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The 14.8-h orbital period of GX339-4

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ABSTRACT

We present the results of photometric observations of the black hole candidate GX339-4, obtained while the system was in an 'off' state. We show that a 14.8-h modulation was present, and provide evidence for a similar periodicity in the 'high' state from a reanalysis of previously published photometry and spectroscopy. The presence of the same period in both states implies that it is likely to be the orbital period of the system. The spectroscopy analysis provides evidence for an apparent change in the systemic velocity of the system. The amplitude of the observed radial velocity variations, however, permits only crude limits to be placed on the mass of the compact object. Only absorption-line spectroscopy of the secondary in the 'off' state will provide a convincing mass determination.

Key words: binaries: close – stars: individual: GX339-4 – X-rays: stars.

1 INTRODUCTION

The X-ray transient GX339-4 has long been considered to be a strong black hole candidate, primarily on the basis of its short-term X-ray variability ($\tau \sim 10$–100 ms), soft ($kT \sim 1$–2 keV) high-state X-ray spectrum, and hard X-ray tail (Markert et al. 1973; Samimi et al. 1979). The source has been observed in high, low and off X-ray states with corresponding X-ray intensities of 80–350, 40–200 and 1.5 μJy. The corresponding optical V-band magnitudes are ~ 17, 15.4 and 17.7–20 respectively (Corbet et al. 1987). Both optical quasi-periodic oscillations (QPO with 7–8 s period: Motch, Ilovaisky & Chevalier 1982) and X-ray QPO (6 Hz: Miyamoto, Kitamoto & Kazuhiro 1989) have been observed from GX339-4. Most models for X-ray QPO require that the degenerate component in GX339-4 be a neutron star, but no X-ray bursts have yet been observed.

It has been suggested by Ricketts (1983) that the *total* X-ray flux from the object when 'on' (i.e. in a 'low' or 'high' state) is a constant and all that occurs is a change of spectral shape, with the spectrum pivoting about ~ 6 keV. The apparent change in intensity is caused by the fact that the X-ray intensity is generally considered over the 1–10 keV region only. Similar pivoting spectral behaviour has also been seen in other transient sources, e.g. A0620 − 00 and GS2000 + 25 (Kaluzienski et al. 1977; Tsunemi et al. 1989).

Although we now know that extreme variability is not in itself a unique signature of a black hole (e.g., Stella et al. 1985), the similarities of GX339-4 with systems such as Cyg X-1 clearly make it a system warranting close study. In particular, the red colour ($B - V \sim 1.1$–1.3) of GX339-4 in the off state implies that the secondary itself is becoming detectable. We therefore embarked upon a campaign of CCD photometry while GX339-4 was in an off state, in the hope of determining the orbital period by detecting the ellipsoidal variations of the secondary.

2 OFF-STATE OBSERVATIONS

These observations consisted of near-contiguous runs in Chile and South Africa during 1987 July 23–29. Fig. 1 shows a finding chart for the optical counterpart of GX339-4 (arrowed). Also marked is its close line-of-sight companion first noted by Remillard & McClintock (1987: star Y).

Cerro Tololo Inter-American Observatory (CTIO) observations were carried out with the 1.5-m telescope using a TI 800 × 800 pixel CCD detector, through Kron–Cousins R and I filters, and calibrated using local standards (Graham 1982). Typical integration times were 900 s. These data were reduced by fitting a point spread function (PSF) to the stellar images using the DAOPHOT software package (Stetson 1987) in La Serena.

South African Astronomical Observatory (SAAO) observations were undertaken using the 1-m telescope and

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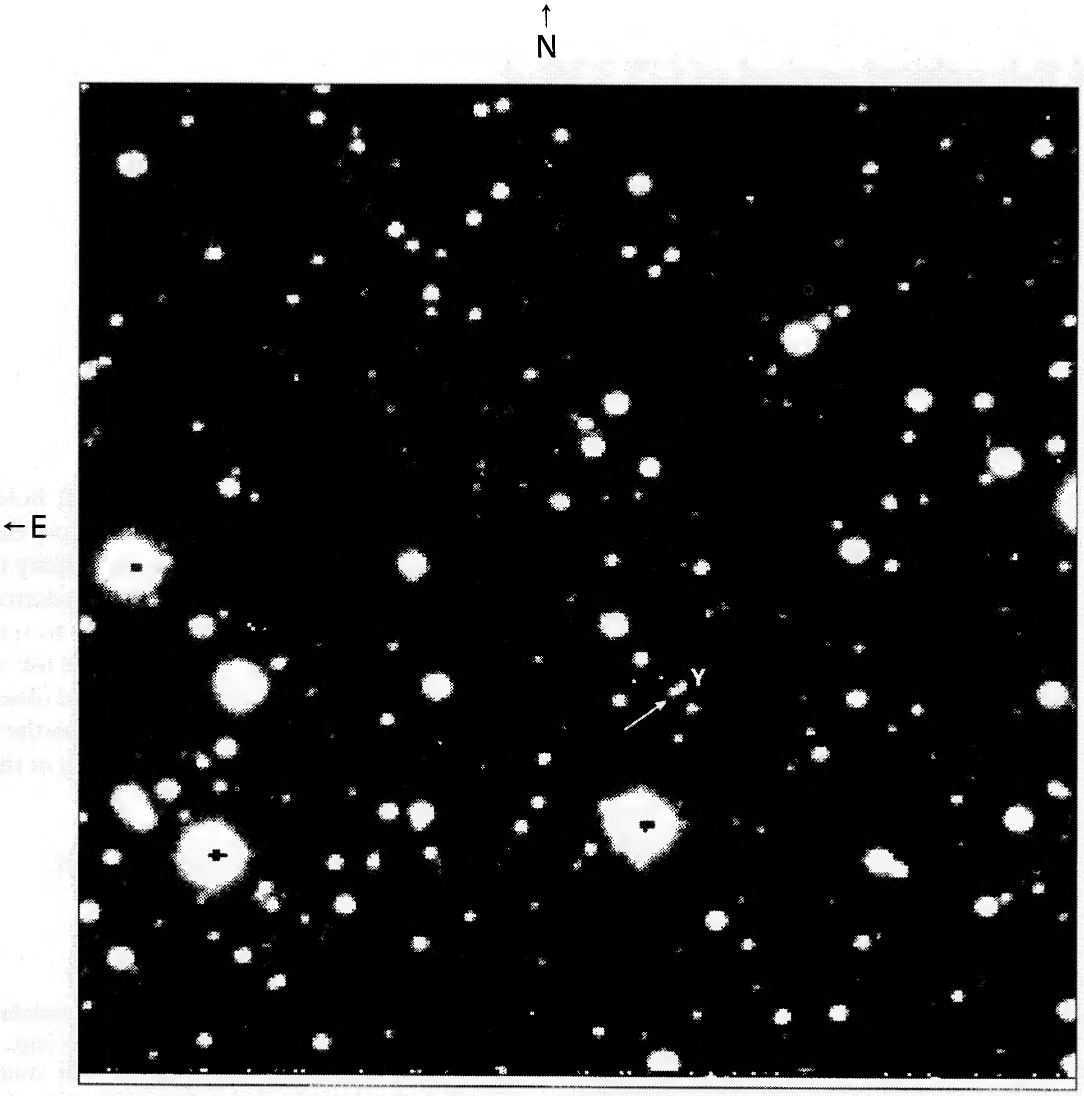

Figure 1. A Finding chart for GX339-4 (R band). Star Y is clearly resolved. The image dimensions are 1.7 × 1.7 arcmin^2. North is up and east to the left.

the UCL RCA CCD system, through Johnson R- and I-band filters. Typical integration times were 1000 s. The quality of these images was such that GX339-4 and star Y could be well resolved in some frames, but not completely resolved in all. For the well-resolved frames a double PSF was fitted, to determine an average separation of GX339-4 and star Y (1.06 arcsec from GX339-4 at an angle of 35°.4 west of north) together with the average intensity of star Y relative to other stars in the field. The unresolved images were then reduced by fitting a double PSF in which the relative separation of the two stars was fixed, together with the intensity of star Y (relative to other stars in the frame). When calibrated with respect to the standard stars, the mean brightness of GX339-4 itself during these observations was found to be $R = 19.4$ and $I = 18.8$ (± 0.1). The SAAO and CTIO data sets were normalized relative to each other by using common comparison stars, producing the total light curve shown in Fig. 2. The error in the relative magnitude estimate is ~0.05 mag. Considerable flickering is present, even in the off state. The lower panel of Fig. 2 shows the data after subtraction of a nightly mean, and smoothing with a six-point running mean. Fig. 3 shows the power spectrum of the combined R and I data sets (after renormalization of the R-band data): a peak at ~0.62 d is present.

A sine-wave fit to the combined data set yields a period of 0.61916 ± 0.00065 d: the error is derived using the prescription of Lampton, Margon & Bowyer (1976) and should be regarded as a lower limit, as there is considerable scatter in the data about the best-fitting sine-wave due to the intrinsic short-term variability of GX339-4. In order to determine a more realistic estimate, we first subtracted the 0.6192-d modulation from the data, and calculated the variance of the resulting light curve. We then used this variance to assign new error bars to the points of the original light curve. The sine-wave fit to this data now provides a formally more acceptable fit (reduced $\chi^2 \sim 1.0$), and indicates a 1σ error in the period of 0.0027 d, which we take as a more reliable estimate of the true error. In order to confirm the validity of the error deter-

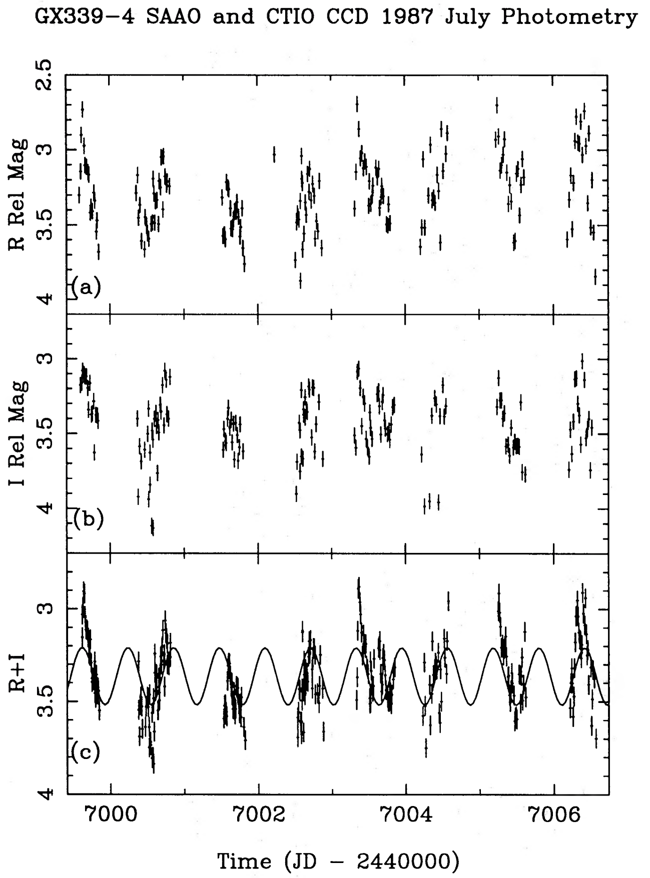

Figure 2. The *R*- and *I*-band SAAO and CTIO 'off'-state observations. The lower panel (c) shows the summed $R+I$ light curve after being smoothed with a running mean (a two-point average). Superimposed is a sine wave of period 0.619 d.

mined by this method, we simulated our data by generating data sets of similar sampling and correlated variability (using an autoregressive process with a similar autocorrelation function to that of the data). The standard deviation of the period determined from these data sets is entirely consistent with the error estimated above.

Also plotted, in Fig. 3, is the combined power density spectrum (PDS) after the subtraction of a sine wave with a period of 0.6192 d from the data. This sine wave is shown in the lower panel of Fig. 2.

Fig. 4 shows the *R*- and *I*-band data folded on the 0.6192-d period. Folding the data on the second highest peak in the PDS produces a modulation with considerably more scatter. In addition, previous observations did not show significant power at this period (see Section 3). We estimate T_0(JD) (minimum light) = 2447000.539 ± 0.015. The *R*- and *I*-band amplitudes are identical within the errors at 0.154 (±0.018) mag.

3 PREVIOUS OBSERVATIONS

3.1 High-state optical photometry

After the discovery of the low-state modulation we decided to reanalyse the previously published high-state photometry of Corbet et al. (1987). These data were Fourier transformed after first removing long-term trends with a second-order polynomial. This transform is shown in Fig. 5. There are several strong periods apparent which have been labelled 1 to 4. Of these, period 4 is found to be equal to 0.618 d. A sine-wave fit to this data set yields a period of 0.6179 ± 0.0016 d (the error is estimated in the same way as for the low-state data), with an amplitude of modulation of 0.054 ± 0.003. The 0.6179-d period was then removed from the data, and the data Fourier transformed once more. This transform is shown as the dashed curve in Fig. 5. It can be seen that the peaks at periods 1 and 2 are greatly reduced thus showing that they are an alias of period 4. Fig. 6 shows the detrended high-state data folded on 0.618 d.

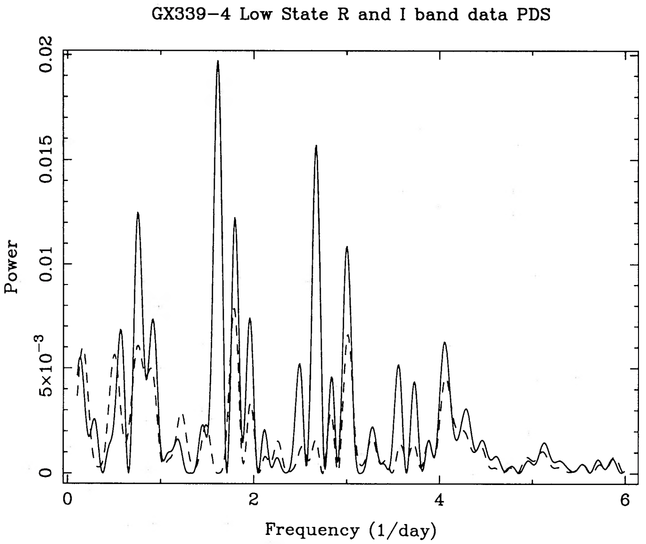

Figure 3. The Fourier transform of the combined *R*- and *I*-band data sets (full line). The dashed line is the transform of the data with the 0.619-d modulation removed.

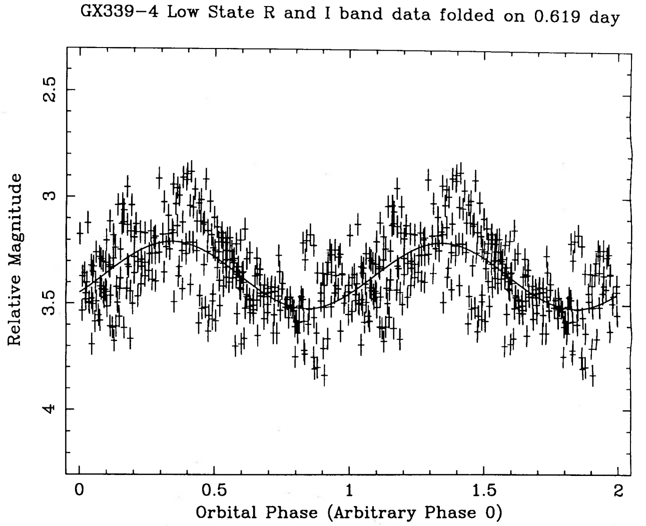

Figure 4. The combined *R*- and *I*-band data sets (as plotted in Fig. 2c) folded on 0.619 d. Considerable flickering is present, even in the off state.

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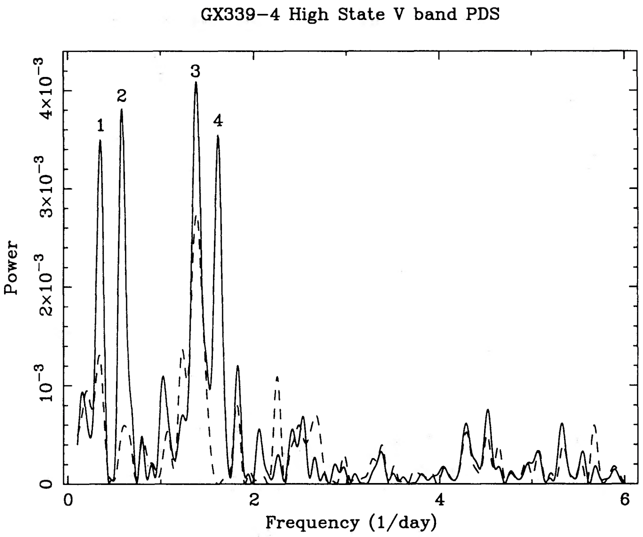

Figure 5. The Fourier transform of the 'high'-state *V*-band data, again with and without the 0.618-d modulation.

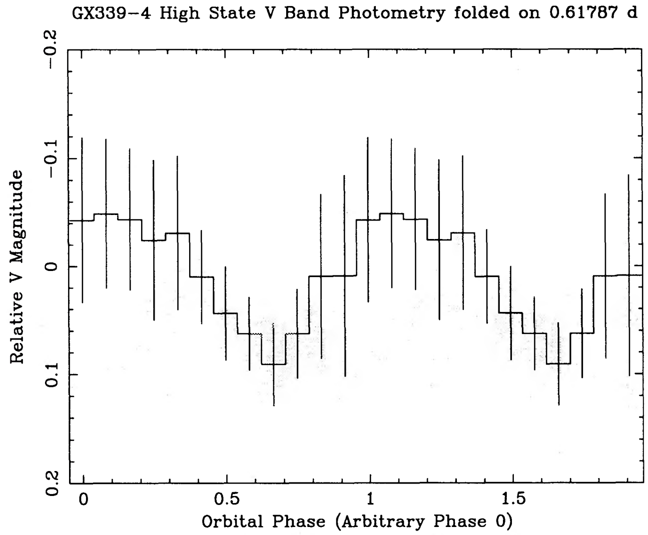

Figure 6. The high-state data folded on 0.618 d. The error bars reflect the scatter in each phase bin (standard deviation).

3.2 High-state spectroscopy

Cowley, Crampton & Hutchings (1987) obtained spectra of GX339-4 in a high state in 1985 and 1986. Fig. 7 shows their two data sets folded on the 0.618-d period. No periodicity is evident in the first data set, but a modulation is present in the second data set. A least-squares sine fit to the second data set folded on 0.618 d yields a semi-amplitude of 78 ± 13 km s^{-1}, and a systemic (γ) velocity of -62 ± 10 km s^{-1}. The accuracy of our photometric period is such that we can extrapolate from the high-state photometry of Corbet et al. to the second Cowley et al. data set. Assuming that maximum light corresponds to closest approach of the compact object, we see that the radial velocity variations are consistent with an origin near the degenerate object (Fig. 7b). The first data set presumably shows no periodicity because of its poorer quality and phase coverage. However, there seems to be a significant shift in the mean radial velocity between the first and second spectroscopic data sets from 95.5 to $-62(\pm 10)$ km s^{-1}.

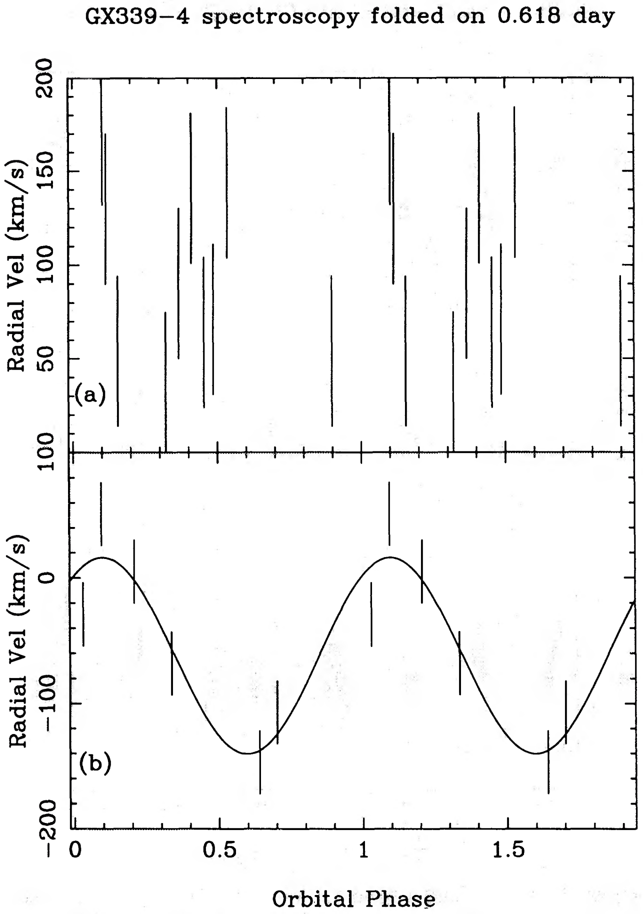

Figure 7. The high-state spectroscopy of Cowley et al. (1987), folded on 0.618 d. The phase for the second data set (b) is that determined from the photometry: the first data set is too far removed in time to allow an accurate extrapolation of the photometric ephemeris.

4 DISCUSSION

What is the nature of the optical modulation? Ellipsoidal variations have been observed in the quiescent states of several low-mass X-ray binaries (LMXBs) where there is little or no X-ray flux (e.g. A0620 − 00: McClintock & Remillard 1986; Cen X-4: Chevalier et al. 1989). GX339-4, however, has been detected with a luminosity of $\sim 2 \times 10^{35}$ erg s^{-1} (for an assumed distance of 4 kpc) while the system was in an off state (Ilovaisky et al. 1986). Only ≤ 1 per cent of this is required to be converted to optical light to explain the observed modulation. In addition, the fact that the same 14.8-h period is present in both the high- *and* off-state data indicates that it is due to X-ray heating, and is likely to be the orbital period. Such a modulation could be caused by the eclipse of an X-ray heated secondary and/or accretion disc. The size of the optical modulation can be produced by a comparatively small change in effective temperature; such a small change is consistent with the fact that we do not see any significant $R-I$ colour variation.

Combining the off-state $(R-I)_0$ colour of ~ 0.1 with the previously reported off-state $(B-V)_0$ colour of ~ 0.4 (Chevalier et al. 1989) yields an effective temperature of $\sim 6800 \pm 1000$ K (Johnson 1966), where we have assumed errors of ± 0.2 mag in the dereddened colours. Assuming for the moment a distance of 4 kpc (Cowley et al. 1987), we estimate a total bolometric luminosity of the counterpart of 0.6 ± 0.2 $L_\odot$, where we have taken $A_v = 2.2$ (Ilovaisky et al. 1986), and have also included the error due to the uncertainty in the bolometric correction. If the secondary is on the main sequence, then using $L \sim M^{3.5}$ implies a mass of 0.86 $M_\odot$. Such a star will not fill its Roche lobe in a 0.618-d binary, however (see, for example, Patterson 1984). An alternative possibility is that the secondary is an evolved subgiant with a core mass $M_{\rm core} \geq 0.15$ $M_\odot$ (e.g. King 1988).

The relationships of Webbink, Rappaport & Savonije (1983) for $P_{\rm orb} = 0.618$ d yield a secondary mass of ~ 0.4 $M_\odot$. Not all of the optical flux comes from such a star, however – there appears to be an X-ray heating effect, and Hα emission has also been detected in the off state (Callanan, Charles & Naylor 1990). Thus we conclude that the mass of the secondary is likely to be less than 0.4 $M_\odot$ if the secondary is an evolved subgiant, for a distance of ≤ 4 kpc.

The recent estimate of 1.3 kpc for the distance of GX339-4 from *ROSAT* measurements of its X-ray halo (Predehl et al. 1991), however, implies an off-state optical luminosity of only ~ 0.06 $L_\odot$. The resulting absolute magnitude of the secondary is ≥ 6.6, similar to that of other soft X-ray transients in quiescence (e.g. A0620 – 00, Cen X-4: van Paradijs 1983). The nature of such an underluminous secondary is unclear, but may be similar to that of Cen X-4 (McClintock & Remillard 1990). Such a low mass for the secondary implies a high mass ratio: this in turn may be related to the transient behaviour, in a way similar to that discussed for GS2000+25 by Callanan & Charles (1991).

A semi-amplitude K_x of 78 ± 13 km s^{-1} implies a mass function for the secondary of 0.0304 $M_\odot$. For an inclination of $\leq 70°$ (no eclipses have been observed), and a secondary mass of ≤ 0.4 $M_\odot$, this value of K_x implies a formal upper limit to the mass of the compact object of only ≤ 1 $M_\odot$. However, although the phasing of the second Cowley et al. data set with our photometric period is encouraging, the different γ velocity between the two spectroscopic data sets implies that we must be cautious in interpreting the radial velocity variations as directly reflecting the motion of the degenerate object. Emission-line spectroscopy of cataclysmic variables (CVs) has yielded similar results (e.g. Marsh, Horne & Shipman 1987). Alternatively, the origin of the variable systemic velocity may be similar to that found in AC211 in M15 (Ilovaisky 1989), where the lines may be formed in a variable-velocity wind being driven from the system (Fabian, Guilbert & Callanan 1987). This wind is associated with an accretion disc corona (ADC) – such an ADC might also account for the hard X-ray tail seen in the X-ray spectrum of GX339-4. Whatever the origin of the emission lines, it is clear that any mass estimate based on them is subject to considerable uncertainty. In addition, our mass estimate of the secondary is derived primarily from evolutionary considerations, and is strongly dependent on the true luminosity of the secondary (and hence on the assumed value of A_v) – no direct evidence (i.e., absorption lines) of the secondary has yet been observed.

The nature of the compact object in GX339-4 has serious implications for the X-ray properties of galactic black holes. The recent discovery of the X-ray transient V404 Cyg as a strong black hole candidate (Casares, Charles & Naylor 1992) implies that not all candidates exhibit ultrasoft spectra. If the primary in GX339-4 is shown to be a neutron star, then not even power-law tails are unique signatures of galactic black holes.

5 CONCLUSIONS

We have identified a 14.8-h photometric modulation in both the high and off states of the black hole candidate GX339-4, which we interpret as the orbital period of the system. The modulation could be caused by the eclipse of an X-ray heated secondary and/or accretion disc. If the distance of GX339-4 is indeed ~ 1.3 kpc, the low luminosity of the secondary implies a high mass ratio (whatever the nature of the compact object), which may be related to the transient nature of the system. Previously published spectroscopy provides evidence for variation in the apparent γ velocity of the system. However, without a direct detection of the secondary, this spectroscopy only permits crude limits to be placed on the mass of the compact object: only absorption-line spectroscopy of the secondary in the 'off' state will provide a convincing mass determination.

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