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Triggering eruptive mass ejection in luminous blue variables

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ABSTRACT

We study the runaway mass loss process of major eruptions of luminous blue variables (LBVs) stars, such as the 1837–1856 Great Eruption of η Carinae. We follow the evolution of a massive star with a spherical stellar evolution numerical code. After the star exhausted most of the hydrogen in the core and had developed a large envelope, we remove mass at a rate of $1\,M_\odot\,\text{year}^{-1}$ from the outer envelope for 20 years. We find that after removing a small amount of mass at a high rate, the star contracts and releases a huge amount of gravitational energy. We suggest that this energy can sustain the high mass loss rate. The triggering of this runaway mass loss process might be a close stellar companion or internal structural changes. We show that a strong magnetic field region can be built in the radiative zone above the convective core of the evolved massive star. When this magnetic energy is released it might trigger a fast removal of mass, and by that trigger an eruption. Namely, LBV major eruptions might be triggered by magnetic activity cycles. The prediction is that LBV stars that experience major eruptions should be found to have a close companion and/or have signatures of strong magnetic activity during or after the eruption.

1. Introduction

Luminous blue variables (LBVs) are massive hot luminous stars. They posses very strong winds that exhibit irregular variabilities on time scales ranging from days to years. On top of these variations, LBVs experience extreme mass loss rate episodes (e.g. Smith and Owocki, 2006; Owocki and van Marle, 2009, and references therein), e.g., the 19th century eruptions of η Carinae (Humphreys et al., 1999), where a mass of ~ 10–$20\,M_\odot$ was lost (Smith et al., 2003b; Smith, 2006; Smith and Owocki, 2006; Smith and Ferland, 2007). These eruptions cannot be accounted for by the regular stellar luminosity, and they require some extra energy source, e.g., internal structural change in the star, that might even increase the stellar luminosity above the Eddington limit (Owocki and van Marle, 2009). However, part, or even all, of the increase in the luminosity of η Car in the 1837–1856 Great Eruption could have come from gravitational energy of the mass accreted by the secondary star (Soker, 2007). The accretion of mass onto the secondary star can explain also the kinetic energy of the Homunculus (Soker, 2007); the Homunculus is the bipolar nebula of η Car that was formed in the Great Eruption (Davidson and Humphreys, 1997).

The influence of radiation on the mass loss process of stars near their Eddington luminosity limit in relation to LBV eruptions is discussed by van Marle et al. (2008, in press) and Owocki and van Marle (2009). In particular, they discuss how the extended porosity formalism (Shaviv, 1998, 2000) can account for the Great Eruption of η Car (Owocki et al., 2004; van Marle et al., 2008, in press). In the present paper, we do not deal with the interaction of radiation with matter. We rather limit ourself to discuss the possible instability process that can lead to the release of a huge amount of energy by internal structural change.

One of the significant differences between our approach and most other studies of the Great Eruption of η Car concerns the energy of the Homunculus. While most studies (e.g. Smith, 2006) attribute the entire energy source to the primary enhanced luminosity, we take the view that most of the kinetic energy of the Homunculus results from two opposite jets that were blown by the companion during the Great Eruption. The companion blew the jets as it accreted mass from the primary dense wind via an accretion disk (Soker, 2007). Therefore, we do not deal with the energy of the homunculus, but only with the energy that is required to unbind a mass of ~ 10–$20\,M_\odot$ during the Great Eruption of η Car, and similar LBV eruptions. The same jets can account for fast ejecta that were blown from the η Car binary system (Smith and Morse, 2004).

The mass of ~ 10–$20\,M_\odot$ (Smith et al., 2003b; Smith and Ferland, 2007) that was ejected in the Great Eruption resides in the outer part of the radiative outer region of LBV stars. In Section 2, we build a stellar model that has a similar structure to that of η Car before the Great Eruption, and discuss some of its properties. Soker (2007) already speculated that the Great Eruption of η Car was triggered by disturbances in the outer boundary of the inner convective region, most likely by magnetic activity, that expelled

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the outer radiative zone. Soker (2007) further mentioned that one way to form an extended envelope is by the contraction of the inner layers. In Section 3, we go one step further and show that indeed, the removal of the outer region of the star causes the star to shrink and release a huge amount of gravitational energy. Earlier suggestions for the cause of LBV instability was summarized by Humphreys and Davidson (1994). Some of them, e.g., the geyser model of Maeder (1992), cannot work for a hot star like η Car. As we show, our model works for blue stars. In Section 4, we discuss in more detail the possibility that the initial mass removal in LBV outbursts is triggered by magnetic activity. We summarize in Section 5.

2. Stellar structure

We evolve a spherical stellar model with the same evolutionary code that was used by us in previous studies over the years (for detail see Soker and Harpaz, 1999). We start at $t = 0$ with a zero-age main sequence star of mass $M_0 = 190\,M_\odot$. Mass loss is not a major part of our study as we are interested in the stellar model toward the end of the main sequence. We simply set the mass loss rate to be $\dot{M} = 2 \times 10^{-5}\,M_\odot\ \mathrm{year}^{-1}$ (for more detail on the evolutionary track of massive stars the reader can consult, e.g. Meynet and Maeder (2003, 2005)). The mass, luminosity, and effective temperature, at four evolutionary points are $[M(M_\odot), L(10^6\,L_\odot), T_e(10^4\ \mathrm{K})] = (190, 3, 5.7)$, $(160, 3, 5.1)$, $(150, 3, 4.4)$, and $(139, 3, 1.6)$. The luminosity does not evolve much, but as the hydrogen in the core is close to exhaustion the envelope swells and the effective temperature decreases (see also Smith and Conti (2008)). In Fig. 1, we show the stellar structure at $t = 0$ and at $t = 2.55$ M year.

Most relevant to us is the entropy profile. The regions where the entropy profile is flat (actually decreasing very slowly) are convective regions. At early times the star is almost completely convective. At later times the entropy is flat in the inner $\sim 80\,M_\odot$. The outer regions are mainly radiative. Above the inner convective region the entropy increases substantially with mass (and radius). Then, in the outer ~ 15–$20\,M_\odot$ the profile becomes shallow, and a second convective region exists there. At late times most of the volume of the envelope is an outer extended region with very low density ($\sim 10^{-7}$–$10^{-6}\ \mathrm{g\ cm}^{-3}$) that contains a relatively small amount of mass ($< 1\,M_\odot$).

The evolutionary numerical code calculates the entropy S_e using the full equation of state. To further elaborate on the entropy behavior to be used later, we examine the quantity $S_\gamma = P\rho^{\gamma_{\rm ad}}$. As evident from Fig. 2, in the massive radiative region above the convective core a value of $\gamma_{\rm ad} = 1.33$ accurately describes the rapid entropy rise. In Fig. 2, we plot the logarithm of the pressure and of the density, the mass, the accurate entropy calculate by the stellar code S_e, and of S_γ for $\gamma_{\rm ad} = 4/3$ (units are given in the caption), as function of stellar radius for the second model shown in Fig. 1. We note again the rapid rise in the entropy from the core, and then the flattening in the outer ~ 15–$20\,M_\odot$, where a second convective region resides in the region $22 \lesssim r \lesssim 28\,R_\odot$. The very extended outer region is not shown, as it contains a small amount of mass $< 1\,M_\odot$.

The important property to take from the graphs is that the mass expelled in eruptions of LBVs, such as the Great Eruption of η Car, is a high-entropy gas.

3. The eruption phase

Stars with a radiative envelope shrink as they loss mass on a time scale shorter than the thermal time scale (Webbink, 1976; Heisler and Alcock, 1986; Maeder, 1992). The release of gravitational energy by the contracting envelope can lead to an increase in the mass loss rate, resulting in a runaway mass loss process.

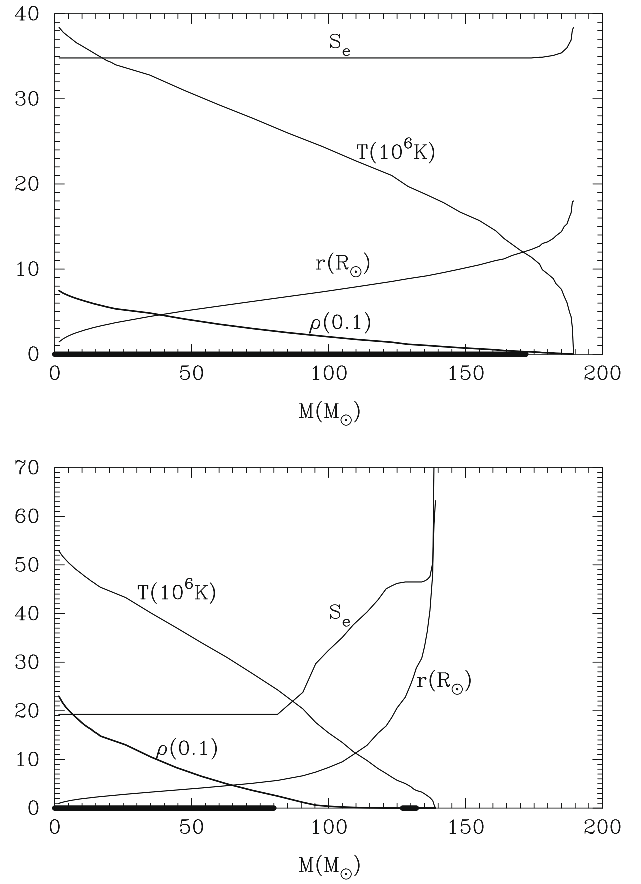

Fig. 1. Density (in units of 0.1 g cm^{-3}), temperature (in units of 10^6 K), entropy S_e (in relative units), and radius (in solar radii), as function of mass for two evolutionary times: $t = 0$ on the upper panel and $t = 2.55 \times 10^6$ year in the lower panel. The two models have $[M(M_\odot), L(10^6\,L_\odot), T_e(10^4\ \mathrm{K})] = (190, 3, 5.7)$, and $(139, 3, 1.6)$, respectively. The thick lines on the horizontal axis mark the convective regions. In the lower panel the photospheric radius is $220\,R_\odot$, and it is outside the graph.

To examine the behavior of our model we start with the star at the evolutionary point $[M(M_\odot), L(10^6\,L_\odot), T_e(10^4\ \mathrm{K})] = (139, 3, 1.6)$, and we remove $\Delta M_{\rm burst} = 20\,M_\odot$ with a constant mass loss rate of $\dot{M}_{\rm burst} = 1\,M_\odot\ \mathrm{year}^{-1}$ for 20 years. The mass is removed from the outer radiative region. This mass loss rate mimics the average mass loss rate during the Great Eruption. We then reduce the mass loss rate to $\dot{M}_p = 2 \times 10^{-4}\,M_\odot\ \mathrm{year}^{-1}$, and follow the star for another 200 years. In Fig. 3, we plot the radius and luminosity of the star as function of time during the eruption.

The mass loss rate during the 20 years eruption proceeds on a time scale much longer than the dynamical time scale, but it is shorter than the thermal time scale. At the beginning of the outburst the stellar radius is $R = 220\,R_\odot$. The average thermal time scale of the outer region of mass dm is $\tau_{\rm th} = GMdm/RL$, while the mass loss time scale is $\tau_{\rm ml} = dm/\dot{M}$. Their ratio is

$$\frac{\tau_{\rm th}}{\tau_{\rm ml}} = 7\left(\frac{M}{140\,M_\odot}\right)\left(\frac{\dot{M}}{1\,M_\odot\ \mathrm{year}^{-1}}\right)\left(\frac{R}{200\,R_\odot}\right)^{-1}\left(\frac{L}{3 \times 10^6\,L_\odot}\right)^{-1}. \quad (1)$$

The thermal time scale is substantially longer than the mass loss time scale. As a result of this the star losses its thermal equilibrium and rapidly contracts, i.e., on a time scale of few years which is much shorter than the thermal time scale. As our model is not fully built to take into account evolution on time scales shorter than the thermal time scale, e.g., it does not take into account the energy re-