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Photometry of Pulsating Stars in the Magellanic Clouds as Observed in the MOA Project

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Abstract. A review of the MOA (Microlensing Observations in Astrophysics) project is presented. MOA is a collaboration of approximately 30 astronomers from New Zealand and Japan established with the aim of finding and detecting microlensing events towards the Magellanic Clouds and the Galactic bulge, which may be indicative of either dark matter or of planetary companions. The observing program commenced in 1995, using very wide band blue and red filters and a nine-chip mosaic CCD camera.

As a by-product of these observations a large database of CCD photometry for 1.4 million stars towards both LMC and SMC has been established. In one preliminary analysis 576 bright variable stars were confirmed, nearly half of them being Cepheids. Another analysis has identified large numbers of blue variables, and 205 eclipsing binaries are included in this sample. In addition 351 red variables (AGB stars) have been found. Light curves have been obtained for all these stars. The observations are carried out on a 61-cm f/6.25 telescope at Mt John University Observatory where a new larger CCD camera was installed in 1998 July. From this latitude (44° S) the Magellanic Clouds can be monitored throughout the year.

1. Introduction

The MOA project *M*icrolensing *O*bservations in *A*strophysics is a collaboration of about 30 astronomers/physicists in New Zealand and Japan working in about 10 different institutions (headquarters Nagoya and Auckland universities). The project was established in 1995. The MOA project goals are (a) the search for dark matter by microlensing in the galactic halo, (b) the search for planets by microlensing, in halo and galactic bulge, (c) the study of variable stars in the Magellanic Clouds and bulge and (d) the optical identification of γ-ray bursters (GRBs).

The observational program is undertaken on the 61-cm Boller & Chivens telescope at the University of Canterbury's Mt John University Observatory in the centre of the South Island of New Zealand. Here there is a dark sky background and typically 1–3 arcsec seeing; between a third and a half of the weather is suitable for CCD photometry. At the latitude of 44° S, the Magellanic Clouds are circumpolar and can be observed all year.

The telescope is a Ritchey-Chrétien cassegrain instrument modified to accommodate wide-field f/6.25 optics and a modern computer control system.

2. Observing Program

Three series of MOA observations have been undertaken as follows:

1. Jan 1996 – Dec 1996; f/13.5 Cass. $30' \times 30'$, MOAcamI;
2. Jan 1997 – Aug 1998; f/6.25 Cass. $1° \times 1°$, MOAcamI;
3. Aug 1998 – present; f/6.25 Cass. $0.92° \times 1.39°$, MOAcamII.

In all cases, very broad-band B and R filters have been used, covering respectively about 395–620 nm ($\lambda_{\rm eff} \simeq 500$ nm) and 620–1050 nm ($\lambda_{\rm eff} \simeq 700$ nm) (see Fig. 1). Series 1 used the f/13.5 optics and encompassed $\simeq 3 \times 10^5$ stars in three LMC fields. Series 2 covered three fields (nlmc1,2,3) in the LMC bar (1×10^6 stars) plus two SMC fields (smc1,2) (4×10^5 stars).

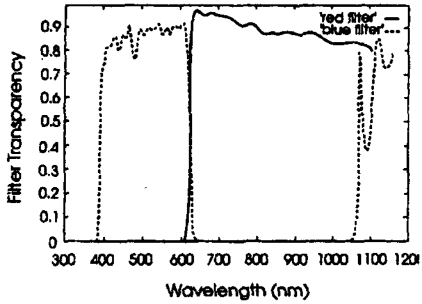

Figure 1. MOA filter functions in B and R broad bands

For series 3, which is currently in progress, the new MOAcamII is used to observe 16 LMC fields (all year) ($\sim 3 \times 10^6$ stars) plus 8 SMC fields (all year) ($\sim 1 \times 10^6$ stars) plus 16 galactic bulge fields (winter only)($\sim 5 \times 10^6$ stars). Each of the MOAcamII fields covers about 1.25 square degrees. Exposure times are 5 min in B and R in the Clouds, 3 minutes in the Galactic bulge.

The CCD camera MOAcamI comprises a mosaic of nine TI TC215 1000×1018 pixel CCDs whose pixel size is 12 μm ($\equiv 0\overset{''}{.}3$ at f/13.5, $0\overset{''}{.}65$ at f/6.25). The chips are not butted, so four consecutive interleaved exposures are required to cover a $1^\circ \times 1^\circ$ field.

The recently acquired MOAcamII has now replaced the first camera. It consists of three butted SITe 2048×4096-pixel thinned, back-illuminated CCDs with 15-μm pixels ($\equiv 0\overset{''}{.}81$ at f/6.25). The peak QE is 85%. The area of the CCD surface is 6.1×9.2 cm, and there are 24 Mpixels. Both cameras operated at a temperature of -100° C with liquid N_2.

Generally we expose each Magellanic Cloud field once or sometimes twice per night in both B and R, and each Galactic bulge field about four times per night in R and once in B, unless a known high magnification microlensing event is in progress, in which case frequent successive exposures are made.

3. Data Reduction

MOA observations of CCD images are recorded to 8-mm Exabyte tape for sending to Japan, while an archival copy on DLT tape is retained at Mt John. For series 1 and 2 observations, all the reductions have been completed using the DoPhot software package. One of us (I.B.) completed an archived database of all series 1 and 2 frames giving magnitudes in B and R. In the case of series 2 images, there are some 200 data points in each colour and about 1.4×10^6 stars.

Series 3 images using MOAcamII have hitherto not been reduced. I. Bond is currently perfecting implementation of the Alard & Lupton (1997) difference imaging technique, which already has shown that a substantial improvement in photometric precision is possible for crowded fields in only moderate seeing. It is hoped to reduce series 3 images early in 2000 and then to be able to reduce all images on site at the observatory in nearly real time. A Sun Enterprise 450 computer with 90 Gbyte hard disk drive is used for on-site data analysis at Mt John.

Mt John B, R MOA photometry gives colours which transform linearly to Johnson colours, as calibrated by Reid, Dodd & Sullivan (1997), as follows:

$$(B - V)_{\mathrm{J}} = 0.356 + 1.036(B - R)_{\mathrm{MOA}}$$

$$(R - I)_{\mathrm{J}} = 0.150 + 0.612(B - R)_{\mathrm{MOA}}$$

The calibration of MOA magnitudes gives the following transformation from the MOA instrumental system to that of the HST Guide Star Catalogue.

$$m_R(\mathrm{GSC}) = m_R(\mathrm{MOA}) + 25.10$$

$$m_B(\mathrm{GSC}) = m_B(\mathrm{MOA}) + 24.82$$

The typical precision of the series 2 MOA magnitudes is ± 0.13 mag at B or $R \sim 19$; ± 0.04 mag at B or $R \sim 14 - 15$.

4. Variable Stars in the MOA Database

Three surveys on variable stars in the MOA database have been undertaken or are in progress. One of these has been by S. Noda (Nagoya Univ., MSc) and M. Takeuti (Tohoku Univ., Sendai), and is a study of variables in series 2 observations. The stars are selected by several criteria (see Noda et al. 2000). Periods have been obtained by the phase dispersion method (PDM). Important aspects of this study include:

- Study of red variables – mainly SR; 188 variables in the LMC, 35 in the SMC
- Study of eclipsing binaries; 69 EB in the LMC, 136 in the SMC
- Study of Cepheids; 78 in the LMC, 38 in the SMC
- Study of blue variables (many detected); may be Be stars, at least one is a so-called bumper, resembling a microlensing light curve

By using another selection, 282 AGB variables were found in the LMC and 69 in the SMC (see Takeuti et al. 2000). The periods and the K-band magnitudes of most of these stars are comparable with those in the literature. The relation between the period and the mean colour for the AGB variables is reported.

Another study has been by N. Rattenbury (Auckland Univ., MSc), using selected MOA fields for series 1 and 2 data. Variable stars were detected by deriving the Welch–Stetson variability index (Stetson, 1996; Welch & Stetson, 1993). Only about 2% of the stars with greatest variability were selected for further study in this preliminary survey. Typically these stars have a range in the R magnitude exceeding 12σ.

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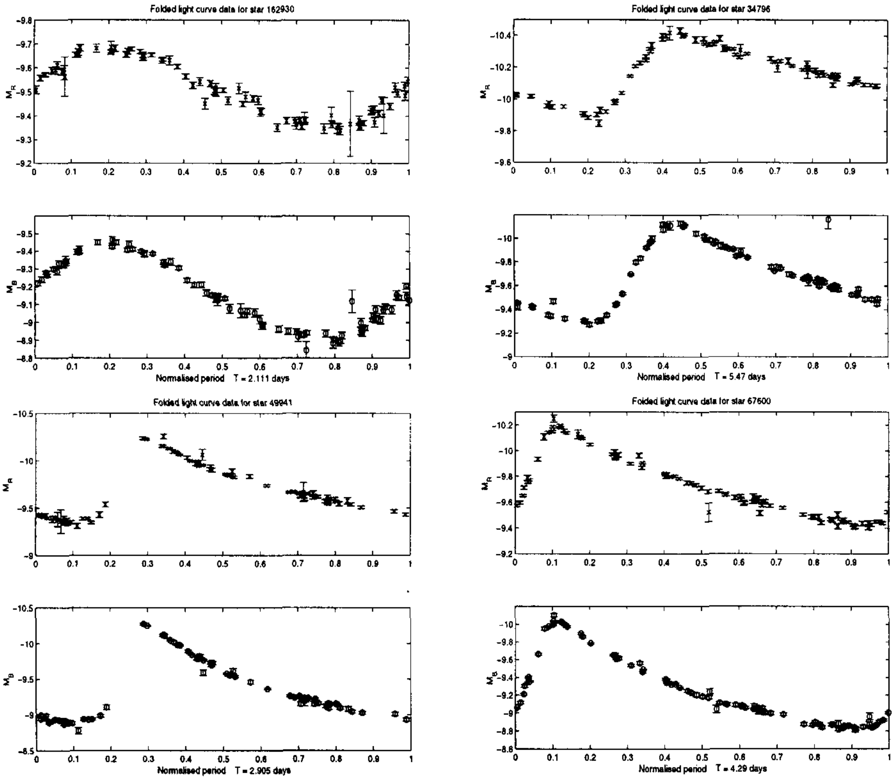

Figure 2. *B* and *R* phased light curves for four Cepheids in field smc2

Periods were analysed in several ways, the most successful algorithm being the date compensated discrete Fourier transform (DCDFT) algorithm of Ferraz-Mello (1981). The following summarizes the preliminary results.

- Study of Cepheids (periods 1–10 d): 70 were identified in the LMC and 420 in the SMC;
- Study of Cepheids or semiregular variables (P 10–50 d): 433 in the LMC, several more in the SMC;
- Eclipsing binaries and RR Lyrae stars (P 1–20 h): 7 in LMC, 71 in SMC;
- Blue variables ($(B-V)_J < 0.36$): 37 were identified in the SMC including 7 of long period or irregular variables, 2 possible "bumpers", and at least 3 eclipsing binaries;
- Red variables with $(B-V)_J > 1.65$ and $P > 100$ d (LPV, SR): 89 were found in the SMC and 5 in the LMC.

Fig. 2 shows *B* and *R* phased light curves for four of the Cepheids in the field smc2 (series 2). Fig. 3 shows unphased quasi-periodic light curves for four long period variables from field nlmc2 (series 2).

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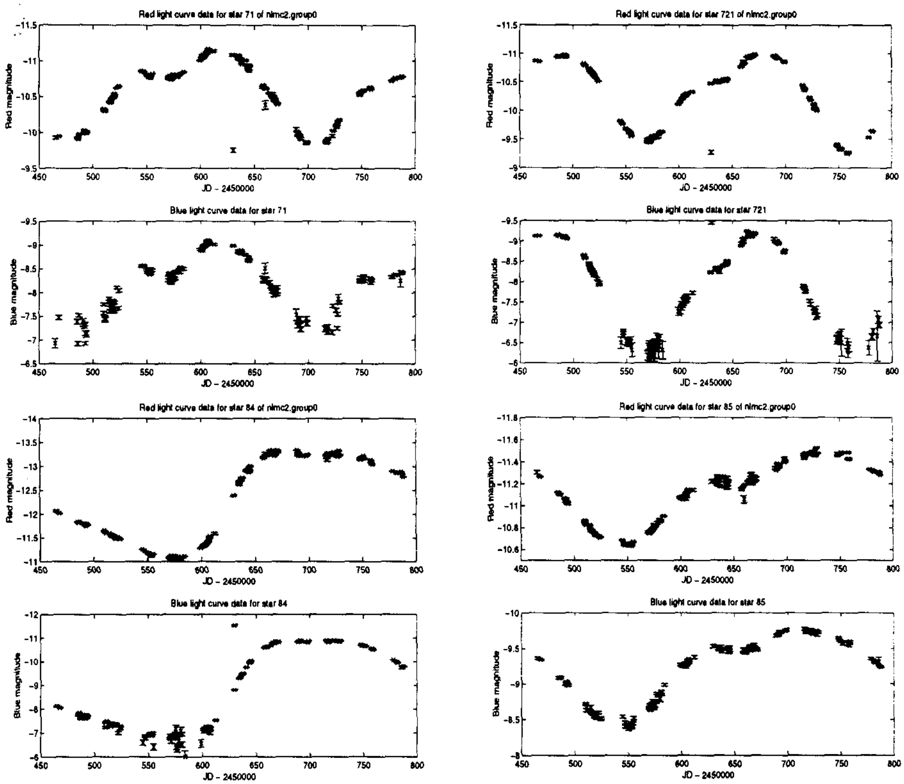

Figure 3. B and R light curves for four long-period red variables in field nlmc2

Finally G. Bayne, W. Tobin and J. Pritchard (Univ. Canterbury, N.Z.) are searching the MOA database for eclipsing binaries and analysing the light curves (series 1, 2). This work is still in progress, using the period-searching algorithm of Grison (1994).

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Discussion

Scot Kleinman: You said that MACHO data of one of the MOA "bumpers" showed additional bumps. What is the time scale of the repeated bumps?

John Hearnshaw: For MOA–LMC-97-1 and MOA–SMC-97-1 there are additional smaller bumps with similar time scales to those found in the MOA data: that is, a time scale of about 70 to 100 days.

Colin Scarfe: Is there any significance in the fact that you have found many more intrinsic variables in the Large Cloud than in the Small Cloud, but the opposite is true for eclipsing systems?

John Hearnshaw: Let me emphasize that the relative incidence of different types of variables in our preliminary surveys is highly biased, and should be interpreted with caution. However, both the Takeuti & Noda and the Rattenbury surveys found more eclipsing binary stars relative to Cepheids in the SMC than the LMC, and the analysis methods in the two galaxies were similar. We cannot explain this difference.

Bohdan Paczyński: Are "bumpers" also known as γ Cas stars?

John Hearnshaw: One of the MOA team (Jugaku-san) has indeed suggested that the so-called bumpers (stars which appear to resemble a microlensing amplification event) may indeed be Be (i.e. like γ Cas) stars undergoing a discrete mass-loss event. The Be star would get a little redder (as observed for MOA–SMC-97-1) during such a brightening.

Joyce Guzik: What is the physical mechanism that causes the bumps in a "bumper"?

John Hearnshaw: As mentioned in the previous answer to Paczyński's question, we do not know the physical cause of bumpers – but they may be due to mass loss from Be stars. I think the apparent magnitude and color index of SMC-97-1 are about right for this.

Mike Jerzykiewicz: Have you considered the possibility that the large bumps in MOA–SMC-97-1 and MOA–LMC-97-1 are microlensing events, while the other ones are intrinsic?

John Hearnshaw: Well, one can speculate on this and really it comes down to probabilities. Microlensing events in the Clouds are very rare, and intrinsic bumpers are also rare. To have both types of event in the same star within a few years seems highly improbable!

Juan Fabregat: There is a Be star in the Galaxy which shows a light curve very similar to the light curve of "bumpers": it is X Persei, a Be/X-ray binary.

John Hearnshaw: Thank you. This confirms what other members of the MOA group have told me and emphasizes the need for great caution in interpreting the light curves of stars which temporarily appear brighter. Even a color change is not a guarantee that the change is intrinsic, because many stars in the clouds are blended, causing a change in color if one is amplified.