Variability in supersoft X-ray sources RX J0537.7-7034 and RX J0038.6+4020

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Abstract. Using long term archival photometric observations from the MACHO (MAssive Compact Halo Objects) and OGLE (Optical Gravitational Lensing Experiment) projects, we find an orbital periodicity of 3.1 hrs for Large Magellanic Cloud (LMC) supersoft X-ray source RX J0537.7-7034. This establishes RX J0537.7-7034 as the supersoft X-ray source with the shortest orbital period. Long term light curves of combined MACHO and OGLE observations of RX J0537.7-7034 also show a steady fading in optical light. Timing analysis performed using *XMM-Newton* archival observations of the M31 transient supersoft X-ray source RX J0038.6+4020 (s2-26) reveal a 35.8 min periodic modulation in the X-ray data.

1. Introduction

Supersoft X-ray sources (SSSs) have been established as a distinct class of X-ray sources which emit most of their energy below 0.5 keV. These sources are characterised with high X-ray luminosities of $\sim 10^{36}$-10^{38} erg s^{-1} but very soft X-ray spectra of low temperatures (kT ~20-100 eV) corresponding to blackbody temperatures of ~10^5-10^6 K (see the most recent review of SSS by [1]). Utilizing the Stefan-Boltzmann relation between luminosity and temperature, it was established that the SSSs radii were of the order $R = 10^{10}$ cm, comparable to those of a white dwarf (WD) [2].

It has thus been suggested that the luminous supersoft sources consist of a WD accreting mass from a Roche-lobe filling companion star, with the material on the surface of the WD undergoing stable nuclear hydrogen burning [2]. In order to sustain the hydrogen burning on the surface of the WD, the accretion rate should be of the order $\sim 10^{-7}$ $M_{\odot}$ yr^{-1}, which is greater than the mass transfer rates in a related class of compact WD binary systems, namely cataclysmic variables (CVs, [3, 4]). This high mass transfer rate can only be possible if the donor star has a mass equal to or greater than that of the WD. With such a high mass ratio, the secondary Roche lobe shrinks, and mass transfer occurs rapidly on the thermal time-scale of the donor. The WD should also be massive enough to support continuous burning of hydrogen on its surface.

In binary systems, mass transfer occurs through two commonly known mechanisms: Roche lobe overflow or through stellar winds from the secondary star.

In this paper, we discuss optical and X-ray variability in SSSs RX J0537.7-7034 in the Large Magellanic Cloud (LMC) and RX J0038.6+4020 (s2-26) in M31. This paper is structured as follows: In §2, a brief literature review of the sources is presented. Archival photometric data of RX J0537.7-7034 from the MACHO (MAssive Compact Halo Objects) and OGLE (Optical Gravitational Lensing Experiment) projects is presented in §3, together with an updated orbital ephemeris for this source. Timing analysis of *XMM-Newton* X-ray data of RX J0038.6+4020 (s2-26) is presented in §4, followed by the conclusions in §5.

2. RX J0537.7-7034 in the Large Magellanic Cloud and RX J0038.6+4020 (s2-26) in M31

ROSAT PSPC and *XMM-Newton* EPIC-pn spectra of RX J0537.7-7034 (hereafter RXJ0537) fitted with a blackbody model are characterised by a temperature between ~18-57 eV and a bolometric luminosity of $(0.6\text{-}1.2)\times10^{37}$ erg s^{-1} with most of the X-ray energy emitted below 0.5 keV [5, 6]. The orbital period of RXJ0537 was first established as 3.5 hours, with the orbital ephemeris given by [7]

$$T_0 = \text{JD } (2451203.6392 \pm 0.0040) + (0.147275 \pm 0.0038)E \text{ days.}$$

RX J0038.6+4020 (hereafter s2-26) is also a ROSAT observed source classfied as a supersoft X-ray source through hardness ratio criteria. The transient nature of the source in the X-ray waveband was established by three observations by the *Chandra* X-ray observatory from 2000 to 2001, since the source was only detected in one of these observations, i.e. in March 2001 [8]. No periodic modulations have been reported for this X-ray source yet.

3. MACHO and OGLE observations of RXJ0537

RXJ0537 was monitored by the MACHO project with observations performed with the 1.27-m Great Melbourne telescope at Mount Stromlo Observatory in Australia from 1992 to 2000. The MACHO project is a survey that was used to monitor the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) for microlensing events [9]. This telescope provides CCD photometry in the 'red' band ~6300-7600 Å and the 'blue' band ~4500-6300 Å. The two-colour instrumental magnitudes were transformed to the standard Kron-Cousins R and V passbands.

RXJ0537 was also observed using the 1.3-m Warsaw telescope at Las Campanas Observatory, Chile as part of the OGLE project, which is still ongoing[1]. The photometric observations of the OGLE project are taken in the I passband (~7000-9000 Å). This project has been in operation since 1992 in phases I (1992-1995), II (1997-2000), III (2001-2009) and IV (2010 up to now). OGLE I was a pilot project and its observations were restricted to the Galactic Bulge. OGLE II observations provide an overlap with the MACHO data.

3.1. MACHO and OGLE light curves of RXJ0537

We show in figure 1 the light curves of RXJ0537 from both MACHO and OGLE observations. The observation dates were converted to Barycentric Julian Date in the Barycentric Dynamical Time (BJD_{TDB}) which corrects the arrival time of photons to the Solar system barycentre [10]. Note the slow decline in optical magnitude of the X-ray source.

3.2. Period analysis and folded light curve

Each light curve in the MACHO V-band, R-band and OGLE II, III , IV was analysed using the Starlink PERIOD package[2] which has analysis options including detrending the data, the task SCARGLE to create Lomb-Scargle (LS) periodograms [11, 12], and also the task FOLD to fold any data with a given period. The long-term fading was removed by subtracting a 2^{nd}-order

[1] http://ogle.astrouw.edu.pl/
[2] www.starlink.rl.ac.uk/star/docs/sun167.htx/sun167.html

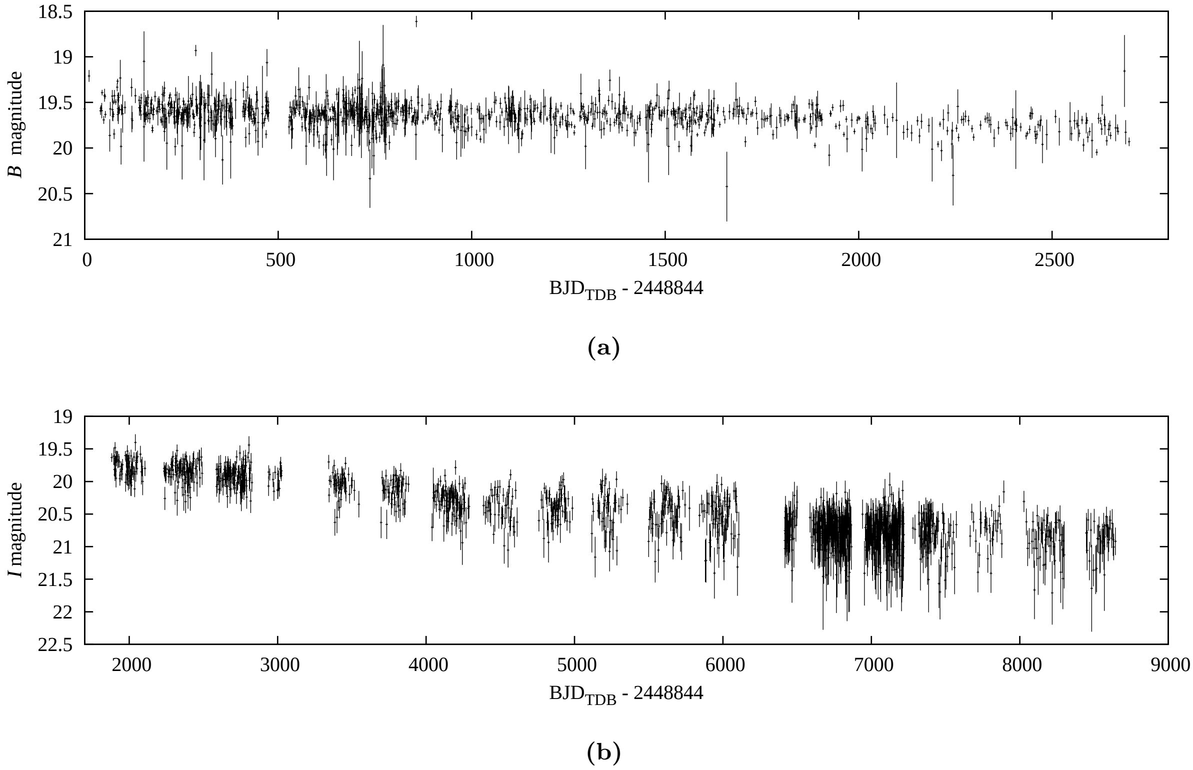


Figure 1: The optical light curve of RXJ0537 from MACHO project observations (top), and OGLE II, III and IV observations (bottom).

polynomial before getting periodograms from the light curves. The MACHO *V*-band, *R*-band and OGLE II and III periodograms showed a strong power peak at $P_{\rm orb} = 0.1286836$ d. In the OGLE IV periodogram, the periodicity is hardly seen. Since a longer baseline enables one to obtain a more accurate value for the period, we decided to combine the detrended MACHO *R*-band and OGLE II+ III *I*-band light curves.

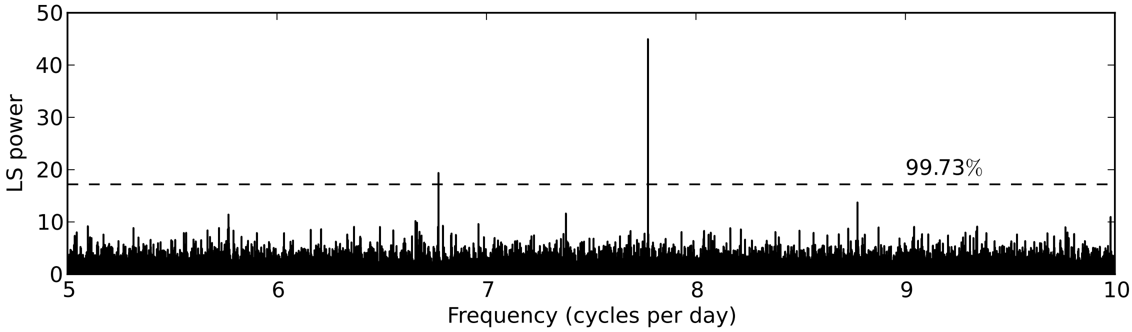
However, to compensate for the different filters of MACHO and OGLE, both these light curves were further detrended separately by subtracting the mean and dividing by the standard deviation, to yield light curves varying around 0, with a standard deviation of 1. Subsequently, the resulting MACHO and OGLE II+ III light curves were combined, removing the OGLE II points overlapping with MACHO, so as to yield a continuous light curve. The resulting periodogram is shown in figure 2 (a), exhibiting a very strong peak at $P_{\rm orb} = 0.1286836 \pm 0.0000014$ d (3.08841 ± 0.00003 hrs) at a $\gg 99.99\%$ significance. The folded light curve is shown in figure 2 (b), exhibiting a quasi-sinusoidal orbital modulation. In order to constrain the time of minimum light, a sinusoid was fitted to the folded light curve, yielding the following updated ephemeris:

$$T_0 = {\rm BJD_{TDB}}\ (2448844.3044 \pm 0.0075) + (0.1286836 \pm 0.0000014)E \text{ days}$$

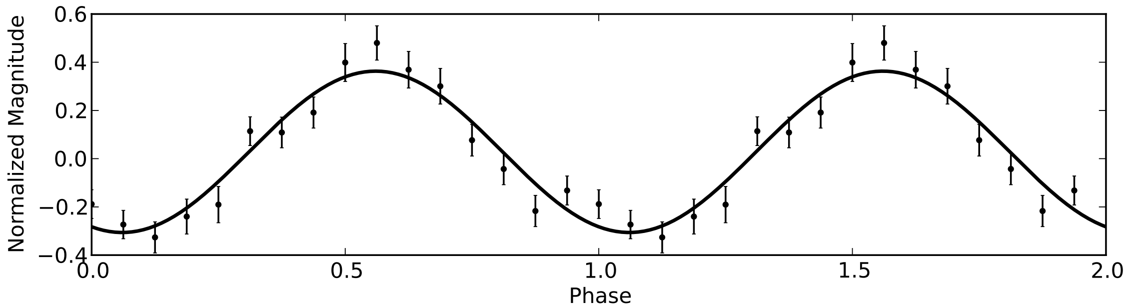
where T_0 is the time of minimum light when the companion is closest to the observer.

3.3. Discussion

With the obtained orbital period and the radial velocity semi-amplitude of the He II $\lambda 4686$ emission-line of $K_1 = 115$ km s^{-1} [7], we estimate a small mass function of 0.020 $M_\odot$ for



(a)



(b)

Figure 2: (a) Lomb-Scargle periodogram of RXJ0537 obtained from the combined MACHO and OGLE II+ III observations. The 99.73% significance level is indicated. Note the strong peak at $P_{\rm orb} = 0.1286836$ d. (b) MACHO and OGLE II+ III orbital phase diagram of RXJ0537 folded on a period of $P_{\rm orb} = 0.1286836$ d. The data have been averaged into 16 bins and fitted with a sinusoid with its period fixed at this value.

RXJ0537 implying a small mass donor star. In this case it has been assumed that the motion of the He II emission line represents the motion of the WD. However, this might not be the case if the emission line is due to the interaction of a wind from the accretion disc and that from the heated side of the donor. This would thus result in a significant underestimation of the mass function. In addition, when estimating the mass function, the semi-amplitude value of 115 km s^{-1}, which was derived by [7] with a corresponding period of 3.3 hrs was used. It is therefore possible that the used value of the semi-amplitude is slightly different from the one that would correspond with the derived period of 3.1 hrs.

The updated orbital period of 3.1 hrs of RXJ0537 confirms that this X-ray source is a very compact binary system and thus the masses of the two stars are not in the range of most known SSSs. Given that most known SSSs have mass ratios of $q \gtrsim 0.83$, where $q = M_{\rm donor}/M_{\rm accretor}$, the high mass transfer occurs when the Roche lobe of the donor star shrinks. This kind of mass transfer is very unstable and occurs on the thermal time-scale of the secondary star [2]. For binaries like RXJ0537 where the system is too small to host such a massive secondary, other methods of mass transfer like the wind-driven binaries should be considered [13]. The observed decline in the optical could be attributed to a decrease in mass transfer in the binary system.

Table 1: *XMM-Newton* observations of s2-26, with the Lomb-Scargle analysis results.

Observation ID	Start date time (UT)	Exposure time (ks)	Mean EPIC-pn counts/s	Period & error (mins)	Significance (%)
0402560101	2006-06-28 07:02:51	60.9	0.0060 ± 0.0041	-	-
0505760101	2007-07-24 17:28:34	58.9	0.0037 ± 0.0013	-	-
0511380101	2008-01-02 10:59:10	45.9	0.0044 ± 0.0011	35.8 ± 0.83	96.7

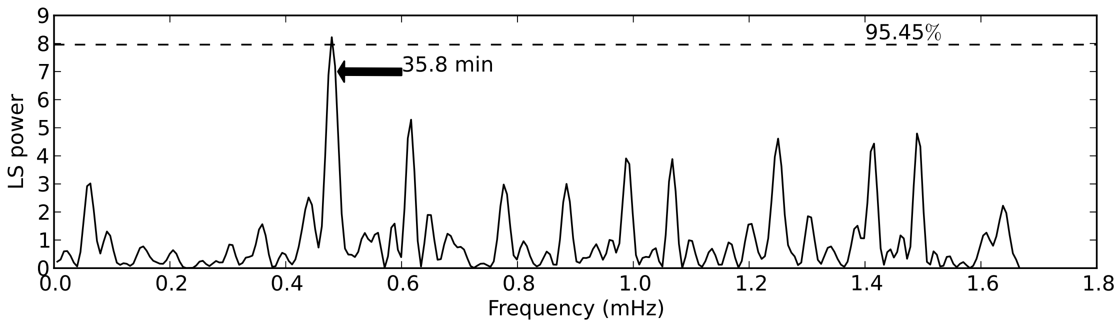


Figure 3: Lomb-Scargle periodogram of the EPIC-pn light curve from observation 0511380101 of s2-26, showing a significant peak of 35.8 mins. The 95.45% significance level is indicated. A light curve bin size of 300 s was used.

4. XMM-*Newton* observations of s2-26

4.1. Observations and timing analysis

s2-26 was observed by *XMM-Newton* in 2006, 2007 and 2008. The data was calibrated using standard data reduction procedures with SAS v. 12.0.1[3] to produce EPIC-pn light curves in the energy range 0.15-2.5 keV. Every EPIC-pn light curve was detrended by subtracting a 2nd-order polynomial. Detrended light curves with different bin sizes were used to search for any form of variability. The SCARGLE task in the Starlink PERIOD package was used to create a Lomb-Scargle (LS) periodogram for each light curve. A periodicity of 35.8 min was evident in the observation performed in 2008, as shown in figure 3 and table 1.

The peak was also present when testing other bin sizes. The observations of s2-26 in 2006 and 2007 did not show any significant peaks. The mean EPIC-pn count rates for s2-26 did not show significant long-term variability between the three *XMM-Newton* observations performed in 2006, 2007 and 2008. This is contrary to what was reported by [8]. The ROSAT survey of M31 was done in 1991 and 1992, and *Chandra* observed it 9-10 years later. Given that this source was detected in *XMM-Newton* suggests that it has been active for close to 20 years.

4.2. Discussion

Periodic modulations on time-scales of minutes to hours have been reported previously in SSSs. CAL 83, which is the prototype of this class of binaries, has shown periodic pulsations of 1-300 mins from timing analysis of *XMM-Newton* data [14, 15]. A ∼38.4 min period of CAL 83 reported from *Chandra* data timing analysis in [16], is interestingly close to the 35.8 min period

[3] http://www.cosmos.esa.int/web/xmm-newton

in s2-26. The ∼38.4 min period of CAL 83 has been associated with WD non-radial *g*-mode (internal gravity waves) pulsations [16]. Seismic waves in pulsating stars are classified depending on the restoring forces; *g*-modes, *f*-modes have gravity and negative buoyancy while *p*-modes are characterised with pressure gradient forces [17].

Non-radial pulsations have also been observed in dwarf novae [18], and it has been shown that novae undergo a supersoft X-ray phase on time-scales of up to 10 yrs [19]. X-ray data of these WD binaries have shown pulsations on time-scales of minutes. E.g. a strong ∼41.7 min periodicity was reported in nova V1494 Aql [20], while a ∼22.1 min modulation was found in V4743 Sgr [21]. The 35.8 min modulation in s2-26 reported here may have a similar origin.

5. Conclusions

An updated orbital ephemeris was presented for RXJ0537, with a slightly shorter period than reported before. The short orbital period of RXJ0537 and the observation of X-rays from this source present very interesting questions in terms of the accretion process that can drive very high mass transfer rates from the companion star. The process through which high mass transfer can occur in a WD binary system like RXJ0537 is still under investigation. RXJ0537 could probably represent a new class of transient supersoft X-ray sources and understanding it will contribute to a better understanding of binary evolution in general.

We found evidence of a 35.8 min modulation in X-ray data of supersoft X-ray source s2-26 which could be associated with *g*-mode oscillations, driven by instabilities due to thermonuclear reactions.

Acknowledgments

This work utilizes public data obtained by the MACHO project, jointly funded by the US Department of Energy, National Science Foundation through the Center for Particle Astrophysics at the University of California and Australian National University. M M Nyamai would like to thank Dr.Andrzej Udalski for providing us with the OGLE data. The financial assistance of the National Astrophysics and Space Science Programme (NASSP) towards this research is hereby acknowledged.

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