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OBSERVATIONS OF GRO J0422+32. III. A LOW-INCLINATION BLACK HOLE X-RAY NOVA

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ABSTRACT

We present the results of our campaign of photometry of the X-ray nova GRO J0422+32 in quiescence, the purpose of which was to confirm the proposed orbital period of ~5.1 hr, and to search for the ellipsoidal variations which are a prerequisite for the mass determination of the primary. We find evidence for a weak ellipsoidal modulation corresponding to an orbital period of 5.1 hr, with a semi-amplitude of ~0.03 mag—the lowest known of any quiescent X-ray nova. With the assumption that the *I*-band contamination by the accretion disk is no greater than that observed in other quiescent X-ray novae, we estimate that the orbital inclination must be $\leq 45°$. Furthermore, a ZAMS secondary implies an upper limit on the distance of ~2.2 kpc, and a quiescent accretion rate ~3% that observed in A0620−00. The inclination estimate implies a mass of the compact object $\geq 3.4\ M_\odot$. *ROSAT* observations constrain the quiescent X-ray luminosity to be less than 2×10^{32} ergs s^{-1} (for a distance of 2 kpc). We speculate that the low quiescent accretion rate through the disk, inferred from the optical observations, may well be related to the large outburst amplitude of GRO J0422+32.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (GRO J0422+32) — X-rays: stars

1. INTRODUCTION

Studies of quiescent X-ray novae have proved to be an especially efficient means of finding stellar mass black holes (e.g., van Paradijs & McClintock 1995). This is primarily because the relatively faint disk allows detailed study of the secondary in a way which is usually impossible for the persistently bright low-mass X-ray binaries (for all except those with the longest orbital periods—e.g., Cyg X-2), In particular, the radial velocity amplitude of the secondary, combined with the depth of the ellipsoidal modulation (due to the tidal distortion of the secondary), allows one to solve for both the inclination and the mass ratio of the binary (e.g., McClintock & Remillard 1986; Shahbaz et al. 1994).

Here we present the results of our optical photometry of the X-ray nova GRO J0422+32, obtained once the system had finally reached quiescence after an unusually protracted outburst and decay (e.g., Callanan et al. 1995). The purpose of these observations was to confirm the proposed orbital period of ~5.1 hr (e.g., Chevalier & Ilovaisky 1994), and to search for the ellipsoidal variations which are a prerequisite for the mass determination of the primary. Furthermore, Filippenko, Matheson, & Ho (1995) have recently determined the mass function to be $1.2 \pm 0.04\ M_\odot$: this is one of the lowest measured values of any X-ray nova and leaves open the possibility that the compact object may be a neutron star. For this reason any additional photometric constraints on the mass ratio and inclination are particularly valuable.

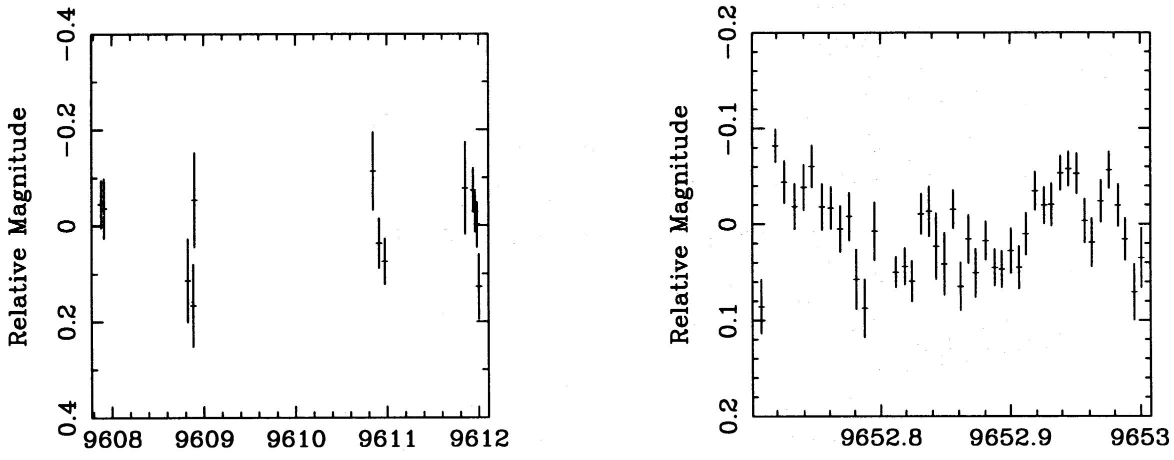
In addition, we discuss constraints on the quiescent accretion rate determined from optical and X-ray observations.

2. OBSERVATIONS

2.1. *Optical Photometry in Quiescence*

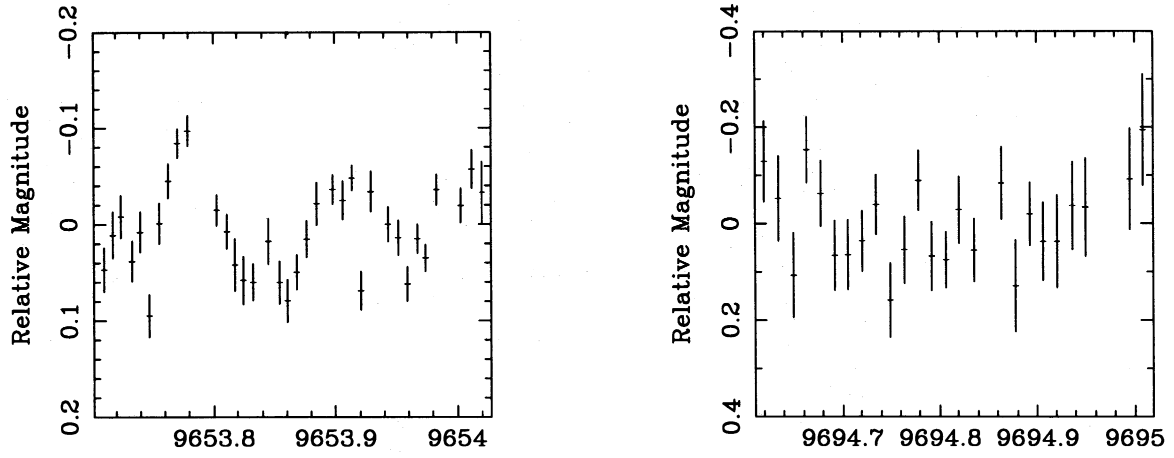
Our long-term monitoring observations of GRO J0422+32 revealed that by 1994 August the decay from outburst had finally leveled off, indicating that quiescence had been reached at $R \sim 21$, some 2 yr after the initial outburst (Callanan et al. 1995; Garcia et al. 1995). Our new photometry was obtained using the Whipple Observatory 48″ (1.2 m) telescope during 1994 September 11–15, December 8, and 1995 January 2, 6, 8, and 9 also using the Michigan-Dartmouth-MIT Observatory 2.4 m telescope during 1994 December 28–29 (see Fig. 1). Conditions during these runs were typically characterized by seeing of ~1″.5–2″, with occasional cloud. The data have been augmented by the photometry of Orosz & Bailyn (1995). See Table 1 for a more detailed log of the observations. All the CCD images were reduced using IRAF, and DAOPHOT was used to perform profile fitting of GRO J0422+32 and nearby stars: these fits were then used to perform the relative photometry. The errors were determined from DAOPHOT and were checked for consistency using photometry of stars of similar magnitude to GRO J0422+32. The mean magnitude of GRO J0422+32 during our observations was $R = 21.0 \pm 0.1$, and $V = 22.3 \pm 0.2$.

Due to the faintness of the object and the variable conditions of several of the observations (particularly those made during 1994 December 29 and 1995 January), we first applied a filter to all our data, using only those for which the error in the relative photometry was less than 0.05 mag. These datapoints (179/292) were *I*-band measurements (with a small admixture of white-light measurements from



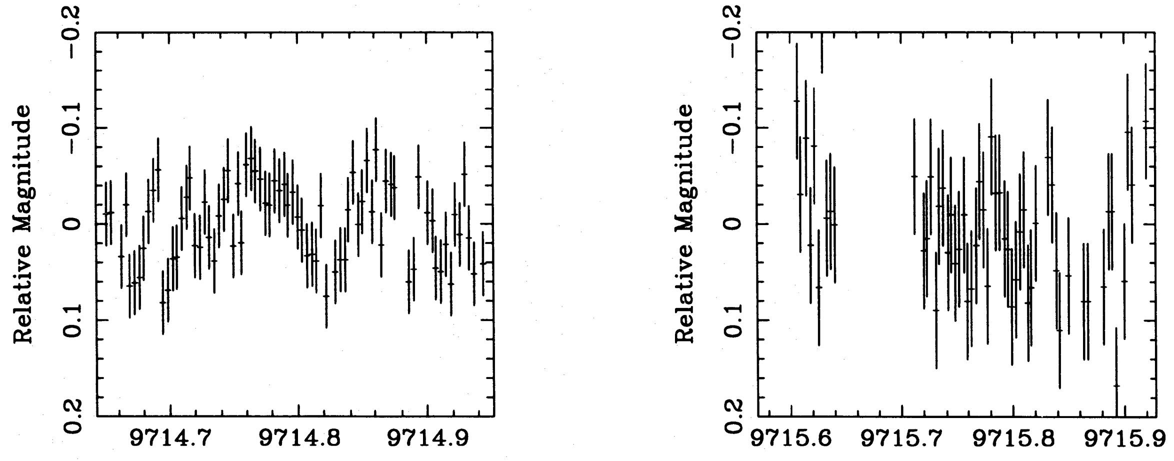
1994 September 11–15 (R band data)

1994 October 27 (I band data)



1994 October 28 (I band data)

1994 December 8 (R band data)

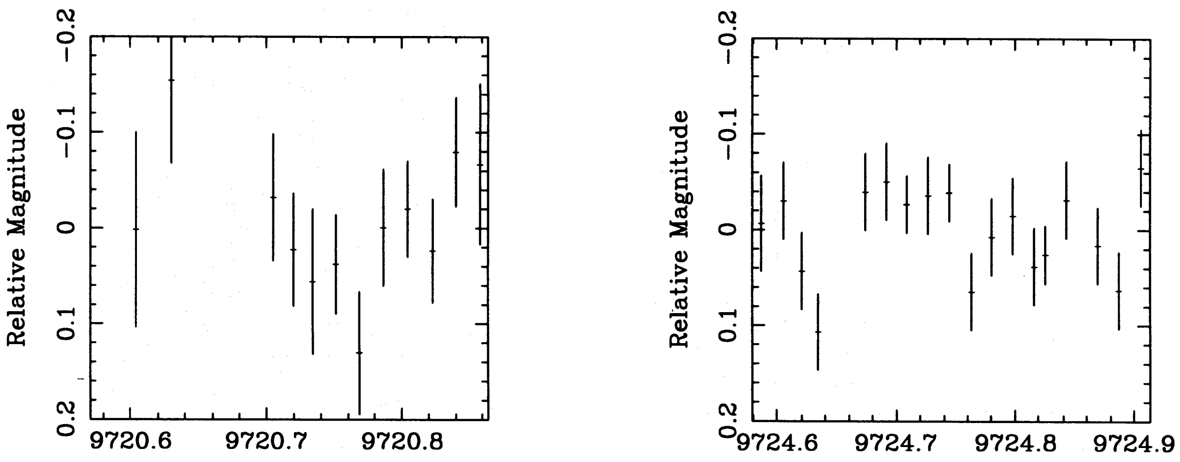


1994 December 28 (I band data)

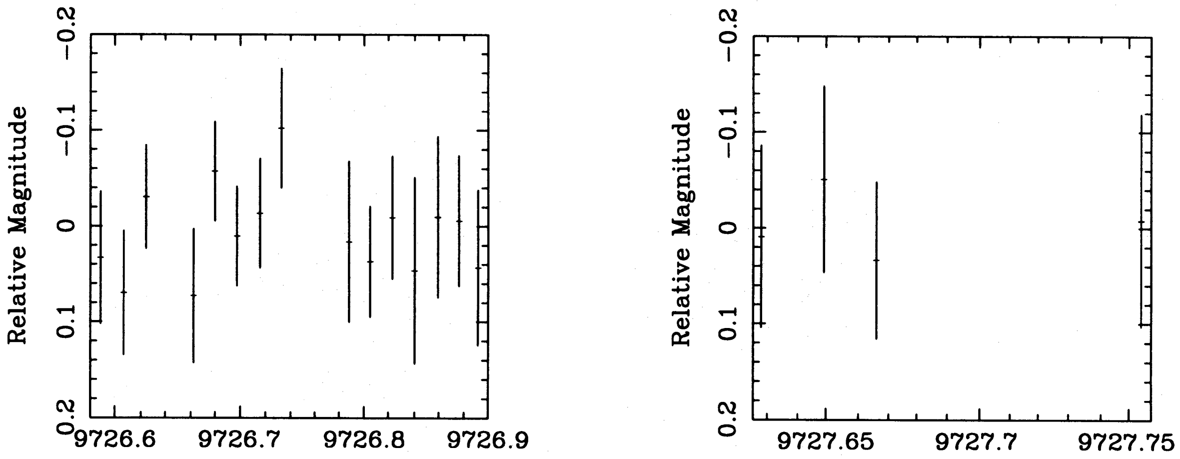
1994 December 29 (I band data)

FIG. 1.—The 1994 September, October, December and 1995 January light curves. Those data sets spanning an entire night were detrended by subtracting a second-order polynomial fit. The *x*-axis is in units of HJD-2,440,000.

1995 January 6). We show in Figure 2 the Fourier transform of this data set. Considerable power is present at frequencies of ∼9.4 cycles per day, and the 1 day alias at 8.4 cycles per day. The power at 9.4 cycles per day is likely to be due to ellipsoidal variability of the secondary for an assumed orbital period of ∼5.1 hr, although it is clear that our data do not allow us to independently determine a unique orbital period. Hence we considered only those periods which lie within $\pm 3\ \sigma$ of the proposed Chevalier & Ilovaisky period (0.212265 ± 0.00007 days). We show in Figure 3 the plot of χ^2 versus period for folds in this period range (where χ^2 is calculated against the hypothesis of a steady flux): there are



1995 January 2 (white light data) 1995 January 6 (white light data)



1995 January 8 (I band data) 1995 January 9 (I band data)

FIG. 1.—*Continued*

two peaks within ~3 σ of the proposed period, with corresponding orbital periods of 0.212036 and 0.212412 ± 0.00006 days (the error is based on the full-width half-maximum of the χ^2 peak). The corresponding time of minimum is T_0(HJD) = 2,449,652.569 (valid for both periods).

A clear modulation at a 5.1 hr period was also observed during the 1993 December minioutburst (Callanan et al. 1995). The phasing of this modulation is consistent with the 0.212036 day period to within 1% of phase (and inconsistent with the second period). Hence we adopt this ephemeris for the rest of the paper, recognizing that more observations are required to confirm it.

2.2. *ROSAT Observations*

The X-ray flux of a quiescent X-ray nova is commonly used as a sensitive indicator of the accretion rate onto the compact object (e.g., McClintock, Horne, & Remillard 1995; hereafter MHR). Although GRO J0422+32 was scanned by the *ROSAT* PSPC, some 6 months before outburst during the *ROSAT* All-Sky-Survey (see, e.g., Trümper 1983 and Pfeffermann et al. 1987 for a description of the satellite and the instrumentation), it was not detected. We place an upper limit of 0.0082 counts s^{-1} (2 σ) on the PSPC count rate: we plot in Figure 4 the upper limit to the unabsorbed X-ray flux (0.01–2 keV) for a variety of blackbody

TABLE 1

LOG OF THE QUIESCENT STATE OPTICAL OBSERVATIONS

Date (UT)	Telescope	Exposure Time (s)	Filter	Number of Exposures
1994 Sep 11–15	48 inch	1200	*R*	13
1994 Oct 27–28	KPNO 2.1 m	600	*I*	79
1994 Dec 8	48 inch	1200	*R*	25
1994 Dec 28–29......	MDM 2.4 m	300	*I*	135
1995 Jan 2, 6.........	48 inch	1600	Whitelight	30
1995 Jan 8–9.........	48 inch	1600	*I*	19

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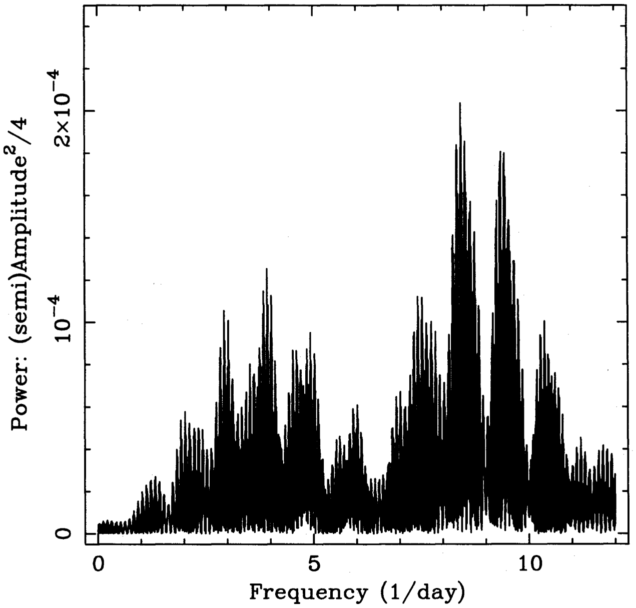

FIG. 2.—The Fourier transform of the data with relative photometry errors less than 0.05 mag.

temperatures and line-of-sight columns. We also plot the column calculated from our extinction measurement of $A_v = 1.2 \pm 0.1$ (Callanan et al. 1995 and Savage & Mathis 1979), and our estimate of the range of likely temperatures of the quiescent X-ray emission of GRO J0422+32 (Verbunt et al. 1994; MHR). For a spectrum similar to that of A0620−00 in quiescence ($kT = 0.16$ keV; MHR), and a column of 2×10^{21} cm^{-2} (for $A_v = 1.2$), the *ROSAT* upper limit corresponds to a quiescent X-ray luminosity (L_X) of $\leq 2 \times 10^{32}$ ergs s^{-1}, for a distance of a 2 kpc (see Fig. 4 and § 3). The accretion rate onto the compact object is then $\leq 3.5 \times 10^{-14}$ $M_\odot$ yr^{-1} (assuming an efficiency of 10%, and zero advected accretion: see, for example, Narayan, Yi, & Mahadevan 1995 for an alternative scenario).

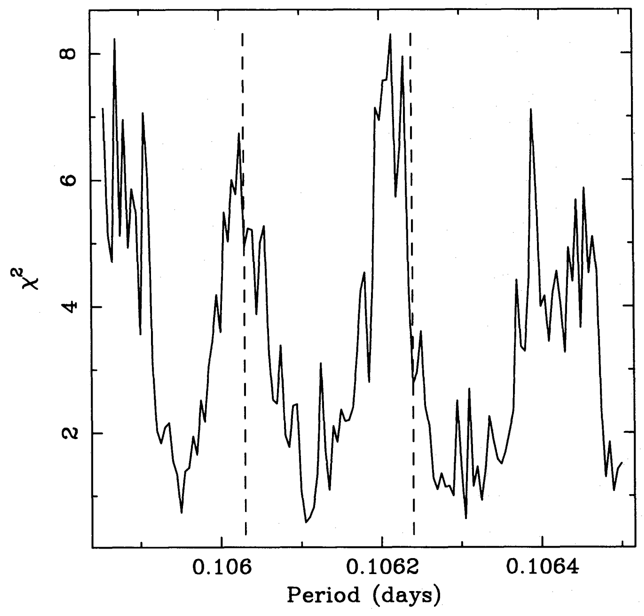

FIG. 3.—χ^2 vs. orbital period for the filtered data set. Those periods consistent to within $\pm 3\,\sigma$ of the Chevalier & Ilovaisky period lie within the vertical dashed lines.

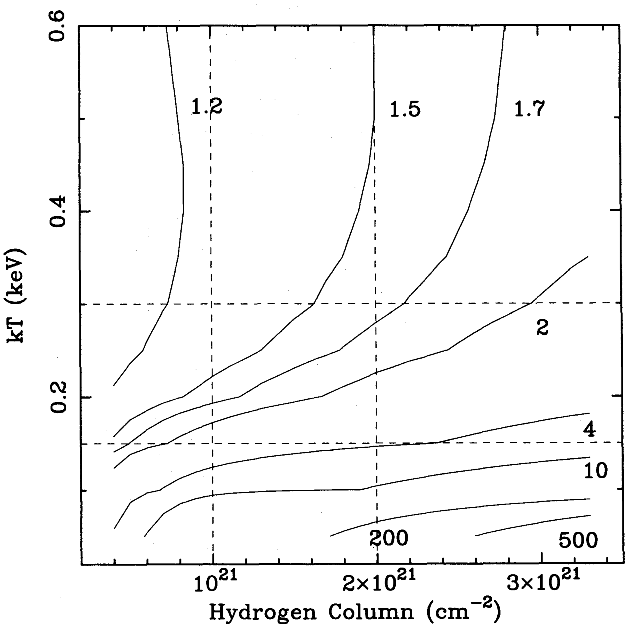

FIG. 4.—The upper limit on the quiescent X-ray emission from the *ROSAT* All-Sky-Survey data, as a function of line-of-sight column and blackbody temperature. Effective temperatures measured for other quiescent X-ray novae fall in the region delineated on the *y*-axis; the range of interstellar column consistent with the optical extinction measurements is indicated on the *x*-axis. Each contour is plotted in units of 10^{-13} ergs cm^{-2} s^{-1}.

3. DISCUSSION

3.1. *Limits on the Binary Inclination and Quiescent Accretion Rate*

In Figure 5 we show the optical data set folded on half the suggested orbital period (to maximize the signal-to-noise of the data), using the ephemeris discussed in § 2.1: the semiamplitude of the ellipsoidal modulation is low, only ~0.03 mag. How large do we expect it to be? Assuming the

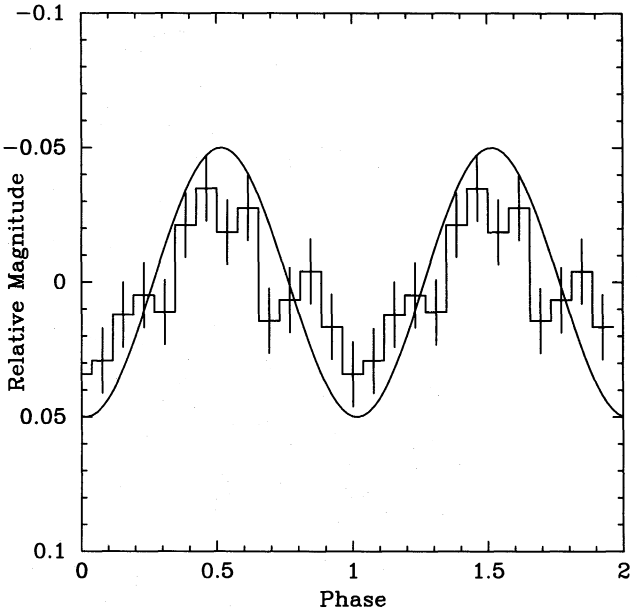

FIG. 5.—Our (filtered) optical data set folded on half the orbital period, using the ephemeris discussed in the text. The error bars have been assigned to each phase bin so that the reduced χ^2 of a sine wave fit to these data is 1. The sine wave shown, which is inconsistent with the data at the 99% confidence level, corresponds to $i = 45°$ (see text).

secondary to be no more massive than a zero age main-sequence star in a 5.1 hr binary (e.g., Bhattacharaya & van den Heuvel 1991), and taking the primary to be at least as massive as a neutron star, we find the mass ratio $q \geq 3$ (for a 0.5 $M_\odot$ secondary: Patterson 1984). The modeling of Bochkarev, Karitskaya, & Shakura (1979) then yields an ellipsoidal (full) amplitude of ~0.3 mag for an inclination ≥70° and a Roche lobe filling secondary, consistent with that observed for other X-ray novae (e.g., McClintock & Remillard 1986; Callanan & Charles 1991), but much larger than observed here for GRO J0422+32.

Such a small semiamplitude must be due to either a low orbital inclination, and/or a dominant contribution from the accretion disk ($L_{\rm disk} \sim 4\ L_{\rm s}$). We believe that a dominant contribution from an *X-ray heated* disk (and/or secondary) is unlikely for the following reasons. Using Kepler's law and the formulae of Paczyński (1971), the effective temperature of an X-ray heated disk in this binary is $\leq 2400(\eta L_{\rm X}/2 \times 10^{32})^{1/4}(D/1.3\ R_\odot)^{-1/2}$ K, where η is the X-ray albedo, D is the outer radius of a Roche lobe filling disk derived from the orbital parameters of Filippenko et al. (1995), and we use the upper limit to the X-ray luminosity derived in § 2.2. The strong, double-peaked Hα profiles observed by these authors implies that the disk fills an appreciable fraction of its Roche lobe. Using the low-temperature model atmospheres of Allard (e.g., Allard & Hauschildt 1995) and taking $\eta = 0.5$, we estimate that ≪1% of the bolometric flux is generated in the V band at these temperatures. Hence we expect a maximum of $\sim 4 \times 10^{-15}$ ergs cm^{-2} s^{-1} to be generated in the V band from X-ray heating, and note that this limit is even more severe in the case of heating of the secondary (for which the effective temperature of the reprocessed emission is even smaller). However, the dereddened V band optical flux from this system in quiescence is $\sim 1.2 \times 10^{-14}$ ergs cm^{-2} s^{-1} (for $A_v = 1.2$). We conclude that an X-ray heated disk (or secondary) does not make a significant (>30%) contribution to the optical flux in quiescence.

To proceed further, we assume that the I-band contamination by the accretion disk in GRO J0422+32 (due now solely to viscous heating) is no more than the R band contamination of other quiescent X-ray novae—i.e., ≤20% (Marsh, Robinson, & Wood 1994; Casares et al 1993). Using the amplitude of a sine wave fit to the data, a limb-darkening coefficient of 0.6 (from Al-Naimiy 1978), and the ellipsoidal amplitudes of Bochkarev et al. (1979) for a Roche lobe filling secondary, the data formally reject an inclination ≥45° at greater than 99% confidence level, for an accretion disk contamination of 20%. In Figure 5 the corresponding sine wave (for $i = 45°$ is superposed. In this sense we conclude that the system is likely to be a low inclination one. We believe that our data set does not warrant more detailed modeling at this stage. Such an inclination constraint increases the lower limit on the mass of the compact object inferred from the mass function to 3.4 $M_\odot$, adding GRO J0422+32 to the list of black hole X-ray novae.

Furthermore, taking the relationship derived by Patterson (1984) between the absolute magnitude of the secondary and binary period (for CVs), we estimate M_v (secondary) ~10. Assuming a contamination from the accretion disk in the V band of ~50% (e.g., McClintock & Remillard 1986), we derive a distance of 2.2 kpc (again for $A_v = 1.2$). M_v (accretion disk) ~10 corresponds to an accretion rate in quiescence of $\sim 3 \times 10^{-12}\ M_\odot$ yr^{-1} (Tylenda 1981). Note that if the accretion disk contributes less than 50% to the optical flux (e.g., Casares et al. 1993), both our distance and accretion rate estimates are upper limits only. This accretion rate is ~3% that inferred through the outer part of the disk in A0620−00 (MHR). Such a low quiescent accretion rate may be related to the large outburst amplitude observed from GRO J0422+32 (e.g., Callanan et al. 1995; Garcia et al. 1995). In particular, Howell, Skzody, & Cannizzo (1995) have recently shown that those cataclysmic variables (CVs) exhibiting the most dramatic outburst behavior (e.g., with amplitudes ~6–10 mag) are also those likely to have very low ($\leq 4 \times 10^{-12}\ M_\odot$ yr^{-1}) accretion rates. The same mechanism may well be at work in the case of GRO J0422+32: furthermore, the low accretion disk viscosity needed to produce these anomalously luminous outbursts would offer a natural explanation for the protracted nature of the main outburst of GRO J0422+32 (e.g., Callanan et al. 1995). These hypothesis will be tested as progressively more X-ray novae are studied in quiescence.

However, we emphasize in the case of GRO J0422+32 that our conclusions are valid only if the secondary can be approximated as a ZAMS star, and if its contribution to the total optical flux is comparable to that in other quiescent X-ray novae. Unfortunately the faintness of GRO J0422+32 will make these assumptions difficult to prove. The large discrepancy between the accretion rate through the outer part of the disk ($3 \times 10^{-12}\ M_\odot$ yr^{-1}, inferred optically), and that onto the compact object ($< 3.5 \times 10^{-14}\ M_\odot$ yr^{-1}, estimated from the *ROSAT* upper limit to $L_{\rm X}$) may be reconciled if the accretion disk is considerably fainter than assumed here (i.e., much fainter than is typical of quiescent X-ray novae). Alternatively, it may imply that only a small fraction (<1%) of the accreted energy is liberated via X-rays, as has already been proposed for A0620−00 in quiescence (MRH). Note that the recent GRO J0422+32 spectra of Filippenko et al. (1995), which appear to show some infilling of the secondary's absorption lines by an additional continuum source, are more consistent with the latter interpretation.

4. CONCLUSIONS

We find evidence for a weak ellipsoidal modulation at a period of 5.1 hr in the quiescent light curve of GRO J0422+32. The semiamplitude of the modulation, ~0.03 mag, is the lowest known of any quiescent X-ray nova. Assuming the secondary is no more massive than a ZAMS star, and that it dominates the optical emission from the system, we estimate the inclination to be ≤45 degrees. The quiescent accretion rate through the outer disk is $\sim 3 \times 10^{-12}\ M_\odot$ yr^{-1}, only ~3% that observed from A0620−00, which may be related to the peculiar outburst properties of GRO J0422+32. However, these estimates assume that the V- and I-band contamination by the accretion disk in GRO J0422+32 is no worse than that observed on other quiescent X-ray novae: this must be confirmed by future spectroscopic observations.

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