Not so cool...
red supergiants
and
the Hayashi-limit
of
massive stars

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IfA
our nearest RSG neighbors...
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THE TEMPERATURES OF RED SUPERGIANTS

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Received 2012 November 15; accepted 2013 February 8; published 2013 March 18

ABSTRACT

We present a re-appraisal of the temperatures of red supergiants (RSGs) using their optical and near-infrared spectral energy distributions (SEDs). We have obtained data of a sample of RSGs in the Magellanic Clouds using VLT+XSHOOTER, and we fit MARCS model atmospheres to different regions of the spectra, deriving effective temperatures for each star from (1) the TiO bands, (2) line-free continuum regions of the SEDs, and (3) the integrated fluxes. We show that the temperatures derived from fits to the TiO bands are systematically lower than the other two methods by several hundred kelvin. The TiO fits also dramatically overpredict the flux in the near-IR, and imply extinctions which are anomalously low compared to neighboring stars. In contrast, the SED temperatures provide good fits to the fluxes at all wavelengths other than the TiO bands, are in agreement with the temperatures from the flux integration method, and imply extinctions consistent with nearby stars. After considering a number of ways to reconcile this discrepancy, we conclude that three-dimensional effects (i.e., granulation) are the most likely cause, as they affect the temperature structure in the upper layers where the TiO lines form. The continuum, however, which forms at much deeper layers, is apparently more robust to such effects. We therefore conclude that RSG temperatures are much warmer than previously thought. We discuss the implications of this result for stellar evolution and supernova progenitors, and provide relations to determine the bolometric luminosities of RSGs from single-band photometry.
red supergiants

Brightest stars at infrared light: \(-8 \geq M_J \geq -11\) mag

Final phase of massive star evolution at Hayashi - limit of fully convective stars

Progenitors of core collapse supernovae

Infrared beacons for abundance studies: individual RSGs in galaxies out to the Coma cluster (TMT and E-ELT)
**RSG - SED:** $T_{\text{eff}} = 3400K$

MARCS model atmosphere, Gustafsson et al., 2008; Plez, 2011
Why $T_{\text{eff}}$ of Hayashi-limit important?

- bolometric correction
- luminosity
- mass
- age of clusters
- age of populations
- abundance studies
- reddening, extinction
- SN progemitors

Pioneering work on $T_{\text{eff}}$ by Emily Levesque & Phil Massey
$T_{\text{eff}}$ from BVRI SED and TiO-bands

$T_{\text{eff}} = 3500 \text{ K}$

$A_v = 4.18$

Model = 3500g–0.5


MARCS Model Atmospheres Gustafsson et al. 2008
$T_{\text{eff}}$ from BVRI SED and TiO-bands

$T_{\text{eff}} = 3625$ K

$T_{\text{eff}}$ from BVRI SED and TiO-bands

$T_{\text{eff}} = 3750$ K

$T_{\text{eff}}$ from BVRI SED and TiO-bands

$T_{\text{eff}} = 4000 \text{ K}$

$T_{\text{eff}}$ vs. spectral type

However .... 

- TiO-method **misses** important part of SED - J, H, K
- does NIR give the same answer ???
- our J-band spectroscopy gives higher Teff
Teff = 3400K

B, V, R, I, TiO
However ....

- TiO-method misses important part of SED – J, H, K
- does NIR give the same answer ???
- our J-band spectroscopy gives higher Teff

ESO VLT XShooter spectra of 25 LMC/SMC RSGs

**XShooter**: simultaneous spectral coverage (R ~ 6000) from 0.35 to 2.4 µ (U-band to K-band)

- check TiO-method for Teff
- test J-band spectroscopy at low metallicity
Galaxy
(Solar metallicity)

Large Magellanic Cloud
(0.4x Solar)

Small Magellanic Cloud
(0.2x Solar)

XSHOOTER (VLT instrument)
$T_{\text{eff}} = 3560 \, \text{K}$

$E(B-V) = 0.10 \, \text{mag}$

**TiO - fit**

$T_{\text{eff}} = 3560 \, \text{K}$

$E(B-V) = 0.10 \, \text{mag}$
$T_{\text{eff}} = 3560$ K
$E(B-V) = 0.10$ mag

TiO - fit
$T_{\text{eff}} = 4280 \text{ K}$

$E(B-V) = 0.47 \text{ mag}$

SED - fit

700 K hotter !!!

$T_{\text{eff}} = 4280 \text{ K}$

$E(B-V) = 0.47 \text{ mag}$
$T_{\text{eff}} = 4280$ K

$E(B-V) = 0.47$ mag
$$T_{\text{eff}} = 3620 \text{ K}$$

$$E(B-V) = 0.10 \text{ mag}$$
$T_{\text{eff}} = 3620 \text{ K}$

$E(B-V) = 0.10 \text{ mag}$
SED - fit

$T_{\text{eff}} = 4200 \text{ K}$

$E(B-V) = 0.40 \text{ mag}$

600 K hotter !!!

SED - fit

$T_{\text{eff}} = 4200 \text{ K}$

$E(B-V) = 0.40 \text{ mag}$

lambda (micron)
$T_{\text{eff}}$ discrepancy of MARCS model fits

- $T_{\text{eff}}$ from full SED-fit
  - ~ 500 K hotter than TiO-fit

- TiO-fit – reproduces TiO features and BVRI flux with low $E(B-V) \sim 0.1$ mag
  - fails at JHK

- SED-fit – reproduces BVRIJHK flux with high $E(B-V) \sim 0.4$ mag
  - fails with TiO features
A more model independent approach....

Definition of $T_{\text{eff}}$

\[
\sigma T_{\text{eff}}^4 = \pi \int_0^\infty F_\lambda^{\text{obs}} \, d\lambda
\]

Observed flux

\[
S_\lambda^{\text{obs}} = (R_*/d)^2 \pi F_\lambda^{\text{obs}}
\]

If $(R_*/d)^2$ is known

Observed integral over $F_\lambda^{\text{obs}}$ yields $T_{\text{eff}}$ independent of model atmosphere
$T_{\text{eff}}$ from flux integration method (FIM)

$$S_{\lambda}^{\text{obs}} = (R_*/d)^2 \pi F_{\lambda}^{\text{obs}}$$

use model fluxes only at longest wavelength $\lambda_0$

$T_{\text{eff}}$ → use $F_{\lambda_0}^{\text{model}}(T_{\text{eff}})$ at $\lambda_0$ and

$$S_{\lambda_0}^{\text{obs}} = (R_*/d)^2 \pi F_{\lambda_0}^{\text{model}}$$

$\sigma T_{\text{eff,new}}^4 = \pi \int_0^\infty F_{\lambda}^{\text{obs}} d\lambda$ → $F_{\lambda}^{\text{obs}}$ → $S_{\lambda}^{\text{obs}}$ and $(R_*/d)^2$

for large $\lambda_0$ → $F_{\lambda_0}^{\text{model}}(T_{\text{eff}}) \sim T_{\text{eff}}, x \approx 1$

method converges for $x < 4$
normalization $\lambda_0$
$T_{\text{eff}}$ from flux integration method (FIM)

\[ S_{\lambda}^{\text{obs}} = (R_*/d)^2 \pi F_{\lambda}^{\text{obs}} \]

use model fluxes only at longest wavelength $\lambda_0$

\[ S_{\lambda_0}^{\text{obs}} = (R_*/d)^2 \pi F_{\lambda_0}^{\text{model}} \]

\[ \sigma T_{\text{eff},\text{new}}^4 = \pi \int_{0}^{\infty} F_{\lambda}^{\text{obs}} d\lambda \]

\[ F_{\lambda}^{\text{obs}} \quad \text{and} \quad (R_*/d)^2 \]

for large $\lambda_0$ \quad $F_{\lambda_0}^{\text{model}}(T_{\text{eff}}) \sim T_{\text{eff}}^x, x \approx 1$

method converges for $x < 4$
**interstellar reddening and FIM**

Reddening: \( E(B-V)_i \)
\[ A_{\lambda,i} = R_{\lambda} E(B-V)_i \]

De-redden:
\[ S_{\lambda}^{obs} \rightarrow S_{\lambda}^0 \]

Use:
\[ F_{\lambda_0}^{model}(T_{eff}) \text{ at } \lambda_0 \]
\[ S_{\lambda_0}^0 = (R_*/d)^2 \pi F_{\lambda_0}^{model} \]

Minimum:
\[ \chi_i^2 = \frac{1}{n} \sum_{j=1}^{n} \left( \frac{F_{\lambda_j}^0 - F_{\lambda_j}^{model}}{\sigma_j} \right)^2 \]
\[ E(B-V), T_{eff} \]
FIM \rightarrow T_{\text{eff}}
E(B-V) = 0.4 \text{mag}
interstellar reddening and FIM

reddening \[ E(B - V)_i \]
\[ A_{\lambda,i} = R_{\lambda} E(B - V)_i \]
de-redden
\[ S_{\lambda}^{\text{obs}} \rightarrow S_{\lambda}^0 \]

use \[ F_{\lambda_0}^{\text{model}}(T_{\text{eff}}) \] at \( \lambda_0 \) and
\[ S_{\lambda_0}^0 = (R_*/d)^2 \pi F_{\lambda_0}^{\text{model}} \]

\[ \sigma T_{\text{eff,new}}^4 = \pi \int_0^\infty F_{\lambda}^0 d\lambda \]

\[ \chi_i^2 = \frac{1}{n} \sum_{j=1}^{n} \left( \frac{F_{\lambda_j}^0 - F_{\lambda_j}^{\text{model}}}{\sigma_j} \right)^2 \]

minimum \[ E(B - V), T_{\text{eff}} \]

\[ (R_*/d)^2 \]
FIM - fit

$T_{\text{eff}} = 4200 \, \text{K}$

$E(B-V) = 0.36 \, \text{mag}$
$T_{\text{eff}} = 4020$ K
$E(B-V) = 0.32$ mag
Flux integration method - FIM

- FIM result is also model dependent
- but model fluxes used only at two wavelengths to constrain $E(B-V)$ and $R/d$
- Model independent lower $T_{eff}$ limits at low $E(B-V)$
change in HRD
3D convection simulation Betelgeuze

Large pressure scale height → huge convective cells

Chiavassa et al. 2011
Temperature structure: 3D vs. MARCS

Chiavassa et al. 2011
3D effects on TiO and SED

1-D model which fits visual spectrum of 3D-model fails in the near-IR \(\rightarrow\) consequences for Teff determination !!!

Figure 6. Analysis of the 3D \textit{CO}^{5}\textit{BOLD} RSG spectrum of Chiavassa et al. (2011) with the 1D MARCS models. The left panel shows the 3D spectrum (black) along with the fit to the TiO bands (green), yielding a best-fit \(T_{\text{eff}} = 3600\) K. The right panel shows that this fit overpredicts the flux at the \(H\)-hump, and in the \(K\) band. Meanwhile, a fit to the NIR continuum regions (magenta) gives a higher temperature of 3800 K, while underpredicting the strengths of the TiO bands. This mimics the behavior seen in our spectra of RSGs in the Magellanic Clouds (see Figure 9).

(A color version of this figure is available in the online journal.)

from Davies, Kudritzki et al., 2013, ApJ 767, 3