*Magnetic stars, 2004, 191-197*

# Spectroscopic study of the Am SB2 eclipsing binary HR 6611

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**Abstract.** Detailed spectroscopic study confirmed a mild Am-peculiarity of both components of the double-lined spectroscopic eclipsing binary HR 6611 and revealed a slightly asynchronous rotation of the primary one. The analysis of Zeeman spectra of the binary and 4 non-magnetic stars, does not exclude an effective magnetic field on HR 6611A, varying cyclically with a semi-amplitude of 0.2 kG, but definitely not with the orbital period 3.895 d.

**Key words:** binaries: eclipsing – stars: individual: HR 6611 – stars: abundances – stars: magnetic fields

## 1 Introduction, motivation

HR 6611 (HD 161321, BD+143329, ADS 10749, V624 Her, HIP 86809) was recognized as a double-lined spectroscopic binary by Petrie (1928). Zissel (1972), based on his own photoelectric observations in $V$ color, discovered shallow eclipses and derived light elements with the orbital period $P = 3.895$ d. He also recomputed the spectroscopic orbit and determined masses and radii of the components. He inspected original spectra as well new ones and noted the spectra of both the components of the binary to be Am. Popper (1984) using an additional set of high-dispersion spectrograms reanalyzed Zissel's (1972) curves and yielded improved parameters of the components. He claimed: *the more massive component of V624 Her appears to be more evolved in the mass-radius, temperature-gravity, and HR diagram than any Am star that has all properties well determined.*

Bertaud & Floquet (1974) summarized spectral types as Am, A3–A7, A3m and A3pm and Ribas et al. (1998) give A3m + A7 V. Cowley et al. (1969) alleged that the metallicity of the primary component was not particularly well developed, while Lacy et al. (2002), comparing WW Cam with HR 6611, even noted that HR 6611 had no observational determination of metallicity but abundances could not be far from solar. The flagrant disagreement in the evaluation of the degree of the chemical peculiarity of both components shows that the detailed abundance study of the binary is very appealing.

Babcock (1958) listed HR 6611 among 66 stars that probably but not definitely show the Zeeman effect. Recently, Elkin et al. (2002) investigated the fine structure of the famous $\lambda$ 5200 Å depression with the 1 m telescope of the Special Astrophysical Observatory. An unidentified feature $\lambda$ 5150 Å has proven to be a relatively reliable indicator of the magnetic field presence. The detail was in the spectrum of HR 6611 relatively strong indicating the possible presence of the field.

These two reasons induced us to start obtaining high-quality spectra of the star with the Zeeman analyzer attached to the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhnij Arkhyz.

# 2 Observations

Our spectroscopic investigation of HR 6611 was based on the analysis of 23 Zeeman spectra obtained with CCD cameras in the Main Stellar Spectrograph of the 6 m telescope from February 2002 to July 2003. The CCD1 camera (1) $1160 \times 1040$, pixel size 16 $\mu$m, gave spectra with $R \sim 20\,000$ and $S/N$ better than 100 within (4445–4605) Å. The CCD2 camera (2) $2050 \times 2050$, pixel size 16 $\mu$m, gave spectra $R \sim 20\,000$ and $S/N$ better than 100 within $(4405 - 4645)$ Å. The observations were carried out with the achromatic circular polarization analyzer (Najdenov & Chuntonov 1976). The technique of the magnetic observations was described in details in Romanyuk et al. (1998). The ESO MIDAS (Kudryavtsev 2000) and NICE software package (Knyazev & Shergin 1995) were used to reduce the spectra. The Zeeman spectra of comparison non-magnetic standards Procyon, Arcturus, Mirfak ($\alpha$ Persei) and HD 158974 were exposed immediately before or after the exposure of the binary.

Table 2 summarizes the spectroscopic material used.

# 3 Spectral analysis

## 3.1 Parameters of the system

The eclipsing binary HR 6611 is a well detached system of two practically spherical stars orbiting around their center of gravity on nearly circular orbits. According to Popper (1984) the inclination of the orbital plane is $i = (79.4 \pm 0.2)^\circ$, the masses and radii of the primary (A) and secondary (B) components are: $M_\mathrm{A} = (2.27 \pm 0.014)\,\mathrm{M}_\odot$, $M_\mathrm{B} = (1.87 \pm 0.013)\,\mathrm{M}_\odot$, and $R_\mathrm{A} = (3.03 \pm 0.03)\,\mathrm{R}_\odot$, $R_\mathrm{B} = (2.21 \pm 0.03)\,\mathrm{R}_\odot$. The eclipses are partial and very shallow. For the orbital phase we adopted Zissel's (1972) light elements of the primary minimum: $JD_\mathrm{min} = 2\,440\,321.005 + 3.894\,977E$.

## 3.2 Atmospheres

As a base for the choice of stellar atmosphere models of components and computing of synthetic spectra we adopted the physical parameters of both the components derived by Popper (1984). Combining spectrophotometric and photometric methods developed for eclipsing binaries, Popper (1984) derived the effective temperatures and surface gravities (in c.g.s.) $T_\mathrm{eff} = 8150\,\mathrm{K}$, $\log g = 3.83$ and $T_\mathrm{eff} = 7950\,\mathrm{K}$, $\log g = 4.02$ for the components A and B, respectively, and the luminosity ratio: $L_\mathrm{B}/L_\mathrm{A} = 0.48$. The line list was extracted from the VALD2 database (Kupka et al. 1999, Ryabchikova et al. 1999).

We interpolated the models of stellar atmospheres in the Kurucz tables (Kurucz 1993) for the parameters given above and used SYNSPEC code (Hubený 1987, Krtička 1998) to compute theoretical spectra for each component. The value of the microturbulence giving the best agreement for both strong and weak spectral lines, $v_\mathrm{turb} = 4.5\,\mathrm{km\,s^{-1}}$, is fairly high and the same for both components.

## 3.3 $V \sin i$ and the character of rotation of components

The value of projected equatorial rotational velocity $V \sin i$ of each component was estimated by comparing the model profiles with the observed ones of a well defined Fe II 4508.2 Å line.

The best fit computed and observed line profiles in disentangled spectra was reached for $V_\mathrm{A} \sin i = 35\,\mathrm{km\,s^{-1}}$ for the A and $V_\mathrm{B} \sin i = 29\,\mathrm{km\,s^{-1}}$ for the B components. The uncertainty of these values was not larger than $1\,\mathrm{km\,s^{-1}}$. The corresponding values of $V \sin i$ for synchronously rotating components with rotational axes oriented perpendicularly to the orbital plane are, however, $38.7\,\mathrm{km\,s^{-1}}$ and $28.2\,\mathrm{km\,s^{-1}}$ for the A and B components, respectively. While the less massive component is well synchronized, the rotation of the more massive component seems to be apparently slower than the synchronized one. The surprising asynchronism could be removed only by admitting a non-perpendicularity of the rotational axis or due to overestimation of the star's radius by Popper by some 10%. Both the admissions appear to be unrealistic, and so we conclude that very probably the rotational period of the A component is $P_\mathrm{rotA} \sim 4.3$ days and it is larger than the orbital period 3.895 d.

The asynchronous rotation of the primary component could be naturally explained by the fact that the primary component has recently entered into the epoch of fast reconstruction of the inner and outer parts of its interior, which necessarily results in changes of the rotational period. As the binary is not very close, the

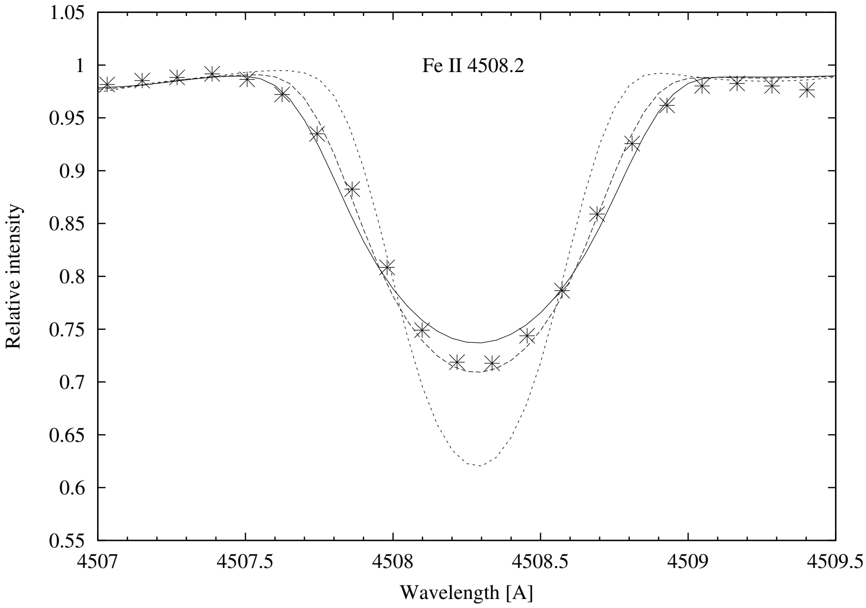



Figure 1: *Comparison of the observed and computed profiles of the Fe* II *4508.2 Å line.* $V \sin i$*: full line –* $39\,\mathrm{km\,s^{-1}}$*; broken line –* $35\,\mathrm{km\,s^{-1}}$*; dotted line –* $29\,\mathrm{km\,s^{-1}}$*; asterisks – observed.*

tidal interaction between the components is not effective enough to reestablish the perfect synchronization of the system.

### 3.4 Abundances

The synthetic spectra of each component were added up for each orbital phase using the luminosity ratio mentioned above and the ephemeris given in Zissel's paper (1974). By fitting the computed and observed lines and repeating the procedure we received abundances of chemical elements in each of the component. In the component A, the underabundant elements are Si and Sc (by a factor of 0.01), C (0.05), O (0.15) and Ca (0.5), while overabundant elements are: Cr and Fe (2), Mg (3), Ti (4), Na, Ni and Zr (5), Ba (14) and Y (20). In the component B, the underabundant elements are: Sc (0.03), Ca (0.07), C (0.3), Mg (0.4), Si (0.5) and Ti (0.7). The overabundant elements in the B component are: Cr and Fe (2), Ni and Ba (6) and Na (8). The value derived for Ti in the B component indicates the inaccuracy of determination rather than the real underabundance.

In general, the abundances derived agree well with the data available in the literature (Conti 1970) and thus the Am classification of both the binary components is confirmed.

## 4 Search for magnetic field

### 4.1 Measuring Zeeman shifts

The synthetic spectrum procedure allowed us to resolve and identify particular spectral lines of both components in the spectrum of the binary. Having the lines identified, we selected those of them that were not seriously blended with other lines in the same component neither were contaminated by lines of the other component projected onto the same wavelength. Unfortunately, there are not too many lines complying with these criteria. Moreover, the spectra of both components are practically identical due to the close atmospheric parameters, and that one taken near the primary minimum ($\varphi = 0$) does not contain any uncontaminated line.

The selected spectral lines used for measuring of Zeeman splits and their Landé factors are listed in Table 1. The Landé factors are from Beckers (1969).

We used 4 to 18 (typically 13) lines in the component A and 2 to 13 (typically 7) lines in the component B.

Table 1: List of spectral lines and their Landé factors.

| $\lambda$ | ion+mult. | $g_{\rm eff}$ | $\lambda$ | ion+mult. | $g_{\rm eff}$ |
|---|---|---|---|---|---|
| 4415.123 | Fe II (41) | 1.167 | 4554.029 | Ba II (1) | 1.167 |
| 4427.310 | Fe II (2) | 1.500 | 4555.893 | Fe II (37) | 1.238 |
| 4447.717 | Fe II (68) | 2.000 | 4558.650 | Cr II (44) | 1.167 |
| 4450.482 | Ti II (19) | 1.029 | 4563.761 | Ti II (50) | 0.833 |
| 4464.450 | Ti II (40) | 0.333 | 4565.740 | Cr II (39) | 0.600 |
| 4466.552 | Fe I (350) | 1.167 | 4571.968 | Ti II (82) | 0.944 |
| 4472.929 | Fe II (37) | 1.500 | 4576.340 | Fe II (38) | 1.200 |
| 4491.405 | Fe II (37) | 0.400 | 4583.837 | Fe II (38) | 1.167 |
| 4501.273 | Ti II (31) | 0.929 | 4588.199 | Cr II (44) | 1.071 |
| 4508.288 | Fe II (38) | 0.500 | 4604.982 | Ni I (98) | 1.855 |
| 4515.339 | Fe II (37) | 1.029 | 4620.521 | Fe II (38) | 1.333 |
| 4520.245 | Fe II (37) | 1.500 | 4629.339 | Fe II (37) | 1.333 |
| 4522.634 | Fe II (38) | 0.900 | 4634.070 | Cr II (44) | 0.500 |
| 4541.524 | Fe II (38) | 0.800 | | | |

The central wavelengths of selected lines in the right circularly polarized ($R$) and left circularly polarized ($L$) strips of the Zeeman spectra were derived by fitting their profiles with a gaussian. If the Zeeman analyzer operates properly, the shift $\Delta\lambda = \lambda_{\rm R} - \lambda_{\rm L}$ will depend only on the product of the longitudinal component of the total magnetic field of the star $B_{\rm eff}$ (effective magnetic field) and the Landé factor $g_{\rm eff}$ specific to the particular line:

$$\Delta\lambda = 9.34 \cdot 10^{-10} g_{\rm eff}\, \lambda^2\, B_{\rm eff} = 0.0193\, (\lambda/4543)^2\, g_{\rm eff}\, B_{\rm eff}, \tag{1}$$

where $\lambda$ is the wavelength of the line in Å and $B_{\rm eff}$ in kG, 4543 Å being the center of the spectral region studied. As the standard deviation of the shift measurements for the A and B components are 0.007 Å and 0.009 Å, respectively, we should expect the typical inner uncertainty of the determination of the effective field of the A and B components to be 0.10 kG and 0.18 kG, respectively.

All measured $R$–$L$ shifts were corrected for some instrumental shifts which occurred to be both time- and wavelength-dependent. The course of the dependence was determined by means of the $R$–$L$ shifts of 33 spectrograms of nonmagnetic sharp-lined standards: Arcturus (19), Mirfak ($\alpha$ Persei) (8), Procyon (3) and HD 158974 (3).

## 4.2 Effective magnetic field of HR 6611 A, B

The search for the effective magnetic field for the A and B components of HR 6611 consists in determination of 23+21=44 values of the effective magnetic field and 15 coefficients describing the behavior of instrumental shifts. This was done simultaneously for all the measured $R$–$L$ shifts (1080 shifts) by the robust regression (Mikulášek et al. 2003) that effectively eliminates the influence of outliers.

Using the measurements of the $R$–$L$ shifts on the 33 comparison Zeeman spectra and the 23 Zeeman spectra of the double-lined spectroscopic binary HR 6611, we find information about the effective magnetic field of both components and its variation, see Table 2.

Some values of $B_{\rm effB}$ of the B component suffer from their uncertainty caused by the small number of the lines measured and the bad phase distribution. The data display an extensive scatter with the center at $B_{\rm effB} = (-0.03 \pm 0.15)$ kG, with a standard deviation of 0.55 kG. The semi-amplitude of sine variations of the effective magnetic field is $(0.0 \pm 0.25)$ kG, see Fig. 2.

Information on the magnetic field of the primary component is more complete. Twenty-three fairly accurate measurements (the typical inner uncertainty 0.10 kG) are satisfactorily well distributed on the orbital phase diagram, so we can test the presence of potential orbital phase variations of the field (see Fig.3(a)).

Fig. 3(a) tellingly displays that the effective magnetic field of the A component very probably does not vary with the orbital period (the amplitude is $(0.12 \pm 0.16)$ kG). Nevertheless, the fact that the typical uncertainty of a single determination of the effective magnetic field is more than two times smaller than the standard deviation of them, $\mathrm{std(B_{effA})} = 0.22$ kG, suggests that another period may be in play, namely, the true rotational period. We have attempted to search for possible better periods that may be candidates for

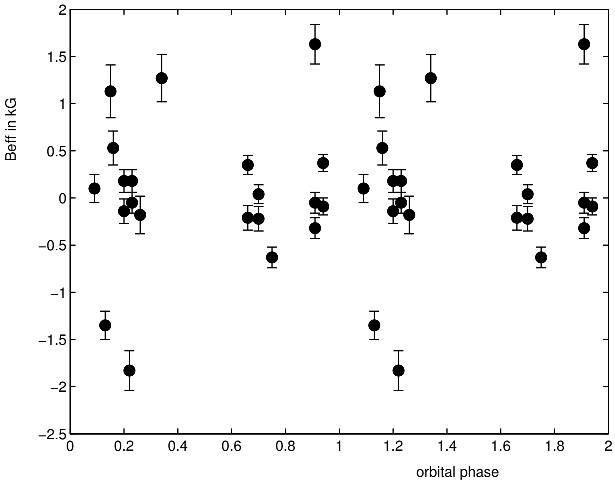
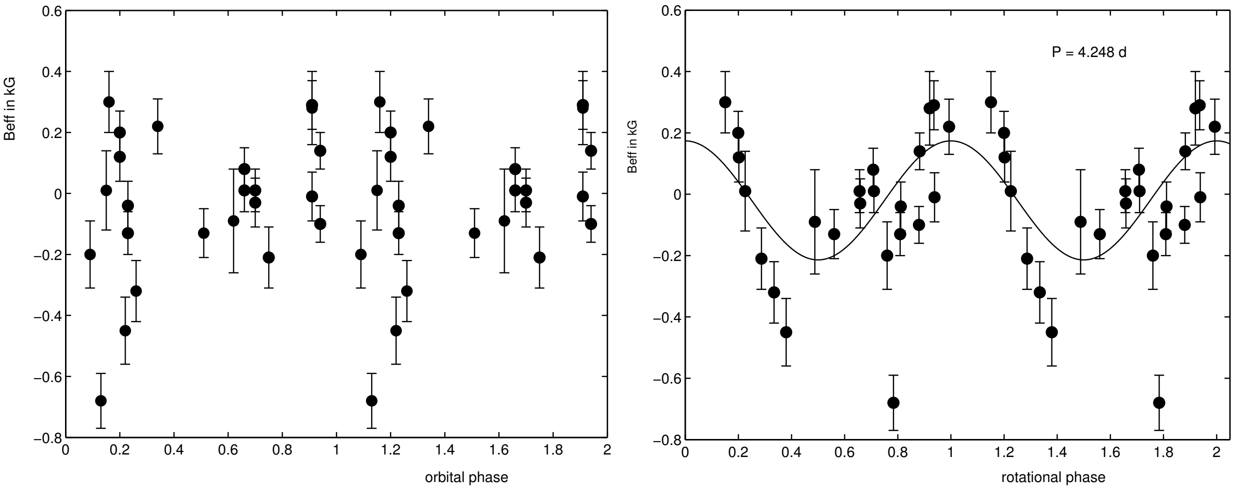



Figure 2: *Dependence of the effective magnetic field of the B component on the orbital phase ($P = 3.895$ d).*




(a) (b)

Figure 3: *Dependence of the effective magnetic field of the A component on (a) the orbital phase ($P = 3.895$ d) and (b) the possible rotational phase ($P = 4.248$ d, $JD_{\max} = 2\,442\,755.1$).*

Table 2: List of Zeeman spectra of HR 6611. Effective magnetic field measured. 1 – number of exposition, 2 – the number of CCD camera used, 3 – $JD_{\mathrm{hel}} - 2\,450\,000$ of the center of exposition, 4 – orbital phase, 5 – effective magnetic field of A component, 6 – effective magnetic field of B component, both in kG

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| 2227 | 1 | 2 333.6160 | 0.130 | $-0.68 \pm 0.09$ | $-1.35 \pm 0.15$ |
| 2522 | 1 | 2 417.3721 | 0.621 | $-0.09 \pm 0.17$ | |
| 2628 | 1 | 2 454.4531 | 0.153 | $+0.01 \pm 0.13$ | $+1.13 \pm 0.28$ |
| 2701 | 1 | 2 457.3948 | 0.908 | $+0.28 \pm 0.12$ | $+1.63 \pm 0.21$ |
| 2702 | 1 | 2 458.3795 | 0.161 | $+0.30 \pm 0.10$ | $+0.53 \pm 0.18$ |
| 2926 | 1 | 2 544.3194 | 0.225 | $-0.45 \pm 0.11$ | $-1.83 \pm 0.21$ |
| 3120 | 1 | 2 660.6354 | 0.088 | $-0.20 \pm 0.12$ | $+0.10 \pm 0.15$ |
| 3121 | 1 | 2 661.6285 | 0.343 | $+0.22 \pm 0.09$ | $+1.27 \pm 0.25$ |
| 3217 | 2 | 2 688.5688 | 0.260 | $-0.32 \pm 0.10$ | $-0.18 \pm 0.20$ |
| 3218 | 2 | 2 689.5323 | 0.507 | $-0.13 \pm 0.08$ | |
| 3614_04 | 2 | 2 805.2944 | 0.228 | $-0.13 \pm 0.07$ | $+0.18 \pm 0.12$ |
| 3614_05 | 2 | 2 805.3014 | 0.230 | $-0.04 \pm 0.08$ | $-0.05 \pm 0.11$ |
| 3616_08 | 2 | 2 807.3243 | 0.749 | $-0.21 \pm 0.10$ | $-0.63 \pm 0.11$ |
| 3709_18 | 2 | 2 830.3535 | 0.661 | $+0.08 \pm 0.07$ | $+0.35 \pm 0.10$ |
| 3709_19 | 2 | 2 830.3604 | 0.663 | $+0.01 \pm 0.07$ | $-0.21 \pm 0.13$ |
| 3710_10 | 2 | 2 831.3181 | 0.909 | $+0.29 \pm 0.08$ | $-0.32 \pm 0.11$ |
| 3710_11 | 2 | 2 831.3250 | 0.911 | $-0.01 \pm 0.08$ | $-0.05 \pm 0.11$ |
| 3711_02 | 2 | 2 832.4444 | 0.199 | $+0.20 \pm 0.07$ | $+0.18 \pm 0.12$ |
| 3711_03 | 2 | 2 832.4514 | 0.201 | $+0.12 \pm 0.08$ | $-0.14 \pm 0.13$ |
| 3713_02 | 2 | 2 834.3806 | 0.695 | $+0.01 \pm 0.07$ | $+0.04 \pm 0.10$ |
| 3713_03 | 2 | 2 834.3875 | 0.698 | $-0.03 \pm 0.08$ | $-0.22 \pm 0.12$ |
| 3714_02 | 2 | 2 835.3333 | 0.940 | $-0.10 \pm 0.06$ | $-0.09 \pm 0.09$ |
| 3714_03 | 2 | 2 835.3403 | 0.942 | $+0.14 \pm 0.07$ | $+0.37 \pm 0.09$ |

the rotational period of the primary and have found the best solution for the elements: $P = (4.248 \pm 0.006)$ d, $JD_{\mathrm{max}} = (2\,442\,755.1 \pm 0.2)$ (Fig. 3(b)). The semi-amplitude of variations is $(0.19 \pm 0.06)$ kG, the mean value is very close to zero: $(-0.02 \pm 0.04)$ kG.

Adopting Popper's values of the radius of HR 6611 A: $R_{\mathrm{A}} = (3.03 \pm 0.03)\,\mathrm{R}_{\odot}$, and of the inclination angle of its rotational axis $i = (79.4 \pm 0.2)^{\circ}$, we arrived for the possible rotational period $P = (4.248 \pm 0.006)$ d, to the $V_{\mathrm{A}} \sin i = (35.5 \pm 0.4)\ \mathrm{km\,s^{-1}}$, which is practically identical with its observed value of 35 $\mathrm{km\,s^{-1}}$.

Nevertheless, to prove or disprove this potential rotational period in question we need definitely to check it by further observational data taken preferably from another observatory. The problem is of high theoretical importance, as no Am star with a variable effective magnetic field and asynchronous rotation has been known up to now.

# 5 Conclusions

Am stars are known as non-magnetic CP stars, which has recently been confirmed by Shorlin et al. (2002) in their highly sensitive search for magnetic fields in B, A and F stars and Monin et al. (2002) in their magnetic survey of bright northern main sequence stars, thus negating all the former positive indications above the observational accuracy limits. On the other hand, the classical understanding of non-magnetic, non-variable CP1 (Am) and CP3 (Hg-Mn) stars became questioned with finding by Adelman et al. (2002) a mercury spot on the HgMn star $\alpha$ And.

Our preliminary spectroscopic study has focused on a bit unusual couple of Am stars creating the SB2 eclipsing binary HR 6611. The exclusiveness of the system refers namely to its primary component which seems to be a star entering the terminal stage of its main sequence life. We confirmed the Am peculiarity of both binary components and revealed the asynchronous rotation of the more massive star, which is most likely a consequence of its proposed fast period of evolution. The measurements of effective magnetic field done by the Zeeman analyzer of the 6 m telescope of SAO AS, Russia, may admit the presence of a variable effective magnetic field in the A component with an amplitude of about 0.4 kG. Up to now we have not known reliably the rotational period and hence the period of possible magnetic variations, but it is definitely not the orbital one.

To test the presence of a measurable magnetic field in the Am component HR 6611A and to find its rotational period, we have to collect more Zeeman spectra, but the effort will surely be paid in return.

**Acknowledgements.** This work was partly supported by the Grant Agency of the Slovak Academy of Sciences, Vega No.3014 and by the Bilateral Czech-Slovak Co-operation in Research, the project No.2002/131(54). Partial supports were provided by the grant No.205/02/0445 of the Grant Agency of the Czech Republic and of the grant APVT No. 51-802 of the Science and Technology Assistance Agency of the Slovak Republic.

We acknowledge the availability of the VALD2 database.

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