ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **128**, 441-445 (1998)

AU Monocerotis–improved elements

P. Vivekananda Rao and M.B.K. Sarma

Centre for Advanced Study in Astronomy, Osmania University, Hyderabad - 500 007, India

Received June 16; accepted 5 August, 1997

Abstract. From an analysis, using Wilson-Devinney method, of the corrected yellow light curve of the semi detached eclipsing binary system AU Monocerotis (AU Mon), obtained by Lorenzi (1980b), an improved value for the mass ratio, q, equal to 0.1985 and reliable geometrical elements were derived.They give the absolute elements as: $m_{\rm h}/m_{\odot} = 5.93 \pm 0.31$; $m_{\rm c}/m_{\odot} = 1.18 \pm 0.16$; $R_{\rm h}/R_{\odot} = 5.28 \pm 0.16$; $R_{\rm c}/R_{\odot} = 10.04 \pm 0.74$; Log $L_{\rm h}/L_{\odot} = 3.16 \pm 0.14$; Log $L_{\rm c}/L_{\odot} = 2.07 \pm 0.21$; Log $g_{\rm h} = 3.76 \pm 0.06$; and Log $g_{\rm c} = 2.51 \pm 0.02$. When compared to main sequence stars of similar mass, the primary is found to have normal luminosity, bigger size and lower temperature while the secondary is found to have higher luminosity, bigger size and normal temperature for their masses. On the HR diagram of the normal main sequence stars, the primary is found to lie near but above the main sequence (brighter by $1\overset{\rm m}{.}4$). The secondary component is far above the main sequence and is overluminous by about $4\overset{\rm m}{.}5$.

Key words: Binaries: eclipsing — stars: AU Mon — stars: fundamental parameters

1. Introduction

AU Monocerotis (AU Mon; HD 50846; BD$-1^{\circ}1449$; $P = 11\overset{\rm d}{.}11$) was discovered to be an eclipsing binary of Algol type by Hoffmeister (1931). From their spectroscopic studies, Sahade & Cesco (1945) reported the spectral types of the primary and secondary components to be B5 and about F0, respectively. Lorenzi (1980a) published the first photoelectric light curve, in yellow, of this system in the form of 2616 individual observations. Later he combined these observations into 183 weighted normal points (Lorenzi 1980b; hereafter L80) and corrected them for a suspected intrinsic variation, with a period of about 411 days and amplitude of $0\overset{\rm m}{.}2$, in the system. Assuming symmetry for the eclipse light curve, he obtained ten normal points from these corrected 183 normals (L80; Table 3). These ten normals were considered by Lorenzi as "representative of an approximate mean light curve of the eclipsing variations". Giuricin et al. (1982) solved this light curve of ten normal points using Wood's WINK program and obtained photometric elements of the system. Since only a mass function, $f(m)$, of 0.04 $m_{\odot}$ (Sahade & Cesco 1945) and not the mass ratio was available to them, Giuricin et al. (1982) assumed a plausible value for the mass of the B5 primary component ($\approx 6.0\ m_{\odot}$) and derived a mass ratio of 0.2 for the system and used this value in their analysis.

In a further study of his observations, Lorenzi (1982, Table 1 and Fig. 1) published the light curve of the variation of the unknown source in the system and provided twenty seven corrected normal points (symmetrized) including eight points from his previous study (L80, Table 3). Forming an average symmetric light curve from these points, Lorenzi (1982) solved it for elements using Russell-Merrill (1952) method. Recently Popper (1989) obtained spectra of both the components of AU Mon and published the amplitudes $K_{\rm h}$ and $K_{\rm c}$ of the radial velocity curves, from which one can get a reliable mass ratio ($q = K_{\rm h}/K_{\rm c}$) of the system. Hence we felt it worthwhile to reanalyse the light curve of Lorenzi (L80) using the mass ratio obtained by Popper (1989) and thus obtain improved elements of AU Mon. In the following we give details of our analysis and its results.

2. Analysis

Using the light curve of variation of the unknown source in the system as given by Lorenzi (1982, Table 1 and Fig. 1) we corrected the 183 weighted normals of Lorenzi (L80; Table 1) for the intrinsic brightness variations and analysed them for elements using Wilson-Devinney (W$-$D) (1971) method. The number of points in each of the 183 normals was taken as its weight. For initiating the W$-$D method, we used the elements derived by Giuricin et al. (1982) as preliminary elements. Since the semi detached nature of this system was confirmed by Giuricin et al. (1982) and Popper (1989), we used code-5 of the W$-$D method meant for such systems and a circular orbit ($e =$

Send offprint requests to: P. Vivekananda Rao,
e-mail: pvr@ouastr.ernet.in

0) was assumed for the analysis. Since the spectral type of the primary component was reported to be B5 (Sahade & Cesco 1945; Giuricin et al. 1982; Popper 1989) we assumed a temperature of 15500 ± 1000 K (Allen 1976; Popper 1980; Schmidt-Kaler 1982) for this component. As regards the other important parameter, $q(K_\mathrm{h}/K_\mathrm{c} = m_\mathrm{c}/m_\mathrm{h})$, the mass ratio, Popper (1989) reported two values for K_h: one of 32 ± 4 km s^{-1} obtained from He and Mg II lines and the other of 28.5 ± 2.5 km s^{-1} obtained from H lines. However, he obtained a unique value of 150 ± 3 km s^{-1} for K_c from the D lines. Hence the value of q is ambiguous: it can be either 0.190 (H lines) or 0.213 (He and Mg II lines). In order to find the value of q that gives minimum Σw (O – C)^2 from the light curve analysis, we analysed the data using a range of q values viz.: 0.190, 0.195, 0.1975, 0.20, 0.21 and 0.22, and along with $T_\mathrm{e,h}$(15500 K) treated it as a fixed parameter. In addition, the limb darkening coefficients x_h(0.38) and x_c(0.60), the albedos, A_h(1.0) and A_c(0.5); the gravity darkening coefficients, G_h(0.25) and G_c(0.08) of the primary and secondary components were also treated as fixed parameters. The following parameters were treated as adjustable: i, the inclination of the orbit; Ω_h, the surface potential of the hotter component; L_h, the relative monochromatic luminosity of the hotter component; $T_\mathrm{e,c}$, the mean effective temperature of the cooler component and l_3, the third light. With these fixed and adjustable parameters, a number of runs of the program (code-5) were made till the sum of the residuals Σw (O – C)^2 showed a minimum and the corrections to the parameters became smaller than their probable errors. The values of Σw (O – C)^2 obtained from the analysis for different q values are given in Table 1. A free hand drawn curve through a plot of q versus Σw (O – C)^2 (Fig. 1) showed a minimum at $q = 0.1985$. Hence we obtained another solution, as before, with $q = 0.1985$ and $T_\mathrm{e,h}$(15500 K) as fixed parameters. In this solution, we treated A_c, x_h and x_c also as adjustable parameters. The results are given in Table 2. One can notice that l_3 is absent in the solution.

Table 1. AU Mon: Σw (O – C)^2 values obtained from the analysis of the light curve using $T_\mathrm{e,h}$(15500) and different q values. Here both $T_\mathrm{e,h}$ and q were treated as fixed parameters

Σw (O – C)$^2 x 10^{-4}$	q
38.30	0.190
38.06	0.195
37.96	0.1975
38.00	0.200
38.60	0.210
40.10	0.220

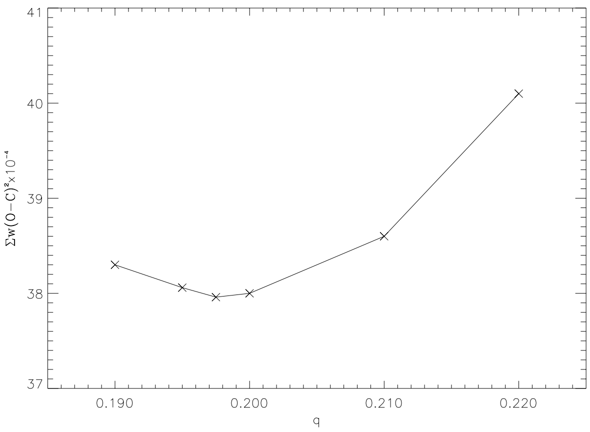

Fig. 1. AU Mon: The relation between the mass ratio, q, and Σw (O – C)^2. The solid line is a free hand drawn curve. The minimum occurs at $q = 0.1985$

The theoretical light curve obtained from the parameters given in Table 2 is shown as solid line in Fig. 2.

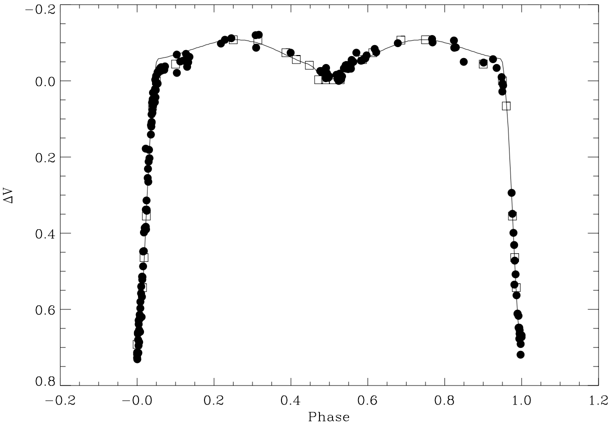

Fig. 2. AU Mon: Light curve in yellow.The solid line is the theoretical curve obtained from the parameters given in Table 2. The filled circles represent the 183 corrected normal points used in the present analysis. The 27 normal points of Lorenzi (1982) are shown as squares

Here the filled circles represent the corrected 183 normal points. The 27 normal points of Lorenzi (1982, Table 3) are shown as squares. Keeping in view the sparse observational coverage at some phases of the light curve, we conclude that the fit of the theoretical curve to the observations is quite satisfactory except in the phase range of 0.88 to 0.96 and 0.04 to 0.12. We attribute this misfit to the presence of gases or gas streams in the system that are favourably situated to absorb some of the light during these phases. The presence of gases or gas

Table 2. AU Mon: Results obtained from the analysis using $T_{\rm e,h} = 15500$ K and $q = 0.1985$ as fixed parameters

Parameter		Values
$^*T_{\rm e,h}$ K		15500 ± 1000
$T_{\rm e,c}$ K		6000 ± 40
$^*q$		0.1985
$i^{\rm o}$		78.74 ± 0.06
$r_{\rm h}$	pole	0.1308 ± 0.0010
	point	0.1311 ± 0.0011
	side	0.1310 ± 0.0010
	back	0.1311 ± 0.0011
$r_{\rm c}$	pole	0.2324 ± 0.0031
	point	0.3408 ± 0.0037
	side	0.2417 ± 0.0033
	back	0.2741 ± 0.0034
$L_{\rm h}/L_{\rm h} + L_{\rm c}$		0.6590 ± 0.0051
$L_{\rm c}/L_{\rm h} + L_{\rm c}$		0.3410
l_3		0.0 ± 0.0004
$x_{\rm h}$		0.428 ± 0.050
$x_{\rm c}$		0.685 ± 0.047
$^*A_{\rm h}$		1.0
$A_{\rm c}$		0.528 ± 0.029
$^*G_{\rm h}$		0.25
$^*G_{\rm c}$		0.08
$^*F_{\rm h}$		1.0
$^*F_{\rm c}$		1.0

* Fixed parameters.

streams in AU Mon was evidenced by the spectroscopic studies of Sahade and Cesco (1945), Sahade & Ferrer (1982), Popper (1962), Peters & Polidan (1984) and Peters (1994). Similar misfits and distortions of light curves due to the presence of gases in the semi detached systems of TT Hya (Vivekananda Rao & Sarma 1994), HU Tau (Parthasarathy et al. 1995), R CMa (Sarma et al. 1996), EU Hya (Vivekananda Rao et al. 1996) and RY Gem (Sarma & Vivekananda Rao 1997) were already reported.

3. Results

3.1. Absolute elements

As already discussed in Sect. 2, the amplitude $K_{\rm h}$ of the radial velocity curve of the primary component has two probable values (Popper 1989) and hence is uncertain. Taking $K_{\rm c} = 150$ km s^{-1}, one gets, from the presently derived photometric mass ratio ($m_{\rm c}/m_{\rm h} = K_{\rm h}/K_{\rm c}$) of 0.1985, a value of 29.78 km s^{-1} for $K_{\rm h}$. This value of $K_{\rm h}$ is almost the same(within errors) as that of 28.5 ± 2.5 km s^{-1} derived by Popper (1989) from H lines for which the systemic velocity, V_0, is the same as that for the cooler component. Hence, we conclude that, within observational errors, the derived photometric mass ratio is equal to that of the spectroscopic mass ratio obtained by Popper (1989) from the H lines and hence would yield reliable absolute elements. Combining the values of $K_{\rm h} = 29.78 \pm 3$ km s^{-1} and $K_{\rm c} = 150$ km s^{-1} with the other required parameters from Table 2 and using the relevant equations, we derived the absolute elements of AU Mon with their errors, as given in Table 3.

Table 3. AU Mon: Absolute elements derived from the values of $K_{\rm h} = 29.78$ km s^{-1} and $K_{\rm c} = 150$ km s^{-1} and other parameters from Table 2

Parameter	Hot Component	Cool Component
$A/R_\odot$	40.30 ± 0.87	40.30 ± 0.87
$m/m_\odot$	5.93 ± 0.31	1.18 ± 0.16
$R/R_\odot$	5.28 ± 0.16	10.04 ± 0.74
Log $L/L_\odot$	3.16 ± 0.14	2.07 ± 0.21
$M_{\rm bol}$	-3.21 ± 0.34	-0.48 ± 0.52
$M_{\rm v}$	-1.77 ± 0.34	-0.39 ± 0.52
log g	3.76 ± 0.06	2.51 ± 0.02

Bolometric corrections (B.C) of $-1\overset{\rm m}{.}44$ for the primary and $-0\overset{\rm m}{.}09$ for the secondary are used (Popper 1980). In deriving ΔLog L, we used $\Delta T_{\rm e,h} = 1000$ K and $\Delta T_{\rm e,c} = 500$ K.

3.2. Spectral types of the components

As the light curve of only one pass band is available for analysis, it is not possible to derive the colours of the individual components and find their spectral types. However, the derived temperature of 6000 K and bigger size (10.04 $R_\odot$) of the secondary component with a log g value of 2.5 suggest it to be of spectral type F9-G0III-II (Allen 1976; Popper 1980; Schmidt-Kaler 1982). According to Dr. Morgan (in Sahade & Cesco 1945) the secondary component is a star of near F0 spectral type. As already stated in Sects. 1 and 2, the observed spectral type of the primary component is B5. According to Dr. Morgan (in Sahade & Cesco 1945) the intensity of H lines in this component was of the same order as in a B5IV star. When compared to a main sequence B5 star, the derived radius of the primary component is larger by about 35%, its log g value (3.76) lies in between the log g values for a B5V (4.04) and B5III (3.49) stars (Schmidt-Kaler 1982) and it has already filled about 25% of its Roche lobe ($r^*_{\rm h}$=0.534; Plavec & Kratochvil 1964). All these properties indicate a slight evolution of the primary component and confirm its classification to be B5IV. Hence AU Mon consists of B5IV plus F9-G0III-II stars as its components.

3.3. Distance modulus

As the difference in the absolute visual magnitudes ($M_{\rm v}$) of the secondary and primary components is 1.38 (Table 3), the ratio of their luminosities $L_{\rm c}/L_{\rm h}$ is equal to 0.28. From this ratio, one can calculate the combined visual absolute magnitude ($M_{\rm v}$) of AU Mon to be -2.04.

The apparent visual magnitude $m_{\rm v}$ at maximum of AU Mon was recorded as 8.5 (Batten 1967) and 8.3 (Wood et al. 1980). Taking an average of these values, along with the combined $M_{\rm v}$ and assuming no space reddening the distance modulus $(m-M)$ of AU Mon is derived as 10.44, from which a distance of 1225±55 pc is obtained. However, Peters (1994) suggested a reddening of $E(B-V) = 0\overset{\rm m}{.}08$ for this system. If this were the case, space absorption $A_{\rm v}$ equals $0\overset{\rm m}{.}264$ (Allen 1976), from which a distance of 1083 ± 50 pc is obtained for AU Mon. For a comparison, the system parameters, as reported by Lorenzi (1982) and Giuricin et al. (1982) along with those obtained from the present analysis are given in Table 4.

Table 4. AU Mon: Comparison of system parameters obtained from different studies

Parameter	Lorenzi (1982)	Giuricin et al. (1982)	Present studies
Method	1	2	3
$T_{\rm e,h}$K	15500*	15000*	15500*
$T_{\rm e,c}$K	5300	6600	6000
q	-	0.2*	0.1985
i°	82.0	78.4	78.74
$L_{\rm h}$	0.93	0.645	0.659
$L_{\rm c}$	0.07	0.355	0.341
l_3	-	-	0.0
$r_{\rm h}$	0.18	0.115	0.131$^+$
$r_{\rm c}$	0.18	0.242	0.249$^+$
Log $L_{\rm h}/L_\odot$	-	2.98	3.16
Log $L_{\rm c}/L_\odot$	-	2.20	2.07
$m_{\rm h}/m_\odot$	6.5*	6.0*	5.93
$m_{\rm c}/m_\odot$	1.4	1.2	1.18
$R_{\rm h}/R_\odot$	7.5	4.6	5.28
$R_{\rm c}/R_\odot$	7.5	9.7	10.04
Sp.typ (Pri)	B5V	B5V	B5IV
Sp.typ (Sec)	-	early F	F9-G0III-II

*Assumed values

$^+r = (r_{\rm pole} + r_{\rm side} + r_{\rm back})/3$

Method:

1. Russell-Merrill
2. Wood's WINK
3. Wilson-Devinney.

4. Discussion and conclusions

Our analysis, with W–D method, of the corrected yellow light curve of AU Mon, obtained by Lorenzi (L80) yielded the most probable value of the photometric mass ratio, $q = 0.1985$. This value is found, within observational errors, to be equal to the spectroscopic mass ratio derived by Popper (1989) from H lines. Hence we conclude that the presently derived absolute elements are most reliable. A comparison of the positions of the primary and secondary components on the Log m, versus $\log L$, $\log R$ and $\log T_{\rm e}$ relations of the normal main sequence stars (Andersen 1991) indicate that while the primary component is having normal luminosity, bigger size and lower temperature, the secondary component is having higher luminosity, bigger size and normal temperature, in comparison to stars of similar mass. The normal HR diagram (Andersen 1991) shows that while the primary component is near but above the main sequence (brighter by $1\overset{\rm m}{.}4$), the secondary is far above it and is overluminous by about $4\overset{\rm m}{.}5$. In this respect, the secondary component shares the common property of overluminosity of the secondaries of the semi detached systems (Sarma et al. 1996). From the properties of the components of AU Mon, we conclude that it is a typical Algol type binary except that the eclipse light variations are superposed by intrinsic brightness variations. We suggest that a detailed study of the nature of the intrinsic variation in AU Mon is very important. According to Peters (1994) this variation is caused by the periodic changes in the rate of mass transfer from the secondary due to pulsations about its Roche surface which, in turn, would cause changes in the temperature of the mass accreting region around the primary. Alternately, we suggest that this variation may be due to the precession of the gaseous disc around the primary caused by the gravitational perturbations of the secondary component. Another point to notice is that while the spectral type of the secondary component as given by Dr. Morgan (in Sahade & Cesco 1945) is F0, the present study suggests it to be a F9-G0 star. Lorenzi (1983) suggests that early G is appropriate from photometry. This large discrepancy of about one spectral class may be attributed partly to the fact that we have observations in one pass band only. More importantly, corrections for the long term variations were not applied to the observations during the eclipse phases (L80) when a part of the variable source is covered causing an error in the depth of the eclipse. It is obvious that extensive photoelectric observations in as many pass bands as possible and high dispersion spectroscopic studies are needed for understanding the long term variations in AU Mon.

Acknowledgements. We are grateful to Professeur K.D. Abhyankar for helpful suggestions. We also thank the referee, Professeur D.M. Popper, for many useful comments. MBKS wishes to thank the Council of Scientific and Industrial Research (CSIR), New Delhi, for financial assistance under the Emeritus Scientists Scheme.

References

Allen C.W., 1976, Astrophysical Quantities, 3rd edn. London: The Athlone Press
Andersen J., 1991, A&AR 3, 91
Batten A.H., 1967, Publ. Dom. Astrophys. Obs. Victoria B. C., Vol. XIII, No. 8, p. 146
Giuricin G., Mardirossian F., Mezzetti M., 1982, MNRAS 199, 131
Hoffmeister C., 1931, Astr. Nachr. 242, 129
Lorenzi L., 1980a, A&AS 40, 271
Lorenzi L., 1980b, A&A 85, 342

Lorenzi L., 1982, Acta Astron. 32, 431

Lorenzi L., 1983, personal communication to Peters and Polidan, 1984

Parthasarathy M., Sarma M.B.K., Vivekananda Rao P., 1995, A&A 297, 359

Peters G.J., Polidan R.S., 1984, ApJ 283, 745

Peters G.J., 1994, in "Interacting Binary Stars", Shafter A.W. (ed.) ASP Conf. Ser. 56, 384

Plavec M., Kratochvil P., 1964, Bull. Astron. Inst. Czechoslovakia 15, 165

Popper D.M., 1962, PASP 74, 129

Popper D.M., 1980, ARA&A 18, 115

Popper D.M., 1989, ApJ 71, 595

Russell H.N., Merrill J.E., 1952, Contr. Princeton Univ. Obs., No. 26

Sahade J., Cesco C.U., 1945, ApJ 101, 235

Sahade J., Ferrer O.E., 1982, PASP 94, 113

Sarma M.B.K., Vivekananda Rao P., Abhyankar K.D., 1996, ApJ 458, 371

Sarma M.B.K., Vivekananda Rao P., 1997, AJ 114, 800

Schmidt-Kaler Th., 1982, in Landolt/Bornstein, Numerical data and functional relationship in Science and Technology, Scaifers K. & Voigt H.H. (eds.). New Series, Group VI, Vol. 2(b). Springer-Verlag, Berlin, p. 453 and 31

Vivekananda Rao P., Sarma M.B.K., 1994, Bull. Astron. Soc. India 22, 451

Vivekananda Rao P., Sarma M.B.K., Abhyankar K.D., 1996, PASP 108, 967

Wilson R.E., Devinney E.J., 1971, ApJ 166, 605

Wood F.B., Oliver J.P., Florkowski D.R., Koch R.H., 1980, A Finding list for observers of Interacting Binary Stars, 5th Edition, Catalogue No. 690, p. 80