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ASTRONOMY AND ASTROPHYSICS

Absolute dimensions of eclipsing binaries

XIV. UX Mensae★

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Summary. New spectroscopic orbits for the 4-day, F8 V eclipsing binary UX Mensae have been determined from CORAVEL photoelectric radial-velocity observations. The masses are $1.24\,M_\odot$ and $1.20\,M_\odot$, with errors of only $\pm 0.5\%$. The new spectroscopic data have been used in a reanalysis of the *uvby* light curves by Clausen and Grønbech (1976). This analysis completely confirms their earlier results, but with much improved reliability. It also permits a reliable determination of the linear limb darkening coefficients. The rotation of both stars is found to be synchronous to very high precision. Finally, the metal abundance of UX Men has been determined from high-resolution CCD spectra to be [Fe/H] $= +0.04 \pm 0.10$, consistent with that derived from the *uvbyβ* indices.

Accurate absolute dimensions are computed for UX Men and show that it is only slightly evolved ($\log g \sim 4.3$). Theoretical evolutionary sequences for the masses and metal abundance of UX Men ($Z = 0.019 \pm 0.004$) have been interpolated from new models by VandenBerg (1988) and Andersen et al. (1988). A detailed comparison shows that models of solar helium abundance ($Y = 0.27 + 0.01$) provide a very satisfactory fit to the observations for an age of $(2.7 \pm 0.3)\,10^9$ yr, the main uncertainty in the comparison being due to that of the observed metal abundance.

Key words: eclipsing binary – spectroscopic binary – stellar masses – stellar radii – stellar evolution

1. Introduction

Binary stars for which masses, radii, luminosities, and metal abundance are accurately determined can be used to critically test theoretical models of stellar evolution, as demonstrated most recently for the evolved system AI Phe by Andersen et al. (1988; hereinafter ACGNV). It was noticed in that paper that the younger main-sequence system UX Mensae had very similar masses as AI Phe, but apparently a different metal abundance. The present paper refines the comparison of UX Men with theoretical models, based on new, accurate observational data.

UX Men (HD 37513, $\alpha_{1950} = 5^h32^m\!.0$, $\delta_{1950} = -76°17'$, $l = 287\!.^\circ8$, $b = -31\!.^\circ1$, $m_v = 8.2$, $P = 4\!.^d18$) is a late F-type (F8 V, Houk and Cowley, 1975), double-lined eclipsing binary. It is among the least-evolved such stars in Popper's (1980) review of reliable stellar mass and radius determinations, based on Imbert's (1974) spectroscopic orbits and the *uvby* light curve analysis by Clausen and Grønbech (1976; hereinafter CG). When the photoelectric radial-velocity scanner CORAVEL became available in the southern hemisphere, we decided to reobserve the system in order to refine Imbert's result, which was based on only 8 double-lined spectrograms at a dispersion of 20 Å mm^{-1}. Moreover, the CORAVEL data could help resolve the indeterminacy encountered by CG regarding the element k, the ratio of the radii, and thus improve the accuracy of the individual radii. Finally, we have determined the metal abundance of UX Men from high-resolution, high-S/N spectra so that all the main observable parameters needed for theoretical modelling of the system are now known (the last, unobservable quantity being the helium abundance).

As discussed in Sect. 5.3, this new set of observational data for UX Men demonstrates, as was done for the older, lower-metallicity system AI Phe by ACGNV, the excellent precision to which VandenBerg (1983, 1985) models are able to reproduce all observable parameters of the real stars while retaining the helium abundance at the solar value.

2. The new CORAVEL data

From October, 1982, through September, 1985, a total of 60 observations of UX Men were obtained with the photoelectric radial-velocity scanner CORAVEL (Baranne et al., 1979; Mayor, 1985), attached to the Danish 1.5-m Ritchey-Chrétien reflector at ESO, La Silla, Chile. The two components were observed separately; 29 observations were made of star A, the more massive and luminous component which is eclipsed at primary eclipse, and 31 observations of the secondary (B) component. Integration times of the order of 5 min were sufficient to accumulate some $2\,10^4$ counts per channel in the cross-correlation profile and define the radial velocity to a precision of ± 0.5–1.0 km s^{-1}. The observations, phased with the CG ephemeris:

$$\text{Min. I} = \text{HJD}\,2\,441\,984\!.^d64388 + 4\!.^d181100 \cdot E \qquad (1)$$

are listed in Table 1 together with their estimated mean errors. These estimates take into account both photon shot noise,

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★Based on observations made with the Danish and ESO telescopes at European Southern Observatory, La Silla, Chile.

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Table 1. Radial velocity observations ($km\,s^{-1}$) of UX Men

UX Men A					UX Men B				
HJD	Phase	Vel.	m.e.	(O-C)	HJD	Phase	Vel.	m.e.	(O-C)
45270.8031	0.9557	69.5	0.7	-2.9	45270.8340	0.9630	27.9	0.7	0.1
45271.7871	0.1910	-33.4	0.9	-0.3	45271.7910	0.1919	133.6	1.0	0.7
45272.8076	0.4351	13.0	0.7	-0.7	45272.8105	0.4358	83.8	0.7	-0.2
45273.7959	0.6715	126.3	1.2	0.9	45273.7998	0.6724	-29.8	1.0	1.4
45275.7881	0.1479	-20.6	0.8	1.1	45275.7920	0.1489	120.4	1.1	-0.8
45276.7939	0.3885	-8.8	0.8	-0.8	45276.7969	0.3892	106.2	0.9	-0.3
45277.7891	0.6265	111.0	0.9	0.2	45277.7930	0.6274	-17.3	0.9	-1.0
45660.6592	0.1981	-34.3	0.8	0.1	45660.6543	0.1970	135.8	0.9	1.9
45660.7012	0.2082	-36.6	0.5	-0.6	45660.6963	0.2070	135.2	0.6	-0.4
45660.7900	0.2294	-39.3	0.5	-1.0	45660.7871	0.2287	138.7	0.5	0.7
45662.7373	0.6952	132.0	0.5	1.4	45662.7344	0.6945	-35.5	0.6	0.8
45662.7881	0.7073	132.5	0.6	-0.2	45662.7842	0.7064	-38.9	0.6	-0.5
45662.8359	0.7187	135.2	0.5	1.1	45662.8320	0.7178	-39.8	0.6	0.1
45662.8770	0.7286	135.4	0.6	0.4	45662.8730	0.7276	-40.2	0.6	0.6
45664.7090	0.1667	-26.2	0.5	1.1	45664.7051	0.1658	125.6	0.5	-0.9
45664.7939	0.1870	-30.6	0.5	1.7	45664.7900	0.1861	132.3	0.5	0.6
45665.7031	0.4045	-2.2	0.5	-1.2	45665.6982	0.4033	100.8	0.6	0.7
45666.7109	0.6455	117.9	0.6	0.3	45666.7070	0.6446	-22.6	0.5	0.0
45666.8027	0.6675	123.6	0.5	-0.7	45666.7959	0.6659	-29.3	0.5	0.1
45667.7354	0.8906	103.6	0.5	-0.3	45667.7314	0.8896	-10.4	0.6	-1.2
45667.8770	0.9244	86.9	0.6	-1.4	45667.8740	0.9237	7.3	0.6	0.4
45668.6953	0.1201	-10.8	0.5	0.7	45668.6914	0.1192	110.4	0.6	0.4
45669.7012	0.3607	-18.5	0.5	0.2	45668.8770	0.1636	124.2	0.6	-1.7
46102.5732	0.8914	103.0	0.6	-0.5	45669.6973	0.3598	118.1	0.5	-0.1
46105.6543	0.6283	113.3	0.5	1.9	46102.5664	0.8897	-10.1	0.8	-1.0
46106.5352	0.8390	121.3	0.5	-1.2	46105.5137	0.5947	-1.5	0.6	0.5
46106.6592	0.8686	112.5	0.4	-0.1	46105.6582	0.6292	-16.7	0.5	0.3
46335.8848	0.6929	130.5	0.9	0.3	46106.5303	0.8378	-28.5	0.6	-0.2
46336.8545	0.9248	87.4	0.9	-0.8	46106.6533	0.8672	-19.0	0.5	-0.7
					46335.8877	0.6935	-36.6	0.9	-0.5
					46336.8574	0.9255	9.4	0.9	1.6

Table 2. Spectroscopic orbital elements of UX Men. σ is the standard deviation of an observation of average weight

Element	This study	Imbert (1974)
K_A ($km\ s^{-1}$)	87.41±0.25	84.4±0.9
K_B ($km\ s^{-1}$)	90.28±0.17	89.4±1.2
γ_A ($km\ s^{-1}$)	48.38±0.20	48.5±0.5
γ_B ($km\ s^{-1}$)	48.56±0.14	$\gamma_B = \gamma_A$
e	Fixed = 0	0.024±0.01
σ_A ($km\ s^{-1}$)	1.1	
σ_B ($km\ s^{-1}$)	0.8	
M_B/M_A	0.968±0.003	0.944±0.016
$a\sin i$ ($R_\odot$)	14.678±0.025	14.36±0.12
$M_A \sin^3 i$ ($M_\odot$)	1.238±0.006	1.173±0.034
$M_B \sin^3 i$ ($M_\odot$)	1.198±0.007	1.107±0.028

scintillation, and instrumental errors as detailed in Baranne et al. (1979) and Andersen et al. (1985b).

Least-squares solutions for the orbital elements were first made with Sterne's (1941) simplified formulae for the case of small eccentricities. In fact, the eccentricity indicated by the departure of secondary eclipse from phase 0P5 is small enough (CG) to be negligible in the determination of the spectroscopic orbital elements, but independent evidence on the value of $e\sin\omega$ would be useful in the photometric analysis. We found $e\cos\omega = 0.0024 \pm 0.0023$, $e\sin\omega = -0.0043 \pm 0.0034$. The orbital elements given in Table 2 assume $e = 0.000$; including $e\cos\omega$ and $e\sin\omega$ as unknowns changes the values of γ and K by less than 10% of their mean errors. The ephemeris (1) was found to require no correction and was kept fixed in the solutions. The observations were weighted as the inverse square of the individual mean errors given in Table 1, but substituting, e.g., equal weights for all observations has negligible effect on the resulting elements. The fit to the observed velocities is shown by the $(O-C)$ columns of Table 1 and in Fig. 1.

As Table 2 shows, we find masses which are somewhat ($\sim 7\%$) higher than those determined by Imbert (1974), but only by about two of his standard deviations (the value of $M_B \sin^3 i$ in his paper contains a misprint, which is corrected in Table 2). The accuracy of the new elements is, naturally, much better, due to the increase in both the number and precision of the radial velocity observations. It is a remarkable coincidence that *both* stars in UX Men have masses identical to those of their counterparts in AI Phe (ACGNV) to within $\pm 0.1\%$. We note that Imbert's value for the γ-velocity of UX Men agrees very well with ours; the discrepancy noted in the case of AI Phe is not seen in UX Men.

The mean observed width of the cross-correlation profile and the calibrations of Benz and Mayor (1981, 1984) yield mean rotational velocities of $v\sin i_A = 16.4 \pm 0.3\ km\,s^{-1}$, $v\sin i_B = 15.1 \pm 0.3\ km\,s^{-1}$, where the errors given correspond to the observational errors only. Uncertainty in the actual value of the turbulence velocity leads to a more conservative error estimate of $\pm 1\ km\,s^{-1}$. The rotational velocities computed from our final spectroscopic and photometric orbital elements under the assumption of synchronism are: $16.3 \pm 0.2\ km\,s^{-1}$ (A) and $15.4 \pm 0.2\ km\,s^{-1}$ (B), in rather spectacular agreement with the observed rotations.

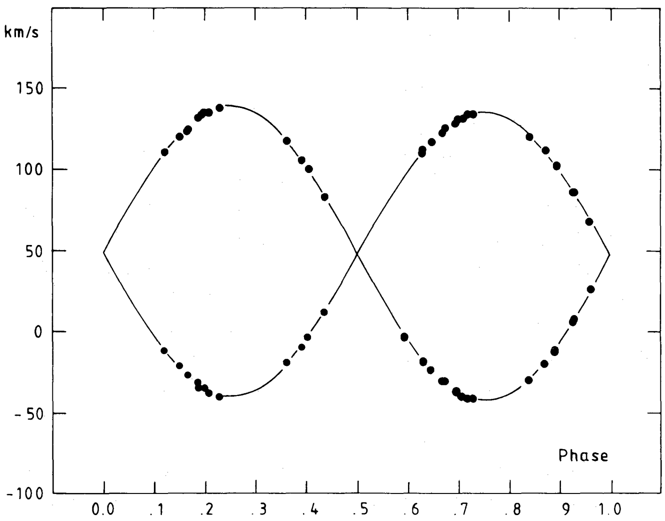

Fig. 1. Observed and computed radial velocity curves for UX Men

The luminosity ratio between the two components can be derived from the ratio of the equivalent widths of the two individual cross-correlation profiles; the observed mean value of this ratio is $W_B/W_A = 0.86 \pm 0.03$. From the $b-y$ indices of the two stars, a relation between $b-y$ and the Geneva photometric index $B_2 - V_1$ (e.g., Hauck, 1985), and the relation between $B_2 - V_1$ and the intrinsic equivalent width of the cross-correlation profile for solar-metallicity dwarfs by Mayor (1980), we can estimate an intrinsic $W_B/W_A = 1.02 \pm 0.01$. As the observed equivalent width ratio is the product of this ratio and the luminosity ratio of the two components, we find the latter to be $L_B/L_A = 0.84 \pm 0.03$.

3. Reanalysis of the light curves

uvby light curves containing 334 points in each colour and with both minima well covered were observed and analysed by CG.

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Due to the similarity of the components, they were unable to determine a precise value of k, the ratio of the radii, since no external constraint on the luminosities was available (cf. Andersen et al., 1980). $k=0.95$ was adopted, but the fit was essentially equally good for all values of k in the range 0.90–1.00.

The CG analysis contained a few other inconsistencies of minor importance: A value of $e\cos\omega=0.001$ was determined, but $e\sin\omega=0.000$ was assumed throughout, in slight disagreement with the spectroscopic result $e=0.024\pm0.01$ found by Imbert (1974). Moreover, possible correlations between k and $e\sin\omega$ were not studied in detail (see, e.g. Andersen et al., 1985a). Finally, the limb darkening coefficients were kept at the theoretical values by Grygar et al. (1972), which most probably need some revision (Wade and Rucinski, 1985). An empirical determination of the limb darkening coefficients was not attempted, although the geometry of UX Men is in fact favourable for this purpose: The relative radii are small and almost identical, and the inclination of the orbit is close to 90° (see e.g. Andersen et al., 1984).

We now have spectroscopic information on the luminosity ratio between the components, as well as on the eccentricity and orientation of the orbit (Sect. 2). Although the values of k and e chosen by CG are supported *a posteriori* by these data, we decided to reanalyse the CG *uvby* light curves on the background of the extensive experience accumulated in the intervening decade.

We have used the Nelson-Davis-Etzel (NDE) model (Popper and Etzel, 1981) in the photometric analysis, as it is economical, convenient, and quite adequate to yield reliable elements for a well-detached system like UX Men. The mass ratio was fixed at 0.968 (Table 2), and no third light was assumed. Reflection and gravity-brightening effects are very small in UX Men, and we have adopted the simple bolometric NDE-model for reflection as well as appropriate gravity-brightening coefficients for atmospheres in radiative equilibrium (Martynov, 1973). An integration ring size of 5° was chosen, and a phase zero-point correction as well as a photometric scale factor were included as free parameters. All observations were used in the solutions, and the four light curves were studied independently.

As a first step, $e\cos\omega$ was determined to be 0.00083 ± 0.00007; this value was then used in the following. Due to a strong correlation between k and $e\sin\omega$, the solutions become unstable when both are included as free parameters in the iterative least squares procedure. We have therefore solved the light curves for a number of fixed values of $e\sin\omega$ between -0.0050 and 0.0100. Acceptable solutions were obtained in the range $-0.0025<e\sin\omega<+0.0075$, which is still compatible with the spectroscopic result $e\sin\omega=-0.0043\pm0.0034$. As expected for two main-sequence stars, primary eclipse is a transit (~90% of the flux of star A eclipsed), while secondary is an almost total occultation (~99% of star B eclipsed).

The photometric elements obtained from the four light curves for $e\sin\omega=0.0025$ are given in Table 3. As will be seen, the results for i, r_A and k agree very well. Linear limb darkening coefficients (assumed to be identical for the two stars) are found to be slightly lower in all colours than the theoretical values by Wade and Rucinski (1985). The luminosity ratio between the components is close to the spectroscopic result, which is based on average line strength ratios in the v, b wavelength range.

Mean elements for a number of values of $e\sin\omega$ within the acceptable range are presented in Table 4; the corresponding changes in k and i are clearly rather small. We note, moreover,

Table 3. Solutions for the four light curves of UX Men. $e\sin\omega=0.0025$ has been assumed

	u	*v*	*b*	*y*
i	89°55 ±10	89°63 ± 9	89°63 ±10	89°57 ± 7
$e\sin\omega$	0.0025	0.0025	0.0025	0.0025
$e\cos\omega$	0.00083	0.00083	0.00083	0.00083
r_A	0.0913 ± 10	0.0919 ± 7	0.0922 ± 7	0.0918 ± 7
k	0.947 ± 20	0.944 ± 14	0.944 ± 14	0.951 ± 19
r_B	0.0865	0.0868	0.0867	0.0873
$u_A = u_B$	0.68 ± 5	0.66 ± 3	0.58 ± 3	0.49 ± 3
$y_A = y_B$	1.70	1.44	1.26	1.09
J_B/J_A	0.904 ± 7	0.923 ± 5	0.941 ± 5	0.947 ± 5
L_B/L_A	0.810 ± 40	0.822 ± 29	0.831 ± 29	0.855 ± 39
σ (mag)	0.0100	0.0078	0.0070	0.0070

Table 4. Mean photometric elements for UX Men for different assumptions on $e\sin\omega$. $e\cos\omega=0.00083$ has been used throughout. Surface flux ratios and luminosity ratios refer to the mean elements

$e\sin\omega$	-0.0025	0.0000	0.0025	0.0050	0.0075
i	89°70	89°67	89°60	89°54	89°51
r_A	0.0924	0.0922	0.0918	0.0912	0.0905
k	0.933	0.936	0.946	0.958	0.972
$r_A + r_B$	0.1786	0.1786	0.1786	0.1786	0.1785
$u_A = u_B$ (y)	0.49	0.49	0.49	0.49	0.49
$u_A = u_B$ (b)	0.57	0.57	0.58	0.58	0.58
$u_A = u_B$ (v)	0.66	0.66	0.66	0.66	0.66
$u_A = u_B$ (u)	0.67	0.68	0.68	0.67	0.67
J_B/J_A (y)	0.956	0.953	0.948	0.943	0.939
J_B/J_A (b)	0.947	0.944	0.939	0.934	0.929
J_B/J_A (v)	0.930	0.927	0.922	0.917	0.916
J_B/J_A (u)	0.913	0.909	0.905	0.899	0.894
L_B/L_A (y)	0.831	0.834	0.848	0.866	0.887
L_B/L_A (b)	0.824	0.826	0.840	0.857	0.878
L_B/L_A (v)	0.809	0.812	0.825	0.841	0.866
L_B/L_A (u)	0.794	0.796	0.810	0.825	0.845

that both the sum of the relative radii and the linear limb darkening coefficients are insensitive to the assumed value of $e\sin\omega$ (or k). The geometry of UX Men, with its almost central eclipses and practically spherical components of near-identical radii and temperatures, thus permits a reliable determination of the limb darkening coefficients (within about ±0.05). As for another F-type system studied by us, DM Vir (Andersen et al., 1984), our empirically determined coefficients are about 0.10 below the theoretical results.

Combining now the constraints on the photometric elements from the three available sources – the light curve analysis, the spectroscopic luminosity ratio, and the spectroscopic result for $e\sin\omega$ – we see that k must be between 0.93 and 0.97. Giving

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lowest weight to the latter constraint, we adopt $e\sin\omega = 0.025$ (or, equivalently, because of their correlation, $k = 0.95$) for the final elements, which are presented in Table 5 together with our estimate of realistic mean errors for the parameters. The relative radii – in perfect agreement with those found by CG – are determined to an accuracy of about 1%. Our more elaborate treatment of the linear limb darkening coefficients yields a slight upwards revision of i by 0°2. From the empirical flux scale by Popper (1980), we find the y flux ratio in UX Men (0.947) to correspond to a temperature difference between the components of about 80 K, in fair agreement with that derived from the *uvby* indices of the two components (Table 7).

4. Metal abundance

From their *uvby* indices of UX Men, CG found its metal abundance to be [Fe/H] = −0.15, very close to that determined spectroscopically for AI Phe by ACGNV. As discussed in that paper, the close similarity of the components of UX Men and AI Phe then suggests that UX Men should fit the same two theoretical evolutionary tracks which were found to reproduce the observed properties of AI Phe with remarkable precision. However, the (preliminary) temperatures then available for UX Men were significantly lower than those of the models in similar evolutionary phases. Hence, the prediction was made that UX Men is in fact *more* metal-rich than the Sun, with [Fe/H] perhaps as high as +0.15. We have obtained high-resolution CCD spectra of UX Men in order to test that prediction.

UX Men was observed on January 22 and 23, 1988 (UT; JD 47182.63 and 47183.63, phases 0P21 and 0P45, respectively) with the ESO Coudé Echelle Spectrometer (CES) fed by the 1.4-m Coudé Auxiliary Telescope (CAT). An RCA SID 503 double-density, thinned, back-illuminated CCD detector (ESO CCD #8) with 660 × 1024 15 × 15-μm pixels was employed at the short-focus spectrograph camera, giving an effective resolution $\lambda/\Delta\lambda \approx 60\,000$; integration times were about 45 min. The spectra were bias subtracted, flat-field corrected, and wavelength calibrated in the usual manner. The final S/N ratio in the continuum is about 200, and the spectral range covered in each exposure is about 50 Å.

Table 5. Adopted photometric elements for UX Men

i	89°60±0.10
$e\sin\omega$	0.0025±0.0050
$e\cos\omega$	0.00083±0.00007
e	$0.0026^{+0.005}_{-0.002}$
k	0.946±0.015
$r_A + r_B$	0.1786±0.0009
r_A	0.0918±0.0009
r_B	0.0868±0.0009

	u	v	b	y
$u_A = u_B$	0.68 ± 5	0.66 ± 5	0.58 ± 5	0.49 ± 5
J_B/J_A	0.905 ± 8	0.922 ± 8	0.939 ± 8	0.948 ± 8
L_B/L_A	0.810 ± 30	0.825 ± 30	0.840 ± 30	0.848 ± 30

The choice of a suitable spectral region proved to be far from easy, due to the significant rotational broadening of the lines and to blending of the double lines caused by the orbital motion. Hence, very weak lines cannot be measured with adequate precision, while strong lines are to be avoided in accurate abundance determinations. We finally decided on the regions λλ 5830–5880 (Jan. 22; used also in AI Phe) and λλ 6797–6850 (Jan. 23). Equivalent widths were measured for a number of unblended (and mostly high-excitation) Fe I lines in these spectra of UX Men, as well as in observations of the same characteristics of the spectrum of the Sun, as reflected off the white dome of the ESO 3.6-m telescope.

Table 6 summarizes our data for the Fe I lines in UX Men. The oscillator strengths were determined from our solar spectra, assuming a solar logarithmic iron abundance of 7.68 (on the usual scale where $\log N_H = 12.00$) and damping widths increased by a factor 2 over the value given by the classical Unsöld formula. The equivalent widths measured for each line component in UX Men have been corrected for the continuum contribution from the companion, using the previously determined luminosity ratio. The (LTE) model atmospheres for the Sun and both components of UX Men were taken from the grid by Magain (1983), which was computed with a version of the Gustafsson et al. (1975) programme. The microturbulent velocities were chosen according to Nissen's (1981) formula, leading to values of 1.14, 1.50, and 1.44 km s^{-1} for the Sun, UX Men A, and UX Men B, respectively. The stellar effective temperatures were determined from the $b-y$ and β indices (Table 7), using the calibrations of Popper (1980), Saxner and Hammarbäck (1985), and Magain (1987), for the appropriate metal abundance. We adopt mean effective temperatures of 6200 and 6150 K for UX Men A and B, respectively (cf. discussion in 5.1).

Table 6. Analysis of Fe I lines in UX Men. Equivalent widths are corrected for continuum contribution from the companion star

			UX Men A		UX Men B	
λ (Å)	χ (eV)	log *gf*	*W*(mÅ)	[X/H]	*W*(mÅ)	[X/H]
5852.22	4.55	-1.38	41	+0.15	-	-
6806.85	2.73	-3.23	21	-0.13	27	-0.01
6810.26	4.61	-1.15	45	+0.01	54	+0.16
6820.37	4.64	-1.33	32	+0.01	35	+0.01
6828.59	4.64	-1.01	52	+0.02	60	+0.14
6843.65	4.55	-1.01	-	-	60	+0.07

Table 7. Combined and individual *uvbyβ* indices for the components of UX Men (dereddened $b-y$ values in parentheses)

	Phase 0P20	Star A	Star B
V	8.22 ± 0.01	8.89	9.07
$b-y$	0.363 ± 0.005	0.359 (0.337)	0.368 (0.346)
m_1	0.167 ± 0.005	0.161	0.174
c_1	0.369 ± 0.005	0.371	0.367
β	2.623 ± 0.010		
$E(b-y)$	0.02 ± 0.02		

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Table 6 gives the abundances derived from the individual Fe I lines measured in UX Men, line components affected by blending having been rejected. The mean logarithmic abundances and their formal errors (s.d.m.) for the two components are [Fe/H] = 0.00 ± 0.05 (A) and $+0.07 \pm 0.03$ (B). The actual uncertainties, taking into account likely errors in the adopted temperatures, surface gravities, and microturbulent velocities, as well as possible departures from local thermodynamical equilibrium are, of course, larger, probably of the order of ± 0.1 dex. Our final result for the metal abundance of UX Men is, therefore, [Fe/H] = +0.04 ± 0.1 dex, translating to $Z = 0.019 \pm 0.004$ for an assumed $Z_{\odot} = 0.0169$ (VandenBerg, 1985).

Our spectroscopic determination of [Fe/H] is marginally consistent with the result [Fe/H] = −0.15 derived by CG from their *uvby* indices, assuming no reddening. Our new *uvbyβ* indices as listed in Table 7, and the reddening of $E(b-y) = 0.02 \pm 0.02$ derived from them, leads to $\delta m_0 = 0.020$ and, from Nissen's (1981) calibration, to [Fe/H] = -0.05 ± 0.15. Hence, the photometric determination, when reddening is included and the most recent calibration used, is now fully consistent with the spectroscopic result.

5. Discussion

5.1. Radiative properties of UX Men

In order to improve our estimates of the radiative properties of the components of UX Men, we have made a new determination (February, 1987) of the standard *uvbyβ* indices of UX Men (Table 7) with the Danish 50-cm telescope at ESO, La Silla, Chile, and a new six-channel photometer (Nielsen, 1983). This instrument essentially combines the two photometers previously used in our programmes of binary photometry and for the extensive *uvbyβ* surveys of Grønbech et al. (1976) and Grønbech and Olsen (1977). The values given in Table 7 are averages of those determined from the 1973 CG observations and the standard indices for the comparison star HR 2125, and from our new observation; these are in very good agreement. From the standard indices of UX Men and the luminosity ratios determined in the solutions, we determine the standard indices of the two components of UX Men also listed in Table 7; note that they are almost identical for the two stars.

The combined standard indices and Crawford's (1975) calibration yield a colour excess of 0.02 ± 0.02; i.e., UX Men is at most only slightly reddened. The observed $(b-y)_0$ values and Popper's (1980) empirical temperature scale then yield effective temperatures of 6150 K (average), 6165 K (A), and 6110 K (B). The Saxner and Hammarbäck (1985) scale gives 6185 K (average), 6210 K (A), and 6155 K (B) from $(b-y)_0$, assuming [Fe/H] = +0.04 (Sect. 4), and an average for both components of 6115 ± 100 K from the β index. Finally, the calibration by Magain (1987) gives 6190 K (average), 6210 K (A), and 6160 K (B) from $(b-y)_0$ and [Fe/H] = +0.04. We adopt mean values of 6200 ± 100 K (A) and 6150 ± 100 K (B) in the following, with bolometric corrections of −0.07 for both stars (Popper, 1980). The temperatures adopted here are 100 K higher than the preliminary values listed by ACGNV (their Table 9), because the actual metal abundance has now been properly taken into account in their derivation, but identical to those adopted by CG.

Table 8. Physical parameters for the components of UX Men

	Primary	Secondary
$M/M_{\odot}$	1.238±0.006	1.198±0.007
$R/R_{\odot}$	1.348±0.013	1.274±0.013
log *g* (cgs)	4.272±0.009	4.306±0.010
vsin*i* (km s^{-1})	16.4±0.3	15.1±0.3
log T_e (K)	3.792±0.007	3.789±0.007
log $L/L_{\odot}$	0.38±0.03	0.32±0.03
M_{bol}	3.74±0.07	3.90±0.07
B.C.	-0.07	-0.07
M_v	3.81±0.07	3.97±0.07
Distance (pc)	100±5	

5.2. Absolute dimensions of UX Men

The absolute values of the masses, radii, and luminosities of the components of UX Men, and parameters derived from them, can now be readily computed from the spectroscopic and photometric elements of the system (Tables 2 and 5) and the effective temperatures derived above.

These data (Table 8) represent about as accurate a determination of fundamental stellar properties as is available for any star other than the Sun. The data given here should clearly supersede those listed in Popper's (1980) review. Among main-sequence binary components with well-determined parameters (Popper, 1980), the primary star of VZ Hya has mass and radius nearly identical to (but rather more uncertain than) those of UX Men A. However, VZ Hya is significantly hotter than UX Men (∼6500 K), which would appear to indicate a different (i.e., lower) metal abundance.

No well-observed binary components have been found which precisely match the properties of the secondary component of UX Men. We have already alluded to the extraordinary coincidence that the masses of *both* stars in UX Men are identical to those in AI Phe (ACGNV) to within ±0.1%. However, even the less massive star in AI Phe is sufficiently evolved that its radius is almost 50% larger than that of its counterpart in UX Men; the large log *g* of both stars in UX Men clearly shows them to be still well within the main-sequence band.

The absolute visual magnitude for the mean component of UX Men as derived from the *uvbyβ* indices and Crawford's (1975) calibration, as improved by Nissen et al. (1987), is $M_v = 4.17$. The mean value from Table 8, derived quite independently from the radii and effective temperatures of the two stars, is $M_v = 3.90$, in good agreement with the former.

5.3. Theoretical models for UX Men

For the more evolved system AI Phe, ACGNV showed that the most recent VandenBerg (1983, 1985) standard stellar evolution models were able to predict all observed properties of both stars with very high precision. These models had the observed metal abundance ([Fe/H] = −0.14), the same age for both stars, and the same helium abundance ($Y = 0.27$) and mixing length parameter ($\alpha = 1.50$) as were required in a solar calibration model. Effects of convective core overshooting were not observable in AI Phe.

ACGNV further noted that Popper and Ulrich (1986) also found a solar helium abundance for the Hyades binary HD

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27130, with a metal abundance twice that of AI Phe. It is therefore natural to also explore the extent to which VandenBerg models with $Y=0.27$ are able to match the observed properties of the components of UX Men. As these stars are in much slower evolutionary phases than those in AI Phe, effects of differential evolution are negligible, and the constraints on the models (helium abundance, overshooting) will be correspondingly less tight.

In order to use a consistent set of the latest VandenBerg models as calculated for AI Phe, i.e. with mixing-length parameter and helium abundance fixed from a solar model, we have used those computed for the precise observed masses of UX Men, $Y=0.27$, $Z=0.024$, and $\alpha=1.50$, and listed by ACGNV (Appendix). A set of new, unpublished models for the solar composition ($Z_\odot=0.0169$) and similarly normalized (VandenBerg, 1988) have allowed us to interpolate to the observed $Z=0.019$ for UX Men. Figure 2 compares these interpolated tracks with the observations in the theoretical H-R diagram. Note that, as the uncertainty in M_{bol} for a given value of T_e depends only on that in $\log R$ (± 0.0045), the 1σ error boxes are parallelograms, not rectangles or ellipses. The approximate effects on the models of changing some of the main parameters within the observational uncertainties (but keeping the age constant) are also indicated; as will be seen, errors in masses and radii are insignificant compared to those in the chemical parameters Y and Z (and in the effective temperatures).

It is obvious from Fig. 2 that the new VandenBerg models, yet again, provide a fully satisfactory fit to the observations, well within the observational errors: increasing Z by only $1/3\sigma$ would move the tracks into complete agreement with the observations. The derived age is $(2.7\pm0.3)\ 10^9$ yr. Note that also the slope of the line joining the two observed points matches that of the 2.7 Gyr isochrone very well; because temperature calibration errors affect the two stars equally, the *slope* of this line is better defined than the absolute positions of the two points.

The computed tracks could also be adjusted to the observations (for an age near $3.3\ 10^9$ yr) by decreasing the model helium abundance by about $\Delta Y=-0.01$. However, our determination of [Fe/H] in UX Men does rest on a small number of spectral lines which are measurable only with some difficulty due to their significant rotational broadening, and we consider the errors in [Fe/H] as the main source of residual uncertainty in the comparison with theory. It is gratifying indeed to find that the new VandenBerg models, for the individually determined metal abundances and for a consistent helium abundance $Y=Y_\odot=0.27$, are able to provide such an accurate fit to both AI Phe ($Z=0.0122$), the Sun ($Z=0.0169$), UX Men ($Z=0.019$), and the Hyades binary HD 27130 ($Z=0.024$).

CG, from a fit to the Hejlesen (1980) models, derived a much lower helium abundance ($Y=0.16\pm0.06$) for UX Men than the solar value $Y=0.27$ which we determine here. This is readily explained, as the higher metal abundance which we now find must be counteracted by an increase in helium abundance and, in addition, the older opacity tables used in the Hejlesen models are now known to produce spuriously low helium abundance estimates in comparisons with late-type binaries (cf. VandenBerg and Hrivnak, 1985, and ACGNV).

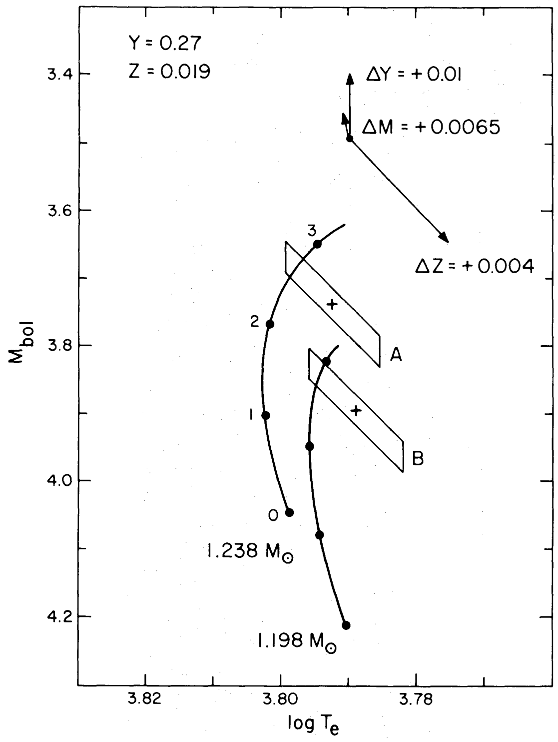

Fig. 2. Comparison of VandenBerg evolutionary sequences for the observed masses and metal abundance of UX Men and $Y=Y_\odot=0.27$ (see text) with the observed properties of the binary (*crosses* and error boxes). Models have been marked at age intervals of 1 Gyr (*dots*). Arrows show the approximate effects of changing the main model parameters by their observational uncertainty (1σ), keeping the age constant

6. Conclusions

The new radial velocity curves and photometric analysis of UX Men have brought the empirical data on its masses, radii, and luminosities up to the best modern standards. In addition, its metal abundance has been determined by high-resolution CCD spectroscopy to be slightly higher than solar, with an uncertainty estimated to be ± 0.1 dex in [Fe/H]. Hence, all parameters needed for a complete specification of theoretical models for the two stars are now known observationally, except for the helium abundance and age which cannot be determined directly.

Evolutionary tracks for the observed masses and metal abundance of UX Men have been derived by interpolation in the models of VandenBerg (1988) and ACGNV. The mixing length parameter and helium abundance have been determined from a solar model ($\alpha_\odot=1.50$, $Y_\odot=0.27$; ACGNV). As shown in Fig. 2, the models fit the observations to well within the observational errors, that of the observed metal abundance being probably the most significant. We derive an age of $(2.7\pm0.3)\ 10^9$ yr for UX Men, and estimate its helium abundance to be $Y=0.27\pm0.01$.

We conclude that the VandenBerg standard stellar evolution models, assuming solar values of mixing-length parameter and helium abundance throughout, are able to match empirical data on stellar masses, radii, luminosities, and abundances to the highest accuracy possible with current techniques, as has now been shown for UX Men, AI Phe (ACGNV), and HD 27130 (Popper and Ulrich, 1986).

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