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THE FORMATION OF COLLIMATED OUTFLOWS AND CONCENTRIC RINGS IN MAGNETIZED PLANETARY NEBULAE

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RESUMEN

Campos magnéticos y asimetrias en los vientos de estrellas con rotación, además de la precesión del eje de rotación, pueden crear la mayor parte de las morfologías y los flujos colimados (jets) observados en Nebulosas Planetarias. La colimaci'on de los flujos debido a la tensión magnética se vuelve muy eficiente después de que el viento magnetizado ha pasado por el choque de reversa. Asimismo, los anillos concentricos observados en algunas PNs pueden ser explicados por un ciclo magnético de tipo solar, con cambios periódicos en polaridad.

ABSTRACT

Magnetic fields and wind asymmetries from rotating stars, along with precession of the stellar rotation axis, can create most of the observed Planetary Nebulae morphologies and collimated outflows (jets). The collimation of the flows by magnetic tension becomes very efficient after the magnetized wind has passed through the reverse shock of the PN. Also, the concentric rings observed in some PNe can be explained by a solar-like magnetic cycle with periodic polarity inversions.

Key Words: **HYDRODYNAMICS — ISM: JETS AND OUTFLOWS — ISM: BUBBLES — PLANETARY NEBULAE: GENERAL — STARS: AGB**

1. INTRODUCTION

Planetary Nebulae (PNe) display a variety of complex shapes with optical emission-line spectra dominated by forbidden lines of different ionic species. They are classified according to shape as spherical, elliptical, bipolar, quadrupolar, point-symmetric, and irregular (see catalog by Manchado et al. 1996), and some of these morphologies may be associated with the mass of the progenitor star (see the paper by García-Segura et al. in this volume). Some PNe display collimated outflows, others show multiple concentric rings (or arcs), and some others a series of knots aligned in a narrow jet-like straight line (see Kwok, Su, & Hrivnak 1998; Balick et al. 2000; Terzian & Hajian 2000; Sahai & Nyman 2000; Guerrero et al. 2001). These features, along with some of the point-symmetric features described by López et al. in this volume, indicate the existence of quasi-periodic events and precession of the rotation axis during the evolution of the nebulae. PNe are formed by the expulsion of the outer layers of a low-mass star at its final evolutionary phase. The AGB wind drives a massive outflow, with speeds of about 20 km s^{-1}, and the wind velocity increases to more than 10^3 km s^{-1} as the stellar nucleus becomes a white dwarf. The wide variety of observed shapes seems to be produced, during the transition from AGB to the PN phase, by the interaction of the slow and fast winds. This model, usually referred to as the "interacting wind" model, has been developed and modified over the last three decades (see recent reviews by Frank 1999, Franco et al. 2001, and Gardiner & Frank 2001), and has been successful in explaining the main properties of PNe.

In particular, MHD processes seem to be key ingredients in shaping the nebulae. Recent high-resolution studies have revealed a wealth of complex structures with fliers, ansae, bipolar jets, multipolar outflows, concentric rings, and narrow and well collimated jet-like blobs. Despite some criticisms about the actual relevance of B-fields in shaping PNe (see Soker 1998, 2000, 2002; Frank 1999), the existence of all these observed features is difficult to understand without the active role of toroidal magnetic fields and solar-like cycles. This view is now reinforced by the recent discovery of a toroidal magnetic field, of milliGauss strength, in the circumstellar torus of the young planetary K3-35 (Miranda et al. 2001). Here we describe, within the interacting wind scenario, the role played by stellar rotation and magnetized winds in the origin of collimated outflows and concentric rings in PNe.

2. STELLAR ROTATION, MAGNETIC FIELDS, AND COLLIMATION

As stated above, the fast wind of the post-AGB phase eventually collides with the slower AGB wind and, as the ejected matter is photoionized by the central star, the main features of spherical and elliptical PNe are satisfactorily explained with a simple interacting wind model (i.e., Dyson & de Vries 1992; Kwok, Purton, & Fitzgerald 1978). For elongated and bipolar morphologies, however, the formation of an equatorial density enhancement during the slow-wind phase plays a major role in the subsequent development of the nebula. By modifying the properties of this equatorial density enhancement, the main observed features in axisymmetric PNe are successfully reproduced (Kahn & West 1985; Mellema, Eulderink, & Icke 1991; Frank 1999). The formation of bipolar morphologies, as discussed by García-Segura et al. in these proceedings, can be due to a variety of different agents ranging from binary systems (e.g., Soker & Rappaport 2000), stellar rotation (e.g., García-Segura et al. 1999), and dipolar B-fields (e.g., Matt et al. 2000). The combined action of these agents and additional possibility of precession can certainly create a variety of interesting features in some particular objects (e.g., García-Segura & López 2000).

The roles played by stellar rotation and magnetized winds in the generation of collimated, high-velocity outflows have been explored only recently, and their relevance becomes clear when considering the variety of observed features such as knots, tails, and fliers that are localized both inside and outside the main nebular shells. These structures are prominent in low-ionization lines such as those of [N II], [O I] and [S II], and are present indistinctly in all morphological classes of PNe (see Balick et al. 1993; Gonçalves, Corradi, & Mampaso 2001). Pure hydrodynamic models face certain difficulties in reproducing these types of structures (i.e., jet-like outflows are very difficult to form because fast winds tend not to converge into stable structures; see Dwarkadas & Balick 1998), and stellar rotation and magnetized winds are logical alternatives to create them (Różyczka & Franco 1996; García-Segura et al. 1999; Matt et al. 2000; Blackman et al. 2001).

As discussed by Bjorkman & Cassinelli (1993) for pressureless rotating winds, rapidly rotating stars can create asymmetrical outflows with equatorial density enhancements. García-Segura et al. (1999) applied these solutions to the initial slow wind of rotating AGB stars, and generated winds with higher densities near the equatorial plane. The resulting torus-like mass concentrations act as obstacles for the faster second wind, and the flow becomes bipolar and evolves along the rotation axis. Similar density enhancements can also be created in binary systems (e.g., Soker & Rappaport 2000), but now the angular momentum of the flow is associated with the orbital motion of the system. Hence, stellar rotation in either single stars or binary systems may be one of the principal causes of the bipolar structures in PNe.

Aside from the asymmetries induced by rotation, magnetic fields can also drive deformations in both the free-expanding wind and in the corresponding wind-driven bubbles. The magnetic field in an outflowing wind from a rotating star has a toroidal component that decreases with distance as r^{-1}, and this component eventually dominates the evolution of the wind. The first description of the configuration of the magnetized wind was given by Weber & Davies (1967) for the case of the solar wind and their solutions were restricted to the flow at the equatorial plane. Later on, Sakurai (1985) made a generalization of the Weber & Davies model, and derived the wind trajectories outside the equatorial plane for the particular case of a rotating split monopole. The main effects of the tension of the toroidal field (also referred to as the hoop stress) are the deflection of the field lines toward the polar direction, and he found that the wind is collimated along the polar axis at large distances from the star. The hoop stress in a stellar wind operates in exactly the same manner as discussed in earlier works for winds from accretion disks (Blandford & Payne 1982), and the only difference is the topology of the initial flow. More recently, several authors (see Rotstein & Ferro-Fontan 1995, and the review by Rotstein 1998) have discussed the outflows resulting from rotating stars with different magnetic multipole structures. They found that the outflows are always collimated towards the rotation axis, and that equatorial density enhancements can also occur when a dipolar field is present. In particular, Matt et al. (2000) derived the density enhancements at the equatorial plane for dipole fields with a variety of wind parameters. All these works have focused, as in the case of accretion disk solutions, on the solutions for freely expanding winds.

Regarding the shaping of nebulae created by *interacting* winds with rotation and magnetic fields, the first and most important step was done by Begelman & Li (1992). They obtained self-similar solutions for aspherical nebulae produced by a rapidly rotating neutron star with a magnetized relativistic wind. They used the thin shell approximation with initial spherically symmetric winds, and the as-

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pherical shapes arose (as in the case of free expanding magnetized winds) solely from the tension of the toroidal magnetic field. This same type of solution, but in the non-relativistic regime, was later applied to PNe by Chevalier & Luo (1994). They found the same steady-state aspherical structures with cylindrical symmetry. Later on, with 2-D MHD simulations in cylindrical coordinates, Różyczka & Franco (1996) found the time-dependent evolution for these interacting magnetized winds. The shapes of the external envelopes are similar to those found in the analytical approximations, but the resulting shocked flows are very complex, with jet-like features and collimated outflows. The generation of a jet-like outflow occurs once the shocked wind region becomes magnetically dominated (the magnetic energy becomes larger than the thermal energy after compression and cooling of the shocked gas). Then the tension of the toroidal field drives a flow from the equatorial parts of the shocked wind region toward the symmetry axis, leading to the formation of a jet. The gas arriving at the polar regions of the nebula forms relatively dense blobs which can be identified with the ansae observed in some PNe. The 3-D computations performed by García-Segura (1997) corroborate the 2-D results and show, in addition, that the collimated flows are probably subject to kink instabilities. This study was extended by García-Segura et al. (1999), who made a series of 2-D spherical calculations to explore the range of shapes that can be ascribed to rotation and magnetic fields. More recently, Gardiner & Frank (2001) made models with even larger magnetic strengths and found that self-collimation can occur even before the fast wind is able to interact with the slow wind. As stated above, this mechanism is actually the one that operates in magnetized accretion disks to form jets, but the most important point to stress here is that magnetic collimation becomes very efficient after the flow has been processed by a shock.

In a further extension of this type of study, García-Segura & López (2000) included the precession of the rotational axis of the progenitor star. They made a computational survey of 3-D MHD simulations for young PNe, and explored the effects of different misalignments of the magnetic collimation axis with respect to the symmetry axis of the bipolar/elliptical wind outflow (see López et al. in this volume). This steady tilt can also be interpreted as the result of a large precession period. The simulations show that in these cases a hydrodynamical deflection of the magnetized, collimated wind on the bipolar/elliptical cavity can produce morphologies that may resemble the presence of precessing or rotating sources. Also, the strength of several features is controlled by varying only the mass-loss rate of the wind, and they are able to reproduce a considerable number of point-symmetric morphologies. The inclusion of a binary system in these models only strengthens the conditions for the development of point-symmetry in the resulting nebulae. All these works indicate that MHD shaping and collimation is a key ingredient in understanding PN formation and evolution.

3. MAGNETIC CYCLES, CONCENTRIC RINGS, AND ALIGNED KNOTS

The presence of multiple concentric rings, or arcs, in some PNe (see Kwok et al. 1998; Balick et al. 2000) indicates the existence of quasi-periodic events, with time intervals of about 500 to 1500 years, during PN formation. The possible origin of these rings has been discussed by Soker (2000) and, after a critical review of the mechanisms that have been proposed to explain them, he concludes that a solar-like magnetic cycle is perhaps the best alternative for their origin. The possibility of a solar-like magnetic dynamo at the AGB phase has been recently discussed by Blackman et al. (2001) and Soker & Zoabi (2002), and they conclude that dynamo amplification is likely to operate in rotating single AGB stars or in binary systems. A logical extension of this result is that solar-like activity, including dynamo and cycles, is also expected in some AGB stars. In Soker's view, however, the magnetic field plays no direct role in the formation of the rings, and he suggests that the magnetic cycle only regulates periodic variations in the mass-loss rate. Thus, in his interpretation, the rings are formed by pure hydrodynamical effects due to variations in mass-loss that follow the cycle activity, and the magnetic field has no dynamical effects.

A variation of this purely hydrodynamic model has been discussed by Simis, Icke, & Dominik (2001), in which a non-magnetic dusty flow from the AGB star develops compressions in the base of the wind. They present detailed 1D hydrodynamical simulations for the acceleration of a dusty AGB wind, without assumptions about the grain-gas coupling. In this case, the drift velocity of recently formed dust grains can be larger than its equilibrium value, creating compressed regions with larger dust-to-gas mass ratios. These compressed zones appear in a cyclic manner in their 1D simulations, driving a variable mass-loss rate that may lead, as in the scheme described by Soker (2000), to the creation of dusty shells. In these purely hydrodynamic models, the periodic formation of shells is only due to the increase in mass-loss, and higher shell densities can be maintained as long as the wind temperature can be lower in these same locations. This is a reasonable possibility during the AGB phase, but it cannot last for a long time. Once the wind is photoionized by the central star, the plasma temperature becomes nearly homogeneous in the nebula, and the rings tend to be washed away in a sound crossing time. Thus, the rings are short-lived in these purely hydrodynamic cases.

A different alternative, exploring the actual dynamical effects of a solar-like magnetic cycle, has been proposed by García-Segura et al. (2001). The novel aspect in this model is that the stellar magnetic field is allowed to change sign in a sinusoidal cycle. Given the lack of knowledge about the true field variations in these stars, this functional form is an adequate first approximation. The model is very simple, without mass-loss variations and considering only a cyclic polarity inversion of the magnetic field at the surface of the AGB star. Their 2-D MHD simulations show that shell formation in a magnetized wind with variable field strength is a straightforward process. The magnetic pressure of the outflowing plasma varies with twice the frequency of the magnetic cycle, and goes to zero at the moment when the magnetic field changes polarity. The plasma in the expanding wind notices the magnetic pressure depressions, both upstream and downstream, and moves towards the low-pressure sites. The wind is then compressed at these locations, increasing the local density, to compensate for the low magnetic pressure values. The rings are easily formed by this mechanism, and they can be long-lived. The density contrast between ring and inter-ring zones is less than 10%, but it can be modified by changing the amplitude of the pressure fluctuations. In addition, the shells formed by these magnetic models are not rapidly washed away by photoionization, and are stable against the Parker and Rayleigh-Taylor instabilities. Thus, modulated mass-loss episodes are not really necessary to generate the observed rings.

The series of bright knots observed by Sahai & Nyman (2000) in He 2-90 can also be explained by this same mechanism. Depending on the field strength, as in the case of magnetized free expanding winds, magnetic collimation can occur during the episodes of polarity inversion. The collimation of these outflows is again solely due to the hoop stress of the toroidal field, but the flow is not accelerated in this case. The models show that the density structure of the jet-like features observed in He 2-90 can be created by this mechanism but, given this collimation without acceleration, the gas velocities have to remain slow. The low and constant radial velocity of the knots observed by Guerrero et al. (2001), of only 26 km s^{-1}, is certainly compatible with this simple model.

4. CONCLUSIONS

The interacting wind model for Planetary Nebulae has been recently modified to include the effects of stellar rotation and magnetic fields. The inclusion of stellar rotation, either in single stars or in binary systems, can result in equatorially confined outflows, and may be one of the primary causes of bipolar PNe. This effect is significantly magnified when the tension of the toroidal magnetic field is amplified at the shocked region, and collimated outflows can be formed. The precise form of the off-equator distribution of this toroidal component is not very important, provided that the field is sufficiently strong to cause a deformation in the shocked wind region. This collimation is operative up to large distances, and anisotropic ambient density distributions are not required. If they occur, they can produce even more elongated structures. Thus, a combination of rotation and a magnetic field can naturally account for some of the most interesting features in PNe. This does not preclude other effects, such as those generated by external density gradients or binary systems, taking place at the same time, resulting in even richer morphological structures.

Point-symmetric structures in PNe are becoming more and more important. Almost every PN that has been observed at high spatial resolution shows some degree of point-symmetry, indicating that the mechanisms that produce it should be rather common. These structures can be reproduced in 3-D MHD simulations with misalignments between the magnetic and outflow axes. The results are very promising, and reproduce a wide variety of observed morphologies. In addition, the effects of magnetic cycles are successful in reproducing the enigmatic concentric rings in some PNe, as well as the highly collimated string of bright knots observed in He 2-90.

Finally, it is important to stress that the recent discovery of a toroidal magnetic field in K3-35 by Miranda et al. (2001), of milliGauss strength, provides very important observational support for this type of model. The main criticism of magnetic models was based on the lack of evidence for the strength and topology of the required fields. The observed properties of the magnetic field in K3-35, which has a collimated bipolar jet, is within the range of values explored by the models.

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