MASS-LOSING PECULIAR RED GIANTS: THE COMPARISON BETWEEN THEORY AND OBSERVATIONS

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ABSTRACT

The mass loss from evolved red giants is considered. It seems that red giants on the Asymptotic Giant Branch (AGB) are losing between 3 and 6 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1} in the solar neighborhood. If all the main sequence stars between 1 and 5 $M_{\odot}$ ultimately evolve into white dwarfs with masses of 0.7 $M_{\odot}$, the predicted mass loss rate in the solar neighborhood from these stars is 8 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}. Although there are still uncertainties, it appears that there is no strong disagreement between theory and observation. However, it could also be that we have not yet identified much of the source of the mass-loss from pre-white dwarf stars.

Approximately half the mass loss from AGB stars is from carbon-rich objects in agreement with previous estimates and the finding that about half of all planetary nebulae are carbon-rich. We conclude that an appreciable fraction, perhaps half, of all intemediate-mass main sequence stars spend ≥ 3 10^{4} years as carbon-rich stars.

1. INTRODUCTION

In the standard picture for their evolution, intermediate-mass stars that initially have between 1 and 5 $M_{\odot}$ (or perhaps as much as 8 $M_{\odot}$) on the main sequence eventually become white dwarfs with ~0.7 $M_{\odot}$ (Iben and Renzini 1983). It is also usually hypothesized that most of this mass loss occurs during the Asymptotic Giant Branch (AGB) phase of the star's evolution. Here, we critically review this hypothesis by using current data on mass loss from red giant stars.

In the standard scenario, just before a star becomes a white dwarf, it is the central star of a planetary nebula (see for example, Osterbrock 1974). Furthermore, it has long been thought that just before a star becomes a planetary nebula, it is a red giant undergoing extensive mass loss (Abell and Goldreich 1966; Kwok 1982). The usual hypothesis is that during the red giant phase, the star loses a large fraction, perhaps more than half, of its initial mass.

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With improvements in millimeter and infrared technology, considerable progess has been made in understanding the mass-loss phenomena from red giants during the past 20 years (Zuckerman 1980; Olofsson 1985). Because AGB stars are intrinsically cool and because they have large amounts of circumstellar dust, they are primarily infrared sources; they are not very prominent, for example, in the Yale Bright Star Catalog (Hoffleit and Jaschek 1982). It is possible, however, to use the Two Micron Sky Survey (Neugebauer and Leighton 1969) and the IRAS data base to identify and study the local AGB stars. This has now been done systematically for carbon stars (Claussen et al. 1987), S Stars (Jura 1988), oxygen-rich stars (Kleinmann et al. 1988) and those stars which are losing large amounts of mass (>10^{-6} $M_\odot$ yr^{-1}, Jura and Kleinmann 1988). About 1/3 of all the stars brighter than K = 3.0 magnitude in the sky are AGB stars. There also have been extensive surveys of the molecular emission from mass-losing AGB stars. The most prominently studied molecule is CO (see Knapp and Morris 1985, Zuckerman and Dyck 1986a,b, 1988, Zuckerman, Dyck and Claussen 1988, Olofsson, Eriksson and Gustafsson 1987, 1988), but there have been extensive surveys of other species such as HCN (Lucas, Guilloteau and Omont 1988) and OH (Engels 1979). With this extensive amount of data, it is now possible to make a much more quantitative test between the standard model for stellar evolution and the observed mass-losing AGB stars.

2. DISTANCES AND LUMINOSITIES

In order to determine the physical properties of these stars, it is necessary to infer their distances and luminosities. Unfortunately, there is no reliable way to determine the distances to AGB stars. In the Magellanic Clouds, carbon stars display a small dispersion in their apparent K-magnitudes (Frogel, Persson and Cohen 1980). Although the distances to the Clouds are uncertain (see, for example, Stothers 1988), the typical inferred luminosity is about 10^4 $L_\odot$, in agreement with theoretical predictions for AGB stars with core masses of 0.6 $M_\odot$ (Iben and Renzini 1983). However, at least for the oxygen-rich AGB stars there is probably a significant range in their luminosities. Jones, Hyland and Gatley (1983) use galactic rotation and the observed fluxes of OH/IR stars to infer that the luminosity of the star apparently increases with the outflow velocity of the gas (see also Jura 1984). Also, according to Glass and Lloyd-Evans (1980) there is a significant period-K magnitude relationship for oxygen-rich Miras in the Magellanic clouds. Therefore, the carbon stars may have an appreciably smaller variation in their intrinsic luminosities than do the oxygen-rich stars. However, Zuckerman and Dyck (1988) find that carbon stars with higher outflow velocities of their circumstellar gas lie closer to the galactic plane than do carbon stars with lower gas outflow velocities, and this suggests that the high-outflow velocity stars have higher luminosity. Such an effect is in agreement with our theoretical understanding of the mass-loss phenomena (Jura 1984). Also, on the basis of galactic rotation, Nguyen-Q-Rieu et al. (1987) argue that some carbon stars have luminosities appreciably greater than 10^4 $L_\odot$.

Even though the distances to AGB stars are somewhat uncertain, we can still hope to make reasonably accurate estimates of the integrated mass loss rate. If we assume that the local Milky Way is a very flat disk, and if our surveys penetrate far enough so that we detect essentially all the stars in an imaginary cylinder whose axis is perpendicular to the galactic disk, then the inferred mass-loss rate is not sensitive to the assumed luminosity of the mass-losing stars (Knapp and Morris 1985). This is because the inferred mass-loss rate per star varies as the distance to the star squared while the inferred surface density of stars varies inversely as the inferred distance squared. The product of the two quantities which gives the integrated mass-loss rate: the mass-loss per star and the number of stars per unit area is then independent of the inferred luminosity.

In conclusion, with an inferred luminosity of 10^4 $L_\odot$ and an insensitivity to the exact value of this inferred luminosity, we can hope to make a reasonable estimate of the integrated mass-loss rate from evolved stars in the solar neighborhood.

3. SURFACE DENSITIES OF AGB STARS IN THE LOCAL GALACTIC DISK

Because there is a probably smaller dispersion in their absolute luminosities, and because this conference is devoted to "peculiar" red giants, in this section we focus on the carbon stars and S-type stars. We assume a number density distribution of carbon stars, ρ, such that

$$\rho = \rho_0 \exp(-z/H)$$

where ρ_0 is the density of stars in the galactic plane, z is measured vertical to the plane and H is the exponential scale height of the stars. We may write for the surface density, σ, of stars in the solar neighborhood that:

$$\sigma = 2 \rho_0 H$$

Claussen et al. (1987) identified 81 carbon stars in the zone surveyed by the Two Micron Sky Survey within 1 kpc of the sun and they inferred that ρ_0 = 100 kpc^{-3}, H = 200 pc and σ_0 = 40 kpc^{-2}. If we include the 11 carbon stars listed by Jura and Kleinmann (1988) that lie within 1 kpc of the sun but are not within the Two Micron Sky Survey, the inferred volume and surface density and exponential scale height are not effectively changed. As discussed below, the inferred total mass-loss rate is substantially increased because the total mass return rate is dominated by the relatively rare stars which are faint at 2 μm because they are so obscured by their own circumstellar dust.

Jura, Joyce and Kleinmann (1988) have found that in the galactic anticenter direction, the surface density of high luminosity carbon stars does not change on a scale of ~ 4 kpc, although the total surface density of all stars almost certainly does decrease on this scale. This increase in the relative fraction of stars that are carbon red giants is

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probably a result of the lower average metallicity in the anticenter direction.

Jura (1988) has used the survey of Wing and Yorka (1988) to find that there are about 1/3 as many S stars as there are carbon stars in the neighborhood of the Sun.

Finally, Kleinmann et al. (1988) discuss the numbers of oxygen-rich AGB stars in the solar neighborhood. There are about an order of magnitude more oxygen-rich than carbon-rich mass-losing AGB stars in the solar neighborhood. However, when one restricts the analysis to only those stars losing large amounts of mass ($>10^{-6}$ $M_\odot$ yr^{-1}), then the numbers of oxygen-rich and carbon-rich stars are about equal (Jura and Kleinmann 1988).

4. MASS LOSS RATES

For most AGB stars, it is not possible to detect the molecular hydrogen which is thought to be the form for most of the mass that is lost (Glassgold and Huggins 1983). Therefore, it is necessary to use indirect means to measure the mass-loss rate. Currently, the two most common procedures are to use the intensity of the CO radio emission (Morris 1985, Knapp and Morris 1985), and the far infrared flux that is produced by the circumstellar shell (Sopka et al. 1985, Jura 1986a). There is reasonably good agreement between the two mass-loss rates as can be seen in Figure 1 where the mass-loss rates derived from the CO radio emission measured by Olofsson et al. (1987, 1988) divided by a factor of 2 are compared with the mass-loss rates derived by the formalism given in Jura (1986a). Since we do not know the ratio of [CO]/[H_2] or [dust]/[gas] in the outflows, and because there are uncertainties in the models, we find better agreement between the infrared and CO derived mass-loss rates if we apply a factor of 2 correction to one or the other. This factor of 2 should be taken as a measure of the systematic uncertainty associated with deriving the net mass-loss rates from AGB stars.

As reviewed by Jura (1986b), studies of the circumstellar envelopes around AGB stars are consistent with the view that the mass-loss process from these objects is a two step process. First, pulsations levitate the matter to a zone above the photosphere. Second, dust grains form and then radiation pressure expels the matter into the interstellar medium.

5. THE INTEGRATED MASS LOSS RATE FROM AGB STARS

Miller and Scalo (1979) have estimated the space densities, exponential scale heights and theoretical lifetimes for the main sequence stars in the neighborhood of the sun. If we assume that all the stars between 1 and 5 $M_\odot$ ultimately become white dwarfs of 0.7 $M_\odot$ (Liebert 1980), then we predict that the mass-loss rate from these stars is 8 10^{-4} $M_\odot$ kpc^{-2} yr^{-1} (see, for example, Jura 1987).

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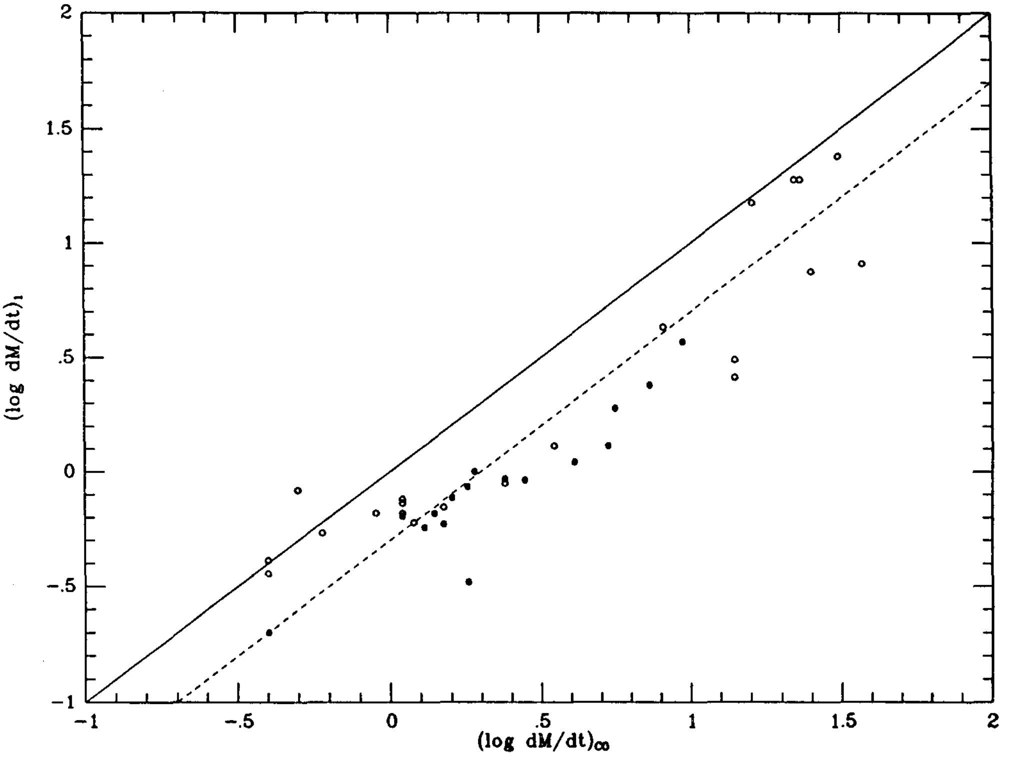

Fig. 1. Plot of the mass-loss rate derived from CO measurements, dM/dt_{CO}, vs. mass-loss rates derived from 60 μm fluxes and the formalism described by Jura (1986a). The units are 10^{-7} $M_{\odot}$ yr^{-1}. The filled circles are from CO data acquired at Onsala (Olofsson et al. 1987) while the open circles are from data acquired at SEST (Olofsson et al. 1988). The solid line is the fit if the two mass-loss rates equal each other; the dashed line is the fit if all the CO-inferred loss rates are reduced by a factor of 2. This figure is reproduced from Jura and Kleinmann (1988).

We now compare this theoretical rate with that inferred from the mass losing AGB stars. First, because the scale height of the carbon-rich AGB stars is about 200 pc, this implies that the progenitors of these objects usually have main sequence masses of 1.5 $M_{\odot}$, in agreement with the compilation of Miller and Scalo (1979).

We can use the infrared catalogs to identify all the mass-losing AGB stars in the solar neighborhood and then infer their mass-loss rates, to infer the total return rate by these stars into the interstellar medium. In Figure 2, we display a histogram of the mass loss rate for all the carbon stars in the neighborhood of the sun from the results from Claussen et al. (1987) and Jura and Kleinmann (1988). The "typical" carbon star is losing ~2 10^{-7} $M_{\odot}$ yr^{-1} (Claussen et al. 1987). However, a few carbon stars are losing more than 10^{-5} $M_{\odot}$ yr^{-1}. These stars, which are not very luminous at 2 μm because of circumstellar extinction, still amount to more than 20% of all the carbon stars, and therefore they dominate the return of matter into the interstellar medium by carbon stars. From the observed 60 μm flux and the procedures outlined by Jura (1986), we find that carbon stars, by themselves, are returning 1.6 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1} in the solar neighborhood. However, as discussed above, the calibration of the mass-loss rates by Olofsson et al. (1987, 1988) indicate that these mass-loss rates may be too low by a factor of 2. In this case, the return of mass into the interstellar medium by carbon stars is 3 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}.

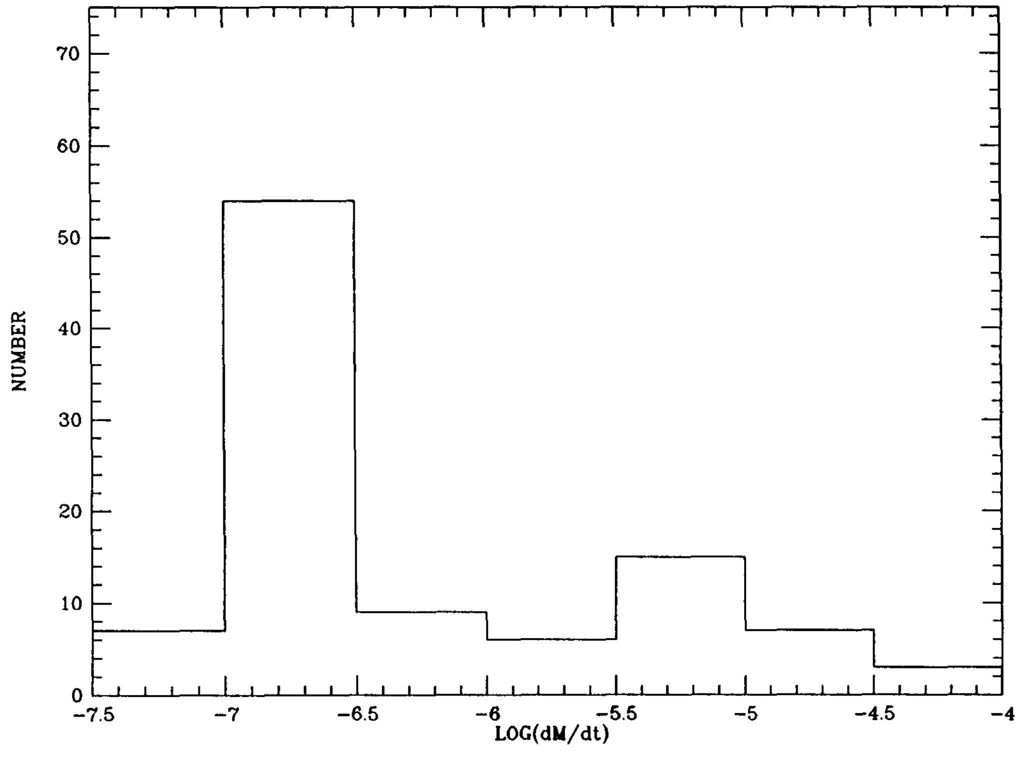

Fig. 2. Histogram of the mass-loss rates for all the carbon stars in the declination range -33°<δ<82° within 1 kpc from the Sun. The numbers are taken from Claussen et al. (1987) and Jura and Kleinmann (1988).

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Another way to derive this integrated mass-loss rate is to use the surface density of very dusty carbon-rich stars of 12 kpc^{-2} (Jura and Kleinmann 1988) and an assumed mass-loss rate per star of between 1 and 2 10^{-5} $M_{\odot}$ yr^{-1} as expected if L = 10^4 $L_{\odot}$ and if the mass-loss rate is controlled by radiation pressure on the grains. The product of the surface density of stars and the mass-loss rate per star indicates that the carbon-rich objects could contribute between 1.2 and 2.4 $M_{\odot}$ 10^{-4} kpc^{-2} yr^{-1}, in agreement with the result derived above from summing the contribution from all the known carbon-rich stars.

Jura and Kleinmann (1988) have shown that very dusty oxygen-rich stars return about as much matter into the interstellar medium as do the very dusty carbon-rich stars. It also appears that the mass return rate by oxygen-rich stars into the interstellar medium is dominated by the relatively few objects that are losing large amounts of mass (Kleinmann et al. 1988). Therefore, the total return rate by both oxygen-rich and carbon-rich stars is about twice the total given above for the contribution simply from carbon-rich stars. Depending upon the calibration of the mass-loss rate from the infrared flux, this means that mass-losing AGB stars are returning between 3 and 6 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}. Given the uncertainties, this result is in reasonable agreement with the predicted value 8 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}.

A number of years ago, Zuckerman et al. (1976) argued that carbon-rich stars accounted for about half of all pre-planetary nebulae. More recently, Zuckerman and Aller (1986) have found that more than half of all planetary nebulae are carbon-rich. It appears that there is now strong evidence on the basis of this analysis of the mass losing stars that this picture is essentially correct: at least half of all main sequence stars enter into the carbon-star phase of evolution. Since there are about 12 carbon-rich high mass-loss rate carbon stars kpc^{-2} in the galactic disk in the neighborhood of the sun and since the death rate of all the main sequence stars between 1 and 5 $M_{\odot}$ in the solar neighborhood is 8 10^{-4} kpc^{-2} yr^{-1}, this phase of stellar evolution probably lasts for $\geq$ 3 10^4 years (Jura and Kleinmann 1988). During this carbon-star phase which lasts 3 10^4 years, a 1.2 $M_{\odot}$ star loses between 1 and 2 10^{-5} $M_{\odot}$ yr^{-1} to shrink to a white dwarf of ~0.7 $M_{\odot}$. The data are therefore consistent with the standard model for the evolution of intermediate mass main sequence stars to white dwarfs.

6. CONCLUSIONS

1. We find that, given the uncertainties in the calibrations of the mass loss rates, there is reasonable agreement between the theoretical mass loss rate of 8 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1} for main sequence stars between 1 and 5 $M_{\odot}$ and the value inferred from the study of mass-losing red giants of 3-6 10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}.

2. It appears that about half of the mass that is lost is from carbon-rich stars. Therefore, roughly half of all intermediate-mass main sequence stars enter the carbon-rich phase for a duration of $\geq$3 10^4

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years. We conclude that "peculiar" red giants are, in fact, a common though short-lived phase of stellar evolution.

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