Astronomy & Astrophysics manuscript no. 7355rich
August 24, 2007

The most rapidly rotating He-strong emission line star: HR 7355*

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Received: <date>; accepted: <date>; LaTeXed: August 24, 2007

ABSTRACT

Aims. We searched for early-type stars showing Balmer-emission consistent with magnetically confined circumstellar material.

Methods. Archival spectroscopic and photometric data were investigated.

Results. HR 7355 is a formerly unknown He-strong star showing Balmer emission. At $V = 6.02$ mag, it is one of the brightest objects simultaneously showing anomalous helium absorption and hydrogen emission. Among similar objects, only σ Ori E has so far been subjected to any systematic analysis of the circumstellar material responsible for the emission. The success of the recently developed Rigidly Rotating Magnetosphere model in explaining the observed variability of σ Ori E spurred us to search for other stars that are suitable for application of the model. For HR 7355, we argue that the double-wave photometric period of 0.52 d corresponds to the rotation period. In tandem with the high projected equatorial velocity, $v \sin i = 320\,\mathrm{km\,s^{-1}}$, this short period suggests that HR 7355 is the most rapidly rotating He-strong star known to date.

Key words. Stars: emission line – Stars: circumstellar matter – Stars: magnetic – Stars: chemically peculiar

1. Introduction

In the early B-type spectral range a subclass of He-strong stars is found, i.e. stars showing Helium lines with abnormally large equivalent widths. The chemical surface abundances of these stars are influenced by the presence of a strong magnetic field, resulting in a He overabundance that typically varies in strength over the stellar surface.

Because He-strong stars are sufficiently luminous to harbour radiatively driven winds (as diagnosed by ultraviolet absorption line diagnostics; see Shore & Brown 1990), they

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* Based on observations collected at La Silla, ESO-Chile (Prop. 063.H-0080, 073.D-0234)

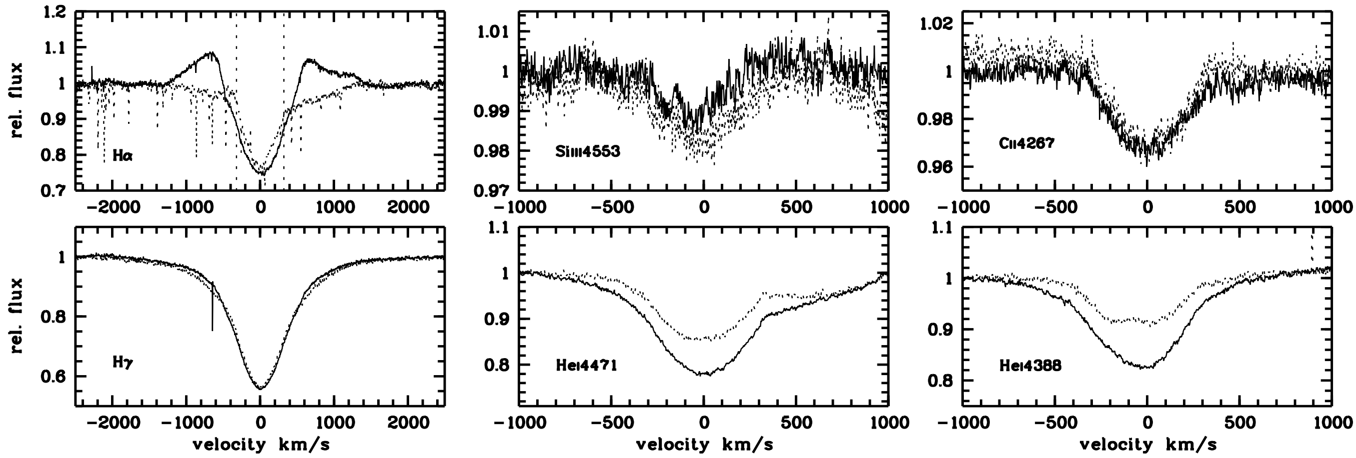

Fig. 1. Changes in several representative lines between the spectra taken in 1999 (solid line) and 2004 (dotted). The 1999 profile has Hα emission extending out to several times beyond $v \sin i$ (the latter indicated by the vertical dotted lines, upper left) Note that for the Balmer lines (left column) a wider range in velocity is shown than in the other panels.

represent ideal laboratories for understanding the process of magnetic wind confinement (Babel & Montmerle 1997). Typically, the fields of these stars are too strong for them to be amenable to the magnetohydrodynamical (MHD) simulations (e,g, ud-Doula & Owocki 2002) that have successfully been applied to other magnetic hot stars (e.g., θ^1 Ori C; see Gagné et al. 2005). However, an alternative Rigidly Rotating Magnetosphere (RRM) model for the circumstellar distribution of magnetocentrifugally confined wind plasma, developed by Townsend & Owocki (2005), has shown much promise in reproducing the detailed optical variability of the archetype emission-line He-strong star σ Ori E. Recent hydrodynamical simulations by Townsend et al. (2007) have reproduced the basic plasma distribution predicted by the RRM model, confirming the model's potential as a key tool for understanding the magnetospheres of He-strong stars.

HR 7355 (HD 182 180, HIP 95 408) is a little-observed B2Vn star of 6$^{\text{th}}$ magnitude ($V = 6.02$, $B = 5.91$), located toward the galactic center. It was listed as MK-standard by Hiltner et al. (1969), but never examined in detail. Other investigators have instead classified it as B5IV (see Jaschek et al. 1964). From studies of larger samples of stars that included HR 7355, we know that the star is very rapidly rotating: Abt et al. (2002) measured $v \sin i = 320\,\mathrm{km\,s^{-1}}$, while Glebocki & Stawikowski (2000) report $v \sin i = 270{\pm}30\,\mathrm{km\,s^{-1}}$. Hipparcos photometric data indicate that the star is a periodic variable, with $P = 0.26\,\mathrm{d}$ (Koen & Eyer 2002).

2. Observations

During guaranteed-time observations with FEROS at the ESO-1.52m telescope in 1999, that included several magnetic and emission-line stars in the target list, HR 7355 was observed once on July 25, 1999 (HJD=2451385.507) with $S/N = 280$ and noted as a weak emission star, but this result was not published (Fig. 1, upper left panel). FEROS is an echelle instrument covering the spectral range 3600-9200 Å with a spectral resolving power of $\Delta\lambda/\lambda = 48\,000$ (Kaufer et al. 1999). When re-scanning available FEROS spectra of Be stars in a search for candidate hot stars having magnetospheres, we noticed that a second FEROS spectrum of HR 7355 had been obtained on July 05, 2004 (HJD=2453191.879) with $S/N = 270$ (Evans et al. 2005). The latter spectrum has been retrieved from the ESO-science archive and reduced with the FEROS standard Data Reduction System, available from ESO. The two spectra suffer from a somewhat imperfect continuum normalization, not untypical for echelle data. This tends to limit the accuracy of equivalent width measurements for Stark broadened lines such as the Balmer lines, and for hot stars such as HR 7355, Helium lines can similarly be affected.

3. Analysis

3.1. Photometry

Photometric data have been obtained from the Hipparcos satellite archive. Two points were removed as outliers, leaving 41 remaining photometric measurements spanning the interval from JD=2447967 to JD=2449061.

We repeated the analysis by Koen & Eyer (2002) and were able to confirm their period for sinusoidal variations: $P_{\text{sin}} = 0.260714 \pm 0.000003\,\text{d}$. Subtracting this peak from the Fourier spectrum significantly decreases the overall power in the variability, and the remaining, second-strongest peak is close to the first harmonic of the strongest one.

3.2. Spectroscopy

Figure 1 shows a selection of the spectral lines observed. Most intriguing are the changes in the He I lines, and the width of the Balmer emission.

In classical Be stars (Porter & Rivinius 2003), where the emission arises from a Keplerian disk having near-circular particle orbits, the highest kinematic velocity possible is the orbital velocity at the stellar surface, typically from a few to about five hundred $\text{km}\,\text{s}^{-1}$ for late and early type B-stars, respectively. In the present case, however, the Balmer emission extends from -1350 to $+1500\,\text{km}\,\text{s}^{-1}$. For a strong emission line, peaking at several times the flux of the local continuum, scattering processes can broaden its base; however, the line seen in HR 7355 is certainly too weak for such broadening to be occurring. We are thus led to to conclude that the extent of the Balmer emission in HR 7355 is governed by the non-Keplerian kinematics of the emitting material itself. Between 1999 and 2004, the emission decreased both in strength and kinematic width, but remained present.

The photospheric absorption lines also differ between the two epochs. The He I lines show the most striking variations – the equivalent widths (EWs) of some change by more than a factor of 2 (see Table 1). The changes arise across the entire line width, affecting the Stark broadening wings as well as the line cores. Such behaviour cannot be explained by pulsation; radial pulsation displaces the entire line, while non-radial pulsation distorts the profile within the limits of $v \sin i$, but tends to conserve the total EW. Neither behaviour is consistent with that seen in HR 7355. To the contrary, the He I profiles obtained in 2004, in particular the 4388 and 4713 lines (Fig. 1), resemble the signature of a spot on a rotating star (cf. Sect. 4.2).

Variations are also seen in lines other than HeI, but they are much weaker. The wings of the Balmer lines are somewhat deeper in the spectrum taken 2004 than in one of 1999, and the EW of SiIII is slightly larger. There are also some lines that do not change: The CII 4267 profile remains unchanged within the limits given by noise and normalization, and the apparent variations of the MgII 4481 profile can be entirely attributed to the changes in the neighbouring HeI 4471 line.

4. Discussion

4.1. The rotational period

The high projected equatorial velocity of HR 7355 suggests that we see the star close to equator-on. If an oblique-dipole magnetic field is responsible for the confinement of the Balmer-emitting circumstellar material, the density of this material should be highest at the twin intersections between the magnetic and rotational equators (see Sect. 4.5). When viewed from an equator-on aspect, these high-density regions will transit the stellar disk twice per rotation cycle, leading to a double-wave photometric signature. In this scenario, the rotation period is identified as twice the observed sinusoidal value, i.e. $P_{\rm dw} = 0.521428 \pm 0.000006\,{\rm d}$. The Hipparcos photometry phased with both of those periods is shown in Fig. 2, with the date of the 1999 spectrum, HJD=2 451 385.507, being adopted as phase zero.

Even with the large temporal separation of the spectra, of almost 5 years, the accuracy of the period above is sufficient to phase the spectra with acceptable uncertainty. Adopting the sinusoidal period, the two spectra are 6929.05 ± 0.07 cycles apart, i.e. having almost the same phase. If we are to seek a common origin for the spectroscopic and photometric variations, this small phase difference is not compatible with the strong changes seen in the spectra. However, with the double wave period, the cycle separation becomes 3464.52 ± 0.04 – a half-phase difference, which is much more plausible.

The two IUE spectra of HR 7355, SWP39549 and 39556, do not show any significant differences. The spectra are separated by 8.879, d; with the above periods this corresponds either to 34.06 or to 17.03 cycles, both values having a small phase difference consistent with the absence of variations.

4.2. Similarity to σ Ori E

The changes in the HeI lines seen in Fig. 1 are a clear indicator of abundance variations across the surface. In particular, the extent of the variability across the entire width of the lines, including the Stark-broadened wings, can hardly be attributed to any other mechanism. The same kind of abundance variations can be seen in σ Ori E; there, the HeI equivalent width changes in anti-phase compared to lines of Carbon, Oxygen, Silicon, and Magnesium. The Hydrogen lines of σ Ori E are also modulated, however in a more complicated fashion due to a combination of photospheric and circumstellar effects. In general, the variations of HR 7355, inasmuch that they can be estimated from only two spectra, are quite similar to those seen in σ Ori E, as reported e.g. by Reiners et al. (2000).

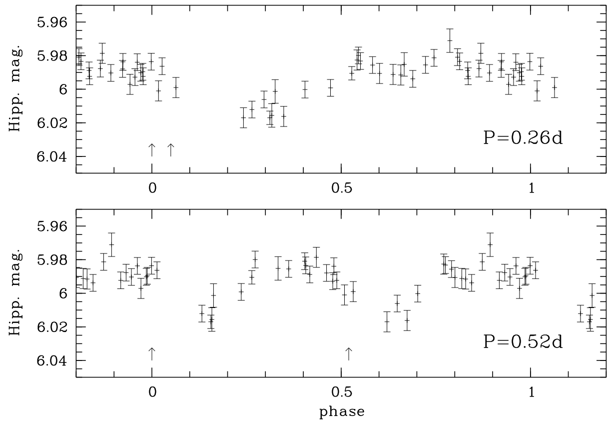

Fig. 2. The Hipparcos photometry sorted with the single and double-wave periods. As epoch the date of the 1999 FEROS spectrum has been chosen; the respective phases of both spectra are indicated by arrows.

Table 1. Equivalent widths of Hγ and selected He I lines, compared to equivalent widths measured from model spectra by Zboril (2000, see Sect. 4.4 for details). Measurements are given in mÅ, and the typical error in the observed values are about 10 %.

Line	1999	2004	He/H=0.4	He/H=0.1
Hγ	6300	6600	6640	6460
He I 4713	430	230	470	306
He I 4388	1650	760	1590	840
He I 5015	490	290	494	318

4.3. Other He-strong emission line stars

In the handful of other He-strong stars showing convincing cases of Hα emission – δ Ori C, V 1046 Ori and HD 64 740 – there are only brief reports noting the emission and its variability, but no in-depth investigations have been published so far (Walborn 1974; Pedersen 1979; Bohlender et al. 1991; Bolton et al. 1998). Two more stars are mentioned in Table 2 of Zboril et al. (1997). However, these authors themselves conclude that in one case, CPD-62° 2142, the emission is probably due to a surrounding nebula; while in the other, HD 124 448, the profile looks very suspicious: Hγ is completely absent, suggesting – rather implausibly – that the profile has been precisely filled in by the emission (see their Fig. 10). To resolve this conundrum, a second spectrum of the star needs to be obtained, preferably covering more Balmer lines.

Some other stars mentioned by Zboril et al. (1997) are suspected on the basis of photometry alone to exhibit Hβ emission; again, however, further spectra are required to confirm these expectations.

4.4. Physical properties of HR 7355

Due to the significant effects of rotational broadening, only the strongest photospheric lines can easily be measured and used to constrain the star's fundamental parameters.

Unfortunately, second only to the (emission-contaminated) Balmer lines in this respect are the He I lines, and these of course are strongly variable. Nevertheless, at least rough estimates can be attempted.

The luminosity classification as dwarf star and the broadening wings of the Hydrogen lines are consistent with a surface gravity $\log g \approx 4.0$. Using this as a reference point, the spectral features, including the equivalent widths of the Balmer lines, point toward an effective temperature on the order of 20 000 K. This value is bracketed by the published spectral classifications, B2V (Hiltner et al. 1969) and B5IV (Jaschek et al. 1964), but is closer to B2V.

The very high projected equatorial velocity of $v \sin i = 320\,\mathrm{km\,s^{-1}}$ makes HR 7355 the most rapidly rotating He-strong star known to date. Statistically, the class of He-strong stars is deficient in rapid rotators (Walborn 1983; Zboril & North 1999), with σ Ori E ($v \sin i = 165\,\mathrm{km\,s^{-1}}$) being one of the record holders so far. Assuming $\sin i = 1$ and identifying the double wave period as rotational, the stellar radius of HR 7355 is found to be about $3.3\,\mathrm{R_\odot}$. With the calibration by Balona (1995), this would correspond to a B4V star, somewhat too late for the above adopted effective temperature. However, HR 7355 is rotating sufficiently close to the critical limit that gravity darkening could bias the measurement of $v \sin i$ toward lower apparent values (Townsend et al. 2004).

To derive a preliminary estimate of the range in surface Helium abundances, we compared the FEROS spectra against models published by Zboril (2000). These models use He/H abundance ratios ranging from 0.1 to 1.0 for a sequence of effective temperatures and surface gravities, including $T_{\mathrm{eff}} = 20\,000$ K, $\log g = 4.0$. The results from equivalent width measurements for a few lines in the observed spectra are compared in Table 1 against values measured from the models for the above parameters and He/H=0.1 and 0.4. The typical EW-error of 10 % was derived by a conservative estimate from repeated manual measurements. We conclude that the disk-averaged stellar hemisphere observed 1999 was enriched in Helium by a factor of about 4, while the one observed in 2004 was about normal or even slightly depleted in Helium. A more detailed study is needed to refine these numbers, however.

4.5. The putative magnetosphere of HR 7355

The absorption-line changes of HR 7355 are a clear indication of spatial structure in the surface abundances at the very least of Helium, Silicon, and possibly Hydrogen. For B-type stars, this structure is the typical signature of a strong magnetic field, on the order of several kiloGauss. The presence of emission – with an extension out to almost $\pm 1500\,\mathrm{km\,s^{-1}}$ that is more likely to be kinematic rather than due to scattering – lends independent support to the presence of a strong field that is able to confine circumstellar plasma and torque it into co-rotation.

The RRM model (Townsend & Owocki 2005) assumes a magnetic field sufficiently strong that the circumstellar environment is completely dominated by the field, i.e. wind plasma upflowing from the star is forced to follow the field lines, but does not influence them. The model predicts the steady accumulation of plasma at points along field lines where the effective (gravitational plus centrifugal) potential is at a local minimum. For an oblique dipole field – the sort most commonly detected in chemically peculiar stars – the locus formed by such minima resembles a warped disk; moreover, the distribution of accumulated plasma in this disk is concentrated into two elongated cloud-like regions, centered along the twin intersections between magnetic and rotational equators.

The RRM model predicts a distinctive observational signature for the warped magnetospheric disk. Because it co-rotates with the star, it exhibits double-peaked emission with a strength that varies due to optical depth and occultation effects. Depending on rotational and magnetic inclination, the disk may transit the stellar disk either once or twice per rotation cycle, in both cases absorbing photospheric flux. In HR 7355, the equator-on aspect means that two such eclipses should occur per rotation cycle (see Townsend 2007), in accordance with our assumption that the double-wave period corresponds to the rotation period.

The changes in the total emission strength between 1999 and 2004 cannot be constrained to a short or long timescale from the two observations alone. However, they are not easily ascribed to any short-periodic type of variation, and are more likely to have occured on longer timescales, for instance during a breakout of accumulated material from its magnetic confinement (see Appendix of Townsend & Owocki 2005; see also ud-Doula et al. 2006).

5. Conclusions

HR 7355 is a previously unknown spectroscopically variable star, and as such it should no longer be used as a spectral standard star. In its capacity as the newest member of the He-strong class, it is not only one of the brighter stars in this class, but is also the most rapidly rotating.

In addition to its spectral variability, HR 7355 is periodically variable in photometry, with either a single-wave sinusoidal lightcurve of $P_{\rm sin} = 0.260714 \pm 0.000003$ d or a double-wave pattern with $P_{\rm dw} = 0.521428 \pm 0.000006$ d. At this point we cannot firmly exclude the possibility that the photometric variations originate in some mechanism other than the surface abundance inhomogeneities. However, the spectra do not show the typical signature of pulsation, and moreover we do not find any other signal in the photometric data consistent with the rotation period. Thus, if the spectral and photometric variations repeat on the same period, then that period is the double-wave period, which also is the rotational period.

We intend to begin a monitoring campaign on the star, to obtain a spectroscopic time series for analysis within the framework of the RRM model of Townsend & Owocki (2005). This model has proven extremely successful in explaining the emission-line variations of σ Ori E (Townsend et al. 2005), and we are optimistic that it can explain the behaviour HR 7355 too.

Acknowledgements. RHDT is supported by NASA grant LTSA/NNG05GC36G. We thank the FEROS consortium for observing HR 7355 in 1999, during the time guaranteed to the consortium for building the instrument. This study made use of the SIMBAD and ADS databases, as well of the ViZiR catalog services.

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