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# THE 8 SECOND OPTICAL QUASI-PERIODIC OSCILLATIONS IN GX 339−4

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## ABSTRACT

Submillisecond optical photometry of the black hole candidate GX 339−4 was obtained on 1989 August 1 (UT) using the 1.5 m telescope of the Cerro Tololo Inter-American Observatory. We find 8 s quasi-periodic oscillations of width 0.02–0.04 Hz and root mean square amplitude 4%–6%. The visual magnitude of GX 339−4 at the beginning of the observation was $m_v = 17.7$. Motch, Ilovaisky, and Chevalier have previously reported 7 s optical quasi-periodic oscillations when GX 339−4 was also $m_v = 17.7$ and in an X-ray off-state. No X-ray observations were made during the present optical observations and so the X-ray state of GX 339−4 cannot be ascertained. In addition, Motch, Ilovaisky, and Chevalier have also reported 20 s optical quasi-periodic oscillations with 30%–40% full amplitude but when GX 339−4 was much brighter, $m_v = 15.4$, and in a hard X-ray state.

*Subject headings:* stars: individual (GX 339−4) — X-rays: binaries

## I. INTRODUCTION

The black hole candidate GX 339−4 exhibits a rich spectrum of temporal activity. Aperiodic, quasi-periodic, and periodic variability on time scales ranging from milliseconds to months have been reported by a variety of observers over the last several years. Given such a panoply of phenomena one would assume that GX 339−4 must be one of the better understood of the compact X-ray sources. This is not the case, however, because much of the reported phenomena have been seen only once making their interpretations ambiguous and their value as probes limited. As a consequence, even some of the more fundamental properties of the GX 339−4 system are poorly known. For example, whether the compact object is a black hole or a neutron star remains an open question (e.g., see Dolan *et al.* 1987), and it has only recently become apparent that GX 339−4 is in fact a binary star system (Honey *et al.* 1988; Callanan *et al.* 1990). It would be profitable to discover and then systematically study some phenomenon exhibited by GX 339−4 which appears more than once. Here, we report the detection of 8 s optical quasi-periodic oscillations (QPOs) of width 0.02–0.04 Hz and root mean square (rms) amplitude 4% to 6%. Optical QPOs in this system with similar properties have been previously reported by Motch, Ilovaisky, and Chevalier (1985). The visual magnitude of GX 339−4 was $m_v = 17.7$ during both observations suggesting that 8 s QPOs may only appear when GX 339−4 is in a particular optical/X-ray state. X-ray QPOs are a common feature of the neutron star low-mass X-ray binary systems (van der Klis 1989), and thus this feature has the potential of settling the issue of the nature of the compact object in GX 339−4.

The rest of this paper is organized as follows. In § II, we present the observations, our analysis techniques, and our results, in § III, we present a discussion of our results, and in § IV, we summarize our principal findings.

## II. OBSERVATIONS AND DATA ANALYSIS

High-speed white light photometry of GX 339−4 was obtained on 1989 August 1 (UT) from 01:35 to 05:56 hr using the 1.5 m telescope of the Cerro Tololo Inter-American Observatory with the Automatic Single Channel Aperture Photometer (ASCAP) and a cooled RCA 31034 GaAs phototube. A 7″ aperture was used, and the data were recorded at a rate of 5 kHz using the "Li'l Wizard Pulsarator" data acquisition system. The visual magnitude of GX 339−4 at the beginning of our observation, based on a comparison of GX 339−4 to star 2 of Grindlay (1979), was $m_v = 17.7$. The white light count rate for our observations averaged over 32.768 s time intervals is presented in Figure 1. During the time of observation, the background count rate was roughly constant with a value of about 190 counts $s^{-1}$. GX 339−4 faded from roughly 300 counts $s^{-1}$ to 270 counts $s^{-1}$ over the 4 hr observation and showed high amplitude variability on time scales of several minutes.

The data were tested for time variability using Fourier techniques. Coherent features were searched for by calculating power spectra for 2 hr segments of the time series at the full time resolution of the data. No allowance was made for secular frequency drifts. Incoherent features were searched for by calculating and then summing the power spectra of 104.8576 s blocks of the time series data degraded to a time resolution of

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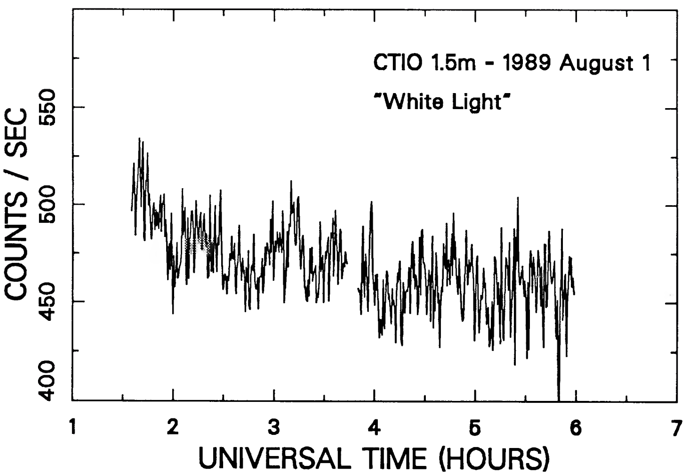


FIG. 1.—The white light count rate for GX 339−4 obtained on 1989 August 1 (UT) using the 1.5 m telescope of the Cerro Tololo Inter-American Observatory. The data are binned in time intervals of 32.768 s. The sky contribution of roughly 190 counts $s^{-1}$ has not been subtracted.

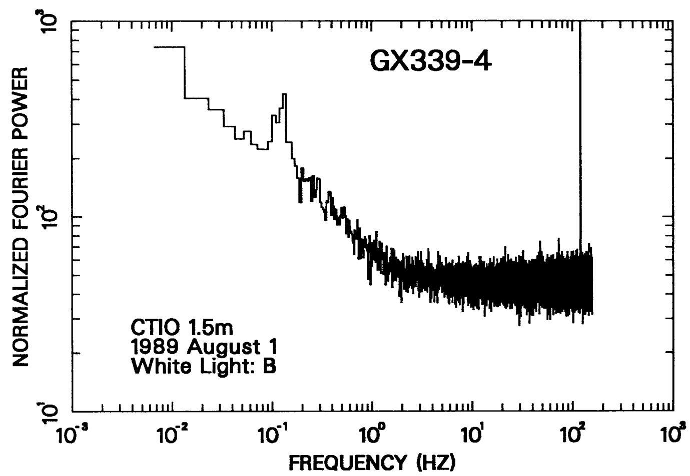


FIG. 3.—The power spectrum calculated using the second 2 hr of the time series data presented in Fig. 1. The time resolution is 3.2 ms. The QPO feature is seen at 0.125 Hz. The feature seen at 120 Hz and its aliases are spurious.

3.2 ms. The individual power spectra were normalized to make the average power level at high frequencies unity.

No coherent features are detected, except for those at 120 Hz and aliases and harmonics of 120 Hz, at 90% confidence rms upper limits of 0.6%. In particular, no evidence is found for the 885 Hz feature reported in Imamura, Steiman-Cameron, and Middleditch (1987) or the 5.25 mHz feature reported in Steiman-Cameron *et al.* (1990). The 120 Hz feature may have been caused by stray light entering the photometer or by any source of electronic interference on the line frequency or harmonics of the line frequency.

An incoherent feature with a period of roughly 8 s is detected in the data for GX 339−4. Power spectra which demonstrate the 8 s QPOs are presented in Figures 2, 3, and 4. Summed power spectra for the first and second halves of the time series are presented in Figures 2 and 3. The low-frequency ends of power spectra calculated in a similar manner, but for 30 minute segments of the time series, are presented in Figure 4. In Figure 4 the time increases from top-to-bottom and the power spectra are scaled arbitrarily to aid in their presentation. The frequency of the QPO does not change when power spectra are calculated using different calculational time bin sizes. The 8 s QPOs are thus not caused by the aliasing of the 120 Hz feature and the sampling rate.

Approximate parameters for the 8 s QPOs are determined by fitting the function,

$$p(f) = a + b \exp(-\gamma f) + c/[(f - f_0)^2 + (\Gamma/2)^2], \quad (1)$$

to the power spectra over the frequency range 0.05 to 5 Hz (see van der Klis *et al.* 1985). The free parameters in the fitting

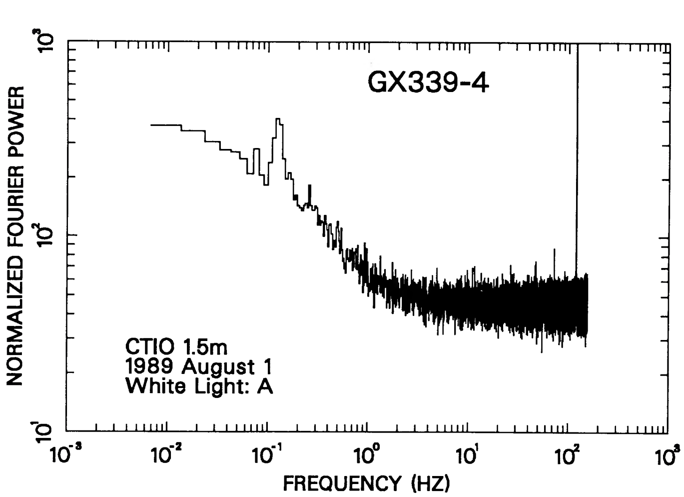


FIG. 2.—The power spectrum calculated using the first 2 hr of the time series data presented in Fig. 1. The time resolution is 3.2 ms. The QPO feature is seen at 0.127 Hz. The feature seen at 120 Hz and its aliases are spurious.

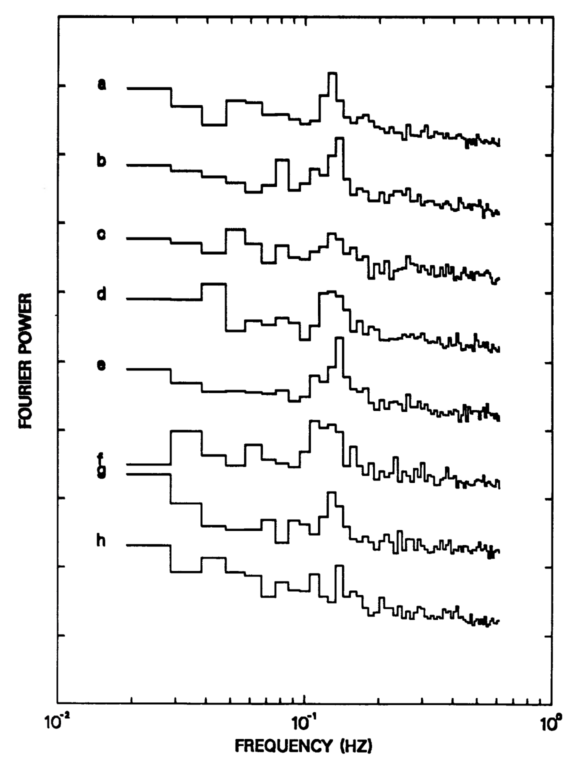


FIG. 4.—The power spectra calculated using roughly 30 minute blocks of the time series data presented in Fig. 1. The Fourier powers are plotted on a linear scale. The time resolution is 3.2 ms. The time increases from top-to-bottom in the figure and the power spectra have been offset to aid in their presentation. The letters labeling each power spectrum are defined in Table 1.

function are the constant power level $a$, the amplitude $b$ and decay constant $\gamma$ of the exponential, and the amplitude $c$, frequency centroid $f_0$, and width $\Gamma$ of the Lorentzian profile. We sum $N_{ps}$ power spectra. The fits to the power spectra have reduced $\chi^2$'s of 0.74 to 1.08 for 511 degrees of freedom. The goodness of fit improves as the frequency range is increased, suggesting that the QPO feature at 8 s is not well-fitted. The formal uncertainty for the parameters are given by the covariance matrix of the $\chi^2$ fit. The results of our analysis are given in Table 1. The fitting routine was unable to locate 8 s QPOs in the final 30 minute interval and so no fitted parameters are given for it in Table 1. The pulsed amplitudes in Table 1 are rms pulsed amplitudes found by integrating the Lorentzian profiles over the frequency range $f = (f_0 - 2\Gamma)$ to $(f_0 + 2\Gamma)$ and assuming that the background count rate was constant at 190 counts $s^{-1}$. Using a Gaussian instead of a Lorentzian profile in the fitting function leads to roughly the same goodness of fit. They yield the same centroid frequencies but find somewhat lower rms pulsed amplitudes than do the Lorentzian fits, 2.5%–3.7% versus 3.8%–6.3%. We conclude that the centroid frequencies are roughly accurate to around the formal errors of the $\chi^2$ fits, $\pm 0.001$ Hz, but that the pulsed amplitudes are accurate only to within the systematic fitting error of $\sim 2\%$.

The 8 s QPOs do not exhibit a significant correlation between centroid frequency and the optical intensity of GX 339−4. There is a suggestion that the pulsed amplitudes of the QPOs may increase as the optical emission of GX 339−4 decreases (see Table 1).

## III. DISCUSSION

GX 339−4 exists in distinct on and off X-ray states, each lasting on the order of months. In the on-state, the X-ray luminosity is roughly $10^{37}$–$10^{38}$ ergs $s^{-1}$ (Dolan *et al.* 1987 and references found therein) while in the off-state, the X-ray luminosity has dropped to as low as $5 \times 10^{34}$ ergs $s^{-1}$ (Ilovaisky *et al.* 1986). In addition, GX 339−4 also shows two distinct modes of behavior in the X-ray on-state. It possesses a soft X-ray state where its spectrum is dominated by a component which resembles a 1 keV Comptonized blackbody, and it possesses a hard X-ray state where its spectrum is adequately fitted by a photon number power law of index 1.6. Rapid variability has been seen in GX 339−4 only in its hard and off X-ray states. The optical luminosity of GX 339−4 varies depending on the X-ray state. It ranges from $m_v = 17.7$ to $m_v = 20.2$ during the X-ray off-state, from $m_v = 15.4$ to 17.5 during the X-ray hard-state, and from $m_v = 16.5$ to 18 during the X-ray soft-state (e.g., see Motch, Ilovaisky, and Chevalier 1985). Because the optical luminosity, in general, is not a single-valued function of the X-ray state, the X-ray state of GX 339−4 cannot be unambiguously determined without the aid of X-ray observations. No such observations were made during our run. GX 339−4 was $m_v = 17.7$ during our observations and could thus have been in any of the X-ray states. We suggest that GX 339−4 was in an X-ray off-state based on similarities to results of Motch, Ilovaisky, and Chevalier, as we discuss below.

Motch, Ilovaisky, and Chevalier (1985) reported the detection of 7 s QPOs in data taken during May of 1982. GX 339−4 was determined to be in an X-ray off-state at this time, based on simultaneous X-ray observations, and had a visual magnitude of 17.7. Our measured visual magnitude of 17.7 and the 8 s time scale for the QPOs suggest that we also observed GX 339−4 when it was in an off-state.

We have over 20 additional hours of high-speed optical photometry of GX 339−4 obtained between the years 1985–1988 which do not show 8 s QPOs (Steiman-Cameron *et al.* 1990). GX 339−4 ranged in visual magnitude from 16.5 to >20 during these times. No simultaneous X-ray observations are available for these data either and so, the presumption that the 8 s QPOs only appear when GX 339−4 is $m_v = 17.7$ and in an X-ray off-state is neither corroborated nor contradicted by our earlier data. The weaker statement that GX 339−4 is capable of generating optical QPOs even when the accretion ceases or is at a low level is correct, however.

The visual magnitude estimate of 17.7 during the X-ray off state observations of Motch, Ilovaisky, and Chevalier (1985) corresponds to an optical brightness roughly comparable to the X-ray luminosity. This, in itself, is unusual for a low-mass X-ray binary system where the typical optical to X-ray luminosity ratios are usually $\ll 1$. Further, because the visual magnitude of GX 339−4 has fallen to as low as 20.2 during an off-state, the measured $m_v$ of 17.7 must either be a short-lived transitional state or indicate that there are stable microluminosity states within the overall on/off X-ray behavior.

GX 339−4 has also shown large amplitude 20 s optical and X-ray QPOs (Motch, Ilovaisky, and Chevalier 1982; Motch *et al.* 1983). The 20 s optical QPOs had a full amplitude of 30%–40% and appeared when GX 339−4 was in the hard

TABLE 1

QPO FIT PARAMETERS

| PARAMETER | DATA INTERVAL a | b | c | d | e | f | g | h |
|---|---|---|---|---|---|---|---|---|
| Time (UT) ....... | 01:35:00 –02:06:27 | 02:06:27 –02:37:55 | 02:37:55 –03:09:22 | 03:09:22 –03:40:50 | 03:50:00 –04:21:27 | 04:21:27 –04:52:55 | 04:52:55 –05:24:22 | 05:24:22 –05:55:50 |
| Counts ........... | 928,357 | 902,774 | 888,853 | 895,147 | 861,905 | 874,593 | 860,313 | 863,973 |
| Amplitude (%) ... | $3.8 \pm 0.4$ | $4.0 \pm 0.7$ | $3.6 \pm 0.7$ | $4.9 \pm 0.7$ | $5.0 \pm 0.5$ | $6.3 \pm 0.7$ | $4.3 \pm 0.6$ | ... |
| a .................. | $19.3 \pm 0.3$ | $19.8 \pm 0.3$ | $19.4 \pm 0.3$ | $19.5 \pm 0.4$ | $19.4 \pm 0.3$ | $18.8 \pm 0.4$ | $19.2 \pm 0.3$ | ... |
| b .................. | $82.4 \pm 4.1$ | $87.3 \pm 4.1$ | $73.1 \pm 4.1$ | $62.8 \pm 3.9$ | $72.0 \pm 3.5$ | $58.9 \pm 4.2$ | $65.7 \pm 3.5$ | ... |
| $\gamma$ ($Hz^{-1}$) ......... | $3.20 \pm 0.17$ | $3.28 \pm 0.17$ | $2.73 \pm 0.16$ | $2.44 \pm 0.16$ | $2.65 \pm 0.15$ | $2.22 \pm 0.16$ | $2.59 \pm 0.16$ | ... |
| $c$ ($Hz^2$) ........... | $7.79 \times 10^{-3}$ | $6.06 \times 10^{-3}$ | $9.33 \times 10^{-3}$ | $2.04 \times 10^{-2}$ | $1.33 \times 10^{-2}$ | $4.34 \times 10^{-2}$ | $8.70 \times 10^{-3}$ | ... |
| | $\pm 1.4 \times 10^{-3}$ | $\pm 1.5 \times 10^{-3}$ | $\pm 3.1 \times 10^{-3}$ | $\pm 3.9 \times 10^{-3}$ | $\pm 1.9 \times 10^{-3}$ | $\pm 7.1 \times 10^{-3}$ | $\pm 1.8 \times 10^{-3}$ | ... |
| $f_0$ (Hz) ........... | $0.124 \pm 0.001$ | $0.130 \pm 0.001$ | $0.127 \pm 0.001$ | $0.127 \pm 0.001$ | $0.132 \pm 0.001$ | $0.118 \pm 0.001$ | $0.126 \pm 0.001$ | ... |
| $\Gamma$ (Hz) ........... | $1.66 \times 10^{-2}$ | $1.27 \times 10^{-2}$ | $2.42 \times 10^{-2}$ | $2.84 \times 10^{-2}$ | $1.99 \times 10^{-2}$ | $3.89 \times 10^{-2}$ | $1.79 \times 10^{-2}$ | ... |
| | $\pm 1.6 \times 10^{-3}$ | $\pm 2.4 \times 10^{-3}$ | $\pm 4.6 \times 10^{-3}$ | $\pm 3.0 \times 10^{-3}$ | $\pm 1.6 \times 10^{-3}$ | $\pm 3.4 \times 10^{-3}$ | $\pm 2.3 \times 10^{-3}$ | ... |
| $N_{ps}$ .............. | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |

X-ray state and optically much brighter, $m_v = 15.4$. The optical QPO amplitude is thus larger and the centroid frequency smaller when the source luminosity is high (Motch, Ilovaisky, and Chevalier 1985).

A range of models for the GX 339−4 optical QPOs is possible. Here, we assume that the 8 s and 20 s QPOs are produced by the same physical mechanism and so, consider models which try to explain the frequency-luminosity behavior implied by the observations. All of the proposed models have difficulty with the large optical to X-ray luminosities.

Consider disk accretion onto magnetic neutron stars. If the QPOs are produced directly at the magnetopause of the neutron star, then the frequency-luminosity behavior is difficult to understand. In this scenario, when the system luminosity increases, the accretion rate goes up and the inner edge of the disk moves closer to the star and the frequency of the QPOs increases ruling out models of this type. The inverse frequency-luminosity relation can be understood, however, if one considers the so-called beat-frequency modulated accretion (BFMA) model suggested for the X-ray QPOs of the neutron star low-mass X-ray binaries (Alpar and Shaham 1985). The BFMA model postulates that the accretion onto the neutron star is modulated on the beat period between the rotation of the neutron star and plasma in Keplerian motion at the magnetopause of the neutron star. If the neutron star rotates more quickly than the inner edge of the accretion disk, then the beat frequency will decrease as the luminosity goes up and the inner edge of the disk moves closer to the star. The feature is incoherent because the orbiting plasma spans a range in radius and thus spans a range of Keplerian frequencies. The BFMA model thus leads naturally to the observed frequency-luminosity behavior. However, it implies that the rotation period of the neutron star is $\sim 7$–8 s. This follows from the fact that the QPO period in the off-state is only a factor of 2.5 smaller than in the high-state, while the system luminosity drops by several orders of magnitude. This can only be understood if the rotation frequency of the neutron star $f_* \sim 0.12$ Hz since the Keplerian frequency at the inner edge of the disk is expected to be $\ll f_*$ during the off-state. A coherent 7–8 s periodicity has never been observed in the optical or X-ray emission from GX 339−4 casting doubt on the BFMA model.

Consider disk accretion onto a compact object when the QPOs are due to disk oscillations and the sole function of the compact object is to supply the gravitational potential well into which the accreting material flows. In this case, the compact object may be a neutron star or a black hole. In general, low-order disk oscillation modes have frequencies proportional to the local Keplerian frequencies. Particular frequencies will be singled out, however, because the region where the bulk of the optical emission is produced depends upon the local disk temperature (e.g., see van Horn, Wesemael, and Winget 1978). So, if the optical emission region moves outward due to the increase of local disk temperatures when the system luminosity increases, the QPO frequency will decrease. The inverse frequency-luminosity relation is thus naturally produced.

Motch, Ilovaisky, and Chevalier (1982) have also proposed that 20 s optical and X-ray QPOs may arise during disk accretion onto a black hole rather than a neutron star. By analogy with the Cyg X-1 system, they suggest that the inner region of the accretion disk is thermally unstable and dense plasma blobs form. They then suggest that the optical emission is due to cyclotron emission from these blobs which are hot, $T_e = 10^9$ K, and which they postulate are weakly magnetic, $B = 10^5$–$10^6$ G. The size of the unstable region of the disk is thought to be several $10^9$ cm and the QPO time scale is determined by the flow time of the blobs across this region. The large optical to X-ray luminosity ratio may be produced by an appropriate choice of parameters (however, see Apparao 1984 for a critical discussion of the model). The frequency-luminosity relationship would arise if the luminosity approaches Eddington in the bright state. In this event, the flow time across the unstable region would increase as the system luminosity increased due to radiation pressure weakening the gravitational attraction and to the likely increase in the size of the unstable region. An increase in the luminosity from $\ll L_{\rm Edd}$ in the low state to $\sim 0.8$ $L_{\rm Edd}$ in the bright state would be sufficient to change the QPO period from 8 s to 20 s.

Because none of the above models is compelling, we consider whether the QPOs may arise in the companion star. The optical luminosity of the GX 339−4 system has been measured at $m_v = 20.2$ during the off X-ray state (Remillard and McClintock 1987). This is presumably due to the companion star and is an order of magnitude less than our observed optical luminosity. Furthermore, the pulsed amplitude of the 8 s QPOs is between 20 and 21 magnitudes which is on the order of the magnitude of the companion star and so a large fraction of the luminosity of the companion star would have to be involved in the 8 s QPOs. If the 20 s QPOs are also considered, these constraints become even more restrictive. It is not likely for the QPOs to arise in the companion star.

## IV. SUMMARY

We report the detection of 8 s QPOs in the optical emission from GX 339−4. The QPOs had an rms pulsed amplitude of 4%–6% and a width of 0.02 to 0.04 Hz. GX 339−4 had a visual magnitude of 17.7 during our observations, and we suggest that it was in its X-ray off-state based on similarities to the 7 s optical QPOs reported by Motch, Ilovaisky, and Chevalier (1985). However, because there were no simultaneous X-ray observations the X-ray state during our observations is unknown. If our conjecture is correct, then the optical luminosity was comparable to the X-ray luminosity during our observations and severe restrictions are placed on models for the observed optical QPOs. The mechanism responsible for the optical QPOs in GX 339−4 is most likely associated with the compact object and not with the companion star. In particular, accretion disk models are consistent with the current data. The question of whether a neutron star or black hole model is preferred is not answered, however. Further optical and X-ray observations of GX 339−4 during times of QPO activity may be able to differentiate between the proposed models and may thus help to determine the nature of the compact object in GX 339−4.

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