Surface imaging of late-type contact binaries II: \( \text{H}\alpha \) 6563Å emission in AE Phoenicis and YY Eridani

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Received ; accepted

Abstract.
We present and discuss the \( \text{H}\alpha \) (\( \lambda = 6563 \text{Å} \)) observations of the contact (W UMa type) binaries AE Phoenicis and YY Eridani, obtained in 1989, 1990 and 1995 with the CAT/CES telescope of the Southern European Observatory (ESO). In particular, we compare the intrinsic equivalent widths of both components with the NextGen theoretical models and the saturation limit. We find that the average \( \text{H}\alpha \) equivalent widths are close to the saturation border and that the primary components have excess \( \text{H}\alpha \)-emission, indicating enhanced chromospheric activity. This is compatible with both theoretical and observational suggestions that the primary is the more magnetically active component and is filled with (mostly unresolvable) dark spots and associated chromospheric plages.

Key words. contact binaries – \( \text{H}\alpha \)-emission – magnetic activity

1. Introduction

AE Phoenicis (AE Phe, G0V, \( P_{\text{orb}} = 0.362 \) d) and YY Eridani (YY Eri, G5V, \( P_{\text{orb}} = 0.312 \) d) are late type contact binaries (W UMa stars) of W-subtype. Their components touch each other inside a common convective envelope of constant entropy. According to the theory (Lucy, 1968) the primary (i.e. the more massive) component should be slightly hotter (by a few hundred degrees) than the companion, but observations show the opposite. Mullan (1975) and Rucinski (1985) ascribed the possible origin of this discrepancy to the presence of cool star spots on the primary. Some of the evolutionary models predict shallower outer convective zones for the secondary, because of its physical status (out of thermal equilibrium), in particular the angular momentum loss via magnetic braking (AML) models, see e.g. Vilhu (1982) and van’t Veer & Maceroni (1988), and the Thermal Relaxation Oscillation models (TRO), see e.g. Webbink (2003). (Note, by the way, that Webbink (2003) does not include the AML-models in his review.) Shallower convection would mean a less magnetically active secondary, because for a fixed rotation rate the dynamo action is stronger in a thicker convective zone (see, e.g. Vilhu, 1987).

The observational confirmation of this prediction has remained mostly unexplored although Maceroni et al. (1994), using both photometry and \( \text{H}\alpha \) spectroscopy, found a primary slightly cooler than the secondary component and large photometric dark spots on the primary surface. Dark spots are generally related to the magnetic (dynamo generated) activity.

More recently, Barnes et al. (2004), using high resolution Doppler imaging techniques, found the primary of AE Phe spectroscopically cooler, and provided a further indication of unresolved dark spots.

In the present paper we re-analyse the \( \text{H}\alpha \)-observations of AE Phe and YY Eri performed by Maceroni et al. (1994, hereafter paper I), together with similar unpublished observations collected in 1995. The motivation is a rejuvenated interest in contact binaries, mostly due to the Doppler imaging techniques (Barnes et al., 2004). The observations are explained in Section 2 and the \( \text{H}\alpha \) equivalent widths compared with model predictions and with the saturation limit (due to the chromospheric emission from plages or from penumbral spot regions filling the photospheric absorption). The results are discussed in Section 3 and the conclusions given in Section 4.

2. Observations and \( \text{H}\alpha \) equivalent widths

The observations were performed with the CAT-telescope (Coudé Auxiliary Telescope) of the European Southern Observatory (ESO at La Silla, Chile) during November 20-25,
1989, November 17-23, 1990, and October 26-31, 1995. The Coude Echelle Spectrometer (CES), with the short camera in the red and resolution of 60 000 (5 km s\(^{-1}\)) at H\(\alpha\) 6563 Å, was used. The exposure times were 15 and 20 minutes for AE Phe (m\(_{V}\) = 7.9) and YY Eri (m\(_{V}\) = 8.4), respectively. This guaranteed orbital smearing of less than 0.05 in phase for both stars. Complementary photometric observations in B, V, and I filters were obtained with the ESO 50 cm telescope. The sky conditions during the 1995 observations, however, allowed to get complete, but low quality, light curves for AE Phe only. The photometric observations were useful, at any rate, to check the correct orbital phasing of the spectra.

A sample of line profiles for the years 1989 and 1990 were shown in Maceroni et al. (1994) and are not repeated here for the sake of brevity. In Fig. 1 the grey-scale dynamic light curves (phase vs. \(\lambda\)) for the year 1995 are shown. The grey-scale is linear, the white corresponding to the continuum and the darkest colour (at phase 0.5) to 60 per cent of the continuum level. The radial velocity curves of the broad H\(\alpha\)-absorption in both components are clearly seen, the curves with larger amplitudes corresponding to the secondary (less massive) component.

The equivalent widths were measured at elongations, as mean values between phases 0.15 - 0.35 and 0.65 - 0.85. The resulting equivalent widths are, however, relative to the total continuum. Since we are interested in the intrinsic equivalent widths of the components, the measured values were further scaled with the component luminosities. If

\[
L_p = L/\alpha \quad \text{and} \quad L_s = L(a-1)/\alpha,
\]

where \(L\), \(L_p\) and \(L_s\) are the total, primary and secondary luminosities, respectively, then

\[
a = 1 + q^{0.92}(T_s/T_p)^4
\]

which follows directly from the contact condition and the definition of effective temperatures \(T_p\) and \(T_s\) (see e.g. Webbink, 2003). Here \(q\) is the mass ratio \(M_s/M_p\).

Using the photometric effective temperatures and mass ratios found by Maceroni et al. (1994): ((\(T_s\), \(T_p\), \(q\)) = (6140 K, 6000 K, 0.39) for AE Phe and = (5590 K, 5390 K, 0.44) for YY Eri), we find \(a\) = 1.46 and = 1.54 for AE Phe and YY Eri, respectively. These values are very close to those of paper I from photometric solutions. The intrinsic equivalent widths can be computed from the measured ones by

\[
\text{EW}_p = a \times \text{EW}_p(\text{measured}) \quad \text{and} \quad \text{EW}_s = a/(a-1) \times \text{EW}_s(\text{measured}).
\]

The equivalent widths are listed in Table 1 and their mean values plotted in Fig.2. We also used NextGen photospheric
models\textsuperscript{1}, with solar abundances and gravity $\log(g) = 4.5$ (Hauschildt et al. 1999; Short & Hauschildt 2005) and computed the $\text{H} \alpha$ equivalent widths for several temperatures, as shown in Fig. 2.

These theoretical models match quite well with the solar value marked in Fig. 2 ($\text{EW} = 3.2$ Å), as observed with the CAT/CES telescope by exposing the twilight sky before the observations. The (absorption) equivalent widths of AE Phe and YY Eri are clearly below the theoretical predictions.

An explanation (which we adopt here) for this deficiency is that chromospheric emission fills-in the photospheric absorption, thus lowering the measured equivalent widths. Herbst & Miller (1989) have estimated this emission for a large sample of K-M stars. They found an upper bound (the saturation limit) to the fraction of star’s bolometric luminosity that can appear as $\text{H} \alpha$ emission: $L_{\text{H} \alpha}/L_{\text{bol}} = 10^{-3.9}$. Using $F_{\text{H} \alpha}/F_{\text{bol}}$-values at different effective temperatures, as computed from the NextGen - models, this relation can be easily converted to the saturation line in Fig. 2.

\textbf{Table 1.} $\text{H} \alpha$ equivalent widths (EW, in units of Ångströms) of the more massive (p, primary) and the secondary (s) components of AE Phe and YY Eri. The values are average values from the observations of 1989, 1990 and 1995. The observed values are direct measurements, with the total luminosity as continuum, over the orbital phases 0.15 - 0.35 (marked as 0.25) and 0.65 - 0.85 (0.75). The intrinsic values are scaled with the components’ individual luminosities (see text). These intrinsic values are shown in Fig. 2. The errors include the differences from epoch to epoch.

| comp   | EW(0.25)  | EW(0.75)  | EW mean  | EW intrinsic |
|--------|-----------|-----------|----------|--------------|
| AE Phe p | 1.25 ±0.1 | 1.05 ±0.05 | 1.15 ±0.07 | 1.68 ±0.10   |
| AE Phe s | 0.90 ±0.07| 0.95 ±0.07| 0.92 ±0.07| 2.92 ±0.20   |
| YY Eri p | 1.00 ±0.10| 0.90 ±0.07| 0.95 ±0.10| 1.45 ±0.15   |
| YY Eri s | 0.70 ±0.07| 0.75 ±0.07| 0.74 ±0.07| 2.00 ±0.20   |

\textbf{3. Discussion}

Both AE Phe and YY Eri clearly have equivalent widths of the $\text{H} \alpha$-absorption smaller than the Sun and as well than those, predicted by NextGen-models for normal main sequence stars of

\textsuperscript{1} The NextGen uses the model atmosphere PHOENIX code. The code is available from http://dilbert.physast.uga.edu/yeti.
similar effective temperatures. This can be interpreted as being due to extra chromospheric Hα emission, that partly fills the photospheric absorption. The average values of both stars lie close to the saturation limit. This behaviour is similar to other chromospheric emission diagnostics (see e.g. Vilhu, 1987), giving additional support for this interpretation.

The components of YY Eri are not very different from each other, but in AE Phe the primary has clearly much more Hα-emission than the secondary. This is presumably due to a weaker dynamo-generated magnetic activity of the secondary. Since both components rotate with the same rate and have almost the same spectral types (effective temperatures) they probably differ with respect to another crucial parameter of dynamo theories, the thickness of the convective zone; the shallower this zone, the weaker dynamo action (see e.g. Vilhu, 1987). Theoretical contact binary models predict shallower convective zones for the secondaries, as well, due to their thermal non-equilibrium condition (AML- or TRO-models, (see e.g. Vilhu, 1982; van’t Veer & Maceroni, 1988). The equivalent widths remained practically the same over all our observing runs, from 1989 to 1990 and 1995. In particular, the 1989 and 1990 observations showed that the larger photometric spots are found on the primary (Maceroni et al., 1994), as well as weaker Hα-absorption, compatible with the present results. Barnes et al. (2004) interpreted their spectroscopic observations (analysed by Doppler-imaging) by introducing unresolved dark spots on the primary. Since the appearance of active chromospheres (plages) and cool spots correlate and are the results of the same physical phenomenon, our interpretation sounds valid.

The phase 0.75 side of the AE Phe primary is chromospherically more active than the 0.25 side (see Table 1). This is compatible with the larger spots found on this side during the first two observing runs by Maceroni et al. (1994) (paper I).

4. Conclusions

We have shown that the contact binaries AE Phe and YY Eri have a weaker photospheric Hα 6563 Å absorption than normal slowly rotating main sequence stars of the same spectral type have. This can be interpreted as due to the enhanced chromospheric emission in the rapidly rotating components of these contact binaries. This emission is close to the saturation limit (see Fig.2) and the behaviour is similar to many other chromospheric diagnostics found earlier.

In AE Phe the primary (more massive component) is clearly more active in this respect (smaller absorption as compared with the secondary or the saturation limit). This is apparently a result from the larger depth of its outer convective zone supporting a stronger dynamo-action, compatible with some structural and evolutionary models of contact binaries: AML-models, (see e.g. Vilhu, 1982; van’t Veer & Maceroni, 1988) and TRO-models, (see e.g. Webbink, 2003) for references.

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Acknowledgements. We are grateful to the 6.5 magnitude earthquake during the 1995 observations, whose only consequence was that we will remember that night forever.

CM acknowledges funding of this research project by MIUR/Cofin and F-INAF programs.