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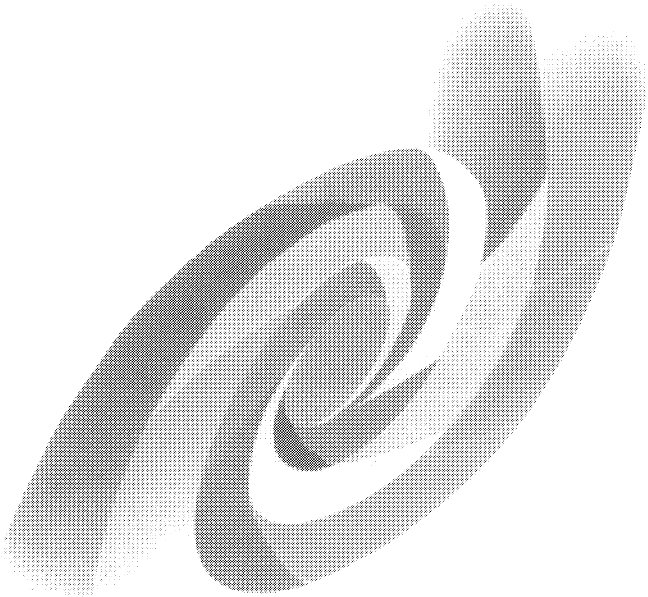

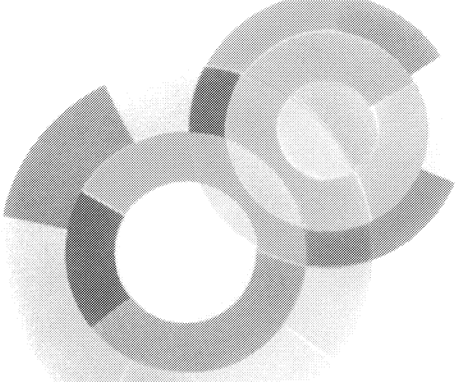

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Transient *I* band excess in the optical spectrum of accreting millisecond pulsar SAX J1808.4-3658

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ABSTRACT
The optical counterpart of the transient, millisecond X-ray pulsar SAX J1808.4-3658 was observed in the four colours (*BVRI*) for five weeks during the 2005 June/July outburst. The optical fluxes declined by ~ 2 magnitudes during the first 16 days and then commenced quasi-periodic secondary outbursts with timescales of several days similar to those seen in 2000 and 2002. The broadband spectra derived from these measurements were generally consistent with emission from an X-ray heated accretion disc. During the first 16 days decline in intensity the spectrum became redder. We suggest that the primary outburst was initiated by a viscosity change driven instability in the inner disc; unlike another accreting millisecond pulsar, XTE J0929–314 for which the spectrum becomes bluer during outburst. At the start of the secondary outbursts on HJD 3546 the *V-I* colour index increased by ~ 0.2 magnitudes for one night only. We suggest that this may have been caused by a mass transfer instability which was associated with the secondary outbursts. On the night of 2005 June 5 (HJD 2,453,527.14) the *I* band flux was ~ 0.45 magnitudes brighter than on the preceding or following nights whereas the *BV* & *R* bands showed no obvious enhancement. The broad band (*BVRI*) spectrum for this night is not consistent with emission from an X-ray heated accretion disc. We suggest the *I* band excess was due to transient synchrotron emission and that this is a common feature of accretion-driven millisecond pulsars.

Key words: binaries close – pulsars general – pulsars individual SAX J1808.4–3658 – stars low-mass – stars neutron – X-rays binaries

1 INTRODUCTION

SAX J1808.4–3658 was the first transient millisecond X-ray pulsar to be discovered and has been studied extensively at all wavelengths (Chakrabarty & Morgan 1998; Wijnands & van der Klis 1998; in 't Zand et al. 1998; Giles, Hill & Greenhill 1999; Wachter et al. 2000; Wang et al. 2001; Wijnands et al. 2001; Homer et al. 2002; Markwardt, Miller & Wijnands 2002; Chakrabarty et al. 2003; Wijnands et al. 2003). Study of these systems is providing important information on the evolutionary path by which a conventional LMXB system becomes a millisecond radio pulsar (Campana et al,2004; Wijnands, 2005; Bogdanov et al, 2005).

The optical spectrum of SAX J1808.4–3658 during 1998 outburst was found by Wang et al (2002) to be consistent with emission from an X-ray irradiated accretion disc although there was a clear IR (*JHK*)excess on one occasion. It is possible that this extended into the optical bands (Giles et al, 2005). A 2 hour orbital period modulation in *V* was detected on one occasion during the 1998 outburst (Giles, Hill & Greenhill, 1999). The amplitude was 0.12 ± 0.02 magnitudes peak to peak but was below the detection threshold on several nights. A much deeper orbital modulation, consistent with heating of the companion by a pulsar generated relativistic particle wind, was present in the quiescent state (Campana et al, 2004).

SAX J1808.4–3658 is the only member of the 7 known accreting millisecond pulsars known to undergo extended low level activity states. These follow the initial outburst and are characterised by erratic, large amplitude variability on timescales of hours to days. Repeated secondary X-ray outburts with durations of several days are sometimes accompanied by optical outbursts (Wijnands, 2004). Disc instability and mass transfer instability models have been suggested as possible mechanisms (Wijnands et al, 2001).

Recently it has become apparent that synchrotron emission, probably from matter flowing out of the system via bipolar jets, makes a highly variable contribution to radio and IR emission from many different classes of X-ray bi-

Table 1. The magnitudes of local standard stars 1-3 in Fig. 1.

Star No.	*B*	*V*	*R*	*I*
1	15.60	14.76	14.23	13.74
2	16.89	15.31	14.50	13.71
3	15.93	15.18	14.71	14.34
Mean	16.02(4)	15.06(3)	14.46(3)	13.89(3)

naries (Fender 2003). In some cases this emission may extend into the optical region (Hynes et al. 2000). Krauss et al. (2005) detected an *I* band excess during the discovery outburst of the accretion-powered millisecond pulsar XTE J1814–318 and Giles et al. (2005) found evidence of a variable *I* band excess from another accretion-powered millisecond pulsar XTE J0929–314. Wang et al. (2001) reported evidence of a transient IR excess in SAX J1808.4–3658 and Giles et al. (2005) suggested that this may have extended to optical wavelengths.

In this paper we describe the broad-band optical spectra of SAX J1808.4–3658 during outburst in 2005 June. Considerable variability was observed both in intensity and spectral slope. On one occasion there was a large *I* band excess.

2 OBSERVATIONS

All the observations described in this paper were made using the 1-m telescope at the University of Tasmania, Mt. Canopus Observatory. The CCD camera, its operating software (CICADA), the image reduction and analysis tools (MIDAS and DoPHOT) were identical to that described in Giles et al. (1999). The data were reduced using the PLANET pipeline QUYLLUR WASI **Ref ?** The CCD camera contains an SITe 512 x 512 pixel thinned back illuminated chip with an image scale of 0.434″ pixel^{-1}. Cousins standard *BVRI* filters (Bessell 1990) were used for the observations. The data were calibrated using a sequence of observations of 3 standard stars within the E7 field of Graham (1982). Both source and standard star fields were observed at virtually identical airmasses (1.01-1.03) and experience with this camera has shown that differential colour corrections are generally negligible. From these observations we derived the magnitudes of 3 local secondary standards close to SAX J1808.4–3658 and within the CCD frame. These local standards are marked as stars 1-3 on the finder chart in Fig. 1 and we tabulate their derived magnitudes in Table 1. The magnitudes for SAX J1808.4–3658 were then obtained using differential photometry relative to these local secondary standards. The complete data set from 2005 June 2 to July 6 [HJD 245[3524) - 245[3558)] is detailed in Table 2 and forms the subject of this paper.

3 RESULTS

3.1 The light curves

The optical *BVRI* band and *RXTE* ASM X-ray light curves are shown in Fig. 2. Both show a similar declining trend until about HJD 3540 followed by two shorter duration flares similar to those seen in the 2000 and 2002 outbursts (Wachter et al , 2000; Wijnands et al, 2001, Wijnands, 2004). There was also a large excess (~ 0.45 magnitudes) in the *I* band but not in the other colours on HJD 3527.

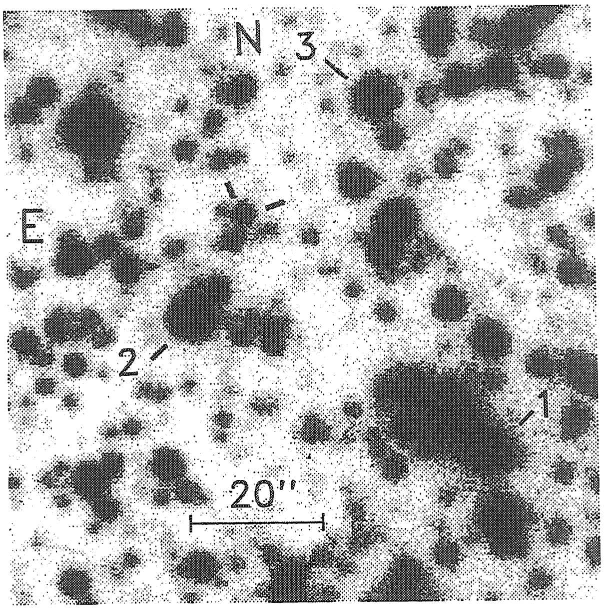

Figure 1. A finder chart for SAX J1808.4-3658. This image was taken when there was an *I* band excess on 2005 June 5 (HJD 2453527) The source magnitude was $I = 16.72$. The three local secondary standards listed in Table 1 are marked with the numbers 1-3.

The decay timescale during the first outburst (HJD 3522 to 3540) was ~ 7 days for both the optical and the X-ray emission. This is very similar to that during the discovery outburst in 1998 (Giles et al, 1999) but much shorter than the ~ 22 day timescale for XTE J0929–314 (Giles et al, 2005). There appears to be a weak correlation between the optical and X-ray fluxes with the optical emission preceding the X-ray by 2 or 3 days as in the 1998 outburst (Giles et al, 1999).

3.2 Spectral changes

In Fig. 3 upper panel we plot the *B-I* colour index changes during the observations. Where two measurements in the same colour were made on the same night we use the mean of the two. The solid line represents a linear fit to the data during the first steady decline in intensity ending at HJD 3540. The anomalous point at HJD 3527 is discussed in section 3.3. Neither it nor the points measured after HJD 3540 are included in the linear fit in this figure nor in the *V-I* plot (Fig.4).

On some occasions the time between measurements was as large as or greater than the orbital period and this could affect the values of the colour indices. We have used the X-ray ephemerides of Chakrabarty & Morgan (1998) to determine the phases of the individual measurements but find no evidence for any modulation effect at a level greater than a few hudredths of a magnitude.

The most obvious feature in the *B-I* plot is the large increase due to the flare in *I* on HJD 3527. Overall *B-I*

Table 2. A journal of the observations.

HJD[a] (-2453500)	*I* mag.	*HJD*[a] (-2453500)	*R* mag.	*HJD*[a] (-2453500)	*V* mag.	*HJD*[a] (-2453500)	*B* mag.
24.0918	17.12(1)			24.0978	17.43(1)		
25.1991	17.15(2)	25.2076	17.14(1)	25.2119	17.31(1)	25.2183	17.29(1)
27.1449	16.72(1)	27.2305	17.19(1)	27.1673	17.29(2)	27.2367	17.36(1)
29.2256	17.20(4)	29.2324	17.33(2)	29.2371	17.45(2)	29.2485	17.48(2)
31.1353	17.25(4)	31.1433	17.33(2)	31.1393	17.48(2)	31.1492	17.60(1)
34.1917	17.36(3)	34.1960	17.56(2)	34.1999	17.82(3)	34.2058	17.79(2)
36.2103	17.65(3)	36.2189	17.86(2)	36.2146	18.03(2)	36.2249	18.17(1)
36.2811	17.63(2)	36.2887	17.80(2)	36.2849	18.01(2)	36.2944	18.04(4)
37.1149	17.76(2)	37.1235	17.98(2)	37.1196	18.19(1)	37.1292	18.23(1)
37.3128	17.73(3)	37.3217	17.95(3)	37.3178	18.21(2)	37.3278	18.36(2)
38.2559	18.00(4)	38.2603	18.26(2)	38.2645	18.53(3)	38.2704	18.63(3)
39.2164	18.19(4)	39.2206	18.40(3)	39.2250	18.58(3)		
40.0592	18.40(4)	40.0738	18.65(3)	40.0675	18.88(3)	40.0807	19.09(4)
45.2344	18.38(9)	45.2387	18.48(8)	45.2425	18.85(14)	45.2482	18.83(12)
46.0150	18.16(4)			46.0064	18.81(4)		
47.1002	17.73(2)	47.2723	17.98(2)	47.1142	18.12(6)	47.2822	18.37(3)
48.0390	18.02(3)	48.1593	18.28(2)	48.0490	18.47(2)	48.1720	18.64(2)
49.1236	18.43(5)			49.1764	18.79(4)		
51.0626	17.85(2)			51.0714	18.20(1)		
55.1715	18.70(16)			55.1920	19.17(6)		
58.1532	18.53(4)			58.1606	19.01(2)		

a Times of mid integration.

increased linearly (became redder) until the intensity had decreased by about two magnitudes at the end of the first outburst at HJD 3540. Thereafter it decreased marginally.

It is clear from a study of the *V-I* colour index (Fig. 4, upper panel) that the inner disc emission was responsible for much of the change in the spectrum. There is a much larger range in magnitude (and a much more regular change with time) in *B-I* than in *V-I*. There is, however, a similar trend towards a redder spectrum during the intensity decline until HJD 3540 - illustrated by the solid line in Fig. 4. During the secondary outburst peaking at HJD ~ 3547 the spectrum was at first significantly redder at HJD 3546 and thereafter *V-I* returned to the values 0.4 ± 0.1 observed at the end of the first intensity decline. Inspection of the light curves in Fig. 2 suggests that the increase in *V-I* on HJD 3546 was due to a brightening in *I* rather than a dimming in *V*. Another sudden change in colour occurred between the first and second nights of our observations (HJD 3524 and 3525). These anomalous changes are suggestive of a mass transfer instability in which cool matter is dumped into the outer disc. This is followed by an increase in optical emission and colour temperature as the matter diffuses inwards.

In the lower panels of Fig. 3 and Fig.4 we show the time depencence of *B-I* and *V-I* during the 2002 outburst in the accreting millisecond pulsar XTE J0929–314 (Giles et al, 2005). Again we note the strong influence of the changes in *B* (predominately inner disc emission) on the spectrum. The change in spectral colour is opposite in direction to that seen in SAX J1808.4–3658 suggesting different outburst mechanisms in the two systems.

On 14 occasions within Table 2 we have 4 colour *BVRI* measurements taken over a short interval (typically ~ 1 hr) on the same night. Using these data and the bandwidth specifications for each filter we have derived broadband *BVRI* spectra for these nights. In Fig. 4 we plot the spectra for 5 representative nights (HJD 3525, 3527, 3536, 3545 & 3547) corresponding to the early bright state, the *I* band flare, the declining phase, the low intensity phase and the peak of the secondary outburst respectively.

Also shown is a solid curve representing a power law approximation to the emission from an optically thick, X-ray heated disc. The distribution is given by the equation $F_\lambda \propto \lambda^{-3} e^{-A_\lambda/1.086}$ where F_λ is the reddened flux at wavelength λ and A_λ is the wavelength dependent reddening correction toward the source. The spectrum is reddened assuming interstellar extinction $A_V = 0.68$ (Wang et al., 2001). The amplitude is arbitrary.

The anomalous spectrum on HJD 3527 will be discussed in the next section. On all other nights the spectra are consistent with the reddened power law approximation expected for an X-ray heated accretion disc with interstellar extinction. Except on the night of HJD 3527, there is no *I* band excess of the kind reported by Giles et al (2005) for RXTE J0929–314.

The spectra became redder (cooler) with time as noted from the *B-I* colour index plot (Fig. 3). A similar cooling trend was also apparent in broadband spectra taken during the 1998 outburst (Wang et al, 2001). There is no evidence for any significant change in spectral shape during the secondary outburst on HJD 3547. Overall the spectra were similar (spectral index $\sim 2.5 - 3.5$) to that in the 1998 outburst (Wang et al, 2001) A somewhat steeper spectrum was reported for the 2003 outburst of the accretion-powered millisecond pulsar XTE J1814–338 (Krauss et al, 2005).

3.3 *I* band flare

On the night of 2005, June 5 the *I* band measurement at HJD 3527.14 revealed a ~ 0.45 magnitude excess above the trend from previous and succeeding nights. There was no

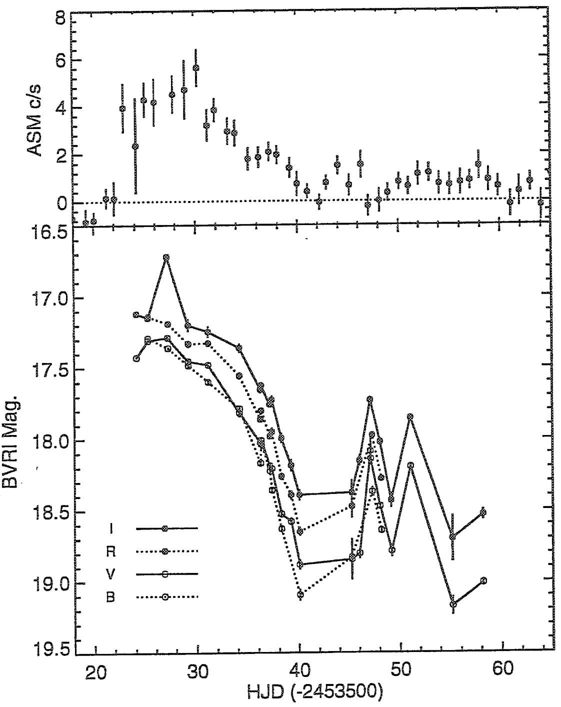

Figure 2. *RXTE* ASM light curve for SAX J1808.4-3658 (upper panel) and *BVRI* band light curves (lower panel).

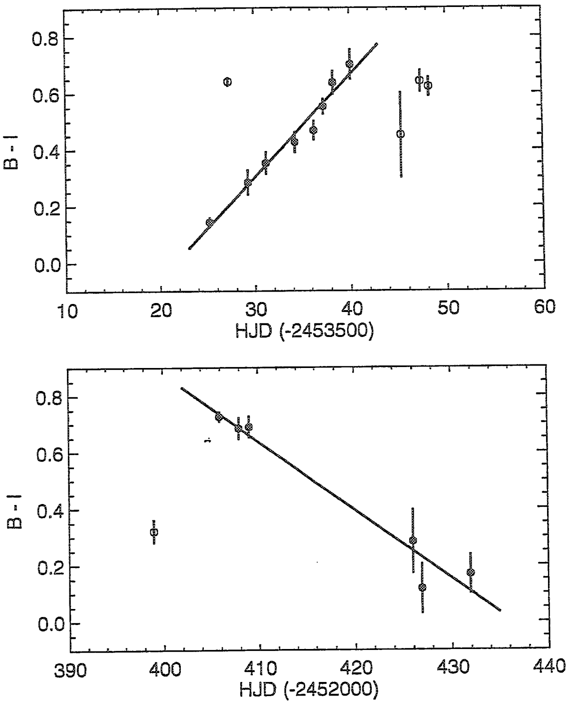

Figure 3. Time dependence of the colour index B - I for the SAX J1808.4–3658 observations (upper panel) and for the accreting millisecond pulsar XTE J0929–314 (lower panel)as measured by Giles et al, (2005).

The solid lines represent linear fits to the points marked by filled circles.

evidence of any excess above the trendlines for any of the other colours all of which were measured within ~ 2 hrs of the I band. The existence of an I band excess is also obvious in the broadband spectrum for the night (Fig. 4).

The absence of any increase in R V *or* B indicates that the enhanced radiation in I was sharply cut-off in wavelength. We reject as highly improbable the possibility that the increase was broad-band but occurred only during the 5 minute I band exposure. It is unlikely to be due to the ~ 2 hr orbital modulation since the amplitude is at least a factor of ~ 4 larger than the peak to peak of the orbital modulation (Giles et al, 2001) and there is no evidence of any significant increase in R measured just one orbital cycle later than I. The X-ray intensity measured by the RXTE ASM a few hours after the enhancement was similar to the mean value for several days before and after the I band enhancement so it is unlikely that the excess was generated by X-ray heating of the companion.

The I band measurement on this night is clearly inconsistent with emission from X-ray heated accretion disc models indicating a second emission process - probably cyclotron radiation. Rupen et al (2005) detected weak 4.86 and 8.46 Ghz radio emission from SAX J1808.4–3658 on 2005 June 7, 11 &16 and suggested it was due to synchrotron emission. Rea et al (2005) measured *V, R & I* magnitudes on 2005 June 5 and set a 5σ upper limit of 16.5 on H band IR emission. Their measurements of the optical magnitudes are of low precision but are more consistent with our 'normal' spectrum of June 3 than with the 'anomalous' data of June 5. Their H band upper limit is slightly above an extrapolation of the 'normal' spectrum but is more consistent with it than with the 'anomalous' one. The measurements by Rea et al (2005) were made ~ 12 hrs before our observations of June 5. It seems likely that the IR excess was not present at the time of their observations and note that no radio emiison was detected on 2005 June 4 the day before our observation (Rupen et al, 2005). We conclude that, if the I band enhancement was due to synchrotron emission, it commenced less than 12 hours before our observation and lasted less than 60 hours since it was not present on June 7 (HJD 3529). This implies also that the cut-off frequency decreased since radio synchrotron emission was detected on that day (Rupen et al, 2005).

Giles et al (2005) reported a variable I band excess in another accreting millisecond pulsar, XTE J0929–314, and suggested that the anomalous optical and IR spectra in SAX J1808.4–3658 reported by Wang et al (2001) may be similar in nature. Krauss et al (2005) observed an I band excess in a third accreting millisecond pulsar XTE J1814–318 and suggested that it was probably due to synchrotron emission. Hence we conclude that variable synchrotron emission is common in these systems. The I band excess observed from SAX J1808.4–3658 on 2005 June 5 (HJD 3527) was due to synchrotron emission extending up to but cut off at I band frequencies. This emission is strongly variable both

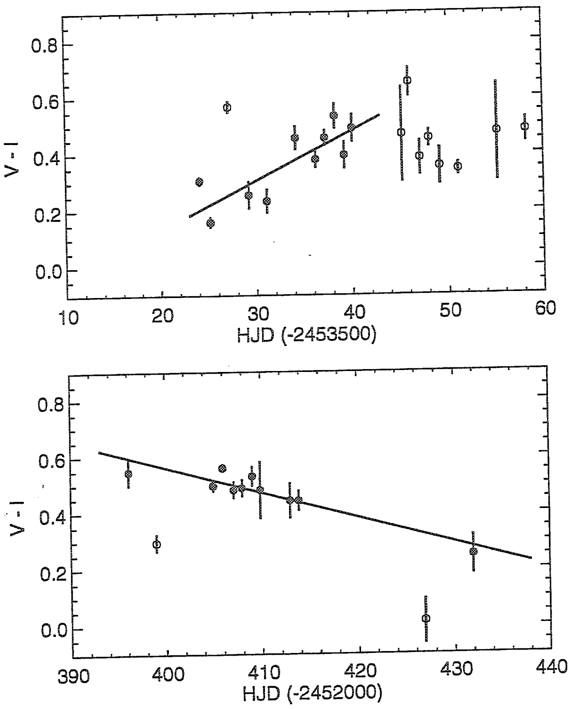

Figure 4. Time dependence of the colour index V - I for the SAX J1808.4-3658 observations (upper panel) and for the accreting millisecond pulsar XTE J0929-314 (lower panel)as measured by Giles et al, (2005).

The solid lines represent linear fits to the points marked by filled circles.

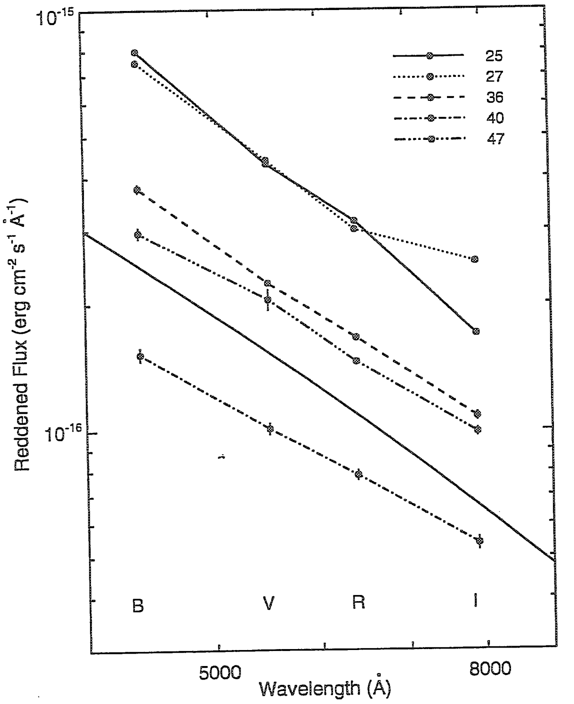

Figure 5. The $BVRI$ broadband spectra for SAX J1808.4-3658. Each day's spectrum is identified by the last two digits of the HJD of the observations. The lines connect to the mean flux values on each night. Many error limits are smaller than the points representing the measurements. The dotted line represents a simple power law disc emission model with exponent -3, arbitrary amplitude and interstellar reddening corresponding to $A_V = 0.68$.

in amplitude and cut-off frequency and was probably not present on 2005 June 4.

4 DISCUSSION

Our observations show that the optical spectrum in outburst was consistent with emission from an X-ray heated accretion disc except on the night of 2005 June 5 (HJD 3527) when a large I band excess was detected. The disc emission spectrum became redder as the intensity decreased. A similar increase in colour temperature was also apparent in the 1998 outburst of SAX J1808.4-3658 (Wang et al, 2001). These changes ares consistent with an 'inside-out' transition in the disc i.e. one triggered by a viscosity change driven instability in the inner disc. The $\sim$ 7 day timescale for the outburst decline corresponds to the timescale for depletion of matter in the inner disc.

These spectral changes are opposite to those in XTE J0929–314 where the disc became hotter as the intensity decreased during the 2002 outburst (Giles et al, 2005). This is suggestive of a mass transfer (outside-in) instability. It is not clear why these systems should differ in this way although we note that the companion in XTE J0929–314 is thought to be a degenerate helium core with remnant envelope and a mass $\sim 0.01 M_\odot$ (Galloway et al, 2002). The companion to SAX J1808.4–3658 is a brown dwarf at least 5 times as massive (Bildsten & Chakrabarty, 2001). This may affect the stability of the atmospheres of the companions while undergoing X-ray heating. We note however that a mass transfer instability may have contributed to the quasi-periodic secondary outbursts in SAX J1808.4–3658 commencing at HJD $\sim$ 3545 during our observation.

Of the seven known accreting millisecond pulsars, three (SAX J1808.4–3658, XTE J0929–314 & XTE J1814–338) are now known to have transient near IR emission. It seems likely that this is due to synchrotron emission which extends at times to I band wavelengths. Synchrotron emission at radio and IR wavelengths has been detected from several other X-ray binaries during outburst (Fender, 2001) but it seems it is particularly common in accreting millisecond pulsars.

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