The optical counterpart to SAX J1808.4-3658: observations in quiescence

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ABSTRACT
We report the first extensive set of optical photometric observations of the counterpart to SAX J1808.4-3658 (V4580 Sagittarius) in quiescence. The source was detected at $V \sim 21.5$ magnitudes fainter than at the peak of its 1998 outburst. However, a comparable $\sim 6\%$ semi-amplitude 2hr modulation of its flux is revealed. This has the same phasing and approximately sinusoidal modulation as seen during outburst, and with photometric minimum when the pulsar is behind the companion. The lack of a double-humped morphology rules out an ellipsoidal origin, implying that the bulk of the optical flux does not arise from the companion. Moreover, applying crude modelling to the disc and X-ray irradiated face of the donor shows that the internal energy release of a remnant disc (with mass transfer driven by gravitational radiation) is sufficient to explain most of the optical emission, and with the modulation due to the varying contribution of the heated star's face. We note that this model is also consistent with the much lower X-ray to optical flux ratio in quiescence versus outburst, and with the phasing of the optical modulation.

Key words: accretion, accretion disks – binaries: close – pulsars: individual: SAX J1808.4-3658 – stars: individual: V4580 Sagittarius – stras: low-mass, brown dwarfs

1 INTRODUCTION
The low-mass X-ray binary (LXMB) transient SAX J1808.4-3658 was first detected (in outburst) by the BeppoSAX Wide field Camera in 1996 September (In’t Zand et al. 1998), following a non-detection in a preceding August observation. Three type-I X-ray bursts were also observed demonstrating the presence of a neutron star accretor. The third exhibited clear double-peaked morphology implying an Eddington-limited photospheric radius expansion event, yielding a distance estimate of 2.5kpc (In’t Zand et al. 2000).

During another outburst in 1998 April/May, SAX J1808.4-3658 was detected by RXTE, enabling the measurement of the fastest ever LMXB X-ray pulsation, with a period of 2.49ms (Wijnands & van der Klis 1998). Chakrabarty & Morgan (1998) utilized precise timing of the millisecond pulses to determine many parameters of its binary orbit: period, epoch of mean longitude, projected semi-major axis, eccentricity and pulsar mass function. Hence, they were immediately able to place constraints on the nature of the system, in particular the secondary’s spectral type, suggesting a very low mass ($\lesssim 0.1 M_\odot$), but irradiation-bloated/ablated, dwarf star. Lastly, Roche et al. 1998 were able to identify an optical counterpart consistent with the BeppoSAX X-ray position, even within the smaller error circle yielded by the RXTE X-ray pulse timing. We note that this counterpart has recently been designated as the variable star V4580 Sagittarius (Kazarovets et al. 2000).

Additional constraints on the secondary can be placed by observations of the optical counterpart. Giles, Hill & Greenhill (1999) report on CCD photometry performed with the Mt Canopus 1m telescope during decline from the 1998 outburst in April–June. Their coverage consists mostly of single pointings a few nights apart, in order to follow the long-term lightcurve, which showed the source to fade from $V=16.72$ to around 18.5, 1 and 3 weeks after the start of the X-ray decline. A later observation on June 27 failed to detect the source,
corresponding to $V \gtrsim 20.5$. They also obtained short $V$-band sequences on three nights, but only amounting to $\sim 0.25$, $\sim 1.0$ and $\sim 1.2$ cycles of the 2 h period respectively. From these sparse data they concluded that there was evidence for a 0.06 mag semi-amplitude modulation at the 2 h X-ray period, with phasing such that the minimum occurs when the companion lies between the observer and pulsar.

In order to place further limits on the secondary, we obtained the first high time-resolution CCD photometry of the counterpart in quiescence, using the 1.9m telescope at the South African Astronomical Observatory (SAAO), and it is these results that we present in this paper.

2 OBSERVATIONS AND DATA REDUCTION

![Finding chart for V4580 Sgr (SAX J1808.4-3658) in quiescence. This is a co-add of 13 $B$-band images and totals 52 min of exposure. Note the faintness of the target and the closeness of neighbouring stars. The three local standard stars used for calibration are indicated.](image)

Observations of a small ($50 \times 33$ arcsecs) region surrounding the optical counterpart to SAX J1808.4-3658 were made using the UCT-CCD fast photometer (O’Donoghue 1995), at the Cassegrain focus of the 1.9m telescope at SAAO, Sutherland on 1999 August 10 and 2000 July 3. The UCT-CCD fast photometer is a Wright Camera $576 \times 420$ coated GEC CCD which was used here half-masked so as to operate in frame transfer mode, allowing exposures of as short as 2s with no dead-time. However, given the faintness of the quiescent counterpart we employed much longer integration times. In 1999, we concentrated on obtaining a high signal-to-noise lightcurve, and therefore we opted for a continuous time-series of 30s white light (no filter) exposures. In 2000, we were again favoured with good seeing and stable photometric conditions initially, so we attempted to obtain colour information on the binary modulation. In fig. 3 we show a deep (52 min exposure) $B$ band finding chart, constructed from the 13 shifted and co-added images from the interval of best seeing during these observations. This demonstrates the difficulties in obtaining good photometry of this faint target, as it is quite severely crowded; only with good seeing, $\lesssim 1''$ (indeed truly excellent for this telescope) is there any possibility of resolving the counterpart from its near neighbour. However, the seeing did deteriorate and become more variable towards the end of the run. In this instance, we cycled through $BVR$ filters, with typical exposure times of 240, 180, 150s in each respectively. For the 2 h period, this still yields approximately 0.1 phase resolution.

We performed data reduction using IRAF, including photometry with the implementation of DAOPHOT II (Stetson 1987). Point spread function (PSF) fitting was always employed, as it is essential for obtaining the best possible photometry, in such crowded conditions. The details of this procedure are given in Homer, Charles & O’Donoghue (1998). Lastly, in order to reduce systematic effects differential photometry was applied, wherein the magnitudes of a star are calculated relative to an ensemble of local standards (bright, non-variable stars).

3 RESULTS

3.1 Colour photometry

For the 1999 August 10 white light observations no strict calibration is possible. However, if we assume that the unfiltered passband of the CCD corresponds roughly to $V$, we may use observations of the E-region standard E752 (Menzies & Laing 1980) to estimate that the counterpart had $V \sim 20$ on that date, consistent with the limit of Giles, Hill & Greenhill (1999) given the uncertainties.

For the sets of colour images from 2000, we use the standard star E508 (chosen for its similar colours, and comparable airmass when observed), and aperture photometry to derive the calibrated magnitudes of local standard stars within the small field of the CCD (see fig. 4). Finally, the magnitude of the target is calculated from its differential magnitude with respect to these local standards, these measurements necessarily making use of PSF fitting. We find $B = 22.0 \pm 0.1$, $V = 21.5 \pm 0.1$ and $R = 20.9 \pm 0.1$ all uncorrected for reddening. The magnitude errors quoted arise largely from counting statistics as the target is simply so faint, together with uncertainties in the transformation between aperture and PSF magnitudes. Compared to its colours during outburst (Roche et al. 1998) of $V = 16.6 \pm 0.2$ and $R = 16.1 \pm 0.2$, i.e. $(V - R)_{{\text{hi}}} = 0.5 \pm 0.3$ cf.
(V − R)_{10} = 0.6 ± 0.2; apart from being 5 magnitudes fainter, they are consistent within the uncertainties, agreeing with theunchanging V − I values found by Giles, Hill & Greenhill (1999) during the decline itself.

Furthermore, in order to facilitate other comparisons we may attempt to correct for interstellar extinction towards SAX J1808.4-3658. We utilize the column density estimated from RXTE X-ray spectral fits by Heindl & Smith (1998) to set an upper limit, and the galactic value in the direction of SAX J1808.4-3658 for the lower limit (Dickey & Lockman 1990), to derive 6.3 ≥ N_H ≥ 1.3 × 10^{21} cm^{-2}. Applying the relations \( N_H = 1.79 \times 10^{22} A_V \) (Predehl & Schmitt 1995), \( E(B−V) = A_V/3.2, A_B = 1.32 A_V, \) and \( A_R = 0.81 A_V, \) we may estimate corrected colours of \( −0.6 \leq (B−V)_0 \leq 0.3 \) and \( −2.4 \leq (V−R)_0 \leq 0.5. \) The corrected flux densities can also be obtained using the calibration for an A0V star in Drilling & Landolt (2000), as may the absolute magnitudes assuming a 2.5 ± 0.1 kpc distance (In’t Zand et al. 2000). All these data are summarised in table 1.

| Quantity          | Band | Lower limit | Upper limit |
|-------------------|------|-------------|-------------|
| Apparent mag.     | \( B_0 \) | 17.7        | 21.0        |
| (de-reddened)     | \( V_0 \) | 18.2        | 20.8        |
|                   | \( R_0 \) | 17.7        | 21.0        |
| Absolute magnitude| \( M_{B0} \) | 5.7         | 9.0         |
|                   | \( M_{V0} \) | 6.2         | 8.8         |
|                   | \( M_{R0} \) | 6.3         | 8.3         |
| Flux density \( (\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}) \) | \( F_{B0} \) | \( 2.5 \times 10^{-17} \) | \( 5.3 \times 10^{-16} \) |
|                   | \( F_{V0} \) | \( 1.8 \times 10^{-17} \) | \( 2.0 \times 10^{-16} \) |
|                   | \( F_{R0} \) | \( 1.3 \times 10^{-17} \) | \( 8.4 \times 10^{-17} \) |

The lightcurve from 1999 August spans a full 2 cycles, with another half cycle, where the effects of airmass (and deteriorating seeing) become a slight problem. Clearly, this is insufficient to make any independent measurement of the period, but we can easily check for consistency with the pulse timing result. In figure 2 we plot the linearly detrended lightcurve, along with a fitted sinusoid with \( P_X = 2.01 h \) and the projected X-ray ephemeris. Clearly, there is no doubt from our dataset that the quiescent counterpart exhibits a smooth approximately sinusoidal modulation at the 2 h period, and the fit gives the semi-amplitude as 0.063 ± 0.003 mag. For this fit and later analysis we opted to omit the last half cycle of data, where the source appears to reach its brightest level, as this may be due to the poorer seeing. We note that the amplitude, like the colours, is consistent with that of the high state source. The scatter seen in the similar lightcurves of Giles, Hill & Greenhill (1999) could be due to an intrinsic property of the high state source (it is known on occasion to exhibit complex X-ray flaring behaviour; van der Klis et al. 2000; Wijnands et al. 2000), which is likely to be present in the reprocessed optical emission. In order to study the morphology more closely, we have also folded and phase binned the data, which is presented in figure 3. The pure sinusoid appears to be a very good fit, only at around 0.9 in phase does the data scatter, which corresponds to a region in phase for which only one cycle of data is present (owing to a gap in the first cycle). Quantita-
Figure 2: Lightcurve of V4580 Sgr (SAX J1808.4–3658), taken in white light (filled circles), with a star of comparable brightness plotted offset below (squares). The data has been binned up a factor of two to 60s time resolution for clarity. Over plotted is the sinusoidal fit to the data (solid line), with only the period constrained to the orbital value. The dotted line indicates the X-ray ephemeris, i.e. the mean orbital longitude of the system as derived from the X-ray pulse arrival time delays (Chakrabarty & Morgan 1998). As during the outburst observations of Giles, Hill & Greenhill (1999), the time of photometric minimum is consistent with a mean orbital longitude of 90°, that is when the pulsar lies behind the companion.

In July 2000 we attempted to investigate the colour dependence of the two hour modulation. However, the target turned out to be even fainter than in August 1999, and hence the signal-to-noise of our data is marginal. In fact, we found it necessary to firstly select the best seeing images (based on check star behaviour), and then phase fold the data. The data have also been detrended using a quadratic polynomial constrained to approximate the airmass variations. In figure 4 we show the resulting $BVR$ lightcurves for V4580 Sgr and a star of comparable brightness. Clearly, the phase folding reveals apparent modulations in each band, although in the case of $V$ the check star also shows only slightly smaller amplitude variations. Given the data quality we must be cautious with regard to the significance of these modulations. However, statistically we do find that a (period and phase constrained) sinusoid fit is always an improvement over a constant value at > 99% confidence level (from an F-test). The fitted sinusoids also provide marginal evidence for a trend towards larger amplitude at longer wavelengths (see table 2). Even less certain is the possible "eclipse" feature present in the $B$ band data at phase~0.0, which, if excluded, does lend further support to a trend in the smooth modulation amplitude. However, it is clear that further observations from a larger telescope with better seeing are needed to confirm these tentative results.

4 ORIGINS OF THE OPTICAL FLUX

The detection of a plausibly phased two hour modulation confirms our identification of the correct counterpart, V4580 Sagittarius, in both sets of observations. However, we have noted that its X-ray to optical luminosity ratio is very small, which implies that it is sur-
prisingly optically bright, especially given the expected very faint emission from any secondary capable of fitting into the Roche lobe of the 2 hr orbit (see below). The possibility that the true quiescent amplitude is much larger than in outburst, allowing for another line-of-sight star, responsible for some of the flux we have measured, can nevertheless be ruled out by the morphology, which is not flat-bottomed but sinusoidal (cf. the case of PSR 1957+20, Djorgovski & Evans 1988). We shall now seek to apply some constraints as to the source of the optical emission, given the available information, although we are limited by the large uncertainties in the absolute magnitude and colours of V4580 Sgr (due to the poorly constrained column).

Firstly, are we simply seeing the companion star and nothing else? Chakrabarty & Morgan (1998) argue that the most probable companion is an extremely low mass star (less than 0.1 M⊙). However, if this lies on the main sequence the expected M_v ∼ 14 implies a brightness that is 5 magnitudes fainter than our observed limit. On the other hand, we might postulate a more massive (0.5–0.8 M⊙) companion, such as a K1 to M0 main sequence dwarf, which would have the correct magnitude. But this is also not tenable. The counterpart is much too blue for such a spectral type ((B−V)_0 ≤ 0.3 cf. a K1 star value of 0.86). The inferred inclination would be extremely low (i ≤ 6°) and therefore improbable, since the a priori probability of seeing a system with i or less goes as (1−cos i). Further compelling evidence is the lack of ellipsoidal variations. If any modulation is to be seen from the light of the companion star alone (as is the case for a number of other soft X-ray transients in quiescence), then its period should be half that of the binary. Hence, we may conclude that no "ordinary" lower MS star provides all the optical emission.

The other possible source of optical emission is a combination of: (i) a remnant accretion disc, (ii) a hotter irradiated accretion disc, (iii) the irradiated face of the companion star. In order to make an approximate quantitative comparison with our data we have undertaken some simplified modelling to obtain predicted broad band spectra. For the details of the modelling see Chakrabarty (1998), §4.3 (accretion disc), and the appendix (heated face of companion star). The resulting spectra are presented in figure [3].

Assuming that an accretion disc is still present, how bright will it be solely due to internal viscous energy release? Here we make use of the results of the α disc prescription, using a nominal but reasonable value of α=0.1, and a canonical 1.4 M⊙ mass for the neutron star. The inner disc radius is set at the co-rotation radius assuming a Keplerian disc and the outer at 9/10 of the primary’s Roche lobe. We may estimate the mass transfer rate assuming that the low mass secondary continues to fill its Roche lobe (requiring either/both an evolved or/and an X-ray irradiation-bloating state), and that the process is solely driven by angular momentum loss due to gravitational radiation (GR; Kraft, Matthews & Greenstein 1962):

\[ \dot{M}_{GR} \approx 0.95 \times 10^{-11} M_\odot \text{yr}^{-1} (M_2/0.05 M_\odot)^2. \]

This is also consistent with the time-averaged value based on the energy released during outbursts (e.g. 1998 April, total fluence \( \approx 4.3 \times 10^{-3} \text{erg cm}^{-2} \); Gilfanov et al. 1998) along with their \( \sim 20 \) month recurrence cycle. The spectrum is plotted as the dotted line in the figure. With a measured value for \( \alpha_1 \sin i \) from pulse timing, the value of \( M_2 \) we choose immediately constrains the inclination angle \( i \). For a 0.05 M⊙ secondary, we find a moderately high inclination \( i = 60^\circ \) (50% a priori probability of detection), and the model curve is consistent with the lower limits on the optical fluxes, and has the correct blue slope (although \( M_2 \) could well be slightly higher than we used). For any higher inclination both the GR-driven mass transfer rate decreases (as the square) and the projected disc size (as \( \cos i \)), making such a system too faint compared to our observations. On the other hand, for more massive secondaries the inclination must be lower and hence so will the a priori probability of seeing such an inclined system, ignoring any selection effects.

Depending on the system inclination a variety of mechanisms can lead to a periodic modulation of the optical flux on the binary period. In the case of SAX J1808.4-3658, the lack of an X-ray eclipse requires \( i < 82^\circ \), whilst we have seen it is more likely to be lower still, \( i \lesssim 60^\circ \). In this range low amplitude (at most a few per-

Table 2: Parameters of sinusoid fits to optical modulations in V4580 Sgr/SAX J1808.4-3658.

| Lightcurve | Phase of | Amplitude (mag) | Sinusoid vs. constant fit |
|-----------|----------|-----------------|--------------------------|
|           | minimum light | Constrained: Period Period and Phase F-test confidence level |
| Whitelight | 0.0084 ± 0.0081 | 0.063 ± 0.003 | 0.063 ± 0.003 | 100.00% |
| B band    | 0.09 ± 0.06 | 0.09 ± 0.03 | 0.08 ± 0.03 | 99.18% |
| B – “eclipse” | 0.14 ± 0.06 | 0.05 ± 0.02 | 0.03 ± 0.02 | 85.23% |
| points    |           |                |                          |
| V band    | 0.02 ± 0.04 | 0.08 ± 0.02 | 0.08 ± 0.02 | 99.99% |
| R band    | 0.08 ± 0.02 | 0.15 ± 0.02 | 0.13 ± 0.03 | 99.98% |
cent) sinusoidal modulations are seen in many LMXBs, which are presumed to arise due to the varying contribution from the X-ray heated face of the secondary as its aspect changes. Within this framework the measured amplitude of modulation enables us to estimate the level of irradiating flux required to be $L_{\text{irr}} \sim 10^{33}$ erg s$^{-1}$. Admittedly, this luminosity is a factor of ten higher than that of the two quiescent X-ray observations of SAX J1808.4-3658 but probably still consistent, given the degree of variability seen in other quiescent sources (e.g. Cen X-4; Campana et al. 1997). We note that this too argues against lower inclinations, as the amplitude will decrease along with the relative contribution of the heated face, and a greater degree of irradiation is not possible. Interestingly, the trend in amplitude fits that implied by the data, decreasing towards the blue, which is a consequence of the cooler variable companion star component.
5 CONCLUSIONS
We have undertaken the first time-series CCD photometry of V4580 Sagittarius, the optical counterpart to SAX J1808.4-3658, in quiescence. We find that it has dropped to $V \sim 21$, five magnitudes from the peak of the 1998 outburst, although its colours are the same within the uncertainties. Furthermore, as during outburst it exhibits a clear 2hr sinusoidal modulation with a $\sim 6\%$ semi-amplitude, and is at a minimum when the pulsar lies behind the companion. Our $BV R$ photometry reveals a possible trend in amplitude, increasing with wavelength. Lastly, a comparison of its X-ray to optical flux ratios in outburst and quiescence shows that if reprocessing of the observed X-ray flux is the dominant mechanism in outburst, this cannot apply in quiescence, as it is relatively optically over-bright.

An analysis of these results has led us to conclude that:

- Unlike other soft X-ray transients in quiescence, the intrinsic emission of the companion star is not the dominant contribution to its optical flux (as evidenced by the lack of ellipsoidal variations).
- If we assume that a low level of mass transfer (driven by gravitational radiation losses) continues, then the disc emission due to internal viscous energy release is the main source of the observed optical flux. However, the observed X-ray luminosity requires that this mass is not being accreted onto the neutron star.
- The observed sinusoidal binary modulation is most consistent with a geometrical (i.e., aspect change) origin, wherein the face of the secondary is irradiated by the quiescent X-ray flux, and makes a variable contribution to the optical flux.

Clearly, with the existing data we have only been able to infer many of the physical details of the system and further observational effort on the quiescent counterpart is still needed.

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APPENDIX A: DERIVING THE
REPROCESSED OPTICAL FLUX FROM
THE SECONDARY’S HEATED FACE

In deriving the optical flux due to the irradiated face of the secondary star, a spherical geometry was assumed, such that the surface need only be divided into annuli, having an angle ($\xi$) between their normal and the radiation incident from the primary. In this way, the method used for the accretion disc can be modified for the star. Hence, the effective temperature is given by:

$$T_{irr}^4 = \frac{(1 - \eta_\star)L_{irr}\cos\xi}{4\pi\sigma d^2}$$

where $\eta_\star$ is the irradiating flux albedo (taken as 0.3; Milgrom & Salpeter 1976) and $d$ is the separation of the annulus from the source. The spectrum is then given by assuming each annulus emits as a blackbody at this temperature, and summing the contribution from each at a given frequency (the shadowing effect of the disc has been taken into account). However, for simplicity the line of sight is taken as lying in the orbital plane, enabling straightforward calculation of the projected surface area of each contributing annulus.