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MECHANISMS FOR MASS LOSS FROM COOL STARS*

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ABSTRACT

The mechanisms believed responsible for the loss of mass from cool, red giant stars are reviewed. While observations indicate that both radiation pressure on dust grains and pulsations are important, theoretical considerations indicate that neither is sufficient by itself to account for the high rates of mass loss that have been observed. The current picture involves a two-step process wherein pulsations act to levitate matter well above the photosphere to the point at which the gas is sufficiently cool for dust grains to form. Radiation pressure on the dust then drives the matter to infinity. Whereas this model is applicable to spherically symmetric mass loss, the outflowing matter in many mass-losing systems displays a pronounced bipolarity, implying axial symmetry on the large scale. A secondary star appears to be responsible for the geometry of such systems. A new scenario involving two winds is presented to describe how the bipolar geometry might be produced.

Key words: mass loss–cool, giant stars–bipolar nebula–binary stars

I. Introduction

The occurrence of copious mass loss from evolved, red giant stars is well established from observations of outflowing material in their extended circumstellar envelopes. The cause of the matter ejection is, however, understood only in broad outline because the near-stellar arena from which the matter is expelled is complex and cannot usually be resolved spatially.

This review presents an observational perspective on the mass-loss process. For relevant theoretical considerations, the reader is referred to the excellent review by Holzer and MacGregor (1985). We first examine spherically symmetric mass loss and emphasize pulsations and radiation pressure on dust grains as ejection mechanisms. The discussion of spherically symmetric systems is apparently applicable to the majority of stars losing mass at a large rate. Second, we address the mass-loss process in bipolar nebulae—systems clearly deviating from spherical symmetry. The additional factor affecting such systems appears to be the presence of a relatively close binary companion. Finally, we describe a new picture of how a binary system can give rise to a bipolar geometry.

II. Spherically Symmetric Mass Loss

No well-observed circumstellar envelope shows an ideal circular symmetry on the plane of the sky, but most outflows are almost circular on large enough scales. For example, 1612 MHz OH masers have the gross characteristics expected for a spherical shell centered on the mass-losing star (e.g., Bowers, Johnston, and Spencer 1983; Diamond, Norris, and Booth 1984). Also, the representative carbon star IRC +10216 is circularly symmetric in the emission from many molecular species (Wannier *et al.* 1980; Bieging, Chapman, and Welch 1984; Bieging and Rieu 1987*a*; Likkel *et al.* 1987*a*). Indirect evidence for rough spherical symmetry is provided by the shapes of the line profiles in almost all circumstellar envelopes for which the signal-to-noise ratio is adequately high (Knapp and Morris 1985; Huggins and Healy 1986); the shapes are equivalent to those expected for spherical systems (Morris 1985).

Deviations from spherical symmetry are apparent on smaller scales. Aperture synthesis observations of OH masers reveal irregular knots and lumps in the otherwise symmetrical intensity distributions (e.g., Diamond *et al.* 1985; Welty *et al.* 1987) and SiO and H_2O masers, which must arise relatively close to the star, have asymmetrical profiles which vary irregularly in time (Lane 1982; Johnston, Spencer, and Bowers 1985). The large-scale symmetry is produced on time scales exceeding a few thousand years from a short-term stochastic process. On short time scales, and in small intervals of radius near the star, there appear to be fluctuations in the direction of the outflow, in the mass-loss rate, $\dot{\mathfrak{M}}$, and perhaps in velocity (Deguchi 1982; Alcock and Ross 1985, 1986; Fix 1987).

Theoretically, major deviations from spherical symmetry in the near-stellar environment might be expected for at least two reasons. First, the size scale of the dominant

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convective elements in red giants is comparable to the stellar radius, so that only a few of them are present on the stellar surface at any time (Schwarzschild 1975). The surface temperature and scale height may therefore vary strongly across major portions of the stellar surface. The other possible source of inhomogeneity, possibly coupled to convection, is the condensation instability proposed by Stencel, Carpenter, and Hagen (1986). They suggest that warm chromospheric gas is subject to a cooling, grain-formation instability initiated by local pressure fluctuations. Both of these processes leading to inhomogeneities in the outflow warrant further investigation, as both are poorly understood at the present time.

We consider here two primary mechanisms for mass ejection from cool stars: pulsations and radiation pressure on dust grains. Other mechanisms have been suggested, but they have not been as successful in accounting for the data. For example, Maciel (1976, 1977) has investigated the importance of radiation pressure on molecules and finds a rather small effect, presumably because only a relatively small fraction of the stellar radiative momentum can be utilized. Also, thermal expansion is not likely to be important because the outflowing gas is simply too cold. Jura (1984*a*) has demonstrated that for stellar parameters of interest, radiation pressure on grains dominates in importance over thermal expansion. Warm chromospheres might be invoked to enhance the thermal expansion, but Jennings and Dyck (1972) showed that there is an anticorrelation between chromospheric activity and $\mathfrak{M}'$, so that mass loss is most significant in stars without chromospheres, or chromospheres are "quenched" in environments giving rise to high rates of mass loss (Stencel *et al.* 1986). Finally, Hartmann and MacGregor (1980) discuss the importance of Alfven waves in driving outflows. They argue that it is possible to obtain the observed rates of mass loss, but that the predicted terminal velocities are too high. The dissipation of Alfven waves should lead to extended, warm chromospheres, so Alfven waves are perhaps more important in stars with lower mass-loss rates than those considered in this review. In any case, this mechanism cannot be ruled out as an important contributor to the mass-loss process.

A. *Pulsations*

Because of the clear tendency for cool, mass-losing stars to be long-period variables, several groups have explored the possibility that the shocks accompanying fundamental or first-overtone-mode pulsations are responsible for mass ejection (Wood 1979; Willson and Hill 1979; Tuchman, Sack, and Barkat 1978, 1979; Bertschinger and Chevalier 1985). The shocks occur because the pulsation period is not a constant function of radius in the outer layers of the stellar envelope, so adjacent layers encounter each other at highly supersonic velocities.

The observational evidence that pulsations play an essential role in mass loss comes from many quarters. Perhaps most striking is the graphic demonstration by Jura (1986*a*) that the binary division of stars into pulsating and nonpulsating objects corresponds closely with the division of stars into those having large and small amounts of circumstellar dust, respectively. The presence of dust, which condenses in the cool, outflowing stellar material, is inferred from the infrared excess in the form of the ratio of fluxes at 12 μm and 2 μm. The 12 μm emission is presumed to arise predominantly from near-stellar dust (in those cases where it is present) and the 2 μm emission arises directly from the stellar photosphere.

The linkage of mass loss to pulsation is more profoundly illustrated by the presence of a correlation between the infrared excess of a star and its period, P. This correlation, interpretable as a correlation between the mass-loss rate, $\mathfrak{M}'$, and P, is independent of the chemistry of the stellar photosphere, be it oxygen-rich (DeGioia-Eastwood *et al.* 1981), carbon-rich (Jura 1986*b*), or in-between (S stars; Jura 1987). An alternative version of the P-$\mathfrak{M}'$ relation is described by Knapp (1986), who uses CO observations to deduce $\mathfrak{M}'$, and normalizes $\mathfrak{M}'$ by the luminosity. Another correlation, between P and the amplitude of the pulsation, has been known for some time (Harvey *et al.* 1974; Ukita 1982). It is easy to imagine that larger-amplitude pulsations lead to a greater rate of mass loss. Indeed, larger-amplitude pulsations cause the shocks to develop fully at a smaller radius where the density is higher, and thus they enhance the density throughout the upper atmosphere (Willson and Bowen 1986). Therefore, the P-$\mathfrak{M}'$ relation should follow from the P-amplitude relation.

Another indication that pulsations may be involved in mass loss is the apparent linear relationship between the period of pulsation, P, of mass-losing stars and the terminal velocity, V_T, of the outflowing matter (Dickinson, Kollberg, and Yngvesson 1975; Morris *et al.* 1979; Zuckerman, Dyck, and Claussen 1986). No compelling theoretical explanation for this relationship has been advanced, and it may be that both P and V_T independently depend in a similar way on some other variable, such as the mass of the star. (Note that this latter comment could apply, in principle, to the P-$\mathfrak{M}'$ and P-amplitude correlations as well.) Furthermore, Ukita (1982) has argued that the V_T-P relation is oversimplified by selection effects. Indeed, more recent data suggest that the relation does not continue to hold for all stars with periods exceeding about 700 days. Still, the relation is striking enough to warrant a close examination with the recent generation of data.

While the case for the involvement of stellar pulsations in the mass-loss process is rather strong, pulsations, *by themselves*, cannot account for the observed winds. According to theoretical treatments, the shocks do not appear to be strong enough. The predicted mass-loss rate is much too low (Drinkwater and Wood 1985; Holzer and MacGregor 1985; Bertschinger and Chevalier 1985; Willson and Bowen 1986).

B. *Radiation Pressure on Grains*

That radiation pressure on grains can drive mass loss from cool stars has been convincingly demonstrated by many investigators (Gilman 1972; Kwok 1975; Lucy 1976; Menietti and Fix 1978; Woodrow and Auman 1982; Tielens 1983), and here we only summarize the concept.

As grains nucleate and grow in the cool, uppermost layers of the stellar atmosphere, they experience a negative gravity as a result of the force exerted by the outwardly directed radiation. The grains reach a terminal outflow velocity dictated by the drag against the gas. This same drag force implies a momentum coupling between grains and gas that leads to an outflow of the gas at a velocity comparable to, though less than, the outflow velocity of the grains.

The evidence is strong that radiation pressure on grains is important in the mass-loss process from red giants. First, infrared spectra of mass-losing red giants reveal an infrared excess that is a clear signature of copious quantities of dust. The dust opacity at 2 μm, where the peak in the photospheric radiation typically occurs, is usually large enough for the dust to intercept, and thus be accelerated by, a substantial fraction of the available stellar photons. Second, the magnitude of the terminal velocity expected for grain-driven mass loss, on the assumption that grain condensation occurs at the radius at which the gas temperature is equal to the condensation temperature, is about equal to that typically observed, 10–20 km s^{-1} (Jura 1984*a*). Carrying this argument further, Gehrz and Woolf (1971) and Jura (1984*a*) deduce, using simplifying assumptions, that $V_T \propto L^{1/4}$, where L is the luminosity of the star. Jura (1984*a*) shows that, given uncertainties in stellar distances, this relation is consistent with the data.

A third argument in favor of dust-driven mass loss is given by considering the available momentum flux. If radiation pressure on dust is responsible for the observed outflow velocities from cool stars, and if $\mathfrak{M}'$, V_T, and L are assumed constant, then the radial momentum flux in the wind, $\mathfrak{M}'V_T$, should not exceed the radial momentum flux in the radiation field, L/c. (Strictly speaking, if the opacity of the shell is large, then scattered and reradiated photons can enhance $\mathfrak{M}'V_T$ by a small factor over L/c, but because of the inevitable degradation of the photon energy once it is absorbed, and because the dust opacity declines with wavelength, this factor is unlikely to ever be greater than about 2.) Radio observations of CO enable one to estimate $\mathfrak{M}'$ (Morris 1980; Knapp and Morris 1985), and thus, by comparison with optical and infrared fluxes, to assess the validity of this inequality. Existing data indicate that, with a few exceptions, almost all stars obey $\mathfrak{M}'V_T \leq L/c$ (Zuckerman and Dyck 1986; Jura 1986*b*). The ratio of $\mathfrak{M}'V_T$ to L/c provides a measure of the fraction of the stellar luminosity intercepted by dust, i.e., the radial dust opacity. The few exceptions to the inequality can be attributed (1) to a sharp decline in luminosity in the $\sim 10^3$-year interval following expulsion of the bulk of the stellar atmosphere during which the CO molecules have coasted to the radius from which they presently emit (Jura 1984*b*, 1986*a*; Likkel *et al.* 1987*b*; Zuckerman and Gatley 1987), or (2) to the additional importance of a secondary mass ejection mechanism, such as may occur in BPNs (see below), or (3) to large errors in the determination of $\mathfrak{M}'$, usually because of uncertainties in the CO/H_2 ratio.

While the evidence is therefore quite good that radiation pressure on dust plays a major role in the mass-loss process, this mechanism cannot, by itself, account for the observed mass loss from cool stars. In static stellar models, the density at the dust condensation point is many orders of magnitude too small to permit mass-loss rates as large as those often observed (e.g., Willson and Bowen 1986): $10^{-6}\ \mathfrak{M}_\odot\ yr^{-1}$ to $10^{-4}\ \mathfrak{M}_\odot\ yr^{-1}$ (Knapp and Morris 1985). In nonstatic, time-independent stellar models (Lucy 1976; Woodrow and Auman 1982) there remains the problem of getting enough material above the dust condensation radius. Attempts to remedy that limitation have led to model circumstellar envelopes which are too thick and opaque to describe those observed (Lucy 1976).

C. *The Two-Step Solution*

The obvious remedy for the difficulties encountered by the pulsating models and the grain-driven models for mass loss is to combine the two, by allowing pulsations and associated shocks to create an extended atmosphere in the form of an unstable "quasi-static" zone extending many stellar radii beyond the photosphere. Then the density at the dust condensation radius, where the local radiative equilibrium temperature drops below about 1000 K (see Gail and Sedlmayr (1986) and references therein), can be high enough for significant mass loss to occur by transfer of radiative momentum to dust grains. This basic picture has, in fact, gained general acceptance (Jones, Ney, and Stein 1981; Woodrow and Auman 1982; Jura 1984*a*, 1986*b*; Willson and Bowen 1986). The levitation of matter above the stellar photosphere can perhaps also be effected, or at least enhanced, by some combination of the other processes mentioned above: Alfven waves, radiation pressure on molecules, or large-scale convection which overshoots the equilibrium photosphere. The evidence suggests, however, that the primary levitation mechanism must at least be strongly correlated with pulsational properties.

Figure 1 presents a sketch of the inner envelope of a mass-losing red giant. As argued above, one must expect the extended static layer to be irregular and aspherical, except in a stochastic sense. Not only is stellar material rising into the quasi-static layer, but where pressure sup-

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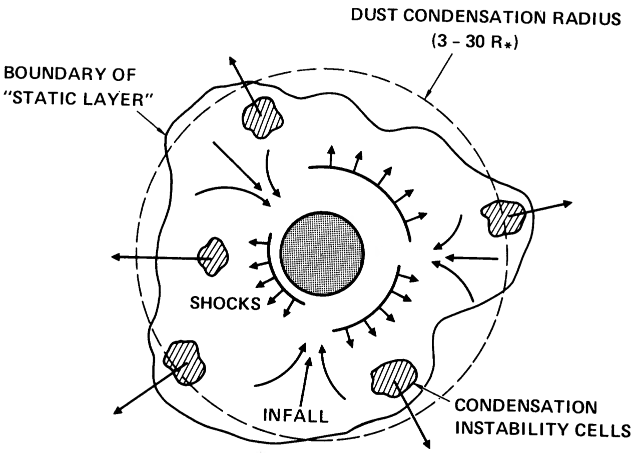

FIG. 1–Schematic view of the innermost region of a circumstellar envelope surrounding a pulsating red giant. Gas from the star is levitated into an extended, quasi-static layer by shocks and other processes. Grain formation leading to radiation-pressure-driven mass loss occurs either beyond the dust condensation radius, where the gas has cooled enough by expansion and by dilution of the stellar radiation field to permit dust to condense, or it occurs in pockets of gas undergoing a cooling, condensation instability. Actual measurements of the inner radius of the dust shell indicate that it is 5–20 stellar radii (Bloemhof, Townes, and Vanderwyck 1984; Dyck *et al.* 1984). Note that infalling gas is envisaged if density enhancements in the quasi-static layer do not undergo grain formation.

port temporarily ebbs, the material must fall back onto the star. One might also imagine the gas in the quasi-static layer cooling more rapidly in some locations than in others because of large-scale surface temperature fluctuations in the underlying star (Schwarzschild 1975). In response, the density would rise in those cooler locations as the pressure equilibrates with that of the surrounding, warmer gas, and infalling flows would be set up, as depicted in Figure 1. The lifetimes of such flows might be comparable to the lifetimes of the cooler surface regions of the star, or to the rotation time of the star. Evidence for such infalling matter comes from blueshifted absorption lines not ascribable merely to the contraction phase of the pulsation (e.g., Hall 1980; see discussion in Jura 1984*a*).

If the cooling cells of gas within the quasi-static layer become dense and cool enough for grains to form, then those cells can be expelled by radiation pressure (Stencel *et al.* 1986). The physical conditions in the quasi-static layer are thus crucial; above some critical, density-dependent temperature the cooling gas is destined to sink, while below that temperature it will ultimately be accelerated outward. The phenomenon is an exceptionally complex one, since one of the primary coolants, at least in the inner parts of oxygen-rich outflows, is SiO, which overwhelmingly becomes a grain constituent (Morris *et al.* 1979). To make matters worse, the cooling is sensitive to the dynamics (Tielens 1983), especially if some of the infrared lines of H_2O undergo laser action, as suggested by Cooke and Elitzur (1985). We note here that maser emission from SiO almost certainly arises in the quasi-static layer, within the dust condensation radius, and it is therefore a valuable probe of that layer's characteristics. A careful, long-term monitoring of circumstellar SiO masers would thereby be useful for defining the time scales and magnitudes of the stochastic variations in velocity and density.

While grain formation and subsequent grain acceleration apparently depend on the pulsational properties of the red giant, the reverse may also be true. Woodrow and Aumann (1982) have modeled a feedback mechanism wherein changes in the atmospheric opacity caused by grain formation lead to substantial changes in the temperature of the hydrogen dissociation zone. An oscillation is set up as the response of the hydrogen dissociation zone travels out to the region of grain production and decreases the dust formation rate. This interesting possibility warrants a closer examination since it would entail a major reassessment of the relationship between pulsation and mass loss.

The shape of the light curves of pulsating stars may have a bearing on this feedback mechanism. Bowers and Kerr (1977) find that stars with circumstellar OH masers have light curves with faster rise times, expressed as a fraction of the period, than variable stars without OH masers. A similar effect was noted when mass loss was evidenced by far-infrared colors (Vardya *et al.* 1986) and by H_2O masers (Vardya 1987). It remains to be established whether the presence of abundant circumstellar dust affects the character of the pulsations, or whether the character of the pulsations affects the rate of mass loss.

III. Axially Symmetric Mass Loss—Bipolar Nebulae

A small but significant fraction of circumstellar envelopes around evolved stars displays a marked bipolar symmetry, usually in the form of two reflection nebulae symmetrically placed on opposite sides of the central, mass-losing star. The reflection nebulae define the "polar" regions where the radial column density of dusty matter is low, allowing light to propagate out and be reflected without severe extinction. Perpendicular to the polar axis is an equatorial distribution of dust and gas which is usually opaque and which manifests itself in the form of a dark absorption band, or a "pinched waist", separating the optical reflection nebulae.

More than ~ 17 such systems are now known. In addition to the 12 listed by Morris (1981), several other evolved, bipolar systems have recently been pointed out, including OH 17.7-2.0 (Le Bertre, Epchtein, and Nguyen-Q-Rieu 1984; Le Bertre 1986), *IRAS* 18059-3211 (or Gomez's Hamburger, Ruiz *et al.* 1987), *IRAS* 09371+1212 (the Frosty Leo Nebula, Forveille *et al.* 1987), V Hydra (Kahane, Maizels, and Jura 1987); and R Aquarii (Mauron *et al.* 1985; Wallerstein and Greenstein 1980). Still, the number of bipolar systems is small compared to the hundreds of circumstellar outflows which have been studied.

The apparently low frequency of bipolarity in circumstellar envelopes may be misleading, since about 50% of all planetary nebulae display a bipolar symmetry (Zuckerman and Aller 1986). Because strong circumstellar outflows are generally thought to be precursors to planetary nebulae, one might expect a similar fraction of them to have an intrinsic bipolar geometry. That this is not the case might be explained in several ways:

(1) Some, perhaps the majority of, bipolar nebulae might not easily be recognized as such because certain orientations of bipolar nebulae with respect to the line of sight may be selected against if the bipolar lobes overlap in projection.

(2) Bipolarity might not be manifested in most systems until the later stages of envelope ejection. Indeed, several of the bipolars listed by Morris (1981) surround relatively early-type stars, suggesting that their evolution toward being planetary nebulae is almost complete. Bipolarity may be lurking unobtrusively in envelopes at earlier stages of evolution (for example, even IRC +10216 has a slight axisymmetric character; Dyck *et al.* 1987) and may, in most cases, be evidenced only by intrinsic polarization of scattered starlight (Dyck *et al.* 1971; Cohen and Schmidt 1982).

(3) Relative to bipolar systems, spherically symmetric systems may not produce planetaries as often, or may not produce such prominent planetaries because, perhaps, of a smaller mass-loss rate.

It seems likely that a bipolar geometry may occur quite frequently in mass-losing systems and the task is to identify the mechanism that differentiates the polar and equatorial regions. The possibility considered foremost in this paper involves the presence of a binary companion. Other possibilities, such as nonradial pulsations, or rotation of the progenitor, are dismissed by Morris (1981) and Pascoli (1987).

Magnetic fields must also be considered, since they present a natural way to define a preferred axis. Pascoli (1987) has argued that an azimuthal magnetic field surrounding the central, mass-losing star can constrain the outflow in such a way as to account for the morphology of bipolar planetary nebulae. His models nicely reproduce the shapes of planetary nebulae and are able to account qualitatively for the fact that the outflow velocity increases with latitude, measured with respect to the system's equatorial plane (e.g., Cohen *et al.* 1985; Morris *et al.* 1987; Heiligman *et al.* 1986). However, it is not clear whether these models can account for the large magnitude of the velocity difference between the equatorial and polar outflows in at least some bipolars (Morris *et al.* 1987). Indeed, if R Aqr is to be classed alongside the other bipolar nebulae, the polar flow can take the form of a jet (Sopka *et al.* 1982). We will reconsider the potential importance of magnetic fields below in the context of binary models.

A. *Binary Models*

In a close binary system, angular momentum provides a clear and natural way to define the equatorial plane and the polar axis. This led Morris (1981) to hypothesize that bipolar nebulae are created from binary star systems by strong tidal interaction between a main-sequence secondary and the expanding red giant primary. A similar consideration had previously led Livio, Salzman, and Shaviv (1979) to suggest that binary planetary nebula nuclei arise in just this manner. The dissipative tidal interaction leads, in their picture, to a merger of the two stars into a common envelope system. Continued loss of envelope material ultimately leads to the exposure of the embedded, very tight binary, consisting of a main-sequence star and a hot degenerate core, at the center of an axisymmetric nebula. In the model of Morris (1981), matter is flung out predominantly in the equatorial plane by the secondary orbiting asynchronously within about 1.3 stellar radii of the red giant. The outflow resulting from this ejection process would be characterized by a decrease in density with systemic latitude. The midplane would ostensibly have a high enough density to account for the absorption observed there, whereas the smaller column density at high systemic latitudes would permit the escape of optical radiation out to the reflection nebula.

A serious problem with this model is that it predicts a maximum outflow velocity in the equatorial plane, which is just the opposite of that observed. Also, Zuckerman and Aller (1986) have argued that the fraction of planetary nebulae which are bipolar is too large to be consistent with the fraction of stars expected to be close binaries having the separation required in the model. A third problem with the model was pointed out by Zuckerman and Gatley (1987), who find from the distribution of bipolar planetary nebulae with galactic latitude that the progenitors of bipolar systems are relatively massive stars with the implication that the bipolarity is a function of stellar mass rather than binarity.

In spite of these difficulties, the binary model warrants resurrection in a modified form because no other model appears capable of accounting for several of the characteristics of bipolar systems. First, the bipolar OH 231.8+4.2 displays an excess blue continuum which implies the presence of a secondary star in the system (Cohen *et al.* 1985), and R Aqr, if it belongs in the category of bipolar nebulae, is a known symbiotic system, very probably a binary. Second, OH 231.8+4.2, and perhaps a large fraction of bipolar nebulae, violates the $\mathfrak{M}'V \leq L/c$ inequality required by the two-step process applicable to spherical mass loss (Jura and Morris 1985; Knapp 1986), so that bipolar nebulae either tend to have a rapidly declining luminosity, or they require an additional mass-ejection mechanism. A binary system can provide such an additional mechanism. Third, high-velocity polar flows, such as those observed, can be produced in a binary system, as argued below.

The previous binary model did not include consideration of an accretion disk around the secondary, whereas it is likely to be important. The proposed new model proceeds as follows (a more detailed discussion will be presented later): at a high enough rate of mass loss from the red giant primary, depending on the stellar separation, the accretion disk acquires mass faster than it can be transferred inward to the secondary. The mass acquired by the accretion disk is either intercepted directly from the wind, or, if the stellar separation is smaller than the size of the "quasi-stationary layer" around the red giant, then it is accreted from this extended, tenuous layer. (Note, however, that in this latter case the system does not qualify as a common-envelope binary.) The disk will then grow until matter at its periphery is susceptible to forming an exterior "excretion disk" orbiting the center of mass of the system (see, for example, Webbink 1976). Note that, as the disk grows, it intercepts an increasing fraction of the mass lost from the primary. As long as mass loss continues and angular momentum from the binary is available, the disk can grow to relatively large proportions as angular momentum migrates outward under the influence of viscous interactions. The disk growth is limited ultimately by the loss of mass and angular momentum from its outer periphery. It is also possible that, before an exterior excretion disk forms, matter at the outside of the accretion disk around the secondary might fall back into the gravitational potential well of the primary, forming a second disk. The sequence of events depends on the mass ratio and stellar separation. Of course, with gas orbiting as many as three centers, the gas dynamics are extremely complex, and the system may have unstable orbits and interacting gas streams during certain phases of its evolution. At those times, the energy dissipated in the tumultuous gas disk may have observable consequences.

The envisioned model is depicted in Figure 2. There are three implications of this model which were not foreseen in the earlier binary model and which receive support from the observations:

(1) The accretion disk around the secondary is hypothesized to be the source of a second wind (wind 2). This wind, which emanates from the innermost parts of the accretion disk, is collimated by the disk along the polar axis of the system. The velocity of this bipolar wind is unrelated to that of the spherically symmetric wind from the red giant companion (wind 1), except inasmuch as it is determined in part by the accretion rate, which depends in turn on the velocity of wind 1.

Bipolar flows in pre-main-sequence objects may share the phenomenology of wind 2 in evolved bipolar systems. Both can have a relatively large outflow velocity (up to 100 km s^{-1}), exceeding by far the velocities normally achieved with radiation-driven mass loss. Hydromagnetic models which have been proposed for bipolar flows in star-forming regions utilize the rotational energy of the accretion disks to drive the outflows (Pudritz and Norman 1983: Pudritz 1985). The large wind velocity is possible in such a model because the outflow is not limited by the available radiative momentum, but rather by the large pool of rotational energy. We do not stress the details of these models here, but propose that the same considerations apply to wind 2 in evolved bipolar nebulae.

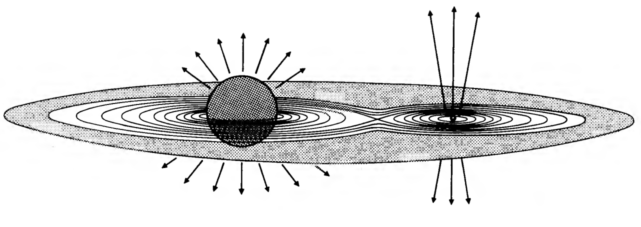

FIG. 2–Binary model for the creation of bipolar circumstellar outflows. The wind of the red giant (wind 1) is partially captured into an accretion disk around the much smaller secondary. This accretion disk grows with time to form an excretion disk, which encompasses the whole system. A second wind arises from the interior of the accretion disk about the secondary.

In a two-wind binary model the winds interact in an interesting and relatively violent manner. The interaction is undoubtedly complex because both winds are probably irregular or intermittent on the scale of the stellar separation. Nevertheless, this interaction may provide an observable diagnostic needed to test the validity of the overall picture. The observation of extended emission from shocked H_2 in the polar regions of a few bipolars (Beckwith, Beck, and Gatley 1984) could be accounted for by the interaction of the winds. Also, the Hα emission observed by Reipurth (1987) in OH 231.8+4.2 appears to occur at the shocked interface between a fast and a slow wind. There the fast wind appears to dominate the interior portions of the nebula, perhaps because of its large momentum flux. In considering the interaction between the two winds, one must admit that their relative importance may vary considerably from one epoch to the next as the mass-loss rate of the red giant and the accretion rate of the companion vary separately.

(2) The disk inhibits the mass outflow from the primary in the equatorial plane, but because the disk stores a larger amount of mass than would be present in an uninhibited outflow, it very effectively absorbs light from the star and from the portion of the reflection nebula it happens to lie in front of. This would account for the very high equatorial extinction inferred for OH 231.8+4.2 by Reipurth (1987). It is also consistent with the molecular line profiles from this same bipolar, which are most straightforward to explain if there is little or no net outflow in the equatorial plane (Morris *et al.* 1987). Not only

is the spherical outflow from the primary inhibited in the equatorial plane, but it can also be diverted into a "biconical" nebula in the manner described by Icke (1981).

(3) The presence of a large rotating disk should manifest itself in high-resolution observations in terms of a velocity gradient perpendicular to the polar axis. Most observations do not resolve the rotational structure within the disk (e.g., Heiligman *et al.* 1986), but in a recent interferometric study of HCN in the well-known bipolar CRL 2688 by Bieging and Rieu (1987*b*), a gradient of the appropriate magnitude (~ 2 km s^{-1} across 8 arc seconds, or $\sim 10^{17}$ cm) was observed. Those authors interpreted the inferred equatorial rotation in terms of a strong, extended magnetosphere around the red giant which enforces corotation in the wind. They invoke a binary companion to provide the requisite high angular momentum by tidally transferring its angular momentum to the atmosphere of the primary, and to provide the dynamo action necessary for the generation of the many-kilogauss magnetic field needed at the surface of the rotating primary. The model of Bieging and Rieu suffers from the absence of evidence for such large field strengths, and it does not incorporate an accretion disk, which may be necessary for the generation of the high-velocity polar streams, as mentioned above.

B. *Discussion*

As in the earlier binary model of Morris (1981) and in the evolutionary model of Livio *et al.* (1979), the fate of the binary system is inevitably to shrink via the loss of angular momentum to the outflowing gas. If the initial separation is not too great, the stars are destined to merge into a common envelope binary, which may continue to feed the equatorial disk as the distended envelope sheds angular momentum (Webbink 1979). Continued mass loss would therefore be expected to maintain a bipolar character as the disk directs the flow.

The importance of magnetic fields should not be underplayed in the revised binary model for bipolar nebulae. The considerations given by Pascoli (1987) of the effects of a magnetic field are still partially applicable. The differentially rotating accretion disk around either star in the system should enhance the azimuthal magnetic field in the disk (indeed, the polar flow may be driven by the buoyancy of this amplified azimuthal magnetic field, as described by Cameron (1985)). The mass outflow should then be confined by this field (as well as by the gas pressure in the disk) in a manner similar to that described by Pascoli.

Finally, we address the question raised by Zuckerman and Gatley (1987): why should bipolar planetary nebulae have relatively massive progenitors? When mass is lost from relatively massive stars, there is relatively more mass available to form a disk. The formation of a substantial disk is also facilitated by the fact that the more massive stars have higher rates of mass loss. We suggest that the larger and more massive the disk is in a system containing a mass-losing red giant, the more pronounced and obvious the bipolar character, both in the pre-planetary bipolar nebula phase and in the planetary nebula phase. The three implications of a disk described above are all accentuated if the disk in question is relatively massive, especially if the thickness of the disk increases with its overall mass. To account for bipolar planetary nebulae, the model need only require that the time scale for the persistence of the disk in the presence of the radiation and winds from the planetary nebula nucleus is comparable to, or longer than, the expansion time scale for the planetary, $\sim 10^4$ years. It is reasonable to expect that the persistence time of the disk increases with its mass and thus with the mass of the system that created it.

In conclusion, the revised binary model for bipolar nebulae can, in principle, surmount the objections encountered by the earlier model. The task remaining is to fill in the complex details of the hydrodynamics. Even before that is done, however, it appears that the addition of a rotating disk has given the binary model a second wind.

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