Astron. Astrophys. 352, L95–L98 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

RW Aur A, a close binary?*

G.F. Gahm[1], P.P. Petrov[2,], R. Duemmler[2], J.F. Gameiro[3,4], and M.T.V.T. Lago[3,4]**

[1] Stockholm Observatory, 133 36 Saltsjöbaden, Sweden
[2] Astronomy Division, P.O. Box 3000, 90401, University of Oulu, Finland
[3] CAUP, Universidade do Porto, Rua das Estrelas, 4150 Porto, Portugal
[4] Departamento de Matemática Aplicada, Rua das Taipas, 135, 4150, Portugal

Received 30 September 1999 / Accepted 2 November 1999

Abstract. We have discovered periodic changes in velocity and equivalent width of a number of different spectral features of RW Aur A, a T Tauri star with a jet, broad emission lines and substantial excess continuous emission. In particular, the photospheric lines vary in radial velocity with an amplitude of $5.7\,\mathrm{km\,s^{-1}}$ over a period of 2.77 days, which appears to have been stable over at least 18 years.

The present *Letter* focusses *solely* on one straightforward interpretation, namely that RW Aur A is a single-lined spectroscopic binary. However, other spectral features vary in or out of phase with the same or the double period. Interpretations, other than a binary model, should be considered but must await the more extended report on our large observational material.

In the binary case, the small amplitude leads to a mass function of only $5\cdot10^{-5}\ \mathrm{M_\odot}$, by far the smallest observed for young binaries. The jet velocity and extent restrict the range of inclinations (if the orbital axis is aligned with the jet), implying a close binary with a secondary at the brown dwarf limit. Further restrictions follow if the primary rotates synchronously.

Narrow emission components of HeI and HeII vary in antiphase with the photospheric absorption lines. We show that it is unlikely that these lines reflect the motion of the secondary.

Key words: stars: binaries: spectroscopic – stars: pre-main sequence – stars: individual: RW Aur A

1. Introduction

A small fraction of the T Tauri stars (TTSs) have extremely prominent emission line spectra. Some of these TTSs also have strong continuous excess emission (veiling). Possibly the most magnificent example is RW Aur, one of the brightest TTSs in the sky. To be more precise we are concerned with the brighter component A in a triplet (components B and C are $1\farcs4$ from A). A bipolar jet, most likely rooted at RW Aur A, extends over $\sim 3'$ (e.g. Mundt & Eislöffel 1998). The presence of a jet, the rich emission line spectrum and the pronounced activity should point at a very early phase of evolution. Yet, the star is located outside any molecular cloud (an isolated TTS).

RW Aur A is also an unusually "wild" TTS, with huge and rapid (hours/days) variations both in brightness and line profiles. The light fluctuations are basically irregular (as summerized by Gahm et al. 1993; Herbst et al. 1994). In contrast, regular variations of the asymmetries of the Balmer emission lines with a period of ~ 5.4 days have been reported by Grinin et al. (1983, 1985). The changes in line fluxes and profiles are large and complex, as can be seen from repeated spectroscopic observations presented e.g. by Gahm (1970), Appenzeller & Wolf (1982), Hartmann (1982), Mundt & Giampapa (1982) and Appenzeller et al. (1983).

Weak, presumably photospheric lines, are best seen in the yellow-red spectral region. A spectral type of K1 was assigned by Mundt & Giampapa (1982), and K4 by Valenti et al. (1993). The lines are broadened by what could be stellar rotation with $v\,\sin\,i \approx 20\,\mathrm{km\,s^{-1}}$ (Herbig & Bell 1988). Hartmann et al. (1986) also found evidence of radial velocity changes, and indicated that RW Aur A may be a spectroscopic binary although no period could be assigned at the time.

In the following, we limit ourselves to a discussion of which implications follow by assuming that the velocity variations of the weak absorption lines reflect binary motion.

2. Observations

High-resolution spectra were collected with the SOFIN échelle spectrograph (Tuominen 1992) at the 2.6m Nordic Optical Telescope (NOT) during three observing periods: Dec. 4 and 6, 1995 (3 spectra), and the consecutive nights of Oct. 25 – Nov. 1 1996 (15 spectra) and Nov. 5–10 1998 (11 spectra). We used the 3rd camera which provides a spectral resolution of $\pm 12\,\mathrm{km\,s^{-1}}$ with an entrance slit width of $1\farcs5$. One CCD frame covers 33 spec-

Send offprint requests to: G.F. Gahm

* Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

** on leave from the Crimean Astrophysical Observatory

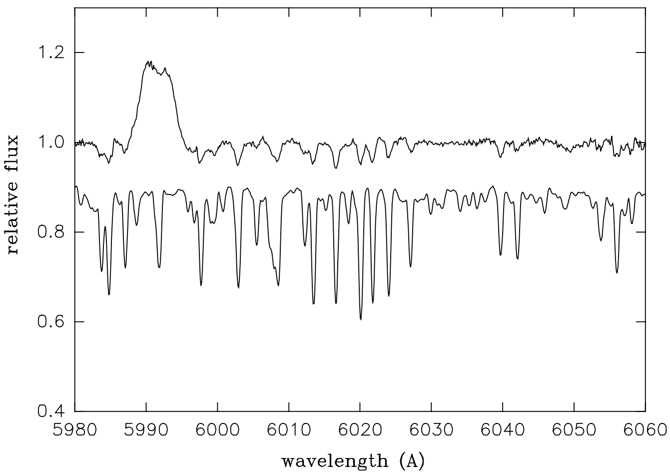

Fig. 1. Average of all 1998 spectra at ∼6000 Å of RW Aur A showing a weak absorption line spectrum (WALs). For comparison a spectrum of γ Cep (K1 III-IV), spun up to 20 km s^{-1}, is shown (below).

tral orders over the range 3900 to 9000 Å with some gaps in the red. The wavelength scale is accurate to 0.3 km s^{-1}. With a 60 min-exposure the S/N ratio is about 200. All reductions were done with the 3A reduction software (Ilyin 1996).

3. Results

Unblended, weak absorption lines of metals (WALs), indicating a K type spectrum (K1–K5), are found mainly in the regions 5550–5610 and 6000–6050 Å (see Fig. 1). These lines vary in strength but not necessarily in spectral type. We identify the WALs as photospheric, which implies a strong variable excess continuum with an average veiling factor of 3. Radial velocities and values of $v \sin i$ were determined with an accuracy of $\pm$2 km s^{-1} by cross-correlation with the template spectrum of γ Cep (K1 III-IV).

We derive an average radial velocity of +16 km s^{-1}, and a distinct periodicity over the 1996 and 1998 SOFIN runs, consistent with the three spectra of 1995. A periodogram analysis of WAL velocities indicates a period P most likely in the range from 2.6 to 2.9 days, the most significant being $P = 2.77218$ days (Fig. 2), and an amplitude of 6 km s^{-1}. Velocities and equivalent widths of many emission lines vary with the same (or the double) period. In addition, we found that the 1980 data of photospheric line velocities given by Hartmann et al. (1986) can be fitted to our period, and hence the indication is that *the period has been persistent for two decades.*

HeI 5875 Å has three components, all time variable: narrow central emission (HeI n), broad emission extending to -300 km s^{-1}, and broad red-shifted absorption extending to +400 km s^{-1} (see Fig. 3). The profile was decomposed into three gaussian profiles, and the radial velocity of the HeI n was measured with an accuracy of about $\pm$3 km s^{-1}. Several emission lines have red-shifted absorption, which like HeI vary in strength but not in velocity of the edge at +400 km s^{-1}.

HeI n varies in anti-phase with the WALs. We therefore attempted another (unweighted) period fit including the WALs

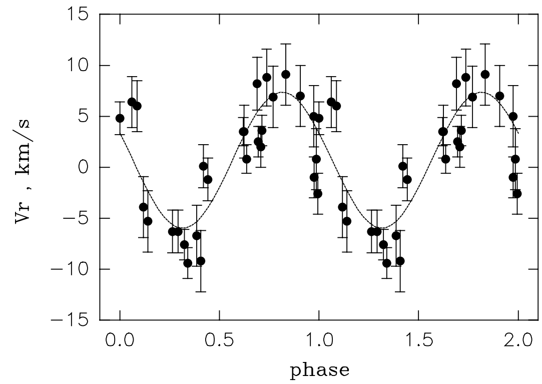

Fig. 2. Phase diagram showing stellar restframe radial velocities of the WALs for the best fit to all SOFIN data with the period 2.77218 days.

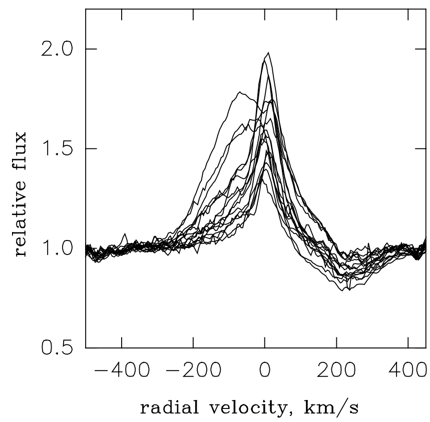

Fig. 3. Normalised HeI 5875 Å profiles, each representing one night, showing variable broad and narrow emission, and extended red-shifted absorption (in stellar restframe velocities).

Table 1. Orbital parameters of RW Aur A from radial velocities based on data from SOFIN and Hartmann et al. (1986).

period (days)	2.77213 ± 0.00010
K_1 (km s^{-1})	5.67 ± 0.76
T_0 (max.RV) HJD	2450387.679 ± 0.075
γ (km s^{-1})	15.87 ± 0.55
$a_1 \sin i$ ($R_\odot$)	0.311 ± 0.042
mass function $f(m_2)$ ($M_\odot$)	0.000052 ± 0.000021
$\sigma_{\rm fit}$ (km s^{-1})	3.54

(SOFIN + Hartmann et al.), and the velocities and equivalent widths of HeI n (see Fig. 4). The resulting period of 2.77041 days is a compromise to fit all the data, but is only slightly different from the one quoted above.

The *measured* value for $v \sin i$ is variable from 18 to about 40 km s^{-1}. These changes are uncorrelated with the 2.77 day period, but very weak asymmetries in the WALs are present on occasion. We conclude that there is some broadening mechanism in addition to rotation. A fair assumption on the actual $v \sin i$ can be the lower limit of ∼18 km s^{-1}.

4. Discussion

4.1. Binary solutions

As the very first step in the analysis of the complex spectral variations of RW Aur A, we assume that the radial velocity changes reflect the motion of the primary in a binary. Given that the accuracy of the radial velocity measurements of the WALs is similar to that of the Hartmann et al. (1986) data, all velocities were put into an unweighted orbital fit. This fit was used in a period search in the interval 2.5 to 3.0 days. The binary solution presented in Table 1 is the set of parameters (with standard notations) belonging to the best period, i.e. the fit with the lowest standard deviation as given by $\sigma_{\rm fit}$. It should be mentioned, however, that there are many minima in the standard deviation at different periods in this interval, and their depths are in many cases similar to that of the best fit. However, the numerical values of all parameters change only slightly with the value of the period. The orbit is close to circular; a statistically insignificant eccentricity of 0.13 ± 0.18 has been found.

The mass function $f(m)$ is lower by more than an order of magnitude than for any pre-main sequence binary studied before (Mathieu 1994). This implies that for a primary mass of $\sim$1 $M_\odot$ or less the secondary has a mass ≤ 0.08M$_\odot$ (brown dwarf case) for all inclinations i larger than about 30°.

4.2. Restrictions on the solutions

According to current ideas the jet implies a large rate of mass accretion ¿from a circumstellar (circumbinary) disk. Since there is no indication of precession of the jets, one can assume that the jet, rotation and orbit are aligned. TTS jets rarely extend more than 2 pc, and have jet velocities of typically <400 km s^{-1} (see e.g. Bally & Devine 1997). With RW Aur at the distance of the Taurus molecular clouds at 140 pc (Elias 1978) the projected length and velocity of the longest jet are 0.08 pc and 190 km s^{-1}, respectively. Alignment implies $2° \leq i \leq 60°$. The majority of low mass TTSs have equatorial rotational velocities $v < 70$ km s^{-1} as implied by the distribution of $v \sin i$ given by Machado et al. (1999). Hence, if the primary of RW Aur A has not been forced to spin up substantially, the range of possible inclinations can be further restricted to $15° \leq i \leq 60°$, provided $v \sin i$ = 18 km s^{-1}.

The luminosity of the $star$ RW Aur A is difficult to establish, but several estimates fall in the range $0.0 \leq \log L \leq 1.0$, consistent with our analysis. Spectral type estimates confine the surface temperature to $3.7 \geq \log T_{\rm eff} \geq 3.6$, provided the photosphere is not very abnormal. These ranges restrict the radius R of the star.

Further restrictions on R, and also the primary mass m_1, follow if we make the very plausible assumption that the redshifted absorption extending to +400 km s^{-1} results from accretion from a circumbinary disk down to the stellar surface. Then $R = m_1(617/400)^2$ in solar units. Each combination of R and m_1 corresponds to an unique point in the HR-diagram of contracting stars. Hence, the evolutionary tracks provide a strict locus of permitted locations of RW Aur A. The values of R, m_1, L, $T_{\rm eff}$ and age can be derived for any given value of i.

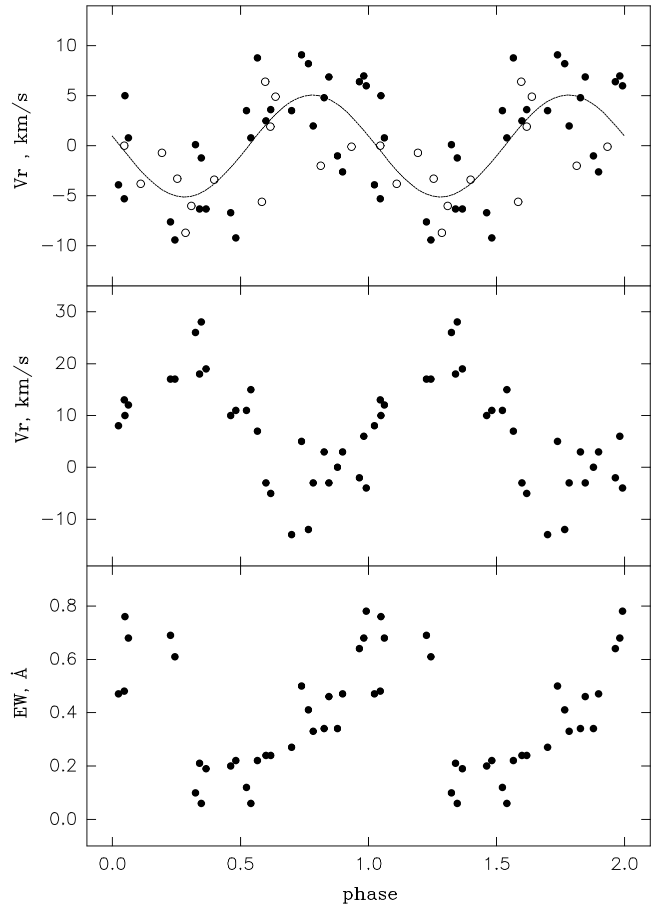

Fig. 4. Phase diagram based on $P = 2\overset{\rm d}{.}77041$, i.e. the best compromise to simultaneously describe the variations in *top:* the radial velocities of the WALs (filled: SOFIN, open: Hartmann et al. 1986) *centre:* radial velocities of HeI n (note the antiphase) *bottom:* equivalent width of HeI n (note the 1/4 phase shift)

This locus is found in Fig. 5, where we compare with the recent models by Palla & Stahler (1999). The primary can rotate synchronously with the secondary. This particular case narrows the range of possible inclinations to $15° \leq i \leq 31°$, as indicated in Fig. 5, and the mass range to $0.8 \leq m_1 \leq 1.6$ ($M_\odot$). For each i, *all orbital parameters can be derived*. Given the range in i the secondary has a mass $0.07 \leq m_2 \leq 0.22$, and is a brown dwarf only when $\log L \approx 0.0$. Most literature values quote $\log L \geq 0.1$, excluding a brown dwarf companion. The components are likely coeval, so we can put also the secondary into Fig. 5.

This method, which provides all parameters of a single-lined spectroscopic binary, is based on the assumptions of alignment and synchronous rotation combined with the evidence of infall and that the star contracts. We note that *permitted solutions require a primary with just the right spectral type and luminosity* (see e.g. Ghez et al. 1997). The secondary has a low mass, 0.15 $\pm$0.07 $M_\odot$, and moves in a nearly circular orbit close (8–10$R_\odot$) to the primary. The system has an age of about 10^6 years.

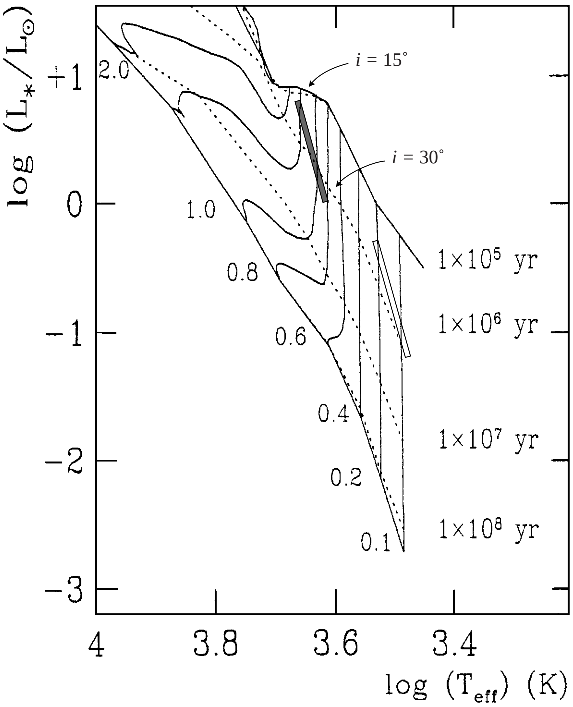

Fig. 5. Schematic presentation of permitted locations of the primary (shaded) and secondary in the theoretical HR-diagram by Palla & Stahler (1999). Limits in inclination i are indicated for the case of corotation plus rotation-orbit-jet alignment.

4.3. The He emission

If the HeI n is formed at for instance a hot spot on the surface of a secondary component, the anti-phase variations could be related to orbital motion of the secondary. Under this assumption, the HeI n and WAL velocities were put into a double-lined fit, resulting in a reduced K_1 of 5.0 $\pm$ 1.1 km s^{-1} and a K_2 of the presumed secondary of 13.2 $\pm$ 1.3 km s^{-1}, implying a mass ratio $q = m_2/m_1 = 0.38 \pm 0.09$. However, while γ in Table 1 is consistent with the centre of mass moving at the same speed as the molecular gas in the area (Taylor et al. 1987) a good fit is possible only if HeI n obtains $\gamma_{\rm HeI} = 24.2 \pm 0.9$ km s^{-1}. The shift relative to γ of +8.3 km s^{-1} is very significant. The central emission of HeII at 4686 Å is also in anti-phase with the WALs, with similar amplitude as for HeI n but the shift is even larger, +16.8 km s^{-1}.

The conflicting γ values do not necessarily exclude that the He emission is rooted on the secondary. For instance, HeI and HeII can be accreting to a hot spot at different average speeds. But there are other difficulties with this scenario. Firstly, we note that with the assumption of jet-rotation alignment there is no way to reproduce the binary solutions presented in Sect. 4.2. Secondly, solutions are possible only for values of $i \approx 6°$ leading to a rapidly spinning primary, v = 160 km s^{-1}.

4.4. Conclusions

We have studied the most obvious explanation of our finding of periodic, small amplitude radial velocity changes of RW Aur A, namely binary motion. This leads to a very close secondary component of a mass at, or just above the brown dwarf limit. This unique combination could also provide a clue to the origin of several of the extreme spectral properties of this unusual T Tauri star. We have also shown that the anti-phase varibility of He emission line components probably is unrelated to the motion of the secondary. Many other lines, with different properties, show different patterns of periodic variability, and scenarios other than binarity must be scrutinized.

Acknowledgements. Pawel Artymowicz is acknowledged for discussions and I. Ilyin for substantial help with observations and reductions. The work was supported by the Crafoord and the Swedish Natural Science foundations, and the Portugese foundation for Science and Technology.

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