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Optical and X-ray study of MS1603+2600*

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Abstract. We present results from ~ 2 years of optical monitoring of an unusual interacting compact binary MS1603+2600 together with the results of ROSAT observations. Our CCD-photometry confirms the erratic behaviour of the optical light curve shape reported by Morris et al.(1990). The ROSAT-PSPC observations suggest that MS1603 might be a short period soft X-ray transient (SXT) never seen in outburst. This would probably require, that the compact object in MS1603 is a black hole rather than a neutron star. In addition to optical photometry and ROSAT data, we present first circular polarimetric observations of the source and discuss the nature and origin of MS1603+2600.

Key words: stars: individual: MS1603+2600 – stars: binaries, close – accretion

1. Introduction

Since its identification as a compact binary system (Morris et al.1990) MS1603+26 has persistently resisted any attempts to classify the system into any main branches of interacting compact binaries. The source was first detected as an X-ray source in the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS, Gioia et al.1990). Since then it has been extensively studied in the optical by Morris et al.(1990). Their optical CCD-photometry and low / medium-resolution spectroscopy does not provide conclusive evidence to resolve whether the source is a low mass X-ray binary (LMXB) or a cataclysmic variable (CV). They, however, prefer the LMXB scenario mainly due to similarities between MS1603+26 and AC211 (Ilovaisky 1989, Naylor et al.1988). In particular, they quote the similarities in changes of the optical light curve shape (Auriere et al., 1989), the constancy of HeII (4686 A) emission over the orbital period (Ilovaisky 1989) and P-Cygni like profiles of Hβ (Ilovaisky 1989). Furthermore they remark that the overall spectral shape is similar to AC211 with HeII (4686A) emission and blueshifted He I absorption. The main complication with the LMXB scenario rises from the location of the source. Given the X-ray flux (0.3–3.5 keV) of $1.14 \times 10^{-12} ergs/\sec/cm^2$ (based on IPC data, Morris et al., 1990) and the galactic latitude of $\sim 47°$ this implies $L_X = 1.4 \times 10^{34}(d/10kpc)^2 ergs/\sec$.This, together with the V magnitude, further implies that the source would be located 22–58 kpc above the galactic plane (Morris et al.1990).

The second alternative classification for MS1603+26 is an AM Herculis system, i.e. a magnetic phase-locked white dwarf accreting from a late main sequence secondary. The periods of these systems actually cluster near the 111 min value of MS1603+26. Also, the F_X/F_{opt}-ratio observed by Morris et al.(1990) is more consistent with the AM Herculis scenario than with a LMXB. Given the much lower X-ray luminosities of AM Hers as compared to LMXB's this would also solve the 'location problem' far in the halo. There are, however, serious drawbacks with this scenario as well. The optical spectrum lacks the very strong emission lines of Balmer series and HeII typical in AM Her spectra. Also, no variable circular polarisation (generally taken as a firm evedence for AM Her nature) is observed up to date.

Ergma & Vilhu (1993) discuss the possible evolutionary schemes for MS1603+26. They present three different evolutionary paths for the LMXB outcome and one for the CV (AM Her) case. Based on published data available at the time they are unable to draw a firm conclusion, but favour the LMXB classification. In this paper we present further optical CCD-photometry and circular polarimetry together with our ROSAT PSPC data and discuss the impact of those on our understanding of MS1603+26.

2. Optical CCD-photometry and circular polarimetry

MS1603+26 has been monitored over a period of 26 months at the Nordic Optical Telescope (NOT) on La Palma. This has partly been carried out as a backup/supplement program and thus many of our datasets do not contain more than one orbital period worth of data. NOT is a 2.56m Cassegrain telescope and was during the monitoring equipped with a front-illuminated TEK 520x520 CCD chip. Most of the data were taken in white light to provide as good a time-resolution as possible, although some earlier observations were taken in V band. Some additional data were also obtained at the Palomar 60" telescope (in white light as well). The differential light curves were obtained using

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* Based on optical observations made at the Nordic Optical Telescope, La Palma

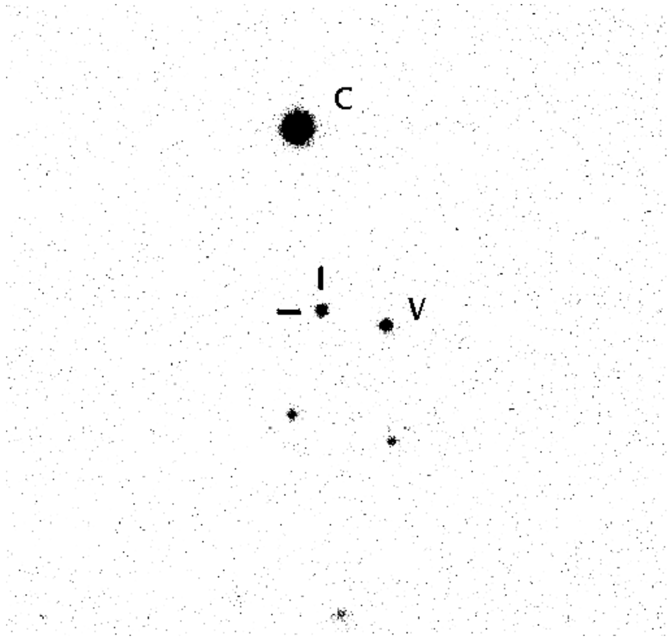

Fig. 1. A combined V band image of the MS1603 field. The source and the two comparison stars are marked (photometric comparison = V and polarimetric comparison = C. The coordinates of MS1603 are: $\alpha(1950.0) = 16^h03^m40.50^s, \delta(1950.0) = +25^o59^{'}48.0^{''}$. North is up and east is left. The diameter of the field is 100"

a star of similar brightness located 10" west and 2" south of the source. This star (V), the other comparision star (C) and MS1603 itself are identified in our finding chart (Fig. 1). More details of the observations including date, time, exposure time and filter information can be found in Table 1.

In addition to the CCD-photometry (plotted in Fig. 2), CCD-polarimetry was obtained some two years later in May 1995. These observations were also obtained at the NOT, but this time an Astromed CCD-camera, equipped with EEV chip and R filter was used. The polarising optics consisting of a calcite block and a superachromatic $\lambda/4$ -retarder plate were used. These were operated in a fixed configuration, that produced two images of the star on the CCD, one image for both the ordinary and the extraordinary beam. The ratio of these images then yields the degree of circular polarisation. The results of these observations are plotted in Fig. 3. The differential photometry gives the delta magnitude against a brighter star (star C in Fig. 1), located 4" east and 26" North from MS 1603.

All the photometric data have gone through standard CCD image reductions including debiasing and flatfielding the images. In case of polarimetric data, the absolute calibration of the circular polarisation zero level is somewhat uncertain due to some vignetting effects and slight overexposure of the standard star. This, however, doesn't pose a big problem as we are mainly interested in searching for variablility in circular polarisation.

It is difficult to draw conclusions about our polarimetric data. The observations only cover about one 0.077108 day period of MS1603 and do not have the signal-to-noise to make any definitive statements. There is not any clear variability present. However, if we take a mean of all the polarimetric data for all the three stars (including MS1603), we find that the mean value for MS1603 is 3.53 $\pm$ 0.74%, whilst for the two other stars we get 1.55 $\pm$ 0.51% and 1.27 $\pm$ 0.06%. We can adopt the value for the 'bright star' (star C in Fig. 1, 1.27 $\pm$ 0.06%) as a reasonably good estimate for the instrumental polarisation. This value is also roughly consistent with the theoretical predictions based on the different refractive indices for the ordinary and the extraordinary beams. The average degree of circular polarisation observed in MS 1603 is thus on the 3σ upper limit of being instrumental. Clearly more polarimetric observations are required.

Table 1. Log of all photometric data

Set	HJD-2440000 range	Telescope	exp. time	Filter
1	8383.4810–8383.6814	NOT	300	V
2	8386.4775–8386.5617	NOT	300	V
3	8408.4461–8408.6905	NOT	300	V
4	8439.7176–8439.9182	Palomar	300	None
5	8440.6801–8440.9240	Palomar	300	None
6	8776.3958–8776.4953	NOT	300	None
7	9093.5036–9093.7227	NOT	300	None
8	9094.6431–9094.7179	NOT	300	None
9	9180.4313–9180.5026	NOT	200	None
10	9181.4294–9181.4853	NOT	200	None
11	9182.4175–9182.4731	NOT	200	None

2.1. Results from optical monitoring

As demonstrated by Morris et al.(1990), the light curve of MS1603 changes drastically from one night to another, or even from one cycle to another. We have fitted all the 11 light curves from our photometric dataset with a 4th harmonic Fourier fit in order to study whether discrete 'modes' are detected. From this exercise we can conclude that there are no clear modes, but the source seems to have at least two different types of light curves. In case **A** the source shows deep (0.5–1 mag.) and sharp eclipse-like dips, whilst outside these dips source is almost constant. Sometimes there appears to be a secondary minimum around phase 0.5. Case **B** represents a state where the light curve lacks the dips and exhibits more sinusoidal variation with a typical amplitude of 0.6 mag. In our dataset, the case **B** seems to occur somewhat more often than case **A**.

3. ROSAT-PSPC observations

The binary system MS1603.6+2600 was observed on 1991 August 26, with the PSPC-B detector (Pfeffermann et al. 1986) on the ROSAT X-ray satellite (Truemper 1983). The PSPC is sensitive to X-rays in the energy range 0.1–2.5 keV and has a $2\deg$ field of view. A total of 23078 seconds exposure on the target were accumulated. The raw data were processed using SASS version 5.6 on 1992 April 9. The distribution files were later processed using both PROS and ASTERIX packages. The pro-

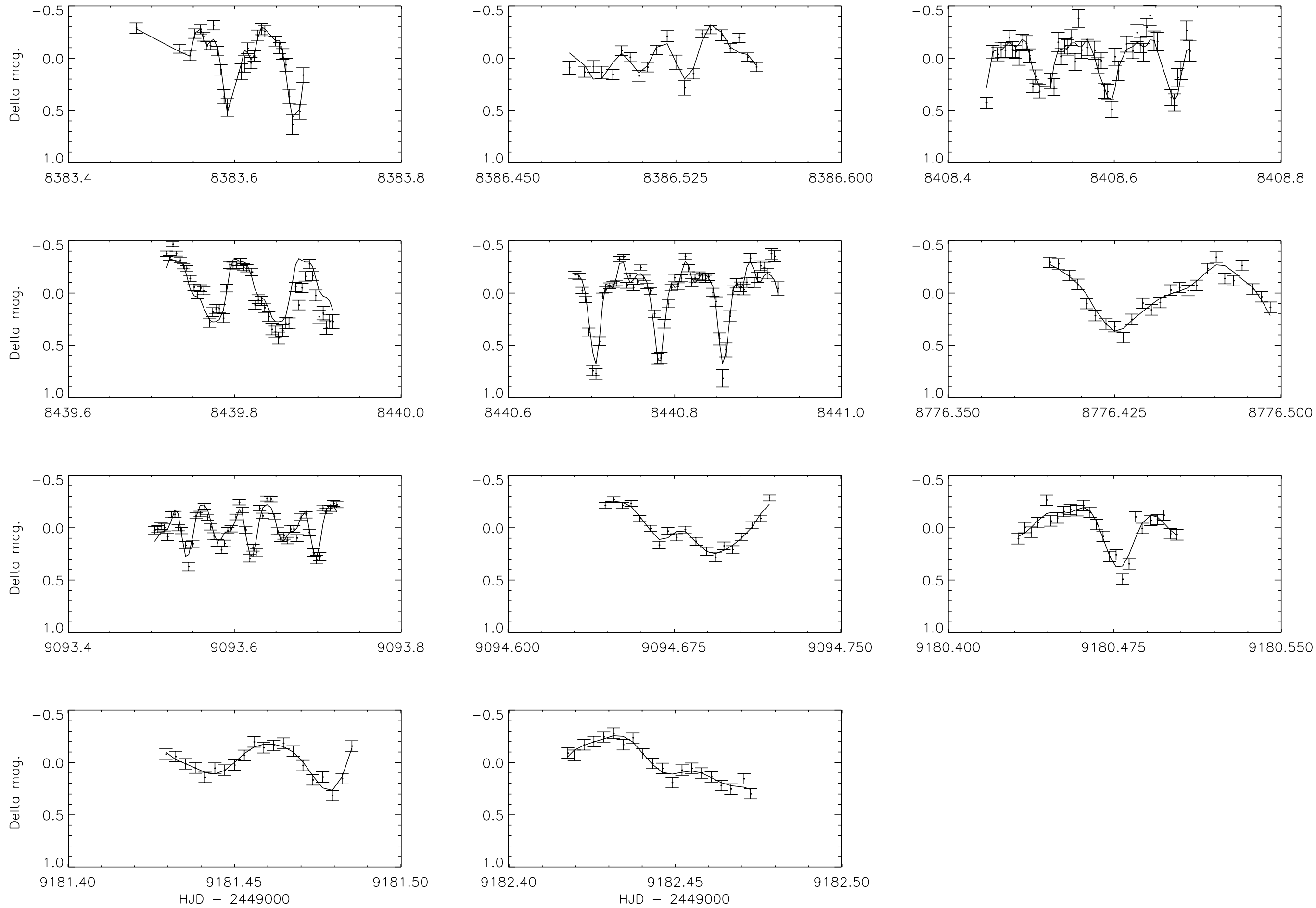

Fig. 2. Light curves of MS1603 from individual nights together fit 4th harmonic Fourier fits used to quantify the variability. Note particularly the second and third plot of the second row, that highlight the contrast between the Cases A and B (respectively) mentioned in text.

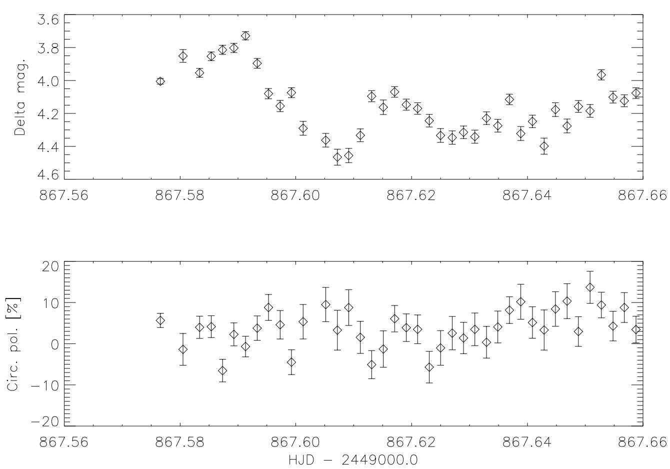

Fig. 3. The R band photopolarimetric data of MS1603. The upper curve is the differential magnitude and the lower one is circular polarisation.

cessing consisted of applying all the spacecraft and instrument specific corrections (elimination of bad time intervals and corrections for spectral response, vignetting gas chamber wires etc.) and the extraction of summed up X-ray spectrum together with the X-ray light curve. The spectrum was then rebinned by a factor of four prior to fitting. Also, a binsize of 300 seconds was used in the light curve extraction.

This piece of data were hoped to provide a definitive piece of evidence either in favour or against the magnetic CV hypothesis of MS1603+26. It is widely known (see Cropper, 1990 for a review on AM Herculis stars) that AM Herculis stars exhibit strong soft X-ray emission, characterized by a black body of kT = 10–50 eV. Also characteristic is the almost on-off modulation of this emission over the orbital period (as the soft X-ray emission region gets self eclipsed by the WD).

We have fitted the PSPC spectrum using the XSPEC package and three different spectral models frequently observed in interacting binaries. The models are: Blackbody (BB) emission (with absorption), The powerlaw (PL) model(again with absorption) and the thermal bremsstrahlung (TB) model. All of them are found to fit the data adequately. These fits have reduced chi-squares of 1.00, 0.78 and 0.78 for the BB, PL and TB models respectively. The resulting best fit parameters can be found in Table 2. We have plotted the ROSAT-PSPC X-ray spectrum of MS1603+26 with the TB model overimposed in Fig. 4a. Figs. 4b–d show the confidence contours (contours of

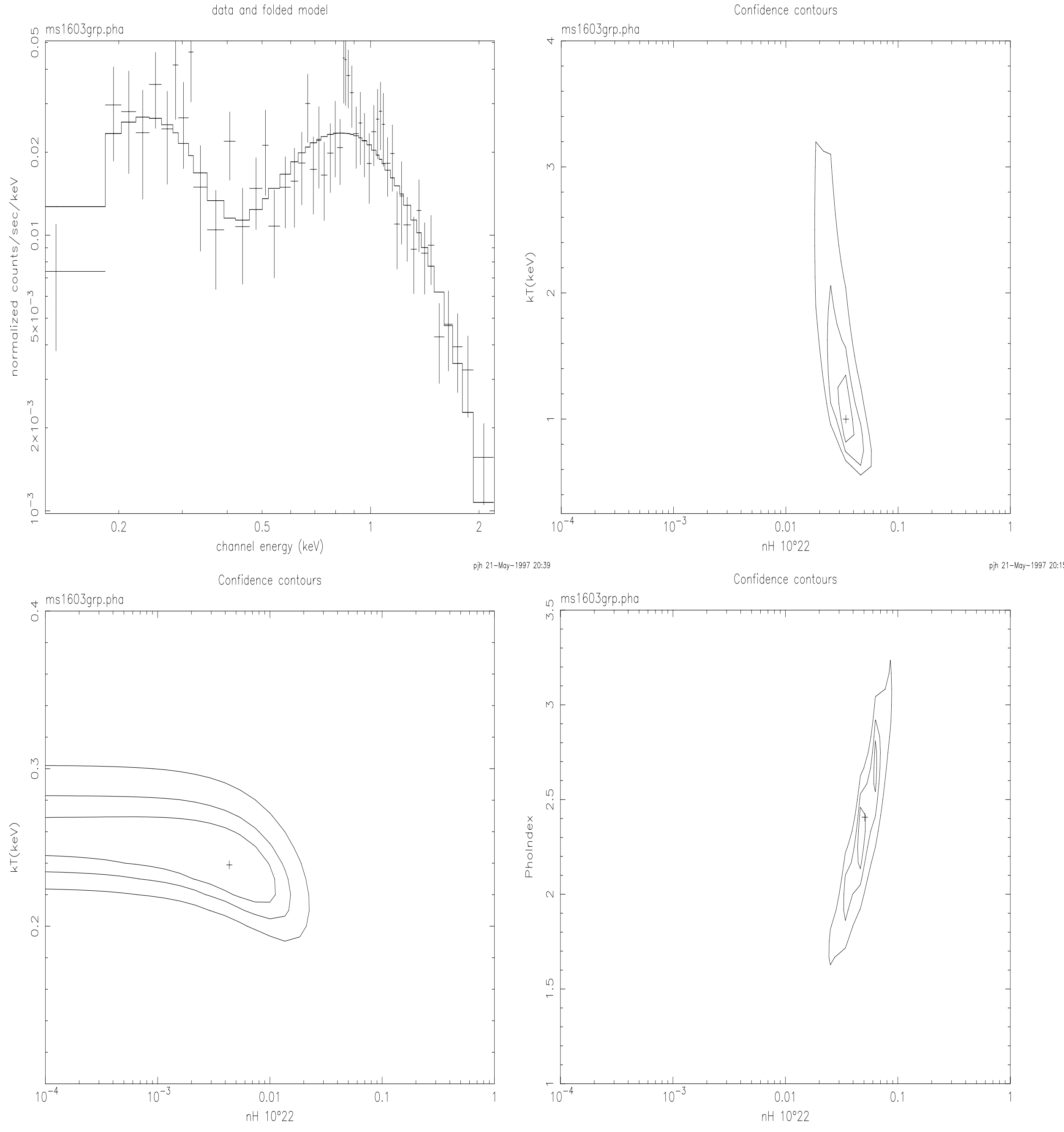

Fig. 4a–d From top to bottom: **a** PSPC spectrum with the best fitting thermal bremsstrahlung (TB) model (with absorption), **b** Confidence contours for the TB model, 90%, 99% and 99.99%, **c** Confidence contours for the blackbody model, **d** Confidence contours for the powerlaw model

Table 2. The results of ROSAT PSPC spectral fits

Spectral model	χ^2_υ	N_H	kT or phot. index
Blackbody+absorption	1.00	$4.35\times10^{19} \pm 3.17 \times 10^{19}$	kT=239±12eV
Powerlaw+absorption	0.78	$5.08\times10^{20} \pm 7.50 \times 10^{19}$	$\alpha = 2.41 \pm 0.20$
Bremsstrahlung+absorption	0.78	$3.43\times10^{19} \pm 0.46 \times 10^{19}$	kT=1.0±0.2 keV

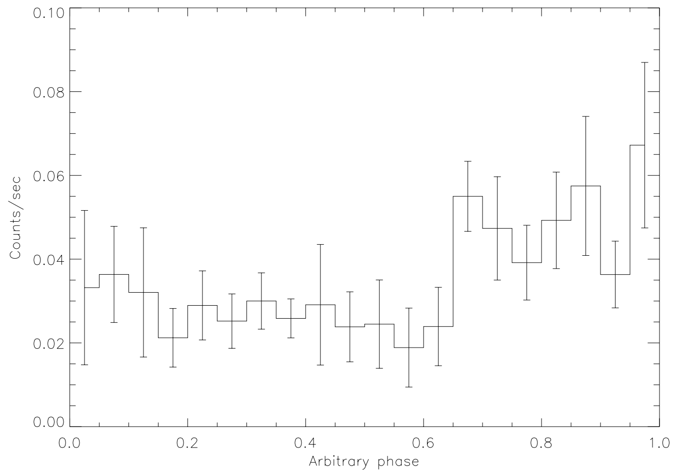

Fig. 5. The ROSAT PSPC light curve folded over the optical period of 0.077108 days

equal $\Delta\chi^2_v$) in the N_H- kT, N_H-photon index and N_H- kT planes for the three models. The three different contours refer to the confidence levels of 90%, 99% and 99.99%.

3.1. Periodogram analysis

A periodogram analysis was performed to test whether the optical period found by Morris et al. (1990) was present in the x-ray data.

The data received from ROSAT are far from being evenly sampled. Once good time intervals are separated and other factors, such as the background 'flares', are removed, one is left with a collection of time intervals which vary in duration and spacing.

This can make it difficult to employ Fast Fourier Transform (FFT) methods in order to determine a period. The 'fft' task in the PROS 'xtiming' package is a period search which uses the FFT. In an attempt to create an evenly spaced data set from the uneven intervals, 'fft' will automatically fill the gaps with zeroes. The user can also choose to interpolate end values into the gaps or fill them with a constant. As noted by Press $et\ al.$ (1992), these techniques have previously been shown to perform poorly on data with large gaps and can lead to spikes in power at low frequencies. We encountered this problem with the MS 1603 data.

The 'period' task uses an epoch folding method which produces a peak chi-squared if a modulation is present. For our dataset, this gave similar results as 'fft', probably also due to the aliasing problem.

In the end, we used the method developed by Lomb(1976) and elaborated by Scargle(1982) via a routine described in Press et al. (1992). The routine corrected properly for the data gaps and produced an x-ray orbital period. Bin lengths of 100, 200, 300, 510 and 1000 seconds were used in the period search to check that the given spike was evident in all cases.

The period determined with 1000 second time bins was 109.2 ($\pm$6.7) minutes with a false alarm probability of 4.7%. The optical period of 111.04 minutes (Morris et al. 1990) lies within the error of the x-ray period.

3.2. The phased light curve

The extracted ROSAT-PSPC X-ray light curve folded on the optical period of 0.077108 d presented by Morris et al.(1990) and binned into 20 phase bins is plotted in Fig. 5. It is clear the source shows variability over this period. The pulse shape is not sinusoidal, but resembles more the off-on behaviour of the AM Herculis systems. The system seems to spend about 60% of the optical period in 'low' state where the flux is ~ 0.025 cts/sec and the remaining 40% in 'high' state with roughly twice the amount of emission (~ 0.05 cts/sec).

4. Discussion

4.1. Cataclysmic variable?

In non-magnetic CV's a hot boundary layer close to the WD is expected to emit most of its flux in x-rays via $\sim$ 1–5 keV thermal bremsstrahlung. In magnetic CV's a shock front is formed within an accretion funnel above the WD surface. The accreting plasma is heated up in the shock and cools via 10–30 keV thermal bremsstrahlung and optical/near IR cyclotron emission. Furthermore, dense blobs of accreting matter can survive the shock and carry their energy directly into the WD photosphere where they are thermalised. This then gives rise to soft 10–50 eV blackbody emission.

Observations and spectral analyses of non-magnetic CVs in the literature (Eracleous et al. 1991, van Teeseling & Verbunt 1994) provide us with optically thin thermal bremsstrahlung fits to a number of sources. Eracleous *etal.* (1991) found a median kT_{brem} $\sim$3 keV, which they claim to be lower than the 10 keV usually cited. In any case, MS 1603's temperature of 1.0 keV is far lower than any median cited thus far.

The AM Herculis systems, on the other hand, are dominated by strong 10–50 eV blackbody emission in the ROSAT energy range. It is quite clear from our data that the best fitting blackbody temperature of 0.239 keV is far too hot for any known polar. In Fig. 6a we have plotted the histogram of polar BB temperatures observed by ROSAT as listed by Ramsay et al. (1994). The 99.99% lower limit we get is about 180 eV, which is still about three times hotter than the hottest polar.

Comparisons of optical and x-ray light curves of nonmagnetic CVs in the literature (e.g.,van Teeseling & Verbunt 1994) with those of MS1603 do not show a satisfactory resemblance. The shape of the CV curve is almost sinusoidal and not relatively deep, unlike MS1603. Also, as noted in Morris et al. (1990), the F_X / $F_{Optical}$ is far too high for a typical non-magnetic CV.

The X-ray light curve of MS1603 resembles those of AM Herculis systems. The changes in flux over the optical period are fairly rapid, as expected if they were to arise from the compact emitting pole on the surface of the white dwarf to be occulted by the white dwarf itself. In this scenario, the detection of net

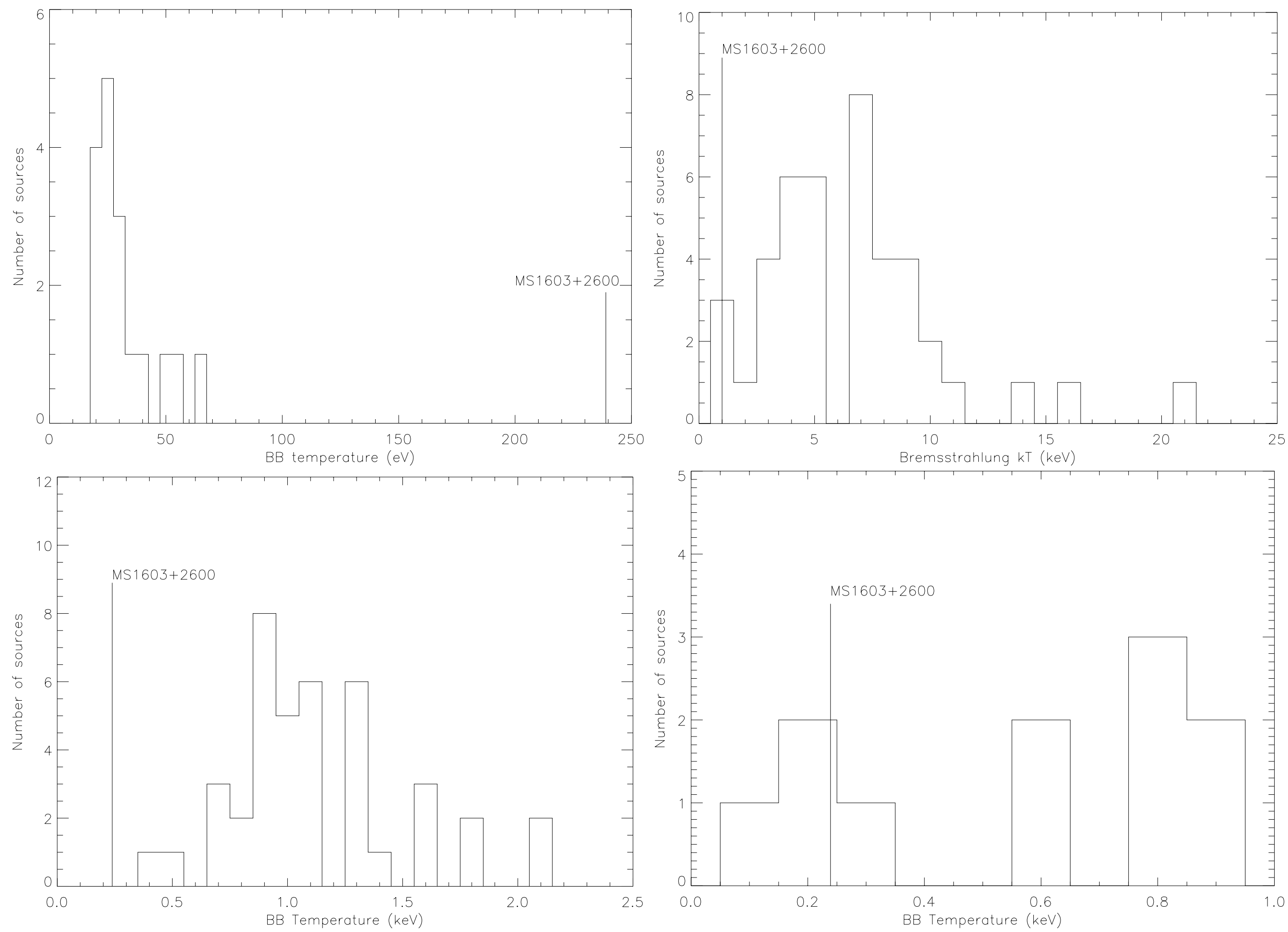

Fig. 6a–d Results from the spectral fits compared to the known distributions of Bremsstrahlung and blackbody temperatures in (from top to bottom) **a** Polar BB **b** LMXB TB, **c** LMXB BB **d** Transient LMXB BB

flux in the 'low' state would mean the presence of two accreting poles.

4.2. Low mass X-ray binary?

Although most CV spectra in the literature are fit to a thermal bremsstrahlung (TB) model, most LMXBs are fit to a blackbody model. We did, however, find a set of thirty-nine LMXB spectra fitted with single component TB (Christian 1993). To remain consistent with our CV comparisons, Fig. 6b illustrates the bremsstrahlung temperatures for LMXBs. The kT_{brem} determined for MS1603 is on the lower limit for this distribution. Blackbody LMXB temperatures are shown in Fig. 6c. Mean kT_{bb}'s have been quoted as ∼1–2 keV and even as high as ∼5 keV. MS1603 lies well below the temperatures found.

LMXB periods are mostly contained in the range of 3–10 hours (Parmar & White 1988), although a few individual periods can stretch from 11 minutes to up to 9 days. No X-ray binaries have periods in the 2–3 hour gap exhibited by CVs, and for LMXBs, this gap may extend to shorter periods.

A number of ADC (accretion disk corona) sources are known to show evidence for an extended accretion disk rim (Mason 1989) caused by interaction with the disk and the stream from the secondary. These sources show non-sinusoidal variabilility over the orbital period, as parts of the ADC are occulted by the rim. If MS1603 is a LMXB and an ADC source, then both the X-ray light curve and the changing optical light curve could be explained as a consequence of 'rim shading'.

4.3. Transient LMXB in quiescence?

X-ray luminosities of SXT's in quiescence have been estimated at $L_x \sim 10^{31-33}$ergs$\cdot s^{-1}$, but during outbursts, the x-ray luminosity can increase to a level comparable to persistent LMXBs. It is clear from previous ROSAT *PSPC* observations(Verbunt et al. 1994) that during quiescence, which can last from ∼0.5–50 years or possibly longer, accretion continues although at a very low rate. It seems possible that MS1603 may be a transient LMXB in quiescence, as is explained below.

Morris et al. (1990) explain that the optical spectrum of MS1603 and its large x-ray to optical flux ratio suggest that the companion is a low-mass M-type star, thus supporting the soft transient claim. Observed x-ray spectra of transient LMXBs in quiescence have previously been fitted to single-component

TB, blackbody and powerlaw models. Low blackbody temperatures have been found for the detections with the ROSAT (Verbunt et al. 1994). These are comparable to those determined for MS1603. In Fig. 6d we have plotted the histogram of known transient BB temperatures together with MS1603.

Few orbital periods of transient LMXBs are known, and the ones that are known vary. According to the criteria outlined by Hameury et al. (1987), all LMXBs with $P \leq 2$ hours would be transient. Coupled with the fact that in quiescence, x-ray flux levels drop below the detection limits of early x-ray satellites, this would explain the lack of short period LMXBs observed. However, recent studies by King, Kolb & Burderi (1996) suggest that if the transient behaviour is due to disk instabilities the disks in systems below the period gap (i.e. below 2 h) are too hot to produce instabilities and thus systems like MS1603 should be persistent. This, however, depends on the nature of the compact primary, and it seems that short period SXT's (shorter than 2 hours) with BH primaries might still exist.

If we assume, based on the evidence in Sect. 4.3, that MS1603 is a transient LMXB in quiescence, then the distances quoted in Morris et al. (1990) are not applicable here. Taking the x-ray luminosity for LMXB transients in quiescence to be $L_x \sim 10^{31-33} ergs \cdot s^{-1}$ and the luminosity formula derived by Morris et al. (1990) for MS1603,

$$L = 1.4 \times 10^{34} (d/10\,kpc)^2 ergs \cdot s^{-1}$$

we have obtained new limits on its distance. Assuming $L_x = 10^{31} ergs \cdot s^{-1}$, a distance of 0.267 kpc is found. This translates into z = 0.195 kpc. The upper limit puts MS1603 at a distance of 2.67 kpc with a height above the disk of 1.95 kpc. van Paradijs & White (1995) have studied the galactic distribution of LMXB's and found an rms value for z to be 1.0 kpc. Thus even at the upper limit of z=2.67 kpc, MS1603 would not severely deviate from the distribution found by van Paradijs & White (1995).

5. Conclusions

We have presented our results of optical and X-ray observations of MS1603+2600. Mainly based on X-ray properties, together with optical results and location constraints, we suggest that MS1603+2600 could be a short period SXT with a possible black hole primary. None of the known SXT's have orbital periods below 2 hours. Thus MS1603 still remains an important target in our understanding of LMXB evolution and the transient behaviour.

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