Rev. Mexicana Astron. Astrof., 14, 402-409 (1987)

A PHOTOMETRIC ANALYSIS OF THE MASSIVE CONTACT BINARY BR MUSCAE

E. Lapasset, M. N. Gómez J. J. Clariá

Observatorio Astronómico, Universidad Nacional de Córdoba, Argentina

RESUMEN. Se analiza la fotometría UBV de la binaria temprana de contacto BR Muscae usando el método de las correcciones diferenciales de Wilson y Devinney. Las mejores soluciones encontradas corresponden a valores de la razón de masas próximos a la unidad. Los restantes parámetros quedan bien definidos y resultan prácticamente independientes de la razón de masas. Se encuentra un porcentaje de sobrecontacto de alrededor del 11 %. BR Muscae aparenta ser un sistema muy próximo a la secuencia principal de edad cero, con características similares a algunos de los sistemas de tipo temprano bien conocidos como BH Cen, AW Lac y V701 Sco. Se presentan y discuten consideraciones generales acerca de las binarias calientes de contacto.

ABSTRACT. The UBV photometry of the early-type contact binary BR Muscae is analysed by means of the differential corrections method of Wilson and Devinney. The best solutions found correspond to mass-ratio values close to unity. The remaining parameters are well defined and practically independent of the mass-ratio. A percentage of overcontact of about 11 % is found. BR Muscae appears to be very close to the zero-age main sequence. It has similar characteristics to some of the well known early-type systems like BH Cen, AW Lac, and V701 Sco. General considerations on the hot contact binaries are presented and discussed.

Key words: PHOTOMETRY -- STARS-BINARY -- STARS-MASS

I. INTRODUCTION

In the last decade a new group of binary stars related to the contact systems has made its appearance : the early-type contact binaries. These are OB and eventually A-type stars exhibiting W UMa shaped light curves. Their effective temperatures determinate that the common envelopes are essentially radiative. Both, the thermal relaxation oscillations (TRO) theory (Lucy 1976; Lucy and Wilson 1979) and the contact discontinuity (DSC) model (Shu et al. 1976; Lubow and Shu 1977) do not contradict the existence of contact configurations with radiative envelopes. But the TRO model places some constraints to unevolved systems having mass-ratios close to unity or being out of equilibrium. As many investigators of this field have often emphasized, the accurate determination of photometric and spectroscopic parameters will certainly help to improve our present knowledge of this contact binary group.

BR Muscae was announced to be a new member of the early-type contact binaries by Clariá and Lapasset (1982; hereafter Paper I). They obtained partial UBV light curves at the 24-inch telescope of Cerro Tololo Inter-American Observatory (CTIO). In addition, they derived the orbital period P = 0ᵈ798196848 and the integrated spectral type B3V. In this paper we present the complete UBV light curves of BR Muscae. In order to establish the main photometric parameters of this interesting system, a detailed analysis by means of the Wilson and Devinney's (1971) model is here performed.

II. UBV LIGHT CURVES

The UBV observations published in Paper I were continued at the 1.54 meter telescope of the Bosque Alegre Station (BAS) of Córdoba Observatory during the 1982 observational season. An RCA 1P21 photomultiplier refrigerated with dry ice and conventional electronics were employed. The differential measurements made at BAS were entirely compatible with those obtained at CTIO. We refer to Paper I for data on the comparison star, standard colors, magnitudes, and ephemeris of BR Muscae.

A total of 811 individual observations were finally plotted in a classical diagram of color and magnitude light curves. The phases of all the observatios were calculated from equation (2) of Paper I. Two new times of minima derived from the BAS data confirmed the old ephemeris.

The light curves of BR Muscae are shown in Figure 1. They exhibit the characteristics of virtual contact systems with partial eclipses and minima of similar depth. From the 811 UBV observations, 68 normal points were derived and weighted according to the number of observations per normal. These normal points are shown in Table 1. They were used to obtain the basic photometric data of this system by means of the Wilson and Devinney computational process.

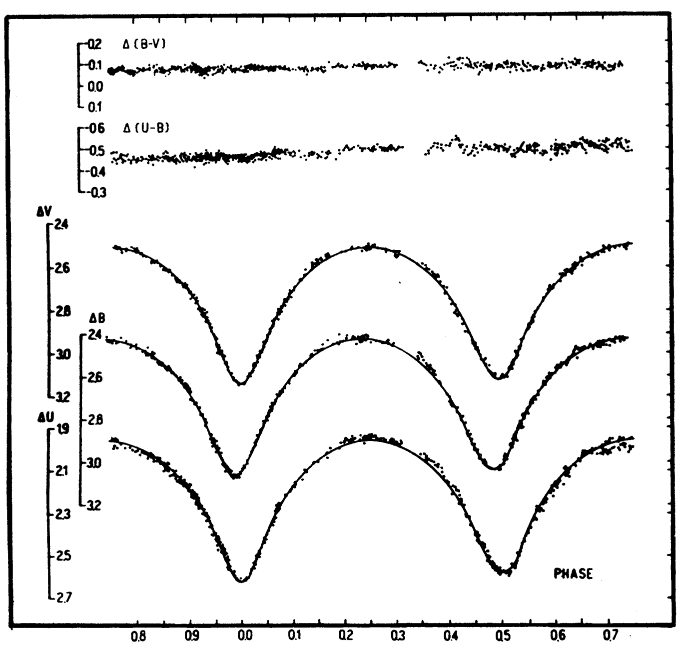

Fig. 1. UBV light curves of BR Muscae. Solid lines represent the solution for q = 1.0.

TABLE 1. NORMAL POINTS OF BR MUSCAE

PHASE	V	B	U	PHASE	V	B	U
0.0035	0.5583 (-0.0006)	0.5567 (-0.0024)	0.5436 (-0.0007)	0.6361	0.8947 (-0.0051)	0.8983 (-0.0020)	0.8923 (-0.0028)
0.0134	0.5697 (-0.0003)	0.5682 (-0.0020)	0.5545 (-0.0008)	0.6517	0.9285 (0.0067)	0.9308 (0.0079)	0.9354 (0.0165)
0.0239	0.5918 (-0.0009)	0.5919 (-0.0004)	0.5805 (0.0009)	0.6658	0.9500 (0.0100)	0.9521 (0.0103)	0.9456 (0.0073)
0.0346	0.6212 (-0.0036)	0.6229 (0.0002)	0.6159 (0.0035)	0.6779	0.9591 (0.0045)	0.9592 (0.0023)	0.9561 (0.0025)
0.0459	0.6603 (-0.0009)	0.6606 (0.0019)	0.6533 (0.0047)	0.6913	0.9637 (-0.0048)	0.9659 (-0.0053)	0.9642 (-0.0042)
0.0554	0.6901 (-0.0037)	0.6918 (0.0009)	0.6828 (0.0007)	0.7033	0.9798 (0.0006)	0.9766 (-0.0058)	0.9749 (-0.0047)
0.0663	0.7317 (0.0018)	0.7271 (-0.0012)	0.7244 (0.0053)	0.7209	0.9907 (0.0002)	0.9808 (-0.0131)	0.9839 (-0.0077)
0.0763	0.7588 (-0.0034)	0.7564 (-0.0036)	0.7595 (0.0072)	0.7376	0.9944 (-0.0020)	0.9912 (-0.0089)	0.9858 (-0.0119)
0.0973	0.8143 (-0.0065)	0.8114 (-0.0080)	0.8076 (-0.0040)	0.7559	1.0027 (0.0054)	0.9972 (-0.0039)	0.9919 (-0.0066)
0.1332	0.9035 (0.0095)	0.8966 (0.0029)	0.8847 (-0.0014)	0.7722	0.9891 (-0.0043)	0.9932 (-0.0037)	0.9850 (-0.0092)
0.1621	0.9526 (0.0182)	0.9452 (0.0097)	0.9269 (-0.0014)	0.7902	0.9908 (0.0072)	0.9866 (-0.0001)	0.9705 (-0.0129)
0.1976	0.9787 (0.0047)	0.9867 (0.0100)	0.9842 (0.0111)	0.8096	0.9749 (0.0078)	0.9693 (0.0003)	0.9525 (-0.0132)
0.2234	0.9964 (0.0049)	1.0029 (0.0080)	1.0036 (0.0115)	0.8291	0.9458 (0.0001)	0.9478 (0.0005)	0.9349 (-0.0076)
0.2391	0.9906 (-0.0060)	0.9918 (-0.0085)	0.9982 (0.0005)	0.8457	0.9246 (0.0004)	0.9256 (0.0007)	0.9135 (-0.0058)
0.2511	0.9942 (-0.0034)	0.9988 (-0.0027)	1.0075 (0.0085)	0.8602	0.9034 (-0.0005)	0.8958 (-0.0079)	0.8913 (-0.0060)
0.2654	0.9979 (0.0022)	1.0028 (0.0034)	1.0086 (0.0116)	0.8719	0.8846 (-0.0011)	0.8802 (-0.0049)	0.8670 (-0.0106)
0.2815	0.9888 (-0.0003)	0.9918 (-0.0008)	0.9945 (0.0043)	0.8823	0.8594 (-0.0079)	0.8631 (-0.0034)	0.8479 (-0.0103)
0.2967	0.9800 (0.0003)	0.9846 (0.0022)	0.9881 (0.0085)	0.8935	0.8454 (-0.0005)	0.8405 (-0.0041)	0.8309 (-0.0050)
0.3161	0.9603 (-0.0007)	0.9664 (0.0029)	0.9722 (0.0117)	0.9015	0.8245 (0.0004)	0.8249 (-0.0021)	0.8151 (0.0005)
0.3661	0.9038 (0.0070)	0.9084 (0.0112)	0.9102 (0.0182)	0.9105	0.8022 (-0.0001)	0.8040 (0.0031)	0.7860 (-0.0054)
0.3862	0.8693 (0.0070)	0.8698 (0.0078)	0.8731 (0.0165)	0.9179	0.7752 (-0.0038)	0.7797 (0.0021)	0.7688 (-0.0002)
0.4078	0.7988 (-0.0131)	0.8011 (-0.0109)	0.8111 (0.0045)	0.9255	0.7546 (-0.0026)	0.7552 (0.0006)	0.7468 (0.0001)
0.4301	0.7328 (-0.0119)	0.7388 (-0.0074)	0.7445 (0.0046)	0.9310	0.7465 (0.0069)	0.7385 (0.0002)	0.7254 (-0.0036)
0.4507	0.6735 (-0.0039)	0.6808 (0.0028)	0.6717 (0.0001)	0.9380	0.7207 (0.0055)	0.7141 (0.0013)	0.7073 (0.0031)
0.4680	0.6227 (0.0015)	0.6210 (-0.0018)	0.6221 (0.0057)	0.9432	0.7071 (0.0087)	0.6962 (0.0006)	0.6868 (0.0020)
0.4832	0.5855 (0.0022)	0.5873 (0.0020)	0.5818 (0.0034)	0.9495	0.6782 (0.0012)	0.6742 (0.0001)	0.6633 (-0.0016)
0.4982	0.5714 (0.0052)	0.5698 (0.0015)	0.5677 (0.0061)	0.9560	0.6532 (-0.0020)	0.6518 (-0.0001)	0.6441 (0.0017)
0.5143	0.5747 (-0.0040)	0.5762 (-0.0042)	0.5667 (-0.0071)	0.9611	0.6399 (0.0006)	0.6367 (0.0009)	0.6314 (0.0054)
0.5307	0.6164 (-0.0010)	0.6189 (0.0002)	0.6033 (-0.0094)	0.9687	0.6173 (0.0030)	0.6159 (0.0034)	0.6095 (0.0078)
0.5473	0.6750 (0.0043)	0.6729 (0.0011)	0.6650 (-0.0001)	0.9738	0.5986 (-0.0003)	0.5986 (0.0005)	0.5877 (0.0015)
0.5625	0.7234 (0.0015)	0.7249 (0.0037)	0.7180 (0.0011)	0.9797	0.5853 (0.0022)	0.5841 (0.0005)	0.5733 (0.0032)
0.5804	0.7835 (0.0054)	0.7761 (-0.0013)	0.7578 (-0.0178)	0.9853	0.5728 (0.0007)	0.5739 (0.0015)	0.5622 (0.0046)
0.6026	0.8414 (0.0055)	0.8378 (0.0005)	0.8187 (-0.0127)	0.9935	0.5606 (-0.0002)	0.5588 (-0.0019)	0.5317 (-0.0144)
0.6182	0.8740 (0.0040)	0.8708 (0.0004)	0.8603 (-0.0045)	0.9980	0.5584 (0.0000)	0.5560 (-0.0026)	0.5431 (-0.0008)

III. LIGHT CURVE ANALYSIS

Each U, B, and V light curve was analysed independently. Some of the fundamental parameters of the photometric solution were not adjusted during the process of differential corrections. Their values were derived as follows : a) the temperature T_1 of the primary component was defined according to the spectral type B3 (Paper I)using the calibration given by Morton and Adams (1968); b) the limb darkening coefficients x_1 and x_2 were derived from the assumed temperature T_1 in the grid model atmospheres of Carbon and Gingerich (1969), for log g = 4; c) for the albedos A_1 and A_2 and the gravity darkening coefficients g_1 and g_2, a common value of 1.0 was adopted according to the criteria established for stars with radiative envelopes (Rucinski 1969; Lucy 1967).

The initial assumption of physical contact between both components of the system was not modified during the procedure of differential corrections. This assumption is satisfied by giving to the modified gravity potentials $\Omega_1 = \Omega_2$ values between both critical potentials of the Roche equipotential surfaces : Ω_i (internal) and Ω_e (external). Mode 3 of the Wilson and Devinney code (see Leung and Wilson 1977), which holds for contact binaries, was always employed. Consequently, the adjustable parameters of the photometric analysis were five : the above mentioned Roche potential Ω , the mass-ratio $q = m_2/m_1$, the orbital inclination i, the temperature of the secondary component T_2, and the monochromatic luminosity of the primary component L_1.

The first approaches to the possible solutions were obtained by generating synthetic light curves (Program LC). This allowed us to limit the range of reliable values of the critical parameter q between 0.4 and 2.5. For $q < 0.4$ or $q > 2.5$, large values of the orbital inclination would be required to repro-

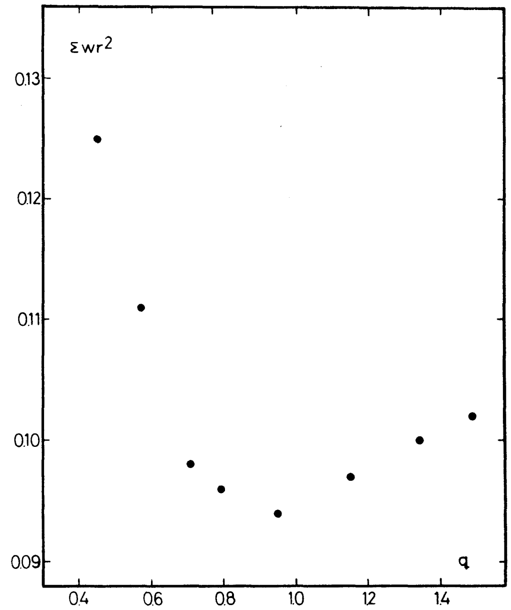

Fig. 2. Sum of squares deviations for ten solutions of BR Muscae light curves (see the text).

TABLE 2. PHOTOMETRIC SOLUTIONS OF BR MUSCAE

	q = 0.8	q = 1.0	q = 1.2
i	78°.5	78°.3	78°.3
T_1^*(°K)	18000	18000	18000
T_2(°K)	17639	17654	17702
$\Omega_1 = \Omega_2$	3.354	3.614	3.924
q	0.793	0.948	1.146
$g_1^* = g_2^*$	1.0	1.0	1.0
$A_1^* = A_2^*$	1.0	1.0	1.0
$x_1^* = x_2^*$ (V)	0.35	0.35	0.35
(B)	0.45	0.45	0.45
(U)	0.40	0.40	0.40
$L_1/(L_1+L_2)$ (V)	0.565	0.517	0.489
(B)	0.562	0.519	0.468
(U)	0.568	0.535	0.481
r_1(pole)	0.383	0.367	0.352
r_1(side)	0.404	0.386	0.370
r_1(back)	0.438	0.421	0.405
r_2(pole)	0.344	0.358	0.374
r_2(side)	0.361	0.377	0.394
r_2(back)	0.397	0.412	0.429
f	0.11	0.10	0.11
Σwr^2	0.0319	0.0313	0.0325

*Not adjusted parameters.

duce the observed depths of minima but in that case, one of the minima would be total. These considerations have been treated in more detail by Lapasset and Clariá (1986). Furthermore, as it will be seen later, the sum of the weighted squares of the residual ($\sum wr^2$) increases with the values of q from 1 to 1.5. Therefore, this latter value was taken as an upper limit in the present analysis. A total of 9 different values of q uniformly distributed between 0.4 and 1.5 were finally examined. As soon as the LC program allowed us to derive a good representation of the observations, the analysis proceeded with the differential corrections (DC) program. The computations were stopped when the corrections to all the adjustable parameters were reduced to values of the order of their probable errors.

In this way, 9 different solutions were obtained with final values of q very similar to the initial ones. A diagram showing the already defined sum ($\sum wr^2$) versus the mass-ratio for each of these solutions is presented in Figure 2. A definite minimum can be observed around q = 1.0. Thus, we conclude from this evidence that BR Muscae is another example of an early-type contact binary with nearly equal masses of both components. Since the differences between the residuals of solutions q = 0.8, 1.0, and 1.2 are not significant, we have plotted these three solutions in Table 2. Thus, a reliable range of possible values of each parameter is provided. We have represented in Figure 1 the synthetic light curves (solid lines) - corresponding to the solution q = 1.0 - among the observed points, while in Table 1 the residuals r from this solution are listed in brackets after the normal points.

Except for the mass-ratio whose value cannot be precisely determined from light curves with partial eclipses (see, for example, Lapasset and Sisteró 1984), the remaining fundamental parameters are well defined. Particularly, we remark the consistency of the values of the overcontact parameter $f = (\Omega - \Omega_i)/(\Omega_e - \Omega_i)$ found in all the solutions here derived. A diagram of f versus q plotted in Figure 3 shows that f is always close to the marginal contact and ranges between 0.09 and 0.17. The independence of the fill-out parameter from q was also noted by Leung and Schneider in other systems (1978a, 1978b). As expected, the relation between temperatures of both components is also well defined and indicative of good thermal contact.

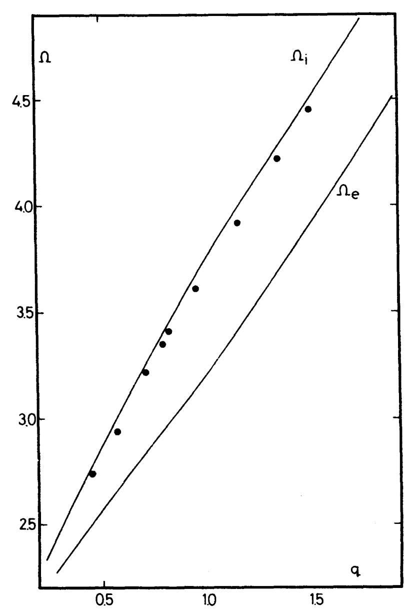

Fig. 3. Gravitational potentials for the photometric solutions of BR Muscae. Solid lines represent the critical internal and external potentials.

IV. DISCUSSION AND CONCLUSIONS

The location of BR Muscae in the period-spectral type diagram, proposed by Leung and Schneider (1978a) as an evolutionary state indicator, is shown in Figure 4 together with some other early-type contact binaries. According to this diagram, BR Muscae is very close to the zero-age main sequence (ZAMS) for q = 1.0. Some different ways of evaluating the degree of evolution have been suggested by Wilson (1978), Van Hamme (1982a, 1982b) and Mochnacki (1981, 1983), among others. Following Van Hamme's arguments and formulae we found that the radii ratio of the primary component to a normal B3 main sequence star is close to unity. The same result is obtained for the mean densities of both components according to Mochnacki's equations. Then, everything points to favour a non-evolved state for BR Muscae.

Three fundamental characteristics of BR Muscae seem to have been unambiguously defined in the present study : i) mass-ratio close to unity, ii)small degree of overcontact, iii) evolutionary state close to the ZAMS. Searching in the literature (see Leung 1979; Wilson and Rafert 1981 for reviews on hot contact systems) we found several systems similar to BR Muscae. They are, in particular, BH Cen (Leung and Schneider 1977; Leung et al. 1984), V701 Sco (Wilson and Leung 1977; Andersen et al. 1980) and AW Lac (Jiang et al. 1983). All these three contact systems have B2-B3 spectral types, with nearly equal mass components and are probably unevolved systems. The main photometric data on this sample of binaries has been listed in Table 3. For BR Muscae we have taken mean values of the parameters derived from the three solutions presented in Table 2. As it can be seen in Table 3, the fill-out parameter f differs from one system to another and BR Muscae appears to be the only one at marginal contact. Thus, BR Muscae contradicts Mochnacki's (1981) assumption that massive contact systems have higher f for larger q.

There are some more hot contact binaries with mass-ratios close to unity, such as SV Cen (Wilson and Starr 1976; Rucinski 1976), AO Cas (Schneider and Leung 1978), V348 Car (Hildicht and Lloyd Evans 1985), RY Sct (Milano et al. 1981) and GK Cep (Hutchings and Hill 1973). In the preceeding list we mean by mass-ratio close to unity, all values of q between 0.8 and 1.25. We know that the photometric determinations of q, particularly those from light curves with partial eclipses, are not accurate. According to Popper (1982), the same is true for spectroscopic determinations.

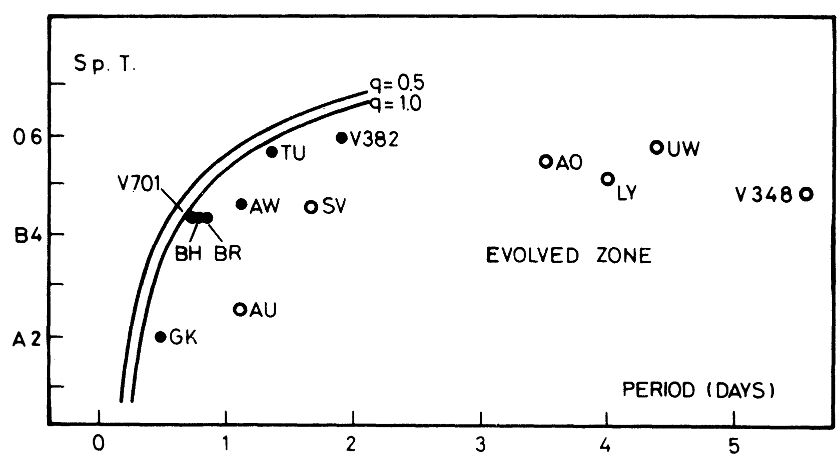

Fig. 4. Period-spectral type diagram. Solid lines represent the theoretical zero-age relation for mass-ratios 1.0 and 0.5. Filled and open circles stand for systems we consider not or slightly evolved and evolved, respectively.

TABLE 3

FUNDAMENTAL PARAMETERS OF MASSIVE CONTACT BINARIES

	BR Mus[a]	BH Cen[b]	V701Sco[c]	AW Lac[d]
Sp. Type	B3	B3	B3	B3
P	$0\overset{d}{.}798$	$0\overset{d}{.}792$	$0\overset{d}{.}762$	$1\overset{d}{.}143$
q	0.96	0.84	1.00	1.00
i	$78\overset{\circ}{.}4$	$90\overset{\circ}{.}0$	$66\overset{\circ}{.}8$	$78\overset{\circ}{.}5$
f	0.11	0.48	0.51	0.71
T_1 (°K)	18000	17900	20500	20500
T_2 (°K)	17665	17431	20586	16754

References : (a) This paper; (b) Leung et al. (1984); (c) Wilson and Leung (1977); (d) Jiang et al. (1983).

Therefore, it is interesting to note that a high percentage of hot contact binaries have nearly equal components. As we have pointed out in the introduction, the TRO theory favours this kind of configurations for unevolved stable systems. On the other hand, most of the massive contact binaries with q ≠ 1 are clearly evolved, like AU Pup (Leung and Schneider 1978a), LY Aur(Eaton 1978; Margoni et al. 1981), UW CMa (Leung and Schneider 1978b) and V729 Cyg (Leung and Schneider 1978c). However, two systems remain as a challenge for the TRO theory : TU Mus (Andersen and Gronbech 1975; Wilson and Rafert 1981) and V382 Cyg (Bloomer et al. 1979). Both systems appear to be only slightly evolved with mass-ratio q = 0.7 (Popper 1982).

Most of the contact binaries here mentioned have been plotted in the period-spectral type diagram of Figure 4, where a large spread of evolutionary states is clearly seen. Other parameters such as q and f are also scattered in the same way. Thus, much classification work and larger statistical recopilations are still needed for a better understanding of the massive contact binaries group.

It is a pleasure to thank J. Laborde and J. Albarracin for the preparation of the diagrams and photograph. This work was partially supported by the Argentinian institution CONICET.

REFERENCES

Andersen, J. and Gronbech, B. 1975, Astron. Astrophys. 45, 107.
Andersen, J., Nordstrom, B. and Wilson, R.E. 1980, Astron. Astrophys. 82, 225.
Bloomer, R.H., Burki, E.W., King, C. and Millis, R.L. 1979, Bull. Amer. Astron. Soc. 11, 439.
Carbon, D.F. and Gingerich, O. 1969, in Theory and Observation of Normal Stellar Atmospheres, ed. O. Gingerich, Cambridge, MA, MIT Press, p. 401.
Clariá, J.J. and Lapasset, E. 1982, Astron. Astrophys. Suppl. 50, 13 (Paper I).
Eaton, J.A. 1978, Acta Astron. 28, 195.
Hildicht, R.W. and Lloyd Evans, T. 1985, M.N.R.A.S. 213, 75.
Hutchings, J.B. and Hill, G. 1973, Astrophys.J. 179, 539.
Jiang, Z., Leung, K.C., and Liangzhad, S. 1983, Astron. J. 88, 1679.

Lapasset, E. and Clariá, J.J. 1986, Astron. Astrophys. 161, 264.
Lapasset, E. and Sisteró, R.F. 1984, Astron. Astrophys. 130, 97.
Leung, K.C. 1979, in IAU Symp. 88, Close Binary Stars : Observation and Interpretation, ed. M. Plavec, D.M. Popper, and R.K. Ulrich, Dordrecht : Reidel, p. 527.
Leung, K.C. and Schneider, D.P. 1977, Astrophys. J. 211, 844.
Leung, K.C. and Schneider, D.P. 1978a, Astrophys. J. 222, 917.
Leung, K.C. and Schneider, D.P. 1978b, Astrophys. J. 222, 924.
Leung, K.C. and Schneider, D.P. 1978c, Astrophys. J. 224, 656.
Leung, K.C., Sisteró, R.F., Zhai, D.S., Grieco, A., and Candellero, B. 1984, Astron. J. 89, 872.
Leung, K.C. and Wilson, R.E. 1977, Astrophys. J. 211, 853.
Lubow, S.H. and Shu, F.H. 1977, Astrophys. J. 216, 517.
Lucy, L.B. 1967, Z. Astrophys. 65, 89.
Lucy, L.B. 1976, Astrophys. J. 205, 208.
Lucy, L.B. and Wilson, R.E. 1979, Astrophys. J. 231, 502.
Margoni, R., Stagni, R. and Mammano, A. 1981, Astrophys. Space Sci. 79, 145.
Milano, L., Vittone, A., Criatti, F., Mammano, A., Margoni, R. and Strazzula,G. 1981, Astron. Astrophys. 100, 59.
Mochnacki, S.W. 1981, Astrophys. J. 245, 650.
Mochnacki, S.W. 1983, in Interacting Binaries, eds. P.P. Eggleton and J.E. Pringle, Dordrecht : Reidel, p. 51.
Morton, D.C. and Adams, T.F. 1968, Astrophys. J. 151, 611.
Popper, D.M. 1982, Astrophys. J. 262, 641.
Rucinski, S.M. 1969, Acta Astron. 19, 245.
Rucinski, S.M. 1976, Pub. Astron. Soc. Pacific 88, 244.
Schneider, D.P. and Leung, K.C. 1978, Astrophys. J. 223, 202.
Shu, F.H., Lubow, S.H. and Andersen, L. 1976, Astrophys. J. 209, 536.
Van Hamme, W. 1982a, Astron. Astrophys. 105, 389.
Van Hamme, W. 1982b, Astron. Astrophys. 116, 27.
Wilson, R.E. 1978, Astrophys. J. 224, 885.
Wilson, R.E. and Devinney, E.J. Astrophys. J. 166, 705.
Wilson, R.E. and Leung, K.C. 1977, Astron. Astrophys. 61, 137.
Wilson, R.E. and Rafert, J.B. 1981, Astrophys. Space Sci. 76, 23.
Wilson, R.E. and Starr, T.C. 1976, M.N.R.A.S. 176, 625.

Emilio Lapasset, Mercedes N. Gómez y Juan J. Clariá : Observatorio Astronómico de Córdoba, Laprida 854, 5000 Córdoba, Argentina.