Characterizing Mass Loss in Asymptotic Giant Branch Stars

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Abstract

Asymptotic Giant Branch (AGB) stars have long been of interest to astronomers. These stars are in a crucial stage of stellar evolution, losing their mass and transitioning into planetary nebulae. Characterizing the long-term evolution of mass loss through a mass-loss formula in these stars has been elusive. To find a mass-loss formula, we analyzed a set of AGB stars in the Large Magellanic Cloud. From models, we expect that a reasonable mass-loss formula should create a sharp turn in luminosity-mass space. We developed a method to determine a mass-loss formula by analyzing the distribution of stars in the pulsation period-luminosity plane, working around the problems present with typical fitting methods. The dimensions of the strip are used to determine a power law formula while minimizing the difference between predicted and observed mass-loss rates. Through this, we found four mass-loss formulas for four different subsets of the AGB population. These formulas reproduce the sharp turn we expect from observations of AGB populations and from theoretical models, putting formulas from theory and observation into agreement.

As a next step, we are generating grids of atmospheric models of AGB stars to compare against the stars seen in the Large Magellanic Cloud. We will be examining how models with typical parameters compare, how they compare when these parameters are pushed to their plausible physical limits, and investigating what details and physical processes might need to be accounted for to make these grids fit stars observed in the LMC.

Relation of Observable Stellar Parameters to Mass-loss Rate of AGB Stars in the LMC [4]

Data Set and Determining $\dot{M}$

The Riebel data set [5, 6] is a mix of semi-regular variable (SRV), AGB, and red supergiant (RSG) stars, further categorized by composition (oxygen-rich M and carbon-rich C stars) and pulsation mode (fundamental 0 and first-overtone 1). The types of stars can be distinguished with a magnitude vs. period diagram (right).
The data set does not include any direct measurements of the total mass-loss rate, but does include calculations of the dust mass-loss rate from the Grid of RSG and AGB ModelS (GRAMS). From this, we calculated the total mass-loss rate using a dust-to-gas ratio formula and assuming a metallicity of $Z = 0.003$.

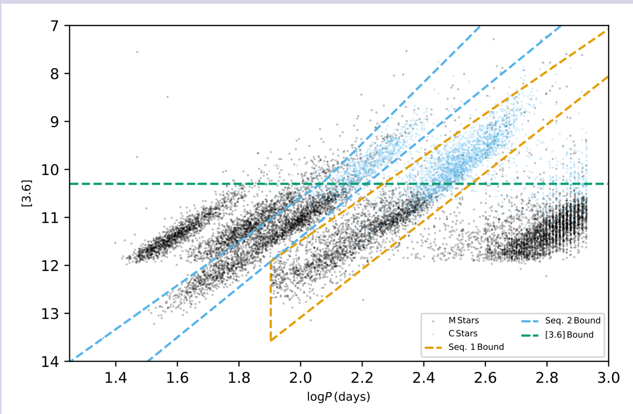


Figure: Seq. 1 corresponds to the fundamental mode and seq. 2 to the first-overtone mode. We have also excluded M stars above the depicted magnitude, as they are super-AGB or RSG stars, and outside the scope of this study.

The Period–Luminosity Strip

It is readily evident that AGB stars form a strip in period-luminosity space. Using the dimensions of this strip, we can determine the exponents of a power law mass-loss rate formula ($\log \dot{M} = \log A_{\dot{M}LP} + B_{\dot{M}LP} \log L + C_{\dot{M}LP} \log P$) associated with a combination of spectral type and pulsation mode. The scaling coefficient $A_{\dot{M}LP}$ can then be calibrated using the mass-loss rates of the measured AGB stars. Using period-mass-radius and radius-mass-luminosity relations [7], these results can be transformed into mass-luminosity space (where the mass loss formula is $\log \dot{M} = \log A_{\dot{M}LM} + B_{\dot{M}LM} \log L + C_{\dot{M}LM} \log M$). The results of this method show significantly better agreement between these mass-luminosity exponents and models than other methods. The results also suggest that the observed AGB stars are in a critical mass-loss phase.

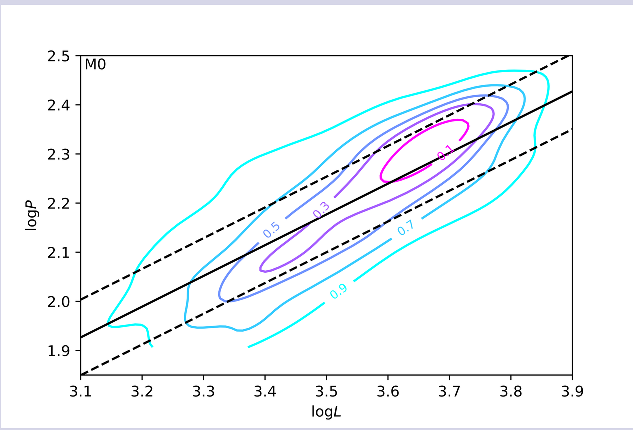


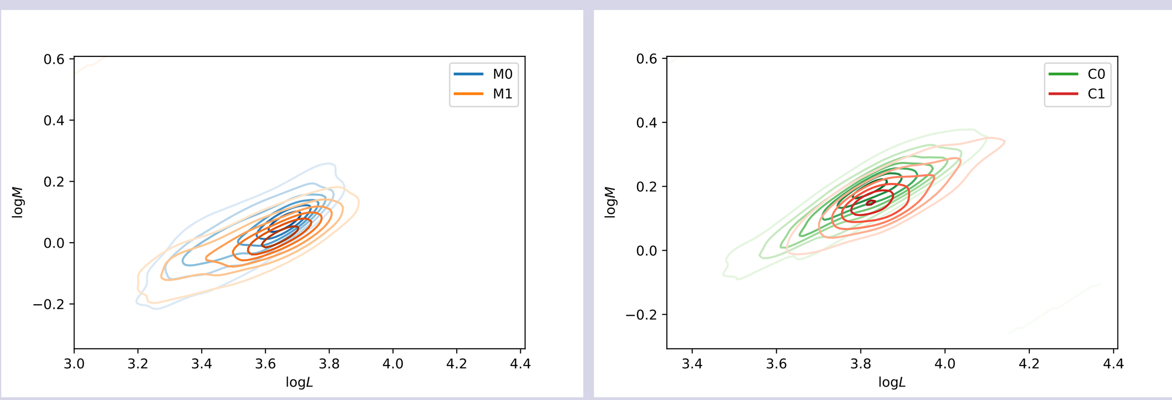
Figure: PL Strip for the M0 AGB stars. The solid black lines are the line of best-fit to the data, dashed lines define the parallelogram that yields the best mass-loss formula. Contours show the fraction of stars within, centered on the peak density.

Subset	Count	$A_{\dot{M}LP}$	$B_{\dot{M}LP}$	$C_{\dot{M}LP}$	$A_{\dot{M}LM}$	$B_{\dot{M}LM}$	$C_{\dot{M}LM}$
M0	1979	-6.63	-6.67	10.7	-35.2	8.24	-13.7
M1	2162	-0.26	-13.9	22.2	-42.8	10.2	-20.5
C0 & C0x	1995	-14.7	-3.59	8.77	-41.0	9.62	-13.9
C1	781	-10.1	-3.94	8.49	-27.8	5.89	-9.44

Results

The clearest result from this work is a resolution to the discrepancy between empirically-determined mass-loss formulas and formulas determined through modelling. Using standard fitting methods is ineffective because of the large amount of scatter in mass loss and luminosity measurements, resulting in regression dilution. Exponents determined directly from the dimensions of the strip are in far better agreement with the mass loss evolution suggested by models of AGB stars and observed AGB populations in stellar clusters.

By tracking models of stars through $\log L$, $\log M$ space we can see that stars evolve at nearly constant mass, pass through a transition in the death zone, and leave evolving at nearly constant luminosity [2, 8]. This insight from modelling in addition to our confirmation that we do see exponents large enough to produce this behavior shows that a large number, if not most, of the stars are passing through the death zone and thus are undergoing terminal mass loss. This suggests that it is not necessary for AGB stars to switch from first-overtone mode pulsations to fundamental mode pulsations to finish the mass-loss process.



(a) (b)

Figure: LM Strips for the four subsets of AGB stars. Contours show the percentage of stars within, centered on 90%, working outwards in increments of 20%.

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Parameter Study of AGB Atmospheric Model Grids

The Atmospheric Pulsation Code

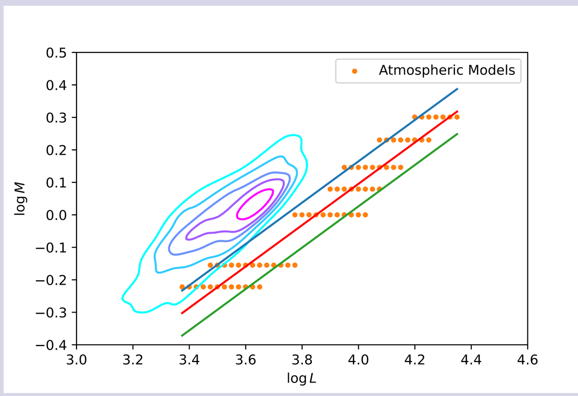
For this work, we are simulating numerous grids of AGB atmospheres. To do so, we are using the code initially developed by George Bowen [1]. The code uses an adaptive 1D Lagrangian grid to track layers of stellar material, as a piston at the bottom of the grid drives material outward and facilitates the development of the dust driven stellar wind.

This code uses several parameters to characterize the processes in the stellar atmosphere. Some of these parameters, such as luminosity, mass, pulsation period, and stellar radius characterize individual stars in the grid. We are interested in the effect of changing the parameters that characterize the physical processes in the star, such as the amplitude of the piston u, the opacity of the dust κ_D, the dust condensation temperature $T_{\text{con.}}$, and the metallicity of the stars Z.

In contrast to more recent 1D codes such as DARWIN [3], this code is heavily parameterized and makes significant approximations to the physics occurring in the star. While making the code inaccurate for detailed predictions for a given star, we can quickly generate numerous grids to capture the effects of modifying the processes in the atmosphere. To obtain a period-luminosity strip, we will not assume the locations of the stars. Instead, the models are set to terminate at a given mass once they reach $\dot{M} = 2 \times 10^{-5}\ \mathrm{M_\odot/yr}$, and a lower bound on the mass-loss rates is set using the range observed in the Riebel et al. data set [5, 6].

Reference Model

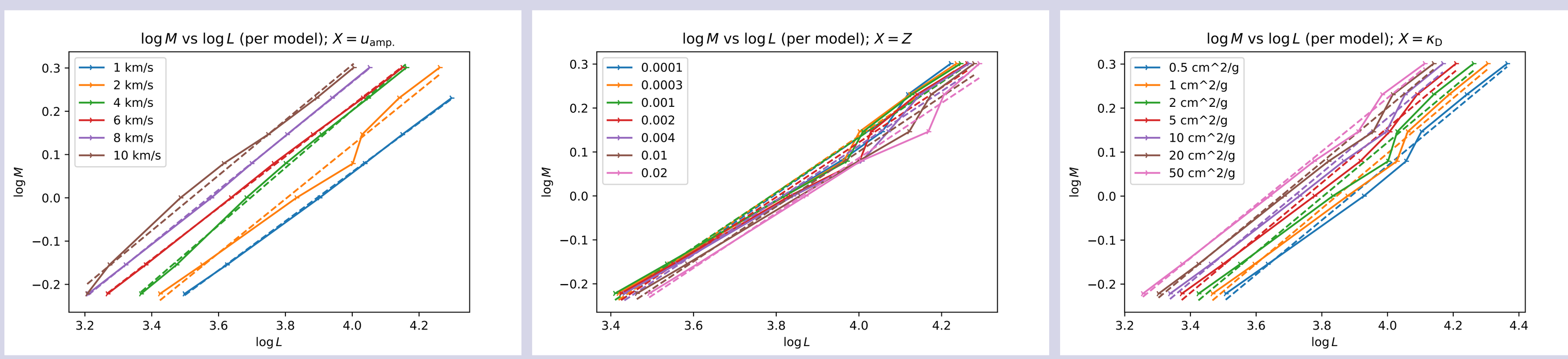
Input Parameter	Description	Values
M	Stellar mass	0.6, 0.7, 1.0, 1.2, 1.4, 1.7, 2.0 $M_\odot$
$\log L_0/L_\odot$	Initial Stellar Luminosity	3.0
$\Delta \log L/L_\odot$	Luminosity step	0.05
$u_{\text{amp.}}$	Piston velocity amplitude	2 km/s
κ_g	Gas opacity	$0.0002\ \mathrm{cm^2/g}$
ρ_{cx}	Gas critical density	$10^{-10}\mathrm{g/cm^3}$
q	Pseudoviscosity Pressure	$4\ \mathrm{dyn/cm^2}$
n_e/n_H	Electron-to-Hydrogen Ratio	0.1%
κ_D	Maximum dust opacity	$2\ \mathrm{cm^2/g}$
$T_{\text{con.}}$	Dust condensation temperature	1450 K
δ_T	Dust condensation temperature range	100 K
κ_W	Molecular opacity	$0.4\ \mathrm{cm^2/g}$
$T_{\text{con.,W}}$	Molecular condensation temperature	2000 K
$E_{\text{disc.,W}}$	Molecular dissociation energy	43 keV
$\rho_{cx,W}$	Molecular critical density	$1 \times 10^{-7}\ \mathrm{g/cm^3}$



Preliminary Results

As evidenced by the reference model, "standard" assumptions do not generate a grid of models in the observed location of AGB stars. Some of this may be attributable to the assumptions in the model. For example, the atmosphere is treated as a simple gray atmosphere and the dust and molecular opacities combine grain/molecule properties with the amount of said material in the layer.

Currently, we have completed the generation of four varying model grids: (constant) piston amplitude, metallicity, dust opacity, and grids that tie piston amplitude to stellar luminosity. The first and last grids show that increasing the strength of pulsations is a straight-forward way to shift the position of the grid with minimal effect on it's orientation. Adjusting the metallicity is somewhat more complicated, as it also adjusts the mean opacity of the atmosphere; however, the effect of adjusting it is small. Conceivably, this should also adjust the amount of dust in the atmosphere as well, but this is being examined independently because of the complicating effects of dredge-up in these stars; increasing the dust opacity also tends to enhance pulsation at lower luminosities. A combination of stronger pulsations and enhanced dust formation can account for the adjustments needed, but note these models do not suggest the mechanism to do this.



(a) (b) (c)

Figure: Death lines generated through the various model grids. (a) shows the effects of adjusting $u_{\text{amp.}}$, (b) shows the effects of varying Z, and (c) shows the effects of varying the opacity of dust.

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