Massive Stars Near and Far
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Analytic, Turbulent Pressure Driven Mass Loss from Red Supergiants

N. Dylan Kee[1] and the MAESTRO Project[2]

[1]National Solar Observatory, 22 Ohi'a Ku St, Makawao, HI 96768, USA
email: dkee@nso.edu

[2]Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

Abstract. Despite the important role mass loss in the red supergiant phase plays in controlling stellar evolution and massive stars final supernova fates, a theoretical explanation of the mechanism driving this mass loss has been elusive. In this contribution we present a recent breakthrough (Kee et al. 2021) showing that turbulent pressure alone is sufficient to markedly extend the atmospheres of red supergiants and allow a wind to be launched. The resulting theory provides a fully analytic prescription for red supergiant mass-loss rates. Moreover, the theoretical mass-loss rates computed from observationally inferred turbulent velocities are in overall good agreement with observationally inferred red supergiant mass loss. A particularly interesting aspect of this theory is that it is not sensitive to metallicity, providing important implications for stellar evolution and the so-called "red-supergiant problem" for supernova progenitors in various environments.

Keywords. supergiants, stars: mass loss, stars: winds, convection, turbulence, stars: evolution, supernovae: general

1. Introduction

Although red supergiants (RSGs) are observationally inferred to be undergoing vigorous mass loss ($\dot{M} \gtrsim 10^{-7} M_{\odot}\ \mathrm{yr}^{-1}$), the physical mechanism driving these stars' winds has remained unknown (see, e.g., Levesque 2017). For lower mass evolved stars, specifically asymptotic giant branch stars, atmospheric pulsations are thought to levitate material up to distances at which dust can form, before radiation pressure on dust opacity drives material out of the stellar gravitational potential (see, e.g., Höfner and Olofsson 2018, for a review). However, due to the higher effective temperatures and lower pulsational amplitudes of RSGs, studies of this mechanism find that an insufficient amount of material can be levitated to distances away from the star where dust can form to be able to explain the winds of RSGs (e.g. Arroyo-Torres et al. 2015).

An alternate explanation is that the deep seated convection cells present in the atmospheres of RSGs (e.g. Freytag et al. 2012) may seed sufficient atmospheric turbulence to augment or replace pulsations in extending the atmospheric scale height (Gustafsson and Plez 1992; Josselin and Plez 2007). Spurred by recent observations revealing just such atmospheric turbulence (e.g. Josselin and Plez 2007; Ohnaka et al. 2017), we build upon the work of Gustafsson and Plez (1992) and Josselin and Plez (2007) to develop an analytic theory leveraging atmospheric turbulence as the primary driving mechanism of the winds of RSGs (Kee et al. 2021).

2. Model

The following section discusses the derivation of the analytic mass-loss rate. As this discussion is abridged, we direct the interested reader to Kee et al. (2021) for the detailed derivation.

As our goal is to obtain a steady state mass loss rate $\dot{M} \equiv 4\pi\rho v r^2$, we need to know velocity v and density ρ at a single radius r. To this end, we begin from the isothermal, steady-state equation of motion

$$v\left(1-\frac{c_\mathrm{s}^2+v_\mathrm{turb}^2}{v^2}\right)\frac{\partial v}{\partial r}=\frac{2\left(c_\mathrm{s}^2+v_\mathrm{turb}^2\right)}{r}-\frac{GM_*\left(1-\Gamma\right)}{r^2}\,, \tag{2.1}$$

expressed in terms of the isothermal sound speed c_s, turbulent velocity $v_\mathrm{turb}=\sqrt{P_\mathrm{turb}/\rho}$, and Eddington factor $\Gamma \equiv \kappa L_*/(4\pi G M_* c)$. Turbulent velocity and the Eddington factor are further functions of turbulent pressure P_turb and opacity κ, stellar luminosity L_*, and stellar mass M_* respectively. Examining Equation 2.1, a convenient radius to consider is the location where $v(r)=\sqrt{c_\mathrm{s}^2+v_\mathrm{turb}^2}$, as the left side of Equation 2.1 is zero at this radius. As this is basically the method used by Parker (1958) to derive the gas pressure driven solar wind, here with a modified, "effective" sound speed $c_\mathrm{s,eff}=\sqrt{c_\mathrm{s}^2+v_\mathrm{turb}^2}$, we refer to this radius as the modified Parker radius

$$R_\mathrm{p,mod}=\frac{GM_*\left(1-\Gamma\right)}{2\left(c_\mathrm{s}^2+v_\mathrm{turb}^2\right)}\,. \tag{2.2}$$

With velocity at a specific radius in hand, what remains is to find the density at the same position. Here we assume that the portion of the wind below the modified Parker radius is nearly in hydrostatic equilibrium, such that

$$\rho(r)=\rho_*\exp\left[-\frac{2R_\mathrm{p,mod}}{R_*}\left(1-\frac{R_*}{r}\right)-\frac{1}{2}\right]\,, \tag{2.3}$$

where the extra factor of $e^{-1/2}$ accounts for the velocity stratification of the region below $R_\mathrm{p,mod}$. The normalization density ρ_* is obtained to be

$$\rho_*=\frac{4R_\mathrm{p,mod}}{3\,\kappa\,R_*^2}\left[1-\exp\left(-\frac{2R_\mathrm{p,mod}}{R_*}\right)\right]^{-1}\,. \tag{2.4}$$

by taking the stellar radius to be at spherically modified optical depth 2/3 (Lucy 1971). Taken all together this gives an analytic mass-loss rate

$$\dot{M}_\mathrm{an}=4\pi\rho(R_\mathrm{p,mod})\sqrt{c_\mathrm{s}^2+v_\mathrm{turb}^2}\,R_\mathrm{p,mod}^2\,, \tag{2.5}$$

for

$$\rho(R_\mathrm{p,mod})=\frac{4R_\mathrm{p,mod}e^{3/2}}{3\kappa R_*^2\left(e^{2R_\mathrm{p,mod}/R_*}-1\right)}\,. \tag{2.6}$$

Relaxing the assumption of isothermality allows us to iteratively converge on a final mass rate for our model. To replace the isothermal temperature structure Kee et al. (2021) took the temperature structure from the Lucy (1971) spherically-modified grey model atmosphere. Comparing the associated numerically determined mass-loss rate to the analytic expression provides us a final mass-loss rate

$$\dot{M}=\dot{M}_\mathrm{an}\left(\frac{v_\mathrm{turb}/(17\,\mathrm{km\,s^{-1}})}{v_\mathrm{esc}/(60\,\mathrm{km\,s^{-1}})}\right)^{1.30}\,, \tag{2.7}$$

for v_esc the escape speed from the stellar surface.

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3. Analysis and implications

Comparing the mass-loss rates provided by our model to the mass-loss rates observationally inferred by Josselin and Plez (2007) and Ohnaka et al. (2017) returns a required turbulent velocity for our model of, on average, $v_{\rm turb} = 18.2 \pm 3.4$ km s^{-1} (Kee et al. 2021). This agrees to better than one standard deviation with the average observationally inferred turbulent velocity inferred by these same authors of $v_{\rm turb} = 20.3 \pm 3.3$ km s^{-1}. Further comparing our mass-loss rate using this average turbulent velocity to the current state-of-the-art in empirical mass loss prescriptions for RSGs used in stellar evolution calculations (e.g. de Jager et al. 1988; Nieuwenhuijzen and de Jager 1990; Vanbeveren et al. 1998; van Loon et al. 1999; Beasor et al. 2020) again shows generally good agreement between our theory and what is observationally inferred. However, it is important to note that there is substantial scatter between the stellar properties and mass-loss rates of individual RSGs, and that this scatter carries over to the differences between different empirical mass-loss rate prescriptions, which in some places in the parameter space grow to multiple orders of magnitude. Therefore, as is the case for the empirically inferred mass-loss rate prescriptions, these theoretical mass-loss rates are robust in describing the average behavior of the population of RSGs, while some care should be taken in describing the mass-loss rates of individual RSGs.

To explain the efficacy of this model, we note that a key parameter is the argument of the exponential stratification in density in Equation 2.3

$$\frac{R_{\rm p,mod}}{R_*} \propto \frac{v_{\rm esc,eff}^2}{c_{\rm s}^2 + v_{\rm turb}^2}\,, \tag{3.1}$$

for effective escape speed $v_{\rm esc,eff} = \sqrt{2GM(1-\Gamma)/R_*}$. For cool evolved stars, like RSGs, the surface escape escape speed is much lower ($\sim$ 60 km s^{-1}) than main-sequence stars ($\sim$ 600 km s^{-1}) such that a relatively modest amount of turbulent velocity $\sim 4\ c_{\rm s}$ is sufficient to make the modified Parker radius an order unity factor times the stellar radius. Meanwhile, for the solar wind, the 10^6 K corona and attendant factor ~ 15 increase in sound speed is required. Beyond this, RSGs are intrinsically quite large compared to main-sequence stars with $R_* \sim 1000 R_\odot$, which only amplifies the effects of looser atmospheric binding as mass-loss rate scales like radius squared.

Given the success of this model, an interesting first step in applying these new theoretical rates is to examine their effects on stellar evolution. To do so, we run two sets of `MESA` models that are identical except in their treatment of the "cool" mass-loss prescription for stars with effective temperature ≤ 8 kK. For the first set, we apply the standard de Jager et al. (1988) mass-loss rates in this regime, while for the second we preferentially use our new Kee et al. (2021) mass-loss rates. As this new theoretical description is intended to apply to the mass loss of RSGs, we take the maximum of the de Jager et al. (1988) and Kee et al. (2021) mass-loss rates for the region where effective temperature is between 5 and 8 kK, and always apply the Kee et al. (2021) rates for stars with effective temperature ≤ 5 kK. The implementation of this "Leuven-modified Dutch mass loss scheme" in the stellar evolution code `MESA` (Paxton et al. 2011, 2013) is available at https://doi.org/10.5281/zenodo.4333564. The inlists describing the remaining input parameters for `MESA` are also available at https://doi.org/10.5281/zenodo.4333564.

The resulting stellar evolution tracks are shown in Figure 1. All stars shown are evolved until carbon core depletion. The difference in evolution between the stars evolved with the de Jager et al. (1988) and Kee et al. (2021) rates is immediately evident, as all stars shown using the de Jager et al. (1988) die on the RSG branch, while stars of initial mass $\geq 17 M_\odot$ evolve back to the blue with the Kee et al. (2021) mass-loss rates. This upper limit to the initial mass of stars that end their lives in core collapse on the RSG branch

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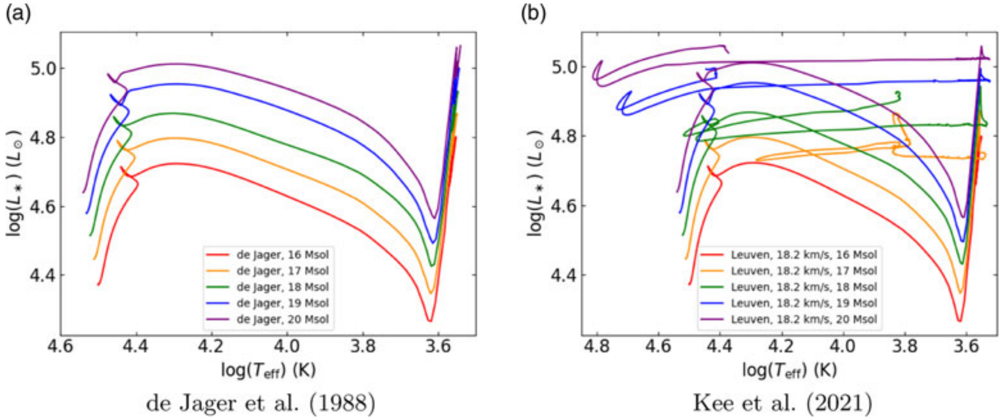

Figure 1. Comparison of stellar evolution tracks using the de Jager et al. (1988) mass-loss rates (left) and the Kee et al. (2021) ('Leuven') mass-loss rates (right) during the RSG phase. The different tracks in each panel correspond to stars with initial masses from 16 to 20 $M_\odot$ in steps of 1 $M_\odot$.

is in broad agreement with what is observationally inferred for the progenitors of Type II-P/L supernovae ($16 \sim 23 M_\odot$, Smartt et al. 2009). On the other hand, this differs from the recent findings of Beasor et al. (2021) (discussed by E. Beasor in these proceedings) where stars of initial masses up to 30 $M_\odot$ die on the RSG branch.

This difference is at its core related again to the aforementioned sensitivity of this mass-loss prescription to the surface gravity of the star. While the Kee et al. (2021) mass-loss rates are in general agreement with the de Jager et al. (1988) and Beasor et al. (2020) rates over the majority of a star's RSG lifetime (e.g. Kee et al. 2021, B. Davies priv. comm.), as a star evolves toward the tip of the RSG branch, its surface gravity decreases and as such the Kee et al. (2021) mass-loss rates increase. This initial increase is still in general agreement with other empirical rates which also increase with increasing stellar luminosity, but has additional implications for the Kee et al. (2021) mass-loss rates. Specifically, as a star loses mass near the tip of the RSG branch its surface gravity further decreases allowing the star to enter a positive feedback loop. This loop drives the star into a short-lived phase (3-14% of the star's RSG lifetime for stars born with 17-20 $M_\odot$) with stellar mass-loss exceeding $10^{-4} M_\odot$ yr^{-1} during which the star sheds its hydrogen envelope and then evolves toward the blue.

Both the initial stellar mass leading to a star entering this feedback loop and the duration a star will spend in this phase, as well as the overall scale of stellar mass loss throughout the remainder of the RSG phase, are of course all dependent on the value of $v_{\rm turb}$ and any dependencies it may have on stellar parameters. Therefore, it is important to disentangle the origins of the atmospheric turbulence to make direct comparisons with the recent studies by Davies and Plez (2021) (discussed in these proceedings by B. Davies) and Beasor and Smith (2022) placing upper limits on the amount of time an RSG could spend in this type of phase of high mass-loss, as well as studies of the mass and luminosity extent of the population of RSGs that are progenitors of Type II-P/L supernovae (e.g. Smartt et al. 2009).

4. Potential origins of atmospheric turbulence

As mentioned in the introduction, a likely origin of the turbulent motions we employ for our model is the deep seated and vigorous convection present in much of the volume of an RSG. Recent radiation-hydrodynamic simulations from Goldberg et al. (2022) (discussed

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in these proceedings by J. Goldberg) do indeed show characteristic velocities in the outer layers of RSGs in line with the velocities that are observationally inferred and those that are required for our model. Analysing those three-dimensional radiation-hydrodynamic models shows that in part the strong convection and resulting atmospheric turbulence are driven by the stellar atmosphere locally breaching the Eddington limit ($\Gamma > 1$ locally) in the regions of enhanced opacity corresponding to hydrogen and helium opacity. Indeed, this is a property that is shared by the total (radiative+convective) luminosity of the 1D stellar evolution models above. This has two immediately evident important implications for the Kee et al. (2021) mass-loss rates. First, assuming otherwise unchanged stellar structure, the hydrogen and helium opacity peaks are metallicity independent, and as such the turbulent velocities and thus also RSG mass-loss as predicted by Kee et al. (2021) are at most weakly dependent on metallicity for otherwise fixed stellar structures (see, however Sabhahit et al. 2021, discussed in these proceedings by G. Sabhahit, for an example of how altered stellar evolution with *decreased* metallicity causes a star to evolve to an altered structure on the RSG branch such that the strength of these opacity peaks is *increased*). Second, the degree to which an RSG exceeds the Eddington limit is linearly dependent on luminosity, such that $v_{\rm turb}$ may be expected to increase with evolutionary phase as a star climbs the RSG branch. This would imply that the feedback loop is even stronger and the duration of a high mass-loss phase shorter than shown in the prior section.

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