Axisymmetrical Structures of Planetary Nebulae and SN 1987A

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Abstract
I summarize some recent models and ideas for the formation of axisymmetrical structures of planetary nebulae and the three rings of SN 1987A, as follows. (a) I review the general role of binary companions, including brown dwarfs and planets. (b) I propose a mechanism for axisymmetrical mass loss on the AGB that may account for the axially symmetric structures of elliptical planetary nebulae and that operates for slowly rotating AGB stars, $10^{-4} \Omega_{\text{Kep}} \leq \Omega \leq 10^{-2} \Omega_{\text{Kep}}$, where $\Omega_{\text{Kep}}$ is the equatorial Keplerian angular velocity. (c) I propose a model for the formation of the two outer rings of SN 1987A, which is based on the numerical simulation of Soker (1989), and discuss a mechanism for their displacement from the exploding star.

In the proceedings of the conference Physical Processes in Astrophysical Fluids (January 1998). Will be published as a special volume of Physics Reports.

1 Introduction

Scanning through recent images of SN 1987A (e.g. Burrows et al. 1995) and through catalogs of planetary nebulae (PNs; e.g., Acker et al. 1992; Schwarz, Corradi, & Melnick 1992; Manchado et al. 1996) we find that the circumstellar media of many stars at their final nuclear burning phase have axisymmetrical, rather than spherical, structures. Axisymmetrical PNs which have two lobes with a morphological “waist” between them are termed “bipolar PNs” (also “butterfly” or “bilobal”), while PNs which have a more elliptical than bilobal structure are termed elliptical PNs (Schwarz, Corradi, & Stanghellini 1993). The axisymmetrical structures of most PNs led to a debate on whether elliptical PNs can be formed through single-stellar evolution, or whether a binary companion is necessary (e.g., Fabian & Hansen 1979; Livio 1982, 1998; Livio, Salzman, & Shaviv 1979; Webbink 1979; Morris 1981; Zuckerman & Gatley 1988; Pascoli 1992; Iben & Livio 1993; Soker 1997, 1998; Balick et al. 1994; Pottasch 1995; Pollacco & Bell 1997; Corradi et al. 1996; Kastner et al. 1996). In the last decade this debate was extended to the formation of the nonspherical explosion and
three rings of SN 1987A. In many PNs, as well as in the three rings of SN 1987A, there are displacements of the nebulae from the central stars, which hint at the interaction of the progenitors with wide binary companions, with close binaries having eccentric orbits, or with the ISM (§5).

In a recent paper (Soker 1997) I suggest that four main evolutionary routes determine the degree of asymmetry of the axially symmetric structures of PNs. I then classify 458 PNs according to the process which caused their progenitors to blow axisymmetrical winds. The classification is based primarily on the morphologies of the different PNs, assuming that binary companions, stellar or substellar, are necessary for axisymmetrical mass loss on the AGB. The four evolutionary classes, according to the binary-model hypothesis, are:

(a) Progenitors of planetary nebula which did not interact with any companion, and therefore they rotate extremely slowly when reaching the AGB. These amount to \( \sim 10\% \) of all planetary nebulae.

(b) Progenitors which interact with stellar companions which avoided a common envelope, \( 11^{+2_-3}\% \) of all nebulae. These form bipolar PNs, as is the case in symbiotic nebulae (Morris 1990; Schwarz & Corradi 1992; Soker 1998a).

(c) Progenitors which interact with stellar companions via a common envelope phase, \( 23^{+11_-5}\% \) of all nebulae. These form extremely asymmetrical structures, i.e., tori, elongated elliptical PNs, and in some cases bipolar PNs.

(d) Progenitors which interact with substellar (i.e., planets and brown dwarfs) companions via a common envelope phase, \( 56^{+5_-8}\% \) of all nebulae. These form elliptical PNs with relatively small deviation from sphericity.

These numbers are compatible with other studies (e.g., Yungelson, Tutukov, & Livio 1993; Han, Podsiadlowski, & Eggleton 1995).

In §2 I discuss the problem of angular momentum of AGB stars, which suggests that to account for the \( \sim 60\% \) elliptical PNs either there are many planetary systems (§3; Soker 1996; 1997) or there is a mechanism to induce axisymmetrical mass loss from very slowly rotating AGB stars. Such a model for singly evolved very slowly rotating AGB stars is the mechanism of mode-switch to nonradial oscillations, proposed by Soker & Harpaz (1992). In §4 I propose yet another model (Soker 1998c) which may operate in singly evolved AGB stars. This model is based on both magnetic activity and radiation pressure on dust. In §5 I propose a model for the two outer rings of SN 1987A.

### 2 Angular Momentum Considerations

If most of the mass loss occurs on the AGB, the ratio of envelope angular velocity on the upper AGB to the Keplerian (critical) angular velocity for a single star evolution is given by (Soker 1998c)

\[
\frac{\Omega}{\Omega_{Kep}} \bigg|_{\text{Single-AGB}} \approx 10^{-4} \left( \frac{\Omega}{0.1 \Omega_{Kep}} \right)_{\text{MS}} \left( \frac{R_{\text{MS}}}{0.01 R_{\text{AGB}}} \right)^{1/2} \left( \frac{M_{\text{env}}}{0.1 M_{\text{env,0}}} \right)^2,
\]

where the subscript MS means that the quantity is taken at the end of the main sequence, and \( M_{\text{env,0}} \) is the envelope mass at the beginning of the AGB. A faster rotation on the AGB can be attained if a binary companion, stellar or substellar,
spins-up the envelope. The orbital separation of a low mass secondary when tidal interaction becomes significant is \( a \sim 5R_* \) (Soker 1998c), where \( R_* \) is the stellar radius. If the secondary deposits all its orbital angular momentum to the envelope of mass \( M_{\text{env}} \), the ratio of envelope angular velocity \( \Omega \) to the surface Keplerian angular velocity \( \Omega_{\text{Kep}} \) is given by

\[
\frac{\Omega}{\Omega_{\text{Kep}}} \approx 0.1 \left( \frac{M_2}{0.01M_{\text{env}}} \right) \left( \frac{a}{5R_*} \right)^{1/2},
\]

(2)

assuming that the entire envelope rotates uniformly and has a density profile of \( \rho_{\text{env}} \propto r^{-2} \). From the last two equations it is clear that for any model that requires AGB angular velocity of more than \( \sim 10^{-3}\Omega_{\text{Kep}} \), a substantial spin-up is required.

The dust-based model for axially symmetric mass loss proposed by Dorfi & Höfner (1996) requires an AGB star of radius \( R = 500R_\odot \) to rotate at \( \gtrsim 10\% \) of the Keplerian angular velocity. We conclude that in order to spin-up the envelope as required by Dorfi & Höfner the secondary mass should be \( M_2 > 0.01M_{\text{env}} \). However, as Harpaz & Soker (1994) show, the envelope’s specific angular momentum of an AGB star decreases with mass loss as \( L_{\text{env}}/M_{\text{env}} \propto M_{\text{env}}^2 \). Therefore, to supply the angular momentum for a longer time, the companion mass should be much larger than \( 0.01M_\odot \), i.e., a brown dwarf or a low main sequence star.

Direct magnetic effects, through magnetic tension and/or pressure, have been suggested to determine the mass loss geometry from AGB stars (Pascoli 1997), or to influence the circumstellar structure during the PN phase (Chevalier & Luo 1994; Garcia-Segura 1997). These models must also incorporate a binary companion to substantially spin-up the envelope (Soker 1998c). The model of Chevalier & Luo (1994) is based on the tension of the toroidal component of the magnetic field in the wind: the wind in the transition from the AGB to the PN phase or the fast wind during the PN phase. Close to the star the magnetic pressure and tension are negligible compared with the ram pressure and thermal pressure of the wind. As the wind hits the outer PN shell, which is the remnant of the slow wind, it goes through a shock, slows down and the toroidal component of the magnetic field increases substantially. This may result in the magnetic tension and pressure becoming the dominant forces near the equatorial plane. The efficiency of this model is determined by a parameter given by (Chevalier & Luo 1994)

\[
\sigma = \left( \frac{B_s^2 r_s^2}{M_w v_w} \right) \left( \frac{v_{\text{rot}}}{v_w} \right)^2 = \frac{\dot{E}_B}{\dot{E}_k} \left( \frac{v_{\text{rot}}}{v_w} \right)^2,
\]

(3)

where \( B_s \) is magnetic field intensity on the stellar surface, \( r_s \) the stellar radius, \( M_w \) the mass loss rate into the wind, \( v_w \) the terminal wind velocity, and \( v_{\text{rot}} \) the equatorial rotational velocity on the stellar surface. In obtaining the second equality the expressions for the magnetic energy luminosity \( \dot{E}_B = 4\pi r_s^2 v_w B_s^2 / 8\pi \) and for the kinetic energy luminosity \( \dot{E}_k = M_w v_w^2 / 2 \) were used. For the model to be effective it is required that \( \sigma \gtrsim 10^{-4} \), but a typical value of \( \sigma \approx 0.01 \) is used by Garcia-Segura (1997). Since the magnetic field is weak near the star \( \dot{E}_B \ll \dot{E}_k \), the model requires, by equation (3), \( v_{\text{rot}} \gtrsim 0.01v_w \).

From this discussion it turns out that to account for the \( \sim 60\% \) elliptical PNs we have to adopt one of the following. Either there are many planetary systems (Soker
or there is a mechanism to induce axisymmetrical mass loss from very slowly rotating AGB stars (Soker & Harpaz 1992; Soker 1998c; §4 below).

3 Planets

As mentioned in §1, if spin-up is required for axisymmetrical mass loss, then \( \sim 1/2 \) of all PN progenitors are influenced by plant or brown dwarf companions. Based on this conclusion I argued (Soker 1996) that substellar objects (brown dwarfs or gas-giant planets) are commonly present within several \( \times \) AU around main sequence stars. For a substellar object to have a high probability of being present within this orbital radius, on average several substellar objects must be present around most main sequence stars of masses \( \lesssim 5M_\odot \). This led me to suggest that the presence of four gas-giant planets in the solar system is typical.

As a star evolves along the RGB or the AGB its radius increases. Any close planet will eventually interact tidally with the star. Since a substellar companion cannot bring the envelope to corotation, it will spiral-in to form a common envelope. This happens when the tidal interaction time is shorter than \( \tau_{ev} \), the time spent by the star on the RGB or AGB. This condition gives the maximal tidal interaction orbital separation in Zahn’s (1989) equilibrium tide model, for \( M_2 \ll M_1 \) and neglecting weak dependences on the luminosity and on the radius (Soker 1996),

\[
a_{max} \simeq 4R_* \left( \frac{\tau_{ev}}{6 \times 10^5 \text{ yr}} \right)^{1/8} \left( \frac{M_{env}}{0.5M_1} \right)^{1/8} \left( \frac{M_{env}}{0.5M_\odot} \right)^{-1/24} \left( \frac{M_2}{0.01M_1} \right)^{1/8},
\]

where \( M_{env} \) is the envelope mass. Stellar quantities are taken at the RGB tip and AGB tip, for RGB and AGB stars, respectively. Other effects of planets on AGB stars are summarized in Soker (1997). Planets with orbital separation of \( \gtrsim 5 \) times the maximum radius of a star on the AGB will not enter the envelope. They will survive to the PN phase, and if they are closer than \( \sim 20 \) AU they will be strongly ionized by the central star, and may reveal themselves as compact ionized high density regions (Soker & Dgani 1998).

Low mass main sequence stars \( M \lesssim 2M_\odot \) swell to large radii already on the RGB. Therefore they are likely to interact with their close planets on the RGB. This will influence their subsequent location on the horizontal branch. Planets, therefore, may cause some anomalies on the horizontal branch of globular clusters, and may be related to the second parameter of the horizontal branch (Soker 1998b).

4 AGB Stellar Spots and Dust Formation

If in the next few years the results of the intensive planet search projects (Marcy & Butler 1998) are that only \(< 50\%\) of all stars have planets, then model will be needed of efficient axisymmetrical mass loss for singly evolved stars. In addition, the mechanism should account for the increase in the degree of asymmetry toward the termination of the AGB evolution (Soker 1997), which is observed in many PNs. Such a mechanism, based on mode-switch to nonradial oscillations, was proposed by Soker & Harpaz (1992). Recently I proposed a different mechanism (Soker 1998c),
which may operate for slowly rotating AGB stars, having angular velocity in the range of $10^{-4} \Omega_{Kep} \lesssim \Omega \lesssim 10^{-2} \Omega_{Kep}$, where $\Omega_{Kep}$ is the equatorial Keplerian angular velocity. Such angular velocities could be gained from a planet companion of mass $\gtrsim 0.1 M_{\text{Jupiter}}$, which deposits its orbital angular momentum to the envelope during the AGB phase or even much earlier during the RGB phase, or even from single stars which are fast rotators on the main sequence. The proposed model incorporates both dynamo magnetic activity and radiation pressure on dust. The magnetic activity results in the formation of cool spots, above which dust forms much easily. The enhanced magnetic activity toward the equator results in a higher dust formation rate there, hence higher mass loss rate. As the star ascends the AGB, both the mass loss rate and magnetic activity increase rapidly. The model is built to explain elliptical PNs, but not the more extremely asymmetrical bipolar PNs, which are thought to be formed from stellar binary systems.

5 The Rings Around SN 1987A

I start by presenting a 2D numerical simulation I performed (Soker 1989) as a speculative effect for shaping proto-PNs. As noted already by Soker & Livio (1989), models for the formation of axisymmetrical PNs may be relevant to SN 1987A as well. In that paper I assumed that in the transition from the AGB to the PN, the star has a short mass loss episode, a “pulse”, due to an interaction with a binary companion. In this pulse, mass loss occurs close to the equatorial plane, and at a velocity faster than that of the slow wind. In that specific simulation I assumed that the pulse occurs 600 years after the end of the slow wind, it lasts for 50 years, and it is concentrated within an angle of $\sim 10^\circ$ from the equatorial plane. The velocity of the material in the pulse is $200 \text{ km s}^{-1}$, and the total mass $3 \times 10^{-4} M_\odot$. This pulse runs into the slow wind, which has a density contrast of 6 between the equator (high density) and polar directions, a mass loss rate of $10^{-5} M_\odot \text{ yr}^{-1}$, and a velocity of $10 \text{ km s}^{-1}$. As the pulse hits the slow wind, a high pressure region is formed in a small region in the equatorial plane (in 3D it has the shape of a ring). The fast release of energy resembles an explosion, and it creates a shell expanding from the high pressure region. Since there is no slow wind material inward, the shell has the shape of a horseshoe as observed in the symmetry plane (the plane perpendicular to the equatorial plane). The density contours and velocity field map in the symmetry plane 570 years after the pulse reaches the slow wind are presented in Figure 1. For SN 1987A different parameters should be used, so this figure should be applied qualitatively rather than quantitatively. The “horseshoe” shape is the projection of a 3D hollowed torus on the symmetry plane. It should be emphasized that the qualitative result, of forming a horseshoe-torus, will still hold for a much longer “pulse”, and it does not depend on a density contrast between the equator and poles. We note that the inner region of the “horseshoe” in Figure 1 is (a) denser than most of the other regions of the torus, (b) its velocity is the lowest, and (c) it is extended in a radial direction more or less.

Assume now that the central star starts to blow a fast wind, which hits the horseshoe-torus and accelerates it. The inner region of the horseshoe-torus will have the lowest acceleration since it is denser, and more over, it is elongated in a more or less radial direction. Therefore, there will be a time in the evolution of this flow when most of the original torus has already been expelled to large distances from the star.
by the fast wind, and hence it has low density. The original inner regions of the torus, by contrast, will expand slower, be relatively close to the star, and be dense, much denser than the wind material around it. These regions now form two rings, one at each side of the equatorial plane.

Let me try to sketch a scenario for the formation of the three rings around SN 1987A based on the discussion above. One assumption that goes here and in the explanation for the displacement of the rings from the exploding star is that of a binary companion in an initial eccentric orbit. There are other reasons to support a binary companion. First, Chevalier & Soker (1989) show that a deformed envelope due to fast rotation can explain the asymmetrical explosion of SN 1987A, which is inferred from polarization data. The direction of polarization is in the direction of the symmetry axis of the ring (or perpendicular to it, depending on the time and emission lines). The angular velocity required can be gained from a companion of mass $\sim 0.5 M_\odot$. Second, the merger of a $\sim 5 M_\odot$ secondary with the progenitor’s envelope makes the envelope shrink, hence the transition of the progenitor to a blue star (Podsiadlowski, Joss, & Rappaport 1990).

There are two possible tracks to the proposed evolutionary sequence, marked A and B here. In this preliminary study, I cannot prefer one or the other. The different stages of the proposed scenario are depicted in Figure 2.

**phase 1:** Slow wind from the red supergiant progenitor. It may have a higher mass loss rate in the equatorial plane due to rotation, or a tidal interaction with the companion. (A) This wind is displaced relative to the central star and perpendicular to the symmetry axis, due to an interaction with the companion which is in an eccentric orbit (Soker, Harpaz, & Rappaport 1998). This explains the displacement of the rings of SN 1987A from the central star. (B) The companion still has a weak influence.

**phase 2:** The binary system blows a faster wind concentrated in the equatorial plane. A horseshoe-torus is formed. (A) The fast winds occurs as the companion approaches the primary (the progenitor of 1987A) and enters its envelope. (B) The fast wind results from a strong interaction with the companion, and it is displaced due to the eccentric orbit (Soker et al. 1998). The eccentricity of the orbital motion of the companion results in the displacement of this faster wind perpendicular to the symmetry axis, and later leads to the displacement of the three rings.

**phase 3:** A slow dense wind is blown in the equatorial plane. The inner edge of this wind forms the inner ring of SN 1987A. (A) The slow wind concentration in the equatorial plane is due to the fast rotation of the envelope, after the companion enters the envelope but before the primary’s shrinkage to a blue giant. This lasts several thousand years (Podsiadlowski et al. 1990). (B) Most of this phase occurs while the secondary is still outside the envelope, and it ends several thousand years after the secondary enters the primary’s envelope.

**phase 4:** Several thousand years after the secondary, both for tracks A and B, enters the envelope, the primary shrinks to a blue giant (Podsiadlowski et al. 1990), and blows a fast wind. This wind pushes most of the previous dense wind to large distances, beside the very dense regions which are also elongated in radial directions: the inner regions of the horseshoe-torus and the dense disk in the equatorial plane.

**phase 5:** Just before explosion the system contains three rings: two outer rings, one at each side of the equatorial plane, which are the remnant of the inner regions of the horseshoe-torus, and a inner dense ring in the equatorial plane.
Several comments should be made here. (a) The proposed scenario accounts for: (i) slow motion of the outer rings; (ii) the high density contrast of the outer rings to their surroundings; (iii) the presence of only two outer rings; (iv) the displacement of the three rings relative to the central star. (b) Phase 2 is the most problematic in the proposed scenario. That is, how come the binary system blows an equatorial wind of velocity $\sim 100 \text{ km s}^{-1}$ before the primary shrinks? The support for such a wind, which is not found in PNs, is that both the progenitor and the companion are more massive than in PNs. A companion of $\sim 5 M_\odot$ has a wind much stronger and faster than the expected companions of bipolar PNs. It is possible that the wind of the companion is forced to the equatorial plane, and is responsible for such a faster wind. Observationally, there is a collimated flow in the equatorial plane (but only in one specific direction) of Eta Carinae, despite the nice two lobes and equatorial waist of Eta Carinae. The equatorial wind, and the other phases, are currently being studied by us (Soker & Rappaport 1998). (c) All three rings are displaced in the same direction relative to the exploding star, though the outer two rings are more displaced. Three process can cause displacement of circumstellar nebulae (Soker 1997): (i) interaction with the ISM: this is not likely here because it cannot influence the inner ring and it will deform the outer rings; (ii) interaction with a wide companion, having an orbital period of several $\times 10^4 \text{ yr}$; (iii) an eccentric close companion (Soker et al. 1998), as we proposed is the case for SN 1987A. (d) The proposed scenario predicts that there is matter extended outward to the two outer rings in the radial direction, and that there is matter from the broken shell between the two rings, but at much greater distances from the exploding star. (e) There are other models for the formation of the rings. Burrows et al. (1995) summarize several models, and find problems in all of them. Meyer (1997) proposes that the rings are formed from ionization that induces hydrodynamic motions. I find two problems in this model. First the density contrast seems to be too low in it, and second, the inner ring would prevent the ionization of the equatorial region between the two outer rings. The last effect will reduce the efficiency of the model, reducing further the density contrast.

ACKNOWLEDGMENTS: I thank Saul Rappaport for several helpful comments. This research was in part supported by a grant from the Israel Science Foundation.

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Figure 1: The projection of the horseshoe-torus on the symmetry plane. The Y axis is the symmetry axis and X axis is in the equatorial plane. The units on the axes are $10^{15}$ cm. Each unit length (as measured on the axes) of the arrows corresponds to a velocity of 12 km s$^{-1}$, and the density levels, in units of $10^{-21}$ g cm$^{-3}$, are 4, 8, 16, 24, 32, 40, 48, 56.

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Figure 2: Schematic illustration of the proposed scenario for the formation of the three rings of SN 1987A.
Phase 1: slow wind
Symmetry axis
Equatorial Plane

Phase 2: faster equatorial wind forms a horseshoe-torus
Symmetry axis
Equatorial Plane

Phase 3: slow wind concentrated in the equatorial plane
Symmetry axis

Phase 4: the progenitor is a blue giant blowing a hot wind
Symmetry axis

Phase 5: just before the explosion - most of the horseshoe material is expelled to large distances by the fast wind
First ring
Second ring
Inner ring