Some Common Problems and Challenges that Emission-Line Stars Present

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Abstract. Four examples are given of problems that arise in the study of emission-line stars, each of which deserves further quantitative study. (1) Archival slit spectra of η Car show that epochs of low excitation have occurred regularly in the 2020 day period of Damineli et al. since at least 1948. They last about 10 percent of the period. Earlier slit spectra (1899-1919) suggest that the object was always in a low excitation state at that time. This result may be connected with the gradual brightening of η Car through most of the 20th century. (2) FeII and [FeII] emission in Mira variables is probably chromospheric. It would be important to understand how this is excited and its relation to mass loss and dust formation in Miras. (3) Declines of RCB stars are due to eclipses by dust clouds. At such times a rich emission line spectrum from the outer atmosphere of the star is seen. The quantitative study of the changes in this spectrum as more and more of the star is eclipsed should yield important information on the extended atmosphere of these objects. (4) In deep minima when the entire star is eclipsed, RCB stars show a broad-line emission spectrum. The excitation of this spectrum, particularly HeI 3888Å, constitutes a puzzle. Two possible excitation mechanisms are discussed.

1. Introduction

The study of emission-line stars presents many opportunities to probe the physical nature of stellar atmospheres and stellar environments and also to investigate little understood modes of stellar evolution. This has been the theme of much of this meeting. In an attempt to show that we have as yet only begun to unlock this rich source of information, this paper begins with a discussion of results obtained using archival spectra of η Carinae and then examines two classes of emission-line stars which have not so far been mentioned at this meeting but which would repay further quantitative study.

2. Archival Spectra of η Carinae

Gaviola (1953) found that there was a marked difference between spectra of η Car taken in 1948 and those taken in 1947 and 1949. HeI, [NeIII] and various other emission lines of above average excitation were missing in 1948. A similar
Figure 1. The phases of high (H), low (L), and intermediate (I), excitation in the 2020 day period since 1948. The open circles represent the two less certain assignments.

low excitation event was found to occur in 1965 (Thackeray 1967, Rogers & Searle 1967) and another in 1981 (Whitelock et al. 1983, Zanella et al. 1984). In the latter case the low excitation phase occurred when the infrared (JHKL) flux was near a maximum in its \( \sim 5 \) year cycle. Damineli (1996) showed that these low excitation events all occurred at the same phase in his proposed 5.52 year period. As one part of a recent study of \( \eta \) Car (Feast, Whitelock & Marang 2000) we have examined spectra in the archives of the South African Astronomical Observatory (SAAO) for further evidence of variability. The bulk of these spectra were taken by A.D. Thackeray between 1951 and 1978. He made a large number of observations of the central object (as seen from the ground) and of portions of the homunculus as well as other surrounding nebulosity. Although there may well be relatively subtle differences between different spectra of the central object, including secular variations, it proved quite easy to classify spectra either as in a high or a low excitation state with only one, rather doubtful, intermediate case. Thackeray’s plates reveal three previously unrecorded epochs of low excitation. Taken together with other evidence in the literature, these results show (see Fig. 1) that epochs of low excitation have occurred regularly in the 2020 day period proposed by Damineli et al. (2000), at least since 1948. The low excitation lasts about 10 percent of the period though there is probably some slight variation in the phase of its onset and end. The epochs of low excitation have the same phase and duration as the eclipse shown by the infrared light curves (Whitelock 2001). It is known (Davidson et al. 1997) that the (sharp) emission lines used to judge the high/low excitation phase come from plasma blobs about 0.2 arcsec from the central object itself. The association of the low excitation phases with the eclipse phases then presumably indicates that the relevant emission lines are radiatively excited and, on a binary model, that the blobs lie in or near the orbital plane of the binary. This is consistent with the blobs lying near the equatorial plane of the bipolar lobes as found by Davidson et al. (1997).

Whilst there are earlier visual and objective prism observations of \( \eta \) Car, the first slit spectrum seems to be that take by Gill at the Cape in 1899. This spectrum could not be located but reproductions of it have been published (Gill 1901). The Cape archives contain slit spectra from 1919 (Lunt 1919) and glass
copies of the Lick Southern Station plates of 1912-14 (Moore & Sanford 1913 and unpublished). All the early spectra are in the low excitation phase and suggest that the object was always in a low state at that time. This result seems consistent with the evidence that the general level of excitation is increasing with time (Whitelock et al. 1983, Damineli et al. 1999). Presumably this is connected with the secular increase in brightness of the system. Although this brightening has in the past been ascribed by some workers to clearing of dust absorption, this seems unlikely to be the basic cause (Whitelock et al. 1983, Davidson et al. 1999). One possibility is that the increase in brightness and level of excitation is due to an increase in output from the “central engine”. On a binary model this could be due to increased wind/disc or wind-wind interaction.

3. Emission Lines in Mira Variables

One can classify the optical emission lines seen in Mira variables into four groups. (There are of course, in addition, maser and non-maser molecular emission lines in the radio region.) First, there are the Balmer lines and a few others which must, at least at some phases, originate within the stellar atmosphere itself because they are at times mutilated by overlying absorption. The evidence for this is rather conclusive (e.g. Merrill 1945, Joy 1947) despite the claim that the resulting unusual Balmer decrement can be alternatively explained by NLTE radiative transfer effects (Luttermoser & Bowen 1992). These lines are general believed to be excited by shock waves generated by stellar pulsation. Secondly, there are what appear at first sight to be a rather random selection of neutral metallic lines (lines of FeI (e.g. 4202A), TiI and InI). These were explained by Thackeray (1937) as due to fluorescent excitation (due to chance coincidences of energy level differences) by lines (principally MgII h and k) which are presumably associated with the first group. Thirdly there are molecular lines, including the fascinating case of AlH emission by inverse pre-dissociation (Herbig 1956, Herbig & Zappala 1968). Finally there are emission lines of FeII and [FeII] which can be found in some, and probably all, large amplitude Miras near minimum light. Along with these lines are semi-forbidden MgI (4571A) and some other forbidden lines ([OI], [SII]). The origin of the FeII and [FeII] lines is particularly interesting. There seems to be no indication that these lines are affected by overlying atmospheric absorption. This needs to be properly checked but it suggests that the lines are excited in an outer region of the star. This is indeed what Herbig (1969) deduced from a relatively simple semi-quantitative analysis of the line strengths. He found that the lines were excited in a chromosphere at $T \sim 4000K$, i.e. significantly hotter than the photosphere. The excitation of chromospheres is a problem of continuing interest. How do Miras do it? The most likely mechanism is probably that pulsational shocks propagate into the outer atmosphere and excite a chromosphere. Wood & Karovska (2000) have recently shown that the intensity of ultraviolet FeII emission lines in Miras varies with phase, consistent with this hypothesis. The case of possible chromospheric emission in Miras is of particular interest because these stars are undergoing extensive mass loss and dust formation. It is not clear how these various processes are related although it is almost certainly misleading to think
Feast of the outer region of a Mira as consisting of well ordered layers. More likely is a low density region containing denser clouds. Chromospheric emission in Miras is particularly interesting since in late type giants and supergiants, in general, the strength of chromospheric emission is reduced by the presence of dust (see e.g. Stencel, Carpenter & Hagen 1986).

4. Emission Lines in R Coronae Borealis Variables (I)

The emission-line spectra seen from time to time in RCB variables raise a number of interesting problems which deserve more extensive quantitative study. These stars are highly evolved carbon-rich, hydrogen-poor objects (see e.g. Clayton 1996, Feast 1996, and earlier reviews). Their evolutionary history is still uncertain. They are high luminosity objects, typically with spectra similar to F or G-type supergiants. But they are almost certainly low mass objects. At random intervals RCB stars decrease rapidly in brightness by many magnitudes and then slowly brighten again. This behaviour is attributed to the star ejecting dense clouds of particles in random directions, one of which occasionally falls in the line of sight and causes an eclipse. It has been suggested (Asplund & Gustafsson 1996, Asplund 1998) that this behaviour is a result of the stars being at an opacity-modified Eddington limit. It may be recalled that the behaviour of the LBV variables, discussed earlier in this meeting, has also been attributed (e.g. Appenzeller 1989) to their being at an opacity-modified Eddington limit. One way in which these objects differ is that whilst RCB stars puff off clouds of limited size, the LBVs are thought to eject complete shells. Asplund & Gustafsson suggest that this difference is due to the fact that the LBVs are evolving to the red. Thus any expansion and cooling makes them more super-Eddington. The RCBs on the other hand are probably evolving to the blue thus expansion and cooling will tend to make them sub-Eddington. Asplund & Gustafsson speculate that this results in a local, rather than a general, instability and gives rise to the ejection of limited clouds rather than complete shells.

Since much of this meeting has been devoted to η Car it is worth noting that Bidelman (1993) thought that the 1893 (objective prism) absorption spectrum of η Car was similar to that of R CrB at maximum light in showing strong CI absorption. If this is actually the case it would add to the puzzle provided by Lamers et al. (1998) who found that the carbon abundance in the stellar wind from η Car is greater than in the surrounding nebulosity. Perhaps this requires a two-wind model of some kind for η Car.

Because the RCB eclipses are due to dust clouds they cannot be expected to repeat exactly, being dependent on the size, opacity etc. of the cloud. Nevertheless on some declines at least a very rich emission-line spectrum is found (e.g. Alexander et al. 1972). This is dominated by FeII and is, with some minor differences, a reversal of the absorption spectrum at maximum light. Evidently the main body of the star is eclipsed and we see the equivalent of the solar-eclipse “flash” spectrum. This spectrum changes, presumably as the eclipsing cloud expands and covers more and more of the outer atmosphere of the star.
From being initially dominated by FeII emission, it changes to being dominated by TiII and ScII. It has been qualitatively suggested that these changes are due to a decrease in temperature, density and self-absorption with height in the outer atmosphere but a full quantitative discussion is required and might throw considerable light on this outer region which probably has a diameter roughly four times that of the photosphere. Note that these spectra are often referred to as “chromospheric”. However there is no evidence that the emission lines come from a region above a temperature minimum.

5. Emission Lines in R Coronae Borealis Stars II

There is another, entirely different, problem concerning the emission-line spectra of RCB stars which also raises a rather interesting physical problem.

In deep minimum the sharp-line spectrum referred to in the last section has completely disappeared. Presumably the star, including its outer atmosphere, is totally eclipsed by a dust cloud. The spectrum then consists of a small number of broad emission lines. The main lines in the optical region are HeI 3888Å, CaII H and K, and the NaI D lines. Their width is $\sim 400 \text{ km s}^{-1}$ (see, e.g. Alexander et al. 1972, Rao et al. 1999). These lines are characteristic of all RCB stars that have been suitably examined in deep minimum. They clearly originate far from the central star since they are unobsured. But where exactly do they originate and how are the excited?

One model has been proposed by Rao et al. (1999). They suppose that R CrB itself, and by implication all RCB stars, are binaries with white dwarf companions. The white dwarf, they suggest, is surrounded by an accretion disc which is the source of the broad emission lines. The width of the lines is due to the Keplerian rotation of the disc. The HeI emission is supposed to come from the inner parts of the disc. It is not then clear why the CaII and NaI lines have similar width to the HeI since they presumably would arise in the cooler, outer parts of the disc (or from elsewhere). This, together with the fact that the model requires that all RCB stars are viewed close to the plane of the supposed binary and the lack of any direct evidence for a white dwarf in any of the variables, makes the hypothesis rather unattractive.

There are in fact purely phenomenological considerations which suggest a quite different model (Feast 1996). When the dust cloud in front of the star is thin enough to see through, so that the star itself is dimly seen, one also detects absorption lines at $\sim -200 \text{ km s}^{-1}$. These lines must come from gas entrained with the dust which is being driven from the star at this speed by radiation pressure. These lines may be seen at the start of a decline, as the dust thickens, or on the rise back to maximum light as the dust cloud expands and thins (see, e.g. Alexander et al. 1972). Evidently we should consider the star as being surrounded by a consortium of clouds, ejected on a quasi-continuous basis in all directions at a typical velocity of $\sim 200 \text{ km s}^{-1}$. The displaced lines found are not only CaII H and K, and the NaI D lines (which are probably easily understood), but also HeI 10830Å (see, e.g. Querci & Querci 1978, Feast
1986). This indicates that these dust and gas clouds contain HeI in the highly metastable $^3S$ state which is the lower level of both the 10830A and the 3888A lines. This being the case it is clear that when all but the consortium of clouds is obscured we would expect to see, as is actually found, resonance emission lines of CaII and NaI and also HeI lines resonantly excited from the $^3S$ state. The width of these lines would be $\sim 2 \times 200 \text{ km s}^{-1}$ as is indeed found. The case that the broad emission lines (including HeI 3888A) arise in the expanding dust/gas clouds thus appears to be rather strong. The problem then is how the $^3S$ HeI level, which is nearly 20 eV above the ground state, is populated. This is a question which has not been fully answered. It may be that some form of atomic collisions (Feast 1996) or shocks (as suggested by J. Linsky in the discussion at this meeting) in the fast moving dust/gas clouds could provide the necessary excitation. It should be remembered that not only is helium the most abundant element in RCB star atmospheres, but also that the metastability of $^3S$ HeI ensures that 3888A (and 10830A) can be resonantly excited many times from an atom in this state before it returns to the ground state. Thus the rate at which HeI atoms need to be raised to the $^3S$ state is likely to be quite low. Progress is likely to come from more quantitative observational work, from theoretical studies and, one might guess, from laboratory experiments. This may indeed be one of those areas where a solution to a problem lies in the collaborative efforts of astronomers and laboratory physicists.

Acknowledgments. I am grateful to Patricia Whitelock for data in advance of publication and for many helpful discussions.

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