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Multi-wavelength study of X-ray binaries in the Magellanic clouds

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Abstract. We present the long-term temporal properties of X-rays binaries in the Magellanic Clouds using archival optical (from MACHO and OGLE) and X-ray (XMM-Newton) observations. The SMC has known to have an interesting over-abundant population of Be/X-ray binaries (BeX) as compared to our Galaxy. The majority of these SMC BeX display superorbital variations, many of them quasi-periodic on timescales of 200-3000 days, which are believed to be related to the formation and depletion of the Be star equatorial disk. The MACHO colour of these systems follow a clockwise loop-like structure in the colour-magnitude diagram. We also found a quasi-periodic variations in the prototype LMC supersoft source CAL 83. Its light curve shows dramatic brightness changes of ∼1 mag on timescales of ∼450 days. This supersoft source spends typically ∼200 days in the optical low state. Moreover, we have seen an anticorrelation between their X-ray and optical behaviour in which supersoft X-rays are detected during optical minima and very weak or completely off at optical maxima. Simple backbody fits to both high and low-state X-ray spectra reveals a decrease of blackbody temperature and luminosity when the optical counterpart brightens.

Key words. Stars: emission-line:Be – Stars: CAL83 – X-rays:binaries – Magellanic Clouds – white dwarf –Accretion, Accretion discs – X-rays: stars

1. Introduction

The Magellanic clouds (MCs) have proven to be the ideal locations for studying all kinds of different types of stellar populations. Their proximity and well-known distance enable us to resolve and study individual stars. They are located at a high declination (continuously accessible for at least half of the year) and at high Galactic latitude where interstellar extinction is low and hence ideal for wide-wavelength studies.

Here we present the long-term properties of two types of Magellanic cloud X-ray sources, namely Be/X-ray binary(BeX) and supersoft X-ray source (SSS), using archival optical and X-ray observations.

2. Optical light curves from the MACHO and OGLE projects

In the last couple of decades several gravitational microlensing projects have been monitoring the galatic bulge and the MCs. Among these are the MACHO and OGLE which, if

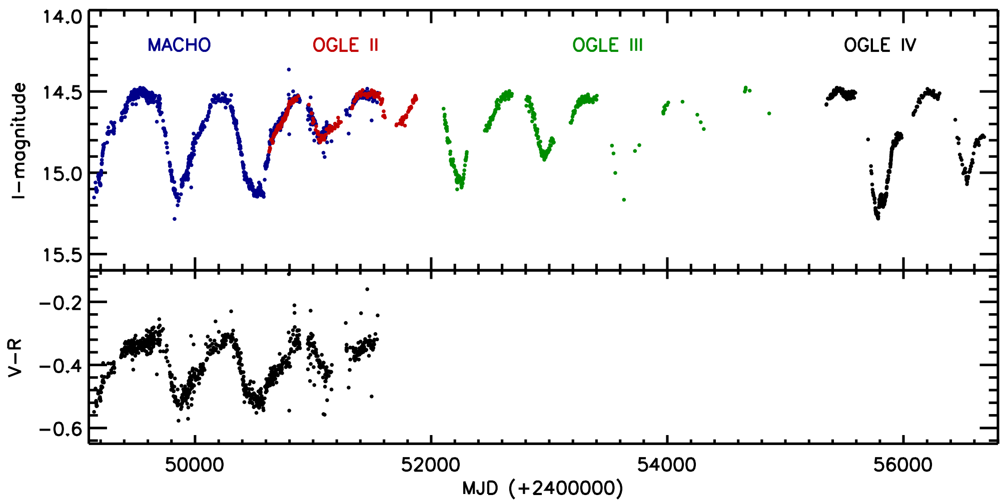

Fig. 1. 22 yr optical light curves from MACHO (blue), OGLE II (red), OGLE III (green) and OGLE IV (black) of SXP6.85, showing a large amplitude long-term modulation with a period of 620 d.

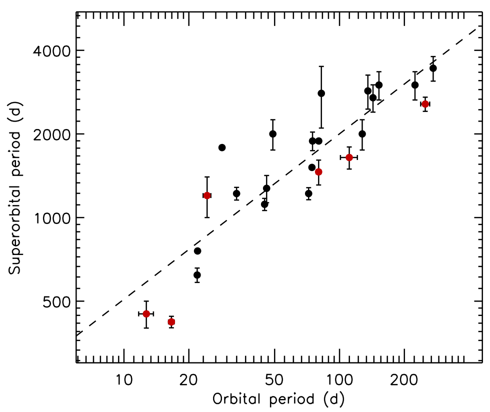

Fig. 2. Plot of the BeX superorbital periods against orbital period. The dashed line represents the best linear fit. The red points are Galactic and LMC BeX sources from Reig (2011).

combined, provide continuous ∼22 yr optical photometric observations of millions of variable stars in the MCs.

Their long temporal coverage (∼22 yr) allows an extensive systematic study of star optical variability, including long-term properties and transient phenomena.

3. X-ray binary population of the MCs

3.1. SMC Be/X-ray pulsars

Be/X-ray binaries (BeX) are binary systems in which a neutron star, usually an X-ray pulsar, is orbiting an early-type non-supergiant Be star. Typically, BeX systems have a wide ($P_{orb} \sim 10 - 300$ days) and rather eccentric orbit ($e \geq 0.3$). In BeX systems, the optical is usually surrounded by a circumstellar disk. During periastron, the X-ray pulsar can interact with this circumstellar disk, giving rise to periodic outbursts that can be observed over a wide range of wavelengths (optical, X-ray,...) (e.g. Okazaki & Negueruela 2001). The optical light curves of these BeX systems show a variety of periodicities ranging from as short as ∼hours to decades.

The Small Magellanic cloud (SMC) is known to host an unusual high number of high mass X-ray binaries (currently more than 70) which is much higher than expected. The optical counterparts of all these SMC HMXBs are now confirmed spectroscopically as Be stars with only one exception, the supergiant system SMC X-1.

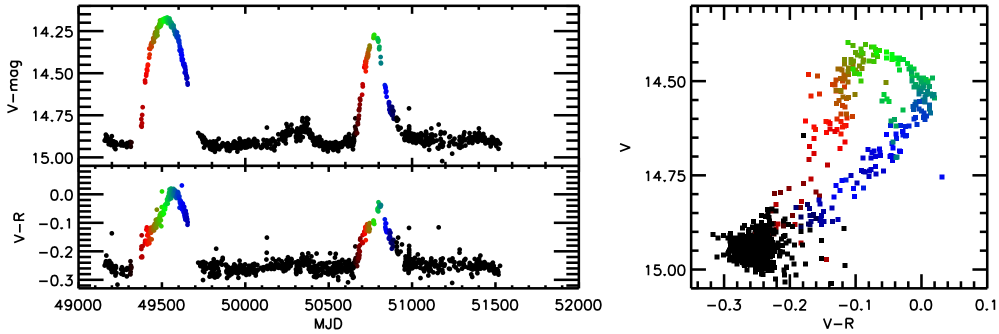

Fig. 3. Left: MACHO light curves and colour variation of SXP18.3. Right: Corresponding colour-magnitude diagram showing the clockwise loop-like structure.

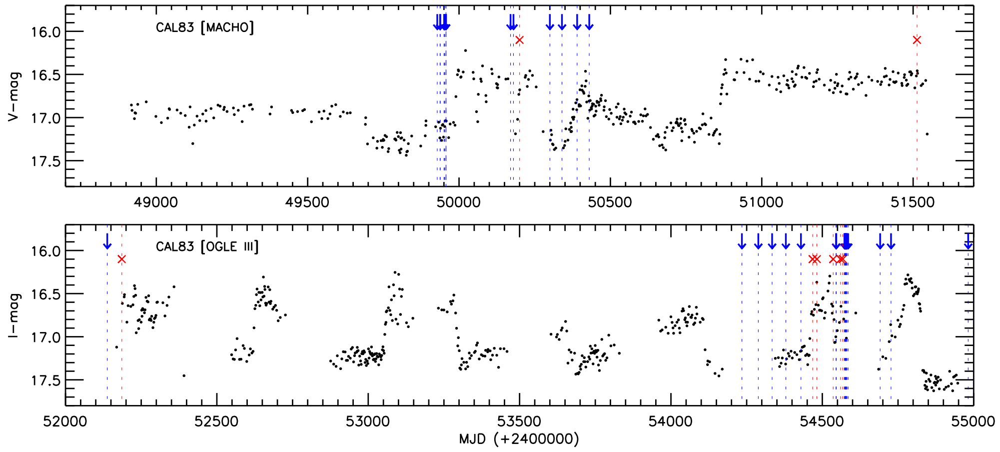

Fig. 4. MACHO (top) and OGLE-III (bottom) light curves of CAL 83, showing a quasi-periodic dimming of $\sim$ 1 mag every 450 days, which lasts for $\sim$ 200 days. The arrows and crosses are at times of X-ray observations, and indicate X-ray on- and off-states, respectively. This clearly demonstrates that the X-ray off-states occur only during optical high states. The X-ray observation shown in the upper panel are those with ROSAT (except the last one near MJD 51500 which was taken with Chandra), and those in the lower panel are those with *XMM-Newton*.

3.1.1. Superorbital period.

Super-orbital variations are very long-term variations in the range of 300-3000 d which are suggested to be related to the formation and dissipation of the circumstellar disk around the Be star. The LMC BeX source A0538-66 is the prototype for such behaviour, with its MACHO light curve displaying a remarkably stable superorbital modulation of 420 d (Alcock et al. 2001). This type of variation has also previously been seen in some LMC BeX system such as in EXO 0531-66 and H 0544-665 (McGowan & Charles 2003).

Rajoelimanana, Charles, & Udalski (2011) have studied the very long-term properties of these MCs BeX sources and found that the majority of them show a variation on timescale of hundreds to thousands of days, with much of it appearing quasi-periodic in nature (see e.g. Fig. 1). They have found 19 superorbital pe-

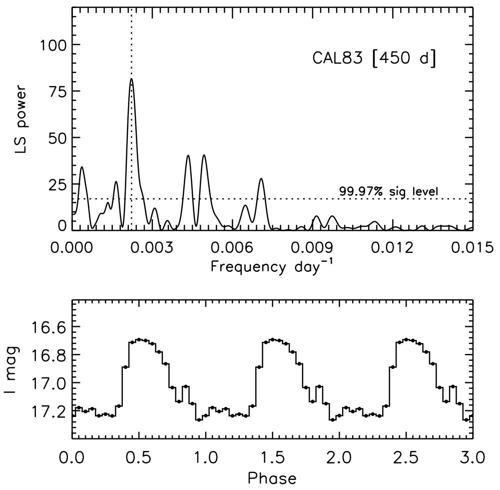

Fig. 5. Lomb-Scargle periodogram of CAL 83 (Top) and its folded light curve (from Figure 4) on the 450 d period

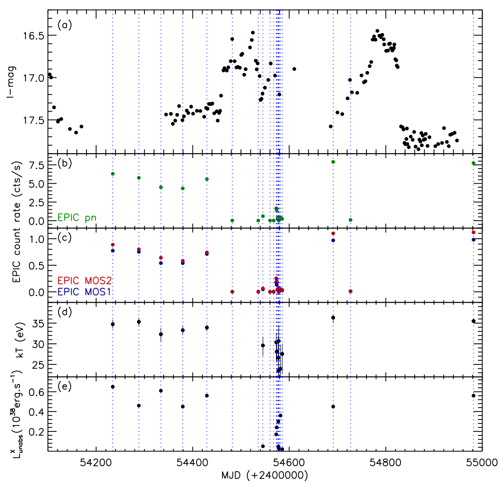

Fig. 6. OGLE-III (a) and *XMM-Newton*/EPIC PN (b), MOS1, and MOS2 (c) light curves of CAL 83, which shows a clear anti-correlation between the optical and X-ray states. Panels (d) and (e) show the temperature and luminosity evolution, respectively.

riods in these SMC systems which they suggest are related to the properties of the Be circumstellar disk. They also found that superorbital periods appear to be correlated with their orbital period when plotted against each other (Fig. 2).

3.1.2. Color-magnitude diagram.

For almost all of these SMC BeX systems, the source gets redder when it brightens which is what might be expected for a low inclination system (see Fig. 1). This is the opposite to that seen in A0538-66 where the source is bluer when it is brighter (Rajoelimanana, Charles, & Udalski 2011). Moreover, the evolution of their MACHO colour shows a clockwise loop-like structure in the colour magnitude diagram (Fig. 3).

3.2. Supersoft X-ray source CAL83

Supersoft sources (SSS) are a class of X-ray object first discovered during a survey of the LMC with the Einstein X-ray observatory in the late 1970s (Long, Helfand, & Grabelsky 1981). The LMC SSS CAL 83 and CAL 87 were the first two sources discovered. They are characterised by their soft (kT ~10-75 eV) X-rays and their extreme luminosity in the range of $10^{36} - 10^{39}$ erg s^{-1}, which suggest an effective emitting radius comparable to the size of typical white dwarf. This led van den Heuvel et al. (1992) to propose that SSS are actually accreting WD binary and that the dominant source of luminosity is steady nuclear burning of the accreted material on the WD surface.

The LMC source CAL83 is considered to be the prototypical supersoft source. Based on photometric and spectroscopic observations of CAL83 Smale (1988) reported an orbital period of 1.0436 d, which was later refined to be 1.0475 d by Cowley et al. (1991). Its orbital inclination was suggested to be in the range of $20 - 30^{\circ}$ (Cowley et al. 1998). Odendaal et al. (2014) reported an X-ray pulsation of 67 s in recent XMM-Newton observations of CAL 83.

3.2.1. Optical light curve of CAL 83

CAL 83 has been observed by the MACHO and OGLE collaborations since 1992, which now provides us with a combined light-curve

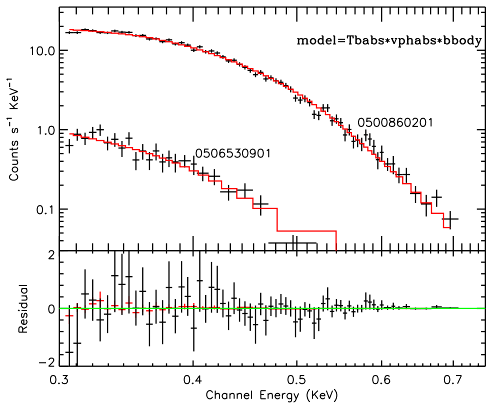

Fig. 7. EPIC PN spectra of CAL 83 plotted with the best blackbody fits.

that span ~22 yr. Fig. 4 represents the combined MACHO and OGLE light curves of CAL 83 where the times of all available X-ray observations are shown.

The MACHO light curve (Fig. 4 top panel) shows a long-lived intermediate state for the first ~700 days, and similar duration high state towards the end of the observations. On the other hand, the OGLE-III light curve (Fig. 4 bottom panel) behaves differently. It exhibits a regular succession of optical high and low states on timescales of 450 days with a difference in brightness of ~ 1 mag which are nicely revealed in the Lomb-Scargle periodogram showing a broad peak at periods of 450±3 days (Fig. 5). CAL 83 spends roughly the same time (~ 200 days) within each state, which is much longer than the duration of the transitions between states (typically ~ $5 - 10$ days).

Rajoelimanana et al. (2013) intepret these long-term variations in terms of the limit-cycle model of Hachisu & Kato (2003a) where the strong wind from the WD is colliding with and stripping off the outer layers of the slightly evolved secondary. This mass stripping will reduce or temporarily stop the mass accretion rate onto the WD.

The times of all available X-ray observations of CAL 83 are also shown in Fig. 4. Interestingly, all X-ray off-states (red crosses in Fig. 4) occur only during optical maxima.

3.2.2. X-ray light curve of CAL83

We used the archival XMM-Newton observation of CAL 83 which was taken between May 2007 and May 2009. The observation were obtained with the EPIC-PN, EPIC-MOS and RGS instruments. All the datasets were reduced with the XMM-Newton SAS version v11.0.0. We then extracted the EPIC-PN and EPIC-MOS light curves in the energy band 0.2-1.0 keV.

Fig. 6 shows clearly the Optical/X-ray anticorrelation. At optical minima, the X-ray count rates are at a maximum (≥4.5 for EPIC-PN, and ≥0.55 for EPIC-MOS). However at optical maxima the X-ray emission from the source is very weak or completely off.

3.2.3. Low resolution spectra

The spectral fitting were performed using XSPEC version (v 12.7.0) and only data in the energy range 0.3-1.0 keV were included. We used a simple blackbody model (*bbody*) together with the Tübingen-Boulder ISM absorption (*TBabs*) model, ISM abundances from Wilms, Allen, & McCray (2000), and the photoelectric absorption cross-sections from Bałucińska-Church & McCammon (1992). We fixed the column density to the value derived by Gänsicke et al. (1998) of $N_{\rm H} = 6.5 \times 10^{20}$ cm^{-2}. We add an additional absorption component with free column density and abundances set to 0.5 solar (LMC abundances) for elements heavier than helium.

The results from the fit with an absorbed blackbody model (Tbabs*vphabs*bbody) are plotted in Fig. 6 which shows the evolution of the blackbody temperature and unabsorbed luminosity with time. The blackbody temperature has a mean value of ~35 eV during optical minima, and reduces to ~30 eV during optical maxima. Fig. 7 shows an example of the blackbody fit of X-ray spectra taken at optical minima and maxima.

4. Conclusions

In summary, the long-term optical monitoring of the MCs by these gravitational microlensing projects is quite valuable for studying the long-term variations of these MCs X-rays binaries. The existence of these large databases led to the discovery of 19 superorbital periods in SMC BeX systems which we suggest are related to properties of the Be circumstellar disc. We have also found a quasi-period variation on timescale of 450 d in the light curves of CAL 83 which is anticorrelated with the long-term X-ray variability. The non-detections of X-ray emission during the optical high state is in good agreement with the photospheric expansion/contraction model suggested by Southwell et al. (1996).

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