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Absolute properties of the main-sequence eclipsing binary FM Leo

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ABSTRACT

First spectroscopic and new photometric observations of the eclipsing binary FM Leo are presented. The main aims were to determine the orbital and stellar parameters of the two components and their evolutionary stage. First spectroscopic observations of the system were obtained with the David Dunlap Observatory and Poznań Spectroscopic Telescope spectrographs. The results of the orbital solution from radial velocity curves are combined with those derived from the light-curve analysis (V-band photometry from the All Sky Automated Survey and supplementary observations of eclipses with the 1 and 0.35 m telescopes) to derive orbital and stellar parameters. JKTEBOP, Wilson–Devinney binary modelling codes and a two-dimensional cross-correlation method were applied for the analysis. We find the masses to be $M_1 = 1.318 \pm 0.007$ and $M_2 = 1.287 \pm 0.007\,M_\odot$ and the radii to be $R_1 = 1.648 \pm 0.043$ and $R_2 = 1.511 \pm 0.049\ R_\odot$ for primary and secondary stars, respectively. The evolutionary stage of the system is briefly discussed by comparing physical parameters with current stellar evolution models. We find that the components are located at the main sequence, with an age of about 3 Gyr.

Key words: techniques: radial velocities – binaries: eclipsing – binaries: spectroscopic – stars: fundamental parameters – stars: individual: FM Leo.

1 INTRODUCTION

Binary stars are the main source of fundamental data on stellar masses and radii. High quality and quantity of binaries' observations can help in testing stellar evolution theory. Accurate masses and radii (determined to better than 3 per cent) derived from the analysis of detached binary systems have led to a number of new and interesting results on the properties and evolution of normal stars (Torres, Andersen & Giménez 2009). Such data can be used to improve the treatment of convection, diffusion and other non-classical effects which are essential to our understanding of stellar structure.

FM Leo, also known as HD 97422 and HIC 54766, is an EA-type eclipsing binary. Its extensive photometry was listed by ASAS (Pojmański 2002) under the code ASAS 111245+0020.9. Its maximum magnitude comes to $V_{\rm max} = 8.47$ mag. An analysis of the light curve reveals two eclipses of nearly identical depth and a flat maximum, proving that FM Leo is a detached binary consisting of two nearly identical spherical components.

An analysis of the All Sky Automated Survey (ASAS-3) (Pojmański 2002) and *Hipparcos* (Perryman et al. 1997) data bases yields an orbital period of 6.728 63 d (Otero 2003). The star is classified as F8 (Perryman et al. 1997). The *Hipparcos* parallax of the binary is $\pi = 8.35 \pm 1.17$ mas.

In this paper, we present results of the exact determination of the stellar parameters of FM Leo. Since there was no radial velocity (RV) curve for this star in the literature, we resorted to our own observations. We also present new photometric observations of eclipses of the binary. Our data and reduction procedures are described in Section 2. In Section 3 we analyse observations using JKTEBOP (photometry) (Southworth, Maxted & Smalley 2004a; Southworth et al. 2004b) and our own procedure (spectroscopy) to find the solution for the system and present absolute properties of FM Leo, while Section 4 is devoted to a discussion on the evolutionary status and the age of the system.

2 DATA AND REDUCTION

2.1 Spectroscopy

Spectroscopic observations were performed with the Cassegrain-focus spectrograph at the 1.9 m telescope of the David Dunlap Observatory (DDO) on 2006 April 28–May 4. The typical exposure

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time was 20 min. A total of 12 spectra cover the wavelength range of 5100–5275 Å at a resolving power of $R \approx 20\,000$. They were obtained with signal-to-noise ratios (S/N) ranging from 30 to 40.

An additional 16 higher resolution ($R \approx 35\,000$) spectra were obtained during the period of 2008 March 31 to May 25 with the Poznań Spectroscopic Telescope (PST) – the binary telescope using one of the 0.4 m mirrors of a Newtonian focus, connected by optic fibres with an echelle spectrograph (Baranowski et al. 2009). The typical exposure time was 30 min. The spectra cover the full range of 4480–9250 Å and consist of 64 orders. The typical S/N is ≈30. The observations were performed in bad weather conditions. All RV measurements are presented in Table A1.

The data reduction was performed with the IRAF package[1] following the standard procedures, i.e. background subtraction, flat-fielding, wavelength calibration using the emission lines of a Th–Ar lamp and normalization to the continuum through a polynomial fit.

In order to determine RVs of components, one- and two-dimensional cross-correlation techniques have been used. We derived RV curves for every component using both methods.

To determine RV curves of the system, the spectra were cross-correlated against various template spectra and by using different procedures. In the case of one-dimensional correlation we took as a template the spectrum of HD 102870, which is of a similar spectral type (F9V) to FM Leo. The template spectrum was obtained during the same observing run as for FM Leo. The RVs were measured using the FXCOR task in IRAF. In the case of two-dimensional correlation, we used synthetic spectra created by ATLAS9 (Castelli & Kurucz 2003) for stars with effective temperatures of $T_1 = 6300$ K and $T_2 = 6200$ K, solar metallicity and rotational velocities of $v_1 = 10\,\mathrm{km\,s^{-1}}$ and $v_2 = 12\,\mathrm{km\,s^{-1}}$, respectively. The cross-correlation was performed with the TODCOR method (Zucker & Mazeh 1994).

The mean formal error of measurements in the case of two-dimensional correlation $\overline{\sigma} = 0.7\,\mathrm{km\,s^{-1}}$ ($\overline{\sigma}_{\rm PST} = 0.4\,\mathrm{km\,s^{-1}}$ and $\overline{\sigma}_{\rm DDO} = 1.1\,\mathrm{km\,s^{-1}}$) was smaller than in the case of one-dimensional correlation ($\overline{\sigma} = 1.4\,\mathrm{km\,s^{-1}}$), so we took the TODCOR result as the final one.

2.2 Photometry

FM Leo was first identified as an EA-type eclipsing binary with a maximum, out-of-eclipse V-band magnitude of $V_{\rm max} = 8.467 \pm 0.016$ mag in the *Hipparcos* catalogue (Perryman et al. 1997).

A total of 324 V-band measurements of the object were gathered between 2000 November and 2004 July during the ASAS-3 survey (Pojmański 2002). The mean error of measurements was $\overline{\sigma} = 0.017$ mag. The resulting light curve exhibits periodic eclipses with a depth of 0.5 mag.

We supplemented the long-term photometry from ASAS with additional measurements of moments of eclipses. 46 V-filter observations with an exposure time of 40 s were obtained with the 1 m Elizabeth telescope at the South African Astronomical Observatory (SAAO) during one run in 2008 December. 2655 supplementary measurements with an exposure time of 5 s obtained with the 0.35 m telescope (Kielce) were gathered over four observing runs between 2008 April 14 and May 28. The Schmidt–Cassegrain telescope located in Kielce Observatory is equipped with the SBIG ST-7XE CCD camera, working typically 25 K below the ambient temperature. A focal reducer of 0.5× allows us to obtain an effective focal length of 1800 mm, providing a 13.0 × 8.9 arcmin field of view. Data were processed with standard data reduction procedures including bias, dark frame subtraction and flat-fielding. Typically, we used median-combined frames composed of five or seven bias/dark/flat images. The aperture photometry procedure provided by the PHOTOM Starlink package[2] was used to measure instrumental magnitudes. Next, using one comparison star (HD 97441) we estimated the differential magnitude and used values averaged over every five measurements for further analysis. The mean error of Kielce observations was $\overline{\sigma} = 0.018$ mag, while for SAAO measurements we obtained $\overline{\sigma} = 0.017$ mag.

3 ANALYSIS

The preliminary orbit solution and physical parameters of FM Leo have been estimated using PHysics Of Eclipsing BinariEs (PHOEBE; Prša & Zwitter 2005), which is based on the Wilson–Devinney method. We used this estimation as input data to the spectroscopic and photometric analysis tools mentioned in this section.

3.1 Spectroscopic analysis

Using the procedure that fits a double-Keplerian orbit to RV measurements and minimizes the χ^2 function with the Levenberg–Marquardt algorithm, we obtained RV curves with rms of fitting for Borowiec data $\sigma_{\rm PST1} = 0.88\,\mathrm{km\,s^{-1}}$ for the primary and $\sigma_{\rm PST2} = 0.97\,\mathrm{km\,s^{-1}}$ for the secondary (without four measurements close to 0 phase, the values are $\sigma_{\rm PST1} = 0.63\,\mathrm{km\,s^{-1}}$, $\sigma_{\rm PST2} = 0.71\,\mathrm{km\,s^{-1}}$), and $\sigma_{\rm DDO1} = 0.86\,\mathrm{km\,s^{-1}}$, $\sigma_{\rm DDO2} = 1\,\mathrm{km\,s^{-1}}$ for DDO measurements. As input data (period P, semi-amplitudes K_1, K_2 and systemic velocity γ), we used values obtained from PHOEBE. The fit where e was set as a free parameter resulted in an eccentricity value indistinguishable from zero (within error limits) and its rms did not differ significantly from that when a strictly circular orbit was assumed. Thus for further analysis we kept $e = 0$ fixed. We assumed period P and inclination i with errors from the preliminary solution of the light-curve analysis (Section 3.2).

This orbit solution yields masses of components M_1, M_2, semi-major axis a, velocity semiamplitudes of K_1, K_2 and the system RV γ presented in Table 1. Final RV curves are shown in Fig. 1.

3.2 Photometric analysis

Using the JKTEBOP procedure by John Southworth[3] (Southworth et al. 2004a,b) based on the EBOP code (Etzel 1981; Popper & Etzel 1981), we fitted the model to photometric observations. We held the mass ratio q derived from the preliminary solution from PHOEBE fixed and orbital period P, ephemeris time-base T_0, light scalefactor, orbit inclination i, surface brightness ratio, sum and ratio of the radii adjusted with the initial values from PHOEBE.

Finally, we derived the radii of the stars R_1, R_2 and improved values of period P and ephemeris time-base T_0. The results are presented in Table 1. Additionally, we used the same procedure for a bootstrapping error analysis. The final light curve of FM Leo is shown in Fig. 2. We obtained rms of fitting of $\sigma = 0.02$ mag.

[1] IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, AZ. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation. http://iraf.noao.edu/

[2] http://starlink.jach.hawaii.edu/starlink

[3] http://www.astro.keele.ac.uk/~jkt/codes/jktebop.html

Table 1. Absolute dimensions of FM Leo. Surface gravity acceleration is denoted with log g, where g is given in cgs units.

Parameter	Primary	Secondary	Unit
T_0	HJD 245 2499.182 ± 0.002		
P	6.728 606 ± 0.000 006		d
e	0		
γ	11.87 ± 0.13		km s^{-1}
i	87.98 ± 0.06		deg
a	20.631 ± 0.052		R$_\odot$
K	76.619 ± 0.273	78.463 ± 0.284	km s^{-1}
M	1.318 ± 0.007	1.287 ± 0.007	M$_\odot$
R	1.648 ± 0.043	1.511 ± 0.049	R$_\odot$
L	1.806 ± 0.086	1.617 ± 0.102	L$_\odot$
$T_{\rm eff}$	6316 ± 240	6190 ± 211	K
log g	4.124 ± 0.023	4.189 ± 0.028	

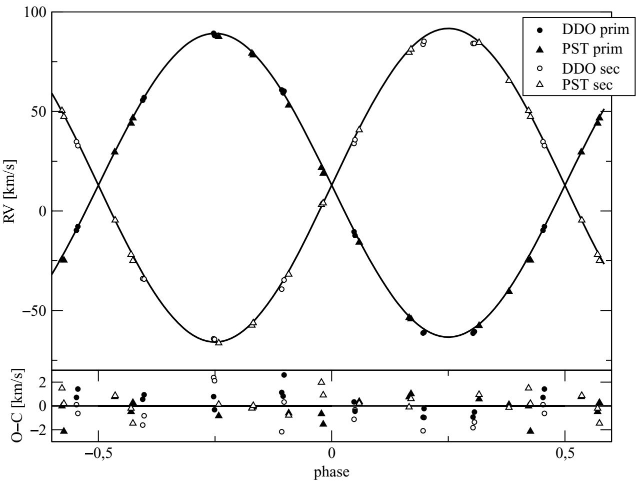

Figure 1. RV curves of FM Leo derived by using the two-dimensional correlation method. The solid lines in the top panel are the best-fitting synthetic curves. The bottom panel shows the residuals of the fits.

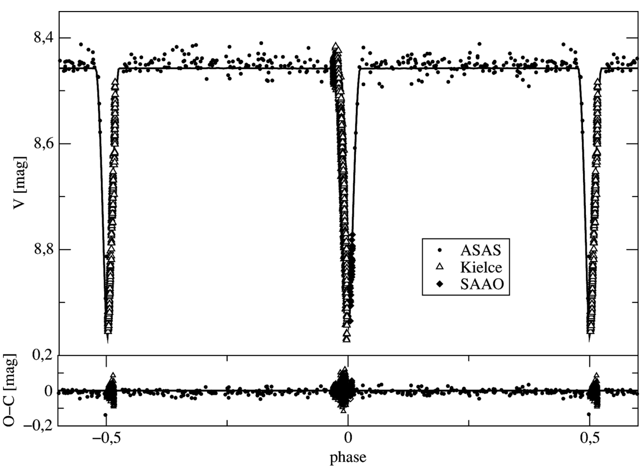

Figure 2. V light curve of FM Leo. The solid line in the top panel is the best-fitting synthetic light curve generated by JKTEBOP. The bottom panel shows the residuals of the fit.

3.3 Absolute dimensions

After using the procedure for fitting the orbit to RV measurements and JKTEBOP for photometric observations, we checked both solutions together in PHOEBE. To calculate the absolute dimensions of the eclipsing binary system, we used the JKTEBOP procedure JKTABSDIM, the code in which attention is paid to correctly propagating the errors. We took velocity semi-amplitudes, orbital eccentricity, periastron longitude, period, orbital inclination, fractional stellar radii, apparent magnitudes and effective temperatures of the stars with uncertainties as input quantities. As a result we derived the absolute masses and radii of two stars, their luminosities and absolute bolometric magnitudes, their surface gravities and synchronous rotational velocities, each with error budget. A full compilation of stellar and orbital parameters of FM Leo obtained by using the code mentioned is presented in Table 1.

3.4 Temperatures

To determine individual effective temperatures of both components, we used colour indices for FM Leo (Cutri et al. 2003) and theoretical colour–temperature relations (Bessel, Castelli & Plez 1998). As a result, we obtained the temperature of the primary $T_{\rm eff1} = 6316 \pm 240$ K. The secondary's temperature was estimated by using PHOEBE with the primary's temperature held fixed. We obtained a value of $T_{\rm eff2} = 6190 \pm 211$ K for the secondary. The combined photometry used to calculate the temperature of the primary led to underestimation of its value (combination with the light of a cooler star) but by less than the uncertainty.

4 COMPARISON WITH STELLAR MODELS

To prove the solution for both components, we compared them with current stellar evolution models and evolutionary tracks for certain masses and checked if a single isochrone fits both stars simultaneously. We interpolated evolutionary tracks at the measured masses of primary ($M_1 = 1.318\,{\rm M}_\odot$) and secondary ($M_2 = 1.287\,{\rm M}_\odot$) components using the YONSEI-YALE code (Yi et al. 2004b) for various metallicities and α-enhancement of zero. We get the best fit for assumed solar metallicity ($Z = 0.018$). The tracks on the log T–log g plane are illustrated in Fig. 3. The parameters of both components are consistent with evolutionary tracks for given masses.

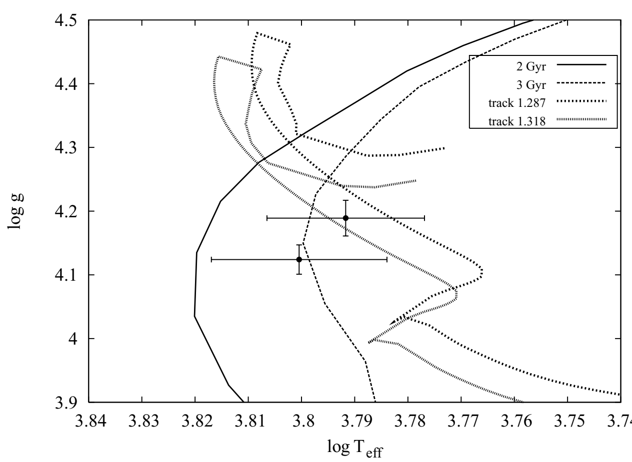

Figure 3. Evolutionary tracks for the measured masses of 1.318 and 1.287 M$_\odot$ and isochrones of ages of 2 and 3 Gyr generated by the YONSEI-YALE code for solar metallicity ($Z = 0.018$) and α-enhancement of zero.

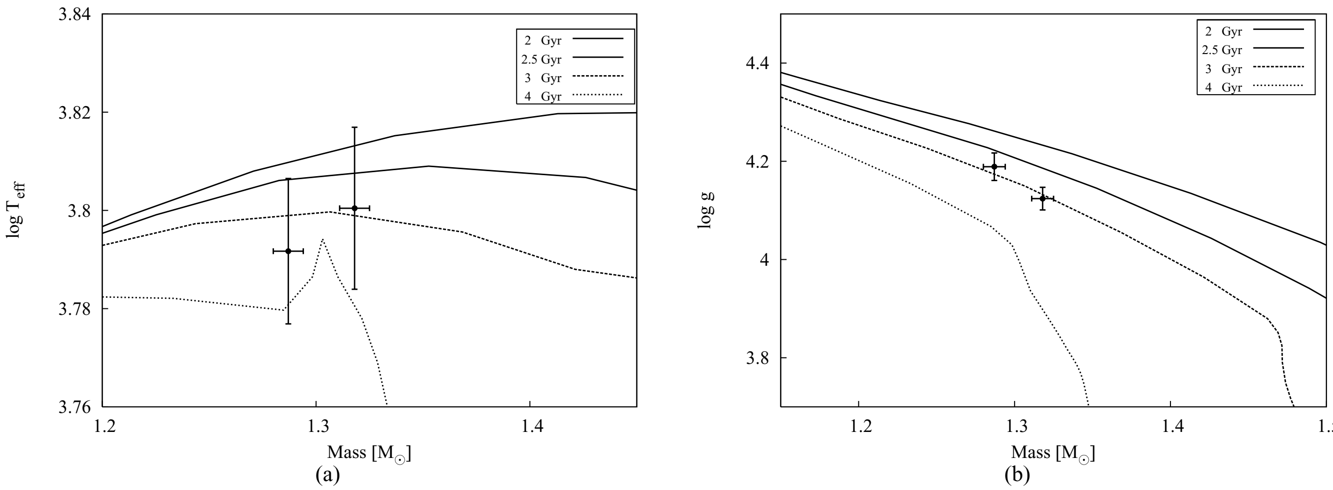

Figure 4. The location of components of FM Leo on several planes, (a) mass–log T and (b) mass–log g, is compared with isochrones from YALE-YONSEI (Yi et al. 2004b) theoretical models. The age for isochrones is 2, 2.5, 3 and 4 Gyr and the adopted metallicity is $Z = 0.018$.

To estimate the age of the system and prove the parameters obtained, we considered three different sets of theoretical calculations: YONSEI-YALE (Yi et al. 2004b), Padova (Marigo et al. 2008) and Geneva (Lejeune & Schaerer 2001) for various ages and metallicities. We obtained the best fitting for ages in the range of 2–4 Gyr and assumed metallicity of $Z = 0.018$.

The location of the two components of FM Leo on the various planes (Fig. 4) suggests an age of about 3 Gyr of the system. We used YONSEI-YALE (Yi et al. 2004b) evolutionary models with improved opacities and equations of state to generate isochrones. Helium diffusion and convective core overshooting have also been taken into consideration during the calculations. We assumed a metallicity of $Z = 0.018$ and α-enhancement of zero.

The location of the components on the mass–log T (Fig. 4a) plane suggests an age of the system in the range of 2.5–4 Gyr; the wide extent is caused by the considerable temperature error. According to the location of the stellar parameters on the mass–log g diagram (Fig. 4b), the 3 Gyr isochrone fits to both components perfectly.

5 CONCLUSIONS

First spectroscopic and new photometric observations of the eclipsing binary FM Leo combined with data from the literature (ASAS photometry) have allowed us to derive definitive orbital parameters and physical properties of the component stars. The orbital and physical analysis is presented for the first time. With the mass and radius of each component of FM Leo determined to better than 1 and 4 per cent, respectively, we compared the observations with current stellar evolution models interpolated for this system. Using several methods with different input parameters and plotting them on various planes, we find that the components are located at the main sequence, with an age of about 3 Gyr. The metallicity of the system is comparable with the solar one.

To confirm the results, we calculated the distance to the system from the determined radius, temperature and apparent magnitude and compared it with the value from *Hipparcos* ($\pi = 8.35 \pm 1.17$ mas, $d = 119.8 \pm 19.5$ pc; Perryman et al. 1997). We estimated the parallax $\pi = 8.55 \pm 2.05$ mas and the distance $d = 130.4 \pm 25.5$ pc to the system. The estimation of reddening was performed by using maps of dust infrared emission by Schlegel, Finkbeiner & Davis (1998). We obtained a colour excess of $E(B - V) = 0.043$. The test confirmed that our estimations are acceptable.

To make radii estimations more precise, new photometric data of times of eclipses are needed. These would open a potential application of a fully characterized FM Leo for tests of evolutionary tracks and isochrones.

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APPENDIX A: RADIAL VELOCITY MEASUREMENTS

Table A1. Single RV measurements for FM Leo.

HJD (245 0000. +)	v_1 (km s^{-1})	σ_{v_1} (km s^{-1})	v_2 (km s^{-1})	σ_{v_2} (km s^{-1})
3853.6735	−61.4142	1.09	84.1333	1.03
3853.6902	−60.5887	1.14	84.1846	1.22
3854.6804	−9.7157	1.04	34.7761	0.95
3854.6978	−7.8169	1.06	32.8196	1.21
3855.6381	55.6258	1.05	−34.00368	1.17
3855.6546	56.9801	1.11	−34.21597	1.21
3856.6581	89.2604	0.96	−64.192	1.32
3856.6740	88.1706	0.95	−64.47747	1.43
3857.6752	60.2235	1.03	−34.6808	0.89
3858.6816	−10.4293	0.88	33.8878	1.35
3858.6975	−12.298	0.96	35.8051	0.97
3859.6785	−61.3133	1.11	83.7468	1.12
3859.6940	−60.947	0.98	85.2303	1.08
4606.354 447	−53.631	0.117	79.604	0.169
4606.380 649	−54.286	0.268	81.256	0.342
4612.364 547	−15.733	0.258	40.693	0.434
4602.344 046	44.082	0.392	−21.850	0.315
4602.372 331	46.661	0.442	−24.969	0.686
4601.345 582	−24.307	0.329	50.360	1.050
4601.371 864	−24.761	0.262	47.36	0.559
4598.359 986	21.701	0.417	3.060	0.244
4598.387 449	18.873	0.371	3.986	0.240
4597.353 753	79.155	0.352	−57.431	0.273
4597.379 573	78.350	0.300	−56.290	0.390
4595.381 744	29.562	0.557	−4.624	0.330
4594.336 033	−40.459	0.698	65.418	0.314
4584.430 998	53.129	0.243	−31.815	0.238
4583.419 625	87.563	0.256	−66.370	0.172
4580.449 742	−57.627	0.154	84.575	0.283
4557.414 037	60.804	0.175	−39.276	0.215

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