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Environments of active close binaries

I. ER Vulpeculae

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Abstract. High-resolution observations of the eclipsing active close binary system ER Vulpeculae have revealed excess emission in the Hα, the Ca II IRT and the Mg I b lines and excess absorption in the He I D_3 line. The emission appears to be from a global phenomenon with the secondary component the more active. Analysis has revealed that the emission arises in plage-like material covering perhaps half of the secondary's surface. This gives credence to X-ray and UV studies which have indicated that ER Vul is near the saturation limit for dynamo-induced activity. No firm spectroscopic evidence for the existence of extended material around ER Vul was found. A consistent velocity offset of $\sim$10 km s^{-1} was observed in the excess Hα emission from the secondary component which may be associated with active regions such as spicules. If so this represents the first observation of the equivalent of solar spicule emission in a stellar system other than the Sun.

Key words: star: binaries: spectroscopic – stars: actively – stars: chromospheres – stars: magnetic fields – stars: ER Vul

1. Introduction

In recent years evidence has been accumulating that some stars have cool coronal condensations analogous to solar prominences. In many respects these features can be regarded as the remaining phenomenon to be confirmed for active stars which are routinely seen optically on the Sun. The present study involves an attempt to detect the presence of such material in a small sample of RS CVn binaries. In this first paper we present a detailed discussion of the techniques used and present the results for ER Vulpeculae.

The detection of cool material overlying the surface of a star is extremely difficult since in all but the most extremely active stars such material would manifest itself as a small additional absorption feature overlying the global absorption lines. This problem is also exacerbated by the fact that other regions such as plages or lower chromospheric structure, which may also be present, can actually fill-in the global absorption profile due to the increasing collisional domination of the source function for the activity sensitive transitions. An attempt at detecting such prominence-like material must therefore account for a variety of effects. To remove the effect of core-filling of active lines, the technique of spectral subtraction is often used. This technique essentially involves subtracting from the spectrum of the active star a synthetic spectrum representing this star in all other respects other than having an inactive chromosphere. The presence of plage-like or prominence-like material is often shown in subtracted spectra as excess emission or absorption features although it is difficult to assign such features unambiguously to absorbing material because they could equally well arise from intrinsic changes in the line-forming regions. Time series of spectra can to a certain extent alleviate this by providing evidence for features which evolve in a self-consistent manner. However the observation of active close binary systems which periodically undergo geometrical eclipses provides a powerful technique whereby absorption features can be unambiguously disassociated from the global absorption or emission lines. If the geometry is suitable, cool coronal material in the atmosphere of the eclipsing star can absorb the photospheric continuum radiation of the star behind.

The observational evidence for stellar prominences is still very sparse. AB Dor is a well studied single K0 dwarf star for which Robinson & Collier Cameron (1986) reported the presence of transient features in the Hα line. Subsequent work on this star (Collier Cameron & Robinson 1989a; Collier Cameron & Robinson 1989b; Collier Cameron et al. 1990) has shown that the most consistent interpretation of these features is of prominence-like condensations of mainly neutral material trapped in corotation with the star by the stellar magnetic field. The variability in the Hα line is consistent with a series of clouds crossing the stellar disk, and by solar analogy these are thought to consist of filamentary structures of cool material. Some other single stars are known to show clear evidence for large circumstellar prominences (Collier Cameron & Woods 1992). The main requirement seems to be the presence of magnetic loop structures extending far into the corona with field strengths suf-

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ficient to support the material against centrifugal ejection. Recent observations by Byrne, Eibe & Rolleston (1996) of HK Aqr revealed similar features which however appeared to form below the corotation radius.

In RS CVn binaries excess absorption features are commonly seen in subtracted spectra and arise due to prominence-like material occulting one of the component stars during eclipses (Hall & Ramsey 1992a). Hall et al. (1990) reported extensive observations of the RS CVn binary SS Boo in the Balmer lines as well as the Ca II H and K and Ca II IRT. An unusual excess absorption occurred near primary eclipse in the Balmer lines and this was attributed to an extended region of 4-4.6$R_{\odot}$. It was further shown that the feature could not be associated with an accretion stream which was seen as an Hα transient feature in similar observations of the UX Ari system by Huenemoerder, Buzasi & Ramsey (1989). In a follow up campaign Hall & Ramsey (1992b) surveyed 10 RS CVn systems and reported stable prominence-like material corotating with either the primary or secondary stars in eight of their targets. This study concluded that amongst the eclipsing RS CVn stars prominence material was a common feature. Buzasi, Huenemoerder & Ramsey (1991) made a study of the HR 1099 system in which spectral subtraction was performed on optical spectra in the Hα, Hβ and Ca II lines. When the excess line fluxes were plotted as a function of time a striking discontinuity was found such that the Hα line flux dropped by about 30% for about a third of the orbit. During the drop the Hα line appeared to be phase modulated whereas before it was not. These authors interpreted this as the disappearance of a large stellar structure which was perhaps prominence-like. In fact Buzasi (1989) concluded that extended prominences are the most reasonable explanation for the Balmer line emission from HR 1099.

Since the geometry of many of these inferred prominences exceeds the Roche lobes of the components it is reasonable to assume they are magnetically confined. This also lends credence to the hypothesis that they are analogous to solar prominences. Recently Hall & Ramsey (1994) have provided a first generation model for analysing the characteristics of prominence absorption in the subtracted spectra of RS CVn binaries. Even though this model is by no means sophisticated it generally produces physical parameters in broad agreement with the solar paradigm.

Less direct methods have been used to infer the presence of prominence material in RS CVn binaries. Buzasi (1989) developed an NLTE radiative transfer model to derive values of the Balmer equivalent width ratio of the Hα and Hβ lines in subtracted spectra. A grid of models was used representing plage-like and prominence-like material over a range of appropriate temperatures, densities and optical depths. These results showed that low ratios of $\sim$ 1-2 could be achieved in both plages and prominences viewed against the stellar disk but that values between $\sim$ 3-15 could only be achieved in prominences seen off the limb of the star. Similar conclusions were given by Heasley & Mihalas (1976) who discussed detailed models of quiescent solar prominences. Observational confirmation of these predictions is given by Landman & Mongillo (1979) who observed high ratios in solar prominences seen at the limb, and by Chester (1991) who found ratios of < 2 in solar plage regions. In RS CVn binaries high Balmer line ratios are often found (Huenemoerder & Ramsey 1987; Huenemoerder & Barden 1986; Newmark 1990; Hall et al. 1990).

The results discussed above, if real, are significant in that previously the extended coronal regions of active stars were the domain of the X-ray and radio observers. They further suggest that there exists cospatial plasma with significant emission measure at both optical and X-ray wavelengths; probably consisting of fine threaded cool regions delineating magnetic loops permeating the hot corona. Since these structures ultimately represent the interface of the stellar atmosphere with the stellar wind they provide important insights into the physics of corona-wind interaction, the eruptive ejection of material into the ambient environment and hence angular momentum and mass loss effects. The unambiguous optical identification of coronal structures in active late-type stars, and in particular in active close binaries, is by no means conclusively proved. However the pursuit of this subject represents one of the last components of the solar paradigm for active stars.

In this paper we discuss in depth the validity of the spectral subtraction technique in the search for prominence-like material in active close binary stars, introduce our observational and analytical procedures and present the results for one of the stars in our survey.

2. ER Vulpeculae

ER Vulpeculae is an eclipsing binary of the short-period RS CVn type with an orbital period of 0.698 days and consists of G0 and G5 main-sequence stars both of radii $1.07R_{\odot}$ at a separation of about $2.01R_{\odot}$. ER Vul was first identified as an eclipsing double-lined spectroscopic binary by Northcott & Bakos (1956). The radial velocity variations and a preliminary photometric light curve solution were presented by Northcott & Bakos (1967) based on these earlier data supplemented with additional observations. The photometric solution given by Abrami & Cester (1963) differed from Northcott & Bakos (1967); this coupled with the observation of Ca II H and K emission by Bond (1970) led Hall (1976) to classify the system as a short-period RS CVn system. The system is obviously detached with an inclination near 70°. Mennella (1990) recently gave a good account of the changes in the light curve of ER Vul and derived a new ephemeris for moments of eclipses. The paper by Hill, Fisher & Holmgren (1990) provides an excellent discussion of both photometric and spectroscopic results for this system.

A spectroscopic orbit for ER Vul was presented by McLean (1982) based on cross-correlation velocities. Analysis of these data gave an estimate of the mass ratio of the system and suggested the presence of circumstellar material near the primary component. This was seen as a variation in the strength of the primary component spectral lines which, if caused by surface star-spots, would require star-spots much larger than those imposed by the photometric constraints. It is interesting to note that Northcott & Bakos (1967) suggested the presence of a gaseous cloud at the inner Lagrangian point extending to one side. This was required to explain the difference in the appearance of spectral lines at different phases. More recently Arevalo, Lazaro & Fuensalida (1988) suggested on the basis of their photometric variations the existence of a gas stream between the two components at a temperature of 1-5 10^4 K which would also account for the observed IR and UV excesses. The evidence for such material is not found spectroscopically. Newmark (1990) found no evidence for extended material around ER Vul in optical spectra while line ratios indicated that the chromospheric activity arises primarily in plage-like structures. The photometric variations have been shown to be broadly consistent with a starspot distribution on the primary component (Budding & Zeilik 1987).

ER Vul has also been studied in wave-bands other than the optical. Budding, Kadouri & Gimenez (1982) demonstrated that both components show emission in the Mg II lines measured with IUE. UV line fluxes were also measured by Rucinski & Vilhu (1983). Vilhu & Rucinski (1983) also measured the various chromospheric and transition region lines in IUE spectra and concluded that the UV line fluxes lie on the borderline between those expected for detached and contact systems based on a UV period-activity relation. The division between these two classes is thought to be due to a saturation limit for magnetic flux generation which implies that ER Vul has an extensively active chromosphere. ER Vul was detected in the X-ray by the *Einstein* satellite with a luminosity of 1.6 10^{30} erg s^{-1} (Walter & Bowyer 1981). A more comprehensive treatment of the system's X-ray emission was achieved by White et al. (1987) using EXOSAT observations in the 0.05-6 keV band. They found that the X-ray spectrum could be fitted well with a two-component thermal emission model with temperatures of 6 10^6 K and 4 10^7 K. The lack of modulation in the X-ray light curve suggested that for both plasma regimes the loop heights are larger than the stellar radius or a multitude of loops are uniformly distributed with longitude. In the radio domain Drake, Simon & Linsky (1986) found that ER Vul was the strongest source (4.97 mJy) detected in their 6-cm survey of short-period active binaries. Morris & Mutel (1988) also detected ER Vul with a flux of 2.7 mJy. A comprehensive study of the 3.6-cm and 6-cm radio light curve using the VLA by Rucinski (1992) revealed complex variability. This suggested the presence of a highly structured radio corona giving rise to a slow variability component with a period somewhat longer than the orbital period. Rucinski (1992) suggests this may be evidence of magnetic structures dragging behind the rotation frame in a spiral pattern. Thus the complex geometry of active regions on ER Vul may preclude any conclusions based on the temporal behaviour of radio and X-ray emissions.

Overall ER Vul is an interesting system that appears to be highly active both in terms of surface features and the extent of its environment. However the presence of extended material around ER Vul which is suggested by some studies is yet to be confirmed spectroscopically.

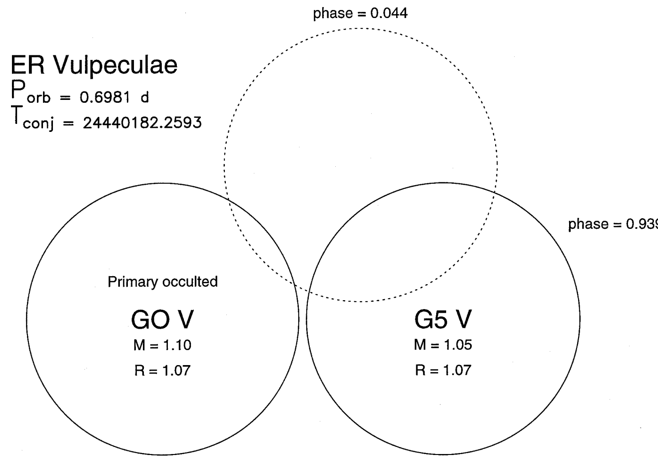

Fig. 1. Schematic representation of the geometry of the ER Vulpeculae system during the spectroscopic observations. The first spectrum was taken at phase 0.939 shortly before eclipse contact. The final spectrum is at phase 0.044 during eclipse egress (dotted disk). The maximum obscuration of the primary disk (phase 0.0) is approximately 12%. Masses and radii are in solar units.

3. Observations and data reduction

High-resolution spectroscopic observations of ER Vulpeculae were obtained during a 4-night observing run in July/August 1993 carried out with the Utrecht Échelle Spectrograph (UES) located on the William Herschel 4.2-meter Telescope (WHT) on La Palma. Descriptions of the telescope can be found in Bingham (1984) and Unger et al. (1988). The UES instrument (Walker & Diego 1985; Unger & Pettini 1993) is located at one of the Nasmyth foci of the telescope. The dispersed light was recorded on an EEV6 CCD detector with a pixel size of 22.5μm and dimensions of 1280 $\times$ 1180. The grating used gave a resolving power ($R = \lambda/\Delta\lambda$) of 52,000. This corresponds to a velocity resolution of 5.77 km s^{-1} or wavelength resolutions of 0.058 Å, 0.115 Å and 0.192 Å at 3000 Å, 6000 Å and 10,000 Å respectively. Observations were timed to encompass the primary eclipse of the target. In total 22 spectra were obtained with 3 minute integration times over the range 4890-8680Å. Fig. 1 shows a schematic representation of the geometry of the ER Vul system for the duration of the spectroscopic observations. Due to the nature of the data reduction and analysis a small set of standard stars were also observed; these were 26 Dra (HD 160269), HR 7504 (HD 186427) and δ Per (HD 22928). The estimated seeing varied from 0.9 to 1.7 arc-seconds throughout the observations.

CCD reduction and spectrum extraction and calibration was performed with IRAF[1]. After bias subtraction, image trimming and flat-fielding, 51 spectral apertures were defined by reference to bright star images and object spectra extracted. Th-Ar calibration frames were extracted and lines identified across

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation (USA).

all orders (typically 200 lines were defined). It was found that wavelength calibrations did not drift by more than 0.02Å and reduced spectra typically had signal-to-noise ratios in excess of 50 per resolution element. Normalisation of the extracted spectra was performed by fitting a spline function across predefined continuum points. Some spectral orders were corrected for the presence of atmospheric lines by means of bright B-star comparison spectra.

4. Spectral subtraction

Stellar activity is seen most often in the hydrogen Balmer lines and Ca II. The Balmer lines are difficult to model with success since at typical chromospheric temperatures and electron densities the source function is collisionally dominated as opposed to photo-ionization dominated (Fosbury 1974). As chromospheric activity increases the Balmer lines react in an increasingly non-monotonic fashion. For M-dwarfs detailed computations by Cram & Mullan (1979), Cram & Giampapa (1987) and more recently by Houdebine, Doyle & Koscielecki (1995) show that as activity increases the Balmer absorption lines first strengthen, then weaken by filling-in of the core relative to inactive stars and finally become pure emission lines. This behaviour of the Balmer lines has been confirmed both for the Sun (La Bonte 1986) and for late-type dwarfs, sub-giants and giants (Strassmeier et al. 1990). Hence some highly active stars which show strong emission in the cores of Ca II H and K (the phenomenon which generally defines the term *chromospherically active*) can often show weaker Balmer line absorption than inactive stars of the same spectral type and luminosity class, even though these lines are also formed substantially in the chromosphere. For this reason a good quantitative assessment of the levels of activity in some stars requires an approach more convoluted than simply measuring the strengths or equivalent widths (EWs) of active lines. What is required is a measure of the additional absorption or emission part of the line due to the atmospheric layer responsible for the activity, i.e. the chromosphere.

Spectral subtraction provides a technique of studying the diverse phenomena of stellar activity by isolating that part of the spectroscopic signature due only to chromospheric activity. This involves simulating the inactive spectrum of the star concerned and simply performing a linear subtraction of this from the observed spectrum. Any manifestation of activity is then visible in the *subtracted spectrum* as emission or absorption features above or below the zero continuum level. Relative changes in these features can then help to determine the time behaviour and spatial locations of any active regions. The problem with the technique then is to simulate the correct spectrum representing the inactive contribution. Two approaches are possible; first to use theoretical spectra based on radiative transfer solutions in model atmospheres or secondly to use observed spectra of inactive stars. Such techniques have been widely used and are becoming more commonplace.

Fraquelli (1984) applied spectral subtraction to spectra of the RS CVn-type star HR 1099 (V711 Tauri). Theoretical absorption Hα profiles were calculated using standard stellar atmosphere codes and using the known effective temperature and surface gravities of the component stars. These profiles were shifted, broadened and combined and then corrected to match the Hα cores of observed comparison stars. Although an investigation was made of the effect of spectral type mismatch on the results no use was actually made of the single star comparison spectra in the profile matching. The problem with theoretical line profiles for spectral subtraction lies in the uncertainty and complexity of the atmospheric conditions giving rise to the profile. Without detailed information concerning the dominating effects on the source functions of active lines and the effects of active regions on these lines it is impossible to form an adequate theoretical representation of the inactive contribution. So although radiative transfer codes are readily available for modelling active lines in late-type chromospheres their use is unwarranted in this sort of study.

For observational comparison spectra the usual method is to use a star which is similar to the program star in all respects other than the level of chromospheric activity. In this work the comparison spectra are referred to as the *spectral standards* or simply *standards*. Herbig (1985) studied the excess emission EW for 40 F8-G3 dwarfs using the same inactive G0 V comparison star. Young et al. (1989) also used observed spectra of inactive M-dwarfs of the same (R-I) colour index as the program stars to derive estimates of excess emission. Thatcher & Robinson (1993) used two comparison stars of spectral types G6 V and K1 V to isolate excess Hα emission in a sample of late-G to early-K stars. Recently Montes et al. (1995) used comparison stars in a study of the excess Hα emission dependence on effective temperature and rotation in a sample of RS CVn binaries. Some authors have chosen to subtract an average or quiescent spectrum of the same object in their analyses (e.g. Young, Rottler & Skumanich 1991; Byrne, Eibe & Rolleston 1996). Such a procedure is often difficult since many targets do not habitually display inactive states and the assumption must be made that the source function of the chromosphere is temporally static. Other authors who have used observational spectra for subtraction include Hall & Ramsey (1992b), Lazaro & Arevalo (1994), Montes et al. (1994) and Frasca & Catalano (1994).

Many assumptions are involved in the spectral subtraction technique. The most important assumption is that there exists a linear radiative transfer relationship between the photosphere and chromosphere in the active star and that there is no significant horizontal radiative coupling between an active region and its neighbouring quiet atmosphere. These are generally not good assumptions for active stars because very large fractional surface coverage by active regions gives rise to extremely non-local radiative transfer. Another important assumption is that the underlying photosphere of the active star is similar to that of the spectral standard. This is also not a good assumption since the observed spectrum of a spectral standard is certainly not due to a simple photosphere with no extra-photospheric contribution. Local and non-local inhomogeneities in the chromospheres and transition regions of a spectral standard will produce some activity signatures in its spectrum. As has been demonstrated by Basri, Wilcots & Stouts (1989) for early-K main sequence stars, some photospheric lines can be affected by magnetic activity. In the solar case, La Bonte (1986) observed broad emission wings in photospheric lines in active regions. The assumption of an underlying photosphere is then only true for very localized or transparent active regions. Consequently the subtraction process will remove some contribution from the chromosphere and transition region of the active star. Nevertheless the application of spectral subtraction often shows excellent cancellation of photospheric lines. Furthermore, analysis of simultaneous optical and UV spectra (which show the photosphere directly) demonstrate the reliability of the technique (Newmark et al. 1990; Huenemoerder, Ramsey & Buzasi 1990; Huenemoerder 1988; Huenemoerder & Barden 1986).

Several questions may be raised concerning the spectral subtraction technique. Firstly is the representation of an inactive spectrum a true depiction of the *basal* state of the photosphere and inactive chromosphere? Secondly is the linear subtraction of an inactive spectrum justified for a regime where highly non-linear radiation transfer takes place? The work of Cram & Mullan (1979) and Cram & Giampapa (1987) show that in atmospheric models of cool stars with no chromosphere the Hα equivalent widths are weaker than those found even for the most inactive of stars. Although the effect is less prominent for earlier stars of spectral types F and later is it debatable whether stars exist with so called *null chromospheres*. No observations have as yet revealed such stars. The conclusion is that the spectral subtraction technique underestimates the degree of chromospheric activity. However in very active stars this effect will be almost negligible and the derived excess emission will fairly well characterise the chromospheric behaviour. This is another point against the use of model calculations to simulate inactive spectra since the results of spectral subtraction will then be model dependent rather than empirical. The technique then provides a consistent set of measurements for comparison and provides the only practical method of studying such stars. It should be realized that the features seen in subtracted spectra reflect differences in the stars as a result of a source function or opacity difference in the line-forming regions. If the source functions of the two stars are equivalent functions of depth, i.e. the optical depth scales are equivalent and only the temperature structures are different, then the subtracted features will be a good measure of the relative degrees of activity. This is because the two atmospheres map onto the line profiles in the same way. An increase in non-radiative heating in one of the stars will increase the source function in the upper atmosphere (assuming LTE) while leaving the deeper layers unaffected. The temperature structure maps onto the line profile with the wings originating at the deeper layer but the core will become filled-in relative to the less active star. This is of course a gross oversimplification since the line core filling could be the effect of a reduced opacity in the line and it may not be reasonable to assume similar source functions in active and inactive stars. The particle densities may be very different (particularly for stars of different surface gravities) leading to very different ionization and excitation equilibria and the dominating processes in line-formation may also be different. Hence the detailed interpretation of subtracted emission or absorption features must await the detailed modelling of stellar atmospheres. Line wing differences may be successfully modelled with the LTE assumption but the structure in active line cores requires detailed NLTE modelling.

Spectral subtraction is thus likely to be an uncertain technique even when used for stars with the same spectral type and luminosity class (or colour and surface gravity) since other parameters will effect the source functions of the lines of interest. The greatest power of the technique is in tracking line variability due to surface activity in a single object or in comparing closely related objects. Even so the technique has had great success in determining consistent phenomena in a wide variety of stars and so has become an acceptable method of deriving first order estimates of activity signatures.

5. Technique

The practical implementation of spectral subtraction can also have problems, particularly for binary systems such as those studied in this work. In all cases it is necessary to choose standards which closely match the spectral type, surface gravity and chemical composition of the active star. A mismatch in spectral types between the inactive and active stars would manifest itself as a concavity or convexity in lines of interest due to the T_{eff} dependence of line wings. However at medium resolution it has been demonstrated that the strength of Hα is relatively constant for the range of spectral types from G2 to K5 (Huenemoerder & Ramsey 1984). The line profiles in many active stars are dominated by Doppler broadening with high rotation rates so standard spectra have to be artificially broadened and shifted to match the velocities of the active star. For the case of binary stars the situation is more complex since the lines from individual components may be highly blended close to conjunctions.

The implementation of the spectral subtraction technique for this work is similar to that discussed by Barden (1984). However we do not use an iterative matching technique to derive radial and rotational velocities and intensity weights due to the blending of lines. We recently checked the validity of the ephemeris and velocity semi-amplitudes of ER Vul (Gunn et al. 1996) so that accurate model velocities could be computed close to conjunction. These along with rotational velocities taken from Barden (1984) were used in the spectral synthesis.

Traditionally intensity weights for spectral subtraction have been obtained from photometric light-curve observations. During eclipse these are not representative of the light ratio for the system hence intensity weights are computed using the assumed component radii for each star and the values of the Planck function for each effective temperature computed at the spectral order central wavelength. The effective temperatures are computed using the standard spectral type-temperature relations given by Schmidt-Kaler (1982). During eclipses an obscuration correction is applied to the intensity weights. This simple geometric model does not take account any inhomogeneities in the surface brightness of the eclipsed star which will arise from ac-

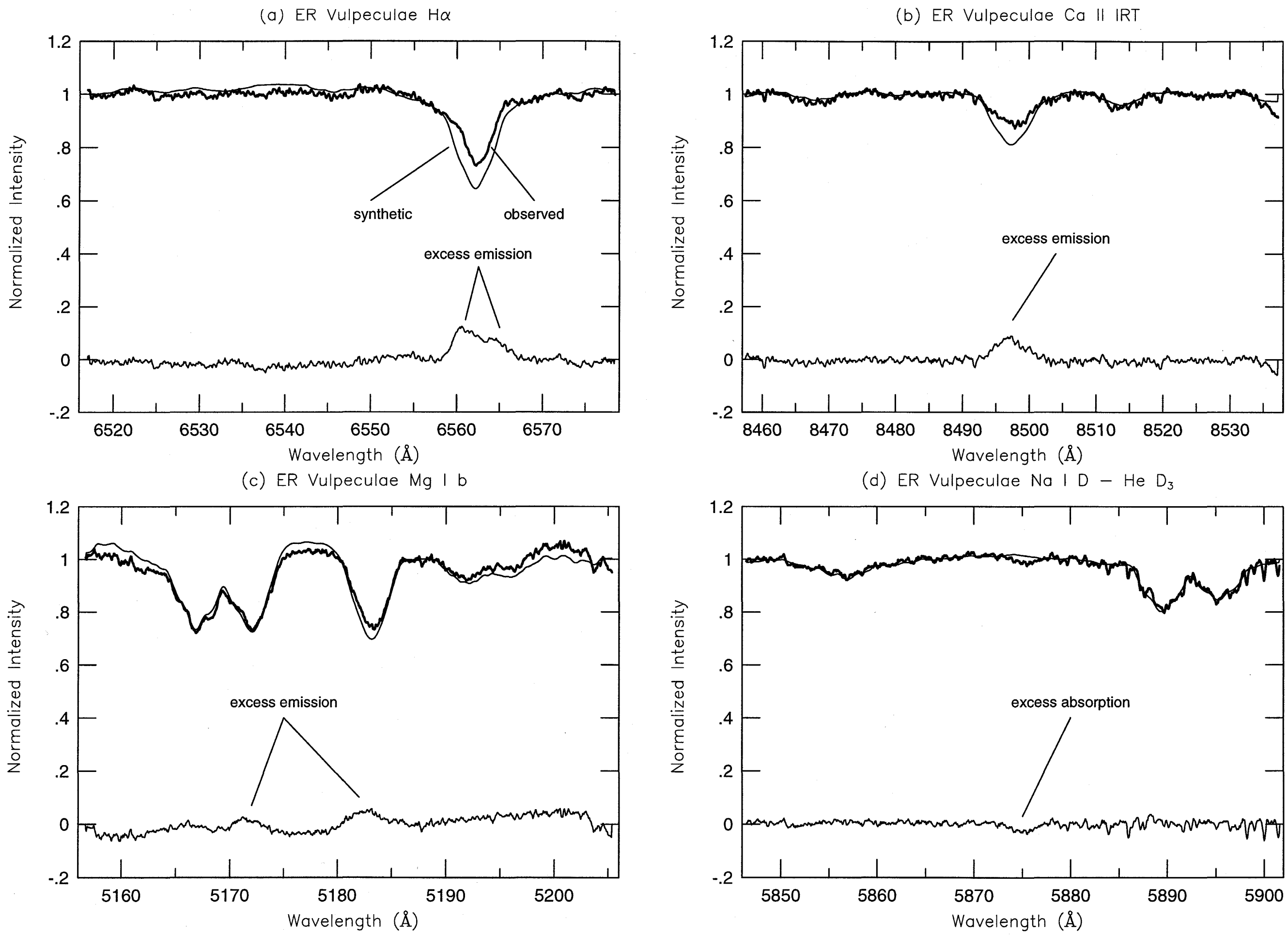

Fig. 2a–d. Observed, synthetic and subtracted spectra for spectral orders containing activity-sensitive lines for a single ER Vulpeculae spectrum (phase 0.939). Lines shown are Hα **a**, the Ca II IRT line at λ8498.02 **b**, the Mg I b lines **c** and the order containing the Na I D_1 and He I D_3 lines **d**. Bold lines indicate the observed spectra with overlying thin lines showing the synthetic spectra. The zero-continuum data are the resulting subtracted spectra showing excess emission/absorption features.

tive regions and limb-darkening effects. Details of how standard spectra are combined to form the synthetic spectrum are given by Barden (1984). The software used for this work is called CORREL (Gunn 1995) and is an interactive command-line driven package allowing complete automation of the analysis procedure. The final subtracted spectra were analysed by measuring excess absorption or emission features in the active lines of the target star.

6. Results

The spectral standard stars chosen to form a match for the ER Vulpeculae system were 26 Dra (G0V) and HD 186427 (G5V). Agreement between the wavelength calibrations of spectral standards and target spectra were checked by measuring the positions of several atmospheric lines visible in all spectra. The maximum deviation was no more than 0.01Å or approximately 0.5 km s^{-1} at Hα.

Spectral synthesis was performed for the active orders for all ER Vul spectra. The lines analysed were Hα (λ6562.85), one of the Ca II IRT lines (λ8498.02), Na I D_1 and D_2 (λ5889.95 and λ5895.92), He I D_3 (λ5875.62) and Mg I b (λ5167.33, λ5172.68 and λ5183.61). Fig. 2 shows examples for each of these orders of the synthetic spectra formed for one ER Vul spectrum. Bold lines are the observed spectra and thin lines the synthetic spectra. Also plotted on these diagrams are the subtracted spectra. In orders containing no activity-sensitive features good cancellation of lines was achieved. As can be seen the Hα line, Ca II IRT and Mg I b lines all show excess emission features. This indicates that these lines have significant filling-in of the global absorption profiles over and above that expected for non-active stars. The small difference in normalisation for the Mg I b order is not thought to effect the degree and position of the excess emission. The Na I D lines show no excess features above the variation due to small atmospheric absorption features. However it is clear that He I D_3 has a high degree of excess absorption in this system. Subsequent analysis concerns the evolution of these excess features throughout the observations.

Fig. 3 shows the results of measurements on the subtracted Hα emission line. There is an indication of a small amount

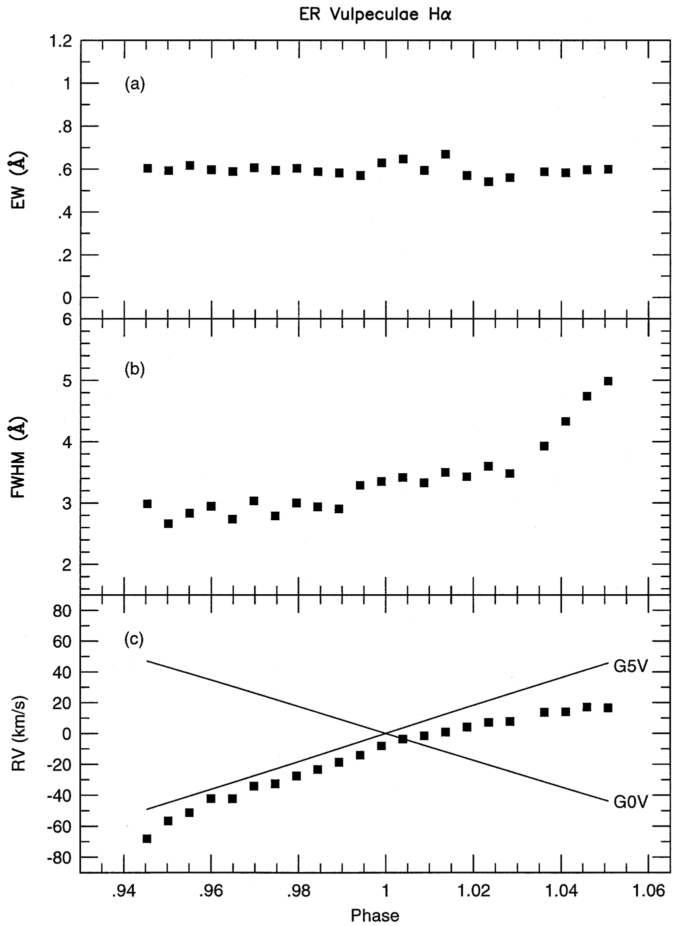

Fig. 3a–c. Results of the analysis of the subtracted H α emission line from ER Vulpeculae. The upper panel shows the variation in EW, the middle panel the variation in FWHM and the bottom panel the radial velocity of the emission compared to the RV curves of each component.

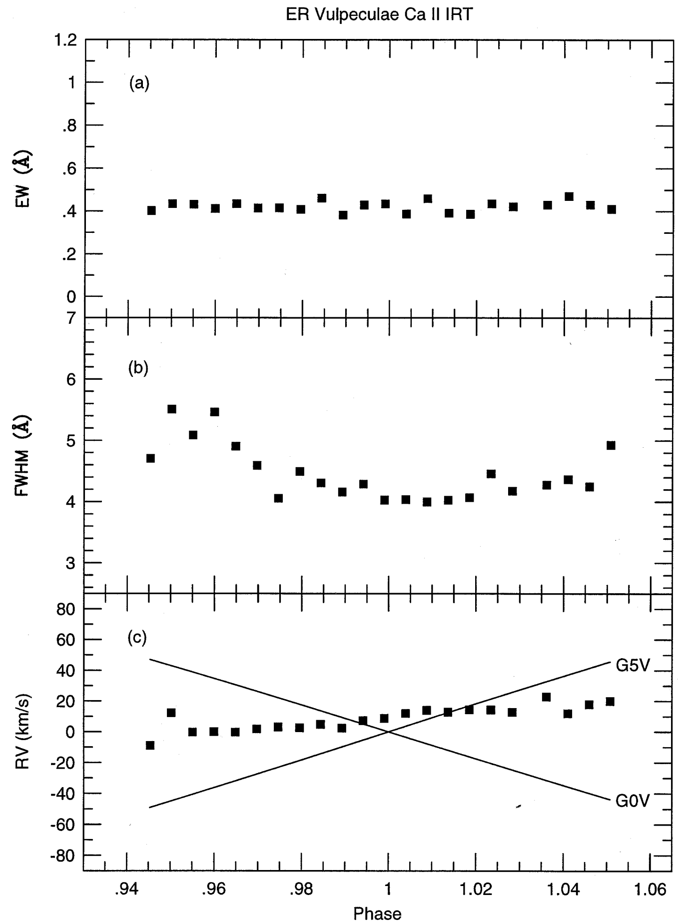

Fig. 4a–c. Results of the analysis of the subtracted Ca II IRT emission line at 8498.02Å from ER Vulpeculae. EW, FWHM and radial velocities are shown.

of excess absorption on the blue edge of the emission profile during the eclipse spectra. Although this feature is not significantly above the noise level it may be real since the fluxes for the continuum level across this order are remarkably consistent throughout the observations whilst the absorption feature is seen to undergo more significant variations. If this feature is real it is absorbing at a velocity of $\sim$ 200 km s^{-1} on the blue edge of the secondary star.

Fig. 3a shows the equivalent width (EW) measurements for the excess Hα emission. As can be seen these values remain essentially constant throughout the observations implying that the total excess emission from both components is not varying with phase. However the FWHM of the emission (shown in Fig. 3b) varies quite substantially being lower during the eclipse. This implies that the emission is indeed originating in both components since it is the relative positions of the features which changes the overall width of the profile. Finally Fig. 3c shows the measured radial velocity of the emission feature (diamonds) against phase with the actual orbital velocity of the primary and secondary components plotted as solid lines. Clearly the majority of the excess emission is associated with the secondary (cool) component of ER Vul.

Fig. 4 shows results for the Ca II IRT (λ8498.02) excess emission profiles from ER Vul. Again the EW is essentially constant while the FWHM varies in a way consistent with emission arising on both components. Measurements of the velocities of these profiles (shown in Fig. 4c) show an almost constant velocity centred around zero. This indicates that the Ca II IRT line from each component are of similar intensity so that the resulting velocity is an average of the orbital velocities of the two components. The small variation with phase indicates that the secondary may be slightly more luminous in Ca II IRT excess emission than the primary.

Fig. 5 shows the results obtained for two of the Mg I b lines for ER Vul. For both these lines the EW remains almost constant while the FWHM varies. Again emission in these lines appears to be originating on both components, although significantly more from the secondary.

Results for the He I D_3 line excess absorption are shown in Fig. 6. This line is very weak in ER Vul and presented some difficulties for the measurement process. However it was possible to determine values for the EW, FWHM and velocity. It appears that He I D_3 absorption is occurring in the atmospheres of both components since the EW remains constant while the FWHM decreases to a minimum during conjunction.

7. Discussion

7.1. The Hα Emission Line

A significant result of these observations is that no obvious excess absorption feature has been detected for ER Vulpeculae which would indicate the presence of extended material surrounding the system. This confirms the results of Barden (1984), Newmark (1990), Lazaro & Arevalo (1994) and Eker, Hall & Anderson (1995). Mention should be made of the small excess absorption feature approximately 200 km s^{-1} blue-ward of the secondary star. This feature appears to be real but is so weak that analysis was impossible.

The observations have revealed a significant amount of excess emission in the core of the Hα line for ER Vul. Analysis of the velocity of this component strongly suggests that the emission is arising predominantly on the secondary (G5 V) star although the variation in the FWHM indicates that there is a small amount of emission from the G0 V primary. The modulation of the excess emission with phase would indicate the appearance and disappearance of discrete active regions as different hemispheres of the stars are presented to the observer. No obvious variation of the emission has been detected for ER Vul over the phase of the observations. Although the phase coverage of the observations is small (0.14) and therefore inadequate to produce a significant variation, the velocity of the emission is highly suggestive that it is not associated with a transient phenomenon such as a flare or with localized individual active regions but arises due to a global phenomenon. Although it has been assumed that the velocity of the emission component is consistent with it arising on the secondary star there is clearly a consistent velocity shift of the emission by about 10 km s^{-1} blue-ward of the secondary position. It is interesting to note that in the solar case, observations in Hα reveal systematic blue-shifts in the emission as a result of spicules (Beckers 1968; Beckers 1972). Spicules are rapidly changing thin filamentary features permeating the solar chromosphere at chromospheric temperatures (T $\sim 10^4$ K) which often extend upward into the hotter corona (T $\sim 10^6$ K). However these features cover only about 1-2% of the solar surface and consequently the disk-integrated Hα solar spectrum does not display the systematic velocities associated with spicules. As will be demonstrated the plage coverage or filling factor for the ER Vul secondary appears to be very high (see below) so this observation may be of disk-integrated blue-shifts associated with active regions such as spicules.

In solar-type stars the radiation temperatures are sufficiently large or the electron temperatures are sufficiently low so that Hα is dominated by photoionization; the Balmer lines are consequently coupled to the photospheric radiation field rather than the local line-formation region. For later stars or those with enhanced chromospheres the Hα source function can become dominated by collisional processes as the electron density becomes higher and the photospheric radiation temperature becomes lower. In this case the Hα core becomes filled-in and indicates the presence of a highly active chromosphere. Very high temperature chromospheres found in M-dwarfs actually drive the Hα line into emission due to the dominance of collisional excitation in the line-forming region. The actual details of Hα formation in late-type stars are extremely complex since many mechanisms and structures contribute to the line profile. However the observation of substantial excess emission in ER Vul is consistent with the general picture of an extremely active chromosphere (see for example Houdebine, Doyle & Koscielecki 1995).

For single stars the filling-in of the Hα core has been well documented (Zarro & Rodgers 1983; Herbig 1985; Thatcher & Robinson 1993) and has also been observed in chromospherically active binaries (Strassmeier et al. 1990; Fernandez-Figueroa et al. 1994; Frasca & Catalano 1994; Eker, Hall & Anderson 1995; Montes et al. 1995). For such binaries the behaviour of the Hα line is often found to be inconsistent with the photometric evolution and has been variously attributed to emission arising from star-spot regions or plages (Ramsey & Nations 1984; Newmark et al. 1990), from chromospheric network-like structures (Huenemoerder, Ramsey & Buzasi 1990) or from extended prominence-like material (Hall & Ramsey 1992b; Hall & Ramsey 1994). Unfortunately the present study does not encompass the variation of excess emission with phase since the primary goal was to detect the presence of extended material during the eclipse of the ER Vul system. However the analysis of the data has revealed evidence that the filling-in of the Hα profile is due to plage regions. This is also confirmed by the appearance of the He I D_3 absorption line in the spectrum (see below).

It is extremely difficult to quantify excess emission for a single star and most studies to date have involved surveys of large samples of active stars with a view to deciphering correlations between different chromospheric diagnostics and between these and other stellar parameters such as spectral type or rotational period (Young et al. 1989; Herbig 1985). Using subtracted spectra to derive physical parameters is dangerous since the technique is best suited to observing line variability in binaries across wide ranges in phase. However some simple calculations concerning the size of the emitting regions are possible as follows.

The continuum flux density in the Hα region for ER Vul was calculated using the stellar atmosphere models of Kurucz (1979) for a G5 V star with solar abundances. The actual wavelength of the calculation was 6575Å and the effective temperature was taken as 5770 K. The resulting flux density is 2.14 10^6 erg s^{-1} cm^{-2} $Å^{-1}$ which differs from the black-body flux at Hα by only 3%. The corresponding luminosity at Hα for ER Vul is 1.5 10^{29} erg s^{-1} $Å^{-1}$ assuming a radius of $1.07R_{\odot}$. The mean equivalent width of the excess Hα emission (0.596Å) was then converted to flux units using the relation;

$$F_e = F_{H_\alpha}(W_{H_\alpha} + \Delta\lambda) \quad (1)$$

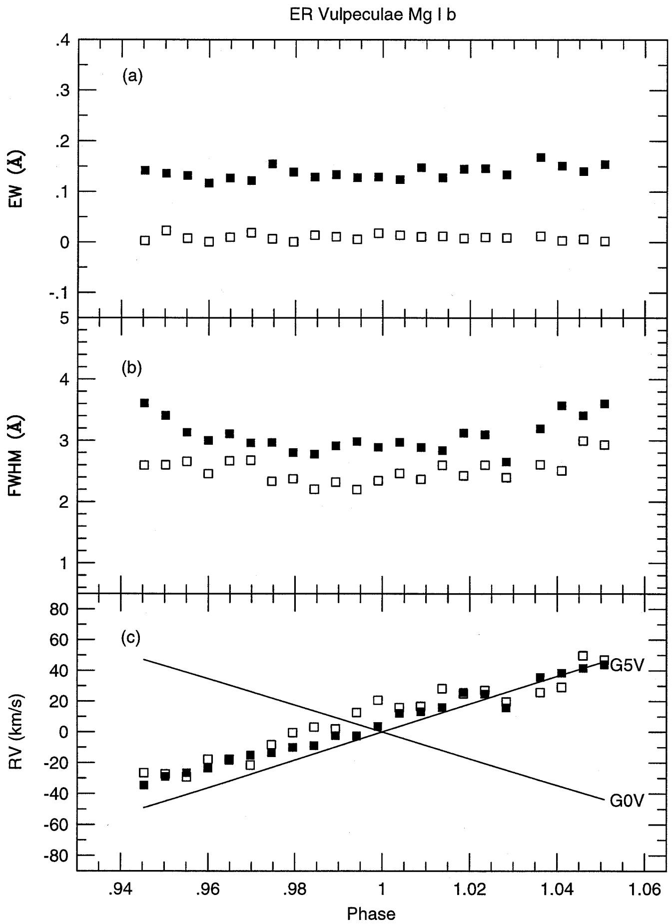

Fig. 5a–c. Results of the analysis of the subtracted Mg I b emission lines from ER Vulpeculae. EW, FWHM and radial velocities are shown for the λ5183.61 line (filled squares) and the λ5172.68 line (open squares).

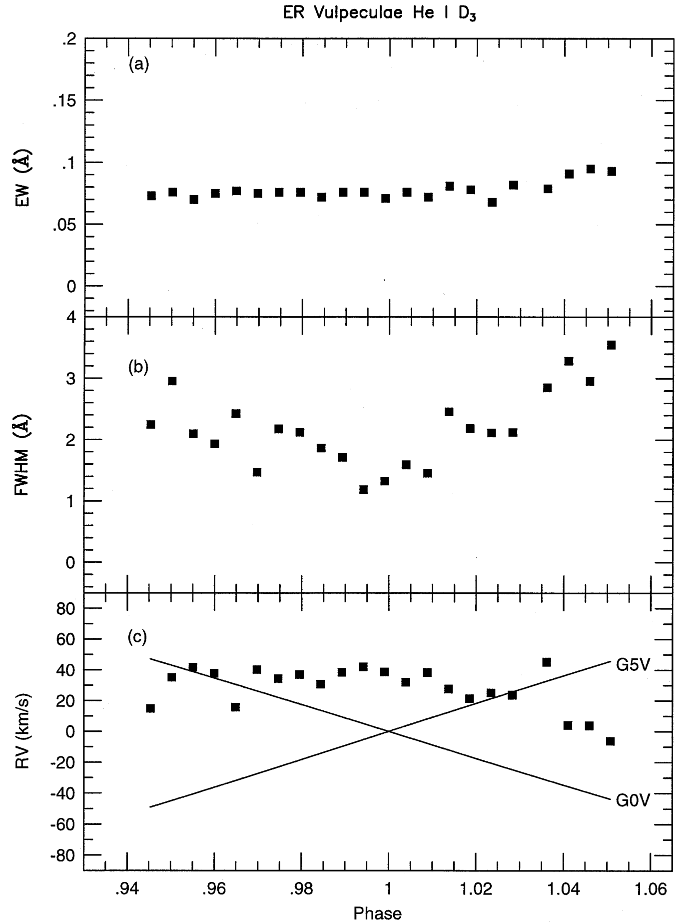

Fig. 6a–c. Results of the analysis of the subtracted He I D_3 absorption line from ER Vulpeculae.

where F_{H_α} is the Hα continuum flux, W_{H_α} is the equivalent width of the excess emission and $\Delta\lambda$ was taken as 2Å, the width of the region used to define W_{H_α}. The resulting excess emission luminosity is 3.9 10^{29} erg s^{-1}.

Fraquelli (1984) gives a relationship between the volume emissivity j, the electron density n_e and temperature of formation of the Hα line T based on the assumption that the dominant emission mechanism is recombination. This mechanism was considered in detail by Burgess (1958). In case **B** of that analysis the assumption is made that the plasma is very opaque to Lyman line radiation and that the absorption from level 1 to level 2 in hydrogen is exactly balanced by the inverse spontaneous transition. The Hα line radiation then results from cascades after electron capture and following absorption of Lyman line radiation. The approximation of Burgess (1958) is better than 1% for electron temperatures less than about 2.5 10^4 K. By comparing the emissivity variation in a non-LTE scaled VAL C model of solar plage regions for Hα (Vernazza, Avrett & Loeser 1981), it has been shown (Andretta 1995, private communication) that within an order of magnitude the results of Fraquelli (1984) are valid. Hence the flux in the Hα emission region is given by;

$$F_e = jV \quad (2)$$

where V is the volume of the Hα emitting region. The volume emissivity of Hα is given by;

$$j = 1.29 \times 10^{-23} n_e^2 T^{-1/2} \log \left\{ \frac{I_H}{kT} \right\} \quad (3)$$

where I_H is the ionization energy of hydrogen. This equation is also based on the assumption that the proton and electron densities are equal ($n_p = n_e$) in this region of the chromosphere which is a reasonable assumption for a star of this spectral type. The same VAL C models show that the region of formation of the Hα line core is at least a factor of three in electron density (1.0 $10^{11} > n_e >$ 3.5 10^{10}) and at least 50% in temperature (6000 $< T <$10000). Taking the ionization energy of hydrogen as 2.18 10^{-11} erg then the corresponding range in the volume of the emission region is 1.6 10^{32} - 2.0 10^{33} cm^3. Assuming the emission region is a homogeneous hemispherical shell then the chromospheric thickness for Hα lies in the range R_c = 0.045 - 0.42$R_\odot$. The chromospheric thickness reported for the Sun is of the order 0.004$R_\odot$ (Athay 1971) while Fraquelli (1984) shows by a similar method that the two components of HR 1099 (consisting of a G5 IV primary and a K1 IV secondary) have chromospheric thicknesses of $0.2R_\odot$ and $0.06R_\odot$ respectively. This may mean that the higher value is appropriate for ER Vul so that the main emission excess is formed at higher temperatures and lower electron densities than assumed by Fraquelli (1984). More detailed chromospheric modelling of the Hα excess emission in active stars is required before any further definitive statements can be made.

7.2. The Ca II IRT emission lines

The observations of ER Vulpeculae have also revealed the presence of significant excess emission in the Ca II IRT line at λ8498. Unfortunately the remaining two lines in this triplet were just on the edge of the spectral coverage for these observations and were impossible to analyse. Analysis of the velocity of the excess emission has suggested that it arises almost equally on both components of the system (probably the secondary is slightly more active in these lines). The FWHM variation for ER Vul is also consistent with a dual emission peak. This is similar to observations of the BY Draconis-type variable DH Leonis studied by Newmark et al. (1990) in which the secondary was found to be more active in the Balmer lines while both stars showed almost equal Ca II IRT emission.

Enhanced emission cores in the Ca II H and K lines at λ3933.66 and λ3968.47 are the primary optical indicators of chromospheric activity. Their source functions are collisionally controlled and so these lines are sensitive probes of the electron density and temperature in the chromosphere. The H and K lines are favoured for chromospheric modelling since they are extremely important cooling mechanisms and their interpretation is relatively straight-forward. However less work has been done on the Ca II IRT although they are formed deeper in the atmosphere and are thus sensitive probes of the temperature minimum region and the temperature rise to the so-called Lyman plateau. Foing et al. (1989) observed the λ8498 and λ8542 IRT lines in a sample of stars from F9 to K4 and found that these lines correlate well with the H and K emission peaks. Linsky et al. (1979) also showed that filling-in of the IRT lines was a good indicator of stellar activity. The IRT lines are formed in the lower chromosphere of the Sun (Vernazza, Avrett & Loeser 1981) and in the temperature plateau in active chromosphere K2 dwarfs (Thatcher, Robinson & Rees 1991). In the quiet solar atmosphere these lines are simple absorption lines but as one goes to plages of brighter Ca II H and K emission the IRT line cores brighten and eventually develops self-reversed emission cores (Shine & Linsky 1972). On this basis it might then be expected that stars with Ca II H and K emissions comparable to those in solar plages will also exhibit IRT emission cores rather than simple filling-in. However this has not been found to be the case. Anderson (1974) surveyed 28 stars from F8 to M2 in the λ8498 line and Linsky et al. (1979) studied 49 stars from F9 to K3 at λ8542. Both studies revealed no distinct emission features even in the most active stars, although they did however display filling-in of the line cores. This behaviour is also displayed by the active components of ER Vul; on the evidence for plage regions on these stars we might expect to see emission cores in the Ca II IRT but instead see only filling-in. It has been suggested that such an emission core may be smeared out by rotation or large velocity fields and thus appear as filling-in (Linsky et al. 1979). However Thatcher & Robinson (1993) pointed out that rotational broadening could not account for the lack of emission cores in all cases. For ER Vul the rotation rate is probably not sufficient to smear the emission core beyond detection and so this star remains part of the Ca II IRT enigma. It can therefore be assumed that some additional broadening mechanism is at work in the plage emission from ER Vul. This is therefore another area where detailed chromospheric modelling is required.

Although the observation of excess emission in the IRT suggests the presence of non-radiative heating in the lower chromosphere for both components of ER Vul, and is consistent with plage emission, a reliable quantitative interpretation would be difficult without more detailed modelling.

7.3. The He I D_3 absorption line

The observations have revealed obvious excess absorption in the He I D_3 (λ5876) line for ER Vulpeculae. The use of He I D_3 as an activity indicator has been largely ignored because it is extremely weak in normal stars and is generally blended with difficult water vapour lines when observed from low-to-medium altitude observatories. However observations of the stronger λ10830 line have been presented for large numbers of stars of different classes by Vaughan & Zirin (1968), Zirin (1976) and Zirin (1982) although observations of the D_3 line are less common.

The triplet lines of He I at λ5876 and λ10830 appear in absorption in the solar spectrum; the weaker D_3 absorption feature appears to be cospatial with plage regions and absent elsewhere. At λ10830 the absorption is strongest above active regions and very weak (with a tendency to be in emission) in coronal hole regions (McCabe & Mickey 1981). Landman (1981) studied high resolution spectra of He I D_3 taken for solar plage regions. In stellar work Wolf & Heasley (1984) observed He I in 18 late-type stars and showed that the line depths, widths and the ratio λ10830/λ5876 in dwarf stars was similar to that measured in solar plages. However they found that the line ratio in giants was much larger than in either solar plages or active dwarfs and suggested that the conditions under which He I forms may be very different in highly luminous stars. The factors which control the formation of the He I triplet lines, in particular D_3 and λ10830, are however not well understood. The basic problem is that the transition region models based on UV and EUV resonance lines cannot account for the observed intensity levels in the quiet Sun He I resonance lines (Jordan 1975). Zirin (1975) suggested that the He I triplet levels are populated by radiative recombinations following photoionization of He atoms by coronal far-UV and X-ray line and continuum radiation. Giampapa et al. (1978) argued that He I D_3 line they found in AD Leonis was not excited by recombination following photoionization since such an assumption would also require unrealistically high X-ray luminosity. Instead they suggest that He I λ5876 is excited by collisions from the ground state in the hotter ($T > 8000$

K) region of the stellar chromosphere. Recently Andretta, Giampapa & Jones (1995) suggest on the basis of their non-LTE calculations that at least some of the He I spectral features in the Sun and late-type stars could be linked to regions of enhanced UV and X-ray emission but that He I formed by photospheric ionization and decay and collisional processes seemed to be present even for the case of an inactive corona.

Despite the confusion as to the details of He I formation in the Sun and stars it is now almost certain that active regions on the stellar surface are the dominant area contributing to the observed flux profiles. The equivalent width of D_3 is controlled by the temperature-density profile in the middle chromosphere and the fraction of disk covered by plages. The observation of He I D_3 absorption in ER Vul is therefore very suggestive of large areas of plage-like plasma in the chromospheres of one or both components in this binary. The equivalent widths of the absorption remain fairly constant with a mean value of 78 mÅ. The velocity measurements of the excess absorption are however confused for all measurements and it can only be assumed that this is due to the weakness of the line and noise effecting the gaussian fitting. It is a reasonable assumption that the majority of the absorption is occurring on the secondary component of the binary since this appears to be the more active star with a higher probability of plage regions. The FWHM variation however clearly implies that absorption is occurring for both stars.

Andretta & Giampapa (1995) presented a computational approach to the He I triplet lines in dwarf F and G stars. They show that the lines can be utilised to infer the fractional area coverage or filling factor of active regions on stellar surfaces if the intrinsic absorption strengths are known. They compute He I profiles using a grid of model chromospheres superposed on late-type dwarf photospheric models. They estimate that in both F and G type stars a conservative value for the maximum absorption equivalent width (W_{max}) in He I D_3 is ~100-150 mÅ. This calculation ignores the quiet component and is therefore appropriate for measurements on the subtracted spectra. A lower limit to the filling factor is then given by;

$$A \geq \frac{W_{obs}}{W_{max}} \quad (4)$$

where W_{obs} is the observed He I equivalent width. Using this relationship the filling factor for the secondary component of ER Vul is 0.53. This is extremely high even if we apportion this value between the two blended components. Unfortunately there are no measurements of the He I λ10830 line for this system which could be used to verify this result. However Andretta & Giampapa (1995) report a filling factor of between 0.5 and 0.6 for the active G8 V star ξ Boo A while O'Neal, Neff & Saar (1994) deduced a filling factor of between 0.41 and 0.52 for II Peg. So although ER Vul has a high filling factor this is not inconsistent with other observations of highly active stars (Wolf & Heasley 1984).

Andretta & Giampapa (1995) also computed the theoretical dependency of the λ5876 equivalent width with the excess emission equivalent width in the core of the Hα line from plage regions, and these predictions showed good agreement with numerous observations of solar plage regions. The results for ER Vul show that the He I D_3 and Hα measurements are again entirely consistent with both observational and theoretical considerations of active plage regions in the solar analogy. In conclusion the He I D_3 observations for ER Vul have demonstrated the existence of very large filling factors presumably associated with the secondary component. ER Vul appears to be highly active with regards to plage regions and the existence of such slab-like structures is entirely consistent with the lack of detection of extended material around the system.

7.4. The Mg I b and Na I D_1 & D_2 lines

Strong neutral metal absorption lines are of special interest for stellar activity studies since they are formed in the lower chromosphere and the region of temperature minimum for solar type stars. Basri, Wilcots & Stout (1989) concluded in their study of 29 main-sequence stars that the Mg I b lines were good diagnostics of photospheric activity. The Na I lines are collision dominated due to the small photoionization cross-section and relatively large collisional cross-section for Na I (Johnson 1964). This means that the source functions of the Na I lines are functions of electron temperature and pressure and so are good indicators of changes in the lower chromosphere.

The observations have revealed a significant amount of excess emission in the Mg I b lines from ER Vulpeculae. Measurements have been made on the lines at λ5172.68 and λ5183.61 while the line at λ5167.33, although present, was too weak to give reliable measurements. The velocities of the two measured lines show that the emission is again predominantly from the secondary component although the FWHM variation is consistent with a small amount of emission from the primary. In contrast, no excess emission has been detected in the Na I D_1 (λ5889.95) and D_2 (λ5895.92) lines in the observations of ER Vul. This is significant since both these neutral metals form in the lower chromosphere. Furthermore the ionization energies of Mg I and Na I are 7.6 eV and 5.1 eV respectively indicating a disparity between the observed emission and that expected from simple energetics. We regard it unlikely that crowded atmospheric absorption could account for a difference in EW between the standard and target stars. An explanation may lie in the existence of a complex chromospheric structure and/or opacity effects.

Further theoretical work is required before any definitive statements about the lack of excess Na I emission in ER Vul can be made. Current work underway by Andretta, Doyle & Byrne (1996) using a more complete set of opacities will provide a better insight into the use of these lines in studies of stellar activity.

8. Conclusions

The primary aim of this study was to search for evidence of regions of extended material around the ER Vul system. Northcott & Bakos (1967) were the first to suggest the presence of a gaseous cloud at the inner Lagrangian point extending to one side. McLean (1982) also suggested the presence of circumstellar material near the primary component in order to account for variations in the primary component spectral lines. Arevalo, Lazaro & Fuensalida (1988) also proposed that a high-temperature gas stream exists between the components based on their photometric variations; this would also account for their suggested IR and UV excesses. Apart from the detection of a very weak absorption feature approximately 200 km s^{-1} blueward of the secondary component the present study has not detected spectroscopically the existence of such extended regions. This confirms the results of Newmark (1990) who also found no spectroscopic signatures of extended material and concluded that the phase variations of the line strengths and widths were incompatible with an origin in extended structures. It is unclear whether the large filling factor derived for this system can account for the variations seen by McLean (1982); even if it does the photometric results would then also show a disparity. If extended material is present then it must be sufficiently distant from the star concerned that it is neither eclipsed nor affects photometric measurements with temporal variations. It is also possible that the appearance of circumstellar material is a transient phenomenon similar to solar prominences but such a conjecture is not testable in the present study. For ER Vul the photometric and spectroscopic inferences must therefore remain in disagreement.

The present observations have clearly detected excess emission in the activity sensitive lines of Hα, the Ca II IRT, and Mg I b as well as absorption in He I D_3. Newmark (1990) also reported excess emission in Hα and the Ca II IRT for ER Vul. He concluded that the emission variations were not correlated with phase; their stochastic nature suggested a global origin. This is also confirmed in this study by deriving the velocities of the excess emission peaks. An important result is that the present observations clearly show that the secondary component of ER Vul is the more active. Newmark (1990) found that the opposite was true. This cannot be accounted for by the eclipse nature of these observations since the maximum obscuration of the primary disk is only 12%; insufficient to affect the factor of approximately two for the emission from the primary over that of the secondary in both Hα and the Ca II IRT found by Newmark (1990). Hence the activity levels of the components of ER Vul must be highly variable. This study has shown that during these observations the secondary component of ER Vul was more active than the primary in Hα and slightly more active in the Ca II IRT.

ER Vul consists of two dwarf stars unlike many other RS CVn systems which are dominated by the emission from a giant or sub-giant primary. Dwarf stars have higher surface gravities and electron densities so their emission regions may be significantly different than in other RS CVn's. In fact Buzasi (1989) has shown that the chromospheric activity in main-sequence stars should be mainly from optically thick plage-like regions where the ratio of excess emission in the Hα and Hβ lines ($EW_{H_\alpha}/EW_{H_\beta}$) can be as low as 2.0. Conversely evolved stars should have higher ratios similar to those found in solar prominences. Chester (1991) recently confirmed the low ratios associated with solar plage regions with high-resolution spectroscopic observations. Newmark (1990) found a $EW_{H_\alpha}/EW_{H_\beta}$ ratio for ER Vul of $\sim$1.09 and suggested that the majority of the emission was associated with plage regions as expected for dwarf stars. This hypothesis has been confirmed in the present study mainly by the detection of significant He I D_3 absorption which is known to be only visible in plages for the solar case. In addition analysis of this line indicates a very large filling factor of 0.53 implying the chromosphere is highly active over the entire surface. The detection of a constant velocity offset for the emitting material is similar to that seen in the solar plages. Since the filling factor is very large for ER Vul the disk-integrated spectra may show such an offset although for the disk-integrated solar spectrum (where the filling factor is only a few percent) this is not seen. Thus it is possible these results represent the first observation of the equivalent of solar spicule emission in a stellar system other than the Sun.

Simple calculations have revealed that the chromospheric thickness for the ER Vul secondary may be very large ($\leq 0.42R_\odot$). The excess emission in the Hα, Ca II IRT and Mg I b lines is indicative of a significant amount of non-radiative energy dissipation at all levels of the chromosphere although the lack of detection of Na I D emission is confusing.

X-ray and UV studies of RS CVn systems suggest that there is a level at which the emission becomes saturated (Vilhu & Rucinski 1983), although alternative explanations exist (Doyle 1996). If such saturation is related to very large filling factors then for these systems little phase variation of the emission should be seen. The very high levels of X-ray (Walter & Bowyer 1981), UV (Rucinski & Vilhu 1983) and radio emission (Drake, Simon & Linsky 1986) for ER Vul suggest it is a system where continuous high levels of activity (e.g. micro-flaring) may be taking place. The optical observations of Newmark (1990) showed no variability in line fluxes which supports the hypothesis that ER Vul is near the saturation limit for chromospheric activity. The present observation of a large filling factor for ER Vul adds credence to this proposition.

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References

Abrami A., Cester B., 1963, Technical Report 320, Osserv. Astr. di Trieste
Anderson C. M., 1974, ApJ 190, 585
Andretta V., Giampapa M. S., 1995, ApJ 439, 405
Andretta V. A., Doyle J. D., Byrne P. B., 1996, A&A (submitted)
Andretta V., Giampapa M. S., Jones H. P., 1995, Irish Astron. J. 22, 177
Arevalo M. J., Lazaro C., Fuensalida J. J., 1988, AJ 96, 1061

Athay R. G., 1971, in Macris C. J., ed, Physics of the Solar Corona. Reidel: Dordrecht, p. 36
Barden S. C., 1984, PhD thesis, Pennsylvania State University
Basri G., Wilcots E., Stout N., 1989, PASP 101, 528
Beckers J. M., 1968, Sol. Phys. 3, 367
Beckers J. M., 1972, ARA & A 10, 73
Bingham R., 1984, Technical Report, RGO/La Palma
Bond H. E., 1970, PASP 82, 321
Budding E., Zeilik M., 1987, ApJ 319, 827
Budding E., Kadouri T. H., Gimenez A., 1982, Ap & SS 88, 453
Burgess A., 1958, MNRAS 118, 477
Buzasi D. L., Huenemoerder D. P., Ramsey L. W., 1991, PASP 103, 1077
Buzasi D. L., 1989, PhD thesis, Pennsylvania State University
Byrne P. B., Eibe M. T., Rolleston W. R. J., 1996, A & A (in press)
Chester M. M., 1991, PhD thesis, Pennsylvania State University
Collier Cameron A., Robinson R. D., 1989a, MNRAS 236, 57
Collier Cameron A., Robinson R. D., 1989b, MNRAS 238, 657
Collier Cameron A., Woods J. A., 1992, MNRAS 258, 360
Collier Cameron A., Duncan D. K., Ehrenfreund P., Foing B. H., Kuntz K. D., Penston M. V., Robinson R. D., Soderblom D. R., 1990, MNRAS 247, 415
Cram L. E., Giampapa M. S., 1987, ApJ 323, 316
Cram L. E., Mullan D. J., 1979, ApJ 234, 579
Doyle J. G., 1996, A & A 307, L45
Drake S. A., Simon T., Linsky J. L., 1986, AJ 91, 1229
Eker Z., Hall D. S., Anderson C. M., 1995, ApJS 96, 581
Fernandez -Figueroa M. J., Montes D., de Castro E., Cornide M., 1994, ApJS 90, 433
Foing B. H., Crivellari L., Vladilo G., Rebolo R., Beckman J. E., 1989, A & ASS 80, 189
Fosbury R. A. E., 1974, MNRAS 169, 147
Fraquelli D. A., 1984, ApJ 276, 243
Frasca A., Catalano S., 1994, A & A 284, 883
Giampapa M. S., Linsky J. L., Schneebergers T. J., Woorden S. P., 1978, ApJ 226, 144
Gunn A. G., 1995, PhD thesis, Queen's University of Belfast
Gunn A. G., Hall J. C., Lockwood G. W., Doyle J. G., 1996, A & A 305, 146
Hall J. C., Ramsey L. W., 1992a, in Giampapa M. S., Bookbinder J. A., eds, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 26, p. 359
Hall J. C., Ramsey L. W., 1992b, AJ 104, 1942
Hall J. C., Ramsey L. W., 1994, AJ 107, 1149
Hall J. C., Huenemoerder D. P., Ramsey L. W., Buzasi D. L., 1990, ApJ 358, 610
Hall D. S., 1976, in Fitch W. S., ed, Multiple Periodic Variable Stars, IAU Coll. 29. Reidel: Dordrecht, p. 287
Heasley J. N., Mihalas D., 1976, ApJ 205, 273
Herbig G. H., 1985, ApJ 289, 269
Hill G., Fisher W. A., Holmgren D., 1990, A & A 238, 145
Houdebine E. R., Doyle J. G., Koscielecki M., 1995, A & A 294, 773
Huenemoerder D. P., Barden S. C., 1986, AJ 91, 583
Huenemoerder D. P., Ramsey L. W., 1984, AJ 89, 549
Huenemoerder D. P., Ramsey L. W., 1987, ApJ 319, 392
Huenemoerder D. P., Buzasi D. L., Ramsey L. W., 1989, AJ 98, 1398
Huenemoerder D. P., Ramsey L. W., Buzasi D. L., 1990, ApJ 350, 763
Huenemoerder D. P., 1988, PASP 100, 600
Johnson H. R., 1964, Ann. d'Ap. 27, 695
Jordan C., 1975, MNRAS 170, 429
Kurucz R. L., 1979, ApJS 40, 1
La Bonte B. J., 1986, ApJS 62, 241
Landman D. A., Mongillo M., 1979, ApJ 230, 581
Landman D. A., 1981, ApJ 244, 345
Lazaro C., Arevalo M. J., 1994, in Caillault J. P., ed, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 64, p. 435
Linsky J. L., Hunten D. M., Sowell R., Glackin D. L., Kelch W. L., 1979, ApJS 41, 481
McCabe M. K., Mickey D. L., 1981, Sol. Phys. 73, 59
McLean B. J., 1982, MNRAS 201, 421
Mennella V., 1990, A & A 234, 203
Montes D., de Castro E., Cornide M., Fernandez -Figueroa M. J., 1994, in Caillault J. P., ed, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 64, p. 444
Montes D., Fernandez-Figueroa M. J., de Castro E., Cornide M., 1995, A & A 294, 165
Morris D. H., Mutel R. L., 1988, AJ 95, 204
Newmark J. S., Buzasi D. L., Huenemoerder D. P., Ramsey L. W., Barden S. C., Nations H. L., Seeds M. A., 1990, AJ 100, 560
Newmark J. S., 1990, PhD thesis, Pennsylvania State University
Northcott R. J., Bakos G. A., 1956, AJ 61, 188
Northcott R. J., Bakos G. A., 1967, AJ 72, 89
O'Neal D., Neff J. E., Saar S. H., 1994, in Caillault J. P., ed, Cool Stars, Stellar Systems and the Sun. ASP Conference Series Vol. 64, p. 726
Ramsey L. W., Nations H. L., 1984, AJ 89, 115
Robinson R. D., Collier Cameron A., 1986, PASA 6, 308
Rucinski S., Vilhu O., 1983, MNRAS 202, 1221
Rucinski S. M., 1992, PASP 104, 1177
Schmidt -Kaler T., 1982, in Schaifers K., Voig H. H., eds, Landholt-Bornstein Vol. 2b. Springer: Heidelberg, p. 451
Shine R. A., Linsky J. L., 1972, Sol. Phys. 25, 357
Strassmeier K. G., Fekel F. C., Bopp B. W., Dempsey R. C., Henry G. W., 1990, ApJS 72, 191
Thatcher J. D., Robinson R. D., 1993, MNRAS 262, 1
Thatcher J. D., Robinson R. D., Rees D. E., 1991, MNRAS 250, 14
Unger S., Pettini M. UES User's Manual. Isaac Newton Group, La Palma, 1993
Unger S. W., Brinks E., Laing R. A., Tritton K. P., Gray P. M., Observer's Guide. Isaac Newton Group, La Palma, 1988
Vaughan A. H., Zirin H., 1968, ApJ 152, 123
Vernazza J. E., Avrett E. H., Loeser R., 1981, ApJS 45, 631
Vilhu O., Rucinski S. M., 1983, A & A 127, 5
Walker D. D., Diego F., 1985, MNRAS 217, 355
Walter F. M., Bowyer S., 1981, ApJ 245, 671
White N. E., Culhane J. L., Parmar A. N., Sweeney M. A., 1987, MNRAS 227, 545
Wolf S. C., Heasley J. N., 1984, PASP 96, 231
Young A., Skumanich A., Stauffer J. R., Bopp B. W., Harlan E., 1989, ApJ 344, 427
Young A., Rottler L., Skumanich A., 1991, ApJ 378, L25
Zarro D. M., Rodgers A. W., 1983, ApJS 53, 815
Zirin H., 1975, ApJ 199, L163
Zirin H., 1976, ApJ 208, 414
Zirin H., 1982, ApJ 260, 655

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