The Metallicity Dependence of Wolf-Rayet Mass Loss

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Abstract

There has been much interest in recent years in Wolf-Rayet (WR) stars as progenitors of supernovae and long-duration gamma-ray bursts. As the background galaxies of these stars can range in metallicity from above solar to near zero metallicity, it is important to understand the effect metallicity has on the mass-loss rate. We produce models of early WN, WC, and WO stars as a function of metallicity. For a WN wind the mass-loss rate plummets as gaps in the spectrum open, allowing photon escape. For a WC or WO wind the mass-loss rate tends to flatten to around 10^{-8} $M_{\odot}$ yr^{-1} at low metallicity because of the self-enrichment of C and O. In addition to the metallicity dependence, we introduce new data from the Los Alamos opacity group for Ni XI - XII, which are unavailable in the Opacity Project or Kurucz list.

Introduction

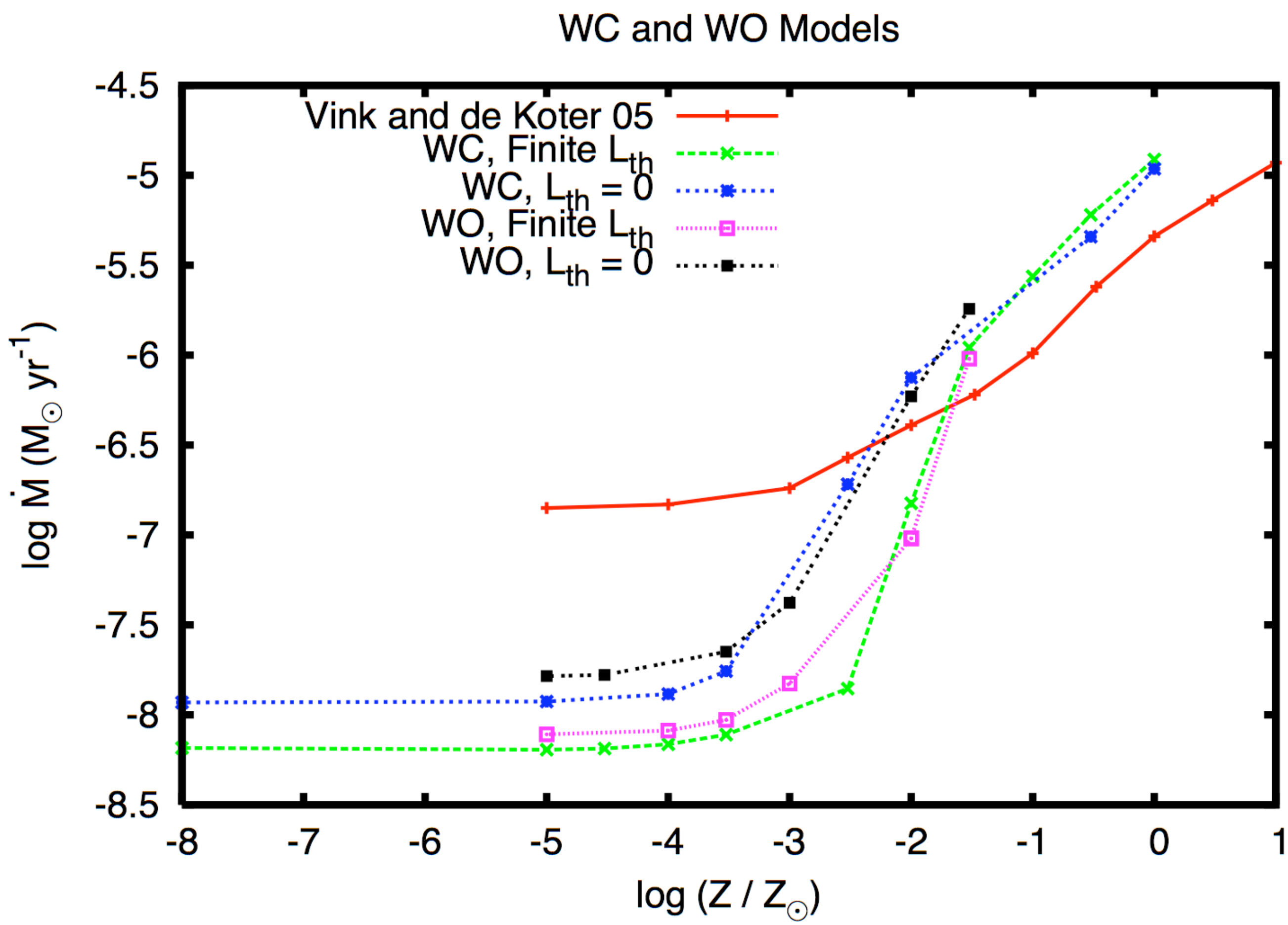
Wolf-Rayet (WR) winds are believed to be driven by radiation pressure on millions of spectral lines. Thus the mass-loss rates of WR stars can be strongly dependent on the metallicity of the background material from which the star formed. However, the self-enrichment of WR stars allows an effective metallicity floor to develop, which can keep the mass-loss rate from dropping at very low metallicity. Vink & de Koter (2005, hereafter VdK05) explored this dependence for late-type WN and WC stars using a Monte Carlo approach, finding a flattening for WN stars by $Z / Z_{\odot} \sim 10^{-4}$ and for WC stars starting at $Z / Z_{\odot} \sim 10^{-3}$. In contrast to the VdK05 approach of modeling the wind globally, we model the local conditions of early-type WN, WC, and WO stars at the critical point using a modified CAK approach, as described in Onifer & Gayley (2006). Since the wind temperature is thought to be ~100,000 K or more near the critical point, the Kurucz list (Kurucz 1979) is insufficient to describe the line opacity, so we augment the Kurucz data with data from the Opacity Project (Badnell & Seaton 2003), and from the opacity group at Los Alamos (Mazevet & Abdallah 2006).

Models

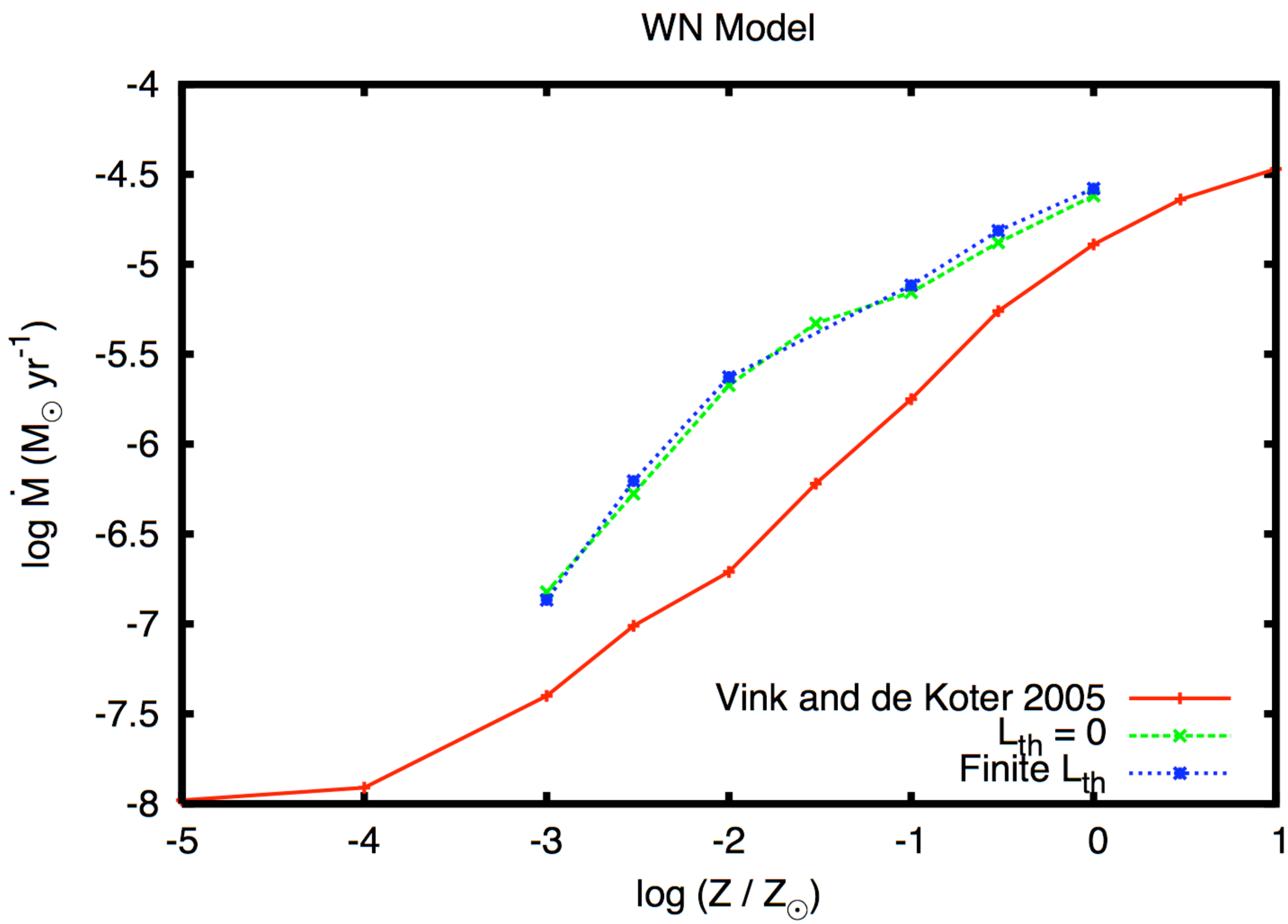
The baseline WN star is based on stellar parameters for the WN4 star WR6 calculated by Hamann, et al. (2006). The baseline WC star is the WC4 star HD 32125 studied by Crowther, et al. (2002). The parameters included from these analyses are the stellar mass M_* and the terminal speed v_∞. The critical point temperature T_c = 1.3x10^5 K. The electron density at the critical point is n_e = 10^{13} cm^{-3}. The luminosity is set such that the Eddington parameter Γ = 0.5 and is fixed throughout the entire metallicity range. The abundances are set as shown in Table 1. The solar metallicity abundances are based on Asplund, et al. (2004). The metallicity is scaled in such a way that the N abundance is fixed. In WC stars the Ne abundance is fixed as are the ratios C / He and O / He. Thus "$Z / Z_\odot$" should be thought of as the metallicity of the WR progenitor, or the ratio of, e. g., Fe abundance, rather than the actual metallicity of the WR wind. A WO star model that has the same parameters as the WC model, but with a smaller C / O and slightly larger C / He ratio was also produced to determine any differences at low metallicity. The C / He and C / O ratios are similar to the Sand 1 model in Kingsburgh, et al. (1995).

Table 1: Parameters for model WN and WC stars at solar metallicity

Parameter	WN	WC	WO
M ($M_\odot$)	19	14.5	14.5
T_c (K)	$1.3\text{x}10^5$	$1.3\text{x}10^5$	$1.3\text{x}10^5$
Γ	0.5	0.5	0.5
X_{He}	0.99	0.48	0.21
X_C	$2.9\text{x}10^{-4}$	0.43	0.51
X_N	$1.0\text{x}10^{-2}$	0	0
X_o	$1.8\text{x}10^{-4}$	0.064	0.25
X_{Ne}	$1.1\text{x}10^{-3}$	0.021	0.021
v_∞ (km s^{-1})	1700	2500	2500



WC models with a finite L_{th} (green) and L_{th} = 0 (blue) are compared to the VdK05 results (red). Our results show a much steeper drop in mass-loss in the range $10^{-3} < Z / Z_{\odot} < 10^{-1}$. WO models, which have more O and less He, are included at low metallicity. The larger fraction of C and O keep the mass-loss rate slightly higher at low metallicity than their WC counterparts.



WN mass-loss rates vs Z for finite L_{th} (blue) and L_{th} = 0 (green), as compared to the results of VdK05 (red). The mass-loss rates are higher because of the much larger number of lines in our models. Our results become steeper at low metallicity, possibly because we allow line-branching and a potentially smaller thermalization length, which means radiation can escape the wind through spectral gaps more easily. No models could be calculated below $Z / Z_\odot = 10^{-3}$.

Thermalization Length

The thermalization length L_{th} is the length over which the opacity can be assumed to not change the frequency dependence of the radiation field via frequency redistribution. This length can contain a potentially large range in temperature such that many different ionization stages are visible to a typical photon. A very short L_{th} corresponds to a highly redistributing wind, and a long L_{th} corresponds to a wind with a small amount of redistribution (effectively gray). Since our model does not self-consistently calculate L_{th}, we have run two sets, one that is in complete frequency redistribution (CRD) and has L_{th} = 0, and one with a thermalization length that corresponds to 6.0×10^4 K $\leq T_c \leq 1.3 \times 10^5$ K.

Conclusions

We have calculated mass-loss rates as a function of metallicity for early-type WN, WC, and WO type stars. We have found that the mass-loss rate flattens for low metallicity WC and WO stars to Mdot ~ 10^{-8} $M_{\odot}$ yr^{-1}. WN star rates do not seem to be dependent on L_{th}, and seem to drop rapidly at low metallicity, contrary to late-type models by VdK05. This may be because they ignore line-branching, causing longer thermalization lengths than we have used in our models.

This represents the first in a grid of models that will also explore the metallicity effects at different luminosities and densities.

References

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Table 2: Mass-Loss Rates compared to references

Model	dM/dt ($M_\odot$ yr^{-1})	Reference dM/dt ($M_\odot$ yr^{-1})
WN	$2.6x10^{-5}$	$5.0x10^{-5}$
WC*	$5.5x10^{-6}$	$1.6x10^{-5}$

WN Reference: Hamann, et al. 2006
WC Reference: Crowther, et al. 2002
*Z/Z_{sun} = 0.3 model used because star is in the LMC

Note that only the mass and terminal speed were used from the references.