Dynamos in Asymptotic-Giant-Branch Stars As the Origin of Magnetic Fields Shaping Planetary Nebulae

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Planetary nebulae are thought to be formed when a slow wind from the progenitor giant star is overtaken by a subsequent fast wind as the star enters its white dwarf stage\textsuperscript{1}. The shock formed near the contact discontinuity between the two winds creates the relatively dense shell that forms the planetary nebula. A spherically symmetric wind produces a spherically symmetric nebula; however, over half of the known planetary nebulae are either bipolar or elliptical, rather than spherical\textsuperscript{2}. A magnetic field may explain the launching and collimation of a bipolar outflow in a planetary nebula, but the origin of such a magnetic field has not been adequately explained. Here we show that a star on the asymptotic giant branch (AGB), which is the precursor of a planetary nebula core, can generate a strong magnetic field in a dynamo located at the core-envelope interface. The field is sufficiently strong to shape the bipolar outflow observed in planetary nebulae and may also explain the puzzlingly slow rotation of most white dwarfs via magnetic braking.

One model for producing bipolar or elliptical planetary nebulae assumes that the slow wind from the progenitor star is denser near the equatorial plane than along the poles\textsuperscript{3}–\textsuperscript{6}. Such an asymmetry can result if the progenitor is part of a close binary star system. However, the incidence of close binaries seems not to be sufficient to account for all asymmetric planetary nebulae.

Magnetic shaping is a promising mechanism for forming asymmetric planetary nebulae. A toroidal magnetic field can constrain the flow in the equatorial plane\textsuperscript{7}, redirecting it preferentially along the poles\textsuperscript{8}, while a dipole field can create a dense torus around the central star which then collimates the wind\textsuperscript{9}. The strength of a toroidal magnetic field in the wind will be increased in the shocked bubble, leading to collimation\textsuperscript{10,11}. Collimation might also occur close to the star through magneto-centrifugal processes\textsuperscript{12}. 
We suggest that the required magnetic field is generated by a dynamo in the central star during its AGB phase. The necessary ingredients for an alpha-omega interface dynamo are very likely to be present near the outer boundary of the degenerate core of an AGB star. Contraction of the core and expansion of the envelope during this stage of evolution will tend to produce strong differential rotation regardless of the initial rotation profile on the main sequence. In the lower part of the deep, rotating convection zone the necessary alpha effect is provided by the helical convection itself or by magnetic instabilities. We note that a previous argument against significant dynamo action in an AGB star was based on a model of a distributed dynamo operating solely within the slowly rotating envelope, a very different picture than the one we present here.

To investigate the possibility of dynamo action in AGB stars, we first estimate the rotation profile in a typical AGB star evolving from a rotating main-sequence star, and we then use this rotation profile in a self-consistent nonlinear dynamo model to test for dynamo action. For a typical AGB star, we use an evolutionary model of S. D. Kawaler (personal communication) for a star of mass $3M_\odot$. We assume that this star is rotating uniformly on the main sequence with angular velocity $1 \times 10^{-4}$ s$^{-1}$ (corresponding to a surface rotation velocity $\sim 200$ km s$^{-1}$, see ref. 14) and that during the subsequent evolution the angular momentum of each spherical mass shell is conserved. (As we expect some angular momentum exchange to occur in any real star, e.g. by magnetic braking, our model exaggerates the degree of differential rotation that may develop; nevertheless, we expect our model to be at least qualitatively correct.) The resulting rotation profile for this star at the tip of the AGB (Kawaler’s model 1401, hereafter SDK 1401) has strong differential rotation, with the innermost core rotating faster and the outer envelope rotating much slower than the initial main-sequence rotation rate. The rotation profile in the neighborhood of the core-envelope interface is shown in Fig. 1. Our resulting rotation profile and thus our approach are strongly supported by observations that have been
interpreted to imply core-envelope decoupling: observed fast rotation in horizontal-branch stars\textsuperscript{15–17} and the existence of young, rapidly spinning pulsars\textsuperscript{18}.

The arrangement of differential rotation and convection in adjacent layers in this AGB star is similar to that in the Sun and strongly suggests the possibility of an alpha-omega “interface” dynamo. To test this possibility we use a simple nonlinear alpha-omega dynamo model that we have used previously to study dynamos in white dwarf stars\textsuperscript{19}. This model, based on a local analysis of the full mean-field dynamo equations, assumes that the dynamo region consists of two adjacent, thin layers – an inner layer in differential rotation and an outer layer of convection in which the alpha effect operates. The solar dynamo is thought to be of this type\textsuperscript{20,21}, and this configuration also corresponds roughly to the situation in our model AGB star. The nonlinear saturation of oscillatory dynamo modes in our model is caused by quenching of the alpha effect by the generated magnetic field. The free parameters in the model are calibrated by applying the model to the Sun and requiring it to produce a dynamo with the correct period (22 yrs) and appropriate amplitude (toroidal field strengths \(\sim 10^4\) G). The calibrated model is then applied to the model AGB star. As input to our dynamo model, we obtain the following values from our model of differential rotation in SDK 1401: a differential rotation layer of thickness \(4.6 \times 10^{10}\) cm lying just below the convection zone (at radius \(9.35 \times 10^{10}\) cm), with angular velocity dropping from \(2 \times 10^{-5}\) s\(^{-1}\) to \(5 \times 10^{-6}\) s\(^{-1}\) across this layer; and an alpha-effect layer of thickness \(1 \times 10^{11}\) cm lying just above the base of the convection zone, with typical convective velocity \(1 \times 10^{5}\) cm s\(^{-1}\) and density \(6.6 \times 10^{-4}\) g cm\(^{-3}\) (see Fig. 1).

For these input values for SDK 1401 we obtain an oscillatory dynamo with a period of \(\sim 0.4\) yrs and a maximum mean toroidal field strength of \(\sim 5 \times 10^4\) G just below the convection zone. (This result is robust, in the sense that it is not sensitive to moderate changes in the values of the input parameters.) The ratio of thermal pressure to magnetic
pressure just below the convection zone is \( \beta \simeq 10^3 \). The field need not be volume-filling, and flux tube formation is very likely as the magnetic field becomes subject to buoyancy instabilities. The fraction of volume filled by flux tubes, and thus the surface-area covering fraction \( f \) for long thin tubes, could be as low as \( \beta^{-1} \) (ref. 22). The strength of a typical flux tube in this case, determined by pressure balance across the tube, is \( 3 \times 10^6 \) G. The strength of such a tube upon rising to the top of the convection zone \((R = 5.5 \times 10^{12} \text{ cm})\) would be \( \sim 400 \) G in pressure balance. Surface magnetic fields of this strength could be associated with flares and coronal mass ejections from the AGB star by analogy with the Sun\(^{23}\). These coronal mass ejections could be responsible for the non-axisymmetric, collimated shapes with unpaired ejections of knots or bullets seen in some planetary nebulae\(^{24,25}\).

An average toroidal field strength of \( 5 \times 10^4 \) G at the interface represents \( 10^{41} \) ergs of magnetic energy in the volume of the shear layer. The rate of magnetic energy flow from the interface layer due to buoyancy is \( \sim (B^2/8\pi)(4\pi R_c^2)v_A \), where \( v_A \) is the Alfvén speed in the layer and \( R_c \) is the radial location of the layer. For \( B = 5 \times 10^4 \) G, a density in the interface layer of \( 1.3 \times 10^{-3} \) g cm\(^{-3} \), and \( R_c = 9.35 \times 10^{10} \) cm, this gives an upward magnetic energy supply rate of \( \sim 4 \times 10^{36} \) erg s\(^{-1} \). This number is comparable to the turbulent energy dissipation rate in the convection zone, given by \( (\rho v^2)(v/l)(V_{\text{conv}}) \sim 10^{36} \) erg s\(^{-1} \), when estimated for typical values, e.g., \( \rho \sim 10^{-4} \) g cm\(^{-3} \) for the density, \( V_{\text{conv}} \sim 5 \times 10^{36} \) cm\(^3\) for the volume, \( v \sim 10^5 \) cm s\(^{-1} \) for the turbulent speed, and \( l \sim 10^{11} \) cm for the characteristic eddy scale. This means that the buoyancy-driven magnetic energy supply rate is an upper limit on the supply rate to the corona, since a sizeable fraction may be shredded and dissipated on its way up through the convection zone. The fraction that does make it to the corona would be available for particle acceleration and coronal emission from the AGB star. Some of this could take the form of localized flares and coronal mass ejections, as on the Sun.
Detection of X-rays from such a corona is unlikely while the star is in either the AGB stage or the proto-planetary-nebula stage due to the high density of the wind. We estimate the optical depth for soft (1 KeV) and hard (10 KeV) X-rays to be $10^1$ and $10^3$, respectively. The X-rays could also produce a layer of highly ionized atoms near the star, but this would likely be enshrouded by much cooler gas in the stellar wind and thus be hard to detect. The deposition of energy into the corona may have consequences for the thermal and dynamical structure of the winds, which will need further investigation. We expect that the corona will be removed along with the bulk of the magnetic flux by the time the star reaches the mature planetary nebula phase.

The core of an AGB star can be expected to rotate very rapidly because of contraction, as illustrated here by our model. However, the white dwarf stars, which develop from AGB cores following the planetary nebula phase, generally rotate much more slowly than expected if angular momentum conservation of the AGB core is assumed. This well-known problem might be resolved as a result of invoking the dynamo action proposed here; the strong magnetic field generated by the AGB dynamo could produce magnetic braking. This would occur during and after the time the AGB star sheds its envelope. Because of flux freezing, the field lines are drawn out with the envelope material but are anchored in the core. In this way the angular momentum of the core is transported outward to the envelope, and the core is spun down by a post-AGB MHD wind. During the braking period, bipolar and multipolar MHD winds could form the shapes observed in some planetary nebulae as the stellar convective envelope is shed.

The MHD wind luminosity then gives an upper limit to the kinetic power. For an MHD wind from field lines anchored in the core, the luminosity can be as high as $L_{MHD} \sim 2 \times 10^{38}(B/10^5 \text{ G})^2(\Omega_c/2 \times 10^{-5} \text{ sec}^{-1})(R_c/10^{11} \text{ cm})^3 \text{ erg s}^{-1}$, where $\Omega_c$ is the angular speed of the core material where the field lines are anchored, and
$R_c$ is the core radius. A $\sim 5\%$ conversion of this is required to account for the energy loss rates of $10^{37}(\dot{M}/6 \times 10^{21} \text{ g s}^{-1})(V/400 \text{ km s}^{-1})^2 \text{ erg s}^{-1}$ characteristic of some proto-planetary nebulae\cite{27}, where $\dot{M}$ is the mass loss rate and $V$ is the wind speed. The time scale for the MHD wind spin-down of the post AGB star is then

$$\tau_s = 140 (M_c/M_\odot)(\Omega_c/2 \times 10^{-5} \text{ s}^{-1})(B/10^4 \text{ G})^{-2}(R_c/10^{11} \text{ cm})^{-1} \text{ yr}.$$ 

The post-AGB wind, produced when the AGB star sheds its outer layers and exposes the rapidly rotating, magnetized core, may be strongly collimated by magneto-centrifugal processes\cite{28}. The degree to which a magnetized rotator will collimate a wind driven off its surface can be expressed via a “rotation” parameter\cite{29} $Q$ given by

$$Q/Q_\odot \simeq 4(\psi_c/5 \times 10^{26} \text{ G cm}^2)(\Omega_c/2 \times 10^{-5} \text{ s}^{-1})(\dot{M}/6 \times 10^{21} \text{ g s}^{-1})^{-1/2}(V/400 \text{ km s}^{-1})^{-3/2},$$

where $\psi_c$ is the magnetic flux at large distances ($\propto BR^2$), $V$ is the outflow speed, and $Q_\odot \sim 0.12$ is the value for the solar wind (using $V_\odot = 400 \text{ km s}^{-1}$, $M_\odot = 1.6 \times 10^{12} \text{ g s}^{-1}$, $\Omega_\odot = 3 \times 10^{-6} \text{ s}^{-1}$, and $\psi_\odot = 1.4 \times 10^{22} \text{ G cm}^2$). We have scaled the flux to the upper limit using $B \sim 5 \times 10^4 \text{ G}$ and $R_c \sim 10^{11} \text{ cm}$ for our dynamo-produced field strength at the AGB core, and we have scaled the outflow parameters $\dot{M}$ and $V$ using proto-planetary nebulae values\cite{27}. For $Q \geq 1$ the system is classified as a fast magnetic rotator. The larger $Q$ is, the more strongly self-collimated the outflow is\cite{30}. We can see that for these parameters collimation greater than that in the solar wind is possible. If we instead use representative outflow parameters for later stages of planetary nebulae\cite{31}, $\dot{M} = 5 \times 10^{-7} M_\odot \text{ yr}^{-1}$ and $V = 1000 \text{ km s}^{-1}$, we find $Q/Q_\odot \sim 15$, which implies that significant collimation is possible. Magnetic collimation may thus be intrinsic to these sources and may not require shocks, as in some models\cite{11}.

Our model leads us to predict that magnetic fields should be apparent in the winds of AGB stars and proto-planetary nebulae. Such magnetic fields should be detectable in some maser spots, and indeed have already been observed in at least one object\cite{32}.
with field strengths consistent with our model (based on flux conservation), although this field might be locally amplified by turbulence. We also predict that strongly collimated flows in proto-planetary nebulae should have signatures of ordered magnetic fields (e.g., polarization, Faraday rotation), reflecting the role of the magnetic field in their launching and collimating. At small distances from the central star, the field should be primarily poloidal and parallel to the jet flow, while at large distances we would expect a dominant toroidal component (perpendicular to the outflow) as the hoop stresses take over the collimation.

Our dynamo model depends on rapid rotation of the AGB core. If a way can be found to measure the rotation rates of AGB cores, it could serve as an observational test of our model. Stars that rotate much more slowly than average on the main sequence would not be expected to produce significant dynamos at the AGB stage and hence would not be expected to produce collimated outflows by magnetic shaping. On the other hand, we expect those AGB stars that do have rapidly rotating cores to produce bipolar planetary nebulae.

As the rotation rate of the degenerate core is reduced by magnetic braking and the convective envelope is removed, the stellar dynamo will shut down. Some remnant field anchored in the core will survive even without a convection zone, although the convective envelope may not be removed completely. Indeed, white dwarfs do have thin surface convection zones which can support a near-surface dynamo in the white dwarf itself¹⁹.

In conclusion, we have demonstrated that dynamos are likely to operate in AGB stars. As a star evolves off the AGB, the dynamo-generated magnetic field will be strong enough to drive a strong, self-collimating outflow and to slow the rotation of the core by magnetic braking. Eruptions analogous to coronal mass ejections, expected as a consequence of the dynamo activity, could produce asymmetric structures in the wind. Thus our model opens
up the possibility of constructing a new, self-consistent paradigm for planetary-nebula formation, beginning with AGB stars and ending with slowly rotating white dwarfs.
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Figure 1. Internal rotation rate of our model $3.0 \, M_\odot$ AGB star as a function of radius near the base of the convection zone. The angular velocity $\Omega$ is given both in units of $s^{-1}$ and in units of the initial (uniform) rotation rate $\Omega_0$ of the star when on the main sequence. The inner core has been spun up by contraction, while the outer layers rotate much more slowly than the initial rate due to the large expansion of the envelope. The dashed line indicates the location of the base of the convection zone; the inner dotted line indicates the inner boundary of the differential-rotation layer assumed in our dynamo model; and the outer dotted line indicates the outer boundary of the alpha-effect layer.

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