

Orbital solution for the MACHO*05:34:41.3–69:31:39 O3 If* + O6:V eclipsing binary system in the Large Magellanic Cloud

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ABSTRACT

An orbital solution for the MACHO*05:34:41.3–69:31:39 eclipsing binary system is presented, based on the published light curve and spectral data obtained with the 2.15-m telescope at CASLEO. Based on these spectroscopic observations, the binary components of this system were classified as O3 If* and O6:V respectively. The radial velocity data along with the published light curve were analysed with the Wilson–Devinney code to derive the following masses and radii for the components of this system: $M_1 = 41 \pm 1.2 M_\odot$, $R_1 = 9.6 \pm 0.02 R_\odot$, $M_2 = 27 \pm 1.2 M_\odot$ and $R_2 = 8.0 \pm 0.05 R_\odot$. The solution shows that the system is in overcontact, as one would expect from the derived masses and the very short orbital period (~ 1.4 d).

Key words: binaries: eclipsing – stars: early-type – stars: fundamental parameters – stars: individual: MACHO*05:34:41.3–69:31:39.

1 INTRODUCTION

One of the consequences of the huge amount of data produced by the MACHO project was the discovery of more than six hundred new eclipsing binary stars in the Large Magellanic Cloud (Alcock et al. 1997a). Given that the brightest among these systems lay within the scope of moderate size telescopes for intermediate dispersion spectroscopy, we began to acquire spectra of those objects using the 2.15-m telescope at CASLEO¹ (San Juan, Argentina), with the aim of producing determinations of physical parameters for them. One of the observed stars, the so-called MACHO*05:34:41.3–69:31:39, located in the HII region DEM 242 (Davies, Elliott & Meaburn 1976), turned out to be a double lined O3 If* + O6:V system, a spectral type we would not expect for such a short-period binary. Apart from the general surveys such as the Digitized Sky Survey, there are no previous observations of this star.

There are an intrinsically small number of early O-type stars, and an even smaller number of them in eclipsing binary systems. No O3 star is known to be an eclipsing binary to date. Besides, the masses predicted from comparison of the luminosities of these very hot stars with numerical models are of the order of $100 M_\odot$, a value much larger than that inferred from observations of binary stars of similar spectral types. For these reasons, each newly

discovered O3 star presents an opportunity to provide new data that contribute to resolving this problem.

Of course, it must be considered that numerical models deal with single and isolated stars, while the binary studied here is an extremely close system, with a period of ~ 1.4 d and undoubtedly subject to very strong interaction effects. Consequently, the masses derived here must be considered with caution when compared with evolutionary models.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Photometric and spectroscopic data

The photometric light curve for MACHO*05:34:41.3–69:31:39 was published by Alcock et al. (1997a,b). Data are available for two bands, namely V and R . The V magnitude at maximum is 13.54, while primary and secondary minima have $V = 13.91$ and 13.89 respectively. The $V - R$ colour of the system is -0.15 (in the Kron–Cousins photometric system), with no noticeable changes with phase. Uncertainties given by Alcock et al. rise to 0.07 in V and 0.03 in $V - R$.

During an observing run in 2000 January with the 2.15-m telescope at CASLEO (San Juan, Argentina), N. I. Morrell acquired eight spectra near the times of quadrature.

A REOSC spectrograph was used in its single dispersion mode, with a $600 \text{ groove mm}^{-1}$ grating and a Tek 1024×1024 CCD as detector, this instrumental configuration giving a reciprocal dispersion of $1.8 \text{ \AA pixel}^{-1}$ in the blue–yellow region of the spectrum. The spectrograms covered the region from $3800\text{--}5440 \text{ \AA}$, with a typical resolution (as measured from the He–Ar comparison lamp

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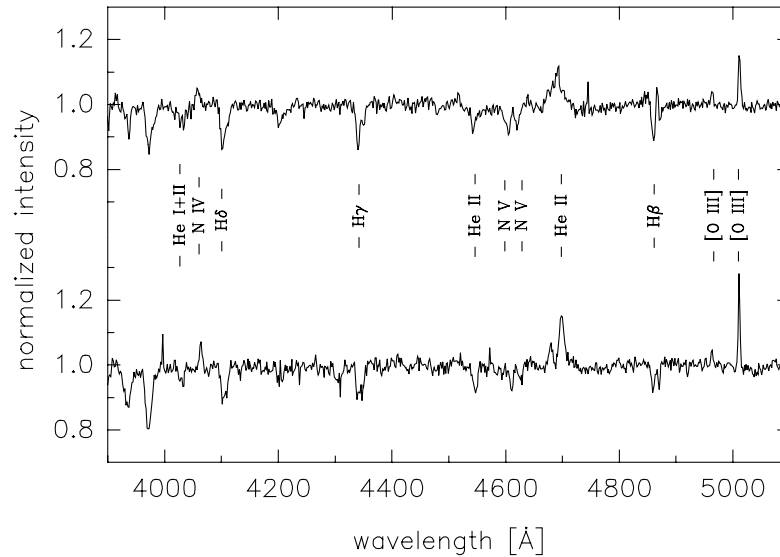


Figure 1. CCD spectrograms of MACHO*05:34:41.3–69:31:39 obtained at CASLEO, corresponding to both quadratures.

Table 1. Observed radial velocities of the eclipsing binary MACHO*05:34:41.3–69:31:39.

HJD $2.5 \times 10^6 +$	phase ^a	Primary V_R (km s^{-1})	Secondary V_R (km s^{-1})
1555.604	0.799	521	−127
1557.588	0.211	−7	659
1562.745	0.882	447	−28
1563.757	0.603	428	−
1564.613	0.212	−47	−
1566.712	0.706	495	−165
1567.622	0.354	55	633
1571.600	0.185	−24	613

^aPhases were calculated with the ephemerides given by Alcock et al. (1997a).

lines) of 2 pixel, and the signal-to-noise ratio ranged from 50 to 100.

The usual sets of bias, dark and flat-field frames were acquired during each observing night. The spectroscopic observations were processed and analysed with IRAF² routines. In order to check the stability of the system for radial velocity measurements, radial velocities for the nebular [O III] emission lines in our spectra were derived, obtaining an average of $+258 \text{ km s}^{-1}$ with a standard deviation of 22 km s^{-1} , a radial velocity that is well within the expected range for Large Magellanic Cloud (LMC) objects.

Just a quick look to the obtained spectrograms revealed that the primary star is an O3 If*^{*}, presenting strong N v 4603–4620 Å absorption lines and emission of N IV, He II and very weak N III. The spectrum of the secondary is hard to classify because of relatively low dispersion data, but considering those observations where the lines are better resolved, it was classified as O6:V. Both components were classified following the criteria described in Walborn & Fitzpatrick (1990). Spectra of MACHO*05:34:41.3–69:31:39 obtained at both quadratures are shown in Fig. 1.

To obtain the radial velocities, the N v $\lambda 4603\text{--}4620 \text{ \AA}$ absorptions and the N IV 4058 Å emission were considered as representative of the motion of the primary O3 If*^{*} component, while for the radial velocities of the secondary component several

He I absorptions were averaged. The measurements were performed through single Gaussian fitting with IRAF routines.

2.2 Light and radial velocity curve solution

The radial velocities derived for the quadratures (Table 1), together with the published photometric light curve, were analysed by means of the Wilson–Devinney code (Wilson & Devinney 1971; Wilson 1990), which is very suitable to model binaries with Roche-lobe filling stars.

From Schmidt-Kaler (1982), a temperature of 50 000 K was assigned for the O3 If*^{*} primary component. The bolometric albedos were set to $A = 1.0$ (Rucinski 1969), and gravity brightening coefficients of value $g = 1.0$ (Lucy 1976) were used. These quantities are the usual guesses for radiative envelopes. Linear limb-darkening coefficients were obtained from van Hamme (1993). A circular orbit was assumed, suggested by the examination of the light curves and as expected for such a close binary. All these parameters, together with the ephemerides supplied by Alcock et al. (1997a) ($P = 1.404740$, $E_0 = 2449073.7109$), were kept constant.

First, the semimajor axis a , the systemic radial velocity V_γ and the mass ratio q were adjusted using only the radial velocity measurements. Thereupon, these parameters were fixed and the orbital inclination i , the temperature of the secondary star T_2 , the luminosity of the primary L_1 and both potentials Ω_1 and Ω_2 were fitted using the light curves. Then these two steps were repeated iteratively until the solution converged. Given that after a few iterations with the differential corrections program (DC) the solution evolved to an overcontact configuration, the program operation was set to mode 1. In this mode, the surface potentials of both stars are kept identical ($\Omega_1 = \Omega_2$), the same as the gravity brightening coefficients ($g_1 = g_2$), the bolometric albedos ($A_1 = A_2$) and the limb-darkening coefficients ($x_1 = x_2$). Besides, the polar temperature of the secondary is set by the gravity brightening law of the entire common envelope. Consequently, in the successive iterations only the parameters i , L_1 and Ω_1 (together with a , V_γ and q) were fitted. The iterations were stopped when the corrections supplied by the DC program were smaller than

²IRAF software is distributed by NOAO, operated by AURA for NSF.

their own errors. Fig. 2 and Fig. 3 show the computed V light and radial velocity curves, together with the observational data.

The adopted and fitted model parameters and the resulting stellar dimensions are listed in Tables 2 and 3, respectively. Fig. 4 displays the aspect of the system at different phases.

2.3 Error estimates

The estimation of the uncertainties in the parameters was attempted in two ways. First, a last run allowing the DC program to fit all the free parameters (i.e. a , V_γ , i , Ω_1 , q and L_1) at one time was performed, and then the standard deviations of the differential corrections supplied by the DC program were used as error estimates. Secondly, the differences between two independent fits, performed using the radial velocity data together with only the V or R light curve separately, were used as error estimates. These differences were smaller than the errors estimated by the first method, which are quoted in Tables 2 and 3.

Weighing the uncertainties of the photometric and spectroscopic data, these error estimates seem rather low. This is not surprising, since in operation mode 1 many parameter constraints are applied, leaving only the six above-quoted quantities to be adjusted. Taking into account this fact, our resulting parameters (and mainly our error estimates) must be considered with caution,

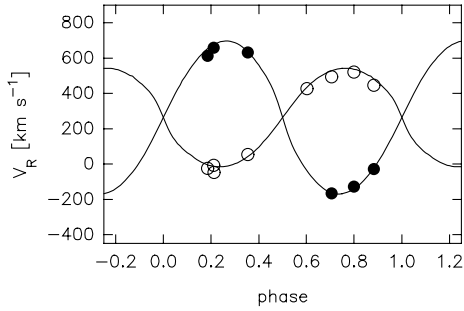


Figure 2. Observed and modelled radial velocity curve for MACHO*05:34:41.3–69:31:39. Open circles correspond to the primary component and filled ones stand for the secondary.

as this very close system, with a ~ 1.4 d orbital period and an O3 star, surely presents appreciable departures from hydrostatic equilibrium geometry because of the strong stellar winds and radiation pressure.

As this star probably belongs to an obscured tight star cluster (the resolution of the Digitized Sky Survey and the MACHO plates does not allow us to address this matter), it was also attempted to include a third light in modelling the light curves. For the best fit, the third light represents only ~ 2.6 per cent of the flux at quadratures, and the other parameters of the model do not change significantly.

Looking at the (O–C) residuals in Fig. 2, two slight systematic trends can be observed. On one hand, the secondary minimum seems not as deep as it is modelled by the Wilson–Devinney

Table 2. Model parameters.

T_1	50000 K (adopted)
g_1, g_2	1.00 (adopted)
A_1, A_2	1.00 (adopted)
x_1, x_2	0.616 (adopted)
e	0.00 (adopted)
a	$22.2 \pm 0.22 R_\odot$
V_γ	$263.1 \pm 3 \text{ km s}^{-1}$
$q (M_2/M_1)$	0.64 ± 0.01
i	$67 \pm 1^\circ$
Ω_1, Ω_2	3.046 ± 0.03
T_2	49490 K

Table 3. Star dimensions.

M_1	$41.16 \pm 1.2 M_\odot$
R_1	$9.56 \pm 0.02 R_\odot$
$M_{\text{bol } 1}$	–9.49
$\log g_1(\text{cgs})$	4.09 ± 0.02
M_2	$27.04 \pm 1.2 M_\odot$
R_2	$7.99 \pm 0.05 R_\odot$
$M_{\text{bol } 2}$	–9.05
$\log g_2(\text{cgs})$	4.07 ± 0.02

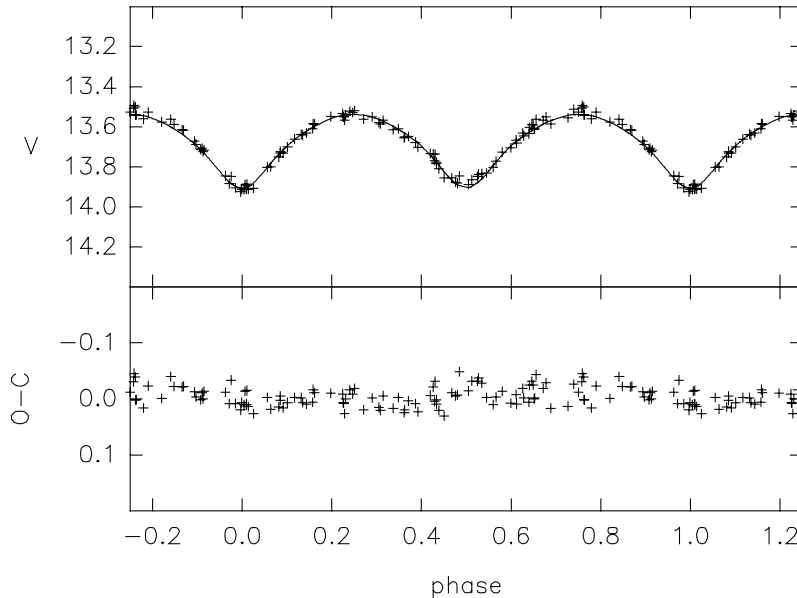


Figure 3. Top: Observed and modelled V light curve for MACHO*05:34:41.3–69:31:39. Bottom: (O–C) residuals for the light curve.

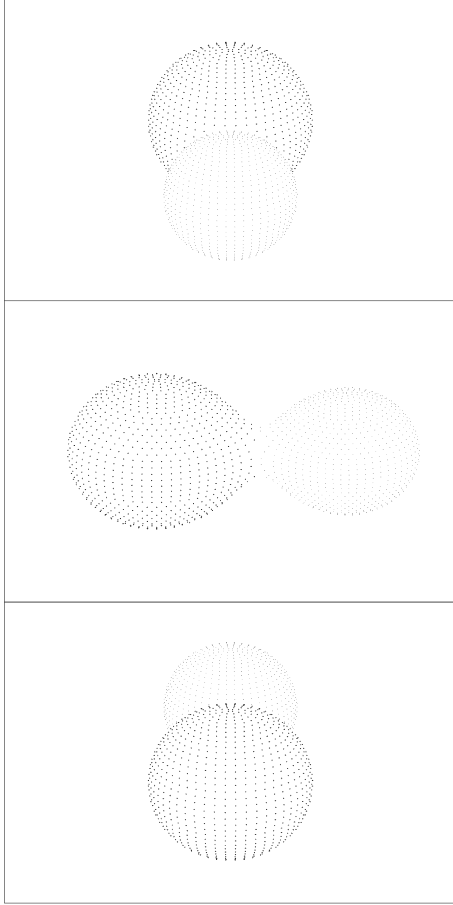


Figure 4. The aspect of the overcontact system MACHO*05:34:41.3–69:31:39. Top: at primary minimum; middle: at first quadrature; bottom: at secondary minimum.

program. This feature indicates a bigger temperature difference between the components, in accord with the spectral types. The mode of operation 3 of the DC program retains all the parameter constraints for overcontact systems, except for the temperature of the secondary T_2 . An attempt to estimate the secondary temperature from the light curves yielded $T_2 = 47\,200 \pm 1700$ K (for $T_1 = 50\,000$ K). However, because the difference in surface temperatures affects mainly the far UV brightness in such very hot stars (for which it is urgent to acquire data) and its influence in the V and R bands is slight, this temperature estimation may be considered with caution. Taking into account the photometric errors, a temperature difference greater than 5000 K between the two components can be rejected. The other systematic deviation of our modelled light curve (very slight also) is an excess of brightness in the maximum following the secondary minimum (O’Connell effect, see Davidge & Milone 1984). The O’Connell effect is often modelled by adding ‘hotspots’ on the surface of the stars, although its physical causes in very hot binaries are not clear. It was not attempted to model this feature, because it also is hardly noticeable in comparison with the photometric errors.

3 RESULTS

It was an absolutely unexpected discovery to find an O3 If*-type star in such a very close binary pair. There are no published evolutionary models suitable for this system, and single-star models are not adequate. The derived masses (~ 41 and $\sim 27 M_\odot$, with an inclination of 67°) seem to be surprisingly low.

Alcock et al. (1997a) presented a fit of the light curves performed by means of the Nelson–Davis–Etzel model (Nelson & Davis 1972; Popper & Etzel 1981). Assuming a mass ratio $q = 0.95$, they derived an inclination of $\sim 57^\circ$. The difference from the results presented here is not surprising, given that the Nelson–Davis–Etzel model is not adequate for highly distorted systems and the value of q derived from the radial velocity measurements is significantly different from the one assumed in Alcock et al.

The system resembles the O4f+O6V binary Sk-67°105 (see Niemela & Morrell 1986; Haefner, Simon & Fiedler 1994) but it is hotter and closer. On the other hand, our mass estimate for the primary is similar to that derived by Antokhina et al. (2000) for the O3 star of the non-eclipsing system HD 93205 ($\sim 45 M_\odot$ for their best fit).

Undoubtedly, this system will require further investigation, especially UV photometry and high dispersion spectroscopy.

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REFERENCES

- Alcock C. et al., 1997a, *AJ*, 114, 326
- Alcock C. et al., 1997b, *AAS CD-ROM Ser.*, Vol. 9
- Antokhina E. A., Moffat A. F. J., Antokhin I. I., Bertrand J. F., Lamontagne R., 2000, *ApJ*, 529, 463
- Davidge T. J., Milone E. F., 1984, *ApJS*, 55, 571
- Davies R. D., Elliot K. H., Meaburn J., 1976, *Mem. R. Astron. Soc.*, 81, 89
- Haefner R., Simon K. P., Fiedler A., 1994, *A&A*, 288, L9
- Lucy L. B., 1976, *ApJ*, 205, 208
- Nelson B., Davis W. D., 1972, *ApJ*, 174, 617
- Niemela V. S., Morrell N. I., 1986, *ApJ*, 310, 715
- Popper D. M., Etzel P. B., 1981, *AJ*, 86, 102
- Schmidt-Kaler Th., 1982, in Shaifers K., Voigt H. H., eds, *Landolt-Börnstein New Ser., Group VI, Numerical data and functional relationships in science and technology, Vol. 2/b*. Springer, Berlin
- Rucinski S. M., 1969, *Acta Astron.*, 19, 245
- van Hamme W., 1993, *AJ*, 106, 2096
- Walborn N. R., Fitzpatrick E. L., 1990, *PASP*, 379, 411
- Wilson R. E., 1990, *ApJ*, 356, 613
- Wilson R. E., Devinney E. J., 1971, *ApJ*, 166, 605

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