Optical Observations of the Be/X-ray Binary A0538-66

A F Rajoelimanana[1], P A Charles[2,3], P J Meintjes[1] and L J Townsend[3]

[1]Department of Physics, University of the Free State, PO Box 339, Bloemfontein 9300, SA
[2]School of Physics and Astronomy, Southampton University, Southampton SO17 1BJ, UK
[3]ACGC, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, SA

E-mail: rajoelimananaa@ufs.ac.za

Abstract.
We present recent results on the study of long-term photometric and spectroscopic properties of the Be/X-ray binary system A0538-66, using photometric data from the MACHO and OGLE-IV archives and spectroscopic observations from the Southern African Large Telescope (SALT). The previously reported 421 d superorbital modulation in the early MACHO data (1992–1996) appears to have shortened in the second half of the data (1996–2000). The OGLE-IV data (2010–present) shows a long-term variation but on a shorter timescale (around 250 d) and smaller amplitude than observed in the MACHO data. The spectroscopic observations from SALT enable us to probe both the evolution of the Be star envelope which can be traced by the Hα profiles and the details of its interaction with the neutron star in its presumed highly eccentric (e$\sim$0.7) orbit. The high-resolution spectra allow us to derive a better spectral classification. In addition, we derive a refined orbital period and ephemeris from the recent OGLE-IV light curves.

1. Introduction

Be/X-ray binaries (BeX) represent the largest sub-class of high-mass X-ray binary, which consists of a neutron star (usually an X-ray pulsar) orbiting an early-type non-supergiant Be star in a wide ($P_{orb} \sim 10 - 300$ days) and eccentric ($0.1 < e < 0.9$) orbit. The neutron star can interact and accrete from the Be equatorial disk during periastron passage, giving rise to periodic outbursts that may be observed over a wide range of wavelengths (e.g. X-ray, optical, IR).

The periodic recurrent transient X-ray source, A0538-66, was discovered in 1977 when two X-ray outbursts, separated by $\sim$ 17 d, were observed with the *Ariel V* satellite [1]. Further outbursts were observed with the *HEAO-1* modulator collimator which was found to recur every 16.66 d [2]. An improved *HEAO-1* position led to the identification of its optical counterpart as a bright (B$\sim$15) Be star in the Large Magellanic Cloud (LMC)[3, 4]. This implies that its peak X-ray luminosity was $\sim 10^{39}$erg s^{-1}, substantially super-Eddington for a 1.4 $M_{\odot}$ neutron star, and still the highest in its class. The discovery of the 69 ms X-ray pulsation in one of the X-ray outbursts observed with the Einstein Observatory indicates that the compact object is a neutron star [5] .

The optical counterpart was classified as a B2 III-V star and was found to reach 12$^{\mathrm{th}}$ mag during X-ray maximum [6]. Furthermore, this optical brightness increases are accompanied by the appearance of He II λ4686 emission [6, 7]. These huge outbursts had diminished by late 1983, and none have been observed since. However, much smaller optical outbursts (few tenths of a magnitude) were seen in both optical and X-ray observations and appeared to recur every 16.65 d which was interpreted as the orbital period of the system [8, 9].

The existence of dedicated telescopes to regularly observe the LMC, such as the MACHO project, has helped in understanding the long-term behaviour of the source. The early ($\sim$5 years) MACHO light curve displays large amplitude variability on a timescale of 421 d [10]. Within this 421 d modulation, the much shorter timescale, 16.6515 d outbursts are clearly visible, but remarkably they are only seen at certain phases of the long-term 421 d cycle. They occur during optical minimum, but not when the star reaches its maximum (quiescent) brightness, which led to the suggestion that these long-term superorbital variations were a result of the formation and destruction (or evaporation) of the circumstellar disc around the Be star [10, 11, 12].

2. Optical light curves from the MACHO and OGLE projects

The MACHO project has regularly monitored photometrically the LMC from 1992 to 2000. The data were taken simultaneously in two wide passbands, a blue band (4500 – 6300 Å) and a red band (6300 – 7600 Å). The complete MACHO light curve (1993-2000) is publicly available at the MACHO website[1] and the data are given in instrumental magnitudes. The field of A0538-66 also lies within the field regularly monitored by the OGLE-IV survey in which the source is identified as the OGLE object LMC 518.26.21298. Its real-time OGLE-IV light curve is available at the X-ray variables OGLE monitoring (XROM) website[2] [13]. Unfortunately, A0538-66 is not covered by the OGLE-II and OGLE-III projects.

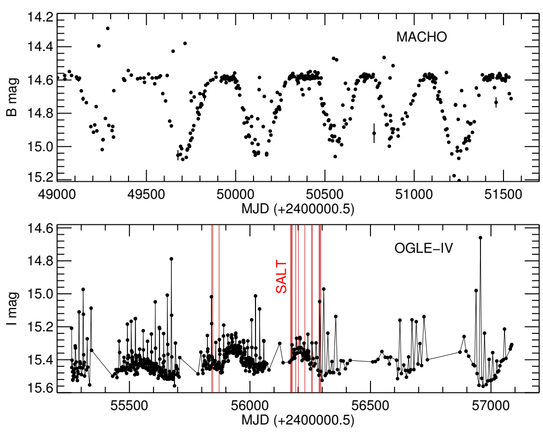

Figure 1. MACHO (top) and OGLE-IV (bottom) light curves of A0538-66. Vertical lines denote times of SALT/RSS observations

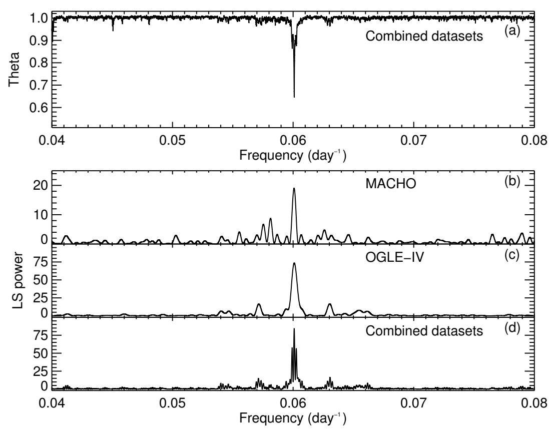

Figure 2. Power spectrum (PDM and LS) of the MACHO (b), OGLE-IV (c) and combined (a) and (d) datasets, showing a peak at 16.6409 d.

The complete MACHO light curve of A0538-66 displays large amplitude long-term variations of $\sim$0.5 mag as reported by [10]. From the complete light curve it appears that the period has slightly shortened in the second half of the data (see Figure 1). We performed Lomb-Scargle periodogram analysis of the two halves of the MACHO data and found the peak period to have

[1] http://wwwmacho.anu.edu.au
[2] http://ogle.astrouw.edu.pl/ogle4/xrom/xrom.html

changed from 439.75 d to 350.5 d (with uncertainties of ∼1 d). The power spectrum of the complete MACHO data shows a large peak at a period of 391.38 d which is slightly shorter than the previously reported 421 d superorbital period. The OGLE-IV light curve also shows a long-term variation but of a smaller amplitude and shorter timescale (∼ 250 days) than that seen in the MACHO light curve (see Figure 1).

In the MACHO data, the amplitude of the regular outbursts is very much dependent on the brightness level, they do not occur at optical maxima and are very strong (∼0.7 mag) at optical minima. This tells us that at optical maxima the equatorial disk is completely dissipated and we only see the naked B star. However, in the OGLE-IV data the 16.65 d regular orbital outbursts are always present, even though the source is at its superorbital maximum. The amplitude of these outbursts clearly varies through the long-term cycle. They are very weak at optical maxima, as the Be star has a smaller size disk during that time, and becomes stronger as the circumstellar disc grows (optical fades).

We have removed the long-term variations from the light curves by splitting them into several segments, the periodic outbursts events were first removed by sigma-clipping the bright points for each segment and then we fitted and subtracted a low-order polynomial from the data. We have run Lomb-Scargle (L-S) periodogram and phase dispersion minimization (PDM) on both individual and combined datasets over the period range ∼14–20 d with a resolution of 10^{-6} cycle d^{-1}. The power spectrum of the detrended MACHO, OGLE-IV and combined light curves (see Figure 2) shows significant peaks at 16.6434±0.0024, 16.6398±0.0026 d and 16.6409± 0.0003 d, respectively, which are slightly shorter than the previously reported values by [10]. These three periods are all consistent within 1-sigma (68% confidence) level. We note that the stated uncertainties on the periods are 1-sigma uncertainties and was calculated by using a Monte-Carlo simulation with 10 000 iterations.

Figure 3 represents the light curves folded on the period of 16.6409 d, showing not only one but two peaks in each orbital cycle. This might be caused by a misalignment between the orbital plane of the neutron star and the spin axis of the Be circumstellar disc. If we have a misaligned system, the neutron star interacts twice with the Be circumstellar disc every orbital cycle. From the folded light curves, we estimate the ephemeris for maximum light to be:

$$\mathrm{HJD_{outburst}} = 2455674.48 \pm 0.03 + \mathrm{n} * 16.6409 \pm 0.0003$$

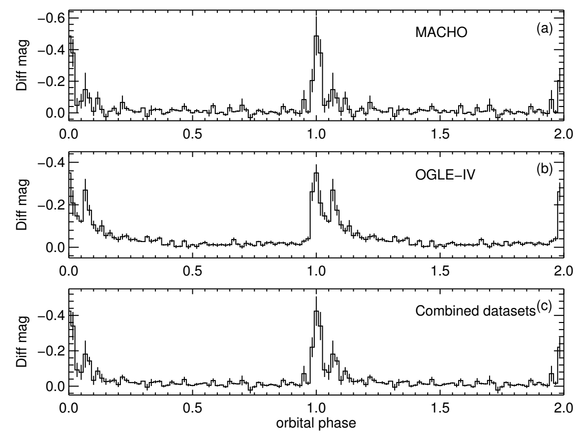

Figure 3. MACHO (a), OGLE-IV (b) and combined (c) light curves folded on the orbital period of 16.6409 d.

3. Optical spectroscopy with SALT

3.1. Broad-band spectra and Hα line profiles evolution

We have also obtained long-slit spectroscopic observations of A0538-66 with the Robert Stobie Spectrograph (RSS) [14, 15] on the Southern African Large Telescope (SALT) [16, 17] at SAAO, Sutherland. Broad-band spectra with a wavelength range of approximately $\lambda\lambda$3100–9000 and a dispersion of 1.0 Å pixel^{-1} were obtained by using two settings of the 900 lines mm^{-1} grating (PG0900). An example of broad-band spectra taken near optical maxima (smaller or no disk) and during the Be phase (with a disk present) are shown in figure 4.

Near the optical maximum (27–28 Aug 2012), the optical spectrum is dominated by the photospheric spectrum of the underlying B star in which all Balmer lines are in absorption. This is a signature of a smaller size or fully dissipated disk as the Balmer emission lines are formed in the circumstellar disk around the Be star. However, as the disk forms the Balmer (and sometimes He I) emission lines start to reappear. Figure 5 shows the time evolution of the Hα line profiles of A0538-66 which are highly variable both in terms of shape and strength. The profiles have various shapes such as single-peaked (07 Oct 2011), double-peaked (e.g. 01 Jan 2013), pure absorption (e.g. 27 Oct 2012) and shell profiles (e.g. 30 Aug 2012). Furthermore, it clearly shows V/R variations which are long-term changes in the relative strength of the violet (V) and red (R) components of the observed Hα emission profiles.

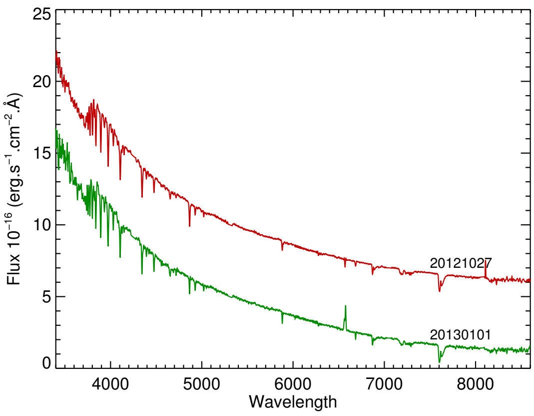

Figure 4. Broad-band spectra of A0538-66 taken near the optical maxima (20121027) and when the star is in a Be phase (20130101).

3.2. Spectral classifications

Figure 6 shows the average high-resolution blue spectrum ($\lambda\lambda$4000–4700) of A0538-66 obtained with the SALT/RSS in which all main spectral features have been identified. The spectra are mostly dominated by Balmer and neutral helium (He I) lines. The absence of the HeII 4686 line indicates a spectral type later than B0.5. The relative weakness of the Mg II 4481 line suggests a spectral type earlier than B2. The strength of the absorption lines of the C III + O II blends at 4070 Å and 4650 Å also indicates a B1 spectral-type source.

For luminosity classification, the ratio between the Si III 4552 and the He I 4387 was used which suggests a luminosity III (giant) star. The strength of the OII lines at 4070(blend), 4415 and 4640(blend) also indicates a luminosity class of III. The strength of these OII lines is rising with increasing luminosity. We conclude, therefore, that the optical counterpart of A0538-66 is a B1e III star which is slightly earlier spectral type than the previously reported (B2 III-V). As a comparison the spectrum of a standard B1 III (HD 147165) and B1 V (HD 144470) from the Walborn & Fitzpatrick spectral atlas [18] were plotted in Figure 7.

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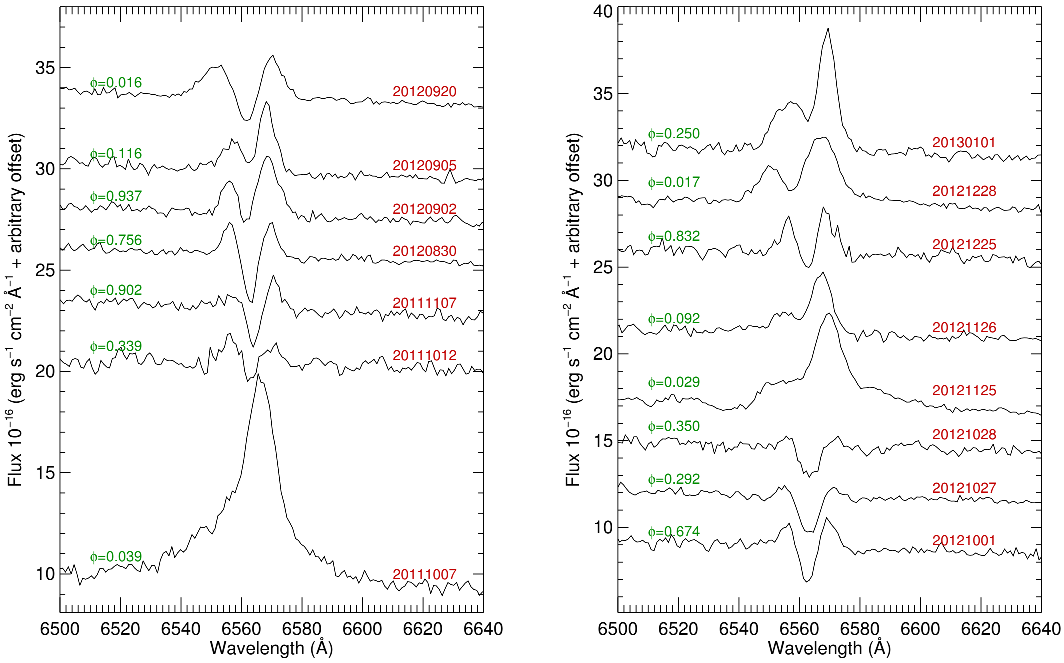

Figure 5. SALT/RSS spectra of the Be/X-ray system A0538-66 showing the evolution of its Hα emission line profiles.

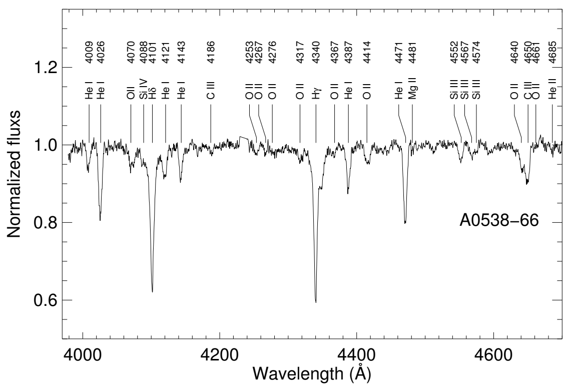

Figure 6. High-resolution spectra of A0538-66 in which all identified lines are also marked.

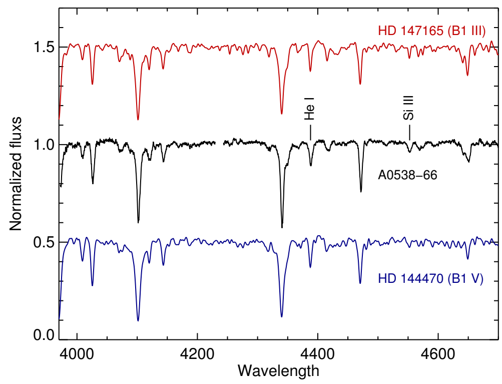

Figure 7. Blue spectra of A0538-66. The spectra of the standard B1 III (HD 147165) and B1 V (HD 144470) are also plotted

4. Conclusion

We have presented the long-term photometric and spectroscopic behavior of the LMC BeX source A0538-66. The previously reported 421 d superorbital modulation has evolved to 350 day in the second half of the MACHO observations and has shortened to $\sim$ 250 d in the OGLE-IV data. A refined orbital period of 16.6409$\pm$ 0.0003 d was derived from data including the most recent OGLE-IV light curve. The folded light curve on this period has a double-peaked profile which we suggest as arising from the misalignment between the Be disk and the orbital plane of the binary system. We have also revised its outburst ephemeris to $2455674.48 \pm 0.03 + n * 16.6409 \pm 0.0003$. The evolution of the H$\alpha$ line profiles in our spectra imply that the size of the equatorial disk around the Be star varies over the years. We refined the spectral classification of its optical counterpart to B1e III which is earlier than the spectral type found in the literature, namely B2 III-V. Further optical and X-ray monitoring are planned with finer timing around periastron.

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