Photometry of Two Unusual A Supergiant Systems in the Small Magellanic Cloud

R. E. Mennickent
Departamento de Astronomía, Facultad de Ciencias Físicas y Matemáticas, Universidad de Concepción,
Casilla 160-C, Concepción, Chile; rmennick@astro.udec.cl

M. A. Smith
Department of Physics, Catholic University of America, Washington, DC 20064

Z. Kołaczkowski
Instytut Astronomiczny Uniwersytetu Wrocławskiego, Kopernika 11, 51-622 Wrocław, Poland

G. Pietrzynski and I. Soszyński
Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

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ABSTRACT. We present multiwavelength broadband photometry and V, I time-resolved photometry for two variable bright stars in the SMC, OGLE004336.91-732637.7 (SMC-SC3) and OGLE004633.76-731204.3 (SMC-SC4). The light curves span 12 yr and show long-term periodicities (SMC-SC3) and modulated eclipses (SMC-SC4) that are discussed in terms of wide-orbit intermediate-mass interacting binaries and associated envelopes. SMC-SC3 shows a primary period of 238.1 days along with a complicated waveform suggesting ellipsoidal variability influenced by an eccentric orbit. This star also shows a secondary variability with an unstable periodicity that has a mean value of 15.3 days. We suggest this could be associated with nonradial pulsations.

Online material: color figures

1. INTRODUCTION

The evolution of massive stars is an important topic of stellar astrophysics because it provides clues to the mechanisms that feed the Galactic medium with the building blocks of future generations of stars. Many of the evolutionary stages of massive stars are short-lived and hence challenge our ability to find enough examples of a common group to characterize them. Detecting objects in these brief phases of evolution is of great use in testing current theories of massive star evolution, especially if they represent populations with low metal abundances, a property of stars in the Magellanic Clouds. A complete census of the pre- and just post–main-sequence population of massive stars in the Clouds has not yet been compiled, and thus attributes of these subpopulations are not well known, but they are known to be generally variable. Catalogs of B stars with unusual variable light curves in the Magellanic Clouds (e.g., Mennickent et al. 2002, hereafter M02, and Sabogal et al. 2005), based on OGLE photometry (Udalski et al. 1997, Szymański 2005), provide excellent material for analysis of massive stars near the main sequence. In an effort to characterize some of these stars, follow-up spectroscopy was conducted for two stars in the Type 3 M02 sample2, which will be given in a future article (Mennickent & Smith 2010, hereafter MS10). Both of these stars turn out to be probable binaries and to have highly peculiar characteristics. In this article we present the photometric results for these stars.

The stars chosen were taken from an initial sample of eight type 3 variables in the M02 catalog satisfying the arbitrary criterion of having visual magnitudes brighter than 14.2. No other criteria were imposed on their selection. The stars selected were OGLE004336.91-732637.7 (SMC-SC3) and OGLE004633.76-731204.3 (SMC-SC4). The light curves span 12 yr and show long-term periodicities (SMC-SC3) and modulated eclipses (SMC-SC4) that are discussed in terms of wide-orbit intermediate-mass interacting binaries and associated envelopes. SMC-SC3 shows a primary period of 238.1 days along with a complicated waveform suggesting ellipsoidal variability influenced by an eccentric orbit. This star also shows a secondary variability with an unstable periodicity that has a mean value of 15.3 days. We suggest this could be associated with nonradial pulsations.

2Type-3 variables are SMC Be star candidates with I-band light curves varying periodically or quasi-periodically.
of Hα emission-line objects by Martayan et al. (2010), their star in cluster SMC-17.

The goals of this article are to characterize the photometric properties of these two stars with the longer time baseline available and gain further insights on the formation and nature of these systems.

2. PHOTOMETRIC RESULTS

We give broadband $V$ and $V_{\text{OGLE}}$ magnitudes and $UBVR$ colors for both program stars in Table 1, along with dereddened colors $(B-V)_0$ and estimated spectral types. For SMC-SC3, we calculated $(B-V)_0$ using $E(B-V) = 0.10$ (Martayan et al. 2010). For SMC-SC4, we assumed $E(B-V) = 0.09$ as representative for SMC (van den Bergh 2000). The spectral types listed in Table 1 were derived from $(B-V)_0$ using the Fitzgerald (1970) calibration and assuming a luminosity class of II or I, derived from their magnitudes and membership in the SMC. The $(B-V)_0$ color suggests middle A spectral types. The previous spectroscopic classifications of A7-F5e for SMC-SC3 and F5Ie + G0I for SMC-SC4, given by M06, were probably influenced by the detection of shell metallic lines in low-resolution spectra, which are formed in relatively cool stellar envelopes.

From the visual magnitudes and SMC distance (Udalski 2000), we can estimate the absolute magnitudes as $M_V = -4.83$ for SMC-SC3 and $-5.05$ for SMC-SC4. Note that this refers to the visual magnitude of the primary since the secondary contributes only a few percent to the light in this region. Using a bolometric correction of $-0.13$ for an A5 supergiant, we obtain $M_{\text{bol}} = -5.0$ and $-5.2$, respectively. From the evolutionary tracks for stars with SMC metallicities by Meynet & Maeder (2001, hereafter MM01), both stars fit tracks of $9 M_\odot$ evolved stars in the MM01 models. As the evolutionary tracks of MM01 depend on the value of stellar mass and rotation velocity, the position of the optical component of these systems in the $M_V - T_{\text{eff}}$ diagram cannot be used with the MM01 models alone to determine the evolutionary state.

SMC-SC3 is a probable member of the open cluster NGC 242, and in fact its angular distance from the cluster center is only $\sim10''$. In Figure 1 we show the color-magnitude diagram for SMC-SC3 and for neighboring stars present in the field. We investigated the light curves for the stars labeled 1, 2, and 3, and we found them to be photometrically constant. The figure also depicts isochrones for the cluster NGC 242 based on the parameters given in the caption. It is clear that the bright objects represented here lie close to the log $t = 7.8$ isochrone. This is approximately the reported age of this cluster (7.9; Ahumada et al. 2002). Figure 1 also depicts the observed position of SMC-SC3. Its unreddened location in the H-R diagram should be projected back along the indicated reddening vector. The position of both objects in the H-R diagram indicates that they are evolved luminous stars found in a stage during core hydrogen exhaustion.

The 2MASS $J-K$ photometry of these two stars is minimally affected by interstellar reddening. These values are 0.27 and 0.35 for SMC-SC3 and SMC-SC4, respectively (Table 2), much larger than the typical $J-K$ color of an A5 supergiant (0.12 mag, Koornneef 1983), as inferred from the $(B-V)_0$. Similarly the $V-K$ colors, of about 0.5 mag and 0.8 mag, respectively, are much larger than the typical $V-K$ color of an A5 supergiant (0.36 mag, Koornneef 1983). Emission caused by scattering of free electrons in circumstellar envelopes is a likely candidate for explaining the infrared excess. Their moderate values exclude the presence of much dust around these stars and explain the discrepancy between spectral types derived from optical and infrared photometric colors.

Deep exposures of sky images surrounding the two program objects reveal no suggestion of nebulosity. However, during our investigation we discovered that SMC-SC3 has a visual companion, the small bump 1° NW of SMC-SC3 in Figure 1. We analyzed its OGLE light curve as part of this study and discovered that this visual companion is an eclipsing binary with an orbital period of 2.96934 days, $V = 16.776$, and $V - I = -0.083$. Its $\Delta I$ range of variability range was 0.77 mag. This nearby star is not in the catalog of SMC eclipsing binaries (Bayne et al. 2002) but was included in the catalog of eclipsing variables by Udalski et al. (1998b) under the designation SMC-SC3 star number 63551. The fact that the star is 2.6 mag fainter than SMC-SC3 makes it unlikely that the periodicities discussed in § 2.1 are caused by the contribution of this star’s light to the photometric colors.

We have included the following data sets in our analysis: OGLE II DoPhot $V$ light curves, OGLE II DIA $I$ light curves, and OGLE III DIA $V$, $I$ light curves. A summary of these data sets is given in Table 3. The range of HJDs shown corresponds roughly from mid-1997 to mid-2009 (Fig. 2).

We proceed to analyze the photometric variations in our time series, using the pvm algorithm (after the phase dispersion minimization algorithm; Stellingwerf 1978).

| Object     | $U$ | $B$ | $V$ | $R$ | $V_{\text{OGLE}}$ | $(B-V)_{\text{OGLE}}$ | $(V-I)_{\text{OGLE}}$ | $(B-V)_0$ | Spectral Type |
|------------|-----|-----|-----|-----|-------------------|----------------------|----------------------|-----------|---------------|
| SMC-SC3    | -   | 13.63 | 13.48 | 13.30 | 14.18          | 0.181            | 0.351                  | 0.08      | A4            |
| SMC-SC4    | 14.34 | 14.15 | 13.94 | 13.70 | 14.06          | 0.206            | 0.385                  | 0.11      | A5            |
2.1. Characterization of the Light Curve of SMC-SC3

The expanded data set allowed us to examine the possible range of periods over a greater range than was available to M02 and M06. In fact, we found a more reliable primary period that is twice as long as these authors had found, namely 238.1 ($\pm$2.3, 13 days, 0.1) days, but it clearly gives the deeper minimum in the $p$dm periodogram. The new baseline in time is sufficient to rule out an even longer (e.g., 476 day) period. The period error is the half-width at half-maximum (HWHM) of the (asymmetrical) periodogram’s peak. The improved ephemeris for the measured centroid of the light curve maximum of SMC-SC3 is

| Object   | I     | J     | H     | K     | JD/Date         | Phase | Source |
|----------|-------|-------|-------|-------|-----------------|-------|--------|
| SMC-SC3  | 13.701(9) | 13.346(22) |       | 12.954(116) | 1998 Aug 12 | 0.52 | 1      |
| SMC-SC3  | 13.847(30) | 13.472(90) |       | 13.050(180) | 2450144.6148 | 0.90 | 1      |
| SMC-SC3  | 13.781(40) | 13.560(110) |       | 13.134(160) | 2451048.7763 | 0.56 | 1      |
| SMC-SC3  |       | 13.545(42) | 13.341(50) | 13.275(40) | 2451034.7109 | 0.50 | 2      |
| SMC-SC3  |       | 13.540(20) | 13.380(10) | 13.180(20) |                  | ...... | 3      |
| SMC-SC4  | 13.655(30) | 13.388(90) |       | 13.316(210) | 2450418.5524 | 0.42 | 1      |
| SMC-SC4  | 13.616(30) | 13.383(130) |       | 13.079(150) | 2451039.7991 | 0.79 | 1      |
| SMC-SC4  |       | 13.403(29) | 13.236(34) | 13.054(35) | 2451034.7134 | 0.76 | 2      |
| SMC-SC4  |       | 13.380(10) | 13.260(10) | 13.170(20) |                  | ...... | 3      |

**Table 2**

**Infrared Magnitudes for Program Stars**

**Note.**—Phase refers to ephemerides given in equations (1) and (4).

**References.**—(1) DENIS (Deep Near Infrared Survey) of the Southern Sky, cds.u-strasbg.fr/denis.html; (2) 2MASS All Sky Survey at IPAC, www.ipac.caltech.edu/2mass/; (3) Kato et al. 2007, pasj.asj.or.jp/v59/n3/590315/.
We modeled the SMC-SC3 light curve with harmonics and sub-harmonics of this fundamental period and, after analyzing residuals, it was clear that, apart from a small seasonal variability, the second periodicity of 15 days, reported by M06, still persisted in the Fourier spectrogram (Fig. 3). For this sinusoidal 15 day periodicity we found the ephemeris:

$$T(\text{HJD}) = 2452739.76 + 15.35(0.02) E.$$  \hspace{1cm} (2)

The Fourier periodogram of SMC-SC3 indicates that sidelobes surround the primary peak. This fact suggests the possibility that the Fourier spectrum shows the combined effect of several close frequencies acting simultaneously giving origin to harmonic interactions. However, in this case we should observe a modulation of the amplitude of the light curve, and this is not observed in our reconstruction of the 15 day light curve. Another interpretation for the existence of sidelobes comes from the analysis of the \(O - C\) diagram (based on observed minus predicted values, we estimate a characteristic noise of 0.01 mag for the SMC-SC4 light curve. However, the somewhat larger (0.1 mag) variability actually observed in the light curve indicates that there is another chaotic signal arising from the star. The new analysis also shows that the former 24 day periodicity reported by M06 was the result of their time-limited data set and the presence in the light curve of noncoherent quasi-periodic modulations, perhaps pulsations. The latter signal is responsible for the large noise visible in the smoothed curves of Figure 6a, particularly outside the primary eclipse. This signal also illustrates the absence of a secondary eclipse in the \(I\) band. The \(V\) band, however, suggests the presence of a very wide secondary eclipse (Fig. 6b). Furthermore, we conclude from this figure that the eclipses are irregular in shape and depth, although they recur periodically. The general appearance of the observed \(O - C\) diagram was also reproduced by our simulation. However, we emphasize that this representation, including the persistence of a 3800 day superperiod, has no predictive power for new additions to this star’s light curve.

As a matter of convenience for the analysis, we will consider this complex variability as the simple periodicity represented by the ephemeris given in equation (2).

Whereas the 15 day cycle is represented roughly by sinusoidal variability, the 238 day periodicity is characterized by two unequal minima, like those observed in ellipsoidal variables (Fig. 5). However, SMC-SC3 does not appear to be a bona fide ellipsoidal variable. The maximum of its light curve is a sharp excursion over a longer asymmetrical variation and the first rising branch is steeper and shorter than the second one. All of these features, especially the double modulation and the two unequal minima not separated by half a cycle, are consistent with ellipsoidal variations in an atypical eccentric binary (Hilditch 2001).

### 2.2. Characterization of the Light Curve of SMC-SC4

The light curve of SMC-SC4 is of interest in that it not only produces eclipses, but the eclipse depths can vary from cycle to cycle (Fig. 2). The ephemeris for the eclipses is:

$$T_{\text{min}}(\text{HJD}) = 2450709.9(2) + 184.26(1.25) E,$$  \hspace{1cm} (4)

where we used the \(\text{pdm}\) algorithm on the expanded \(I\)-band data set to search for periods. From the median of the absolute values of the differences between magnitudes of point-to-point measurements, we estimate a characteristic noise of 0.01 mag for the SMC-SC4 light curve. However, the somewhat larger (0.1 mag) variability actually observed in the light curve indicates that there is another chaotic signal arising from the star. The new analysis also shows that the former 24 day periodicity reported by M06 was the result of their time-limited data set and the presence in the light curve of noncoherent quasi-periodic modulations, perhaps pulsations. The latter signal is responsible for the large noise visible in the smoothed curves of Figure 6a, particularly outside the primary eclipse. This signal also illustrates the absence of a secondary eclipse in the \(I\) band. The \(V\) band, however, suggests the presence of a very wide secondary eclipse (Fig. 6b). Furthermore, we conclude from this figure that the eclipses are irregular in shape and depth, although they recur periodically.

### Table 3

| Object     | Data Set | HJD–Start | HJD–End  | Number of observations |
|------------|----------|-----------|----------|------------------------|
| SMC-SC3    | OGLE I band | 50621.83606 | 54866.55206 | 1022 |
| SMC-SC3    | OGLE V band | 50670.89064 | 54792.59219 | 82  |
| SMC-SC4    | OGLE I band | 50612.79700 | 54954.8836  | 1067 |
| SMC-SC4    | OGLE V band | 50645.91866 | 54954.89402 | 94  |

Note.—HJD zero point is 2,400,000. Data are from OGLE I, II, and III.
with a mean period of 184 days. They are about as deep in $V$ as in $I$, 0.5–0.6 mag. Changes in the eclipse shapes and depths occur, and the latter appear to be modulated. For instance, OGLE III data suggest a supercycle for the eclipse depth of about 8 times the basic period, but this tendency disappears when considering the earlier OGLE II data set (i.e., those obtained before HJD 2,452,000, Fig. 2). We argue that the same low-frequency variability observed outside eclipse could be responsible for the observed changes in eclipse shape, but not for the depth changes.

3. DISCUSSION

In this section we will evaluate the interesting attributes of SMC-SC4 light curve, and follow with a discussion on the even more remarkable properties of SMC-SC3.
The fact that eclipses of SMC-SC4 are irregular in depth but with an arguably regular timing indeed indicates that the A star is eclipsed by an almost opaque but possibly ever-changing body, rather than by the secondary star. There are at least two additional reasons that the eclipse cannot reasonably be ascribed to a star-star eclipse:

1. A large fraction of the A star is eclipsed, and if they were caused by the much hotter star (such as we observe in the near-UV, see MS10), the eclipse depths would be larger in the $V$ magnitude than in $I$.

2. The radius of the secondary star is likely to be smaller than the A star’s and cannot account for the large geometric obscuration observed in the $I$ band, yet the long ($\sim 0.2$ cycles) duration of the eclipse implies that a large body orbits near the A star. This body is warm (accounting for the nearly equal eclipse depths in the two photometric bands) and is therefore likely to be within a stellar radius or so from the A star.

We conclude that the eclipses are inconsistent with a third star in a dynamically stable orbit. Rather, they are caused by a large, almost opaque body, probably extending well out of the orbital plane of the SMC-SC4 system and intruding into our line of sight during this phase. It appears to be due to an impermanent, ever-replenished structure that co-orbits within the binary star system.

The photometric variability of SMC-SC3 analyzed in this article consisting of a main ellipsoidal variability is consistent with a binary nature. As mentioned earlier, the double minima of the 238 day folded light curve exhibit unusual signatures which can be interpreted only in terms of an ellipsoidal variable. The unequal amplitudes, spacings, and asymmetries of the minimum lobes strongly suggest that this object is a binary with a mild eccentricity. Model light curve grids of Soszyński et al. (2004) suggest that the asymmetry of, especially, the time of second minimum is sensitive to a large orbital eccentricity. A comparison of these models indicates that the orbital eccentricity is nonzero but modest, e.g., $e \approx 0.2$. However, another diagnostic argues that any eccentricity in this system is actually somewhat larger. In particular, the sharp maximum observed for SMC-SC3 at phase 0.0 (Fig. 5) is not typical of small eccentricities, but examples have been well documented. For example, a similar feature has been observed, but much less pronounced, in V380 Cygni (Guinan et al. 2000, see other examples in Fig. 8 of Soszyński et al. 2004). These maxima are frequently interpreted as the reflection of the hotter star on the distorted and more distended cooler star at minimum binary separation. According to

![Figure 3](image1.png)  
**Fig. 3.**—Fourier spectrum of such a residual light curve along with the scaled and vertically shifted window spectrum. The main peak is the 15 day periodicity.

![Figure 4](image2.png)  
**Fig. 4.**—$O - C$ diagram for the maxima of the 15 day periodicity of SMC-SC3. This figure shows a time scale of variability for the 15 day cycle of 3800 days, corresponding to twice the distance between maximum and minimum (about 250 cycles).

![Figure 5](image3.png)  
**Fig. 5.**—Spline function representing the ellipsoidal variability of SMC-SC3 folded over a period of 238.1 days. Spectra to be discussed in MS10 are at phases 0.28, 0.69, and 0.44.
canonical interpretations of ellipsoidal variable light curves, the light maximum corresponds to a time when the visible star (in this case, the secondary at optical wavelengths) presents its maximum area in the plane of the sky. The fact that we see evidence in the form of an absolute light maximum at this same phase indicates that this phase corresponds nearly to periastron passage as well. Although this places some geometrical constraints on the orbital parameters, it is clear that a precise determination of the orbital parameters requires a set of RVs sampling the whole binary cycle. Most importantly, given a period as long as 238 days, the semimajor axis of the orbit must be large, and this, together with the presence of a reflection effect suggests that the eccentricity is large, perhaps $e \approx 0.9$.

We are not yet able to reconcile these considerations, but we have a preference currently for the high eccentricity because we believe the “reflection effect” is the more robust interpretation.

We note the similarity of the photometric behavior of our targets with the recently released light curves of OGLE-LMC-LPV-41682, that with $V = 13.958$ shows eclipses of variable depth with period 219.9 days, and a second periodicity of 44 days, and possibly OGLE-LMC-LPV-15046, that with $V = 16.887$ shows a main period of 148.67 days, along with lower amplitude periods of 272.60 days and 181.88 days, resulting in a light curve with oscillations of variable amplitude (Soszyński et al. 2009). This opens the possibility that SMC-SC3 and SMC-SC4 are not rarities, and can be understood within the context of luminous interactive binaries in which mass loss and/or exchange may be occurring. These objects will be discussed in a forthcoming article.

Regarding the short photometric cycles observed in both systems (15 day cycle in SMC-SC3 and otherwise still unspecified noncoherent variations in SMC-SC4), we consider the possibility that they could be linked to nonradial pulsations of the A supergiant. The variability of the 15 day photometric cycle observed in SMC-SC3 suggests a nonbinary nature. It is generally believed that hot and luminous stars of the $\alpha$ Cygni type show irregular variability driven by nonradial pulsations on time scales of weeks (e.g., de Jager et al. 1991). These are supergiants of spectral types B-A and amplitude of variability $\sim 0.1$ mag. It is then possible that part of the photometric variability observed in our program objects corresponds to pulsational activity. The amplitude of these pulsations in SMC-SC4 is large enough that we suspect that even partial eclipses of the A-type supergiant allows their detection.

We considered also the possibility that the 15 day cycle corresponds to advection of stellar spots. However, for $v \sin i = 20 \pm 5$ km s$^{-1}$ and $R = 30 R_\odot$, derived by MS10, the rotational period of the A supergiant should be 76 sin $i$ days. This is too long to fit the 15 day periodicity and, assuming that its orientation is not nearly pole-on, not synchronous with the binary period.

4. CONCLUSIONS

We have presented the analysis of OGLE light curves of two SMC bright systems showing novel photometric properties. These properties are consistent with the interpretation that these stars are long-period interacting binaries with an evolved most-luminous stellar component. We find eclipses in SMC-SC3 with $P_e = 184$ days modulated in depth and perhaps shape on time scales of hundreds of days, suggesting the presence of a variable and nonstellar eclipsing region. In addition, we discovered an unusually strong reflection effect in the orbital light curve of SMC-SC3 ($P_o = 238$ days) and a short variability with a quasi period of 15.3 days changing on time scales of 3800 days. We note the possibility that the short-term fluctuations observed in

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**Fig. 6.**—Coplotting of eclipses in SMC-SC4 (upper panel). The factor “2” in the x-axis label accounts for the data seasonal gaps. The star was observed annually at the same time of year, and one season happens to be roughly twice the orbital period of the star. Light curves for $I$ and $V$ filter OGLE data are folded with the ephemerides given in equation (2) of the text, i.e., with the period of 184.25 days (bottom panel). The $V$-band data were taken over part of the longer time span of the $I$-band observations. Note that the eclipse minima in $V$ are at least as deep as for the $I$ filter. Spectra to be discussed in MS10 are at phases 0.10, 0.23, and 0.66. See the electronic edition of the PASP for a color version of this figure.
both stars are signatures of nonradial pulsation. This may explain the “drifting” of a single 15 day periodicity in the light curve of SMC-SC3.

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