SOME OBSERVATIONAL ASPECTS OF R CORONAE BOREALIS STARS

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Abstract.
Some of the observational aspects related to the evolutionary status and dust production in R Cor Bor stars are discussed. Recent work regarding the surface abundances, stellar winds and evidence for dust production in these high luminosity hydrogen deficient stars are also reviewed. Possibility of the stellar winds being maintained by surface magnetic fields is also considered.

1. Introduction

R Coronae Borealis stars (RCBs) are dust making hydrogen deficient, carbon and helium rich F-G supergiants. The major puzzles they pose are two: namely, what are their origins (i.e., their place in the stellar evolution of single or double stars, their predecessors and descendants) and how do they make dust in their warm atmospheres. I would like to explore in this article some of the observational aspects that concern these two issues. There are two major scenarios that have been proposed to account for their origins. The first one involves a single star – a result of a ‘final He-shell flash’ in a post-asymptotic giant branch star that is passing through the white dwarf cooling track. The energy released is expected to make the star a hydrogen deficient, cool luminous star that evolves relatively rapidly across the HR diagram back to the white dwarf track for a second time. This is dubbed as ‘final flash (FF)’ scenario. The second one involves a pair of white dwarfs, a C-O white dwarf and a He white dwarf that merge together by emitting gravitational waves. The He white dwarf is accreted on to the C-O white dwarf leading to the formation of H-poor cool supergiant with a white dwarf at its core. This is dubbed as ‘double-degenerate (DD)’ scenario. The life times in H-poor supergiant stage are supposed to be longer in the DD scenario. Although there are no decisive observational tests, presently, to choose either one (or any other alternative) of the scenarios, the accumulated observations so far seem to favour the DD scenario.

2. The Number and Distribution of RCBs

Do the estimated number of RCB stars in the galaxy provide any clues regarding the two scenarios proposed for their origins? Presently known members in the galaxy amount to about 40 (Zaniewski et al. 2005), about 21 are known in LMC (including DY Per stars) and about 2 in SMC (Alcock et al. 2001; Kraemer et al. 2005). The statistics is more complete for LMC objects. By scaling the LMC population to the Galaxy, Alcock et al. estimate the total number of RCBs
in the Galaxy as over 3200. According to [Iben et al. (1996)] the two evolutionary scenarios proposed (DD and FF) individually could only account partially for the number of RCBs present in the Galaxy. Thus both schemes might be contributing to the total number. However, based on the data of white dwarf binaries from SPY project, [Mitchell & Clayton (2005)] claim that an estimate of the expected population of RCBs in the galaxy produced by DD scenario is consistent with numbers expected in the Galaxy. A detailed reassessment using updated evolutionary time scales would be worth while.

The galactic distribution of RCBs seem to suggest that they might belong to the thick disk population ([Zaniewski et al. (2005)] although few of them might even be part of the halo e.g. U Aqr ([Cottrell & Lawson 1998]). The existence of RCBs in the galactic bulge as well as SMC suggests a spread in metallicity. The similarity of kinematics with planetary nebulae of Peimbert’s III group seem to suggest that majority of them are likely to be moderately metal poor ([Rao & Lambert 1996]).

3. Properties at Maximum light

3.1. Spectral analyses

Most of the spectral analyses that were attempted to arrive at the surface abundances and other properties like \( T_{\text{eff}} \) and \( \log g \) etc are based on the LTE line blanketed model atmospheres computed at Uppsala (Asplund, Gustafsson, Eriksson) for \( T_{\text{eff}} < 9000 \) K and at Armagh (Jeffery and collaborators) for \( T_{\text{eff}} > 9000 \) K. Some of the major uncertainties in these analyses are the C/He ratio (the number density of carbon to helium) and the famous ‘carbon problem’ ([Asplund et al. 2000]). The C/He is needed to estimate the mass fraction of elements and cannot directly be estimated from observations. It has been assumed as 1%, same as the mean estimated value from observations of extreme helium stars (EHes) (see further for a comment on this assumption). This value seems to be consistent with the metallicity expected from the galactic distribution ([Rao & Lambert 1996; Pandey et al. 2001]).

3.2. Carbon Problem

The problem (which would be discussed in detail in Gustafsson’s review) is that the carbon abundance estimated from the observed C \(\text{i} \) lines is four times less than the input abundance of carbon (based on C/He) in the model. Where did the missing carbon go. The answer to this puzzle is still missing. The continuous opacity in the atmosphere of RCBs is controlled by the photoionization of C \(\text{i} \) from excited levels and the observed lines arise from the levels marginally lower in excitation potential. Thus the equivalent width of C \(\text{i} \) lines are independent of \( T_{\text{eff}} \) and \( \log g \) (and mildly dependent on microturbulence). This is confirmed by observations. Figure 1 shows the spectrum of six RCBs over plotted in the region of 6380 to 6412 Å. Lines of C \(\text{i} \) are of same strength in all the stars where as lines of other elements like Fe\(\text{i} \), Fe\(\text{ii} \) vary enormously in strength. A similar comparision of the spectrum of RY Sgr (\( T_{\text{eff}} \sim 7200 \) K) and H rich, Fe poor RCB star V854 Cen (\( T_{\text{eff}} \sim 6750 \) K) also shows that the C \(\text{i} \) lines are marginally stronger in RY Sgr relative to V854 Cen in the 6380 to 6412 Å region.
as expected. However a comparision of these two stars in the UV region 1500 to 1800 Å shows a very different appearance (see the figure in Clayton & Ayers 2001 illustrating the HST spectra). The C1 lines eg. 1657 Å in V854 Cen is very much stronger than in RY Sgr contrary to that seen in optical region. I asked my friend Martin Asplund ‘what is the cause of this?’ He did a qualitative computation of the line strengths of C1 lines in both stars using abundances obtained from the optical region (Asplund et al. 1998, 2000) and told me that C1 is not the source of continuous opacity in the UV region, in fact it is Si1 photoionization that provides the continuous opacity thus carbon becomes a trace element and the line strengths computed are similar to that observed. It is in principle possible to obtain the correct carbon abundance by analysing the C1 lines in UV, like the other elemental abundances estimated in optical region. This approach might show a way to resolve the carbon problem. In analysing the [C1] lines in RCBs, Pandey et al. (2004) suggest that a chromosphere like temperature rise in the atmosphere of the stars might provide a solution to the carbon problem. However, inspite of the carbon problem, Asplund et al. (2000) found the abundance ratios are unaffected.

4. Abundance Patterns

The surface abundance patterns in RCBs and EHes have recently been reviewed by Rao (2005). The surface abundances provide the most vital clues towards the understanding the origins of these stars. The first major study of the surface abundances of large number of RCBs by Lambert & Rao (1994) revealed two distinct patterns in [Si/Fe] and [S/Fe] plot. Majority of the stars (14 out of 18) showed these ratios to be around 0.5 with a mild Fe deficiency relative to solar, whereas minority of four stars showed very high values of [Si/Fe] and [S/Fe] with a large deficiency of Fe. A similar pattern of majority and minority is also seen in EHe stars (see Rao & Lambert 2007 for a recent plot of [Si/Fe] vs [S/Fe]). So far mainly the warm RCBs (F,G type) have been analysed spectroscopically. The cool RCB and DY Per stars need to be analysed comprehensively for abundances although few attempts have been made by Kipper (2002); Kipper & Klochkova (2006); Zacs et al. (2005, 2007). The mean abundance of several elements in the majority and minority groups in RCBs and EHes has been given in Rao (2005). The dispersion around the mean in each group is surprisingly small e.g. ~ 0.27 dex for the majority group in RCB and EHes. Figure 2 (lower panel) illustrates the differences in mean abundance of elements in the majority group of RCB(mean of 15 stars) and EHe (mean of 12 stars). Figure 2 (upper panel) shows similar plot for minority group (4 RCBs and 2 for EHes).

If RCBs and EHes are related objects (or one group evolving into the other) it is expected the abundance of most elements would be similar (same) except for those that might get affected in that particular stage of evolution. Thus the difference in abundances between mean RCBs and mean EHes are expected to be around zero. Figure 2 (lower panel) brings out two aspects clearly. Four elements H,N,Ne and Mg show significant differences in the majority group between RCBs and EHes. N is enhanced in RCBs where as H,Ne and Mg are enhanced in EHes suggesting $^{14}$N could have been alpha processed to $^{22}$Ne and $^{25}$Mg in EHes. Thus EHes might be a later phase to RCBs. There is a systematic shift of $-0.3$ dex for
Figure 1. Spectra in the region of 6380 to 6415 Å of six RCB stars are superposed to illustrate the constancy of C\textsc{i} line strengths in these stars of varying $T_{\text{eff}}$ and metallicity. Note the variation in strength of Fe\textsc{i} and Fe\textsc{ii} lines where as the variations in C\textsc{i} lines are minimal.

Figure 2. lower panel: The difference in abundances of RCBs and EHes of majority group. Except for H, N, Ne and Mg the abundances in these two types of stars are similar but shifted by a constant factor possibly due to a difference in C/He ratio. upper panel: A similar plot as lower panel but for the minority group. Si, S, Ca, Sc are enhanced in RCBs. All the rest of the elements have similar abundances (within the errors).

all elements suggesting that the the abundances of RCBs are systematically lower to that of EHes. This might be a consequence of the assumption, C/He being same (1%) for both groups, since the mean metallicity of RCBs is not expected to be lower than that of EHes from the galactic kinematics and distribution. Thus C/He for the majority RCBs is suggested to be higher than that of majority EHes so that the metallicity of both groups remain the same.

On the other hand in the minority group (although the numbers are small) Figure 2 (upper panel) shows no systematic shift for most of the elements except Si, S, Ca, Sc which are enhanced in RCBs. Thus the C/He ratio might be same for both groups. Generally the elements Si, Ca, Sc, may be S get locked up in grains, the enhanced abundance of these elements in RCBs might be a consequence of dust production in minority RCBs?

4.1. Comments on individual elements

The Hydrogen abundance in majority of RCBs is low by a dex relative to majority EHes. The hydrogen abundance varies enormously in the group < 4.0 to 7.0. The minority objects show even higher H abundance. Kipper (2002);
Kipper & Klochkova (2006), Zacs et al. (2005, 2007) have made estimates of H-abundance in cool RCB stars Z Umi, DY Per using the Hα region in these stars. Estimates based on the presence of such a high excitation line in the region with heavy blending due to CN, C2 molecules is going to be very uncertain. A better way would be to use the G-band lines (CH) in the blue. Figure 3 shows the synthesis of the spectral region in the cool RCB star U Aqr, using Uppsala models and line lists provided by Betrand Plez. An atmospheric model of $T_{\text{eff}}=5400 \text{K}$ and log $g=1.0$ seem to be appropriate to the star and leads to estimate of H abundance of 9.5. Although there are some uncertainties related to the metallicity, the cool RCBs (and DY Per) seem to indicate higher H abundance in the range 8.5 to 9.5. Incidentally studies of the spectra of DY Per, both at maximum and minimum light suggest that it does belong to RCB group (Rao et al. 2007; Zacs et al. 2007). The question whether all cool RCB (and HdC) stars show higher H abundance needs to be explored.

It is often asserted that the ratio of $^{12}\text{C}/^{13}\text{C}$ is high in RCBs, few exception still exist. V Cr A the minority RCB shows a value between 4 to 10 (Rao & Lambert 2007), and DY Per, which shows presence of $^{12}\text{C}^{13}\text{C}$ bands in the optical spectrum, is estimated to have a value around 20 (Rao et al. 2007; Zacs et al. 2007).

The nitrogen abundance in RCBs is high suggestive of not only conversion of initial C and O to N but even further conversion of synthesized C to N. The N abundance in many RCBs and EHes imply wholesale conversion of O to N.
via ON cycles. Many stars are not O deficient suggesting O is synthesized along with C.

The dramatic discovery of large abundance of $^{18}\text{O}$ and low abundance ratio of $^{16}\text{O}/^{18}\text{O}$ in HdC stars and cool RCBs by Clayton et al. (2005, 2007) brought DD scenario into fore. High resolution spectroscopy of CO bands at 2.3 microns show an estimate of $^{16}\text{O}/^{18}\text{O}$ of 0.3 to 0.5 for three HdC stars and a value of 16 to cool RCB star S Aps (García-Hernández et al. 2007). Again the discovery of high Fluorine abundance, several hunderd times solar, in EHees and RCBs seems furthur support to hot DD scenario (Pandey 2006; Pandey et al. 2007). The absence of $^{18}\text{O}$ and low abundance (or lack) of F in Sakurai’s object (Geballe et al. 2002; Pandey et al. 2007), which is a typical FF object does support the DD scenario as the origin for at least majority RCBs.

What about lithium and s-processed elements? Lithium is present in four of the fifteen analyzed majority RCBs and in one of the five HdCs (Lambert & Rao 1994; Rao & Lambert 1996) with an appreciable abundance of about $\log \epsilon(\text{F})=3$. Even cool RCB star Z UMi shows high abundance of lithium (Goswami et al. 1997; Kipper & Klochkova 2006). The origin of this lithium is a special challenge to the DD scenario. Particularly the presence of high abundance of F, $^{18}\text{O}$, and Li in the same time in some of the stars shows lot more is needed to develope a convincing explanation for their origins than the present form of the DD scenario.

The s-process elemental abundances and their variation with metallicity in RCBs and EHees has been discussed by Rao (2005) and Pandey et al. (2006). The lighter s-process (ls) elements are enhanced relative to heavy s-process elements (hs) in both RCBs as well as EHees (Pandey & Reddy 2006). The variation of this ratio [ls/hs] with respect to metallicity ([Fe/H]) is quite different to that displayed by post-AGB objects (Rad 2003) which follow Busso et al’s (2001) model ST/1.5. This might suggest that s-processing in RCBs is not a result of conventional third dredgeup but could have been a result of second passage through the AGB stage. Although lot of progress is achieved in the study of surface abundances of RCBs, clarity about their origins is yet to emerge.

5. Stellar Winds

Clayton et al. (2003) discovered that the He I 10830 Å line in many of the RCBs show P-cygni type or blue shifted strong absorption profiles indicative of shell of hot gas moving with velocities over 200 km s$^{-1}$, much above their escape velocity. Several cool RCBs also seem to possess such P-Cyg profiles. The source of excitation of this hot gas and its connection with photosphere of the stars is not clear. Rao et al. (2006) showed that in R CrB the strong photospheric lines, particularly the O i 7774 Å line profiles had a pronounced blue wing suggesting mass loss with an expansion velocity of 130 km s$^{-1}$ (predicted escape velocity is about 30 - 70 km s$^{-1}$). The O i lines provide the link between the hot gas responsible for the He I line and the stellar photosphere, a strong stellar wind. In addition to the O i lines, other strong (or resonance) lines of lower excitation potential (e.g., Al i 3944 Å) also showed asymmetric profile and mass loss but with lower velocity of expansion. More over the blue wing of the low excitation lines show considerable variation in strength where as the high excitation O i lines remained constant in the same period. Rao et al. (2006) showed that
the inferred wind velocity decreases with excitation potential, linking He\textsc{i} lines showing high velocity part and low excitation Al\textsc{i} lines with low velocity variable component of the wind. An interpretation of the extended blue wings is that the wind begins at the top of the photosphere and increases in velocity and excitation with height above its base. Such wind profiles to O\textsc{i} 7774 Å lines have now been observed for several RCBs showing that stellar wind is a common characteristic feature of the RCB stars (Rao & Lambert 2007, and in preparation). The wind profiles in R CrB as well as in V CrA were unchanged even during most of the deep light minimum (particularly the wings) suggesting stellar wind is a global phenomenon where as dust obstruction (production) might even be a local phenomenon effecting limited part of the star.

It should be noted that He\textsc{i} lines seen at light minimum of RCBs might represent the stellar wind profiles that are present all the time and unconnected to the minimum (and dust production). Thus the morphology of these profiles differ from that of broad Na\textsc{i} D lines, Ca\textsc{ii} H & K lines, K\textsc{i} lines seen at light minimum ([Rao et al.] 1999; [Rao & Lambert] 2003; [Rao et al.] 2006).

What drives the wind and provides the energy to heat the gas to cause He\textsc{i} excitation? Heating of the wind may be by deposition of mechanical energy (sound or hydromagnetic waves). The photospheric absorption lines have widths indicating mass motions with velocities exceeding local sound speed. The Ca\textsc{ii} infrared triplet lines (e.g., 8542 Å) in V CrA and some other RCBs show similarity to solar chromospheric lines with an absorption core flanked by emission peaks. This may be indicative of magnetic activity. In this context we examined the absorption spectrum of R CrB in the region of 6170–6180 Å where magnetically sensitive line of Fe\textsc{i} 6173 Å occurs. Figure 4 shows the region in R CrB on several occasions. The Fe\textsc{i} lines 6173.34 and 6180.22 Å have very similar lower excitation potentials (2.248 and 2.759 eV) and similar log $gf$ values ($-2.88$, $-2.78$) but differ in their Lande g factor (2.50 and 0.600), respectively. The magnetically sensitive 6173.3 Å line with higher Lande g value shows large variations when compared to 6180.2 Å line that is magnetically much less sensitive. May be magnetic fields play a role. This is an aspect that needs to be studied.

6. Pulsations and Dust production

It is well known that RCBs show a semi-periodic variations attributed to pulsations ([Lawson & Cottrell] 1997; [Lawson & Kilkenny] 1996). [Pugach] (1977) was the first to make an attempt to link the deep light declines to the pulsation phase of the stars. So far this linkup could not be convincingly demonstrated for any RCB star. Recently [Crause et al.] (2007) in a systematic study of four RCBs over several decade of photometry been able to show that pulsation is linked to the deep declines. Although decline does not happen at every pulsation cycle but when a deep decline occurs it occurs at a specific phase of pulsation cycle. This for the first time links the pulsation to dust production.

Pulsation linked models of dust production have been proposed by [Woitke et al.] (1996) for RCBs. In this model pulsation induced shocks propagate through the atmosphere and when shock amplitudes get stronger the gas behind the shock front (preshocked gas) could attain temperatures and densities sufficiently cool and dense for the nucleation to occur. It is of utmost interest to see whether such
Figure 4. The several spectra of R CrB at maximum light are superposed to illustrate the large variation in the magnetically sensitive Fe I line at 6173.3 Å whereas the less sensitive line of similar excitation and log gf value at 6180.2 Å remained more or less constant in strength.

A cool gas can be detected during such decline events. Such cool gas has been detected in three RCBs (V854 Cen, R CrB and V CrA) during the light minima through the observations of absorption lines of C$_2$ molecule arising from the Phillips system (i.e. the ground electronic state of the molecule). The rotational temperature of 1100 K to 1230 K have been deduced for the gas (Rao & Lambert 2000, 2007; Rao et al. 2006) which is well within the range of temperatures expected for nucleation of carbon dust. This detection certainly provides confidence that dust condensation does indeed take place during these large light decline events. It is required to study the atmospheric phenomenon in detail during the passage of the shock and link the observations to the models.

7. RCBs and Helium enrichment in globular clusters

I would like to conclude the observational aspects with a suggestion. It is now becoming very clear that multiple main sequences and extended blue horizontal branches exist in massive globular clusters like omega Cen, NGC 2808 etc. These sequences can only be explained by a sequential enrichment of He in intercluster gas and subsequent star formation (Piotto et al. 2005, 2007). It is suggested that multiple stellar generations and He enrichment to the extent of Y of 0.4 (mass fraction) could only take place in clusters which have deep potential wells favouring the retention of low-velocity stellar winds. Various species that could create He enriched winds have been investigated ranging from Supernovae to AGB stars. Most promising source seemed to be slow winds from AGB stars. Even
this source is not apparently sufficient to enrich the He content to the required degree\textsuperscript{(Karakas et al. 2006)}. In addition, the large mass fraction of the He-enriched population relative to the enriching one would apparently ‘require an extremely flat initial mass function’\textsuperscript{(Piotto et al. 2007)}. In this context it is significant to note the discovery of ZNG1 in the globular cluster M5 as a hot hydrogen deficient carbon rich post-AGB star by\textsuperscript{Dixon et al. (2004)}. M5 is also a cluster having extended horizontal branch with a possible gap. The surface properties and abundances obtained by Dixon et al. for ZNG1 are very similar to EHes and RCBs including C/He ratio (2%). Thus, it is expected that there would be a population of hydrogen deficient stars in the globular clusters. If DD scenario (double degenerate binaries) is prefered for their orgins, (as the current thinking suggests) then their life times as HdC luminous mass loosing stars would be longer and the mass of the ejecta would also be larger (than for single stars). They would provide mostly helium gas without enriching too much carbon (C/He of 1%). The final flash objects are expected to show comparable carbon (and oxygen) to helium (C/He of 40-50%) that might pose problems. Quantitative estimates for the population of HdC stars in globular clusters is lacking, their importance to the helium enrichment might be significant. At the least they might compliment the helium enrichment to the AGB star ejecta to the intercluster medium. It would be worth while to evaluate this aspect in massive globular clusters as the helium enrichment has relevance to the cluster population in external galaxies.

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