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New type of brightness variations of the colliding wind WO4 + O5((f)) binary WR 30a*

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Abstract. We present new photometric observations in Johnson *V* and *B* of WR 30a, revealing relative dramatic changes in brightness of $0^{\rm m}\!.2$. These variations occur on a time scale of hours, and are only seen in *V*. We argue that they are not caused by dust extinction, but either by a dramatic change in the strength of the C IV 5801-12 Å emission line doublet due to a de-excitation process, or by some unknown continuum effect.

Key words. stars: binaries – stars: Wolf-Rayet – stars: individual: WR 30a

1. Introduction

WO stars are a rare species, representing the final evolutionary stage in the Wolf-Rayet phase of massive stars, and as such they are supernova progenitors. In massive WCE and WO stars, carbon and oxygen are produced continuously in the non-degenerate He-burning core and are exposed by mass loss stripping (Maeder 1991; Meynet & Maeder 2003). WO stars have number abundance ratios (C+O)/He $\simeq$ 0.62 (Kingsburgh et al. 1995), initial masses $M_{\rm i} > 40\ M_\odot$ and WO-lifetimes of 27 000 yr to 62 000 yr, depending on initial mass and rotation on the main sequence (Meynet 2003, private communication). WO stars could very well be Gamma-Ray-Burst-associated supernova progenitors (e.g., Reeves et al. 2002; Woosley et al. 2002; Kaper 2003). Only three WO stars out of a total of 253 WR stars are known in the Galaxy: WR 30a (WO4+O5((f))) at d = 7.8 kpc, WR 102 (WO2) at d = 5.6 kpc, and WR 142 (WO2) at d = 1.0 kpc (van der Hucht 2001, 2003), with terminal stellar wind velocities of, respectively, $v_\infty = 4500, 4600$, and $5500\ {\rm km\,s^{-1}}$ (Kingsburgh et al. 1995), the largest wind velocities known among Population I WR stars. Especially the nearest one, in Cygnus, will be a spectacular sight when it explodes.

The classification of the WR star of WR 30a had been taken to be WC4 by Lundström & Stenholm (1984b), and later WO4 by Smith et al. (1990a,b) and Crowther et al. (1998), while the companion star has been classified as O4 (Moffat & Seggewiss 1984). Niemela (1995) reported the first radial velocity study for WR 30a, and suggested that WR 30a might be a short period binary.

Gosset et al. (2001) presented a detailed study of WR 30a, confirming that this is indeed a binary, with a period of $4^{\rm d}\!.6$. They give estimates of the orbital elements and the masses of the two stars ($M_{\rm WO}/M_{\rm O} = 0.16$, $M_{\rm WO} \sin^3 i = 0.69\ M_\odot$ and $M_{\rm O} \sin^3 i = 4.34\ M_\odot$), and classify the companion star as an O5((f)) main-sequence star or giant. Thus, assuming $M_{\rm O} \simeq 60\ M_\odot$ would imply $M_{\rm WO} \simeq 10\ M_\odot$ and $i \simeq 25°$. This WO star mass corresponds best to evolutionary models with $M_{\rm i} = 120\ M_\odot$ and $v^{\rm i}_{\rm rot} = 300\ {\rm km\,s^{-1}}$ (Meynet 2003, private communication).

Evidence for colliding wind effects in WR 30a has been given by Bartzakos et al. (2001), who demonstrated C IV 5801-12 Å emission line profile variablity.

In this paper we present new photometric observations of WR 30a. In Sect. 2 we describe the observations, and in Sect. 3 we show the results. We discuss the results in Sect. 4, and we draw our conclusions in Sect 5.

2. Observations and reductions

In Table 1 the three observation runs are listed. All observations were done using the Dutch 90 cm telescope at ESO, La Silla, Chile, through Johnson *V* and *B* filters. A 512x512 CCD detector was used, with typical integration times of 5 min in *V* and 10 min in *B*. Daily flat-field calibrations were obtained using the twilight sky.

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* Tables 2–4 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/404/L29

Table 1. Log of observations: three sets of V, B CCD photometry, obtained at the ESO-Dutch 90 cm telescope in 2001.

observer	epoch	*#nights*	*#points*
Brogt (I)	02/07/01-22/07/01	14	40
Meijerink (II)	30/10/01-15/11/01	4	21
Gieles (III)	15/11/01-15/12/01	23	71

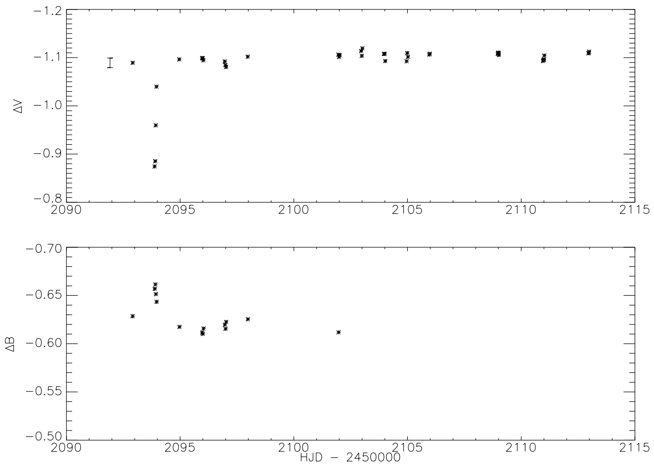

Fig. 1. Light curves for data set I. On the vertical axis the differential magnitudes are shown, bright is up. 2σ error bars are shown on the left.

All reductions were carried out with the MIDAS package (version 02feb). Differential aperture photometry was done using DAPHOT (de Jong 1998). In the field of WR 30a are enough comparison stars, see Gosset et al. (2001). For every data set a suitable set of comparison stars was selected, based on their appearance on the frames, their brightness relative to WR 30a and their variability from night to night. The positions of the stars on the CCD frame varied from frame to frame, and even more so between the different data sets. Therefore, we could not use the same set of comparison stars for all data sets, so the data sets can not be compared in absolute sense. We confirm the variability of the anonymous star C mentioned in Gosset et al. (2001). This star was therefore excluded as comparison star.

During the collection of data set II, WR 30a appeared very close to the horizon, and was therefore observed with high airmass. This has been taken into account in the analysis.

3. Analysis and results

The light curves for the first data set are shown in Fig. 1, and the measurements can be found in Table 2. Immediately the eye is drawn to the large brightness drop in V at HJD 2452094 of about $0\overset{\mathrm{m}}{.}2$. At the same time, WR 30a gets a little brighter in B. More of these features can be seen in the second and third

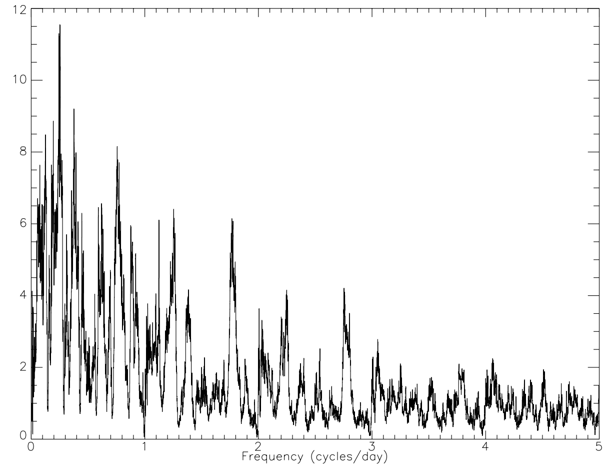

Fig. 2. AOV-periodogram for the last part of the V light curve of data set III. The peak frequency lies at 0.238 cycles/day.

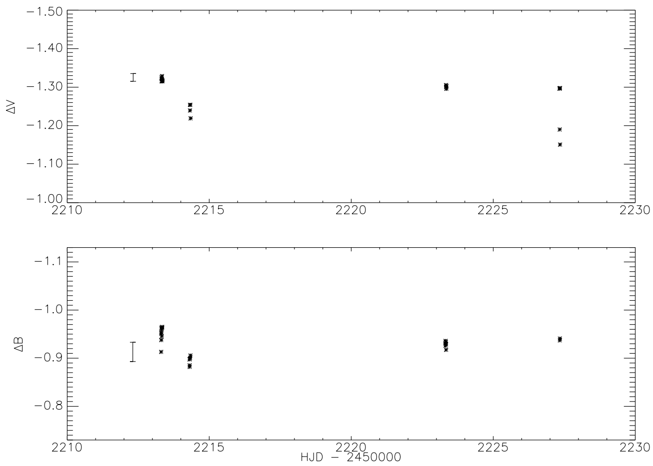

Fig. 3. Light curves for data set II. On the vertical axis the differential magnitudes are shown, bright is up. 2σ error bars are shown on the left.

data sets (see Figs. 3 and 5; the measurements can be found in Tables 3 and 4), showing that this is certainly not a rare event, although the B curve often stays unaffected.

The appearance of these enigmatic variations in brightness is independent of the choice of comparison stars or the aperture used to calculate the magnitudes. We can therefore safely conclude that this variability is intrinsic to WR 30a.

The presence of these minima makes it difficult to search for the binary period in the V data sets, while the errors in B are of the same order of magnitude as the expected amplitude of the brightness variations: about $0\overset{\mathrm{m}}{.}02$ (Gosset et al. 2001). However, we performed a period analysis on the last part of the V curve of Fig. 5 by means of the AOV routine in MIDAS. The resulting periodogram is shown in Fig. 2. Two families of aliases can be seen: one with peak frequency 0.238 cycles a day

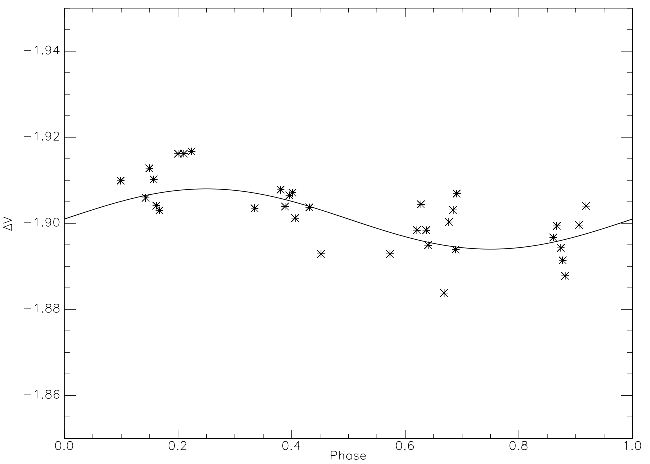

Fig. 4. Phase diagram for part of the V data set III, with period 4.2 days.

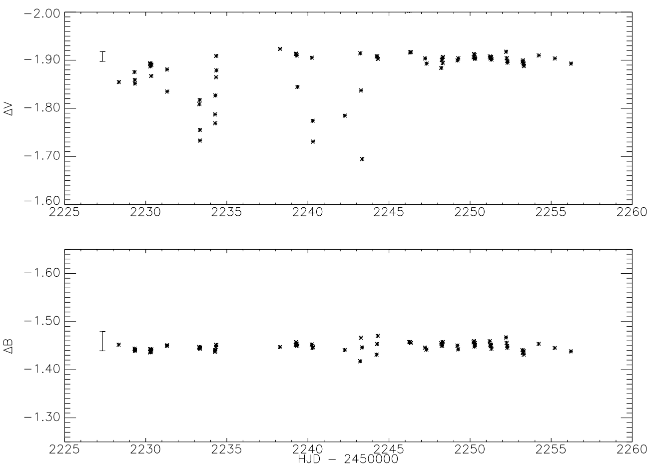

Fig. 5. Light curves for data set III. On the vertical axis the differential magnitudes are shown, bright is up. 2σ error bars are shown on the left.

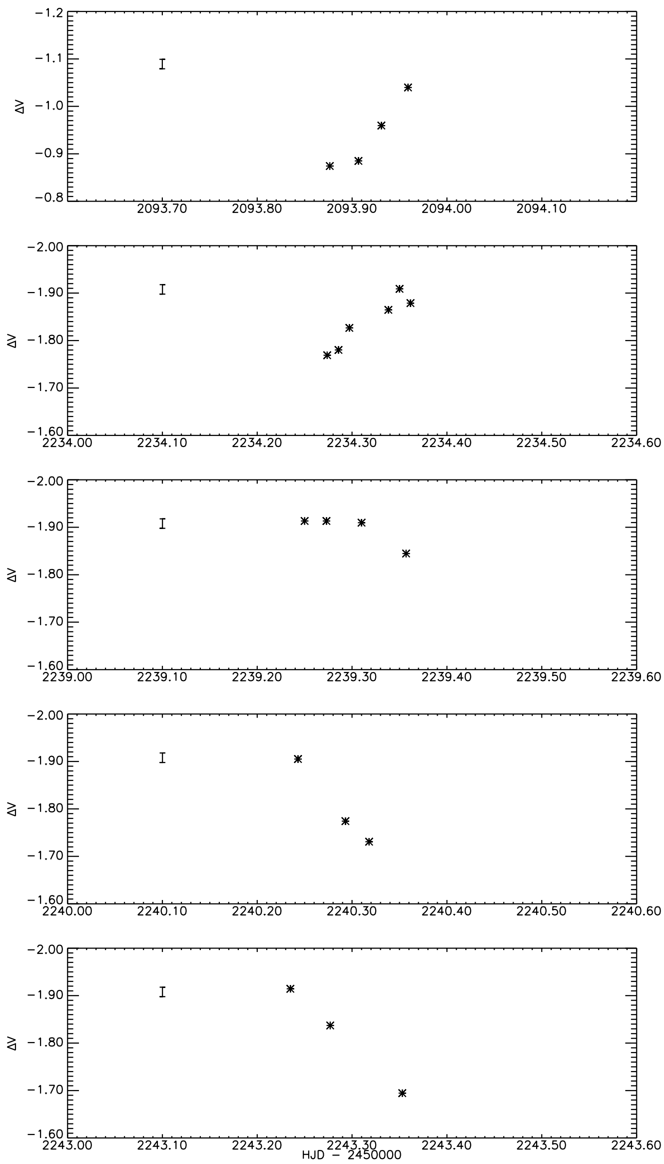

Fig. 6. Close-ups on the six clear minima.

and one with peak frequency 0.8 cycles a day. As the former is the largest peak, we derive a binary period for WR 30a of:

$$P = 4.^{\rm d}2 \pm 0.^{\rm d}5. \quad (1)$$

This is in reasonable agreement with the period of 4.6 days found by Gosset et al. (2001), considering that our estimate is based on observations covering only two periods. The second frequency might be an artifact due to the small amount of measurements available for the frequency search. Figure 4 shows a phase diagram for our period.

We now turn to the larger brightness variations. These observed minima occur extremely fast: within one or two hours the brightness goes down or up. The only way to detect this phenomenon is to make continuous runs within one night, and this may well be the reason why Gosset et al. did not detect it in their data set. It is reasonable to assume that we missed several minima as well, and therefore it is difficult to relate their appearance to the period found by Gosset et al. It is also quite well possible that these minima are only confined to short time intervals, after which they are not present for some time. It appears that they are not related to the binary period (see below): they occur at all phases of the binary period. In Fig. 5 it seems that the minima come in pairs with a separation of approximately one day. As the minima are not resolved, their time of appearance is very uncertain.

If we call the time of the first clear minimum in Fig. 5, HJD 2452233.4, $t = 0$, the other 5 clear minima occur at $t = 1, 6, 7, 9, 10$ days, respectively. The pairs of minima seem to appear every 3 days, not consistent with the estimate of the binary period. Furthermore, in Fig. 3 (upper panel) we can see a minimum at $t = -6$, and two shallow minima in Fig. 5 at $t = -3$ and $t = -2$, supporting the period of about 3 days. However, this means that we have missed several minima after $t = 10$ (HJD 2 452 243.4), and the result remains very speculative.

The large variations in V do not always have a counterpart in B, often a small opposite one. In one case B shows a minimum as well, see Fig. 3 at HJD 2 452 214. The amplitude in B is always very small, consistent with the fact that the emission line C III,IV 4650 Å situated in the B band could be used to determine the period (Gosset et al. 2001).

In Fig. 6 close-ups for five minima are shown. None of them are well resolved, but it seems that from top to bottom we can see the light curve just after minimum light, just coming back after a minimum, just beginning a minimum and finally two light curves dropping towards minimum light. Interestingly, the last two parts of the light curve seem to have the same steepness.

4. Interpretation

What is the cause of these brightness variations? The nearly absence of variations in B rules out occasional eclipses by dust formation like in late-WC (WCL) stars (Veen et al. 1998), because then we would expect a larger depression in B than in V.

It is possible that the photometric variability is caused by an emission line that varies in strength. Lundström & Stenholm (1984b) show a spectrum for WR 30a in their Fig. 1, and we can see that the strongest emission line is the C IV 5801-12 Å doublet, which is well within the Johnson V band. Variability of that doublet has been shown by Bartzakos et al. (2001) (their Figs. 1f and 11), but not to the extent of a total disappearance of that doublet. Apparently, the dramatic variability we observed did not occur during their observations. We can roughly estimate the contributions to the total flux from the continuum and the line, taking into account the V filter profile, and we estimate that the total disappearance of the line would result in a V magnitude change of about $0\overset{m}{.}2$. The observed brightness variations are indeed of the order of $0\overset{m}{.}2$ mag, but if these are caused by the varying line strength, then dramatic variations of the C IV doublet would be required.

The short duration of the relative deep minima (rising or dropping within several hours) in V, containing the C IV doublet, the often small opposite behaviour in B (containing the C III,IV line complex, but with much less contribution) suggest that the ionization processes in the responsible emission region are subject to fast changes in temperature and pressure. It is conceivable that if the C IV emission decreases by cooling, the C III emission can profit from that. In the one particular case mentioned in Sect. 3, when the B showed a minimum as well, the ionization process for C III dropped apparently also due to an even lower temperature. Thus, we believe that a de-excitation process could well be the explanation for the very short lasting minima, whatever the causes of the temperature variations in the WO wind may be. Perhaps shock waves in the WO atmosphere are involved.

Due to the very short time scales, it will be difficult to track these variations with spectroscopic observations, but they will be needed to decide whether this is a pure continuum phenomenon or a case of varying line strength.

5. Summary and conclusions

We have presented new photometric observations on the colliding wind W04+O5((f)) binary WR 30a, revealing interesting depressions in brightness. WR 30a appeared to be variable on time scales of hours with an amplitude up to $0\overset{m}{.}2$. These variations might be periodic with a period of about 3 days, but this is as yet highly uncertain.

The small amplitude variations due to the binarity indicate a period of $4\overset{d}{.}2 \pm 0\overset{d}{.}5$, consistent with the period found by Gosset et al. (2001). The large amplitude variations remain a mystery: we can exclude dust extinction, but the question remains open whether we are dealing with a change in the continuum or a change in line strength of C IV 5801-12 Å, possibly due to de-excitation.

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