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VARIABLE STARS IN THE MOA DATA BASE

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Abstract. The microlensing project MOA, by its nature, has generated a large volume of photometric data containing valuable information on variable stars. Observations were collected using a 0.6-m and 1.8-m telescope at Mt John University Observatory, New Zealand. This paper is a review of results on variable stars obtained from the MOA microlensing survay. We describe the reduction procedure and methods used for the identification and classification of long-period variables and peculiar variables.

1. INTRODUCTION

A number of scientific projects have been established in the past couple of decades throughout the world with the original aim to search for microlensing events. The Microlensing Observations in Astrophysics (MOA) is one of them, established in 1995 as a collaboration between several New Zealand universities and the Nagoya University in Japan. Due to the rare nature of microlensing events many stars have to be observed in order to find one event. By monitoring several tens of millions of stars photometrically in the galactic bulge direction with a wide-field telescope and large CCD cameras every clear night, microlensing events can be discovered. Since its first discovery in 1993, microlensing has been used to detect extrasolar planets, study nature of the dark matter, study limb darkening in distant stars, and structure of the Milky Way.

In addition to discovering microlensing events the MOA survey has generated a large database of different objects including normal stars over a range of spectral types, eclipsing binaries (Bonanos et al. 2004), pulsating stars, exploding stars, cataclysmic variables (Bond et al. 2005) and other type of objects. The long time series of MOA observations (over ten years) is especially important in the detection and analysis of long period variables (LPVs). The LPVs belong to the red giant or supergiant pulsating stars with periods ranging from about 10 days to a few years. Traditionally, LPVs are classified into Mira stars, semiregular variables (SRVs) and slow irregular variables and are a powerful tool for measuring distances in the galaxies.

With the large databases of microlensing surveys, like MACHO, OGLE, EROS and MOA, the number of known LPVs was dramatically increased. Wood et al. (1999) and Wood (2000) used MACHO photometry of about 1500 LPVs in the Large

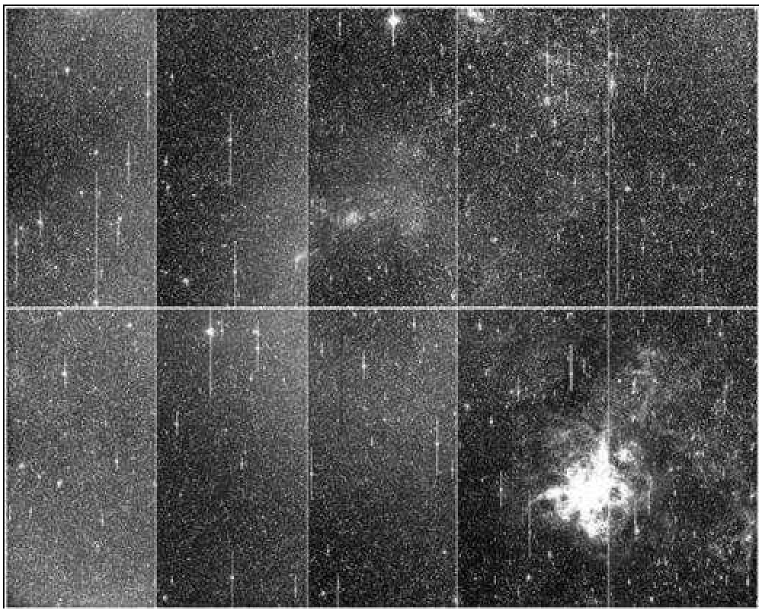

Figure 1: Ten chips (2046 X 4096) pixels of MOAII-cam3. LMC with Tarantula Nebula.

Magelanic Cloud (LMC) to show that these stars follow five distinct period-luminosity sequences. This result was confirmed by many other studies including ones from the MOA survey (Noda et al. 2002, 2004). The largest catalog of LPVs (56453 stars) in the LMC available to date was published by Fraser et al. 2008 on the basis of the MACHO photometry.

In this paper, we describe details of the automated reduction procedure of MOAII survey as well as results on analysis of long period variables and unusual variables as part of the MOAI database. We first describe the outlines of the MOA project, observations and reduction procedure in Section 2 and details of the analysis in Section 3.

2. OBSERVATION AND DATA REDUCTION

MOA observations have originally been carried out with a 61-cm reflector (MOAI) between 1998 and 2005 and then replaced with a new 1.8-m wide field telescope (MOAII). The MOAI telescope has been used with wide field camera MOA-cam2 composed of three chips each of (2046$\times$4096) pixels and two broad passbands (MOA blue and MOA red) (Yanagisawa et al. 2000). The total field of view over three CCDs is (55 $\times$ 83) arcmin and the pixel size on the sky is 0.81 arcsec.

The new MOAII telescope was installed at the Mt John Observatory in 2004 and became operational in 2006. This is the largest telescope in the world dedicated to microlensing observations. The new telescope is equipped with mosaic CCD camera composed of ten chips each with (2046 $\times$ 4096) pixels and total field of view of (1.6 $\times$ 1.3) degrees (see Figure 1).

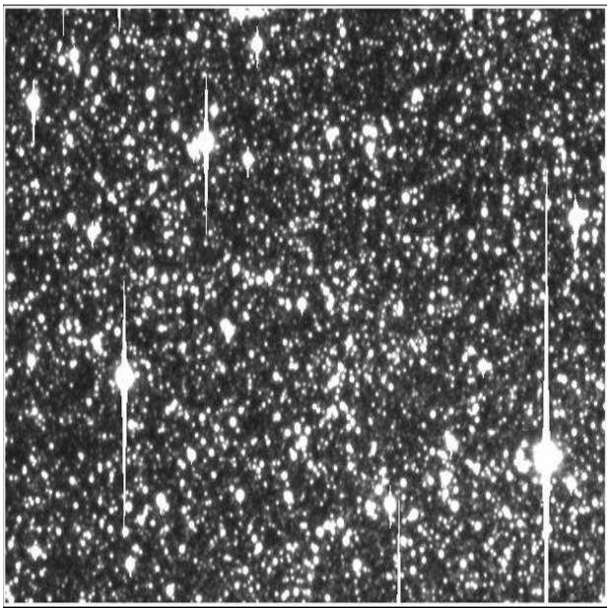

Figure 2: A small part of MOA camera reference image showing a large density of faint stars.

The MOA survey concentrates on small selected areas of the Galactic Bulge (GB) and Magellanic Clouds. Compared to some other microlensing surveys (such as OGLE) that typically collect their observations at 1-2 day intervals, MOAII operates at much higher sampling rate. A complete cycle of images for the GB fields take only about 40 minutes to collect, which enables about 15 consecutive exposures in an average clear night. This provides extremely well sampled photometry suitable for the detection of short period variables such as M-giants, pulsating in high overtone modes (Koen & Laney, 2000). Two standard filters V and I were used with this setting and 22 of GB, 14 LMC and 10 SMC fields have been observed regularly (see Figure 3).

After data acquisition the images were analysed and alerts issued in real-time using a difference imaging technique (especially applicable to dense stellar fields) developed by Alard and Lupton (1998) and applied and improved to the MOA images by Bond et al. 2000. Two geometrically aligned images taken under conditions of different seeing are related through the convolution relation $i(x, y) = r \star k(x, y) + b(x, y)$, where r is the reference image(Figure 2), i is the current and $b(x, y)$ is observational image. The convolution kernel $k(x, y)$ includes seeing differences and b represents the sky background differences between the two images.

Difference imaging technique measures flux differences. To convert δF flux measurements into a magnitude scale, it is necessary to determine a corresponding total flux. This is given by $F = Fref + \Delta F$ where $Fref$ is the flux of the object on the subtraction reference image.

A pipeline reduction procedure with variety of levels of automatisation has been developed for reduction of CCD images collected with the 1.8-metre telescope (see Figure 5). A set of Python, PyRAF and C programs have been written for the reduction

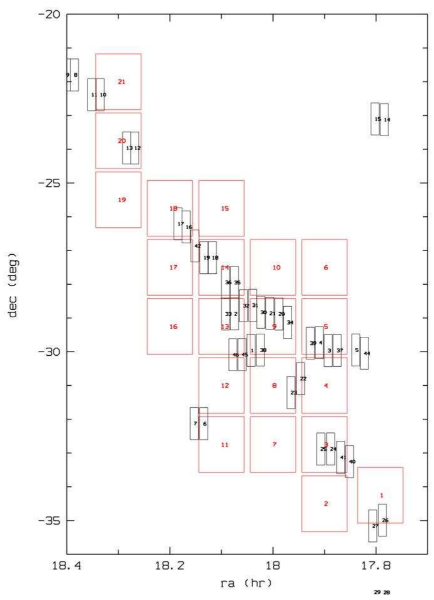

Figure 3: 22 MOA GB fields (large rectangles) compared to OGLE-II fields (small rectangles).

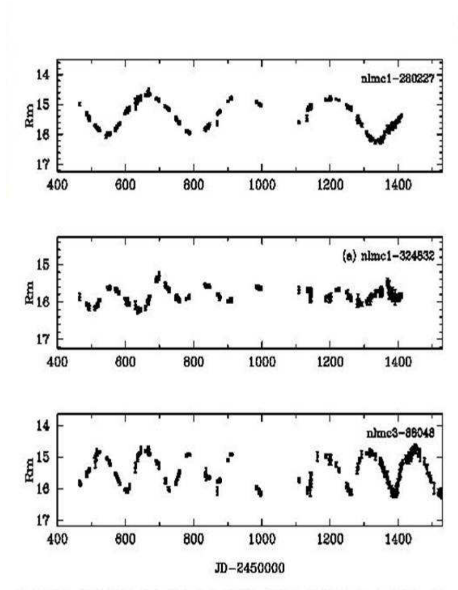

Figure 4: Example of light curves for the LMC LPVs.

of stellar images and organisation of an extensive MOA database. IRAF/DAOPHOT software package was used for the photometry in crowded stellar fields. 2D Gaussian point spread function that vary across the CCD was applied to the stellar profile in order for instrumental magnitude to be determined. This software was successfully used for about 300 CCD images from the 1.8-m telescope and the MOA catalogue has been created.

For the astrometric and photometric calibration the following standard catalogues: OGLE catalogue for I and V magnitudes, 2MASS catalogue for infrared (J, H & K) magnitudes and USNO catalogue for astrometric coordinates as well as Hubble Space Telescope catalogue were used. The MOA I and V catalogue is used for identification and analysis of the MOA microlensing events and as a reference catalogue during the regular image reduction procedure.

3. VARIABLES IN THE MOA DATA BASE

Long period red variables are numerous with high luminosity making them powerful tool in measuring distances in the Galaxy. However they are the least-studied star type, because of their complex pulsation mechanism. Miras can be distinguished from SRVs by their regular light curves and V-band amplitudes larger than 2.5 mag. Irregular variables theoretically exhibit no sign of periodicity in their light curves, but in practice many SRVs with insufficient number of observations to determine periods are categorized as irregulars.

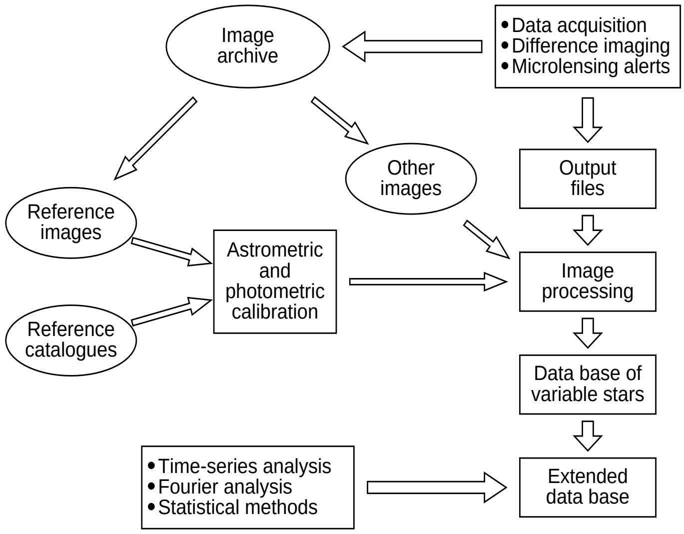

Figure 5: Schematic diagram of the MOA pipeline reduction procedure.

Long period red variables of LMC from the MOA database were studied in Noda et al. 2002, 2004. Period analysis has been done using the phase dispersion minimisation method (Stellingwerf, 1978) modified to operate on large photometry data sets. Some examples of light curves of long-period variables are shown in Figure 4. Stellar positions from the MOA catalogue were compared with those in the Deep Near Infrared Survey (DENIS) catalogue toward the Magellanic Clouds.

In Figure 6 the colour-magnitude diagram <Vm> − <Rm> versus <Rm> is presented. Three bright vertical bands at 0.1, 0.4 and 0.8 − 0.9 mag for <Vm> − <Rm> correspond to the main sequence of the LMC, foreground Galactic disc stars, and the red supergiants of the LMC, respectively. The tip of the red giant branch is located at $Rm \approx 16$ mag above the RG branch. The stars redder than $< Vm > - < Rm > \approx 1.2$ mag are AGB stars. The faintest vertical strip at the position of <Vm> − <Rm> ≈ 0.6mag and <Rm> ≈ 18-19 mag is below the detection limit of DENIS and includes horisontal-branch, red clump and AGB bump stars.

The period-luminosity diagram of about 4000 pulsating stars is shown in Figure 8. Variables are observed to have strip like patterns already reported by Wood et al. (1999, 2000). The most abundant strip is marked as C and includes about 1860 oxygen-rich Miras and SRVs with the mean brightness of 11.0. About 88 per cent of the sample belongs to sequences B and C. Five other peaks are labelled as D, E, F, B and A with F having the shortest period. About 59 stars were identified in the sequence A and they all belonged to the oxygen rich SR variables. There were about 1250 oxygen and carbon rich stars in the group B. The concentration of sequences D and E towards the LMC centre is weak, about 286 oxygen rich SRVs, while the sequence E contains 99 oxygen rich SRVs. Although the stars in sequences D and E are very few, such a difference suggests a difference in their nature. Low-mass stars which evolve to the tip of the red giant brunch (Alcock et al. 2000) are old stars and widely spreaded. Typical position of classical cepheids on the period-luminosity

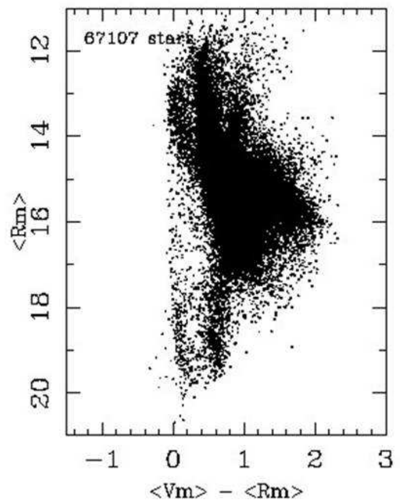

Figure 6: Color-magnitude diagram for LPVs in MOA database. <Vm> & <Rm> are mean visual and red magnitudes.

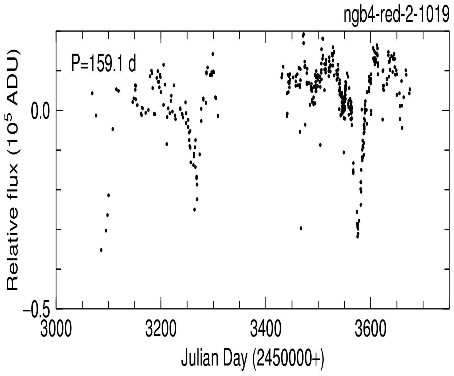

Figure 7: Example of peculiar variable in the MOA database (candidate for RCB star).

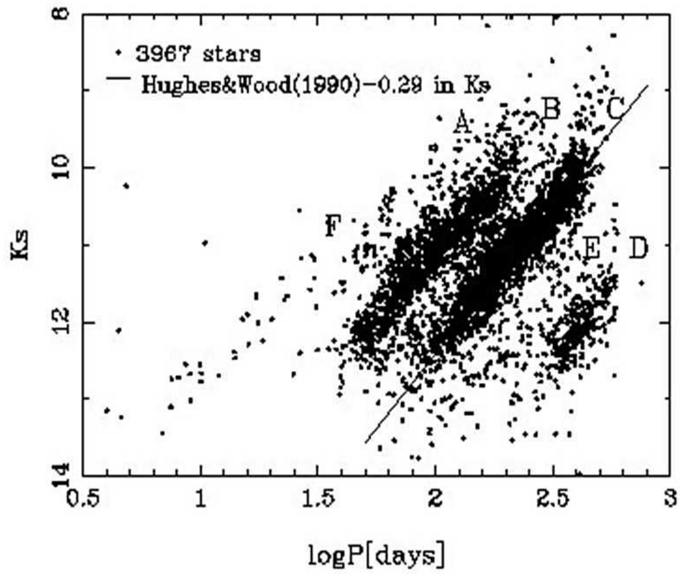

Figure 8: Period-luminosity (logP, Ks) diagram for the LMC red variables.

diagram is Ks $\approx$ 11.1 mag for log P(d) $\approx$ 1.5 and correspond to the sequence F (Cioni et al. 2001).

Another analysis of the MOAI database of 12540 variable stars has been completed using the standard Fourier analysis procedure and most of the regular variable stars from the database were classified into short-period (less than 30 days) and long-period (longer than 30 days) variables (Skuljan L., Bond I.A., 2006). About 35% from the group were classified as long period variables with most of them belonging to the Mira, semi-regular and RV Tauri type. About 25% of stars were classified as short-period variables including Cepheids, RR Lyrae and eclipsing binaries. From the remaining group some were classified as irregular variables while especially emphases was on peculiar and eruptive variables, such as extreme helium stars (EHe), hydrogen deficient carbon stars (HdC) and R Coronae Borealis (RCB) type (see Figure 7). A typical light curve of RCB stars exhibit deeper or shallower declines at irregular intervals which are common features in C-rich giants. Some of the candidates for RCB show characteristic light curves with rapid, deep and irregular declines in brightness, other candidates are not so evident and require spectroscopic confirmation.

4. CONCLUSION

In this paper we present an overview of study on variable stars using the MOA database. This database was generated from the MOA project microlensing survey. The MOA database contains a large number of stars in the GB, LMC and SMC with a relatively small sample used for studying of photometric properties of variable stars so far. Long-period red LMC variables (about 4000) from 3 years (1998-2001) of observations were studied and their periods, magnitude colour, amplitude and periodicity were determined. The properties of variables on the colour-magnitude diagram of the LMC stars is briefly discussed and the multiplicity of the period luminosity relation is confirmed. Most of these periodic variables were found in the AGB phase. In addition about 12500 light curves from the MOA database (in the period between 1999 and 2005) were analysed and searched for the new peculiar variables.

The MOA database still offers many opportunities for studying other type of variable stars including short period and eruptive variables. Photometric observations covering a longer time-span and larger sample of variable stars will also provide opportunity to address some key aspects of stellar evolution.

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