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FORMATION OF BIPOLAR LOBES BY JETS

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ABSTRACT

I conduct an analytical study of the interaction of jets, or a collimated fast wind (CFW), with a previously blown asymptotic giant branch (AGB) slow wind. Such jets (or CFWs) are supposedly formed when a compact companion, a main-sequence star, or a white dwarf accretes mass from the AGB star, forms an accretion disk, and blows two jets. This type of flow, which I think shapes bipolar planetary nebulae (PNs), requires three-dimensional gasdynamical simulations, which are limited in the parameter space they can cover. By imposing several simplifying assumptions, I derive simple expressions which reproduce some basic properties of lobes in bipolar PNs and which can be used to guide future numerical simulations. I quantitatively apply the results to two proto-PNs. I show that the jet interaction with the slow wind can form lobes which are narrow close to, and far away from, the central binary system, and which are wider somewhere in between. Jets that are recollimated and have constant cross section can form cylindrical lobes with constant diameter, as observed in several bipolar PNs. Close to their source, jets blown by main-sequence companions are radiative; only further out they become adiabatic, i.e., they form high-temperature, low-density bubbles that inflate the lobes.

Subject headings: circumstellar matter — ISM: jets and outflows — planetary nebulae: general — stars: AGB and post-AGB — stars: mass loss

1. INTRODUCTION

Planetary nebulae (PNs) and proto-PNs possess a rich spectrum of different structures, with spherical and bipolar PNs at the two extremes of that spectrum. Bipolar PNs are defined as extreme aspherical PNs having two lobes with an "equatorial" waist between them (Schwarz, Corradi, & Stanghellini 1992). Several models have been suggested to explain the formation of lobes. One of the popular models a decade ago was the interacting wind model, where a fast wind blown by the central star of the PN is collimated by a previously ejected AGB stellar dense equatorial wind (e.g., Balick 1987; Soker & Livio 1989; Frank & Mellema 1994; Mellema & Frank 1995; Mellema 1995). When the equatorial-to-polar density ratio is very high, a bipolar nebula was supposed to be formed. However, the numerical simulations did not form bipolar PNs with very narrow waists, but rather formed elliptical PNs or bipolar PNs with wide waists. García-Segura et al. (1999, their model L) obtain marginally narrow waists, but the shape in the outer region of the bubble does not resemble the structure of many bipolar PNs. In general, extremely high density in the equatorial plane can form narrow waists (e.g., Langer, García-Segura, & Mac Low 1999 for a massive star), but such a flow requires a binary companion to AGB stars (e.g., Mastrodemos & Morris 1999). Such a companion will blow jets or a CFW (Soker & Rappaport 2000, hereafter SR00). Another problem of the interacting wind model is the high momentum and kinetic energy observed in several bipolar PNs and proto-PNs (Bujarrabal et al. 2001; see Balick 2000 for some other problems). Therefore, the simple interacting wind model, although being successful in explaining many properties of PNs, cannot explain all properties in many of the observed bipolar PNs. It seems that in order to form many bipolar PNs, e.g., those with very narrow waists and those with multipolar lobes, a collimated fast wind (CFW) is required (Morris 1987; Sahai & Trauger 1998; SR00). Such preliminary simulations, in which the CFW was blown by the primary star, were performed by Frank, Ryu, & Davidson (1998), who show the potential of such a flow structure to form very narrow waists. A similar type of flow, in which magnetic fields are involved in shaping the jets (García-Segura 1997) and which, in some cases, include equatorial-to-polar density contrast in the slow wind, were performed by García-Segura & López (2000) and García-Segura et al. (1999). Although they also demonstrate the potential in using a CFW, they use magnetic fields at large distances from the star, which is not relevant to the present study. Other types of models are based on magnetic fields playing a dynamical role in the mass-loss process from AGB stars (e.g., Pascoli 1992; Matt et al. 2000; Blackman et al. 2001). There are some severe problems with dynamical magnetic models (Soker & Zoabi 2002). The main problem is that the AGB has to be spun up by a stellar companion in order to possess the required activity; hence, we are in the regime of binary models.

As reviewed recently by SR00, a promising mechanism for the formation of bipolar PNs with narrow waists is based on an accreting compact companion to the mass-losing AGB star. In most cases, the companion is a white dwarf or a main-sequence star (SR00). When a compact binary companion accretes matter with sufficiently high specific angular momentum, an accretion disk is formed. When the accretion rate is above some threshold (SR00), two jets are expected to be blown by the companion. If the jets are not well-collimated, the outflow from the companion is termed CFW. In addition, the companion may lead to a concentrated equatorial flow (Mastrodemos & Morris 1999), further increasing the equatorial-to-polar density ratio. The

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formation of bubbles (or lobes) by jets has been studied in a variety of astrophysical flows, e.g., young stellar objects (Masson & Chernin 1993), clusters of galaxies (Reynolds, Heinz, & Begelman 2001), and gamma-ray burst environments (Ayal & Piran 2001). However, the condition of jets blown into AGB winds are different from those in these cases.

To study the interaction of the two winds blown simultaneously, the slow wind by the AGB star and the CFW (or two jets) by the accreting compact companion (see Figs. 1 and 2 in SR00), a three-dimensional gasdynamical numerical code is required. Such numerical simulations require heavy computer resources and as a result can cover only a small number of cases. Therefore, it will be helpful to derive simple expressions which can both describe the general structure of lobes obtained by different jets and guide future numerical simulations. This paper is aimed at reaching these objectives by exploring part of the parameter space of jets interacting with spherical AGB winds and under simplifying assumptions. To manifest analytical solutions, I consider two extreme cases, which are described in § 2 and studied in § 3 and § 4. A short summary is in § 5.

2. JET PROPAGATION

In the present analytical study, I treat the flow at large distances from the binary system, neglecting the deflection of the jets (or CFW; see SR00). I assume an axisymmetric flow in which a jet expands along the symmetry axis and into a previously ejected, spherically symmetric, slow AGB wind. The slow wind density as a function of distance from the binary system is $\rho_s = \dot{M}_s/(4\pi v_s r^2)$, where v_s is the slow wind speed and $\dot{M}_s$ is the mass-loss rate, both are constant, and where mass-loss rate is defined positively. The gas inside the undisturbed jets, one at each side of the equatorial plane, expands at a constant speed v_j, the mass-loss rate into each jet is $\dot{M}_j$, and each jet expands into a solid angle of $\Omega_j = 4\pi\beta$. The density inside an undisturbed, radially expanding jet, i.e., its cross section, increases as r^2 is $\rho_j = \dot{M}_j/(4\pi\beta v_j r^2)$. The velocity of the jet head, v_h, is determined by equating the slow wind pressure on the jet head with that of the jet material. Since thermal pressure can be neglected in the preshocked media, the expression is $\rho_j(v_j - v_h)^2 = \rho_s(v_h - v_s)^2$. In the present analytical study, I treat two extreme cases: slow-propagating and fast-propagating jets. In the slow-propagating jet case, the jet head proceeds at a speed $v_h \ll v_j$, while in the fast-propagating jet case, the jet head does not slow much, $v_s \ll v_h \lesssim v_j$.

The velocity of a slow-propagating jet to be treated in the next section is given by

$$v_h \simeq v_s\left[1 + \left(\frac{\dot{M}_j v_j}{\beta \dot{M}_s v_s}\right)^{1/2}\right] \text{ for } \rho_s \gg \rho_j \; . \qquad (1)$$

I therefore assume that $\dot{M}_j v_j \lesssim \text{few} \times 10\beta \dot{M}_s v_s$, so that $v_h \sim 2\text{–}10 v_s$. Since I neglect the bending of the jet by the AGB slow wind close to the binary system, the momentum flux of the jet must be (SR00) $\dot{M}_j v_j \gtrsim \dot{M}_s v_s \tan\alpha$, where α is the half-opening angle of the jet (SR00). For $\tan\alpha \ll 1$, $\tan\alpha \simeq 2(\beta)^{1/2}$. For $\alpha = 10°$, for example, $\beta = 0.0076$, $2\beta^{1/2} = 0.174$, and $\tan\alpha = 0.176$. Over all, the treatment of the slow-propagating jet is applicable to the case $(\dot{M}_j v_j)/(\dot{M}_s v_s) \sim 0.1\text{–}0.5$ for a half-opening angle of $\alpha \sim 5°\text{–}30°$. However, as we will see later, the derived expressions are not so sensitive to the different variables, so the results will be applicable to a much larger parameter space.

From the expressions developed above, we can find the density of the jet-shocked material, and from that, the radiative cooling time, $t_{\rm cool} = (5/2)nkT/(n_e n_p \Lambda)$, where n, n_e, and n_p, are the total number, electron, and proton, postshock densities, respectively, taken to be 4 times the preshock densities; for the considered temperature range, which is determined by the speed of the jet material, $\Lambda \simeq 10^{-22}$ ergs cm^3 s^{-1}. The cooling time of the shocked jet material is obtained by substituting typical values

$$t_{\rm cool}({\rm jet}) \simeq 17\left(\frac{v_j}{400\ {\rm km\ s^{-1}}}\right)^3 \left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ {\rm yr^{-1}}}\right)^{-1} \times \left(\frac{\beta}{0.01}\right)\left(\frac{r}{10^{16}\ {\rm cm}}\right)^2 {\rm yr} \; . \qquad (2)$$

This timescale is much longer than the flow time along the jet diameter. However, the cooling time of the postshocked material should be treated differently and compared with another flow timescale. This is done for the two flow cases in the next two sections.

3. SLOW-PROPAGATING JETS

3.1. *Jet Interaction with the Slow Wind*

The general flow structure is as follows. A jet expands from the center along the symmetry axis, which we take to be the z axis. (Another jet expands in the opposite direction.) The jet material, and/or the ambient material ejected by the AGB star, are shocked and radiatively cool. Close to the center, the density is high and cooling time is very short; therefore, no bubble is inflated. Further away, the density drops and postshock cooling time increases. When cooling time becomes long enough, a bubble is inflated. To find the distance from the central source, where cooling time is long and a bubble is inflated, I consider the initial stage, when the bubble is still small, such that its radius R_b is much smaller than its distance from the central source $R_b \ll z$. Under this assumption, the variation in the ambient density with distance from the center r can be neglected in the vicinities of the bubble. During the initial stages of bubble inflation, all the jet's energy can be assumed to be deposited in one spot. In reality, this spot will move outward as the jet propagates (see next subsection). The flow to consider, at early stages of bubble inflation, therefore, is that of a shocked gas which expands and forms a hot, low-density bubble that accelerates the dense, slow-AGB wind material around it. The results of Castor, McCray, & Weaver (1975) for a stellar wind bubble in a dense interstellar medium can be used. In the present case, the shocked, fast wind is not a spherically symmetric wind, but rather the shocked material at the head of the jet. However, after being shocked, the hot gas, whether it is the jet's material or the ambient gas, exerts pressure in all directions, such that the spherical results of Castor et al. (1975) can be used, with the center being at the head of the jet and not the center of the PN. Using their equation (6) for the radius of the expanding bubble as a function of the expansion time of the bubble, t_b, gives

$$R_b = 0.76\left(\frac{0.5\dot{M}_j v_j^2}{\rho_s}\right)^{1/5} t^{3/5} = 1.0\times10^{16}\left(\frac{v_j}{400\ \mathrm{km\ s^{-1}}}\right)^{2/5} \times\left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ \mathrm{yr}^{1/5}}\right)^{1/5}\left(\frac{v_s}{15\ \mathrm{km\ s^{-1}}}\right)^{1/5} \times\left(\frac{\dot{M}_s}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1/5}\left(\frac{z}{10^{16}\ \mathrm{cm}}\right)^{2/5} \times\left(\frac{t_b}{100\ \mathrm{yr}}\right)^{3/5}\ \mathrm{cm}\ , \quad (3)$$

where the local slow-wind density at $r = z$ was taken in the second equality. (Again, r and z are the distance from the source of the jet and the slow wind, in spherical coordinate system and along the symmetry axis, respectively.) The expansion velocity of the bubble's surface is

$$v_b = 0.6R_b/t = 20\left(\frac{v_j}{400\ \mathrm{km\ s^{-1}}}\right)^{2/5}\left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ \mathrm{yr}^{1/5}}\right)^{1/5} \times\left(\frac{v_s}{15\ \mathrm{km\ s^{-1}}}\right)^{1/5}\left(\frac{\dot{M}_s}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1/5}\left(\frac{z}{10^{16}\ \mathrm{cm}}\right)^{2/5} \times\left(\frac{t_b}{100\ \mathrm{yr}}\right)^{-2/5}\ \mathrm{km\ s^{-1}}\ . \quad (4)$$

The expansion time of the hot bubble, t_b, should be compared with the cooling time of the hot gas inside the bubble. The density inside the bubble is given by $\rho_b = \dot{M}_j t_b/(4\pi R_b^3/3)$, from which the cooling time is derived

$$t_{\mathrm{cool}}(\mathrm{bubble}) \simeq 30\left(\frac{v_j}{400\ \mathrm{km\ s^{-1}}}\right)^{2}\left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1} \times\left(\frac{R_b}{5\times10^{15}\ \mathrm{cm}}\right)^{3}\left(\frac{t_b}{100\ \mathrm{yr}}\right)^{-1}\ \mathrm{yr}\ . \quad (5)$$

The condition for the hot gas (the shocked jet material) to inflate a bubble is that the cooling time is longer than the expansion time, i.e., $t_{\mathrm{cool}}(\mathrm{bubble}) > t_b$. Substituting for $t_{\mathrm{cool}}(\mathrm{bubble})$ from equation (5) and eliminating R_b by equation (3) gives the distance along the symmetry axis beyond which the shocked jet material will not have time to cool before inflating a large bubble (which will evolve to a nebular lobe),

$$z_s \gtrsim 4.4\times10^{15}\left(\frac{v_j}{400\ \mathrm{km\ s^{-1}}}\right)^{-8/3} \times\left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/3}\left(\frac{v_s}{15\ \mathrm{km\ s^{-1}}}\right)^{-1/2} \times\left(\frac{\dot{M}_s}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{t_b}{100\ \mathrm{yr}}\right)^{1/6}\ \mathrm{cm}\ . \quad (6)$$

The scaling in the last equation shows that the adiabatic phase, where the cooling time of the shocked material is very long, starts at $r \sim 10^{16}$ cm. However, the parameters change from one system to another and sometimes within a system (see end of § 4.1).

3.2. *The Bubble Shape*

From equation (3) it turns out that the radius of a spherical bubble, R_b, under the assumption that all the jet energy is deposited in one point at a distance z, increases with z much slower than $R_b \propto z$. For example, at a distance from the center 32 times that which was used in equation (3), the bubble radius will be only 4 times larger, keeping the time and the other parameters unchanged. However, the bubble will not be spherical, since the jet propagates outward and a more accurate treatment is required. I assume that the bubble expands perpendicular to the symmetry axis, along the y direction, i.e., parallel to the equatorial plane. I also take the density in planes parallel to the equatorial plane to be the same as the density where the plane intersects the symmetry axis. The distance of the plane from the equatorial plane is the coordinate z. The relevant quantity is the energy deposited per unit length along the jet's propagation, which is $e_0 = 0.5\dot{M}_j v_j^2/v_h$. I use the relation between pressure and energy and the momentum equations as in Castor et al. (1975) and neglect the thermal energy of the swept slow-wind material. The last assumption is adequate since I neglect the slow-wind radial expansion and the dependence of density on the distance from the symmetry axis, while the assumptions allow a simple expression for the energy equation. The energy equation reads $e = e_0 - e_k$, where e is the thermal energy per unit length (along the symmetry axis) in the bubble, and e_k is the kinetic energy per unit length of the swept-up slow-wind gas. Neglecting the density variation perpendicular to the symmetry axis and the radial expansion of the slow wind gives the distance of the bubble surface from the symmetry axis

$$y_b(z) = \left[\frac{16}{5\pi}\frac{e_0}{\rho_s(z)}\right]^{1/4} t^{1/2} \simeq \left[\frac{e_0}{\rho_s(z)}\right]^{1/4} t^{1/2}\ , \quad (7)$$

where z and y are the coordinates parallel and perpendicular to the symmetry axis, respectively. Substituting in the typical values used here, with v_h by equation (1), gives

$$\frac{y_b}{z} \simeq 1.3\left(\frac{v_j}{400\ \mathrm{km\ s^{-1}}}\right)^{1/2}\left(\frac{\dot{M}_j}{10^{-7}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/4}\left(\frac{v_h}{4v_s}\right)^{-1/4} \times\left(\frac{\dot{M}_s}{10^{-5}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1/4}\left[\frac{t_b(z)}{100\ \mathrm{yr}}\right]^{1/2} \times\left(\frac{z}{10^{16}\ \mathrm{cm}}\right)^{-1/2}\ . \quad (8)$$

For the same parameters, the velocity is

$$v_b \equiv \frac{dy_b}{dt} \simeq 0.5\frac{y_b}{t} \simeq 20\left[\frac{t_b(z)}{100\ \mathrm{yr}}\right]^{-1/2} \times\left(\frac{z}{10^{16}\ \mathrm{cm}}\right)^{1/2}\ \mathrm{km\ s^{-1}}\ . \quad (9)$$

Because of the assumption that density does not depend on the y coordinate, the last two equations are less accurate for $y_b > z$, i.e., close to the central binary system.

It should be noted that in the last two equations, the time $t_b(z)$ is counted from the moment the jet reaches the point z; hence, t_b is longer for lower values of z, i.e., closer to the center of the nebula. If the nebula is observed at a time t_{obs} after the jets are launched and the jets proceed at velocity v_h, then $t_b(z) = t_{\mathrm{obs}} - z/v_h$. Substituting this in equation (8), keeping the other variables the same, gives

$$y_b \simeq 1.3 \times 10^{16} \left[\frac{t_{\rm obs} - (z/v_h)}{100 \text{ yr}} \right]^{1/2} \left(\frac{z}{10^{16} \text{ cm}} \right)^{1/2} . \quad (10)$$

The maximum width of the lobe, $y_{b\,\rm max}$, occurs at

$$z(y_{b\,\rm max}) \simeq \frac{v_h t_{\rm obs}}{2} = 1.6 \times 10^{17} \text{ cm} \left(\frac{t_{\rm obs}}{1000 \text{ yr}} \right) \times \left(\frac{v_h}{100 \text{ km s}^{-1}} \right) \text{cm} , \quad (11)$$

assuming the jet life time was $> t_{\rm obs}/2$. For this time of observation, $v_h \simeq 100$ km s^{-1}, and with the other values in equation (8), the maximum width is $y/z \simeq 0.7$. Due to the decrease of the density with distance from the symmetry axis and the radial expansion of the slow wind, the lobe will actually be somewhat wider. These values for the location of the widest lobal point and its width there are typical for many young bipolar PNs. The derivation above shows that the bubble, or lobe, is narrow close to the central system, then becomes wider, and then narrows again. If the density of the material on the outer portion is too low to be observed, the observed lobe surface will only widen with distance from the equatorial plane.

There are several strong assumptions in the derivation above; in particular, (1) neglecting the variation of the slow wind-density perpendicular to the symmetry axis, (2) treating the slow wind as a static medium rather than a radially expanding medium, and (3) the assumption that the bubble surface only expands perpendicular to the symmetry axis (the y direction). The last assumption is reasonable at the intermediate values of z, but not close to the equatorial plane (small values of z). The expansion there is more appropriately described by equations (3) and (4). Also, from equation (6), it is clear that the center of each bubble will be at a large distance from the equator. Hence, the expanding bubble surface facing the equatorial plane will push material toward the equatorial plane, substantially increasing the density there. This supports the claim of SR00 that jets (or a CFW) can compress the gas near the equatorial plane, contrary to some claims that the dense equatorial gas collimates the jets. If the bubble surface reaches the equatorial plane, it will collide with the bubble on the other side of the equatorial plane, and the lobe sides will be observed to emerge from the equatorial plane at a large distance from the center. Such a structure is observed, for example, in the PN He 2-104 (Sahai & Trauger 1998). Alternative explanations exist for similar, but not identical, structures of bipolar lobes near the equatorial plane, e.g., due to effects of ionization and/or other types of slow-wind geometries (e.g., García-Segura et al. 1999; their model K). The inflation of the bubble away from the central system implies that the bubble boundary may not reach the equatorial plane. This effect is stronger if we consider the outward motion of the slow wind, which was ignored in the derivation above. However, the distance of the bubble surface from the equatorial plane will be very small, since the bubble is starting to be inflated by the jet (or CFW) at $z \sim 400$ AU (eq. [6]). To observe a bubble not touching the equatorial plane, the nebula must be observed almost edge on. These two constraints imply that only a very small number of such bipolar PNs should be observed. Taking into account its inclination, it seems that the lobes of the bipolar PN Hb 12 do not cross the equatorial plane (Sahai & Trauger 1998). At larger values of z, the jets may cease to exist and a different treatment is required. Despite these approximations, the treatment above gives the basic shape of lobes in some bipolar PNs and demonstrates the capability of the binary-blown jets to form bipolar lobes. Note that the basic structure obtained here is different from a case where a spherical fast wind, instead of a jet, expands into the same slow-wind medium assumed here, i.e., $\rho_s \propto z^{-2}$. In the spherical fast wind flow, the lobes are much wider near the equatorial plane (Fig. 9 of García-Segura & Franco 1996).

The scaling of the jet velocity, 400 km s^{-1}, is typical for jets blown by main-sequence stars, which have similar escape velocities (Livio 2000). Jets blown by white dwarfs will have much higher velocities of the order of the escape velocity from white dwarfs ($\sim$5000 km s^{-1}). Such velocities are directly observed in some PNs and proto-PNs; e.g., a wind velocity of 2300 km s^{-1} was reported by Sánchez Contreras & Sahai (2001) in the proto-PNs He 3-1475. Note that this ultrafast wind is found in the inner region smaller than 3″, where the wide lobes are observed, and does not refer to the knots further out (Borkowski, Blondin, & Harrington 1997). In that case, we find from equation (6) that the shocked-jet material will not cool and the bubble will be inflated as soon as the jet encounters the slow-wind gas. In these cases, the lobes that are formed will have a wide opening very close to the equatorial plane, e.g., as in the symbiotic Mira He 2-104 (the Southern Crab, Corradi et al. 2001).

4. FAST-PROPAGATING JETS

4.1. *Jet Interaction with the Slow Wind*

When the density of the gas in the jet is much larger than that of the slow wind, it will not slow much, and equation (1) is not applicable. Instead, the jet head proceeds at a velocity given by

$$v_h \simeq v_j \left[1 - \left(\frac{\rho_s}{\rho_j} \right)^{1/2} \right] \text{ for } \rho_j \gg \rho_s . \quad (12)$$

Most of the thermal energy released is that of the shocked slow-wind material rather than that of the shocked jet material, as in the slow-propagating jet case. Thermal energy injected to the shocked slow-wind material per unit time and unit length are $\dot{E}_0 = 0.5 A_j \rho_s v_j^3$ and

$$e_0 = \dot{E}_0 / v_h \simeq 0.5 A_j \rho_s v_j^2 , \quad (13)$$

respectively, where A_j is the cross section of the jet.

As in the slow-propagating jet, bubble inflation starts when the shocked material has no time to cool. To find this distance z_s, the calculations that led to equation (6) are repeated with the following changes: (1) the energy injection rate $0.5 \dot{M}_j v_j^2$ in equation (1) is replaced by $\dot{E}_0$ given above, with $A_j = 4\pi\beta r^2$, and (2) the shocked material now is the slow-wind gas. Hence, the term for the total shocked mass $\dot{M}_j t_b$ in the derivation of equation (5) is replaced by the mass of the shocked slow wind during time t_b: $\beta \dot{M}_s t_b v_j / v_s$, where, as before, t_b is the expansion time of the bubble. The condition that the cooling time be longer than the expansion time

t_b becomes a condition on the location of the jet head

$$z_s \gtrsim 6.1 \times 10^{15} \left(\frac{v_j}{400 \text{ km s}^{-1}}\right)^{-7/3} \left(\frac{v_s}{15 \text{ km s}^{-1}}\right)^{-5/6} \times \left(\frac{\dot{M}_s}{10^{-5} M_\odot \text{ yr}^{-1}}\right)^{5/6} \left(\frac{t_b}{100 \text{ yr}}\right)^{1/6} \times \left(\frac{\beta}{10^{-3}}\right)^{1/3} \text{ cm} . \quad (14)$$

This condition is very similar to the one for slow-propagating jets (eq. [6]) . As with slow-propagating jets, jets blown by main-sequence stars, for which $v_j \simeq 400$ km s^{-1}, will start to inflate a bubble only after propagating a significant distance from their origin; this will push slow-wind material toward the equatorial plane. Jets blown by white dwarf companions, for which $v_j \gg 1000$ km s^{-1}, on the other hand, will start to inflate a bubble very close to their origin at $z \sim 10$ AU. They will also push material toward the equatorial plane, but in a complicated flow which requires three-dimensional numerical simulations to be treated correctly (SR00).

I consider here the interesting proto-PN OH 231.8+4.2, in which the expansion velocity ~400 km s^{-1} and maximum distance from the center along the symmetry axis $z \simeq 9 \times 10^{17}$ cm of the southern lobe are ~2 times as large as those of the northern lobe (Sánchez Contreras et al. 2000a, 2000b; Alcolea et al. 2001). The mass-loss rate is very high at 2×10^{-4} $M_\odot$ yr^{-1} (Alcolea et al. 2001 and references therein). If we take the mass-loss rate in the AGB wind of OH 231.8+4.2 to be 10 times higher than the values used in the scaling of equation (14), we find the adiabatic phase to start at $z_s \sim 4 \times 10^{16}$ cm from the central source for $v_j = 400$ km s $^{-1}$. This is much smaller than the size of the southern lobe; hence the southern lobe is expected to be inflated, as is indeed seen in the Hα+[N II] image (Sánchez Contreras et al. 2000a). Taking for the northern lobe the same mass-loss rate as for the southern lobe and a velocity appropriate for the northern lobe $v_j = 200$ km s^{-1}, we find the adiabatic phase to start at $z_s \sim 2 \times 10^{17}$ cm. This is about half the size of the lobe—hence the adiabatic phases just started. Considering the many uncertainties, it is possible that the adiabatic phase started much more recently. This is compatible with the small size of the Hα lobe. The small Hα lobes around the head of the northern molecular flow justify the assumptions I used in deriving equation (3). In any case, I emphasize that OH 231.8+4.2 is a complicated bipolar proto-PN with an intense molecular outflow (Kastner & Weintraub 1995; Bujarrabal et al. 2001; Alcolea et al. 2001). It is even plausible that Roche lobe overflow occurred in the past, with a higher mass-loss rate into the jets (Soker 2002). This implies more than one mass-loss episode. My main point here is that the basic different shape of the northern and southern Hα+[N II] lobes can be explained by the discussion presented in this subsection.

4.2. *The Bubble Shape*

I consider two cases which bound the two extremes of a jet's possible cross section. In the first case, the jet expands radially so that $A_j = 4\pi\beta r^2$ at all times. In the second case, the jet expands radially at early times, but it is then recollimated by the pressure of the surrounding shocked gas or by an internal magnetic field (e.g., Kössl, Müller, & Hillebrandt 1990) such that its cross section stays constant at $A_j = \pi a_j^2$, where a_j is the radius of the jet. I do not study these processes here, and simply assume that after opening up, the jet is reconfined near the place where bubble inflation starts, $z_s \simeq 10^{16}$ cm by equation (14), and I scale the jet radius by $a_j = 0.1 z_s \simeq 10^{15}$ cm. Jets propagating with their cross section increasing at a rate much slower than $A_j \propto r^2$, and even with constant cross section along a fraction of their path, are observed in different objects. Examples are the radio jet in the radio galaxy 3C 111 (Linfield & Perley 1984) and the molecular outflows in the young stellar objects HH 288 (Gueth, Schilke, & McCaughrean 2001) and HH 34 (Reipurth et al. 2000).

4.2.1. *Freely Expanding Jets*

Substituting the relevant cross section, $A_j = 4\pi\beta r^2$, in the rate of thermal energy released per unit length (eq. [13]), and then in equation (7), gives the radius of the axisymmetric bubble as a function of the distance, x, from the equatorial plane

$$\frac{y_b}{z} \simeq 1.0 \left(\frac{v_j}{400 \text{ km s}^{-1}}\right)^{1/2} \left[\frac{t_b(z)}{100 \text{ yr}}\right]^{1/2} \times \left(\frac{z}{10^{16} \text{ cm}}\right)^{-1/2} \left(\frac{\beta}{10^{10^{-3}}}\right)^{1/4} . \quad (15)$$

We find that the basic shape of the lobe is the same as in the case of a slow-propagating jet; hence, the analysis from equation (8) to the end of the previous section is applicable to the present case as well.

4.2.2. *Reconfined Jets*

Substituting the constant cross section in the thermal energy released per unit length (eq. 13), and then in equation (7), gives the radius of the axisymmetric bubble formed by a reconfined jet

$$y_b \simeq 1.3 \times 10^{16} \left(\frac{v_j}{400 \text{ km s}^{-1}}\right)^{1/2} \left(\frac{a_j}{10^{15} \text{ cm}}\right)^{1/2} \times \left[\frac{t_b(z)}{100 \text{ yr}}\right]^{1/2} \text{ cm} . \quad (16)$$

The shape here is different from that in previous cases; rather than widening, the cylindrical lobe has a constant radius. Since the jet propagates outward, the expansion time at location z from the equatorial plane is $t_{\rm obs} - z/v_j$, where $t_{\rm obs}$ is the observing time measured from the birth of the jet. Since in the present case the jet propagates much faster than the slow-propagating case, this delay is less significant than the case analyzed in equations (10) and (11). In any case, for the same parameters as in the last equation, the bubble radius will be

$$y_b \simeq 4.0 \times 10^{16} \left(\frac{v_j}{400 \text{ km s}^{-1}}\right)^{1/2} \left(\frac{a_j}{10^{15} \text{ cm}}\right)^{1/2} \times \left[\left(\frac{t_{\rm obs}}{1000 \text{ yr}}\right) - 0.40 \left(\frac{z}{5 \times 10^{17} \text{ cm}}\right) \times \left(\frac{v_j}{400 \text{ km s}^{-1}}\right)^{-1}\right]^{1/2} \text{ cm} . \quad (17)$$

The proto-PN Hen 401 has cylindrical lobes with almost constant radius of $y_b \simeq 5 \times 10^{16}$ cm up to a distance of

$\sim 3.5 \times 10^{17}$ cm from the central source (Sahai, Bujarrabal, & Zijlstra 1999). Sahai et al. (1999) present detailed study of the lobes. They argue, based on the theoretical study of molecular outflows by Masson & Chernin (1993), that the structure of Hen 401 can be explained by interaction between a well-collimated outflow and the slow wind, which intermediate between being radiative and being adiabatic. Some basic ingredients of their scenario apply here as well. According to the model presented here, the initial jet interaction with the slow wind is radiative, i.e., the shocked slow-wind material has time to cool radiatively. This is appropriate for a jet blown by a main-sequence companion; the case of a white dwarf companion is discussed below. As the jet expands to $z \sim 10^{16}$ cm (eq. [14] above), the adiabatic phase starts with the inflation of a bubble (which will become the observed lobes, one lobe at each side of the equatorial plane). This part of the bubble compresses the material near the equatorial plane. This explains the wide opening of the lobe close to the equatorial plane, which cannot be explained with a fully radiative flow. The jets then expand with a constant cross section. Further out, the jets may become weaker and the interaction becomes unstable (Sahai et al. 1999). To quantitatively match the structure of Hen 401, $y_b = 5 \times 10^{16}$ cm up to $z = 3.5 \times 10^{17}$ cm, the age of the jet and its velocity should be known. This information is not available; hence, I consider a few examples. We can take $a_j = 3 \times 10^{15}$ cm, keeping the other parameters as in equation (17), or we can take $t_{\rm obs} = 1500$ yr , $v_j = 500$ km s^{-1}, and keep a_j as in equation (17). For a white dwarf companion, we set $v_j \simeq 5000$ km s^{-1} and take $a_j \simeq 2 \times 10^{14}$ cm $\simeq 13$ AU, keeping the observing time as in equation (17). In this case, the bubble inflation starts much closer to the binary system (eq. [14]). To summarize, the flow structure presented here, despite its several assumptions, e.g., neglecting the decrease in the slow-wind density along the y direction (perpendicular to the symmetry axis), can explain the structure of the lobes in Hen 401 and similar PNs having cylindrical lobes (see Sahai et al. 1999 for more examples).

5. SUMMARY

In the present paper, I studied the interaction of jets, or a collimated fast wind (CFW), with a previously blown AGB wind, and reproduced some basic properties of bipolar PN lobes. My view (SR00) is that the jets (or CFW) are blown by an accreting compact companion simultaneously with the slow wind. To facilitate analytical solution, I had to assume axisymmetric flow as well as several other simplifying assumptions. In addition, I studied only two extreme cases, a slow-propagating and fast-propagating jets, which occur when the slow-wind density is much larger, or much lower, than the respective jet densities. The goal was to derive simple expressions from which the properties of PN lobes blown by jets can be inferred. This can be used both to analyze observations (see discussions following eqs. [14] and [17]) and to guide future numerical simulations.

The main results can be summarized as follows:

1. The interaction of jets (or CFW) blown by main-sequence companion stars, having a speed of $v_j \sim 200$–500 km s^{-1}, with the slow AGB stellar wind close to the central binary system is radiative, i.e., the shocked gas, the jet's material and/or the ambient slow wind material cools in a short time. Further away, the interaction becomes adiabatic, i.e., a bubble of hot gas which cools slowly is formed. The distance from the center where this transition takes place for the two types of jets studied here is given by equations (6) and (14). The expressions are scaled for jets blown by main-sequence companions. Jets blown by white dwarf companions move much faster, $v_j \sim 5000$ km s^{-1}, and start to inflate a bubble very close to the binary system.

2. As noted by SR00, the interaction between the CFW and the slow wind pushes material toward the equatorial plane. The formation of the inflated bubble at a distance from the equatorial plane in jets blown by main-sequence stars increases the efficiency of this process.

3. The basic interaction of a radially expanding jet with the slow wind forms an axisymmetric bubble which is narrow close to the central star(s) and far from the central star(s); its widest diameter is somewhere in between. This type of structure is observed in many bipolar PNs.

4. If a jet is recollimated, e.g., by magnetic fields inside the jet, such that its cross section stays constant, then the lobe widens close to the center but acquires a cylindrical shape with a constant diameter. Such lobes are observed in several bipolar PNs.

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