A 421-d activity cycle in the BeX recurrent transient A0538–66 from MACHO monitoring

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ABSTRACT
We present a ∼5-yr optical light curve of the recurrent Be/X-ray transient A0538–66 obtained as a by-product of the MACHO Project. These data reveal both a long-term modulation at $P = 420.8 \pm 0.8$ d and a short-term modulation at $16.6510 \pm 0.0022$ d which, within errors, confirms the previously found orbital period. Furthermore, the orbital activity is only seen at certain phases of the 421-d cycle, suggesting that the long-term modulation is related to variations in the Be star envelope.

Key words: binaries: close – stars: individual: A0538–66 – X-rays: stars.

1 INTRODUCTION
The recurrent X-ray transient A0538–66 was discovered using Ariel V when two outbursts, separated by ∼17 d, were observed (White & Carpenter 1978). Further outbursts were observed with HEAO-1 which, when the source was active, was found to have a periodicity of 16.668 d (Johnston et al. 1979; Johnston, Griffiths & Ward 1980; Skinner et al. 1980; Skinner 1980), the precision of which led to its interpretation as being orbital. Skinner (1981) used archival plates taken over ∼50 years in order to obtain an improved value of 16.6515 d for this periodicity, based on the recurrence of the outbursts.

A0538–66 has been optically identified with a B star ($V \sim 15$) (Johnston et al. 1980), and an X-ray pulse period of 69 ms indicates that the compact object is a neutron star (Skinner et al. 1982). In quiescence (X-ray ‘off’) the colour, magnitude and radial velocity are consistent with a B2 III–IV star in the Large Magellanic Cloud (LMC) (Charles et al. 1983), but during outburst [which can reach as high as $V \sim 12$; see Densham et al. (1983)] it is redder with a spectral type of B8–9 I. During long phases of inactivity (there have been no large X-ray or optical outbursts reported since 1983) there is evidence that a remnant envelope is still present in the system (Smale et al. 1984). A0538–66 has usually been interpreted as a Be-type system that exhibits extreme outbursts as a result of its neutron star companion interacting with the Be star in a highly eccentric orbit (Charles et al. 1983).
Here we exploit the fortuitous location of A0538–66 in a MACHO (Alcock et al. 1995a) field and the extended (∼5 yr), regular (∼nightly) monitoring by the MACHO project in order to examine the quiescent variability of this, the most X-ray luminous of all Be X-ray transients.

2 OBSERVATIONS

The MACHO observations were made using the 1.27-m telescope at Mount Stromlo Observatory, Australia. A dichroic beamsplitter and filters provide simultaneous charge-coupled device (CCD) photometry in two passbands, a ‘red’ band (∼6300–7600 Å) and a ‘blue’ band (∼4500–6300 Å). The latter filter is a broader version of the Johnson V passband (see Alcock et al. 1995a, 1999 for further details).

The images were reduced with the standard MACHO photometry code sodophot, based on point spread function fitting and differential photometry relative to bright neighbouring stars. Further details of the instrumental set-up and data processing may be found in Alcock et al. (1995b, 1999), Marshall et al. (1994) and Stubbs et al. (1993).

3 MACHO PROJECT PHOTOMETRY

3.1 Light curve

In Fig. 1 we show the ‘blue’ and ‘red’ photometry of A0538–66, the magnitudes of which were transformed to Johnson V and Kron–Cousins R, respectively, using the absolute calibration of the MACHO fields. This absolute calibration depends on the colour of the object itself; therefore, at times when there were no red data available a mean colour for the data was used. The data consist of MACHO project observations taken during the period 1993 January 14 to 1998 May 28. There are fewer data points in the R-band because half of one of the four CCD chips in the red focal plane was inoperative. Owing to the German telescope mount, the focal plane may be rotated by 0° or 180° relative to the sky (depending on hour angle), hence A0538–66 falls on the dead area in about half the observations. As the V-band light curve has denser sampling than the R-band, only the V-band light curve was used in the rest of the analysis.

3.2 Period analysis and folded light curve

To search for periodicities in the V-band light curve two different frequency domain techniques were employed: (i) we calculated a Lomb–Scargle (LS) periodogram (Lomb 1976; Scargle 1982) on the data set, to search for sinusoidal modulations [this periodogram is a modified discrete Fourier transform (DFT), with normalizations which are explicitly constructed for the general case of time sampling, including uneven sampling; see Scargle (1982)]; (ii) we constructed a phase dispersion minimization (PDM) periodogram, which works well even for highly non-sinusoidal light curves (see Stellingwerf 1978).

As a modulation on longer time-scales is clearly evident in the light curve the data were searched over the frequency range 0.001–0.01 cycle d\(^{-1}\) with a resolution of 1 \(10^{-5}\) cycle d\(^{-1}\) (Fig. 2). To search for modulations in the region of the previously quoted 16.6-d period the long-term variations were removed. The data were split into 15 sections and each section was detrended separately by subtracting a linear fit. A frequency space of 0.01–1.2 cycle d\(^{-1}\) was searched with a resolution of 1 \(10^{-4}\) cycle d\(^{-1}\) (see Fig. 5 in Section 3.2.2).

3.2.1 The 421-d period

In the longer-period search a dominant peak was found in the LS periodogram at \(P = 420.52\) d (Fig. 2). The peak in the LS has a

![Figure 1. The V- (top panel) and R-band (bottom panel) light curves of A0538–66 from MACHO project observations. The V and R magnitudes have been calculated using the absolute calibrations of the MACHO fields.](https://academic.oup.com/mnras/article-abstract/321/4/678/996909)
confidence of greater than 99 per cent as determined from a cumulative probability distribution (CDF) appropriate for the data set. By constructing the cumulative probability distribution (CDF) of the random variable \( P_X(\omega) \), the power at a given frequency, where \( X \) is pure noise (Scargle 1982), we can measure the significance of the peaks in the LS periodogram. In practice the CDF was constructed using a Monte Carlo simulation method. Noise sets with the same sampling as the MACHO data were generated, and the LS periodogram was run upon each one. The peak power occurring in the periodogram due purely to noise was then recorded. This was repeated for 10,000 noise sets, to produce good statistics. From these values the probability of obtaining a given peak power from pure noise can then be calculated and the CDF derived. In order to test the significance of peaks from a given data set, the generated noise sets should have the same variance. Therefore, each noise set was generated from a random number generator that takes values from a Gaussian distribution with the same variance as the data set. The dip in the PDM periodogram corresponding to the peak in the LS periodogram is broad and highly structured, therefore a centroiding technique was employed to calculate the mode of the dip giving a period of 420.82 d (Fig. 2).

The MACHO \( V \)-band data were folded on \( P = 420.82 \) d (Fig. 3, top panel), and then binned (Fig. 3, middle panel), to examine the form of the modulated variability. Burst points that correspond to the 16.6-d period are evident in the data (see Section 3.2.2), these were removed and the remaining data were bin-folded (Fig. 3, bottom panel). To see whether the broadness of the peak (FWHM = \( 6.0 \times 10^{-4} \) d\(^{-1} \)) in the LS periodogram for the longer-period search was as a result of it being quasi-periodic we simulated a truly sinusoidal light curve to be used in period searching. The light curve was produced using a Gaussian random number generator with the same mean and standard deviation as the data plus a sinusoid with a frequency set to the period found. A period search was performed over the frequency range 0.001–0.01 cycle d\(^{-1} \) with a resolution of \( 1 \times 10^{-6} \) cycle d\(^{-1} \). The resulting LS periodogram is shown as a broken curve in Fig. 4. The peak produced from the simulated light curve has a FWHM = \( 5.5 \times 10^{-4} \) d\(^{-1} \) and is almost as broad as that for the real data, which shows that the modulation found is truly periodic.

In order to estimate the uncertainty in the 420.82-d dip in the PDM periodogram, we performed a Monte Carlo simulation in which we created artificial light curves with the same mean and standard deviation as the \( V \)-band data. Phase dispersion minimization periodograms were constructed and the minimum value found for each artificial data set using the centroiding technique near the dip of interest was recorded. The results had an average scatter of \( \pm 0.79 \) d.

### 3.2.2 The 16.6-d period

The resulting LS periodogram for the short-period search has a peak with much greater than 99 per cent confidence at \( P = 16.6667 \) d, together with two marginally significant peaks around 1 d (Fig. 5). To identify the origin of these peaks more simulated data sets were created, which had the same mean and standard deviation as the detrended data. These were produced using a Gaussian random number generator plus a sinusoid with period 16.6667 d. The resulting light curve was searched over a frequency range of \( 0.01–1.2 \) cycle d\(^{-1} \) with a resolution of \( 1 \times 10^{-4} \) cycle d\(^{-1} \). As can be seen from the resulting LS periodogram (Fig. 5) the two peaks are 1-d aliases arising from the sampling of the data set. Using the centroiding technique again, the dip in the PDM periodogram for the short-period search was found to correspond to \( P = 16.6510 \) d (Fig. 5).

The detrended \( V \)-band data were folded on \( P = 16.6667 \) d and \( P = 16.6510 \) d using Skinner’s ephemeris (1982). The folded light
curves showed that the modulation was highly non-sinusoidal, hence we took the PDM value for the orbital period, and the bin-folded light curve using $P_{\hat{\nu}}^{16} = 6510$ d is shown in Fig. 6. The error on the period was propagated using the same method as for the long-period search producing a value of $\Delta \hat{\nu} = 0.0022$ d.

4 DISCUSSION

These extensive MACHO observations have revealed, not only a remarkably stable long-term modulation, but also the presence of the same 16.6-d orbital modulation (in the form of mini-outbursts) that had been seen (on a larger scale) in the 1980s. However, the key additional point is that these mini-outbursts are constrained in 421-d phase to only occur during minima, thereby establishing a physical link between the two. What can this be?

To explain the origins of the long-term variability in A0538–66 it is instructive to consider other systems that show modulations on these time-scales. The soft X-ray transient (SXT) 4U 1630-47
is the shortest known recurrent black hole SXT, with an outburst recurrence interval of \( \sim 600–690 \) d (Jones et al. 1976; Priedhorsky 1986; Kuulkers et al. 1997). The outburst recurrence times vary, as do the intensities at the peak of the outburst and its duration (Kuulkers et al. 1997), this behaviour is also seen in A0538–66 (Skinner et al. 1980). Both sources also undergo transitions between high and low activity on time-scales \( \sim 1 \) yr (4U 1630–47; Kuulkers et al. 1997, A0538–66; Skinner et al. 1980, Pakull & Parmar 1981), and exhibit inter-outburst activity (4U 1630-47; Parmar et al. 1997; Kuulkers et al. 1997, A0538–66; Densham et al. 1983). Kuulkers et al. (1997) showed that the outburst recurrence time cannot be related to orbital variations of 4U 1630-47. Owing to heavy reddening the optical counterpart has not yet been detected in 4U 1630-47, and so a Be-type secondary cannot be excluded.

Analysis of X-ray observations of another Be/X-ray transient, A0535+26, led to an orbital period of 110.3 d for the source (Finger, Wilson & Harmon 1996). Analysis of the long-term

Figure 5. Phase dispersion minimization periodogram (top panel) and Lomb–Scargle periodogram (middle panel) for a short-period search of detrended V-band data, frequency space 0.01–1.2 cycle d\(^{-1}\) and resolution \(1 \times 10^{-5}\) cycle d\(^{-1}\). Bottom panel, Lomb–Scargle periodogram for the simulated light curve which contained a sinusoidal signal of 16.6667 d.

Figure 6. V-band data, detrended and folded on \( P = 16.6510 \) d in 20 phase bins, using \( T_0 = \text{MJD} 2443423.96 \pm 0.05 \) (Skinner 1981). Error bars for the binned light curve are the standard errors for the data points in each bin.
optical light curve by Clark et al. (1999) showed periodicities at $\sim 1400$, $\sim 476$ and $\sim 103$ d, but no evidence was found for the $\sim 110$-d presumed orbital period of the neutron star. Clark et al. (1999) could not identify the origin of these quasi-periods, and it was not clear whether they were coherent over time.

In normal Be star shell ejection events, which recur on timescales of years, the circumstellar matter lost forms an equatorial disc around the Be star owing to its rapid rotation (Slettebak 1987). The Paschen continuum of the equatorial envelope is in emission and thus emits optical light which is redder in $B-V$ than that emitted by the early-type star. The formation of the disc will either add red light and increase the optical brightness of the system or will mask the early-type star and make it appear fainter, depending on the inclination (Corbet et al. 1986; Janot-Pacheco, Motch & Mouchet 1987). The photometric behaviour of the Be star in A0538–66 in the $V$, $V-R$ diagram (Fig. 7) shows a reddening as the source becomes fainter. The fading and rising events in the light curve of A0538–66 could be caused by the formation and depletion of an equatorial disc seen at high inclination.

If this is the case, the fact that the neutron star is believed to be in an eccentric orbit around the Be star could set a limit on the size of the equatorial disc that can form producing the 421-d periodicity. Using this model the mini-outbursts only occur when the disc reaches the upper limit set by the orbit of the neutron star. Although Okazaki (1998) and Negueruela et al. (1999) suggest that the presence of the neutron star in orbit around the Be star will tidally truncate the circumstellar disc of the Be star well within the orbital radius of the neutron star, thus preventing accretion, modelling by Haynes, Lerche & Wright (1980) and Brown & Boyle (1984) shows that matter can escape from the Be star and be spread over a domain in the vicinity of the orbit of the compact star near periastron. Therefore, the ‘flat’ part of the light curve of A0538–66 is when we are seeing the normal B star without any equatorial disc, hence no outbursts can occur. If this is correct, the previously obtained spectra thought to be taken during ‘quiescence’ were really taken during the extended dips in A0538–66’s light curve. This indicates that the true quiescent magnitude of the system is $\sim V = 14.4$, and the quoted quiescent spectral-type must be redetermined. As the colours obtained from the MACHO data are not precise enough we cannot confirm the previously determined spectral classification for A0538–66. A study of archival data of A0538–66, including data taken before 1980, will be presented in a future publication.

Skinner (1981) found the recurrence of the outbursts of A0538–66 to be $16.6515 \pm 0.0005$ d or $16.6685 \pm 0.0005$ d. We find the periodicity to be $16.6510 \pm 0.0022$ d, which within errors confirms the first of the orbital periods for A0538–66 suggested previously by Skinner.

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Figure 7. Colour magnitude diagram of A0538–66 showing that the star is redder when fainter, which is interpreted in classical Be models as a consequence of the formation of an equatorial envelope seen at high inclination. Open circles correspond to the 16.6510-d burst points, filled triangles to all other data. The $V-R$ values are purely instrumental, whereas the $V$ magnitudes have been calculated using the absolute calibrations of the MACHO fields (see Section 3.1 for details).
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