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Evolutionary Tracks of Betelgeuse

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We have constructed a series of quasi-hydrostatic evolutionary models for the M2 Iab supergiant Betelgeuse (α *Orionis*). Our models are constrained by the observed temperature, luminosity, surface composition and mass loss for this star, along with recent parallax measurements and high resolution imagery which directly determine its radius. The surface convective zone obtained in our model roughly accounts for observed variations in surface luminosity and the size of detected surface bright spots. In our models these result from upflowing convective material from regions of high temperature in the surface convective zone. We also account for the observed periodic variability as the result of the equation of state in a simple linear pulsation model. Based upon a best fit to all observed data we suggest a mass estimate of $\approx 21 \pm 2$ M$_\odot$.

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1. Introduction

The M2 Iab supergiant Betelgeuse (α *Orionis*) is an ideal laboratory to study advanced stages of stellar evolution. It has the largest angular diameter of any star apart from the Sun and is one of the brightest M giants. As such, it has been well studied. Direct HST imagery exists of this star (Gilliland & Dupree 1996; Lobel 2001) as well as other high resolution indirect imagery (Balega et al. 1982; Buscher et al. 1990; Marshall et al. 1992; Burns et al. 1997). These high resolution data indicate the appearance of intermittent bright spots associated with irregular variability in the star's luminosity and temperature. It is also known that this star exhibits periodic ($\approx$420 day) modulation of the optical and UV flux most likely associated with photospheric pulsations (Dupree et al. 1987). A shell of circumstellar material has also been detected around this star (Noriega-Crespo et al. 1997; Lobel 2001, 2003), and it appears to be losing mass at a rate of 2-4 $\times 10^{-6} M_{\odot}$ y^{-1} (Plez et al. 2002; Ryde et al. 2006; Harper et al. 2008). Isotopic CNO abundance data are also available (Gautier et al. 1976; Harris & Lambert 1984; Lambert et al. 1984) which may show evidence of deep interior mixing. These measurements have been complemented by the availability of high precision parallax measurements from the *Hipparcos* satellite, which have been recently revised (Harper et al. 2008). New absolute luminosities and photospheric radii are sufficiently well determined to seriously constrain models for this star.

Here we apply a quasi static stellar evolution code from the pre-main sequence to the completion of core carbon burning. We find the combinations of stellar mass, mixing length, and Reimers (1975) mass loss parameter *eta* which best reproduce the observed radius, temperature, and luminosity for this star. We then study the observed abundances, brightness variations, and periodicity in the context of this model.

2. Data

Over the years a great deal of data has accumulated for α *Orionis*. Because of the variability of the star during observations, however, it is difficult to ascribe an uncertainty to the visual magnitude. The error associated with the quoted apparent visual magnitudes are largely a measure the observed variability of the star during the observation epoch. They are, therefore, not a true measurement error. Hence, to assign an uncertainty to the adopted mean visual magnitude we simply take the unweighted standard deviation of the various determinations of the mean value. The assumption made here is that the true measurement error is roughly constant for these data. Fortunately, our results are nearly independent of this particular choice for the uncertainty in the mean luminosity, since the uncertainty in the final absolute luminosity is largely determined by the distance uncertainty.

The quoted parallax measurements by *Hipparcos* ($\approx$131 pc) and *Tycho* ($\approx$54 pc) disagree by more than a factor of two. This is well outside the range of quoted errors. Moreover, there has recently been a new determination of the distance to Betelgeuse of $\approx$197 pc (Harper et al. 2008). This new *VLA-Hipparcos* distance is derived from multi-wavelength observations and is the value adopted here as having the greatest accuracy and least distortion from the variability.

Determination of the angular diameter Θ_{disk} of this star from the observations is also complicated by the pulsations. Quoted values in the literature are distributed into two distinct groups, centered around 44 mas (Perrin et al. 2004; Haubois et al. 2006) and 57 mas (Burns et al. 1997; Tuthill et al. 1997; Weiner et al. 2000). We adopt the more recent value of 42 ± 0.06 from Perrin et al. (2004) and Haubois et al. (2006). This adopted angular diameter, combined with the VLA-Hipparcos distance, yields a radius of 889 ± 205 $R_\odot$. These parameters, along with the observed CNO abundances and lack of s-process abundances (Lundqvist & Wahlgren 2005), allow for highly constrained models.

3. Model

A spherical, nonrotating stellar evolution was calculated using the stellar evolution code originally developed by Eggleton (1971), but with updated nuclear reaction rates and an expanded network, along with modern opacities and EOS tables (Iglesis & Rogers 1996). The models for α *Orionis* were constructed using an approximately solar composition with $X = 0.70$, $Y = 0.28$, $Z = 0.02$ (Lambert et al. 1984). We utilized 300 radial mesh points held roughly constant in mass during the evolution. The calculations were followed from the precollapse of an initial protostellar cloud through the completion of core carbon burning. Mass loss was followed along the giant branch using a Reimers rate. The models were varied in initial mass and mixing length. The model that best fit the observations was a 21 $M_\odot$ star with a mixing length parameter of $\alpha = 1.6$.

The currently observed mass loss rate is $3 \pm 1 \times 10^{-6}$ $M_\odot$ y^{-1} (Harper et al. 2001; Plez et al. 2002; Ryde et al. 2006). For a Reimers (1975) mass loss rate,

$$\dot{M} = -4 \times 10^{-13} \eta \frac{L}{gR} \ \ \mathrm{M_\odot yr^{-1}} \tag{3.1}$$

The observed rate requires a mass loss parameter of $\eta = 1.6 \pm 1$ for a ≈ 21 $M_\odot$ star of the adopted L and R. This value is not atypical for giants.

In Dupree et al. (1987) and Smith, Patten, & Goldberg (1989) a pulsational period of 420 days was detected. It is worthwhile to see what kind of periodicity might emerge from this model. We can estimate the period to be expected from a linear adiabatic wave analysis of radial oscillations (Cox & Giuli 1958). For a star of mean density ρ_0 and mean equation of state index γ_0, the pulsation period Π is,

$$\Pi = \frac{2\pi}{\sqrt{(3\gamma_0 - 4)(4/3)\pi G \rho_0}} \ \ . \tag{3.2}$$

For our best fit model the mean density is $\rho_0 = 2.45 \times 10^{-8}$ g cm^{-3} and the mean polytropic index is $\gamma = 1.55$. This implies a pulsation period of $\Pi = 830$ d. Even using this crude linear pulsation model, we achieve a period that is off by only a factor of 2. The fit is a good one considering the crudeness of this first pulsation modeling attempt.

4. Conclusions

Our model for α *Orionis* is consistent with all of the presently known observables within the accuracy of a simple nonrotating, spherical model. The mass loss, surface temperature and luminosity are all consistent with this star being on the giant branch. Our best model is consistent with a mass of 21 $M_\odot$ and a mixing length parameter of $\alpha = 1.6$. Figure 1 shows the HR diagram

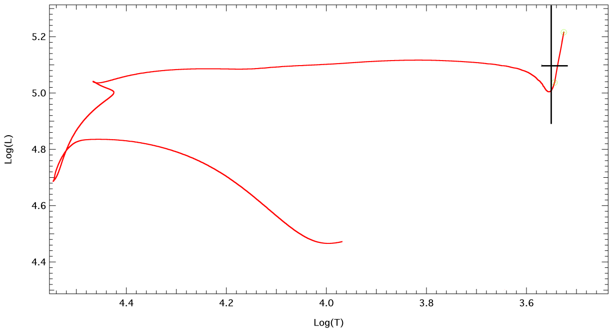

Figure 1: HR diagram for 21 $M_\odot$ model. Error bars indicate observed values and associated error.

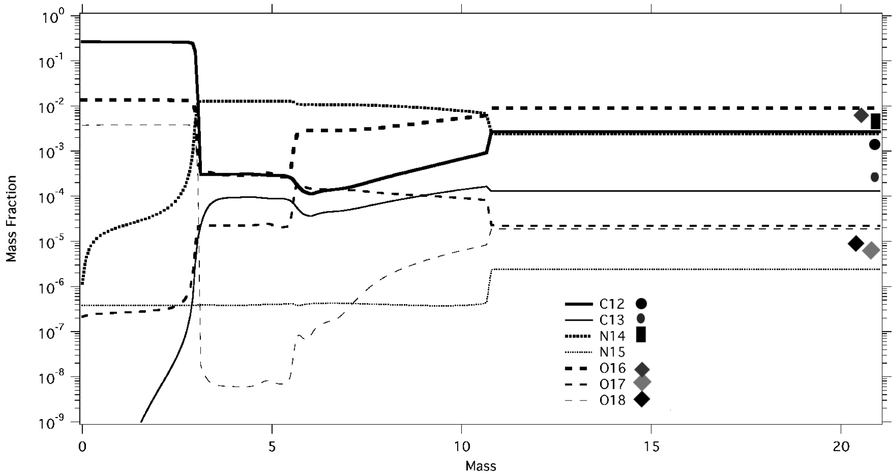

Figure 2: CNO abundaces for 21 $M_\odot$ model. The carbon-oxygen core ends at around 3 $M_\odot$, the helium and hydrogen shell end at around 6 $M_\odot$ and 12 $M_\odot$ respectively, surrounded by the outer convective envelop extending to the surface. Points on the far right indicate the observed abundances at the surface.

of that model. The cross bars on this graph indicate the currently observed properties. Figure 2 shows the CNO abundances of our 21 $M_\odot$ model. The points on the figure indicate observed surface values (Lambert et al. 1984), which are in good agreement with this model. With added deep interior mixing, the amounts of ^{12}C and ^{16}O would be lowered, as well as raising the levels of ^{13}C and ^{14}N, matching observed values almost exactly. The model agrees well for a star that is just beyond the initiation of core He burning.

What is perhaps most needed now are multidimensional turbulent models together with a non-linear pulsation treatment to further probe the nature of pulsation and surface convection.

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