Physical parameters of the O6.5V+B1V eclipsing binary system LS 1135

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ABSTRACT
ASAS photometric observations of LS 1135, an O-type SB1 binary system with an orbital period of 2.7 days, show that the system is also eclipsing. This prompted us to re-examine the spectra used in the previously published spectroscopic orbit. Our new analysis of the spectra obtained near quadratures, reveal the presence of faint lines of the secondary component. We present for the first time a double-lined radial velocity orbit and values of physical parameters of this binary system. These values were obtained by analyzing ASAS photometry jointly with the radial velocities of both components performing a numerical model of this binary based on the Wilson–Devinney method. We obtained an orbital inclination $i \sim 68.5\degree$. With this value of the inclination we deduced masses $M_1 \sim 30 \pm 1 M_{\odot}$ and $M_2 \sim 9 \pm 1 M_{\odot}$; and radii $R_1 \sim 12 \pm 1 R_{\odot}$ and $R_2 \sim 5 \pm 1 R_{\odot}$ for primary and secondary components, respectively. Both components are well inside their respective Roche lobes. Fixing the $T_{\text{eff}}$ of the primary to the value corresponding to its spectral type (O6.5V), the $T_{\text{eff}}$ obtained for the secondary component corresponds approximately to a spectral type of B1V. The mass ratio $M_2/M_1 \sim 0.3$ is among the lowest known values for spectroscopic binaries with O-type components.

Key words: stars: binaries : spectroscopic – stars: binaries : eclipsing – stars: early-type – stars: individual: LS 1135

1 INTRODUCTION
The star LS 1135 ($\alpha_{2000.0} = 08^h 43^m 50^s$, $\delta_{2000.0} = -46^\circ 07'$), a member of the OB association Bochum 7 (Vela OB 3), was discovered by Corti et al. (2003, hereafter CNM) to be a single-lined binary (SB1) system with an orbital period of 2.7532 days. The spectrum was classified as O6.5V (f)). The rather high amplitude of the radial velocity variations and the lack of detected spectral lines of the secondary component led CNM to suggest that the secondary might be an early B type star.

Magnitudes and colors for LS 1135 from photoelectric photometry have been published by Moffat & Vogt (1975) as $V = 10.88, B - V = 0.4, U - B = -0.68$, and by Drilling (1991) as $V = 10.88, B - V = 0.38, U - B = -0.66$. LS 1135 was found to be a photometrically variable star in the “All Sky Automated Survey” (ASAS) (cf. Pojmanski 2003). It is catalogued as an eclipsing system, and a period of 2.7532 days was found independently in the photometric data, in perfect agreement with the period obtained from the radial velocities by CNM. The fact that LS 1135 is an eclipsing binary, motivated us to search for signatures of the secondary component by re-inspecting the spectra used by CNM. Here we report the discovery of the spectral lines of the secondary, and calculate for the first time a double-lined radial velocity orbit and a set of values of the main physical parameters of the components of LS 1135. These are based on a simultaneous analysis of the photometric light curve and radial velocity variations of both components by means of the Wilson-Devinney (W–D) Code (Wilson & Devinney 1971, Wilson 1990, Wilson & Van Hamme 2004).

2 OBSERVATIONS
2.1 The ASAS V light curve of LS 1135
ASAS (cf. Pojmanski 2002) has been monitoring photometrically a large part of the sky down to stellar magnitude $V \sim 14^{\text{mag}}$. The ASAS instrument was upgraded in late 2000, being then called ASAS-3 (Pojmanski, 2001). The current configuration obtains images with a wide-field ($8.8^\circ \times 8.8^\circ$) CCD camera, using a standard $V$ filter. The scale...
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Figure 1. A 4’ x 4’ image of the Digitized Sky Survey, centered in LS 1135. The circle represents the ASAS 3-pixels (= 46”.5) photometric aperture. (North is up and East to the left).

(∼ 15”/pixel) of the system results in sub-sampled images, which are suitable to be analyzed through aperture photometry. Figure 1 shows a 4’ x 4’ region of the sky around LS 1135.

LS 1135, catalogued as ASAS 084350-4607.2, is classified as an eclipsing binary of type ESD/ED (semi-detached/detached) in the ASAS-3 Catalog of Variable Stars, available in the Internet (cf. ASAS Web Site). We have retrieved from the ASAS-3 database the V photometric data of LS 1135 observed between 2000, November, and 2005, July. The light curve is shown in Figure 2. The data in this figure correspond to V values measured with the 3 pixel (= 46”.5) aperture. We selected 313 data values corresponding to this aperture because they show the light curve with the lowest dispersion of data points, and avoid the introduction of third light due to the star located 27” to the S-W of LS 1135 (see Fig. 1).

We note that there are several much fainter stars included in the photometric aperture. Taking into account that according to the “The Tycho-2 Catalogue of the 2.5 Million Brightest Stars” (Høg et al. 2000), the magnitude difference between LS 1135 and the neighbour at 27” to the S-W is ∼ 2.3 magnitudes, the other stars included in the aperture appear to be more than 5 magnitudes fainter than LS 1135. Thus their contribution to the total light would be less than 1%, which has been ignored in our analysis.

The zero point calibration used by ASAS photometry is based on the Hipparcos photometry (Perryman et al. 1997).

### 2.2 Spectroscopy

Photographic and digital spectra in the blue spectral region, as previously described by CNM, were used in our study of LS 1135. We have re-examined those spectra observed near the quadratures of the orbital motion in a search for spectral signatures of the secondary component. We found that some of the HeI absorption lines appear double near the maximum radial velocity separation of the components. We could measure the radial velocities from these lines due to the secondary component in ten spectra. The values of these radial velocities were obtained fitting gaussians to the spectral lines within the IRAF routine spplot, and are tabulated in Table 1 according the Heliocentric Julian Date (HJD) of observations. The instrumental configuration is given in column 3, following the notation from Table 1 in CNM. Typical errors in the determination of the radial velocities of the faint lines of the secondary component are rather large, ∼ 40 km s⁻¹.

| HJD 2 400 000 - | RV (km s⁻¹) | IC |
|-----------------|-------------|----|
| 45508.463       | -360        | I  |
| 45511.453       | -302        | I  |
| 50508.549       | -276        | II |
| 50538.586       | -277        | II |
| 50541.567       | -289        | II |
| 50845.620       | 440         | II |
| 50848.609       | 350         | II |
| 50859.600       | 406         | III|
| 50860.652       | -287        | III|
| 50965.647       | -307        | III|

### Table 1. Observed heliocentric radial velocities of the spectral lines of the secondary component of LS 1135. IC refers to the instrumental configuration in CNM.

3 THE RADIAL VELOCITY ORBIT

As a first step to estimate values of the physical parameters of the components of the binary system LS 1135, we determined a double-lined radial velocity orbit for the binary. For this we adjusted circular orbits to the complete set of radial velocities i.e. those published by CNM for the primary, and the values listed in Table 1 for the secondary. Because the radial velocities of the secondary component have considerably larger errors, they were assigned lower weight. For the determination of the orbital elements we used an improved version of the code originally published by Bertiau & Grobben (1969). Eccentricity was fixed to 0.0 since both minima in the light curve appear symmetrically separated. We also calculated an orbital solution leaving the eccentricity as a free parameter. This solution gave a very small value of the eccentricity, comparable with the error of the circular orbit. We have therefore adopted $e = 0$ for further analysis in this paper.

The initial value for the period was set to 2.7532 days from the previously published single-lined radial velocity orbit. The value obtained for the double-lined radial velocity orbit resulted in almost the same value, namely 2.753205 ± 10⁻⁵ days. The values of the orbital parameters are presented in Table 2. These values are to be considered as pre-

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1 IRAF is distributed by the NOAO, operated by the AURA, Inc, under cooperative agreement with the NSF, USA.
components of LS 1135
Circular orbital elements from radial velocities of both
Table 2.

| Element       | Primary   | Secondary  |
|---------------|-----------|------------|
| a sin i [R\(_{\odot}\)] | 6.15 ± 0.13 | 19.98 ± 0.13 |
| K [km s\(^{-1}\)]  | 114 ± 3   | 370 ± 13   |
| M sin\(^3\)i [M\(_{\odot}\)] | 24.6 ± 3.3 | 7.6 ± 1.2  |
| M\(_2\)/M\(_1\) | 0.31 ± 0.02 |
| T\(_{RF,Max}\) [HJD] | 2445508.5 ± 0.1 |
| Period [days]  | 2.753205 ± 10\(^{-5}\) |
| V\(_i\) [km s\(^{-1}\)] | 65 ± 2 |

liminary estimates, awaiting more accurate radial velocities for the secondary component from high resolution spectra with higher signal-to-noise ratio.

4 W–D ECLIPSING BINARY MODEL For THE LIGHT AND RADIAL VELOCITY CURVES OF LS 1135

In order to obtain the absolute values of the physical parameters of the binary components, we need to determine the orbital inclination \(i\) of the system. To this end, we adjusted a numerical eclipsing binary model to the observations, using the W–D Code. We used the PHOEBE package tool (Prša & Zwitter, 2005) for the light curve (LC) and differential corrections (DC) fits. ASAS photometric data and radial velocities of both components of the binary system were used to adjust the model.

The code was set in Mode 2 for detached binaries with no constraints on the potentials (except for the luminosity of the secondary component). The simplest considerations were applied for the emission parameters of the stars in the model, i.e. stars were considered as black bodies, approximate reflection model (MREF=1) was adopted, and no third light or spots were included. Gravity darkening exponents \(g_1 = g_2 = 1\) and bolometric albedos \(Alb_1 = Alb_2 = 1\) were set for radiative envelopes. We used the square root limb darkening law. Bolometric and \(V\) band limb darkening coefficients were taken from Van Hamme (1993). We adopted the mass ratio \(q = M_2/M_1 = 0.31\) from our radial velocity orbit. The temperature for the primary component was set to the corresponding value from the Spectral Type-\(T_{\text{eff}}\) calibration tables published by Martins et al. (2005). \(T_1\) was fixed in this value and \(T_2\) was computed with the model fit. We considered that the system has a circular orbit and that both components rotate synchronously \((F_1 = F_2 = 1)\). The radial velocity of the centre of mass of the binary system was fixed in the value obtained from the radial velocity orbit.

Photometric data were weighted from the original magnitude errors provided by the ASAS database taking the weight as \(w \propto 1/m_{err}^2\), in such a way that the observations with the lowest magnitude error had weight \(= 1\). We then generated synthetic light and radial velocity curves by means of the LC program of the W-D code, and adjusted them to the observations. In order to get a better delineated light curve, we proceeded to calculate normal points of the ASAS photometric data taking 0.02 phase bins. A weighted average of the magnitudes was computed for every bin, using the individual errors provided by ASAS database. A typical \(\text{rms} \sim 0.024 \text{ mag}\) is present in each mean point for the aperture considered in this paper. The results of our best fitting model are depicted in Figures 2 and 3 together with the normal points of the ASAS light curve of LS 1135, and the observed radial velocities of both components, respectively. The physical parameters of the system are presented in Table 3.

4.1 Ephemeris

The ASAS-3 variable star catalog \(^2\) provides for the \(V\) data of LS 1135 an epoch \(T_0 = HJD 2451872.87\) together with the period which is used to construct the light curve as a function of the orbital phase. This epoch does not correspond to a time of minimum light. We obtained the time corresponding to the principal eclipse with the W-D model as an output of the DC program. In this way both photometric and radial velocity data contribute to this result.

\(^2\) available in Internet
Figure 3. Normal points of the ASAS $V$ light curve of LS 1135 phased with the binary period of 2.7532 days. The continuous line represents our best fit W-D model.

Table 3. Preliminary physical parameters of the binary components of LS 1135 from the best fitting WD Model. $R_L$ stands for effective radius of the Roche lobe (cf. Eggleton 1983).

| Parameter          | Primary     | Secondary   |
|--------------------|-------------|-------------|
| Period [days]      | 2.753205 ± 2 × 10$^{-5}$ |             |
| $T_0$ [HJD]        | 2451871.91 ± 1 × 10$^{-2}$ |             |
| $V_\gamma$ [kms$^{-1}$] | 65$^*$         |             |
| $M_2/M_1$          | 0.31$^*$     |             |
| $i$ [$^{\circ}$]  | 68.5 ± 1     |             |
| $a$ [$R_\odot$]    | 28.1 ± 0.2   |             |
| $M$ [$M_\odot$]    | 30 ± 1       | 9 ± 1       |
| $R_{\text{mean}}$ [$R_\odot$] | 12 ± 1       | 5 ± 1       |
| $\text{Teff}$ [K]  | 37870 $^a$   | 25500 ± 500 |
| $M_{\text{bol}}$   | -8.8 ± 0.1   | -5.3 ± 0.1  |
| $L_2/L_1$          | 0.11 ± 0.05  |             |
| $\text{Log g}$ [cgs] | 3.76 ± 0.05  | 3.96 ± 0.05 |
| $R_L$ [$R_\odot$]  | 13.6 ± 0.1   | 7.95 ± 0.1  |

$^*$: Fixed from the radial velocity orbit of Table 2. $^a$: Fixed according spectral type (cf. Martins et al. 2005).

The epoch was selected being approximate to the time provided by ASAS. The ephemeris for the main minimum of the LS 1135 binary system then results as follows:

$$ \text{Min I} = \text{HJD} 2451871.91(10) + 2.7532044(20) \cdot E \quad (1) $$

5 CONCLUSIONS

We have obtained in this work a first approximation to estimate the absolute physical parameters of the LS 1135 O-type binary system. From a simultaneous analysis of the radial velocities and the light curve with the W–D code, we find the following:

- Fixing the $T_{\text{eff}}$ of the primary component to the value corresponding to its spectral type, namely O6.5V, from the best fitting W–D model we find $T_{\text{eff}} 25500$ K for the secondary component. This value corresponds approximately to a spectral type B1V, according to the scales of different authors (Böhm-Vitense, 1981; Schmidt-Kaler, 1982; Crowther, 1997).

- The inclination of the orbital plane of the system relative to the sky plane was found to be 68.5 ± 0.5$^\circ$ according the best fitting W–D model. With this value of $i$, we have obtained values for the individual masses of the primary and secondary components $M_1 = 30 \pm 1 M_\odot$ and $M_2 = 9 \pm 1 M_\odot$ and for the mean radii $R_1 = 12 \pm 1 R_\odot$ and $R_2 = 5 \pm 1 R_\odot$. Both components appear to be well inside their respective Roche lobes, and therefore LS 1135 is a detached binary still on the main sequence. Detached eclipsing binaries with accurate elements at the high mass end of the main sequence are exceedingly few in number, and are very much needed as the benchmarks of theoretical stellar models. Thus LS 1135 appears as an excellent candidate for an accurate determination of physical parameters in a high mass binary system. Within the uncertainties, the first values of physical parameters of the binary components of LS 1135 which we have determined are in fair agreement with recent tabulations of Galactic O star parameters based on models of stellar at-
mospheres (cf. Martins et al. 2005). Of course, for more accurate values a better defined light curve is needed, as well as spectra with higher signal-to-noise ratio for a more accurate determination of the radial velocities of the secondary component.

- It is also interesting to mention that the mass ratio which we have obtained from the radial velocities \( q = \frac{M_2}{M_1} \sim 0.31 \), if confirmed, would be among the lowest values recorded for O type main sequence binaries. Therefore, the physical parameters of the primary O6.5V type component would be better defined in this case, since the perturbations introduced by the secondary component on the spectral behaviour of the primary would be minor as compared to binary systems with similar components.

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