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THE MASS OF THE PROBABLE BLACK HOLE IN THE X-RAY NOVA GRO J0422+32[1]

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ABSTRACT

A series of 21 moderate-resolution (~2.4 Å) spectra of the now quiescent Galactic X-ray nova GRO J0422+32, obtained in 1994 November and 1995 January with the W. M. Keck 10 m telescope, is used to derive the physical parameters of the binary system. The Hα emission-line profile exhibits large variations in consecutive half-hour exposures taken in 1994 November, but smaller variations in 1995 January. Cross-correlation of the 6000–6500 Å spectral region with that of late-type dwarf stars yields reliable absorption-line radial velocities for the secondary star. The orbital period is found to be $0^{\rm d}.21159 \pm 0^{\rm d}.00057$, with a semi-amplitude of 380.6 ± 6.5 km s^{-1}; the implied mass function is 1.21 ± 0.06 $M_\odot$. Inspection of the averaged spectrum of GRO J0422+32 in the rest frame of the secondary star suggests that the secondary is an M2 V star, but the accretion disk contributes 30%–60% of the light at ~6300 Å.

Fits to the wings of the strong, double-peaked Hα emission line yield approximate radial velocities for the compact primary; the velocity curve has a semi-amplitude of 41.6 ± 3.2 km s^{-1}, but with a phase offset by 253° (rather than 180°) from that of the secondary star. The offset, which is similar to that of several other X-ray novae and many dwarf novae, may be indicative of geometric distortions or additional emission components on the accretion disk; hence, the observed semi-amplitude does not necessarily reflect the true motion of the compact primary. Under the assumption that it *does*, however, we find $q = 0.1093 \pm 0.0086$, the mass ratio of the secondary to the primary.

If the secondary star is a normal M2 dwarf ($M = 0.39 \pm 0.02$ $M_\odot$), as suggested by its spectrum and (independently) by the requirement that it fill its Roche lobe, the mass of the primary is 3.57 ± 0.34 $M_\odot$, somewhat higher than the theoretical upper limit (~3.2 $M_\odot$) for a slowly rotating neutron star with an extremely stiff equation of state, and considerably above the measured masses of neutron stars. We conclude that the compact object is probably a black hole, as suggested by its hard X-ray spectrum during outburst. The derived inclination angle of the system ($48 \pm 3°$) is consistent with the apparent absence of eclipses of the accretion disk.

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

1. INTRODUCTION

On 1992 August 5 UT, the *Compton Gamma Ray Observatory* (*CGRO*) detected a bright, transient, hard X-ray source designated GRO J0422+32 (Paciesas et al. 1992). By August 8 the flux in the 20–300 keV band had reached ~3 Crab. Significant flux could be seen to at least 600 keV, and there was strong variability on all timescales (Harmon et al. 1992; Cameron et al. 1992; Sunyaev et al. 1992). Preliminary analysis showed the spectrum to be similar to that of the black hole candidate Cygnus X-1, with a hard power-law tail. A "new" star of peak magnitude $V \approx 13$ was identified optically at the position of GRO J0422+32 (Castro-Tirado et al. 1992; Shakhovskoj 1992); no object down to $R \approx 20$ mag is visible on the Palomar Observatory Sky Survey plates (Castro-Tirado et al. 1993; Shrader et al. 1994). Periodicities of ~2.5, 5, 10, and 16 hr in the optical brightness were found by a number of observers (e.g., Harlaftis et al. 1994; Kato, Mineshige, & Hirata 1995; Callanan et al. 1995; Chevalier & Ilovaisky 1995; Martín et al. 1995), but it was not known with certainty whether any of these correspond to the orbital period. Optical and ultraviolet spectra of the object (e.g., Shrader et al. 1994) showed it to be typical of other low-mass X-ray binaries (Bradt & McClintock 1983), and its distance was estimated to be ~2.4 kpc.

The specific properties of GRO J0422+32 (also designated Nova Per 1992 and V518 Per), especially its hard X-ray tail, most closely resemble those of the subset of X-ray transients (or "X-ray novae") in which a late-type (K or M) secondary orbits a black hole rather than a neutron star; see Cowley (1992), White (1994), Tanaka & Lewin (1995), and van Paradijs & McClintock (1995) for reviews. The three best examples are A0620−00 (V616 Mon), GS 1124−68 (Nova Mus 1991), and GS 2023+338 (V404 Cyg). Spectroscopic monitoring of A0620−00 in quiescence revealed an orbital period of 7.8 hr and established that the mass function is 3.18 $M_\odot$ (McClintock & Remillard 1986; see also Johnston, Kulkarni, & Oke 1989). This is a firm lower limit to the mass of the compact primary; a more recent analysis suggests a mass range of 3.3–4.2 $M_\odot$ (Marsh, Robinson, & Wood 1994; but see Shahbaz, Naylor, & Charles 1994a, who prefer 10 $M_\odot$). GS 1124−68 has a mass function of 3.1 ± 0.4 $M_\odot$ and a probable mass of 4–6 $M_\odot$ for the compact object (Remillard, McClintock, & Bailyn 1992).

In the case of GS 2023+338, Casares, Charles, & Naylor (1992) deduced a mass function of 6.26 ± 0.31 $M_\odot$ 2 years after outburst. Tighter constraints on the mass of the black hole came from the study of ellipsoidal variations in the light curve

[1] Based on observations obtained with the W. M. Keck Observatory.

(Wagner et al. 1992). Subsequently, Casares & Charles (1994) revised their mass function to $6.08 \pm 0.06\ M_\odot$, and measurements of ellipsoidal K-band brightness variations led Shahbaz et al. (1994b) to deduce a mass of $\sim 12\ M_\odot$ for the primary. This is the most persuasive case yet for the existence of a Galactic black hole.

Based on the possible "superhumps" measured in the optical light curves, Kato et al. (1995) suggested a lower limit of $2.9\ M_\odot$ for the mass of the compact object in GRO J0422+32; however, a secure determination of the physical parameters of the binary requires measurements of radial velocities of the secondary star. Several attempts were made to measure the mass functon of GRO J0422+32 while it was fading to quiescence. Some of these were thwarted by additional outbursts (e.g., Filippenko & Matheson 1993), but eventually it became clear that the faintness of the secondary star would be the limiting factor. In 1994 February/March the system was at $V = 20.7$ mag and $R = 20.0$ mag (Zhao et al. 1994a; Martín & Serra-Ricart 1994), and in 1994 September it was measured at $V = 22.4$ mag and $R = 21.1$ mag (Zhao et al. 1994b); by this time the light was dominated by the secondary star of probable spectral type M0 V (Chevalier & Ilovaisky 1995). Orosz & Bailyn (1995) obtained a series of spectra with the Kitt Peak 4 m reflector in 1994 November. Although reliable radial velocities could not be extracted from the individual 30 minute exposures, a range of semi-amplitudes (300–400 km s^{-1}) was derived from the co-added data using an innovative cross-correlation analysis developed by Remillard et al. (1995), under the assumption that the 5.1 hr photometric period is equal to the orbital period. The implied mass function was 0.5–1.4 $M_\odot$, and the spectral type of the secondary was consistent with early M.

Here we present a definitive absorption-line radial velocity curve for the secondary star using spectra obtained with the Keck telescope. The derived mass function is $1.21 \pm 0.06\ M_\odot$. We also discuss a plausible radial velocity curve for the compact primary based on the Hα emission from the accretion disk. If this curve accurately reflects the motion of the compact object, which is not necessarily the case (we see an unexplained phase offset), the mass ratio of the secondary to the primary is 0.1093. Hence, the mass of the primary is $3.57\ M_\odot$ if the secondary (type M2 V) has a mass of $0.39\ M_\odot$.

2. OBSERVATIONS AND REDUCTIONS

GRO J0422+32 was observed with the Low Resolution Imaging Spectrometer (Oke et al. 1995) at the Cassegrain focus of the W. M. Keck 10 m telescope during the nights of 1994 November 8–9 and 1995 January 26–27 UT; a journal of observations is given in Table 1. The sky was clear, and the atmospheric seeing ranged from 0\".8 to 1\".3. We used a Tektronix 2048 × 2048 pixel CCD with a scale of 0\".205 pixel^{-1}. The data were read out with two separate amplifiers whose values for the gain (~ 1.7 electrons count^{-1}) and readout noise (~ 8 electrons pixel^{-1}) differ from each other by $\sim 10\%$; consequently, a discontinuity occurs in the middle of each raw spectrum, but its effects are largely removed during reductions. On-chip binning of 2 in the spatial direction (0\".41 per bin) reduced the effective readout noise.

The long slit of width 1\" was oriented at position angle (P.A.) 63°.8 to include the star 4\".8 northeast of GRO J0422+32. This was done in order to monitor possible variations in the flux of the nova, as well as to test for systematic shifts in the wavelength scale as a function of hour angle. Most of the 21 integrations were 30 minutes in duration. Emission-line comparison lamps (Hg-Ne) were observed every 1–1.5 hr. A 1200 groove mm^{-1} grating blazed at 5000 Å, providing a dispersion of 0.65 Å pixel^{-1} and a full width at half-maximum (FWHM) resolution of ~ 2.4 Å (~ 110 km s^{-1}), was used over a wave-

TABLE 1

JOURNAL OF OBSERVATIONS AND RADIAL VELOCITIES

HJD[a]	UT Date	Exp. (s)	Airmass[b]	Phase[c]	v_2 (km s^{-1})[d]	v_1 (km s^{-1})[e]
9664.9118	1994 Nov. 8	1800	1.11	0.21592	227 ± 62.3	-4.29 ± 8.82
9664.9639	1994 Nov. 8	1800	1.03	0.46206	-371.1 ± 25.2	35.59 ± 7.95
9664.9875	1994 Nov. 8	1800	1.03	0.57364	-342.6 ± 12.9	63.82 ± 9.09
9665.0264	1994 Nov. 8	1800	1.06	0.75744	-0.6 ± 22.6	76.47 ± 10.91
9665.4792	1994 Nov. 8	1800	1.10	0.89749	304 ± 19.0	78.62 ± 8.88
9666.0243	1994 Nov. 9	1800	1.06	0.47375	-337.2 ± 23.9	60.80 ± 8.34
9666.0493	1994 Nov. 9	1800	1.11	0.59191	-297.7 ± 25.8	94.51 ± 8.94
9666.0722	1994 Nov. 9	1800	1.19	0.70018	-70.1 ± 38.1	58.38 ± 9.24
9666.0938	1994 Nov. 9	1800	1.29	0.80194	173.5 ± 22.5	60.80 ± 9.03
9743.7458	1995 Jan. 26	1800	1.03	0.79682	185.9 ± 23.6	47.28 ± 8.91
9743.7674	1995 Jan. 26	1800	1.03	0.89857	262.3 ± 22.9	22.20 ± 11.90
9743.7889	1995 Jan. 26	1800	1.04	0.00033	408 ± 14.9	0.79 ± 10.29
9743.8118	1995 Jan. 26	1800	1.06	0.10865	265 ± 21.0	-2.34 ± 9.54
9743.8333	1995 Jan. 26	1800	1.11	0.21036	111.2 ± 37.9	-29.69 ± 10.52
9743.8542	1995 Jan. 26	1800	1.17	0.30885	-135.1 ± 20.5	-27.96 ± 10.58
9743.8795	1995 Jan. 26	2100	1.28	0.42861	-334.4 ± 15.3	-17.22 ± 12.20
9743.9044	1995 Jan. 26	2200	1.45	0.54624	-360.3 ± 30.8	43.94 ± 18.44
9743.9337	1995 Jan. 26	2700	1.74	0.68462	-59 ± 46.3	43.90 ± 17.42
9744.7424	1995 Jan. 27	1800	1.03	0.50656	-382.8 ± 23.0	12.65 ± 10.05
9744.7639	1995 Jan. 27	1800	1.03	0.60832	-230.1 ± 40.5	42.85 ± 12.17
9744.7868	1995 Jan. 27	1800	1.04	0.71664	-158.7 ± 21.2	35.22 ± 9.54

[a] HJD-2,440,000 at midpoint of exposure.
[b] Airmass at midpoint of exposure.
[c] Using $P = 0^d.21159$ and $T_0 = 9661.4807$.
[d] Secondary star radial velocity.
[e] Hα centroid radial velocity, from fit to emission-line wings.

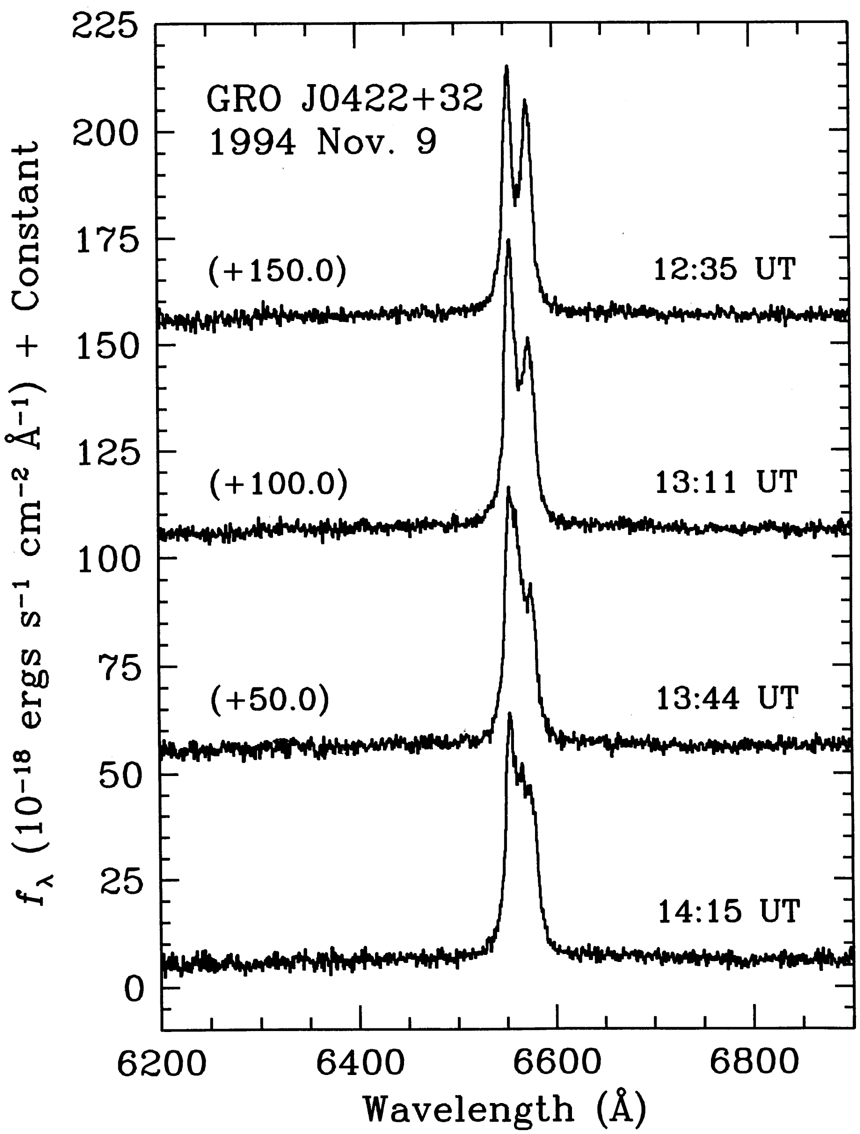

FIG. 1.—Portions of consecutive spectra of GRO J0422+32 obtained on 1994 November 9 UT. The ordinate units are 10^{-18} ergs s^{-1} cm^{-2} Å^{-1}, but constants have been added to the top three spectra for clarity. Note the striking variations in the emission-line profile, even in the bottom two spectra.

length range of ~5630–6930 Å.[2] No order-blocking filter was necessary, since the camera optics are opaque to light blueward of ~3600 Å. Several late-type velocity standards, mostly dwarfs in the range K7–M2, were observed with the same setup, as were sdF stars (Oke & Gunn 1983) for flux calibration and removal of telluric absorption.

One-dimensional sky-subtracted spectra were extracted from the data in the normal manner with IRAF.[3] Depending on the atmospheric seeing conditions, extraction widths of either 3 or 4 pixels (1".2–1".6) were chosen. Cosmic rays were removed through comparison of consecutive exposures. For one exposure there were no contiguous integrations, so this technique could not be applied; hence, we eliminated the cosmic rays by inspection. We used our own software for flux calibration, wavelength calibration, and removal of telluric features (e.g., Filippenko & Sargent 1988). To ensure accurate wavelength calibration, final corrections to the wavelength solution were obtained from night-sky emission lines. The relative fluxes of all spectra were adjusted through comparison with the flux of the star near GRO J0422+32, whose brightness was assumed to be constant. The typical signal-to-noise (S/N) ratio per final 0.75 Å bin is ~3.6 in the continuum.

The spectra of GRO J0422+32 consist of a faint, nearly featureless continuum on which are superposed weak He I λ5876 and strong Hα emission lines (see also Bonnet-Bidaud & Mouchet 1995; Orosz & Bailyn 1995). The Hα profile, which is generally double peaked ($\Delta v \approx 900$ km s^{-1}), varies rapidly in

[2] On 1994 November 8 UT we also obtained two 30 minute exposures in the wavelength range 7540–8830 Å, to see whether the Ca II near-infrared triplet absorption lines would provide superior radial velocities. However, the night sky OH emission is strong in this spectral region, and deep telluric absorption bands must also be removed accurately; moreover, it appeared that the Ca II lines might actually be in emission. Hence, we subsequently chose to concentrate our efforts on the 5630–6930 Å region.

[3] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

the 1994 November data set; as shown in Figure 1, successive half-hour exposures often exhibit striking changes in the relative intensities of the red and blue peaks, and in the depth of the valley between them. Changes in the total equivalent width of the line (~250 Å), on the other hand, amounted to only a few percent in consecutive spectra. The profile variations are considerably smaller in the 1995 January spectra. Variability of GRO J0422+32, based on these data as well as on spectra obtained over the course of 2 years at Lick Observatory, will be discussed in more detail elsewhere.

3. ANALYSIS

3.1. *Cross-Correlations*

We employed the FXCOR package ("Release 9/13/93") in IRAF to cross-correlate the spectra of GRO J0422+32 with the various observed velocity standards. This follows the cross-correlation technique outlined by Tonry & Davis (1979). The correlation was done over the range 6000–6500 Å to avoid the Hα and He I λ5876 emission lines as well as the Na I D absorption. In cases where a definitive correlation peak was not obvious, the strongest correlation within ±500 km s^{-1} of zero velocity was chosen. Typical values of the Tonry & Davis significance threshold, R, were 3–4; for comparison, other recent studies of X-ray novae (e.g., Remillard et al. 1992, 1995) have adopted a minimum value of 2.4–2.6 for R.

Unfortunately, FXCOR does not use equation (20) of Tonry & Davis (1979), but rather a similar formula to calculate the 1 σ uncertainty in the determination of the centroid of the cross-correlation peak. To evaluate the uncertainty via the standard Tonry & Davis method, we exploited the Fourier transform properties of Gaussians (the functions used in fitting the cross-correlation peaks) to determine that FXCOR overestimates the uncertainty by a factor of 2.77. Although Tonry & Davis explicitly point out that the velocity uncertainties usually will need to be adjusted to reflect the external errors in the data, we had no objective method for finding the exact values; thus, we adopted the FXCOR uncertainties reduced by a factor of 2.77, but we suspect that these might be too small by ~20%–30% (see below).

The best correlation, both in terms of strength of correlation and magnitude of uncertainties, was with BD +42°2296, an M0 V star. The results with BD +24°2824, a K8 dwarf, were only slightly different. (In § 3.2, however, we show that an M2 V star provides the best overall match to the spectrum, if one includes the broad undulations seen in the continuum.) Using the radial velocities evaluated from the correlations with BD +42°2296 (corrected for the radial velocity of BD +42°2296 itself; Table 1), we conducted a least-squares fit to obtain the best cosine curve to match the data. The four-parameter fit (zero point, semi-amplitude, period and phase) yielded a systemic velocity of $\gamma_2 = 7.0 \pm 5.7$ km s^{-1}, a semi-amplitude of $K_2 = 380.6 \pm 6.5$ km s^{-1}, a period of $P = 0^{\rm d}.21159 \pm 0^{\rm d}.00057$ (5.0782 hr), and a starting time (heliocentric Julian day) for the phase of T_0 = HJD 2,449,661.4807 ± 0.0012, where T_0 is defined as the point of maximum *redshifted* velocity. The results are shown in Figure 2. A better measurement of the systemic velocity is $\gamma_2 = 9.2 \pm 3.3$ km s^{-1}, the weighted average of results obtained with five different standard stars. For comparison, Orosz & Bailyn (1995) obtained $P = 0^{\rm d}.2107 \pm 0^{\rm d}.0012$ (from I-band photometry), T_0 = 2,449,661.4930 to 2,449,661.5080 (range of probable values), and $K_2 = 350 \pm 50$ km s^{-1}.

All the uncertainties except that of the period are the formal 1 σ values derived from the least-squares fit. For the period, a plot of χ^2 versus period (Fig. 3) indicates that several values

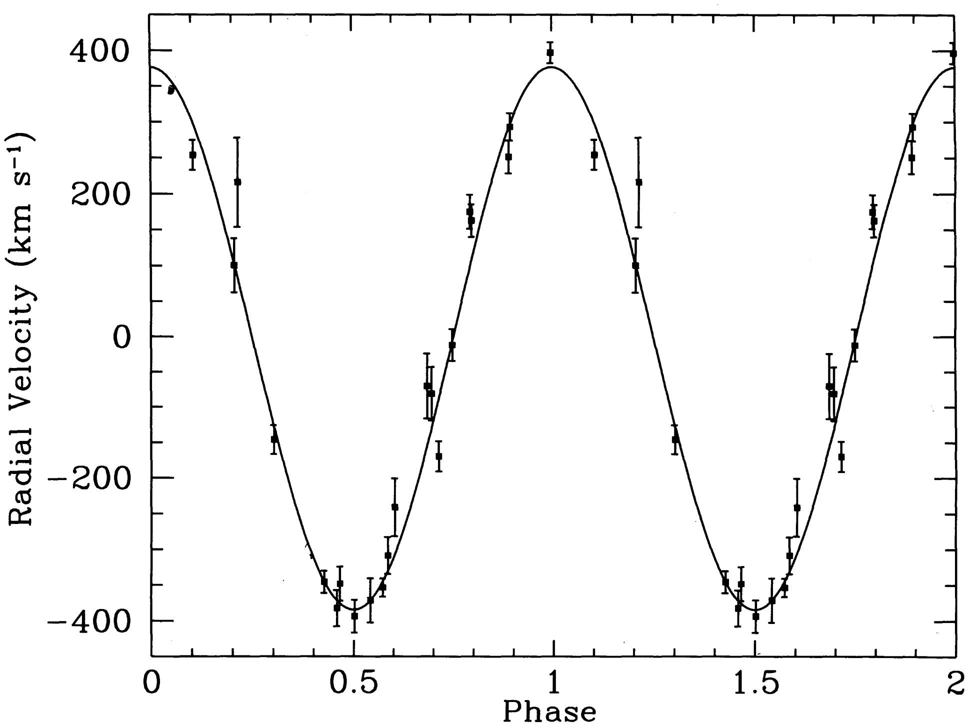

FIG. 2.—Radial velocity curve of the secondary star in GRO J0422+32, derived from cross-correlations of individual spectra with those of the M0 V star BD +42°2296. The radial velocity of the comparison star, 11.1 km s^{-1}, has been added to all values. The orbital period is $0^{\rm d}.21159 \pm 0^{\rm d}.00057$. Formal error bars are 1 σ, but these might be too small by 20%–30%.

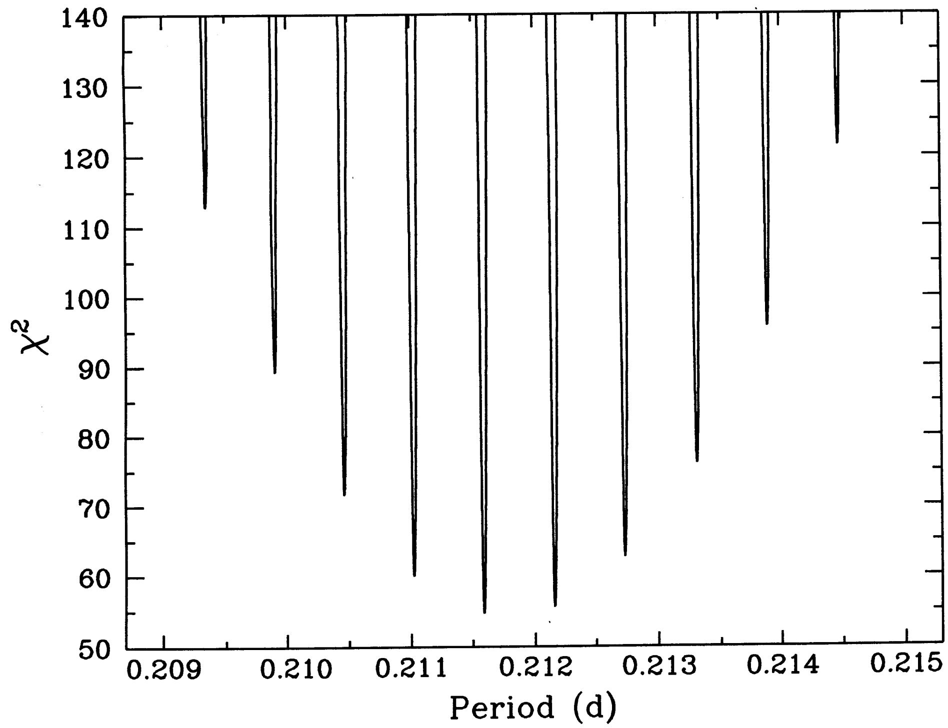

FIG. 3.—Value of χ^2 versus adopted period for GRO J0422+32, using the 21 spectra discussed in this paper. Only the lowest values of χ^2 are shown; $\chi^2 \approx 4000$ at typical trial periods. There is more than one acceptable period because of an ambiguity of one or two in the number of cycles between the 1994 November and 1995 January observing runs. The lowest value of χ^2 corresponds to a period of 0$^{\rm d}$21159.

would give a low χ^2 with arbitrarily small differences. This is the result of effectively having only two well separated epochs of observation (1994 November and 1995 January); the insertion of one or two extra cycles into the gap between those epochs produces a similar fit to the data. Without further observations, we cannot determine which of our five deepest χ^2 minima (corresponding to $P = 0^{\rm d}21045$, $0^{\rm d}21102$, $0^{\rm d}21159$, $0^{\rm d}21216$, and $0^{\rm d}21273$) is correct; we therefore adopt the period with the *global* χ^2 minimum, but we estimate our uncertainty as the *separation* between the minima. The formal reduced χ^2 (χ^2_ν) for the best fit is 3.3, not especially good. However, the true value is probably lower; indeed, after removing one discrepant point (at phase 0.72 in Fig. 2), χ^2_ν approaches a value of unity if the velocity uncertainties are actually 20%–30% larger than assumed. Note that our adopted period ($P = 0^{\rm d}21159 \pm 0^{\rm d}00057$) is consistent with the photometric result obtained by Kato et al. ($P = 0^{\rm d}21211 \pm 0^{\rm d}00002$), although the latter did not influence our choice.

As a consistency check on our correlation results, we also cross-correlated the star 4″8 northeast of GRO J0422+32 with all of our velocity standards. No significant periodicity was evident, and the scatter of the values was ~ 30 km s^{-1}, on the order of the uncertainties determined for the cross-correlations for GRO J0422+32. The absence of variation in the radial velocity of this star indicates that any systematic effects in our velocity curve for GRO J0422+32 due to telescope position or instrument orientation are negligible.

Inspection of Figure 2 reveals that a majority of the measurements having large uncertainties are on the steeply rising or falling parts of the radial velocity curve. One cause of this is almost certainly the orbital broadening of the lines. As pointed out by Marsh et al. (1994) and others, the motion of the secondary star during a given exposure smears the lines by up to $2\pi K_2 T/P$ km s^{-1}, where T is the exposure time. In our case ($T = 1800$ s) this amounts to 235 km s^{-1}, considerably larger than the spectral resolution of FWHM ≈ 110 km s^{-1}. Even a typical value for the smearing ($4K_2 T/P \approx 150$ km s^{-1}) exceeds the spectral resolution. Near times of maximum redshift or blueshift (quadrature), on the other hand, the orbital smearing is much less, allowing the absorption lines to contribute more effectively in the cross-correlation. The line width is then dominated by rotational broadening, $v \sin i = 90$ km s^{-1} using $q = 0.1093$ (§ 4) and the formula $v \sin i = 0.462 K_2 q^{1/3} (1+q)^{2/3}$ (Wade & Horne 1988).

3.2. *The Averaged Spectrum*

Having determined the orbital parameters of the secondary star, we obtained its master "rest-frame" spectrum by averaging all 21 of our individual spectra after Doppler shifting each one to zero velocity.[4] This represents a total integration time of nearly 11 hr, but of course the S/N ratio is lower than for a single 11 hr exposure (ignoring cosmic rays) due to the increase in readout noise.

Figure 4 illustrates the master spectrum, in comparison with spectra of the M0 V and M2 V velocity standards. The depths of the broad undulations, produced largely by TiO, appear more similar to those in the M2 V star than in the M0 V star (consistent with the conclusion of Garcia et al. 1994). One can also see distinct absorption lines in the secondary that are common to the standard stars. Their relative weakness in

[4]Note that the Hα and He I emission lines are smeared out by this process, since they are produced in the accretion disk around the compact primary star.

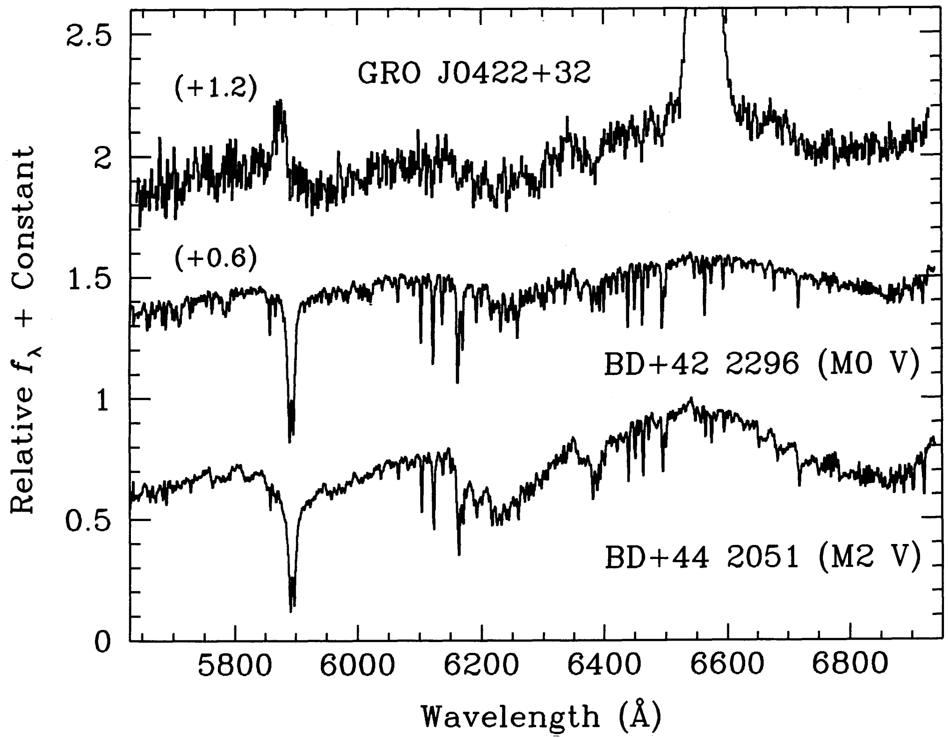

FIG. 4.—Rest-frame spectrum of the secondary star in GRO J0422+32, obtained by averaging all 21 exposures after Doppler shifting each one to zero velocity. The strong Hα emission line is clipped. Scaled spectra of two velocity standard stars are shown for comparison.

GRO J0422+32 is probably caused by three effects: (1) orbital broadening, (2) rotational broadening, and (3) contamination by a featureless continuum from the accretion disk. After adjusting the slope of the M2 V star's continuum to account for the larger reddening of GRO J0422+32, we attempted to quantify the contribution of the accretion disk in GRO J0422+32 by comparing its spectrum with that of the M2 V star, broadening and diluting the latter by various amounts. A good match to the depths of the undulations and the narrow absorption lines was found with contamination fractions of 30%–60% (at ~6300 Å) by the accretion disk. Owing to the uncertainties in the adopted parameters (broadening, spectral type) and the low S/N ratio of the GRO J0422+32 spectrum, however, we cannot confidently exclude contributions somewhat outside this range.

A peculiar aspect of Figure 4 is that the Na I D absorption line appears far weaker in GRO J0422+32 than in the late-type comparison stars. To test whether this is an artifact of contamination by double-peaked He I λ5876 emission, we shifted tne Hα profile (in velocity space) to the expected position of He I and scaled it so that the blue peak matched that of the observed He I line. The residuals were examined after subtracting the Hα profile, and only weak Na I D absorption was evident. We conclude that although the He I line does indeed contaminate the absorption line, the magnitude of this effect is too small to reproduce the observed spectrum. Thus, Na I D absorption must be intrinsically weak in GRO J0422+32. This is very puzzling; earlier spectra of the object obtained by Callanan et al. (1995) and our own group (unpublished) exhibit strong Na I D absorption, at a time when Hα emission was quite prominent. Moreover, Na I D is strong in spectra of A0620–00 (Marsh et al. 1994) and Nova Mus 1993 (GS 1124–68; Remillard et al. 1992) obtained at comparable stages of evolution.

An absorption line of Li I λ6708 might be present in our spectrum, slightly blueward of the stronger Ca I λ6718 absorption, but the S/N ratio is too low for a definitive conclusion. Its formal equivalent width is 0.15 Å, and the 3 σ upper limit is 0.6 Å. Unexpectedly strong Li I λ6708 absorption (EW ≈ 0.25–0.48 Å) is seen in the spectra of several other X-ray novae. This line was discovered in GS 2023+338 (V404 Cyg) by Martín et al. (1992) and independently by Wallerstein (1992). It was subsequently found in spectra of A0620–00 (V616 Mon; probable black hole primary; Marsh et al. 1994; Shahbaz et al. 1994a) and Cen X-4 (probable neutron star primary; Martín et al. 1994a). The radial velocity curve suggests that the Li line in Cen X-4 is associated with the secondary star (Martín et al. 1994a), but Li should have an extremely low surface abundance due to mass loss via accretion and to burning in deeper, convectively mixed layers. Either these binary systems are implausibly young, or there is a production mechanism of Li which is likely to be associated with the outbursts of X-ray novae. The energy implications of the latter are discussed by Martín, Spruit, & van Paradijs (1994b).

3.3. Hα *Measurements*

We also examined the temporal behavior of the Hα emission line. The profile shape varies quite dramatically from exposure to exposure in the 1994 November data (but to a lesser extent in 1995 January), and is probably dominated by disk effects (e.g., hot spots) or the accretion stream over short timescales. However, to investigate the motion of the compact primary rather than the outer regions of the disk, we *excluded* the core of the line and fitted a Gaussian to the high-velocity wings

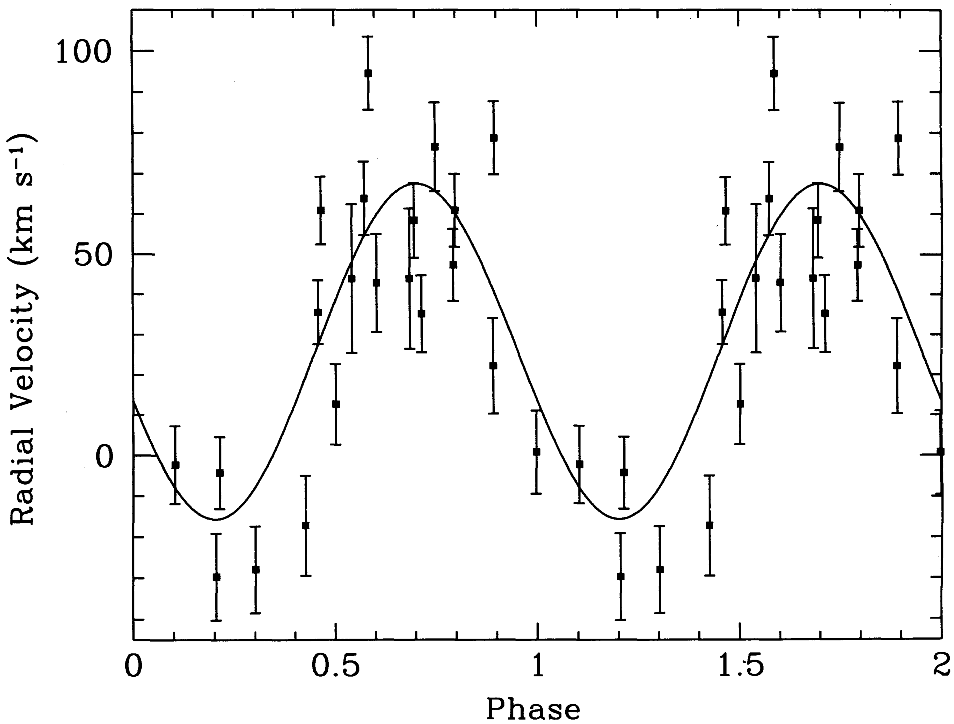

FIG. 5.—Radial velocity curve of the centroid of the Hα emission line, determined by fitting a Gaussian to the high-velocity wings. The period was forced to equal that of the secondary star, but all other parameters were allowed to vary. Most of the scatter is probably produced by temporal and spatial inhomogeneities in the accretion disk. These, as well as geometric distortions or perhaps the accretion stream, might be the source of the phase offset.

($v \approx$ 560–2000 km s^{-1})[5] using the IRAF STSDAS task SPECFIT; the velocity of the peak of the Gaussian was adopted for each spectrum. The specific regions of the fit (including the continuum) were 6415–6550 Å and 6575–6700 Å. The 1 σ uncertainties indicated by the task do not include errors due to the placement of the continuum. Tests made with different approximations to the continuum indicate that the true uncertainties are ~50% larger, and these are adopted in Table 1.

We used a least-squares fit to determine the radial velocity cosine curve, forcing the data to have the same period as that found for the secondary star but allowing all other parameters to vary. The formal results (Fig. 5) are as follows: zero point of 6563.37 ± 0.051 Å (γ_1 = 26.0 ± 2.3 km s^{-1}), semi-amplitude of 0.910 ± 0.071 Å (K_1 = 41.6 ± 3.2 km s^{-1}), and a zero point in the phase of HJD 2,449,661$^{\rm d}$.6292 ± 0$^{\rm d}$.0026. For comparison, Garcia et al. (1994) measured K_1 = 30 ± 6 km s^{-1}.

As before, the zero point of the phase is the maximum *redshifted* velocity; it implies that the compact object is 253° out of phase with the secondary star. If the high-velocity wings of the Hα emission line were produced by the inner parts of an axisymmetric, nonvariable accretion disk, we would expect the centroid to exactly reflect the orbital motion of the compact primary. In this case, the measured radial velocities should closely coincide with the fitted cosine, with a phase shift of 180° relative to the secondary star. Although the behavior is clearly sinusoidal, the high χ^2_ν of our fit (5.7) indicates that a simple function is a poor match, probably because the disk is geometrically distorted, or has spatial and temporal inhomogeneities; this could also account for the observed phase shift of 73° relative to the expected shift (180°).

Similar phase shifts relative to 180° are seen in two other Galactic black hole candidates: Orosz et al. (1994, their Table 6) find shifts of 43° and 36° in the Hα radial velocity curves of A0620−00 and Nova Mus 1993 (GS 1124−68), respectively. As reviewed by Shafter (1992), phase shifts are also seen in many cataclysmic variable stars, with roughly an inverse correlation between the magnitude of the phase shift and the orbital period. The phase shifts are especially large (40°–80°) among the novalike variables. These distortions in the Hα radial velocity curves of X-ray novae and cataclysmic variables suggest that the disks often have nonaxisymmetric distributions of surface brightness or noncircular velocities (e.g., Robinson 1992; see Kaitchuck et al. 1994 for Doppler tomograms). In addition, winds can complicate matters, especially during outburst (Warner 1992). Part of the observed phase shift might also be produced by large, long-lived inhomogeneities in the surface brightness of the late-type secondary stars; see Robinson's remarks in Warner (1992). In any case, the existence of phase shifts casts some doubt on the use of Hα radial velocity curves to determine the motion and mass of the primary star.

On the other hand, Orosz et al. (1994) point out that the value of K_1 found from their Hα radial velocity curve of A0620−00 is consistent with that derived by Marsh et al. (1994) from a measurement of the rotational broadening of the absorption lines in the secondary star's spectrum. The resulting value of q, the mass ratio (M_2/M_1), is also in reasonable agreement with that found by Haswell et al. (1993) from light-curve models. Although many more systems need to be tested in a

[5] Adopting $M_1 = 3.57\ M_\odot$ (see § 4), the radial distance of gas having a typical velocity in this range (1300 km s^{-1}) is ~0.4 $R_\odot$, considerably smaller than the effective radius of the Roche lobe of the primary (~1.4 $R_\odot$).

similar way to gain confidence, this hints that the semi-amplitude derived from the Hα radial velocity curve may be reliable, despite the presence of a large phase shift. In the next section we will adopt this assumption, using the measured value of K_1 (41.6 ± 3.2 km s^{-1}) to derive the probable mass of the compact primary.

4. THE MASS OF THE COMPACT PRIMARY

From the period ($P = 0^d.21159 \pm 0^d.00057$) and semi-amplitude ($K_2 = 380.6 \pm 6.5$ km s^{-1}) of the radial velocity curve of the secondary star, we find a mass function $f(M) = PK_2^3/2\pi G = 1.21 \pm 0.06\ M_\odot$. The semi-amplitude of the radial velocity curve of the primary, $K_1 = 41.6 \pm 3.2$ km s^{-1}, implies a mass ratio $q = 0.1093 \pm 0.0086$; hence, if the secondary is an M2 dwarf ($M_2 = 0.39\ M_\odot$; Allen 1976), as seems likely from its spectral properties, then the mass of the primary is $M_1 = 3.57 \pm 0.28\ M_\odot$. If we adopt $K_1 = 48$ km s^{-1}, 2 σ higher than measured, then $q = 0.1261$ and $M_1 = 3.09\ M_\odot$.

An independent determination of the mass ratio could be made if the rotational broadening ($v \sin i$) were measured with the formula of Wade & Horne (1988) given in § 3.1. Unfortunately, both the spectral resolution (~110 km s^{-1}) and especially the orbital broadening (typically 150 km s^{-1}; § 3.1) exceed the expected rotational broadening of 90 km s^{-1} (§ 3.1), precluding a useful measurement. If we restrict our attention only to the spectra near quadrature, thereby minimizing the orbital broadening, the resulting S/N ratio is too low.

However, a useful consistency check can be obtained by calculating the effective Roche lobe radius (R_L) of the secondary star, defined such that the total volume of the Roche lobe is equal to $(4/3)\pi R_L^3$. Using equation (2) of Eggleton (1983), we find that $R_L = 0.2122a = 0.50\ R_\odot$, where a is the separation between the two stars (2.37 $R_\odot$, from Kepler's third law). This is exactly equal to the expected radius of an M2 dwarf (Allen 1976). Thus, the secondary barely fills its Roche lobe, enabling mass transfer. If the secondary were more massive (e.g., $M_2 \approx 0.43\ M_\odot$ for an M1 V star), its radius (0.57 $R_\odot$; Allen 1976) would significantly exceed $R_L = 0.52\ R_\odot$; mass transfer should have begun long ago, resulting in a gradual decrease in M_2. Conversely, if the secondary were less massive (e.g., $M_2 \approx 0.33\ M_\odot$ for an M3 V star), its radius (0.42 $R_\odot$) would be smaller than $R_L = 0.47\ R_\odot$, and mass transfer would not be possible.[6] The classification of the secondary is therefore very likely to be in the range M1.5–2.5 V, consistent with its observed spectrum. Adopting a corresponding uncertainty of 0.02 $M_\odot$ in M_2, the overall uncertainty in the derived mass of the compact primary is 0.34 $M_\odot$.

The inclination angle of the system can be obtained from the mass function: $\sin^3 i = f(M)(M_1 + M_2)^2/M_1^3$. We find $i = 48° \pm 3°$, consistent with the presence of a double-peaked Hα emission line. Since $R_L = 0.2122a$, an inclination angle of $\gtrsim 78°$ is necessary to eclipse the compact object itself. The inner Lagrangian point, on the other hand, would be eclipsed if $i \gtrsim 45°$ (where we have neglected the slightly nonspherical shape of the Roche lobe), close to the derived inclination angle. Thus, most or all of the accretion disk in the GRO J0422+32 system remains uneclipsed from our perspective, although part of the observed variations in the Hα emission profile might be produced by eclipses of the outer disk and hot spot.

Finally, recall that the zero point in the Hα velocity curve is measured to be $\gamma_1 = 26.0 \pm 2.3$ km s^{-1}, whereas that of the secondary star is $\gamma_2 = 9.2 \pm 3.3$ km s^{-1}. Could this difference, $c\Delta z = 16.8 \pm 4.0$ km s^{-1}, be produced by a gravitational redshift? Since $v^2 \approx GM/r$ and $M/r \approx c^2\Delta z/G$, we have $v \approx c(\Delta z)^{1/2}$. Thus, we expect gas with $c\Delta z = 16.8$ km s^{-1} to have a velocity of ~2240 km s^{-1}, higher than observed in the wings of the Hα line ($v \approx 560$–2000 km s^{-1}). On the other hand, reasonable consistency is obtained if the true gravitational redshift is ~9 km s^{-1}, or 2 σ lower than quoted above: we then expect $v \approx 1600$ km s^{-1}, somewhat on the high side of the profile wings. Of course, even better agreement ($v \approx 1200$ km s^{-1}) is obtained if the true gravitational redshift is 3 σ lower, or ~5 km s^{-1}.

In view of the large discrepancy between the predicted and "measured" redshifts, this rather speculative idea is unlikely to be correct. This is especially the case given the uncertainty in the fundamental interpretation of the Hα velocity curve, as manifested in the phase shift of unknown origin (§ 3.3). The phase shift is a much more obvious effect than the difference in γ; perhaps the latter is somehow related to the former. Note that some cataclysmic variables show similar offsets (but of low significance) in the zero points of the primary and secondary velocity curves (e.g., Szkody et al. 1992), or in the zero points of velocity curves determined from different emission lines (e.g., Schlegel, Kaitchuck, & Honeycutt 1984). Recall that many cataclysmic variables also exhibit phase shifts in their emission-line velocity curves (Shafter 1992).

5. CONCLUSIONS

The maximum gravitational mass of a slowly rotating neutron star is widely believed to be 3.0–3.2 $M_\odot$ (Rhoades & Ruffini 1974; Chitre & Hartle 1976), based on a minimal set of physical constraints (Hartle 1978) such as causality (i.e., the sound speed should not exceed the speed of light). Most nonrelativistic equations of state yield values between 1.3 and 1.9 $M_\odot$, but some extreme cases (as well as stiff equations of state including relativistic interactions) reach 2.7 $M_\odot$ (Arnett & Bowers 1977; Prakash, Ainsworth, & Lattimer 1988). Very rapid, uniform rotation increases the maximum mass up to ~3.2 $M_\odot$ for extreme equations of state (Friedman, Ipser, & Parker 1986). Brown & Bethe (1994) argue that kaon condensation softens the equation of state of dense matter, in which case the maximum neutron star mass is only ~1.5 $M_\odot$. Observations of neutron stars in binary systems almost always yield masses in the range 1.0–1.8 $M_\odot$ (Thorsett et al. 1993; Finn 1994), as expected from theoretical studies of core-collapse supernovae (Woosley & Weaver 1992). Thus, the derived mass of 3.57 ± 0.34 $M_\odot$ implies that the compact primary in GRO J0422+32 is probably a black hole.

On the other hand, for sufficiently (*a*) high rotation rates, (*b*) high central mass-energy densities, and (*c*) low values of the assumed density at which the equation of state is forced to reduce to the "known" form, the maximum possible mass achieves much larger values $M \gtrsim 7$–9 $M_\odot$ (Friedman & Ipser 1987). The so-called "Q stars" of Bahcall, Lynn, & Selipsky (1990), for example, can easily exceed 10 $M_\odot$ because they are based on matter whose equation of state differs from the

[6] In X-ray binaries, the optically visible star is frequently less massive than implied by its temperature and luminosity (e.g., Hutchings 1982); the evolutionary history of stars in such systems differs from that of single stars or those in wide binaries. However, this is probably not a significant effect in GRO J0422+32. The secondary has an unusually low mass, and its evolutionary timescale is far greater than its current age. In the absence of strong and sustained X-ray heating, the M-type dwarf should have a normal mass-radius relationship.

"known" relation even below nuclear densities. Bahcall et al. argue that the equation of state for nuclear matter has not been tested for large (>1000) concentrations of baryons; hence, there is no laboratory evidence against their hypothesis. Relaxing the causality constraint (as might be justified because neutron stars are dispersive, so the group and phase velocities of hydrodynamic waves may differ substantially) further increases the upper mass limit (Hartle 1978; Friedman & Ipser 1987). We therefore cannot completely eliminate the possibility that the compact primary of GRO J0422+32 (or any of the other Galactic black hole candidates) is a neutron star. For the purposes of the remaining discussion, however, we will assume the conventional limit for a neutron star, 3.0–3.2 $M_\odot$.

Although the mass of the secondary star in GRO J0422+32 determined from the spectral type (0.39 $M_\odot$) is consistent with that of an M2 V star filling its Roche lobe, it is conceivable that the true mass is lower (e.g., Hutchings 1982; van den Heuvel 1983), and hence that the compact primary is also less massive than we have estimated. For example, if $M_2 = 0.33$ $M_\odot$, then $M_1 = 3.0$ $M_\odot$ using $q = 0.1093$, barely consistent with the maximum mass of a neutron star. If, in addition to $M_2 = 0.33$ $M_\odot$, we adopt our 2 σ upper limit of $q = 0.1261$, we find a lower limit of $M_1 = 2.6$ $M_\odot$—below the extreme limit, but above the maximum mass of most realistic equations of state for slowly rotating neutron stars. As mentioned by Orosz & Bailyn (1995), if we *assume* that the hard X-ray tail observed in outburst is a signature of black holes (e.g., Kitamoto et al. 1992; Sunyaev et al. 1993), a low mass for the compact primary could provide evidence against very stiff equations of state for neutron stars.

An exact determination of the mass of the compact primary requires independent knowledge of the inclination of the system, which can be deduced from detailed modeling of ellipsoidal brightness variations. This is best done at infrared wavelengths, where the contribution of the accretion disk is negligible (e.g., Shahbaz et al. 1994b, for GS 2023+338). We plan to obtain the necessary measurements during the coming year.

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