6-21-2005

Observational studies of early-type binary stars: MP Centauri

Dirk Terrell

Ulisse Munari

Tomaž Zwitter

George Wolf
Missouri State University

Mon. Not. R. Astron. Soc. **360,** 583–586 (2005) doi:10.1111/j.1365-2966.2005.09046.x

Observational studies of early-type binary stars: MP Centauri

Dirk Terrell,[1★] Ulisse Munari,[2★] Tomaž Zwitter[3★] and George Wolf[4★]

[1]*Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 400, Boulder, CO 80302, USA*
[2]*Osservatorio Astronomico di Padova, Sede di Asiago, I-36032 Asiago (VI), Italy*
[3]*Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia*
[4]*Department of Physics, Astronomy and Materials Science, Missouri State University, Springfield, MO 65804, USA*

Accepted 2005 March 23. Received 2005 March 22; in original form 2005 March 3

ABSTRACT

We present photometric and spectroscopic data on the early-type binary MP Centauri. The photometric data are analysed simultaneously with radial velocities to derive preliminary absolute dimensions for the binary components. Analysis of the spectra shows that the stars rotate synchronously and that the line of sight to the system crosses two kinematically sharp and well-separated interstellar reddening sources. It is shown that MP Cen consists of a B3 primary with $M_1 = 11.4 \pm 0.4\,\mathrm{M}_\odot$, $R_1 = 7.7 \pm 0.1\,\mathrm{R}_\odot$ and a lobe-filling B6–B7 secondary with $M_2 = 4.4 \pm 0.2\,\mathrm{M}_\odot$, $R_2 = 6.6 \pm 0.1\,\mathrm{R}_\odot$.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: early-type – stars: evolution – stars: individual: MP Cen.

1 INTRODUCTION

MP Centauri (HD 308976) is an eclipsing binary, listed in the HD catalogue as having a B3 spectral type. Its orbital period of 2.99 d makes it a very difficult target to obtain complete light curves from a single location in one observing season. It is a member of a rare group: massive eclipsing binaries with short orbital periods. It lies in the Galactic plane ($b = 0\overset{\circ}{.}08, l = 295\overset{\circ}{.}01$) and its eclipsing nature allows for the determination of its absolute parameters and distance, as well as the reddening along the line of sight. We have obtained *uvby* photometry over several years and the system was also observed in V and I_C by the All Sky Automated Survey (ASAS; Pojmanski 2002).

As part of a programme on early-type overcontact and near-contact binaries, we observed MP Cen with the European Southern Observatory (ESO) La Silla 2.2-m telescope and the Fibre-fed Extended Range Optical Spectrograph (FEROS) spectrograph at high resolution ($R = 48\,000$) in 2003 February. Combining radial velocities from these spectra with the *uvby* photometry, and V and I_C data from ASAS, we present the first comprehensive study of this evolved binary.

2 OBSERVATIONS

2.1 Photometry

GW observed MP Cen in 1982 and 1989 using the 24-inch (0.6-m) telescope and single-channel photometers equipped with *uvby* filters at the Mt John Observatory at Lake Tekapo, New Zealand. The comparison star used was HD 102139, for which the SIMBAD data base gives a B4 III spectral type. A 17-arcsec aperture was used and offset slightly to avoid contamination from nearby companions.

The ASAS project has also obtained V and I_C CCD photometry of MP Cen. Because the goal is to survey large areas of the sky, the ASAS setup is not optimal for photometry of stars in crowded fields like MP Cen. However, MP Cen is the brightest object in the measuring aperture and a proper treatment of the third light (l_3) contamination makes it possible to use the ASAS data. The scatter in all passbands was approximately 2 per cent.

2.2 Spectroscopy

Seven ESO 2.2-m + FEROS spectra have been secured, in two groups of three spectra each on 2003 February 23 and 24 near quadratures and a single spectrum on 2004 February 25 in primary eclipse (Table 1). The wavelength range of the spectra extends from 3900 to 9200 Å with $R = 48\,000$ and a 1200-s exposure time. The signal-to-noise ratio (S/N) is evaluated around 5850 Å and the orbital phase is computed with the ephemeris given in Section 3.

Our estimate of the spectral type of the primary, based on the relative intensities of Mg II 4481, He I 4471, C II 4267, He I 4388, He I 4009 and He I 4026, is B3 with an estimated error of one spectral subclass. Because of the relative faintness of the secondary and its lines, it is more difficult to estimate its spectral type, but a value in the range B6 to B7 seems reasonable, based on the ratio of He I 4471 to Mg II 4481, and is consistent with our light-curve solution.

★E-mail: terrell@boulder.swri.edu (DT); munari@pd.astro.it (UM); tomaz.zwitter@fmf.uni-lj.si (TZ); georgewolf@smsu.edu (GW)

Table 1. ESO 2.2 m + FEROS Spectra of MP Cen.

Spectrum number	Date	UT of mid-exposure	S/N	Orbital phase
1440, 1441, 1442	2003 Feb 23	05:40	75	0.28
1552, 1553, 1554	2003 Feb 24	09:15	77	0.66
1632	2003 Feb 25	06:48	85	0.96

2.2.1 Rotational velocity

To derive the rotational velocities we used the relation

$$V_{\rm rot} = 42.42 \times \text{HIW} - 35\,\text{km s}^{-1} \qquad (1)$$

calibrated by Munari & Tomasella (1999) on the width at half maximum (HIW) of He I 5876 Å in high-resolution spectra of O and B stars. The deconvolution of the He I 5876 Å line profile in the MP Cen quadrature spectra gives a HIW of 4.12 Å for the primary and 3.18 Å for the secondary, which corresponds to 140 and 100 km s^{-1}, respectively.

The Munari & Tomasella relation was calibrated using single and thus axially symmetric stars. In previous work on the overcontact binary TU Mus (Terrell et al. 2003), we found that it was necessary to correct the HIW for the distorted shapes of the two stars. The MP Cen primary is reasonably spherical so no correction is necessary, but the secondary is highly distorted so, following the procedure outlined in Terrell et al. (2003), we find that the corrected rotational velocity of the MP Cen secondary is 95 km s^{-1}. The profiles, however, are not indicative of purely rotational broadening, with atmospheric effects and circumstellar activity probably distorting the profile. In the absence of more sophisticated modeling, we see no evidence of asynchronous rotation and thus assume synchronism in the rest of our analysis.

2.2.2 Reddening

Munari & Zwitter (1997) demonstrated a method of using the interstellar Na I and K I lines to estimate the reddening affecting stars, independent of the knowledge of the intrinsic colours. The profile of Na I D1 and D2 lines in our FEROS spectra of MP Cen are shown in Fig. 1 and are clearly composed of at least two components. The seven individual spectra give very consistent results and indicate a value of $E(B - V) = 0.30$. The two-Gaussian mean fit is overplotted on the D2 line in Fig. 1 to show the accuracy of the fit.

The heliocentric radial velocities of the two components are 6.23 ± 0.13 and $23.57 \pm 0.08\,\text{km s}^{-1}$. The accuracy of these velocities is not fictitious because nearby telluric absorptions show the same wavelength stability from one spectrum to the other and it matches the expected high FEROS spectrograph stability, suitable for extrasolar planet searches. The line of sight to MP Cen therefore crosses two kinematically very sharp and well-separated sources of reddening of purely interstellar origin because neither of the components shows a radial velocity change with orbital phase nor shares the systemic velocity of the binary.

The Tycho $B_{\rm T} - V_{\rm T} = 0.13 \pm 0.04$ corresponds, according to Bessell (2000), to a Johnson $(B - V) = 0.11$. We denote an intrinsic (i.e. unreddened) colour by $(B - V)'$ and an observed colour by $(B - V)$ with subscripts 1, 2 and C denoting the primary component, the secondary component and the composite value for the binary respectively. With an assumed intrinsic colour for the primary, $(B - V)'_1$ and the magnitude differences between the two components in each filter, Δm_B and Δm_V, from our light-curve solution, we can compute the intrinsic composite colour of the binary, $(B - V)'_{\rm C}$, as

$$(B - V)'_{\rm C} = (B - V)'_1 - 2.5\ \log\left[\frac{1 + 10^{(-0.4\times\Delta m_B)}}{1 + 10^{(-0.4\times\Delta m_V)}}\right].$$

Assuming a value of $(B - V)' = -0.22$ for the B3 primary (Flower 1996) and the Δm_B and Δm_V values of 1.16 and 1.12 respectively from the light-curve solution, we find $(B - V)'_{\rm C} = -0.21$. This result, combined with the observed $(B - V)_{\rm C}$, yields a reddening of $E(B - V) = 0.32$, in excellent agreement with the results from analysis of the interstellar Na I and K I lines.

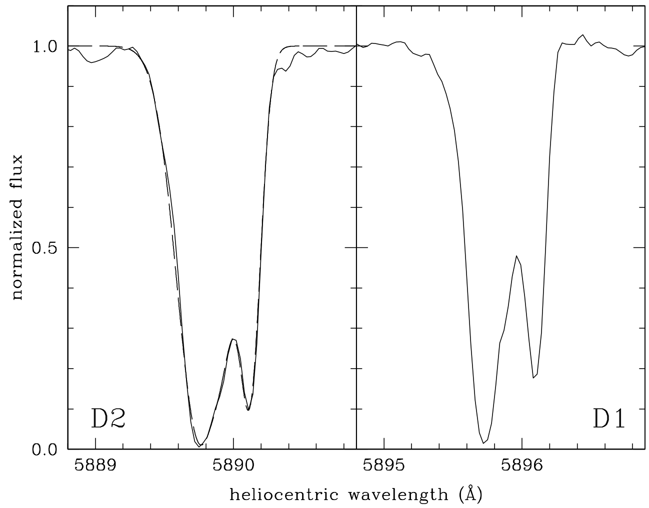

Figure 1. The interstellar lines of Na I, averaged from seven spectra, with the two-component Gaussian fit to the D2 line used in the reddening determination. The similar shape of the D1 line shows that the shape of D2 is not an artefact of noise or atmospheric lines.

2.2.3 Radial velocities

The radial velocities of the MP Cen components have been measured on the two groups of spectra in Table 1 obtained close to quadrature phases. The spectrum taken at orbital phase 0.96 is very close to conjunction and thus has insufficient velocity separation between the two components to obtain reliable radial velocities. Line splitting at quadrature is wide, and allows an easy and firm determination of the radial velocity, as shown for He I 5876 in Fig. 2. The radial velocities have been obtained by Gaussian deconvolution of the profiles into two components, which provide a good overall fit to the observed line profile. The measured lines are He I 4016, 4388, 4471, 5876, 6678, 7065, and half-weight contributions from Hγ, Hβ and Hα. The means of the radial velocities (and associated standard errors) derived from these lines are given in Table 2.

3 DATA ANALYSIS

We performed a simultaneous analysis of the ASAS photometry, our *uvby* photometry and our radial velocities with the 2003 version of the Wilson–Devinney (Wilson & Devinney 1971; Wilson 1979, 1990; hereafter WD) program. As we had limited telescope time available to us for spectroscopy, we could not obtain as many radial velocities as we would have liked and, therefore, we present our solution as preliminary until more extensive spectroscopic observations can be made. However, our spectra are of high quality and resolution, giving us confidence that our results are reliable and

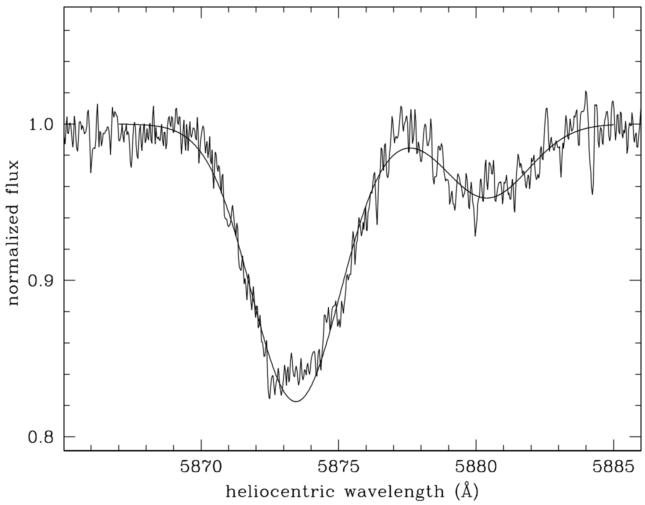

Figure 2. The He I 5876 profile of MP Cen for the averaged February 24 spectra. The overplotted curve is the fit of two gaussians at the radial velocities of the two components given in Table 2.

Table 2. Heliocentric radial velocities of MP Cen.

Spectra	Phase	Primary (km s^{-1})	Secondary (km s^{-1})
1440–1442	0.28	-97.4 ± 2.7	$+256.0 \pm 4.8$
1552–1554	0.66	$+88.6 \pm 2.3$	-216.9 ± 3.3

certainly better than a solution based solely on the photometry. We have shown previously that our velocities for TU Mus (Terrell et al. 2003), obtained in the same observing run as the MP Cen spectra, were in excellent agreement with earlier data from Andersen & Grønbech (1975).

We also performed tests of our solution results by generating 1000 sets of synthetic radial velocities with Gaussian errors based on our four velocities and their estimated errors. We solved each set of four velocities, and found that the average and standard deviation of each parameter was consistent with the results of our full solution. In particular, the average value of the semimajor axis of the relative orbit, of critical importance in determining the absolute dimensions of the binary, was $21.9 \pm 0.2\,R_\odot$, matching exactly the result from the full solution.

WD now uses Kurucz (1993) stellar atmospheres to model the radiation from the stars. WD can also use either binary orbital phase or time as the independent variable (Wilson & Terrell 1998). In order to investigate possible changes in the orbital period, we used time as the independent variable, and adjusted the orbital period (P), its first time derivative ($\dot{P}$) and the reference epoch (HJD_0). We began our light-curve fitting experiments in mode 2 of WD, appropriate for detached binaries (Leung & Wilson 1977), but found that a semidetached configuration with the secondary filling the lobe was required to fit the observations, so we continued our analysis in mode 5 of WD.

Other parameters adjusted in the simultaneous solution were the semimajor axis of the relative orbit (a), the binary centre of mass radial velocity (V_γ), orbital inclination (i), secondary mean effective temperature (T_2), modified surface potential of the primary (Ω_1), mass ratio (q) and the bandpass-specific luminosity of the primary (L_1). Certain parameters, such as the bolometric albedos and gravity brightening exponents, were held fixed at their expected theoretical values. The logarithmic limb darkening law was used with coefficients from Van Hamme (1993). The mean effective temperature of the primary was set to 18 750 K based on the B3 spectral type (Bessell, Castelli & Plez 1998). Data set weights were determined by the scatter of the observations.

Table 3. Parameters of MP Cen.

Parameter	Value
a	$21.9 \pm 0.2\,R_\odot$
V_γ	2.7 ± 1.7 km s^{-1}
i	$82\overset{\circ}{.}2 \pm 0\overset{\circ}{.}2$
T_1	18 750 K
T_2	$12\,390 \pm 50$ K
Ω_1	3.29 ± 0.03
q	0.390 ± 0.008
HJD_0	$244\,7627.9453 \pm 0.0006$
P	$2.993\,456 \pm 0.000\,001$ d
$\dot{P}$	$8.7 \times 10^{-9} \pm 6.1 \times 10^{-10}$
$L_1/(L_1 + L_2)_u$	0.83 ± 0.01
$L_1/(L_1 + L_2)_v$	0.76 ± 0.01
$L_1/(L_1 + L_2)_b$	0.75 ± 0.01
$L_1/(L_1 + L_2)_y$	0.74 ± 0.01
$L_1/(L_1 + L_2)_V$	0.74 ± 0.01
$L_1/(L_1 + L_2)_I$	0.72 ± 0.01
$l_3(V)$	0.04 ± 0.02
$l_3(I)$	0.05 ± 0.02
$l_3(uvby)$	0.00 ± 0.02
R_1	$7.7 \pm 0.1\,R_\odot$
R_2	$6.6 \pm 0.1\,R_\odot$
M_1	$11.4 \pm 0.4\,M_\odot$
M_2	$4.4 \pm 0.2\,M_\odot$
$\log L_1/L_\odot$	3.8 ± 0.2
$\log L_2/L_\odot$	3.0 ± 0.2
$\log g_1$	3.7 ± 0.2
$\log g_2$	3.4 ± 0.2

Quoted errors are formal 1σ errors from the solution. l_3 values are in units of total system light at phase 0.25. Luminosity errors are estimates based on an uncertainty of 2000 K in the effective temperature of the primary. The error contributions to the luminosities due to the errors in the radii are more than an order of magnitude smaller. The $\log g$ values are in cgs units.

Given the large apertures used in the ASAS photometry and the moderately crowded field around MP Cen, we adjusted third light and found statistically significant values for the ASAS data but not our *uvby* photometry. Images of the MP Cen field show two companions to the north-east approximately 13 arcsec away. These stars fit within the ASAS aperture but were avoided in our *uvby* photometry.

Table 3 shows the results of the simultaneous solution, and Figs 3 and 4 show the fits to the Strömgren and ASAS data respectively. Fig. 5 shows the fits to the radial velocities. The light curves show some disturbances, particularly at the maximum preceding primary eclipse, as expected if a mass transfer stream from the secondary is impacting the primary.

The ASAS data show that the system has $V = 9.95$ and, with the third light correction from our light-curve solution, $V = 9.99$ for the binary at maximum brightness. Correcting this value for the reddening [assuming a ratio of total to selective absorption of $R_V = 3.1$ and our $E(B - V) = 0.30$], we find that the apparent V magnitude of the binary is 9.08. Using the V luminosity ratio $L_2/L_1 = 0.36$ from our light-curve solution, this transforms into

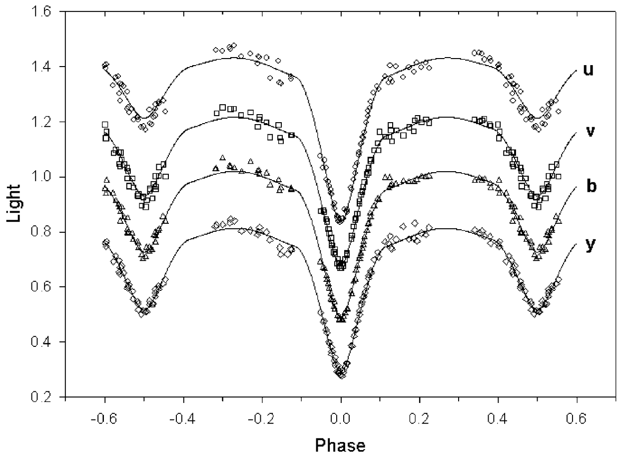

Figure 3. The Strömgren photometry and computed light curves.

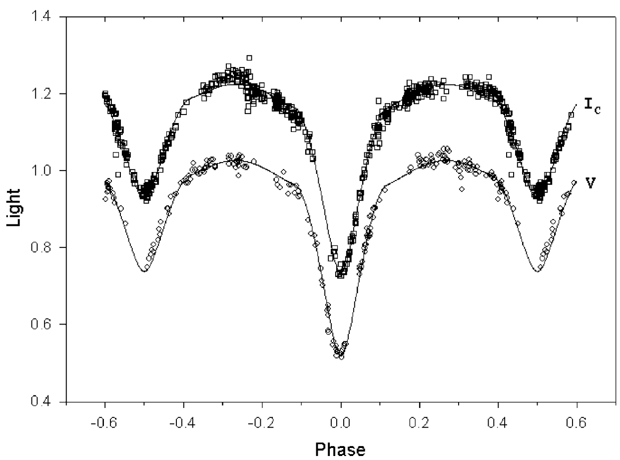

Figure 4. The ASAS V and I_C photometry and computed light curves.

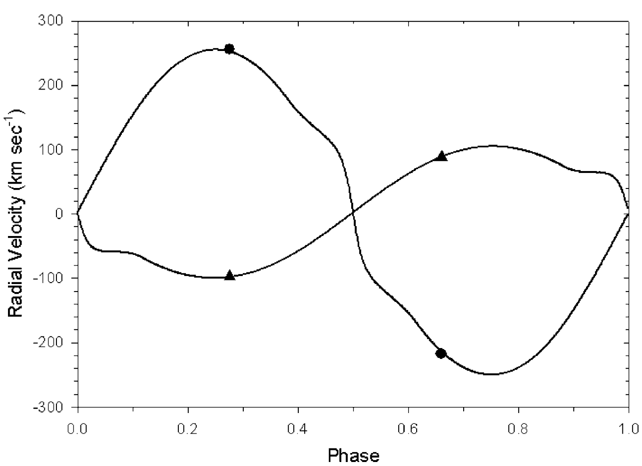

Figure 5. The observed radial velocities and computed curves.

Johnson V magnitudes of $V_1 = 9.41$ and $V_2 = 10.53$. With our log luminosity of $3.8\,L_\odot$ for the primary, the distance to the primary amounts to 3.0 kpc using a bolometric correction of -1.75 from Flower (1996). The same calculation for the secondary results in the same distance. We therefore adopt 3.0 kpc as the distance to MP Cen, placing it on the far side of the Sagittarius arm.

MP Cen lies in the Galactic plane and we can compare our estimate of the reddening with the Neckel & Klare (1980) extinction maps. MP Cen lies at the boundary of four cells (294/−1, 296/−1, 297/0 and 292/2). Given the low resolution of the cell boundaries, we cannot unambiguously assign MP Cen to a particular cell. Our value of $E(B - V) = 0.30$ leads to $A_V = 0.93$. Looking at the individual cells, we find:

(i) 294/−1, the distance is greater than 1 kpc;
(ii) 296/−1, the distance could be as high as 4 kpc;
(iii) 297/0, distances from 1 to 4 kpc are supported;
(iv) 292/2, distances from 0.5 to 4 kpc are supported.

Thus, the Neckel & Klare (1980) maps do not provide a conclusive comparison with our derived distance, but their fig. 9 supports the idea that the line of sight to MP Cen goes through clouds A and G, and just misses clouds L, M and R.

4 CONCLUSIONS

We have presented preliminary values for the parameters of MP Cen based on photometry and limited spectroscopic data. The masses and radii of the stars, along with the semidetached configuration, indicate that the system is evolved. The radii, $R_1 = 7.7\,R_\odot$ and $R_2 = 6.6\,R_\odot$, are consistent with a giant or subgiant classification for both stars for the derived masses of $M_1 = 11.4\ M_\odot$ and $M_2 = 4.4\,M_\odot$. The $\dot{P}$ we have measured implies a conservative mass transfer rate of $1.1 \times 10^{-7}\ M_\odot\ yr^{-1}$, making it a fairly active system. Light-curve variations from season to season, most likely arising from this mass transfer activity, are apparent in the photometric data. We also see emission features in our spectra but the limited phase coverage of the spectra makes any discussion of the circumstellar environment little more than speculation at this point. More extensive spectroscopy and polarimetry will be required to fully map the circumstellar environment of the system.

ACKNOWLEDGMENTS

This research has made use of the SIMBAD data base, operated at the Centre de Données astronomiques de Strasbourg (CDS), France.

REFERENCES

Andersen J., Grønbech B., 1975, A&A, 45, 107
Bessell M. S., 2000, PASP, 112, 961
Bessell M. S., Castelli F. B., Plez B., 1998, A&A, 333, 231
Cox A. N., 2000, Allen's Astrophysical Quantities. Am. Inst. of Phys., New York
Flower P. J., 1996, ApJ, 469, 355
Kurucz R. L., 1993, in Milone E. F., ed., Light Curve Modeling of Eclipsing Binary Stars. Springer-Verlag, New York, p. 93
Leung K. -C., Wilson R. E., 1977, ApJ, 211, 853
Munari U., Tomasella L., 1999, A&A, 343, 806
Munari U., Zwitter T., 1997, A&A, 318, 269
Neckel T., Klare G., 1980, A&AS, 42, 251
Pojmanski G., 2002, Acta Astron., 52, 397
Terrell D., Munari U., Zwitter T., Nelson R. H., 2003, AJ, 126, 2988
Van Hamme W., 1993, AJ, 106, 2096
Wilson R. E., 1979, ApJ, 234, 1054
Wilson R. E., 1990, ApJ, 356, 613
Wilson R. E., 2001, Inf. Bull. Variable Stars, No. 5076
Wilson R. E., Devinney E. J., 1971, ApJ, 166, 605
Wilson R. E., Terrell D., 1998, MNRAS, 296, 33

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