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FROM WIND TO SUPERWIND: THE EVOLUTION OF MASS-LOSS RATES FOR MIRA MODELS

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ABSTRACT

Dynamical atmosphere models were calculated for a large grid of variables with Mira-like properties satisfying the Iben radius-luminosity-mass relationship for evolving AGB stars. Their masses ranged from 0.7 to 2.4 $M_\odot$, and their periods from 150 to 800 days. All were fundamental-mode pulsators, had solar metallicity, and included effects of dust. As a natural consequence of evolutionary changes in stellar parameters, the mass-loss rate increases as an approximately exponential function of time, reaching $-\dot{M} \sim 10^{-5}$–10^{-4} $M_\odot$ yr^{-1}. Further evolution is dominated by the powerful wind, which strips the star's envelope from the core. This "superwind" is a remarkably robust effect. It occurs for all initial stellar masses and all modeling parameters that have been tested. Dust promotes the effect but is not essential for it. Models with very low metallicity also show the effect, but at higher luminosities, which has intriguing implications for the number of supernovae in early low-metallicity populations and for the chemical evolution of galaxies.

Subject headings: stars: evolution — stars: long-period variables — stars: mass loss — stars: winds

1. INTRODUCTION

Rapid and extensive mass loss via outflowing winds is common during late stellar evolution. The consequences can be profound. In particular, mass loss from stars of low to intermediate mass on the asymptotic giant branch (AGB) plays a key role in determining not only the properties of the AGB population itself, but also the distribution of white dwarf masses, the maximum white dwarf progenitor mass (hence the minimum supernova progenitor mass), the number and character of planetary nebulae, the composition of the interstellar medium (by returning to it large amounts of material with enhanced abundances of *s*-process nuclides and much dust), and the chemical evolution of galaxies; indirectly it affects the character of the entire stellar population. Knowledge of what determines a star's mass-loss rate, and of how that rate changes during evolution is thus extremely important.

The empirical mass-loss relation of Reimers (1975) has been widely used in evolutionary calculations. It can be written as

$$\dot{M} = -(4 \times 10^{-13})\eta LR/M \,, \qquad (1)$$

where $\dot{M}$ is in units of $M_\odot$ yr^{-1}, the star's luminosity L, radius R, and mass M are in solar units, and η is an adjustable fitting parameter of order unity. This relationship implies that the rate of increase of gravitational energy for mass removed from the star is a constant fraction ($1.25 \times 10^{-5}\eta$) of the luminosity, but it is not a deduction based on a specific physical mechanism.

The Reimers relation does not give good agreement with observations and evolution theory through the entire AGB phase, however. At best it gives a mass-loss rate that increases too slowly over too long a period of time, and the maximum value it reaches is too small ($\sim 10^{-6}$ $M_\odot$ yr^{-1}). Renzini (1981) discussed these and other difficulties, pointing out that in fact a much stronger wind must develop quite rapidly at a crucial point in evolution, reach a mass-loss rate of 10^{-5} to 10^{-4} $M_\odot$ yr^{-1}, and end the AGB by stripping the envelope from the core. Renzini (1981) used the name "superwind" for this phenomenon. There has been much speculation concerning its nature and cause (e.g., Iben & Renzini 1983; Iben 1987).

This *Letter* presents dynamical modeling results for a large grid of long-period variables with Mira-like properties, showing how the mass-loss rate changes during AGB evolution because of other changes occurring in the star. The effects are dramatic. At first, via nuclear evolution at almost constant total mass, a given star develops larger core mass, luminosity, radius, and pulsation period; the atmosphere becomes more extended, and the mass-loss rate increases as an approximately exponential function of time. As $-M/\dot{M}$ becomes comparable to and then smaller than the nuclear time scale, mass loss becomes the dominant evolutionary process and the star's envelope is rapidly removed. During the final stage of precipitous mass loss a model with solar metallicity resembles an OH/IR star: it is very large and luminous, with a very long period, optically thick circumstellar dust, and $-\dot{M} \sim 10^{-5}$ to 10^{-4} $M_\odot$ yr^{-1}. The final masses that result are in the range expected for the central stars of planetary nebulae (Weidemann 1987). The models thus exhibit the properties and behavior expected for terminal AGB evolution with a superwind.

We wish to emphasize at once that these results are in no way contrived. There are no ad hoc assumptions concerning the existence or character of the superwind. No special processes or mechanisms have been added to the models, and no special choice of modeling parameters has been made for this purpose. The calculated results have been checked for sensitivity to all parameters, with these conclusions: (1) The existence of the "superwind effect" in the models is a very robust result; it occurs for all combinations of parameters that have been tested. (2) The point in evolution (specifically, the luminosity or core mass) at which the effect occurs for a given star is determined mostly by the star's mass and metallicity, together with the evolving radius they imply; it is relatively insensitive to other parameters used in the modeling calculations. Uncertainties in the modeling parameters are unlikely, therefore, to affect the validity of our principal conclusions. We believe the results described here are not artifacts, but are in fact closely related to phenomena in real stars.

2. METHODS

The dynamical calculations were made with the method described by Bowen (1988a, b), which can be summarized as follows. Basic hydrodynamic and thermodynamic equations are written for a model with spherical symmetry and no magnetic effects. Artificial viscosity is included in order to handle shocks. Effects of time-dependent thermal relaxation and of radiation pressure on grains are included. The inner boundary of the model, placed inside the photosphere near the driving region for pulsation, is constrained to move radially as a sinusoidal function of time, simulating the effects of pulsation in the stellar interior. The equations are solved by explicit numerical integration to learn the dynamical structure and behavior of the atmosphere.

The stellar parameters used to characterize the models were the star's mass, M, and its fundamental-mode pulsation period, P_0. The corresponding value of the stellar radius, R (typically a few hundred $R_\odot$), was calculated from the Ostlie & Cox (1986) period-mass-radius relation for Mira variables:

$$\log P_0 = -1.92 - 0.73 \log M + 1.86 \log R . \quad (2)$$

The luminosity, L, was then determined from the Iben (1984) radius-luminosity-mass relation for evolving AGB stars,

$$R = 312(L/10^4)^{0.68}(M/1.175)^{-0.315}(Z/0.001)^{0.088}(l/H_p)^{-0.52} , \quad (3)$$

and the effective temperature, $T_{\rm eff}$, was calculated using $L = R^2(T_{\rm eff}/5770)^4$. In these equations P_0 is in days; M, R, and L are in solar units; Z is the mass abundance of heavy elements; (l/H_p) is the ratio of mixing length to pressure scale height; $S = 0$ for $M \leq 1.175$, and $S = 1$ otherwise. Except where otherwise stated, all models described in this *Letter* had parameters based on the values $(l/H_p) = 0.90$ and $Z = 0.020$.

All models were driven at their fundamental period. There is increasing consensus, based on observations, that Mira variables normally are fundamental-mode pulsators (Willson 1982; Wood 1990). Moreover Bowen (1990) has pointed out theoretical reasons for suspecting that this *must* be so: the density gradient causes reflection in the vicinity of the photosphere for waves with periods longer than a critical value (Stein & Leibacher 1974); for Mira variables the periods are such that acoustic power transmission into the atmosphere gives strong damping of overtone pulsation, but little damping of the fundamental mode except at large amplitude.

The velocity amplitude of the inner boundary, which affects the mass-loss rate, was adjusted so that the peak mechanical power input to the model at its inner boundary was equal to the star's luminosity, L. The rationale for this follows. Dynamic interior models have very large growth rates for small-amplitude oscillations, and it has not been clear what limits the pulsation amplitude in stars (Ostlie & Cox 1986; Wood 1990). In our models the average mechanical power required to drive large-amplitude pulsation approaches L. This must surely be a firm upper limit, but we suggest that the amplitude normally has a smaller value determined by the *peak* power the driving region is able to deliver during the pulsation cycle. (The driving zone expands and contracts, doing positive and negative work at a varying rate. At any given amplitude the peak power is larger than the average. Increased amplitude requires greater peak power.) We estimate the greatest possible peak power to be of the order of L, and pending further study we have used that value to determine the pulsation amplitude. This has given a consistent pattern of behavior for the models over a wide range of stellar parameters. (The inner boundary velocity amplitude was generally in the range 2–5 km s^{-1}; the maximum velocity amplitude of the resulting shocks was 26–36 km s^{-1}.) Our conclusions do not depend critically on the value assumed for the peak driving power.

Dust was included in most models. The cross-section of dust for radiation pressure was assumed to be a function of the local equilibrium temperature for grains and was adjusted to give $\Gamma \equiv (a_{\rm rad}/g) = 1.00$ in the coolest regions. That choice was based on modeling results which have shown that there is little effect if $\Gamma < 0.5$ but rapid outward acceleration if $\Gamma > 1.0$, together with the conjecture that when the acceleration becomes large the grains will be swept rapidly out of the region where conditions permit further growth. Grain growth would then be self-limiting at $\Gamma \sim 1$. The nominal grain condensation temperature was ordinarily set at 1350 K. The function used to specify the radiation pressure cross section then gave $\Gamma = 0.50$ (a very weak effect) at 1350 K, increasing to $\Gamma = 0.97$ (a strong effect) at 1000 K. In the light of recent papers by Danchi et al. (1990) and Bester et al. (1991), these temperatures seem reasonable and appropriate.

3. RESULTS

Figure 1 shows the stellar parameters for the main grid, which consisted of 105 fundamental-mode models calculated as described above. The results of mass-loss calculations for those models are presented in Figure 2.

To show the relationship of mass loss and evolution we have used the Paczynski (1970) relation between the star's hydrogen-depleted core mass, M_c, and its luminosity,

$$L = 59{,}250(M_c - 0.522) , \quad (4)$$

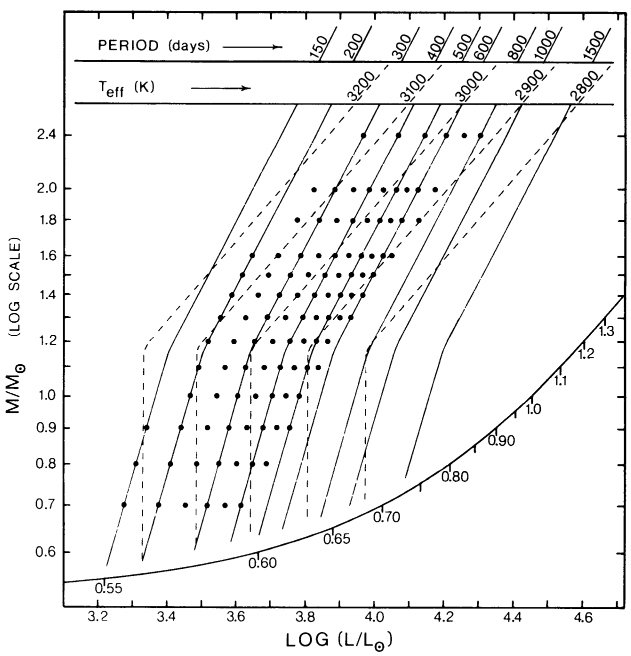

FIG. 1.—Stellar parameters for the main grid of models. Positions of the models are indicated by dots. All are fundamental mode and include radiation pressure on dust. The parameters were calculated from eqs. (2) and (3), with $Z = 0.020$ and $(l/H_p) = 0.90$. Solid lines are lines of constant period; dashed lines are lines of constant $T_{\rm eff}$. The lowest curve is the Paczynski (1970) luminosity-core mass relationship, given by eq. (4).

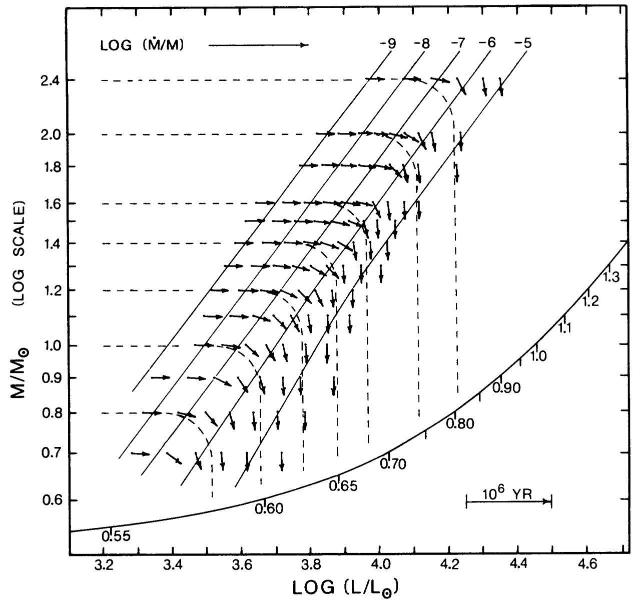

FIG. 2.—Mass loss and evolution for the models of Fig. 1. The small arrow at the position of each model shows the direction of its evolution. (All arrows are of equal length.) The solid lines show the approximate loci of models for which $(-\dot{M}/M) = 10^{-9}$, 10^{-8}, 10^{-7}, 10^{-6}, and 10^{-5} yr^{-1}. The dashed lines show approximate evolutionary tracks for several representative masses.

with both quantities in solar units. A curve showing this relationship is included in both figures. Since equation (4) gives $dL/dt \propto dM_c/dt$, and since $L \propto$ the hydrogen fusion rate $\propto$ dM_c/dt also, the rate of change of the star's abscissa in this plot is $d \log L/dt = 0.434(dL/dt)/L =$ constant; its value is 0.245 Myr^{-1}, which is indicated by the arrow at the lower right in Figure 2. Thus nuclear evolution causes a star to move horizontally to the right at that same rate everywhere in the diagram. In effect, the horizontal axis is also a time axis.

The direction of evolution for each model is shown in Figure 2 by an arrow parallel to a vector whose horizontal component is $d \log L/dt = 0.245$ Myr^{-1}, and whose vertical component is $d \log M/dt = 0.434\dot{M}/M$, as determined from modeling calculations. The evolutionary track for a given star is a continuous line whose slope at every point is that of such an arrow. Approximate evolutionary tracks have been drawn for several initial masses, using slopes interpolated between grid points. In each case there is a rapid transition from slow early nuclear evolution on an almost horizontal track to a final plunge down an almost vertical track, with mass loss via the "superwind." The mass of the remnant object (planetary nebula nucleus or white dwarf) is indicated by the intersection of the evolutionary track with the core mass line.

Lines showing the approximate loci of models for which $-\dot{M}/M = 10^{-9}$, 10^{-8}, 10^{-7}, 10^{-6}, and 10^{-5} yr^{-1} are also drawn in Figure 2. An evolutionary track has a slope of -1.00 when $-\dot{M}/M = 5.65 \times 10^{-7}$ yr^{-1}, so these lines of constant $\dot{M}/M$ correspond to slopes from -0.0018 to -18. The approximately uniform spacing of these lines in the horizontal direction (the evolutionary time axis) indicates that $-\dot{M}$ increases approximately exponentially with time.

What is the cause of the rapidly developing, massive outflow that we have called the superwind effect? Since $-\dot{M} = 4\pi r^2 v\rho$, we ask first which of these factors gives the increase in $\dot{M}$. The modeling calculations show conclusively that it is not the wind speed v (which in fact decreases slightly), but an increase in the density, ρ, at any given radius, r, in the wind region that gives the increasing mass-loss rate.

Why does ρ increase so much in the wind region during evolution? Plots of ρ versus r for model calculations like these always show the same character. Inside the radius at which shocks are formed the density is an exponentially decreasing function of the radius which is almost the same as that for a comparable hydrostatic model; outside that is a region with strong shocks and rapid acceleration; and beyond that is the wind region, where the gas has almost constant speed and a slowly decreasing density proportional to r^{-2} (Bowen 1988b, 1990). The density in the wind region is determined mostly by how far the density falls in the innermost region. The density scale height there, $H \propto T/g \propto R^2T/M$, changes substantially during evolution because R and M change by sizable factors; and since H appears in the argument of an exponential function describing ρ, both the density in the wind region and $\dot{M}$ change very rapidly with H. Thus, in Figure 2, $\dot{M}$ increases by several orders of magnitude during the early evolution at almost constant mass because R is increasing, so H in the inner region and ρ in the wind region are also increasing. When $\dot{M}$ becomes large and M decreases significantly, H and ρ increase further, and the mass loss becomes still more rapid. Growth of the wind is inexorable.

We have tested the modeling results for sensitivity to each parameter used in the calculations by systematically varying one parameter at a time in an otherwise standard model. We know of no plausible conditions for which the models fail to give the superwind effect. Even rather large changes in most parameters change the point in evolution at which the effect occurs by only small amounts. To make this quantitative, take the luminosity, L_{sw}, at which a star of given mass reaches a specified value of $\dot{M}/M$ (say 10^{-6}) as a measure of when the superwind effect occurs. For most parameter changes, $|\Delta \log L_{sw}| \le 0.04$ (i.e., 0.1 mag). A complete report on those results will be included in a longer paper to be submitted. Here we shall describe only the effects of dust and metallicity, which are of special interest.

What is the role of dust in the mass-loss process? How essential is it? The driving mechanism for a stellar wind must supply both energy and momentum. For Mira variables the power requirement is trivial, usually less than $10^{-4}L$, but the momentum requirement, $\dot{M}v_{wind}$, is severe ($\sim L/c$ for a very strong wind). One expects dust to aid mass loss by receiving momentum from the star's radiation field and transferring it to the gas by collisions; the modeling calculations show that it can do so. Test series of models with the maximum Γ increasing from 0.0 to 2.0 show increasing $\dot{M}$ because v_{wind} increases. (The wind density is determined mostly by processes in the dust-free inner region, not by Γ.) Changes in the assumed grain condensation temperature have similar effects because they change the total dust cross section for radiation pressure. And in Figure 2 all models with rapid mass loss, say $-\dot{M} > 2 \times 10^{-6}$ $M_\odot$ yr^{-1}, have optically thick circumstellar dust. Any change in the model that changes the amount of dust changes $\dot{M}$ correspondingly. An increase in dust cross section does not merely accompany increasing mass loss; it causes it.

Substantial mass loss can occur with little or no dust present, however. For example, comparing otherwise identical 1.0 $M_\odot$, 300 to 400 day models with and without dust, a model without dust has $\dot{M} \sim 0.1$ and $v_{wind} \sim 0.2$ times the corresponding values for the dusty model, so its wind carries away momentum at only $\sim 2\%$ of the rate. What drives this wind? There is heating by shocks in both cases, but rapid expansion in the low-density, effectively adiabatic outer atmosphere of the dusty model keeps the gas kinetic temperature there low; in the much more slowly expanding no-dust model there is an extended region of elevated temperature in the outer atmosphere (Bowen 1988a, b), and the resulting pressure gradient drives a slow wind. (This does not occur when the model is constrained to have isothermal shocks.) Onset of a superwind in the evolution of a model without dust is delayed until the star reaches a larger radius, with a larger scale height and greater wind density. The resulting shift in luminosity is $\Delta \log L_{sw} \approx +0.12$.

The mass-loss rate of a star with low metallicity is affected in two ways: (*a*) Less dust can be formed because of lower abundance of the elements needed for grain formation. We estimate that for $Z < 0.1 Z_\odot$ there will usually be too little dust to produce significant dynamical effects. (*b*) For given M and L, equation (2) gives smaller R, so H is reduced; ρ_{wind} and $\dot{M}$ are much smaller. The superwind effect is thus displaced to substantially larger luminosities. A complete grid has not yet been calculated, but results for a modest number of low-metallicity models indicate that for $Z < 0.1 Z_\odot$ these two effects give $\Delta \log L_{sw} \approx 0.12$–$0.13 \log (Z/Z_\odot)$.

4. DISCUSSION

These modeling results would be interesting in any case simply because they give increased understanding of processes occurring in stars, but they are especially important because of their implications for stellar evolution. We are studying the characteristics of evolving AGB populations with mass-loss rates like those found in the modeling calculations: distributions of their observable properties, interrelationships of those properties, their changes with population age, and the ultimate fates of the stars. Comments follow on some further things related to mass loss and evolution that seem particularly interesting.

Intermittent helium shell flashes are expected to cause sizable changes in the star's luminosity and radius (Boothroyd & Sackmann 1988), and these should cause large variations in the mass-loss rate. Preliminary estimates suggest that the integrated effect is small compared to the total mass loss, and it has not been included in our modeling. There should be substantial effects, however, on the structure of the circumstellar region out to 10^{17}–10^{18} cm, including variations in the density, velocity, temperature, and composition, with formation of apparently detached shells (Olofsson et al. 1990). Modeling of helium shell flash effects should soon be feasible.

The relationship of initial and final masses for AGB evolution can be inferred from our modeling calculations, as illustrated by the evolutionary tracks sketched in Figure 2. From the distribution of initial AGB masses one should then be able to deduce the distribution of final masses, a result of much interest in studies of planetary nebulae and white dwarfs. This cannot yet be done very accurately, but it seems clear that the predicted final mass distribution will have a rather narrow peak in the vicinity of 0.6 $M_\odot$.

What is the largest initial mass for which the stellar envelope is lost before the core mass reaches 1.4 $M_\odot$? Incautious extrapolation of the results in Figure 2 suggests a value of at least 5–6 $M_\odot$, but probably less than 8 $M_\odot$. We have not yet made systematic calculations for models of such high mass, however, and no firm conclusion should be drawn concerning the maximum white dwarf progenitor mass. Effects that appear to become important in more massive stars include (1) radiation pressure on molecules in the atmosphere, and (2) reduced atmospheric damping of the overtone mode, which may permit pulsation in the overtone as well as the fundamental mode and lead to complex double-mode behavior. Work on these things is proceeding.

For models of very low metallicity the shift of the superwind effect to higher luminosity is large enough to have major consequences. All have less mass loss during AGB evolution, and only relatively low-mass stars would escape becoming supernovae. For example, at $Z = 0.001 Z_\odot$ a model of initial mass 2.0 $M_\odot$ was found to have rapid enough mass loss to lose its envelope before reaching $M_c = 1.4 M_\odot$, but only barely so; one whose initial mass was 2.4 $M_\odot$ did not. Compared to a stellar population of solar metallicity, a population of very low metallicity should have more very luminous AGB stars, more supernovae, and more high-mass white dwarfs. The early chemical evolution of a galaxy should be affected significantly by the increased number of supernovae.

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