Eclipsing binaries in the open cluster NGC 2243 - I. Photometry

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ABSTRACT

We obtained BV time series photometry for 12 variable stars from the field of the old open cluster NGC 2243. The sample includes 3 newly identified detached/semi-detached binaries. There are now four detached eclipsing binaries which are likely members of the cluster. Determination of the absolute parameters of the components would provide a valuable check on evolutionary models of low-mass stars. An accurate ephemeris and orbital period analysis are presented for the previously-known detached binary NV CMa. We also provide ephemerides for 7 other periodic variables. We show that 3 contact binaries are likely members of the cluster.

Stars: binaries: eclipsing, binaries – stars: individual: NV CMa – open clusters and associations: individual: NGC 2243

1 Introduction

Detached eclipsing binaries (DEBs) at the moment provide the most accurate determinations of the absolute stellar parameters of mass and radius (Andersen 1991, 1998). Although recent developments in high-precision astrometry, combined with radial velocity measurements, hold great promise in this respect (eg. Muterspaugh et al. 2005), DEBs can be observed at much larger distances than visual binaries and, moreover, they allow a more direct determination of stellar radii and temperatures. Systems of early spectral type can be used as standard candles as far as in the Local Group Galaxies (Paczyński 1997; Clausen 2004; Ribas et al. 2005). DEBs located in open and globular clusters provide a particularly interesting check on stellar evolution theory (Paczyński 1997).

NGC 2243 is an intermediate age open cluster located in the direction of Galactic anticenter (l = 239.5°, b = −18.0°) in a region of low reddening. An early photometric study of the cluster by Hawarden (1975) was followed by CCD-based studies by Bonifazi (1990) and Bergbusch et al. (1991), and more recently by Anthony-Twarog et al. (2005). The last authors used uvbyCaHβ photometry to derive reddening $E(B-V) = 0.055 \pm 0.004$, metallicity $[\text{Fe/H}] = -0.57 \pm 0.03$, age of $3.8 \pm 0.2$ Gyr, and an apparent distance modulus $(m-M)_V = 13.15 \pm 0.1$. Spectroscopic studies conducted by Gratton & Contarini (1994; only two giants observed) and Friel et al. (2002) gave $[\text{Fe/H}] = -0.48 \pm 0.15$ and $[\text{Fe/H}] = -0.49 \pm 0.05$, respectively. The CCD-based color magnitude

*This paper is based in part on data obtained at the South African Astronomical Observatory.
diagrams of NGC 2243 (see references above) exhibit a well marked sequence of ‘photometric binaries’, formed by stars located about 0.7 mag above the main sequence defined by the ‘single’ stars. This indicates that the cluster possesses a rich population of binary stars with mass ratio close to unity.

The field of NGC 2243 was surveyed for variable stars by Kaluzny et al. (1996; hereafter KKM). The sample of 6 detected objects included 3 DEBs, 2 contact binaries and a background RR Lyr star. Recently, Anthony-Twarog et al. (2005) identified 4 new candidate variables in the cluster field.

The present study resulted from an effort aimed mainly at obtaining a good quality light curve for the eclipsing binary V1=NV CMa detected by KKM. The system is located near the main-sequence turnoff on the cluster color-magnitude diagram. Its light curve exhibits two eclipses of similar depth with $\delta V \approx 0.6$ mag. The flatness of the light curve outside of eclipses together with an orbital period of $P=1.19$ days indicates that the binary has a detached configuration and hence deserves more detailed study. As a first step toward this goal we present $BV$ light curves of V1=NV CMa. We also report some results for other objects, including the detection of new variables in the central field of the cluster.

## 2 Observations and Data Reduction

New observations aimed primarily at obtaining complete $BV$ light curves of NV CMa were obtained with the 1.0-m Swope telescope at Las Campanas Observatory. The telescope was used at the f/13.5 focus without a Gascoigne corrector lens which is employed in its normal f/7 configuration. The atypical f/13.5 configuration allowed better sampling of the point spread function (PSF) at a cost of a reduced field of view. It was considered important to obtain well sampled images as NV CMa possesses a close visual companion located at an angular distance of about 1.6 arcsec. It would be difficult to obtain accurate time series photometry of the variable if the stellar images were poorly sampled. The first data set was collected on 6 nights between 1995 December 29 and 1996 January 4 (run #1). We used the Tektronix 1024 $\times$ 1024 TEK1 detector giving a scale 0.36 arcsec/pix. Exposure times ranged from 90s to 120s for the $V$ filter and from 90 s to 240 s for the $B$ filter. A total of 55 $B$-band and 689 $V$-band images were collected. The second observing run occurred during the period 1997 January 6-10 (run #2). The Tektronix 2048 $\times$ 2048 TEK5 detector subrastered to 1200 $\times$ 1200 pixels was used. The scale was 0.33 arcsec/pixel. The exposure time was set to 200s for the $B$ band and to 120s for the $V$ band. A total of 160 $B$-band and 225 $V$-band images were collected. During runs #1 and #2 the cluster was monitored for a total of about 57 hours.

Some additional data aimed at a photometric calibration of the cluster field were obtained on 2 nights in 1999 November. The $2048 \times 4096$ SITe3 detector subrastered to $2048 \times 3150$ pixels was used at the f/7 focus of the Swope telescope (run #3). This configuration resulted in images with a scale of 0.435 arcsec/pixel.

The last set of observations was collected with the 1.0-m telescope at SAAO observatory (run #4). These observations were directed toward a photometric calibration of the cluster field. An additional goal was to improve the ephemeris for NV CMa by determining the moments of two minima of light. The detector was a STE4 1024 $\times$ 1024 camera giving a scale of 0.31 arcsec/pixel. During that run the cluster was observed for a total of 9 hours on 5 nights spanning the period 2005 October 18-25.
The raw data were pre-processed with the IRAF-CCDPROC package. In particular frames obtained during run #3 were corrected for the known non-linearity of the SITe3 camera. Time series photometry was extracted using the ISIS-2.1 image subtraction package (Alard & Lupton 1998; Alard 2000). Our procedure followed closely that described in some detail by Mochejska et al. (2002). Instrumental magnitude zero points for the ISIS differential light curves were determined from the template images using the DAOPHOT/ALLSTAR package (Stetson 1987). Aperture corrections were measured with the DAOGROW program (Stetson 1990). Instrumental magnitudes were transformed to the standard $BV$ system using a large assembly of local standards established during run #3 (see below).

3 Photometric Calibration

We first attempted to obtain a photometric calibration for the monitored field during run #2. Unfortunately, later analysis showed that all nights during that run were only marginally photometric. To resolve this, we observed NGC 2243 along with several Landolt (1992) fields on two photometric nights, 1999 November 16 and 18, during run #3. Transformation coefficients calculated for these two nights are consistent with each other. Further standards were observed on the night of November 16. Specifically, on that night 7 $BV$ observations of 3 standard fields (T Phe, RU 149 and RU 152) were collected. There were a total of 41 standard stars in these fields with photometry available from Stetson (2000). The following relations between instrumental and standard magnitudes were obtained:

\[
v = V - 0.010(3) \times (B - V) + 0.15 \times (X - 1.25) + 2.967(2),
\]

\[
b - v = 0.965(3) \times (B - V) + 0.12 \times (X - 1.25) + 0.240(3),
\]

\[
b = B - 0.049(3) \times (B - V) + 0.27 \times (X - 1.25) + 3.208(2).
\]

The standards were observed over small range of air-mass, $1.06 < X < 1.20$. Therefore, no attempt has been made to derive extinction coefficients. Instead average values of extinction at Las Campanas were adopted. This has little effect on the calibration of NGC 2243 field as the cluster was observed at an air mass of $X = 1.12$, which falls within the range of air-masses covered by the standards. In Fig. 1 we show residuals between the standard and recovered magnitudes and colors for Stetson standards from Landolt’s fields. Aperture photometry was extracted for standards with the DAOPHOT and DAOGROW programs (Stetson 1987, 1990). As for the cluster, field extraction of profile photometry with DAOPHOT/ALLSTAR was followed by determination of aperture corrections for frames with all stars subtracted except those used for determination of the PSF. Specifically, aperture corrections were determined for a pair of NGC 2243 frames: $V$–300s and $B$–420s. Photometry based on these frames was supplemented by measurements extracted from two shorter exposures: $V$–60s and $B$–90s. The one sigma uncertainty of the zero points of our photometry is about 0.015 mag for both bands (this includes errors of transformation coefficients and errors of aperture corrections). Cluster stars with $BV$ photometry

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‡The current version of the catalog is available at [http://cadcwww.hia.nrc.ca/astrocat](http://cadcwww.hia.nrc.ca/astrocat).

Throughout this paper we use Stetson’s photometry dated at May 2 2005.
based on the data from run #3 were subsequently used as local standards. In particular instrumental photometry from runs #1 and #2 was tied to these local standards. The observations obtained on 1999 November 18 resulted in $BV$ photometry of NGC 2243 with an average difference in the zero points with respect to the November 16 data of $\Delta V = 0.001$ and $\Delta(B - V) = 0.002$.

As shown below, there is an unexpectedly large offset of the zero point of our $V$ photometry relative to Stetson (2000). To clarify this issue an effort was made to obtain yet another independently calibrated set of $BV$ photometry of NGC 2243. During run #4 on the night of 2005 October 20, we observed the cluster along with five Landolt fields containing a total of 21 $BV$ standards. The air-masses covered by the observations of the standards spanned the range 1.12–1.76. Each of the Landolt fields was observed several times and we obtained a total of 66 measurements of standards for each of the filters. The following relations between instrumental and standard magnitudes were obtained:

\[ v = V - 0.020(3) \times (B - V) + 0.140(7) \times (X - 1.25) + 2.572(2), \]  
\[ b - v = 1.073(6) \times (B - V) + 0.125(16) \times (X - 1.25) + 0.484(5). \]

The cluster was observed at an air-mass of $X = 1.01$. As shown below, $BV$ photometry obtained at SAAO remains in good agreement with results obtained at LCO.

### 3.1 Comparison with Previous Photometry

Three sets of CCD based $BV$ photometry of NGC 2243 were published so far. Bonifazi et al. (1990) calibrated their data using local standards from the cluster field established by van den Bergh (1977). Bergbusch et al. (1991) tied their photometry to standards from Landolt (1983) and Graham (1982). Photometry for 14 stars included in Stetson (2000) data base is tied to Landolt (1992) standards. In addition, Anthony-Twarog et al. (2005) list $V$ magnitudes for
1267 stars observed on the $uvby$ system. Table 1 summarizes the comparison of our photometry from run #3 with the data sets listed above. Also included is a comparison with photometry obtained by us at SAAO (run#4). The mean residuals, in the sense "run #3" minus references, were calculated for stars brighter than $V = 19.5$. All stars with residuals above or below 0.05 mag from the mean were excluded from an analysis using an iterative procedure. No significant systematic dependence of residuals on color could be noted in all but two cases: a systematic trend is seen for $\Delta(B - V)$ for Bonifazi et al. (1990); also, some systematic deviation is present for $\Delta V$ in case of the reddest stars from the sample of Anthony-Twarog et al. (2005). A plot illustrating these two cases is shown in Fig. 2. As for the zero point of the $V$ magnitude, there is generally good agreement between all the sources of photometry considered except that of Stetson (2000). Both our data sets imply slightly bluer colors than the remaining 3 surveys. However, note that for Bonifazi et al. (1990) the $\Delta(B - V)$ is correlated with the color.

### Table 1: Comparison with other $BV$ surveys of NGC 2243

| Source                        | $\Delta V$  | $N_V$  | $\Delta(B - V)$ | $N_{(B-V)}$ |
|-------------------------------|-------------|--------|----------------|-------------|
| Bonifazi et al. (1990)        | -0.007(17)  | 291    | -0.035(21)      | 287         |
| Bergbusch et al. (1991)       | 0.010(16)   | 347    | -0.040(20)      | 343         |
| Stetson (2000)                | -0.083(9)   | 11     | -0.024(15)      | 11          |
| Anthony-Twarog et al. (2005)  | 0.007(19)   | 481    |                 |             |
| run #4                        | 0.023(15)   | 244    | -0.002(18)      | 236         |

**Fig. 2.** Left – differences between our magnitudes and those obtained by Antony-Twarog et al. (2005). Right – differences between our colors and those obtained by Bonifazi et al. (1990).

### 4 Variables

Times series photometry based on the data from runs #1, #2 and #4 was analyzed with the TATRY program kindly provided by Alex Schwarzenberg-Czerny. This program is suitable for the detection of various types of variable stars and uses in one of its modes the AoV algorithm (Schwarzenberg-Czerny 1996). A total of 12 variables were identified. Their equatorial coordinates tied to the astrometric frame of the USNO-B catalog are listed in Table 2. Finding charts are presented in Fig. 3. Variables V1-6 were already listed in KKM. All but one of the remaining objects are new identifications. Star V7 was noted earlier as a candidate variable by Anthony-Twarog et al. (2005; their candidate
We did not obtain any new time series photometry for eclipsing variables V4 and V5. These were observed out of eclipse during run #3; we used these data for determination of $V_{\text{max}}$ and $(B-V)_{\text{max}}$. Table 3 lists ephemerides for objects whose periods could be unambiguously determined based on the available data. Phased light curves for these stars are shown in Fig. 4. Two eclipse events were observed for variable V8. The first was centered at $HJD \approx 2448286.70$ while the second occurred at $HJD \approx 2450457.835$. The light curve, including photometry from all observing seasons, can be phased with $P = 6.2568$ d. However, some longer periods are also allowed by our data.

The second of the observed eclipses of V8 is shown in Fig. 5. Two primary ($HJD \approx 2449342.56$, $HJD \approx 2450456.57$) and one secondary ($HJD \approx 2450086.76$) eclipses were detected in the light curves of variable V9. Two of these eclipses are shown in Fig. 5. All observations of V9 can be phased with a period of $P = 3.257344$. However the adoption of such a period would imply noticeable eccentricity of the binary orbit. This is a rather unlikely configuration for a short-period main-sequence binary belonging to a cluster with an age of about 4 Gyr. Our spectroscopic data (Kaluzny et al. 2006, in preparation) indicate that V9 is indeed a radial velocity member of NGC 2243, hence the listed period for V9 is most likely spurious.

Variable V12 has been classified as an eclipsing contact binary of W UMa type; its color is too red for a $\delta$ Sct variable. The situation is more complicated in case of V10. With an unreddened color of $(B-V) \approx 0.40$ it can be either a $\delta$ Sct star with $P \approx 0.128$ d or a low-amplitude contact binary with twice that period. The available photometric data do not allow us to distinguish between these two possibilities. The variable V13 has been preliminarily classified as a

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§Candidate variables #1419 and #1463 from Antony-Twarog et al. do not show any evidence for variability in our data. Candidate #2445 was not observed by us.
Table 2: Coordinates and photometric parameters of variables from NGC 2243 field.

| Name   | RA$_{2000}$ | Dec$_{2000}$ | V$_{MAX}$ | $\Delta V$ | (B−V)$_{MAX}$ | Type            |
|--------|-------------|--------------|-----------|------------|--------------|-----------------|
| V1=NV CMa | 6:29:35.49  | -31:16:53.6  | 16.40     | 0.61       | 0.44         | Ecl             |
| V2=NU CMa | 6:29:33.81  | -31:17:03.4  | 17.86     | 0.27       | 0.66         | Ecl-EW          |
| V3=NS CMa | 6:29:44.92  | -31:18:19.4  | 16.69     | 0.25       | 0.43         | Ecl-EW          |
| V4=NS CMa | 6:29:09.59  | -31:15:34.0  | 14.11     | 0.7        | 0.35         | Ecl             |
| V5=NX CMa | 6:29:56.07  | -31:20:19.1  | 16.34     | 0.25       | 0.51         | Ecl             |
| V6=NT CMa | 6:29:33.58  | -31:17:58.4  | 16.89     | 0.93       | 0.16         | RRab            |
| V7     | 6:29:35.74  | -31:17:04.3  | 15.15     | 1.05       | 0.32         | Ecl             |
| V8     | 6:29:45.33  | -31:17:19.2  | 18.39     | 0.35       | 0.61         | Ecl             |
| V9     | 6:29:34.30  | -31:16:18.1  | 17.17     | 0.16       | 0.64         | Ecl             |
| V10    | 6:29:33.44  | -31:16:24.1  | 15.88     | 0.03       | 0.45         | δ Sct/Ecl-EW?   |
| V11    | 6:29:32.79  | -31:17:46.1  | 15.59     | 0.04       | 0.74         | ?               |
| V12    | 6:29:33.01  | -31:17:53.6  | 17.38     | 0.05       | 0.57         | Ecl-EW          |
| V13    | 6:29:27.11  | -31:18:28.8  | 16.07     | 0.02       | 0.43         | γ Dor?          |
| V14    | 6:29:41.09  | -31:19:06.2  | 13.75     | >0.09      | 1.03         | ?               |

Table 3: Ephemerides for periodic variables from NGC 2243 field.

| Name   | Period[d] | T0            |
|--------|-----------|---------------|
|        | HJD 2400000+ |              |
| V1=NV CMa | 1.18851590(2) | 48663.70748(5) |
| V2=NU CMa | 0.2853011(1)  | 48224.8492(1)  |
| V3=NS CMa | 0.3564557(1)  | 48225.0181(1)  |
| V6=NT UMa | 0.5865921(2)  | 48225.0471(2)  |
| V7     | 1.382703(2)  | 48225.7332(15) |
| V10    | 0.12785(4)   | 50081.6711(1)  |
| V12    | 0.28598(11)  | 50081.6456(20) |
| V13    | 0.76793(2)   | 50081.6077(15) |
Fig. 4. Phased $V$ light curves of NGC 2243 variables.

$\gamma$ Dor type pulsator based on its period and the shape of the light curve. Time domain light curves of the unclassified variables V11 and V14 are presented in Fig. 6. In case of V11 useful data were collected only during run #1. The photometry from run #2 is affected by some instrumental effects, while that from KKM is rather noisy (note the small amplitude of variability). In the case of variable V14 useful photometry was obtained only during run #2. During all other runs this relatively bright star was overexposed on all images.

Figure 7 shows the location of all variables from Table 2 on the cluster color-magnitude diagram. The eclipsing binary V7 is a candidate for a NGC 2243 blue straggler. Its light curve (see Fig. 4) is typical for low mass-ratio semi-detached binaries. Our photometry implies noticeable season-to-season variations of the light curve of V7. Such variability is quite common among algols of late spectral type. Variable V4 is the brightest eclipsing binary in the present sample. It is located in the outskirts of the cluster. Based on the measured radial velocity of V4 (Kaluzny et al. 2006, in preparation) one may conclude that it is a foreground object not related to the cluster. The cluster velocity is $+55$ km/sec (Friel et al 2002). All remaining eclipsing variables are located either on the
main sequence of the cluster or on a sequence of ‘photometric binaries’ located slightly above the main-sequence.

An estimate of the absolute magnitudes of contact binaries can be made using the calibration due to Rucinski (2004):

\[ M_V = -4.4 \log P + 3.02 (B - V)_0 + 0.12 \]  

We obtain \( M_V = 4.37 \), \( M_V = 3.24 \) and \( M_V = 4.09 \) for V2, V3 and V12, respectively. Assuming these absolute magnitudes, and adopting a distance modulus for the cluster of \( (m - M)_V = 13.15 \) (Anthony-Twarog et al. 2005), we derive \( V_{\text{max}} = 17.52 \), \( V_{\text{max}} = 16.39 \) and \( V_{\text{max}} = 17.24 \) for V2, V3 and V12, respectively. These magnitudes differ by 0.14-0.34 mag from the values listed in Table 2. Hence all three contact binaries are very likely members of NGC 2243.

A determination of the systemic radial velocities is the best way of answering the question of cluster membership of the remaining eclipsing variables from our list. Finally, we note that the two reddest identified variables — V11 and V14 — are candidates for cluster subgiants. Their low amplitude variability is likely related to so-called ‘spot activity’ which is observed in many binaries hosting cool sub-giants.

### 4.1 Period Study of NV CMa

The variable NV CMa=V1 is of particular interest, as noted in section 1. In the second paper of this series we plan to present a full analysis of its photometric and spectroscopic observations, for which the spectroscopy was collected during...
the last two observing seasons (falls of 2004 and 2005). To obtain accurate phases for the moments of spectroscopic observations, it is necessary to have an up to date ephemeris. From the available data, we can derive a total of 9 times of minimum light for NV CMa; their values, along with errors determined using the method of Kwee & Van Woerden (1956), are given in Table 4. The last of the listed minima was observed in 2005 October. The O-C values listed correspond to the linear ephemeris:

\[ MinI = HJD \ 2448663.70748(5) + 1.18851590(2) \]  

(7)
determined from a least squares fit to the data. The obtained fit gives a reduced \( \chi^2 \) equal to 1.5, which indicates that the adopted formal errors of times of minima are slightly underestimated. A linear ephemeris provides a good fit and there is no evidence for any detectable period change during the interval 1992–2005 covered by our data.
5 Discussion and Summary

We have expanded from 6 to 14 the sample of variable stars known in the field of the open cluster NGC 2243. Of primary interest are 5 detached or semi-detached binaries which are likely members of the cluster. Detailed analysis of these objects can provide a direct measure of the distance to NGC 2243 based on the surface brightness method. Four out of five binaries are composed of stars located in different parts of the cluster main sequence — assuming that all 4 binaries are members of NGC 2243. Determination of absolute parameters for up to 8 stars of the same age, metallicity and distance would provide a powerful test of evolutionary models of low mass stars.

Unfortunately, for the moment orbital periods are known with confidence only for one detached and one semi-detached binary: V1 and V7. We have also obtained almost complete light curves for these two systems. A dedicated extended photometric survey will be necessary to determine periods and to obtain good coverage of eclipses for the remaining 3 detached eclipsing binaries. In addition, spectroscopic data suitable for accurate determination of systemic velocities of all the binaries are needed to confidently resolve the question of their membership status. (It should be noted that stars in old open clusters exhibit small dispersions of radial velocities. For example Mathieu et al (1990) quote a value of 0.5 km/s for M67 whose age is comparable to that of NGC 2243. Hence, measurement of radial velocities provides a powerful discrimination between field stars and cluster members.)

There are three certain and one likely W UMa type variables in the central area of the cluster. The surveyed sample included about 1000 stars and is dominated by cluster members, as can be seen in Fig. 7. Hence, the relative frequency of occurrence of contact binaries in NGC 2243 is about 0.3-0.4%. This is comparable to the frequency of 0.2% observed for binary dwarfs in the Solar neighborhood (Rucinski 2002).

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