnetic field covering the initial 1000 years of evolution. The data on PPNs from Bujarrabal *et al.* (2001) are indicated as crosses in these plots. The values for most of these objects seem to be well bracketed by models B (1 G) and C (5 G). Therefore, magnetic-driven winds are able to provide the necessary energy budget to power the outflows of PPNs.

7. Magnetic Cycles

Magnetic cycles, and their associated field reversals, have been proposed as a plausible origin for the multiple, regularly spaced, and faint concentric shells around some planetary nebulae observed with the Hubble Space Telescope (Soker 2000; García-Segura *et al.* 2001). In fact, OH maser observations by Szymczak *et al.* (2001) suggest that changes in the polarized maser emission in some stars could be caused by turbulence in the circumstellar magnetic field and by global magnetic field reversals.

García-Segura *et al.* (2005) explored the effects of magnetic field reversals in magnetic-driven winds, and compared the results with objects displaying collimated outflows with periodic outburst features. An interesting example is He 2-90, a PPN whose symmetric and highly collimated, knotty, bipolar outflow was described by Sahai & Nyman (2000). The radial velocities of the knots have been measured by Guerrero *et al.* (2001), and the corresponding proper motions subsequently derived by Sahai *et al.* (2002). An interesting, and puzzling characteristic in this case is that the collimated outflow, or jet, maintains a nearly constant apparent width throughout all its extent, i.e. it does not fan out at large distances from the star, and the velocity of the regularly spaced knots seems to be the same. The “jet” speed is somewhere between 150–360 km s⁻¹, its dynamical time is at least 1400 yr, and the knots are created at the rate of one pair roughly every 35–45 yr. An extensive numerical study can be found in Lee & Sahai (2004), who concluded that the inclusion of a magnetic field was necessary.

8. Bipolar and elliptical nebulae: the role of binaries

The morphology and galactic distribution of PNs was discussed by García-Segura *et al.* (2002). We here review the important points.

During the last decade, two important surveys were carried out on both hemispheres. For the southern hemisphere, *The ESO Survey*, the study was published in a series of papers by Schwarz, Corradi & Melnick (1992), Stanghellini, Corradi & Schwarz (1993; 250 PNs), Corradi & Schwarz (1995), and Corradi (2000; 400 PNs). For the northern hemisphere, *The IAC Survey* was published by Manchado *et al.* (1996; 243 PNs) and Manchado *et al.* (2000; 255 PNs). The first detailed study of the differences between ellipticals and bipolars was done by Corradi & Schwarz (1995) with the ESO Survey (see also Corradi 2000). They found that the bipolar class has a smaller scale height, 130 pc, than that for ellipticals, 320 pc. Also, bipolars have the hottest central stars among PNe, and display smaller deviations from pure circular Galactic rotation than other morphological types. In addition, bipolars also display the largest physical dimensions and have expansion velocities of up to an order of magnitude above the typical values for PNe. These properties, together with the chemical abundance results by Calvet & Peimbert (1983), indicate that bipolar PNe are produced by more massive progenitors than the remaining morphological classes.

Table 1.

Morphological Class (IAC Survey)	< z > pc
B	110
BPS	248
E	308
EPS	310
R	753

The average scale height over the plane, $\langle z \rangle$, for different PN morphological classes can be compared with those of different stellar masses and populations. For instance, we know that massive stars are located much closer to the galactic plane than the population of stars with lower initial mass. The outcome from the ESO and IAC surveys is certainly coincident: the bipolar (B) class has $\langle z \rangle = 130$ pc (ESO) and $\langle z \rangle = 179$ pc (IAC), for ellipticals (E) $\langle z \rangle = 320$ pc (ESO) and $\langle z \rangle = 308$ pc (IAC), and for round nebulae (R) $\langle z \rangle = 753$ pc (IAC).

In the recent analysis of the IAC Survey by Manchado *et al.* (2000), the bipolar and elliptical objects with point-symmetric features (BPS and EPS) were separated from those which do not present such kind of symmetries, i.e., from the B and E classes respectively. The new results from the IAC Survey are given in Table 1.

Comparing the results of the IAC Survey with those described by Miller & Scalo (1979) for the average scale height of stars with different masses, an average value equal or smaller than 110 pc corresponds to stars with initial masses above $1.9 M_{\odot}$. Lower mass stars have average scale heights well above this value. These results are in line with the pioneering suggestion of Calvet & Peimbert (1983) and the more recent discussion made by García-Segura *et al.* (1999).

The relation between morphology and galactic distribution was explained by García-Segura *et al.* (2002) as :

- Bipolars Type I Peimbert = (B):

Small $\langle z \rangle$ (110 pc) \iff Massive Progenitor \iff Stellar Rotation \iff Ω Limit \iff Classical Bipolarity

- Bipolars with Point-Symmetry = (BPS):

Moderate $\langle z \rangle$ (248 pc) \iff Non-Massive Progenitor in Tidally interacting Binary System \iff Tidal Spin-Up \iff Shaping by Ω Limit + MHD Effects + Precession/Wobbling \iff Bipolarity with Point-Symmetry (Lobes, FLIERS, Jets)

- Ellipticals = (E):

Medium $\langle z \rangle$ (308 pc) \iff Non-Massive Progenitor \iff Shaping by MHD Effects \iff FLIERS & Jets with Axisymmetry

- Ellipticals with Point-Symmetry = (EPS):

Medium $\langle z \rangle$ (310 pc) \iff Non-Massive Progenitor in Wide Binary System \iff Shaping by MHD Effects + Precession \iff FLIERS & Jets with Point-Symmetry

- Round = (R):

Large $\langle z \rangle$ (753 pc) \iff Low-mass Progenitor \iff Neither Rotation nor MHD effects

To conclude, the direct signature of a binary is well traced in nebulae with any kind of point-symmetry (BPS and EPS classes), however, the direct link between binarity and bipolarity cannot be concluded (the EPS class is the counter example) from the galactic distribution. It is clear that bipolars are associated with more massive stars. **If binaries play a role in the formation of bipolars, at least one or both stars in the binary system must be massive.**

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