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Optical variability of the black hole candidate GX339−4 (X1659−487, V821 Ara) – limits on periodic modulation

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Summary. We present results of extensive CCD optical photometry (over 1000 frames representing ~150 hr of integration time) of the optical counterpart of the X-ray source GX339−4 obtained during the high (soft) state. The source was seen to be significantly variable. We do not, however, detect any periodic modulation with semi-amplitude greater than ~0.03 mag for periods less than ~0.5 day or semi-amplitude greater than ~0.07 mag for longer periods. An optical spectrum obtained shortly after GX339−4 made a transition from a 'low' to a 'high' state is also presented and compared with previous results. The width of the He II λ4686 emission line in the spectrum implies that GX339−4 does not have an unusually low inclination angle and we therefore conclude that the orbital period of GX339−4 is probably longer than ~0.5 day.

1 Introduction

The X-ray source GX339−4 (X1659−487) has long been regarded as a strong candidate for a system containing a black hole. The main reasons for this are the fast flaring activity on time-scales as short as 10–20 ms (Samimi *et al.* 1979) and the two-state X-ray spectrum similar to that of Cyg X-1 (Doxsey *et al.* 1979). The fast flaring behaviour is now known, however, not to be a unique signature of an accreting black hole. Similar flaring behaviour has been observed in V0332+53 (Stella *et al.* 1985) which also exhibits 4.4 s pulsations which indicates that the compact object in V0332+53 is a neutron star. The optical counterpart of GX339−4 was identified by Doxsey *et al.* (1979) with a faint (V~17) blue star with He II λ4686 and $\lambda\lambda$4640–50 emission

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Table 1. X-ray activity states of GX339−4.

State	kT (keV)	α	L_X (μJy)	V mag	References
High (soft)	0.8–1.5	4	80–350	16.5–17	2, 3, 4, 6
Low (hard)	$\geqslant 4$	0.5–2	40–200	15.4	1, 3, 4, 5, 6, 7
Off		1.8	$\leqslant 2$	17.7–20	2, 4

Notes:
X-ray spectral parameters for GX339−4 have been quoted for a variety of models including thermal bremsstrahlung, power law and a soft unsaturated Comptonized spectrum. α above is the power-law photon index. Recent *EXOSAT* results from Ilovaisky *et al.* (1986) show a soft state with an L_X less than the hard (sometimes called 'low') state. Optical photometry has only been obtained during one low (hard) state (Motch *et al.* 1985).

References:
1, Doxsey *et al.* 1979; 2, Ilovaisky *et al.* 1986; 3, Maejima *et al.* 1984; 4, Markert *et al.* 1973; 5, Motch *et al.* 1983; 6, Ricketts 1983; 7, Samimi *et al.* 1979.

features. At least three different X-ray states have been seen in this source which have generally been classified as follows: (i) high (soft X-ray spectrum), (ii) low (hard X-ray spectrum) and (iii) off (very weak X-ray flux, hard X-ray spectrum). We summarize in Table 1 the 'typical' properties during these states. The Maejima *et al.* (1984) Hakucho observations demonstrated the clear bimodal behaviour of the X-ray spectrum [they observed a transition from a low (hard) to a high (soft) state], however the range of X-ray intensities observed by a variety of satellites shows that it is difficult to assign the state by X-ray intensity alone (Ilovaisky *et al.* 1986). The lack of simultaneous optical coverage for many of the X-ray observations means that the correlation between optical brightness and X-ray state is also poorly defined. However, it has been noted by Motch *et al.* (1985) that the star does appear to be faintest in the 'off' state, and brightest during the low (hard) state but at an intermediate level during the high (soft) state. During a low (hard) state, rapid (down to 50 ms) variations were observed both in the optical and X-ray wavebands (see e.g. Motch *et al.* 1985). During the 1981 May low (hard) state, optical quasi-periodic oscillations with 40 per cent full amplitude and a period of 20 s were detected (Motch, Ilovaisky & Chevalier 1982). X-ray quasi-periodic oscillations were also observed at this period and its first harmonic (Motch *et al.* 1983). In 1982 May optical quasi-periodic oscillations were again seen (7 s period) when the star was moderately faint (V=17.7) and GX339−4 was in an 'off' state (Ilovaisky *et al.* 1986). The large optical variability (V=15.4–~20) and optical spectrum of GX339−4 imply that it is a member of the low-mass X-ray binary (LMXB) class (review by van Paradijs 1983).

In spite of the length of time that GX339−4 has been known (discovered by Markert *et al.* 1973) until very recently (Cowley, Crampton & Hutchings 1987) no binary period had been suggested and indeed no direct evidence to show that GX339−4 is a binary had been found. The recent radial velocity data obtained by Cowley *et al.* (1987) suggest that the orbital period of GX339−4 may be between 0.2 and 2 day. The binary period is of key importance to an understanding of the properties of any X-ray binary (e.g. the mass transfer mechanism and the nature of the mass-donating star). In a number of LMXBs optical variability is seen on the orbital period caused by e.g. the variable aspect of the X-ray heated face of the mass-donating star, azimuthal asymmetries in the accretion disc or a partial eclipse of the accretion disc by the non-degenerate star (*cf.* Mason, Parmar & White 1985; Corbet *et al.* 1986). We might therefore expect the orbital period of GX339−4 to be revealed by optical photometry. Previous optical observations of GX339−4 have, in general, concentrated on studying the rapid time variability (e.g. Motch *et al.* 1983). The largest body of optical photometry published prior to this paper is the analysis of archive Harvard plates by Grindlay (1979). His periodicity search was limited, however, to periods longer than 3

day with amplitudes greater than 30 per cent. He detected no such period. Only small amounts of *UBV* photoelectric photometry have been obtained (e.g. Makishima *et al.* 1986; Grindlay 1979) which are insufficient for a periodicity search.

We present here the results of CCD photometry obtained from two continents. These observations thus have the advantage of very high internal accuracy and extended time coverage which reduces potential aliasing problems caused by sampling with a 1 day period.

2 Observations

Photometry of GX339−4 was obtained on the following occasions (see summary in Table 2):

(i) At the Cerro Tololo Inter-American Observatory (CTIO) 1.0-m telescope using a GEC epitaxial CCD system with *V* filter on 1984 June 25 and 26.

(ii) At the South African Astronomical Observatory (SAAO) 1.0-m telescope equipped with the UCL CCD system (Walker *et al.* 1985) between 1986 April 1 and 7 and again between 1986 June 30 and July 7.

(iii) At the CTIO 1.5-m telescope using an RCA CCD system between 1986 June 27 and July 4.

Exposures were made through filters approximating the Johnson *V*- and *B*-bands and were typically 300 and 480 s (*V*-band) and 600 and 480 s (*B*-band) in length at SAAO and CTIO, respectively. These observations were designed to enable a search for possible periods of length ~hours and we thus cannot comment on the presence of short time-scale variability as is sometimes seen in GX339−4 (e.g. Motch *et al.* 1983).

Variations in detector efficiencies across the field were corrected either through exposures of an illuminated target inside the dome (CTIO) or through exposures of the twilight sky (SAAO). The SAAO CCD images were analysed using an automated computer reduction system developed at Oxford and the 1986 CTIO images were reduced using DAOPHOT. Both systems determine the point spread function for each image from the observed profile of a bright star in the field of view. This profile is then fitted to the target star and several other comparison stars which provide a check on the accuracy of the derived magnitudes. Differential magnitudes with respect to the brighter star are thus produced which are relatively insensitive to changes in sky transparency. The 1984 images were reduced using a similar system then available at CTIO. For the 1986 June/July SAAO data the relatively poor seeing meant that it was necessary to simultaneously fit a faint star ~4 arcsec NE of GX339−4 together with GX339−4 itself. In Fig. 1 the results of the photometry are shown. The magnitude of 'Star 8' (Grindlay 1979) located ~8 arcsec NE of GX339−4 is also shown for comparison. The errors quoted in Table 2 are for the

Table 2. Observations of GX339−4.

Dates	Telescope	Filter	No of frames	Typical error (mags)
1984 June 25-26	CTIO 1.0m	V	119	0.025
1986 April 1-7	SAAO 1.0m	V	311	0.024
		B	3	0.060
1986 June 30 -July 7	SAAO 1.0m	V	275	0.031
		B	31	0.078
1986 June 27 -July 4	CTIO 1.5m	V	258	0.009
		B	66	0.022
1981 July 25	AAT 3.9m	Spectroscopy		

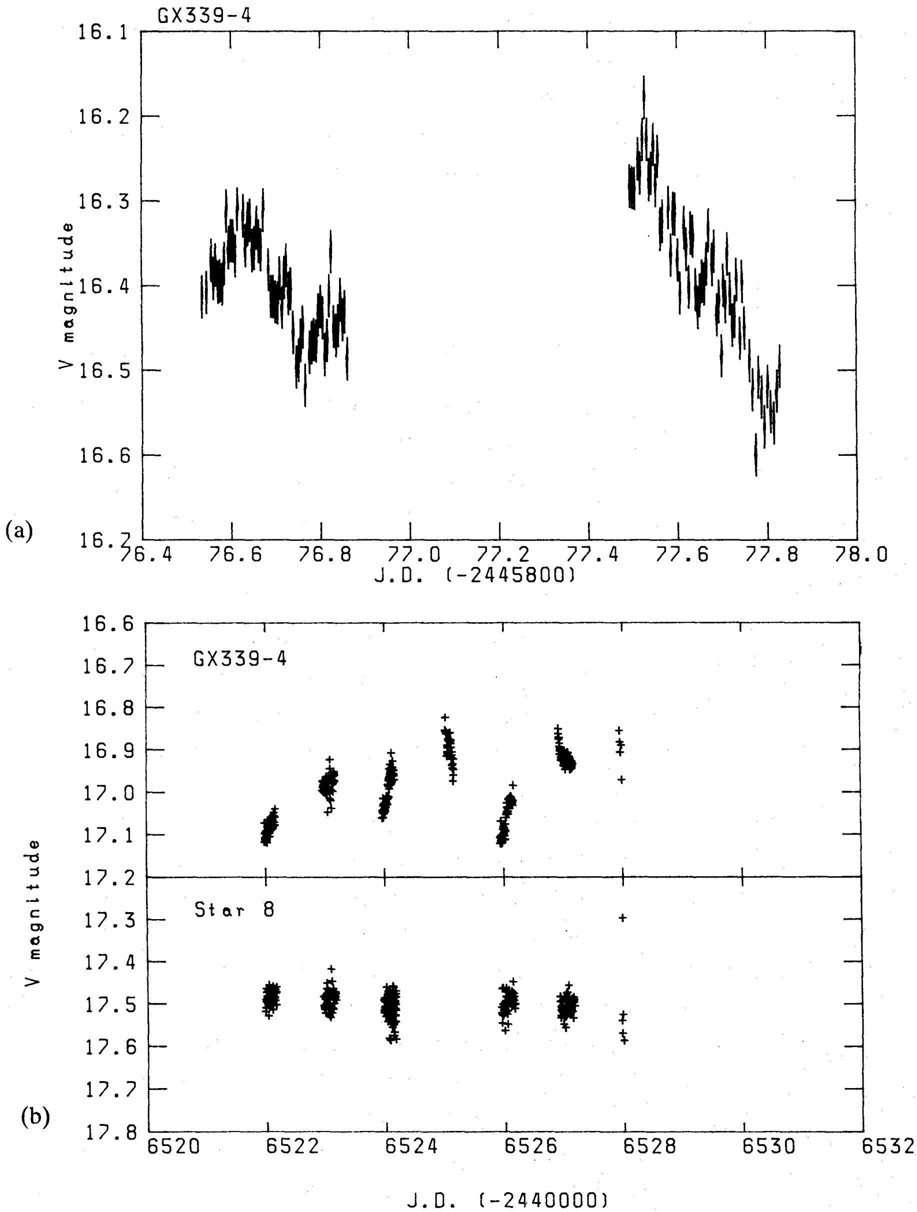

Figure 1. *V*-band photometry of GX339−4. (a) CTIO 1984 June, (b) SAAO 1986 April, (c) SAAO and CTIO 1986 June/July.

instrumental system and are the scatter in magnitude of Star 8 which is ~0.5–1 mag fainter than GX339−4 at the time of the observations and thus the errors are slightly overestimated. This star was used as a comparison, however, as it potentially suffers from the same crowding problems as GX339−4. The conversion to the standard *UBV* system was made using the magnitudes given by Grindlay (1979) for his stars numbers 2 and 8 which appear on all our CCD frames. The relative magnitude of Star 2 compared to Star 8 was found to be 3.49 compared to the value of 3.5 given by Grindlay (1979).

3 Variability

GX339−4 was found to be in a bright state in all our observations. The light curves show it to be clearly variable by several tenths of a magnitude during each observation (Fig. 1) and GX339−4

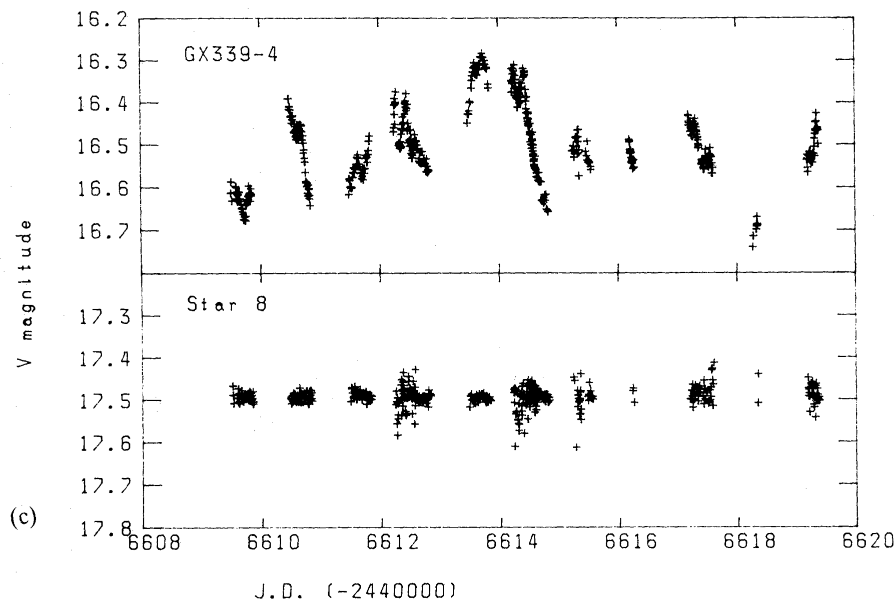

Figure 1–*continued*

also brightened by 0.5 mag between 1986 April and June. Fig. 2(a) and (b) show examples of variability within a 'night' and demonstrate the advantages of extended time coverage produced by combining data from two observatories widely separated in longitude.

A period search was performed on the photometric data using a Fourier transform routine. This search was made on the combined 1986 June/July SAAO and CTIO data sets and also on the SAAO and CTIO data sets individually, with the exception of the 1984 June data which cover too short a period for useful analysis. Periods between the Nyquist period (~0.01 day) and half the length of the individual data sets were searched. Although there are many peaks in the power spectra (Fig. 3) we cannot identify any of the strongest peaks with the orbital period. In particular we note that the transforms of the 1986 June and April data sets differ considerably. The tentative periods suggested by Cowley *et al.* (1987) are marked in Fig. 3 by dashed lines. Of the possible periods obtained by Cowley *et al.* their 'favourite' period of 0.87 day (f=1.15 day^{-1}) may be present at a low amplitude (semi-amplitude ~0.04 mag) but it certainly cannot be said to be confirmed by our data.

The strongest limits on periodic modulation are set by the combination of our CTIO and SAAO 1986 June/July data sets. From the transform of these data we adopt limits of semi-amplitude <~0.03 mag for periods less than ~0.5 day and semi-amplitude <~0.07 mag for longer periods. As a check of our analysis we also performed a transform on the magnitudes of 'Star 8' (Grindlay 1979). In no case was a signal present with a semi-amplitude greater than 0.015 mag (SAAO 1986 April data set) and the strongest period for the combined 1986 June/July Star 8 data set has a semi-amplitude of 0.006 mag. The sensitivity of our measurements to the detection of coherent periodicities is thus limited by the intrinsic non-periodic variability of GX339−4 rather than measuring errors.

4 Colour changes

Although there are relatively large changes in V during the 1986 June/July observations there are no accompanying variations in the $(B-V)$ index which remains constant to better than 0.02 mag at 1.0±0.1 (systematic error). The correlation coefficient between V and $(B-V)$ is 0.06. This is in

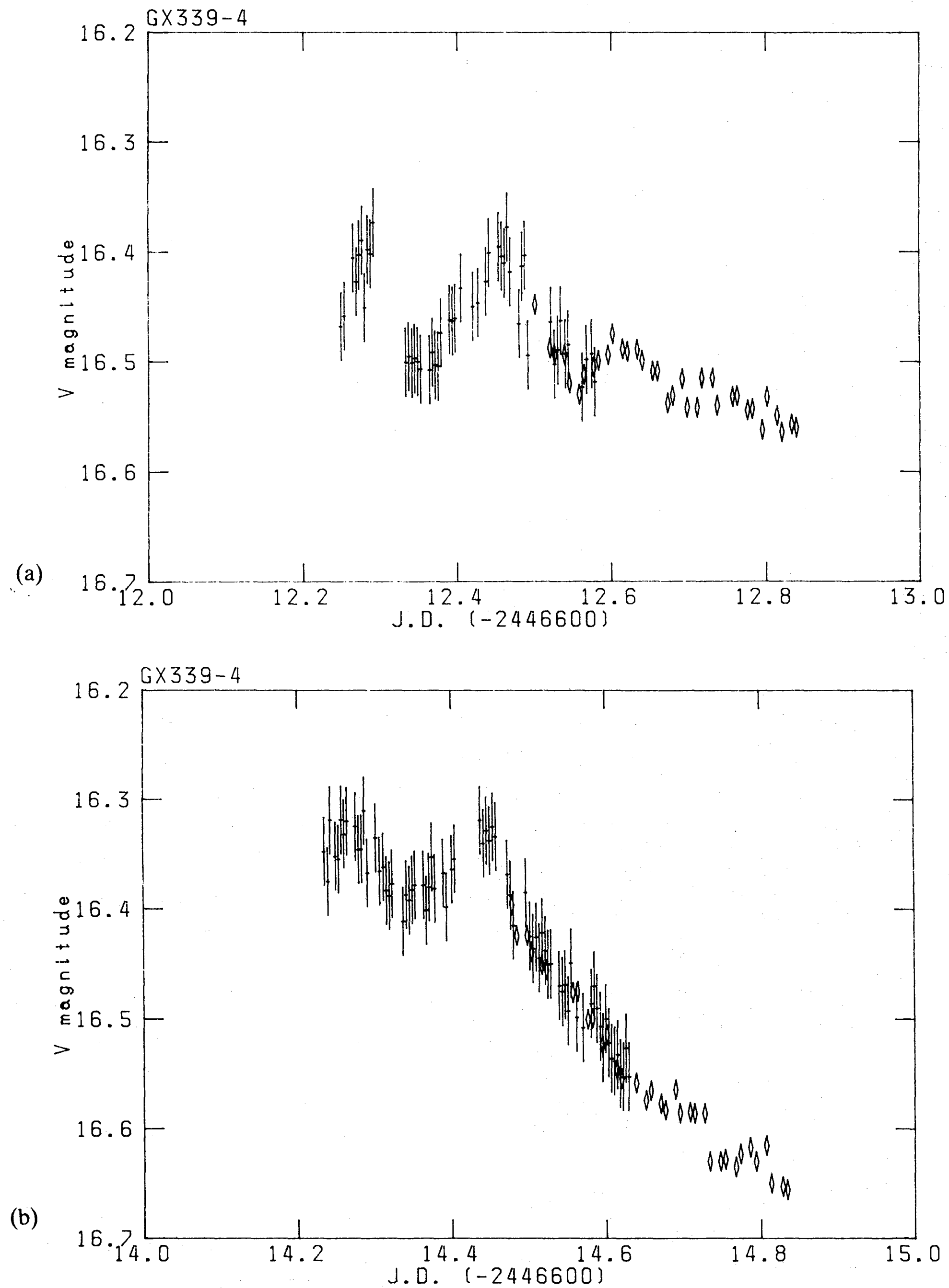

Figure 2. (a) and (b). Expanded plots of sections of 1986 June/July photometry. Error bars show SAAO data and diamonds are CTIO data.

contrast, for example, to the behaviour of the LMXB 2S0921−630 which shows highly correlated variations between brightness and $(B-V)$ (Chevalier & Ilovaisky 1982; Branduardi-Raymont *et al.* 1981).

5 Post-transition optical spectroscopy

In 1981 April GX339−4 was in an X-ray 'off' state and at $B=20.3\pm0.1$ (Ilovaisky *et al.* 1986; Oda *et al.* 1981; Hutchings, Cowley & Crampton 1981). By 1981 May the X-ray source had turned back

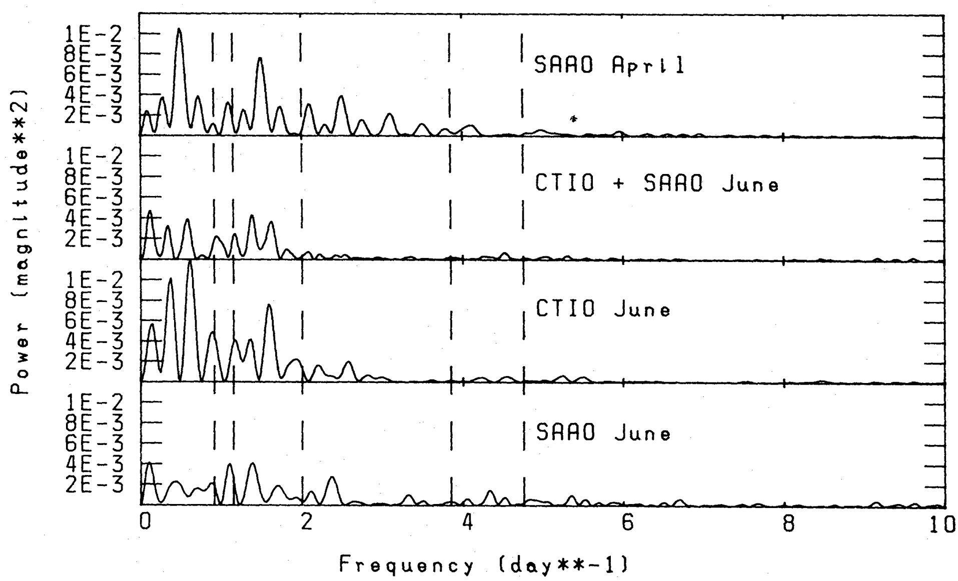

Figure 3. Power spectra of *V*-band photometry of GX339−4. The dashed lines indicate the tentative periods suggested by Cowley *et al.* (1986).

on and the optical counterpart had brightened to 15.4 (Motch *et al.* 1982). This was followed by a transition into the high (soft) state around 1981 June 25 which was observed by the *Hakucho* X-ray satellite (Maejima *et al.* 1984). The X-ray observations continued until 1981 July 17 and showed GX339−4 to be still in the high (soft) state. On 1981 July 25, shortly after this return to a high (soft) state, we obtained optical spectra of GX339−4 with the 3.9-m AAT. The RGO spectrograph, IPCS detector and 600 $1\,mm^{-1}$ grating were employed, giving a dispersion of 66 Å mm^{-1} (equivalent to a resolution ~4 Å). The spectrum obtained is shown in Fig. 4. Condi-

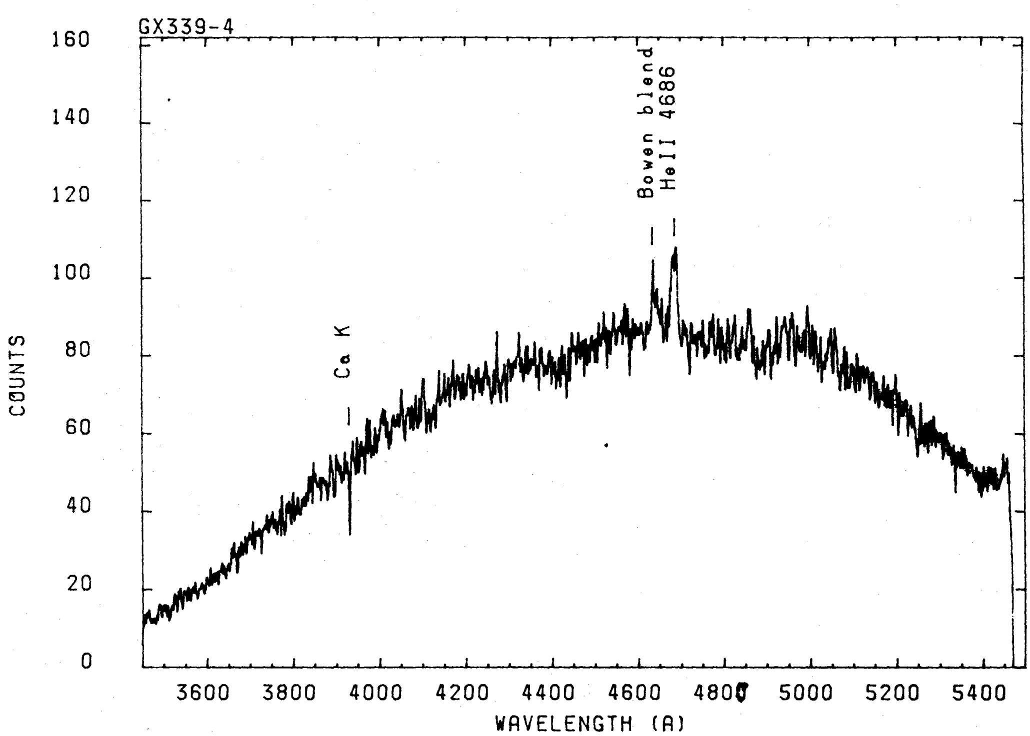

Figure 4. Optical spectrum of GX339−4 obtained on 1981 July 25.

tions were not photometric; however, from the TV guider we estimated $V\sim17$. The principal features in the spectrum are emission at He II λ4686 and the Bowen blend at ~λ4640. Ca K is also seen in absorption with an equivalent width of ~1.0 Å.

6 Discussion

6.1 ORIGIN OF THE OPTICAL EMISSION

Because of the fast optical flaring observed during the low (hard) state, Fabian *et al.* (1982) attribute the optical emission to cyclotron emission from hot gas at $\sim10^9$ K. However, Apparao (1984) claims that cyclotron emission is unable to account for the observed optical luminosity by a factor of 10^3. Furthermore, during the high (soft) state Makishima *et al.* (1986) argue that since the colours, L_X/L_{opt} ratio and optical spectrum are similar to those of other LMXBs the dominant source of optical emission must be the same, i.e. X-ray reprocessing in the outer accretion disc. Ilovaisky *et al.* (1986) find, however, a good correlation between the optical luminosity and the hard component of the X-ray flux rather than the total X-ray flux which is incompatible with the simple reprocessing model.

6.2 WHY IS NO ORBITAL PERIOD DETECTED?

Our photometry excludes any orbital modulation greater than ~0.03 mag for periods less than ~12 hr. The majority of LMXB orbital periods measured to date typically have values ~4–5 hr (White 1986). There is, however, a strong selection effect against measuring longer periods. There are several possible ways of accounting for our failure to detect an orbital period in GX339−4:

(i) If the inclination angle of GX339−4 were extremely unfavourable then the optical modulation might be very low. However, the width of the He II λ4686 emission line (FWB velocity $\sim1200\ \mathrm{km\ s^{-1}}$) argues against this interpretation. If we naively assume that the observed optical modulation in an LMXB will scale simply as sin *i* then the observed modulations seen in Sco X-1 (~0.1 mag, Gottlieb, Wright & Liller 1975) and X1735−444 (~0.08 mag, Corbet *et al.* 1986) and inclination angles of 30° and 35° respectively (Crampton *et al.* 1976; Smale 1986) imply that GX339−4 has $i<10$–13° for $P<0.5$ day and $i<20$–30° for $P>0.5$ day.

(ii) If the orbital period is extremely short (*cf.* the ~685 s period of 4U1820−30; Stella, Priedhorsky & White 1987) or very long (*cf.* the 9 day period of 2S0921−630; Cowley, Crampton & Hutchings 1982) it would be undetectable in our data. However, both these explanations are apparently excluded by the results of Cowley *et al.* (1987) which indicate a period between 0.2 and 2 day.

(iii) The mass donating star in the system may be completely shielded from X-rays by an accretion disc.

(iv) The orbital period is similar to the characteristic time-scale for non-periodic variability and is thus masked unless many binary periods are observed. We note that the 0.8 day period of Sco X-1 (Gottlieb *et al.* 1975) initially remained undetected for many years in spite of extensive photometric and spectroscopic observations.

(v) GX339−4 is not a binary system.

If we assume that GX339−4 is not grossly different from the majority of other LMXBs in its orbital period and geometry then the most likely explanation for our failure to detect a periodicity is option (iv) above.

6.3 X-RAY ACTIVITY STATES OF GX339−4

Reports on the long-term variability of GX339−4 can be found in Motch *et al.* (1985) and further information is presented by Ilovaisky *et al.* (1986). In 1984 May, one month before our first set of photometric observations, GX339−4 was in a high (soft) state. In 1985 April the source was in an 'off' state with V=17.7. Our 1984 June observations were therefore very probably made during a high (soft) state. In 1986 April and June/July the mean magnitude of GX339−4 was 17.0 and 16.5, respectively. For comparison Ilovaisky *et al.* (1986) report V=15.4 during the low (hard) state and V=16.8 for the high (soft) state. Makishima *et al.* (1986) give V=16.4 during their observations of a high (soft) state. We therefore conclude that our 1986 observations were probably also obtained during a high (soft) state as was our optical spectrum (with V~17).

6.4 COMPARISON WITH X-RAY VARIABILITY

The X-ray flux from GX339−4 during the high (soft) state shows only a small amount of variability. Ilovaisky *et al.* (1986) give a 1σ upper limit of 0.8 per cent on any variability for time-scales less than 6 hr. From their 11 day *Tenma* observation Makishima *et al.* (1986) find no evidence for variability on time-scales of hours to days but a gradual ~15 per cent increase, although the hard X-ray component showed a somewhat larger variability. In contrast all our CCD observations of GX339−4 show variability >0.1 mag on time-scales of hours. Although we have no simultaneous X-ray data this may be further evidence that the optical emission is related to the hard X-ray flux rather than the total X-ray flux.

7 Conclusion

Since no periodicity in GX339−4 has yet been found by either optical or X-ray photometry it is likely that the binary period will only be found by radial velocity studies of the emission lines in the optical spectrum. We also point out that all optical spectra of GX339−4 obtained to date (this paper Section 5; Grindlay 1979; Makishima *et al.* 1986; Cowley *et al.* 1987) have been taken during the high (soft) state. Spectroscopy of GX339−4 in the low (hard) or 'off' states may provide further constraints on models for this source. With the exception of fast photometry no large body of optical photometry has yet been obtained during the low (hard) state.

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