The Origin of Outflows in Evolved Stars
Proceedings IAU Symposium No. 366, 2022
L. Decin, A. Zijlstra & C. Gielen, eds
doi:10.1017/S1743921322000989

Analytic, Turbulent Pressure Driven Mass Loss Rates from Red Supergiants

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Abstract. Although red supergiants (RSGs) are observed to be undergoing vigorous mass loss, explaining the mechanism launching their winds has been a long-standing problem. Given the importance of mass loss to stellar evolution in this phase, this is a key uncertainty. In this contribution we present a recently published model (Kee et al. 2021) showing that turbulent pressure alone can extend the stellar atmosphere of an RSG to the degree that a wind is launched. This provides a fully analytic mass-loss prescription for RSGs. Moreover, utilising observationally inferred turbulent velocities for these objects, we find that this wind can carry an appropriate amount of mass to overall match observations. Intriguingly, when coupled to stellar evolution models the predicted mass-loss rates show that stars with initial masses above $M_{\rm ini} \sim 17 M_\odot$ may naturally evolve back to the blue and as such not end their lives as RSGs; this is also in overall good agreement with observations, here of Type II-P/L supernova progenitors. Moreover, since the proposed wind launching mechanism is not necessarily sensitive to metallicity, this could have important implications for stellar evolution predictions in low-metallicity environments.

1. Introduction

The lack of a satisfactory theory explaining the strong, $> 10^{-7}$ $M_\odot$ yr^{-1}, mass loss for evolved massive stars on the red supergiant (RSG) branch has been a long standing problem in our understanding of these objects (see Levesque 2017, for a recent review). Namely, while for lower-mass asymptotic giant branch (AGB) stars it is generally assumed that strong pulsations lift gas up to radii where radiation pressure on dust grains can drive it out of the stellar potential (see, e.g., contribution by S. Höffner in these proceedings), in comparison the dust-condensation radius of RSGs is believed to (on average) be located much further away from the stellar surface. Indeed, modeling attempts have been generally unsuccessful in generating the atmospheric extensions of RSGs necessary to put enough material at the dust sublimation front (e.g., Arroyo-Torres *et al.* 2015).

An alternative suggestion has been that pulsational motions might be accompanied or replaced by significant atmospheric turbulence (Gustafsson & Plez 1992; Josselin & Plez 2007), and that this turbulence might be seeded by the vigorous convection expected in the atmospheres of RSGs (Freytag *et al.* 2012); indeed, observations of red supergiants do indicate that the outer layers of these stars are very turbulent (e.g., Josselin & Plez 2007; Ohnaka et al. 2017). Inspired by the work of Gustafsson & Plez (1992) and Josselin & Plez (2007), we have recently derived analytic mass-loss rates that focus on these large observed turbulent velocities present in RSGs (Kee et al. 2021).

2. The model

As outlined in detail by Kee et al. (2021), for a constant mass-loss rate $\dot{M} = 4\pi\rho v r^2$ we write the 1D, stationary equation of motion as

$$v\left(1 - \frac{a^2 + v_{\rm turb}^2}{v^2}\right)\frac{dv}{dr} = \frac{2\left(a^2 + v_{\rm turb}^2\right)}{r} - \frac{GM_*\left(1-\Gamma\right)}{r^2}\,, \qquad (2.1)$$

where a is the isothermal sound speed, $v_{\rm turb} = \sqrt{P_{\rm turb}/\rho}$ is the turbulent velocity with associated turbulent pressure $P_{\rm turb}$, and $\Gamma \equiv \kappa L_*/(4\pi G M_* c)$ is the Eddington factor expressing the ratio of radiative to gravitational acceleration for an opacity κ, stellar luminosity L_*, and stellar mass M_*.

The location of the modified Parker (1958) radius, defined here as the point at which the flow velocity equals an 'effective' sound speed $a_{\rm eff} \equiv \sqrt{a^2 + v_{\rm turb}^2}$, is

$$R_{\rm p,mod} = \frac{G\,M_*\left(1-\Gamma\right)}{2\left(a^2 + v_{\rm turb}^2\right)}\,, \qquad (2.2)$$

yielding the generic mass-loss rate

$$\dot{M} = 4\,\pi\,\rho(R_{\rm p,mod})\,a_{\rm eff}(R_{\rm p,mod})\,R_{\rm p,mod}^2\,. \qquad (2.3)$$

For a given effective sound speed $a_{\rm eff}$, the problem in hand thus boils down to estimating the density ρ at this modified Parker radius $R_{\rm p,mod}$.

Assuming first an isothermal atmosphere with temperature $T = T_{\rm eff}$ and constant opacity κ, this density can be analytically estimated by computing the optical depth τ from an assumed stellar radius at $R_* \equiv r(\tau = 2/3)$ to $R_{\rm p,mod}$ (see Kee et al. 2021, their Sect. 2., for details). This yields a fully analytic expression for $\dot{M}$ as function of the input stellar parameters L_*, M_*, R_*, and (an assumed constant) $v_{\rm turb}$. Relaxing the isothermal assumption, we next compute a temperature structure following Lucy (1971) (see also eqns. 16-17 in Kee et al. 2021), numerically solve the equation of motion, and iterate toward an internally consistent mass-loss rate; comparing this then to the fully analytic isothermal result, we derive a non-isothermal correction factor to the analytic model. This yields a final mass-loss rate as predicted by our model:

$$\dot{M} = \dot{M}_{\rm an}\left(\frac{v_{\rm turb}/(17\,{\rm km\,s^{-1}})}{v_{\rm esc}/(60\,{\rm km\,s^{-1}})}\right)^{1.30}\,, \qquad (2.4)$$

where $v_{\rm esc}$ is the escape speed from the stellar surface R_*, and the analytic mass-loss rate $\dot{M}_{\rm an}$ is given by equations (5),(7),(8),(11), and (13) in Kee et al. (2021).

As demonstrated, the above essentially is a modified Parker-like wind model, where the potential for initiating a large RSG mass loss simply lies in the very loosely bound envelopes of these stars. This can be seen more directly by using the effective (i.e., the one reduced by $1-\Gamma$) escape speed from the stellar surface to re-write the modified Parker radius as

$$\frac{R_{\rm p,mod}}{R_*} = \frac{1}{4}\frac{v_{\rm esc,eff}^2}{a_{\rm eff}^2}\,. \qquad (2.5)$$

For a sun-like star the escape speed from the stellar surface ($v_{{\rm esc},\odot} \sim 600\,{\rm km/s}$) is very much larger than the effective photospheric sound speed ($a_{\rm eff} \sim 8{\rm km/s}$). This means that a very hot corona with $T \sim 10^6$K is required to lift material up to a Parker point located only a few radii above the stellar surface. On the other hand, for RSGs the effective escape speed is about an order of magnitude lower than for sun-like stars, so that only a modest amount of turbulent velocity is required to shift the location of the Parker point to regions reasonably close to R_*. This is the essential point as to why such atmospheric

https://doi.org/10.1017/S1743921322000989 Published online by Cambridge University Press

turbulence can play a key role in initiating significant mass loss from the very extended RSG atmospheres, while it will be a very ineffective mechanism for high-gravity stars on the main-sequence.

3. Some first analysis and implications of new mass-loss rates

Because of the essentially exponential dependency of density on the effective atmospheric scale-height, the predicted mass-loss rates in our model are extremely sensitive to the quantitative input value of $v_{\rm vturb}$. However, from the RSG samples compiled by Josselin & Plez (2007) and Ohnaka et al. (2017) a high mean observed velocity dispersion $v_{\rm disp} = 20.3\,{\rm km/s}$ can be inferred (Kee et al. 2021). In these studies, the characteristic values of $v_{\rm disp}$ have been obtained from analysing line-of-sight velocity shifts in spectral lines using a tomography technique (Josselin & Plez 2007) and by means of direct mapping of the projected velocity across the stellar surface as observed in some strategic molecular lines (Ohnaka et al. 2017); on the other hand, reproducing the corresponding observationally inferred mass-loss rates for the same stars within our model only requires $v_{\rm turb} = 18.2\,{\rm km/s}$ (Kee et al. 2021). As such, to the extent that we may identify these inferred velocity dispersions with the turbulent velocity entering our model, the predicted mass-loss rates indeed lie in the correct range. This illustrates the large potential of turbulent pressure for levitating RSG atmospheres, and lends some first support to the proposed mass-loss model. Nonetheless, we emphasise that these characteristic values should be interpreted only in this kind of average manner; when inspecting individual RSGs, there is large scatter both regarding inferred velocity dispersions and empirically derived mass-loss rates.

The latter is also reflected in the large discrepancies present in the various empirical mass-loss recipes for RSGs present on the market. Indeed, even for a given luminosity these empirical mass loss scalings can differ by huge amounts, up to several orders of magnitude depending on the chosen recipe (see Kee et al. 2021, their Fig. 8, for a comparison of different recipes). Given these large uncertainties in current empirical calibrations, the model proposed here may also be taken as a reasonable option for various applications where RSG mass loss is important.

As just a first example of this, we here compute stellar evolution tracks using i) the (quite standard) empirical mass loss calibration by de Jager et al. (1988) and ii) our new predicted rates. Specifically, while the applied mass-loss rates are assumed to be equivalent for hot stars ($T_{\rm eff} > 10$ kK), for cool stars ($T_{\rm eff} < 10$ kK) we do two separate simulation sets. The first of these retains the standard de Jager et al. (1988) mass-loss rates as a baseline. The other preferentially uses our new Kee et al. (2021) prescription with the suggested default $v_{\rm turb} = 18.2$ km s^{-1} from that paper and above. However, turbulent pressure initiated mass loss is developed for application on the RSG branch itself, and as such is not (yet) well calibrated for yellow supergiants. We therefore take the maximum between the de Jager et al. (1988) and the Kee et al. (2021) mass-loss rate whenever 10 kK $> T_{\rm eff} >$ 5 kK. This has the effect of using the de Jager et al. (1988) rates on the first crossing of the Hertzsprung gap, before the star inflates on the RSG branch, and instead using the Kee et al. (2021) rates for post-RSG objects. Finally, for $T_{\rm eff} < 5$ kK, this new scheme always uses Kee et al. (2021). The implementation of this "Leuven-modified Dutch mass loss scheme" in the stellar evolution code MESA (Paxton et al. 2011; Paxton et al. 2013) is available at https://doi.org/10.5281/zenodo.4333564.

Further specifications for these MESA calculations regard possible C/O enhancements in opacities as discussed in Paxton et al. (2011), mixing length theory applied according to the Ledoux criterion with a semiconvective mixing efficiency 0.01, and the MLT++ prescription as described in Paxton et al. (2013), their Section 7.2. In order to simplify

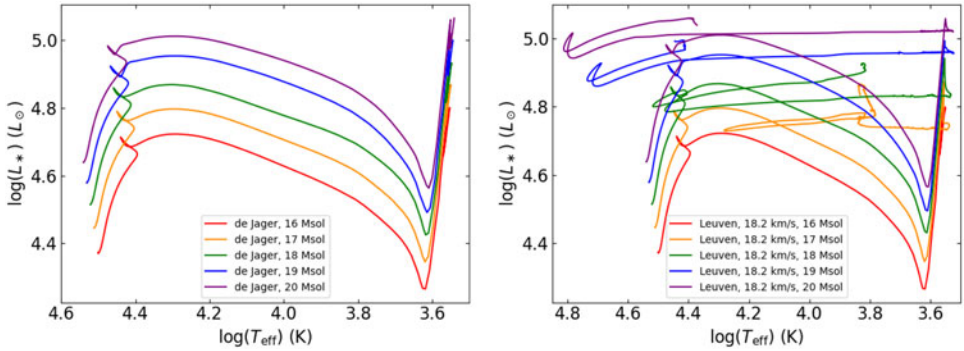

Figure 1. Comparison of stellar evolution tracks beginning from zero-age main sequence masses 16 to 20 $M_\odot$ in 1 $M_\odot$ increments. Stars in the left panel have been evolved with the de Jager et al. (1988) RSG mass-loss rates, while stars in the right panel were evolved using our new 'Leuven' mass-loss rates as described in the text.

the current models, we further omit convective overshooting in the simulations. The inlist files used for these simulations are available at https://doi.org/10.5281/zenodo.4333564.

Figure 1 shows simulated evolution tracks of stars with initial masses from 16 to 20 $M_\odot$ using the de Jager et al. 1988 mass-loss rates in the left panel and the simulations with our new ('Leuven') rates in the right panel. All stars are evolved up to carbon core depletion. The difference between these simulations is strikingly evident as all simulations using the de Jager rates die on the RSG branch while stars with initial mass $M_{\rm ini} \geq 17$ $M_\odot$ using the Leuven mass-loss rates do not. Indeed, this is in general good agreement with the observationally inferred upper limit to the initial mass for Type II-P/L SNe ($16 M_\odot \lesssim M_{\rm ini} \lesssim 23 M_\odot$ (Smartt et al. 2009). These results are different than what was found in the recent study by Beasor *et al.* (2021), where the authors used their own new empirical RSG mass loss scaling in similar evolution models and found that then stars with initial masses below $30 M_\odot$ do not evolve back to the blue.

This difference in behaviour of the evolution models arises from the strong dependence of the Leuven mass-loss rates on stellar surface gravity ($\propto M_*/R_*^2$). Namely, as the star climbs up the RSG branch and loses mass, its surface gravity decreases further, thereby increasing the mass-loss rate in a positive feedback loop. This feedback of increased mass loss with RSG evolution effectively generates a competition of time scales between mass-loss induced stripping of the star's hydrogen envelope and the core nuclear burning timescale. Below the critical transition mass, here ~ 17 $M_\odot$, the star runs out of nuclear fuel before losing its hydrogen envelope and ends its life as a Type II-P/L supernova. At that transition mass and above, mass loss wins out, the star loses almost its entire Hydrogen envelope, and in reaction the star contracts off the RSG branch back toward hotter effective temperatures.

Actually, also according to our models the stars lose mass at quite moderate rates during most of their time as RSGs. However, as the star evolves toward ever lower masses it eventually enters a short-lived RSG phase with strongly enhanced mass loss, which ultimately allows the star to lose most of its hydrogen envelope. In the evolution models displayed in the right panel of Fig. 1 here, the $M_{\rm ini} = 17 M_\odot$ ($M_{\rm ini} = 20 M_\odot$) model spends 3 % (14 %) of its RSG life-time having $\dot{M} > 10^{-4}$ $M_\odot$/yr. The de Jager et al. 1988 prescription misses this as their mass-loss rates do not scale with stellar mass, and it is further also unclear how well the new empirical scalings by Beasor *et al.* (2021) are able to capture these short-lived phases associated with strongly enhanced RSG mass loss.

Finally, the value of the maximum initial mass below which stars are predicted to die on the RSG branch indeed also depends on the choice of $v_{\rm turb}$ for the Kee et al. (2021)

https://doi.org/10.1017/S1743921322000989 Published online by Cambridge University Press

mass-loss rates. Here we have taken an average value (see above) as being characteristic for the complete RSG phase, but it would certainly not be unreasonable to suspect that this might also vary with the RSG evolution. Nonetheless, it is interesting to note that the simple average $v_{\rm turb} = 18.2\,{\rm km/s}$ applied here, and obtained directly from comparison to empirical studies, immediately yields an upper limit to the initial mass for Type II-P/L SNe that seems to agree rather well with observations.

4. Origin of the turbulent velocity?

The turbulent velocity enters our model as an essentially free input parameter, albeit adjusted according to the observations that clearly indicate its presence. Naturally, however, a fully consistent theoretical model for RSG mass loss must also be able to predict $v_{\rm turb}$. As mentioned in the introduction, a natural candidate for this regards the vigorous convective motions expected to occur in the surface and sub-surface layers of RSG stars. Although such convective simulations typically have shown turbulent velocities that are smaller than suggested by observations (e.g., Arroyo-Torres *et al.* 2015), we note that the characteristic velocities observed in the recent radiation-hydrodynamic simulations by Goldberg et al. (2021) seem to be significantly higher. Moreover, these 3D simulations (as well as 1D evolution models such as those presented above) also show that RSG atmospheres breech the Eddington limit (defined by $\Gamma = 1$) already in deep sub-surface atmospheric layers. That is, just like for hotter stars (see contributions by S. Owocki, N. Moens), an approach accounting carefully for also the radiative acceleration around sub-surface (atomic) "opacity bumps" might be necessary when modelling the turbulent RSG surface and wind initiation. Moreover, if this wind launching mechanism ultimately is connected to hydrogen (or helium) recombination, this might have far-reaching consequences for massive-star evolution at low metallicity; indeed, assuming a constant $v_{\rm turb}$ the Kee et al. rates do not contain any direct dependency on the stellar metallicity.

References

Arroyo-Torres, B., Wittkowski, M., Chiavassa, A., et al. 2015, *A&A*, 575, A50
E.R. Beasor, B. Davies, N. Smith, 2021, *ApJ*, 922, 55
de Jager, C., Nieuwenhuijzen, H., & van der Hucht, K. A. 1988, *A&AS*,72, 259
Freytag, B., Steffen, M., Ludwig, H. G., et al. 2012, *J. of Comp. Ph.*, 231, 919
Goldberg, J. A., Jiang, Y.-F., & Bildsten, L. 2021, accepted for publication in *ApJ*, *arXiv e-prints, arXiv:2110.03261*
Gustafsson, B. & Plez, B. 1992, in Instabilities in Evolved Super- and Hypergiants, ed. C. de Jager & H. Nieuwenhuijzen, 86
Josselin, E. & Plez, B. 2007, *A&A*, 469, 671
Kee, N. D., Sundqvist, J. O., Decin, L., de Koter, A., & Sana, H. 2 2021, *A&A*, 646, A180
Levesque, E. 2017, Astrophysics of Red Supergiants IoP ebook (IoP Publishing, Bristol)
Lucy, L. B. 1971, *ApJ*, 163, 95
Ohnaka, K., Weigelt, G., & Hofmann, K. H. 2 2017, *Nature*, 548, 310
Parker, E. N. 1958, *ApJ*, 128, 664
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, *ApJS*, 192, 3
Paxton, B., Cantiello, M., Arras, P., et al. 2013, *ApJS*, 208, 4
Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, *MNRAS*, 395, 1409