Mon. Not. R. Astron. Soc. **367,** 1709–1713 (2006) doi:10.1111/j.1365-2966.2006.10074.x

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

E. Fernández Lajús★† and V. S. Niemela‡
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Argentina

Accepted 2006 January 11. Received 2006 January 5; in original form 2005 November 22

ABSTRACT

The 'All Sky Automated Survey' (ASAS) photometric observations of LS 1135, an O-type single-lined binary (SB1) system with an orbital period of 2.7 d, 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, reveals 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 analysing the ASAS photometry jointly with the radial velocities of both components by performing a numerical model of this binary based on the Wilson–Devinney method. We obtained an orbital inclination $i \sim 68\overset{\circ}{.}5$. With this value of the inclination, we deduced masses $M_1 \sim 30 \pm 1\,\mathrm{M}_{\odot}$ and $M_2 \sim 9 \pm 1\,\mathrm{M}_{\odot}$, and radii $R_1 \sim 12 \pm 1\,\mathrm{R}_{\odot}$ and $R_2 \sim 5 \pm 1\,\mathrm{R}_{\odot}$ for primary and secondary components, respectively. Both the components are well inside their respective Roche lobes. Fixing the T_{eff} of the primary to the value corresponding to its spectral type (O6.5V), the T_{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: binaries: eclipsing – binaries : spectroscopic – stars: early-type – stars: individual: LS 1135.

1 INTRODUCTION

The star LS 1135 ($\alpha_{2000.0} = 08^{\mathrm{h}}43^{\mathrm{m}}50^{\mathrm{s}}, \delta_{2000.0} = -46^{\circ}07'09''$), a member of the OB association Bochum 7 (Vela OB 3), was discovered by Corti, Niemela & Morrell (2003, hereafter CNM) to be a single-lined binary (SB1) system with an orbital period of 2.7532 d. 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 colours 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. Pojmański 2003). It is catalogued as an eclipsing system, and a period of 2.7532 d 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 the 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 (LC) and radial velocity variations of both the 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* LC of LS 1135

ASAS (cf. Pojmański 2002) has been monitoring photometrically a large part of the sky down to stellar magnitude $V \sim 14$ mag. The ASAS instrument was upgraded in late 2000, being then called ASAS-3 (Pojmański 2001). The current configuration obtains images with a wide-field (8.8×8.8-deg^2) CCD camera, using a standard V filter. The scale ($\sim$15 arcsec pixel^{-1}) of the system results in subsampled images, which are suitable to be analysed through aperture photometry. Fig. 1 shows a 4×4-arcmin^2 region of the sky around LS 1135.

LS 1135, catalogued as ASAS 084350−4607.2, is classified as an eclipsing binary of type semi-detached/detached (ESD/ED) in the ASAS-3 catalogue of variable stars, available on the Internet (cf. ASAS website). We have retrieved from the ASAS-3 data base the V photometric data of LS 1135 observed between 2000 November

★E-mail: eflajus@fcaglp.unlp.edu.ar
†Fellow of CONICET, Argentina.
‡Member of the Carrera del Investigador Científico, CIC-BA, Argentina.

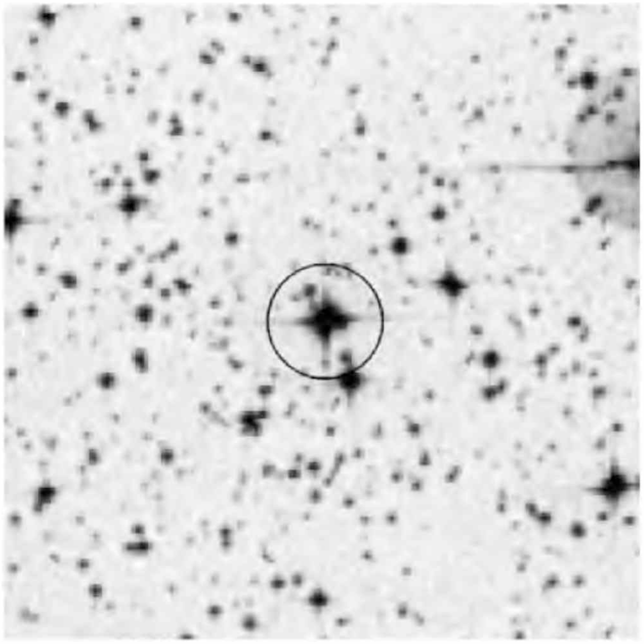

Figure 1. A 4 × 4-arcmin^2 image of the Digitized Sky Survey, centred in LS 1135. The circle represents the ASAS 3-pixel (=46.5-arcsec) photometric aperture. (North is up and east to the left-hand side).

and 2005 July. The LC is shown in Fig. 2. The data in this figure correspond to V values measured with the 3-pixel (=46.5-arcsec) aperture. We selected 313 data values corresponding to this aperture because they show the LC with the lowest dispersion of data points, and avoid the introduction of third light due to the star located 27 arcsec to the south-west 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 arcsec to the south-west is ∼2.3 mag, the other stars included in the aperture appear to be more than 5 mag fainter than LS 1135. Thus, their contribution to the total light would be less than 1 per cent, which has been ignored in our analysis.

The zero-point calibration used by the 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 He I 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 10 spectra. The values of these radial velocities were obtained by fitting Gaussians to the spectral lines within the IRAF[1] routine SPLOT, and are tabulated in Table 1 according to the Heliocentric Julian Date (HJD) of the 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}.

[1] IRAF is distributed by the National Optical Astronomy Observatory (NOAO), operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation (NSF), USA.

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, that is, 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 LC 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 d 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, 2.753 205 ± 10^{-5} d. The values of the orbital parameters are presented in Table 2. These values are to be considered as preliminary estimates, awaiting more accurate radial velocities for the secondary component from high-resolution spectra with higher signal-to-noise ratio (S/N).

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 LC and differential correction (DC) fits. The ASAS photometric data and the radial velocities of both the 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, that is, 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–$T_{\rm eff}$ calibration tables published by Martins, Schaerer & Hillier (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 the components rotate syncronously ($F_1 = F_2 = 1$). The radial velocity of the centre of mass of the

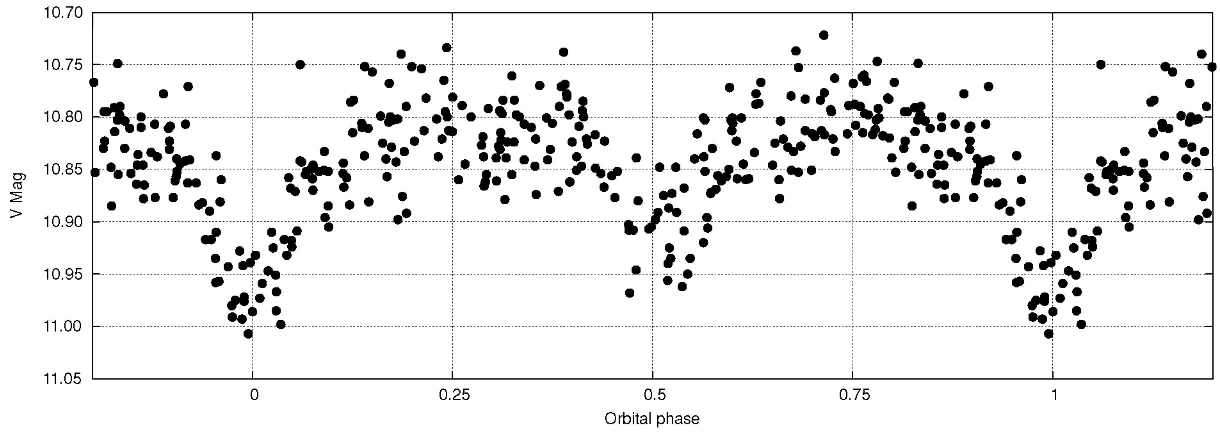

Figure 2. The ASAS-3 V LC of LS 1135. Mag are those measured using a 46.5-arcsec-diameter aperture. The data correspond to observations adquired between 2000 November and 2005 July.

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.

HJD 2 400 000-	Radial velocity (km s^{-1})	IC
45508.463	−360	I
455 11.453	−302	I
505 08.549	−276	II
505 38.586	−277	II
505 41.567	−289	II
508 45.620	440	II
508 48.609	350	II
508 59.600	406	III
508 60.652	−287	III
509 65.447	−307	III

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 data base taking the weight as $w \propto 1/m_{\mathrm{err}}^2$, in such a way that the observations with the lowest magnitude error had weight $w = 1$. 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 LC, 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 data base. A typical rms ~0.024 mag is present in each mean point for the aperture considered in this paper. The results of our best-fitting model are depicted in Figs 3 and 4 together with the normal points of the ASAS LC of LS 1135, and the observed radial velocities of both the components, respectively. The physical parameters of the system are presented in Table 3.

4.1 Ephemeris

The ASAS-3 Variable Star Catalogue[2] provides for the V data of LS 1135 an epoch T_0 = HJD 245 1872.87 together with the period which is used to construct the LC 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. 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:

$$\mathrm{Min}\, I = \mathrm{HJD}\, 245\, 1871.911(10) + 2\overset{\mathrm{d}}{.}7352044(20)E. \quad (1)$$

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 LC with the W–D code, we find the following.

(i) Fixing the T_{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 $T_{\mathrm{eff}} = 25\,500$ 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).

(ii) The inclination of the orbital plane of the system relative to the sky plane was found to be $68\overset{\circ}{.}5 \pm 0\overset{\circ}{.}5$, according to 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 $M_1 = 30 \pm 1\,\mathrm{M_{\odot}}$ and $M_2 = 9 \pm 1\,\mathrm{M_{\odot}}$, and for the mean radii $R_1 = 12 \pm 1\,\mathrm{R_{\odot}}$ and $R_2 = 5 \pm 1\,\mathrm{R_{\odot}}$. Both the components appear to be well inside their respective Roche lobes, and therefore LS 1135

Table 2. Circular orbital elements from the radial velocities of both the components of LS 1135

Element	Primary	Secondary
$a \sin i$ ($\mathrm{R_{\odot}}$)	6.15 ± 0.13	19.98 ± 0.13
K (km s^{-1})	114 ± 3	370 ± 13
$M \sin^3 i$ ($\mathrm{M_{\odot}}$)	24.6 ± 3.3	7.6 ± 1.2
M_2/M_1	0.31 ± 0.02	
$T_{RV_{\mathrm{Max}}}$ (HJD)	2445 508.5 ± 0.1	
Period (d)	2.753 205 ± 10^{-5}	
V_{γ} (km s^{-1})	65 ± 2	

[2] Available on the Internet.

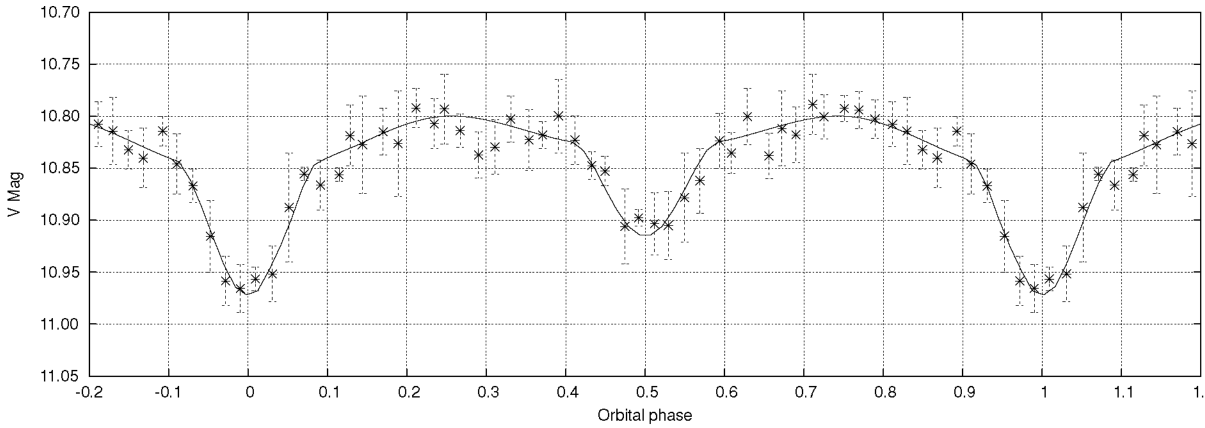

Figure 3. Normal points of the ASAS V LC of LS 1135 phased with the binary period of 2.7532 d. The continuous line represents our best-fitting W–D model.

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 the recent tabulations of the Galactic O star parameters based on the models of stellar atmospheres (cf. Martins et al. 2005). Of course, for more accurate values, a better defined LC is needed, as well as spectra with higher S/N for a more accurate determination of the radial velocities of the secondary component.

(iii) It is also interesting to mention that the mass ratio which we have obtained from the radial velocities q, $M_2/M_1 \sim 0.31$, 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.

Table 3. Preliminary physical parameters of the binary components of LS 1135 from the best-fitting W–D model. R_L stands for effective radius of the Roche lobe (cf. Eggleton 1983).

Parameter	Primary	Secondary
Period (d)	$2.753\,205 \pm 2 \times 10^{-5}$	
T_0 (HJD)	$2451\,871.91 \pm 1 \times 10^{-2}$	
$V\gamma$ (km s^{-1})	65^a	
M_2/M_1	0.31^a	
i (°)	68.5 ± 1	
a ($R_\odot$)	28.1 ± 0.2	
M ($M_\odot$)	30 ± 1	9 ± 1
$R_{\rm mean}$ ($R_\odot$)	12 ± 1	5 ± 1
$T_{\rm eff}$ (K)	$37\,870^b$	$25\,500 \pm 500$
$M_{\rm bol}$	-8.8 ± 0.1	-5.3 ± 0.1
L_2/L_1	0.11 ± 0.05	
Log g (cgs)	3.76 ± 0.05	3.96 ± 0.05
R_L($R_\odot$)	13.6 ± 0.1	7.95 ± 0.1

[a]Fixed from the radial velocity orbit of Table 2.
[b]Fixed according to spectral type (cf. Martins et al. 2005).

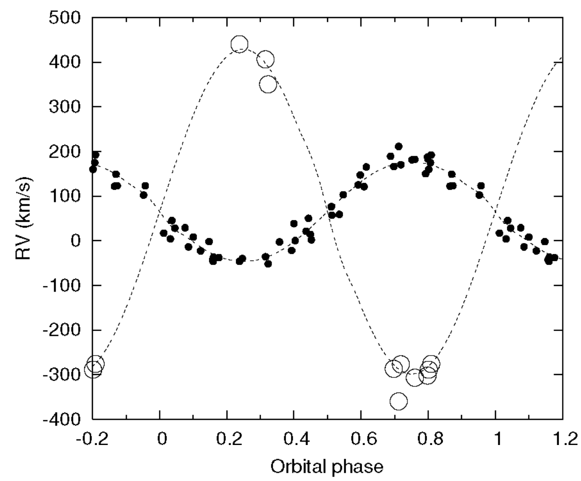

Figure 4. Observed radial velocities of both the components of LS 1135 phased with the binary period of 2.7532 d. The curves represent the best-fitting W–D model.

ACKNOWLEDGMENTS

We are indebted to Dr. Nidia Morrell for the loan of five spectrograms and for reading a preliminary version of this paper. We thank Federico Bareilles for providing the improved version of the Bertiau and Grobben code. We would also like to thank an anonymous referee for a careful reading of the manuscript. This research has received partial support from IALP, CONICET, Argentina.

REFERENCES

Bertiau F. C., Grobben J., 1969, Ric. Astron. Spec. Vaticano, 8, 1
Böhm-Vitense E., 1981, ARA&A, 19, 295
Corti M., Niemela V., Morrell N., 2003, A&A, 405, 571 (CNM)
Crowther P. A., 1997, in Bedding T. R., Booth A. J., Davis J., eds, IAU Symp. 189, Fundamental Stellar Properties: The Interaction between Observation and Theory. Kluwer, Dordrecht, p. 137
Drilling J. S., 1991, ApJS, 76, 1033
Eggleton P. P., 1983, ApJ, 268, 368
Høg E. et al., 2000, A&A, 355, L27
Martins F., Schaerer D., Hillier D. J., 2005, A&A, 436, 1049
Moffat A. F. J., Vogt N., 1975, A&AS, 20, 85
Perryman M. A. C., Lindegren L. et al., 1997, A&A, 323, L49

Pojmański G., 2001, in Paczynski B., Chen W.-P., Lemme C., ed., ASP Conf. Ser. Vol. 246, Small Telescope Astronomy on Global Scales. Astron. Soc. Pac., San Francisco, p. 53
Pojmański G., 2002, Acta Astron., 52, 397
Pojmański G., 2003, Acta Astron., 53, 341
Prša A., Zwitter T., 2005, ApJ, 628, 426
Schmidt-Kaler Th., 1982, in Schaifers K., Voigt H. H., eds, Landolt-Börnstein, New Series Group, VI, Vol. 2b. Springer-Verlag, Berlin, p. 1
Van Hamme W., 1993, AJ, 106, 2096
Wilson R. E., 1990, ApJ, 356, 613
Wilson R. E., Devinney E. J., 1971, ApJ, 166, 605
Wilson R. E., Van Hamme W., 2004, Computing Binary Star Observables, available at ftp://ftp.astro.ufl.edu/pub/wilson/lcdc2003/

This paper has been typeset from a TEX/LATEX file prepared by the author.