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Mass loss rates of Li-rich AGB/RGB stars

W. J. Maciel* | R. D. D. Costa

Astronomy Department, University of São Paulo, São Paulo, Brazil

***Correspondence**
W. J. Maciel, Astronomy Department, University of São Paulo, São Paulo, Brazil.
Email: wjmaciel@iag.usp.br

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A sample of AGB/RGB stars with an excess of Li abundances is considered in order to estimate their mass loss rates. Our method is based on a correlation between the Li abundances and the stellar luminosity, using a modified version of Reimers formula. We have adopted a calibration on the basis of an empirical correlation between the mass loss rate and some stellar parameters. We conclude that most Li-rich stars have lower mass loss rates compared with the majority of AGB/RGB stars, which show no evidence of Li enhancements, so the Li enrichment process is apparently not associated with an increased mass loss rate.

KEYWORD

stars: mass loss–stars: RGB/AGB–stars: late-type

1 | INTRODUCTION

It is well known that most metal-rich AGB/RGB stars present strong Li underabundances, in view of the fact that Li is easily destroyed in stellar interiors. However, several stars, including Red Giant Branch (RGB) and Asymptotic Giant Branch (AGB) objects, present some Li enrichment, which can be characterized by abundances $\epsilon(\mathrm{Li}) = \log\,(\mathrm{Li/H}) + 12 > 1.5$. The mechanism producing the Li excess is not clear, and possibilities include the Cameron–Fowler mechanism (Cameron & Fowler 1971), presence of planets, etc. [see, e.g., the recent discussions by Casey et al. 2016 and Kirby et al. 2016].

Li enrichment has been associated with an enhanced mass loss ejection. de La de Reza et al. (1996, 1997) and Monaco et al. (2011) comment that some Li-rich giants show evidence of mass loss and chromospheric activity. However, Fekel & Watson (1998) and Jasniewicz et al. (1999) suggested that no important mass loss phenomena are associated with these stars, which is supported by the results by Lebzelter et al. (2012) based on $K - [12\,\mu\mathrm{m}]$ colors of the three Li-rich stars. This is in agreement with a suggestion in the literature [cf. Mallik 1999 and Luck 1977] that an enhanced mass loss would remove the stellar outer layers where most Li atoms are located.

In order to clarify the possible association of higher mass loss rates with the Li enhancements in AGB/RGB giants, in this work, we estimate the mass loss rates of a sample of Li-rich AGB/RGB stars based on a correlation between the Li abundance and the stellar luminosity. We use a modified Reimers formula calibrated on the basis of an independently derived empirical correlation between the mass loss rate and some stellar parameters, as suggested in the literature. As a result, we estimate the mass loss rates of a large sample of AGB/RGB stars with well-determined Li enhancements.

2 | THE DATA

The data for the Li-rich stars include RGB and AGB stars and are based on the sample adopted in our previous papers (Maciel & Costa 2012, 2015), with additional data from Maciel & Costa (2016) and Casey et al. (2016). The original sources of the data are: Brown et al. (1989), Mallik (1999), Gonzalez et al. (2009), Monaco et al. (2011, 2014), Kumar et al. (2011), Lebzelter et al. (2012), Kővári et al. (2013), Martell & Shetrone (2013), Lyubimkov et al. (2012), and Casey et al. (2016). Apart from their own data, the latter also gives a list of previously analyzed stars, mainly from Ruchti et al. (2011) and Kirby et al. (2012, 2016). In order to apply our method, the effective temperature T_{eff}, gravity $\log g$ and Li abundance $\epsilon(\mathrm{Li})$ of the Li-rich stars must be known. Applying this condition and removing some objects that lie outside the range of the adopted stellar parameters, a final sample of 159 Li-rich stars is obtained.[1]

[1]A detailed table with the full list of objects, input data, and mass loss rates can be obtained from the corresponding author

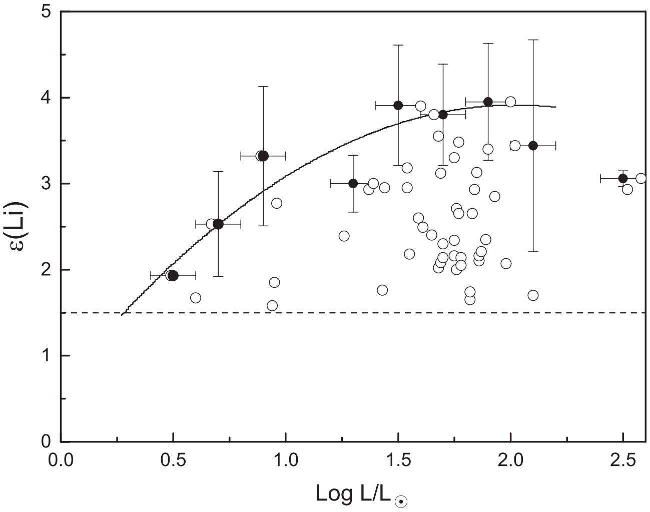

FIGURE 1 Li abundances as a function of the luminosity for Li-rich stars. Empty circles: data for stars with well-determined abundances and luminosities; filled circles: maximum abundances in each luminosity bin; the error bars show the average dispersion at each bin; solid line: quadratic fit of the maximum abundances; dashed line: adopted baseline value for Li-rich stars, $\epsilon(\mathrm{Li}) = 1.5$

3 | THE ϵ(LI) $\times$ log $L/L_\odot$ CORRELATION

From Maciel & Costa (2016), we obtain a plot of the Li abundances as a function of the luminosities for a selected sample of Li-rich stars containing 57 objects in the range $0 < \log L/L_\odot < 2.6$, as shown in Figure 1 (empty circles). It can be observed that the Li enhancements show some dispersion for each selected luminosity as, for some stars, Li may have been more strongly destroyed than for others. In other words, an upper envelope can be observed in the maximum Li abundances, which represent the maximum Li enrichment at each luminosity interval. The maximum Li enrichment presents a clear dependence on luminosity, in the sense that the most luminous giants reach larger Li abundances. Therefore, we will choose the *maximum* contribution at each bin as representative of the Li enhancement process. Adopting nine luminosity bins, we obtain the results shown by the black circles, where the error bars show the average dispersion at each bin.

It is clear that the maximum Li abundance increases with the stellar luminosity up to $\log L/L_\odot \simeq 2.2$, but the behavior of the correlation is not clear for the high-luminosity stars. As the vast majority of stars in our sample have luminosities similar or lower than this limit (49 stars out of 57, or 86%), we will adopt the following ranges where the correlation is better determined, that is:

$$1.5 \leq \epsilon(\mathrm{Li}) \leq 4.0 \qquad 0.2 \leq \log L/L_\odot \leq 2.2 \tag{1}$$

In Figure 1, the dashed line shows the baseline corresponding to the limit of Li-rich stars, for which $\epsilon(\mathrm{Li}) \geq 1.5$, and the solid line is a polynomial fit to the maximum abundances at each luminosity bin given by:

$$\epsilon(\mathrm{Li}) = a + b \ \log L/L_\odot + c \ (\log L/L_\odot)^2 \tag{2}$$

where $a = 0.657 \pm 0.937$, $b = 3.221 \pm 1.771$, and $c = -0.797 \pm 0.734$. This equation is assumed to be valid in the intervals given by Equation (1) and can be easily solved for the luminosity.

As the observed Li abundance may have any value lower or equal to the maximum value, it can be seen that the corresponding luminosity calculated by the solution of Equation (2) is generally a lower limit. For lower values of ϵ(Li), close to the minimum value of 1.5, the uncertainty is larger as the stellar luminosity can be much larger than the value obtained from Equation (2). On the other hand, for the values of the Li abundances close to the maximum value of 4.0, the luminosity is better determined as lower luminosities are excluded from the maximum values adopted in each bin. As it is assumed that the correlation is valid for luminosities up to $\log L/L_\odot \leq 2.2$, we have $\log L/L_\odot \leq \log L/L_\odot(\mathrm{true}) \leq 2.2$. Naturally, this excludes the objects with luminosities higher than 2.2, which are a small fraction of the Li-rich objects, in agreement with the data in Figure 1.

4 | MASS LOSS RATES OF LI-RICH AGB/RGB STARS

In order to determine the mass loss rate, we have adopted the following procedure: for each Li-rich star, we consider the Li abundance ϵ(Li) and estimate the luminosity using Equation (2). From the luminosity and the effective temperature, the stellar mass can be estimated using recent detailed evolutionary tracks for giant stars. We have adopted the tracks by Bertelli et al. (2008); also see Kumar et al. (2011). The tracks can be applied to solar metallicity stars with masses in the interval $1.0 < M/M_\odot < 3.0$ and effective temperatures in the approximate range $3800 < T_{eff}(K) < 5600$. From the effective temperature and luminosities, the determination of the stellar mass is a straightforward procedure. Using the stellar gravity g taken from the same sources as the effective temperature and Li abundances, the radius can be simply estimated by $R^2 = G\,M/g$.

In order to obtain the mass loss rates (in $M_\odot$/yr), we have adopted a modified version of Reimers formula given by:

$$\frac{dM}{dt} = 4 \times 10^{-13} \eta \ \frac{(L/L_\odot)(R/R_\odot)}{(M/M_\odot)} \tag{3}$$

[see, e.g., Lamers & Cassinelli 1999]. The η parameter is considered a free parameter, to be determined on the basis of an adequate calibration involving independently derived mass loss rates of AGB/RGB stars. From Equation (3), it can be observed that the mass loss rates increase as the luminosity increases. This is a result that was already obtained earlier in the literature [see, e.g., van Loon et al. 2005] and is probably related to the fact that the mass loss is caused by the action of the stellar radiation pressure on grains, atoms, and ions in the stellar atmosphere. This can be seen in Figure 3, where the solid dots represent Li-rich stars, and a particular value of parameter η was used, as we will discuss in Section 5. Of course, the mass loss phenomenon may also be affected by other parameters, such as the chemical composition, ionization state, etc., but it seems clear that the main mechanism is related to the stellar radiation, so a relation between the mass loss rate and luminosity is expected.

van Loon et al. (2005) derived an empirical formula to estimate the mass loss rate for oxygen-rich AGB stars and red supergiants as a function of the stellar luminosity and effective temperature. The formula is based on the modeling of the spectral energy distributions of a sample of red giants in the Large Magellanic Cloud. It is believed that the mass loss process in these stars originates from the action of the stellar radiation pressure on solid grains in the external stellar layers, so it is expected that the mass loss rate depends on the stellar luminosity, responsible for the radiation pressure, as well as the stellar temperature, which affects the process of grain formation. Previous results by van van Loon (2000) have already shown that the measured mass loss rates in LMC AGB stars generally present an increase with the stellar luminosity, which is in agreement with our adopted modified Reimers formula. In van Loon et al. (2005), the mass loss rates were derived using a dust radiative transfer code applied to infrared photometry data to obtain the spectral energy distribution. The derived equation can be written as

$$\log \frac{dM}{dt} = \alpha + \beta \ \log \left(\frac{L}{10000 L_\odot} \right) + \gamma \ \log \left(\frac{T_{eff}}{3500\mathrm{K}} \right), \quad (4)$$

where the mass loss rates are given in $M_\odot/year$. For M-type stars, the constants are $\alpha = -5.64 \pm 0.15$, $\beta = 1.05 \pm 0.14$, and $\gamma = -6.3 \pm 1.2$. This corresponds to an approximately linear relation between the mass loss rate and the stellar luminosity, in agreement with predictions from dust radiative-driven winds. From Equation (4), it can also be seen that the mass loss rate decreases with increasing temperatures, which is expected on the basis of the dust formation process. The uncertainty in the mass loss rates from Equation (4) is estimated as $\Delta \log dM/dt \simeq 0.3$ or, approximately, a factor 2 for typical mass loss rates of 10^{-5} $M_\odot$/year expected for the most luminous objects.

Although based on LMC objects, which typically have lower metallicities than Galactic objects, Equation (4) can be applied to Galactic objects as well, as shown by a comparison of the mass loss rates in the LMC with independently derived rates for galactic AGB stars, as discussed by van Loon et al. (2005). In other words, the mass loss rates are not strongly affected by the metallicity, at least within the estimated uncertainties.

5 | RESULTS AND DISCUSSION

We have applied Equation (4) to our sample of Li-rich AGB stars, adopting the luminosities derived from the correlation between the stellar luminosity and the Li abundance.

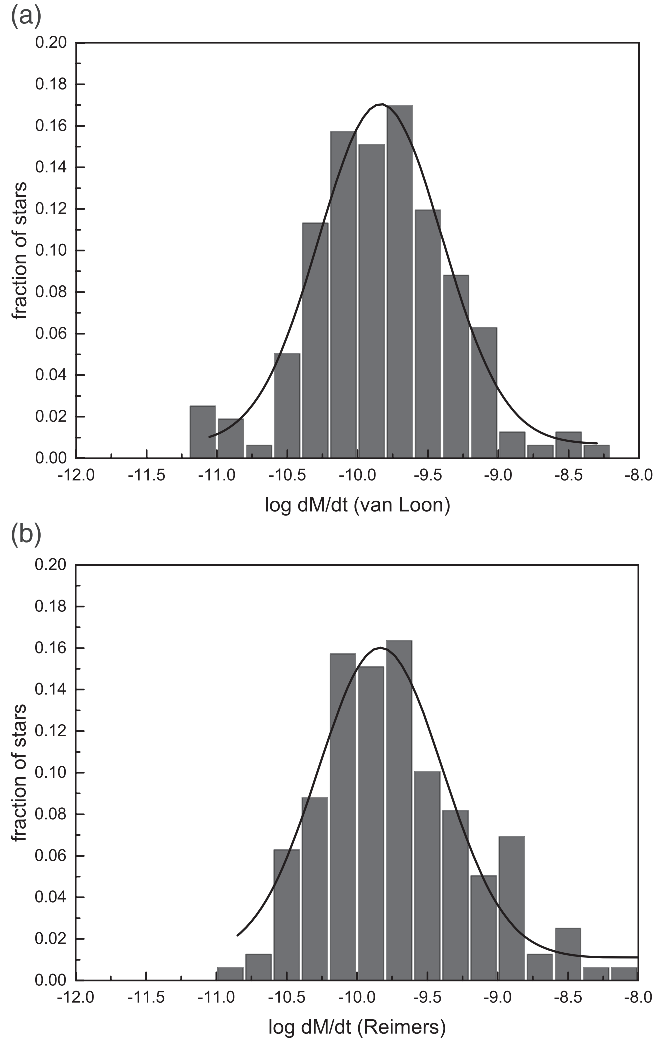

FIGURE 2 Distribution of the mass loss rates of Li-rich stars using (a) the empirical formula by van Loon and (b) the results of the modified Reimers formula for $\eta = 5.7$. The solid curves are Gaussian fits

As a result, we obtain the distribution shown in Figure 2a, where the solid curve represents a Gaussian distribution. In order to calibrate our method, we have adopted a linear relation between the mass loss rate and the luminosity of the form $\log dM/dT = A + B \log L/L_\odot$. It is easy to see that the slope of this relation does not depend on the η parameter. Applying this correlation to the sample of Li-rich stars with 159 objects, we find that $B = 1.057 \pm 0.105$. The intercept A can be obtained provided we estimate the η parameter on the basis of an adequate calibration. This can be achieved by selecting the η value that reproduces the distribution given by Figure 2a. As a result, we have $\eta = 5.7$ with $A = -10.620 \pm 0.099$ and $B = 1.057 \pm 0.105$, with a correlation coefficient $r = 0.63 \pm 0.45$. The corresponding distribution is shown in Figure 2b, and it can be seen that both distributions are very similar.

The uncertainties of the derived mass loss rates can be roughly estimated by considering that typical uncertainties in the Li abundances are of the order of 0.20 dex; for the effective temperature, we have uncertainties better than 100 K for most

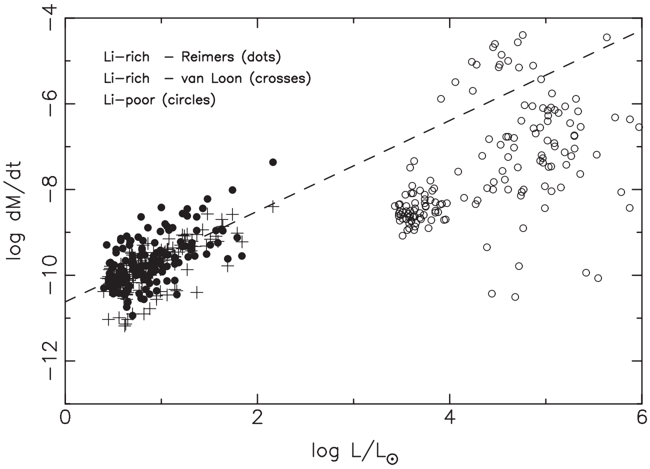

FIGURE 3 Mass loss rates ($M_\odot$/yr) as a function of luminosity. Dots: Li-rich stars, Modified Reimers Formula; crosses: Li-rich stars, van Loon Equation; empty circles: Li-poor stars from the literature; dashed line: linear correlation for the Li-rich stars

stars; the stellar gravity has a typical uncertainty of 0.20 dex. From the adopted correlation involving the stellar luminosity, an average uncertainty of about 0.20 dex is expected. Therefore, we have an uncertainty of about 0.5 $M_\odot$ for the stellar mass, and a final uncertainty of about 0.50 dex for the mass loss rate logdM/dt. This is comparable with the uncertainties in the mass loss rates of AGB/RGB stars with no indications of Li enhancements, as given by Gullieuszik et al. (2012). In this case, an average dispersion of about 0.5 dex for logdM/dt corresponds roughly to a factor 2 for a typical mass loss rate of $dM/dt \sim 10^{-6}$ $M_\odot$/year. Groenewegen et al. (2009) give a slightly smaller uncertainty of 0.43 dex for AGB stars and red supergiants in the Magellanic Clouds. As our main goal is to compare the mass loss rates of the Li-rich stars and the Li-poor stars, the absolute values of the rates are of secondary importance.

Figure 3 shows the derived mass loss rates as a function of the luminosity for our full stellar sample, containing 159 stars. In this figure, the black dots on the left side of the figure are the results using the modified Reimers formula (Equation 3), while the crosses indicate the rates obtained by the empirical formula by van Loon (Equation 4). The dashed line shows the final correlation obtained for Li-rich stars. It can be seen that the adopted linear correlation between the mass loss rates and the luminosities is a realistic one, falling in the adopted luminosity range given by Equation (1). We would like to stress that the dashed line is not a fit for the Li-poor stars as the corresponding sample is far from complete. We have selected a significant number of objects to stress the apparent dichotomy between Li-poor and Li-rich stars, which is a reflection of the lower luminosities of the latter.

As we have mentioned before, in view of the adopted correlation between the Li abundance and the luminosity, it can be seen from Figure 1 that the objects with lower values of ϵ(Li) may have higher luminosities than those obtained by Equation (2). For intermediate values of ϵ(Li), the uncertainty is lower, and for the highest values of the Li abundance, the calculated values are approximately correct as the derived luminosities are close to the maximum value. This means that our luminosities should be considered the lower limits, especially for those stars with Li abundances $\epsilon(\mathrm{Li}) < 2.0$ approximately, which are a small fraction of the objects in our sample (about 8%). As a consequence, the position of the stars on the $dM/dt \times L/L_\odot$ plane is more strongly affected for the objects with lower Li abundances. This conclusion has been confirmed by simulations for a few stars with different Li enhancements within the range shown in Figure 1. As expected, the objects with lower enhancements are slightly displaced upward in Figure 3, while those stars near the maximum Li abundances remain essentially at the same position in the diagram, so the general trend shown by the solid dots of Figure 3 is not significantly changed.

There are many reliable determinations of the luminosities and mass loss rates of AGB/RGB stars with no evidence of Li enhancements in the literature. As an example, we have considered the samples by Gullieuszik et al. (2012) and Groenewegen et al. (2009), selecting the O-rich stars. We have also included the results for Local Group galaxies by Groenewegen & Sloan (2018), again selecting the O-rich objects. Excluding objects for which a complete calculation could not be made due to the lack of accurate determinations of the mass loss rate dM/dt and/or the luminosity log$L/L_\odot$, we have a final sample of 156 stars, which is a representative set for these objects. The estimated uncertainties are generally of 10% for the luminosity and 25% for the mass loss rate. These objects are also included in Figure 3 as empty circles, mostly located on the right side of the figure. It is possible that some of the luminous stars at the right side of Figure 3 may have some excess Li, but it should be recalled that the Li-rich stars are a tiny fraction of all RGB/AGB stars, so our assumption that most of the objects on the right side of the figure are indeed Li-poor is quite reasonable. It can be seen that most of these objects have higher luminosities and mass loss rates compared with the Li-rich stars, with very few exceptions. It can then be concluded that the results obtained by the modified Reimers formula indicate that the Li-rich objects are generally associated with mass loss rates much lower than in the case of the majority of AGB/RGB stars, which are Li-poor objects. In other words, Li enhancements seem to be a low-luminosity feature associated with lower mass loss rates compared with the majority of these stars, in agreement with our preliminary estimates using a linear correlation between the Li abundances and the luminosities, as discussed in Maciel & Costa (2016).

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