Are the declines of R Coronae Borealis stars caused by super-Eddington luminosities?

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Abstract. The recently constructed line-blanketed, hydrogen-deficient model atmospheres show a very steep temperature gradient. In the inner layers ($\tau_{\text{Ross}} > 10$), the models show density inversions and for certain low gravity models the luminosity exceeds the local Eddington limit and hence gas pressure inversions also occur. Comparison of this latter limit with recent spectroscopic estimates of stellar parameters for the R Coronae Borealis (RCB) stars indicate that the stars are indeed located along the limit. We propose that the declines of RCB stars are triggered by an instability occurring in their atmospheres due to the super-Eddington luminosities. Their probable ancestors, the hydrogen-deficient carbon (HdC) stars, should on the other hand still be sub-Eddington. We also note the interesting similarity with the Luminous Blue Variables (LBV) regarding the closeness to the Eddington limit.

1. Introduction

The reason for the famous declines of R Coronae Borealis stars are, two centuries after their first discovery, still a mystery. The general picture with a opaque dust cloud forming in the line-of-sight which subsequently disperses was first proposed by Loreta (1934). Observations indicate that the dust condensation occurs close to the stellar surface (Whitney et al. 1992) and also that it is limited to smaller locations rather than a spherical shell, since the IR emission remains the same during a decline. However, the triggering mechanism for this scenario is not known. Furthermore, something seems special with the RCB stars compared to the HdC and Extreme Helium (EHe) stars, since those show no declines. Pulsations has often been proposed to cause the declines but several problems with this remain, the main objections being that there seems to be no correlation with pulsation amplitude and frequency of declines, and that the HdC stars also pulsate without experiencing the fading events.

Since the dust seems to form close to the stellar surface one may suspect that the condensation is in fact triggered by phenomena in the surface layers or even in the atmosphere. During the construction of new line-blanketed, model atmospheres for hydrogen-deficient stars (Gustafsson & Asplund 1996; Asplund et al., in preparation) we noticed the presence of density inversions for all models, which is related to the helium ionization zone (lowering of the mean molecular weight and large radiation pressure). This is an effect of the very steep temperature gradient, in turn caused by the heavy line-blanketing. Some low-gravity
models even show gas pressure inversions, which for the hydrostatic case is the result of the luminosity of the model exceeding the Eddington limit locally (Asplund & Gustafsson, in preparation). Here we propose that the declines of RCB stars are caused by a super-Eddington luminosity. The hypothesis is supported by the location of RCB stars in relation to the limit.

2. The Eddington limit

The Eddington limit is reached when the outwards directed radiative acceleration equals the gravitational acceleration inwards. Since hydrostatic equilibrium is assumed for the models this must be compensated by the development of a gas pressure inversion:

\[ \frac{1}{\rho} \frac{dP_{\text{gas}}}{dr} = -g_{\text{eff}} = -g_{\text{grav}}(1 - \frac{g_{\text{rad}}}{g_{\text{grav}}}) = -g_{\text{grav}}(1 - \Gamma), \]

with the radiative acceleration defined as

\[ g_{\text{rad}} = \frac{1}{c_P} \int_0^{+\infty} \chi_{\nu} F_{\nu} \, d\nu, \]

and \( F_{\nu} \) being the flux and \( \chi_{\nu} \) the extinction coefficient (Asplund & Gustafsson, in preparation). A super-Eddington luminosity is favoured by a low surface gravity, high opacity and large flux, all occurring in RCB stellar atmospheres at \( \tau_{\text{Ross}} \sim 10 \) where He ionizes. The main opacity source is He I bound-free and not line opacity but the effect of the latter is indirect through their steepening of the temperature gradient. Compared to the classical Eddington limit, with only Thomson scattering and assuming complete ionization, this opacity-modified Eddington limit occurs at significantly larger \( \log g \), see Fig. 1.

In a model with super-Eddington luminosity the gas basically floats upon a bed of photons. It may be questioned whether this is a physically possible situation, especially since strong convection is predicted by the models further in. In fact, for \( T_{\text{eff}} < 8500 \) K the Eddington limit is restricted by the presence of the convection zone, which decreases the temperatures and hence the opacity in the inner layers. Otherwise the limit would occur for yet larger gravities. For higher temperatures convection becomes inefficient and the temperature stratification resembles more the radiative equilibrium one: the location of the limit is not dependent on the convection. The convection is treated through the mixing length theory for the models and one may question its usefulness in these extreme situations. It should be emphasized though that the atmosphere is not Rayleigh-Taylor unstable in the gas pressure inversion, since the direction of acceleration is outwards for these layers. However, it is not clear that a radiatively driven wind is initiated as in hot stars, since \( \Gamma_{\text{max}} \) occurs in rather deep layers. More work on the stability is definitely called for.

Comparing the observed parameters of RCB stars (Lambert et al., in preparation) with the derived limit from the models (\( \Gamma_{\text{max}} = 1 \)) as in Fig. 1 shows a suggestive connection between them. Rather than being randomly scattered in the \( T_{\text{eff}} - \log g \)-diagram the stars lay along the limit, mainly on the unstable side. The limit has been calculated assuming C/He=1%, the same ratio as observed for EHe stars. Turbulent pressure has been neglected but it would bring
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Figure 1. The location of the Eddington limit compared to observed parameters of RCB stars (17 stars in total). Also shown are the classical Eddington limit and the parameters for the EHe and hot RCB stars.

The limit towards larger gravities (by about 0.3 dex). Pulsation is expected to further destabilize the stars by shifting them in periods towards higher temperatures ($\Delta T_{\text{eff}} = \pm 250 \text{ K}$ for R CrB, Lambert et al., in preparation). Since the RCB stars are thought to evolve towards higher temperatures (Kilkenny 1982) at constant luminosities (the same slope as in Fig. 1 for the classical Eddington limit) they also evolve from sub-Eddington to super-Eddington luminosities. Unfortunately there exist to date no accurate estimates of fundamental parameters for the cool RCB stars or the probably related HdC stars, but we predict that the latter should have sub-Eddington luminosities from the fact that they do not show the typical RCB decline phenomena. We have not yet explored the limit for high $T_{\text{eff}}$s and can therefore not say how the EHe stars are located in relation to the limit. However, in the case of solar abundances the limit bends up towards the classical Eddington limit around $T_{\text{eff}} = 10\,000 \text{ K}$ (Lamers & Fitzpatrick, 1988; Gustafsson & Plez, 1992) and a similar behaviour at higher temperatures is expected for the hydrogen-deficient case.

The lack of IR excess for HdC stars can be explained by the fact that the gas ejections have not yet started, since they are presumably still sub-Eddington. For EHe stars the circumstellar material is dispersing due to the cease of declines. It is however not clear how the hot RCB stars (MV Sgr, V348 Sgr and DY Cen) fit into this picture since they have similar parameters as the EHe stars. Their declines could possibly have another cause than the other RCB stars rise time.

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3. The RCB-LBV connection

There are interesting similarities between the RCB stars and the Luminous Blue Variables (LBV) with respect to the near- or super-Eddington luminosities and the eruptive behaviour. The difference that LBVs seem to eject gas in all directions while RCB stars probably do it locally may be qualitatively understood as a consequence of the direction of their evolution: LBVs evolve towards cooler temperatures while the opposite is true for RCB stars. In Fig. 2 we schematically plot the variation of the Eddington limit as a function of effective temperature at constant luminosity for LBVs and RCB stars. As an LBV evolves towards cooler temperatures it comes closer to the Eddington limit which causes an expansion of the star and hence even lower temperatures, which in turn brings it yet closer to the limit (Appenzeller 1989). This runaway is a global instability. For a RCB star, which approaches higher temperatures, the levitation due to the Eddington limit will try to cool the surface layers and hence counterwork the evolution. Therefore a global instability will not occur but a local instability may still take place as a result of e.g. photon bubbles (Arons 1992).

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