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ON THE MASS OF THE BLACK HOLE IN GS 2000+25

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ABSTRACT

We present *J*- and *K*′-band (1.95–2.35 μm) photometry of the quiescent X-ray nova GS 2000+25, obtained in an attempt to constrain the mass of the compact object (M_X). Combined with the mass function of 4.97 $M_\odot$, the infrared light curves imply $M_X \leq 11\ M_\odot$ (90% confidence level), regardless of the evolutionary state of the secondary, for a mass ratio q of $4 < q < 30$. For a secondary mass in the range $M_2 = 0.4-0.9\ M_\odot$ (as expected for a K dwarf companion), and assuming a negligible contribution from the disk at these wavelengths, we find $M_X = 8.5 \pm 1.5\ M_\odot$ and an inclination of 65° ± 9°. The observed infrared color is consistent with that expected of a K dwarf secondary. If the accretion disk continuum is given by $f_\lambda \propto \lambda^{-1.8}$, as observed in other quiescent X-ray novae, we constrain the accretion disk contribution to the K' flux (independently of optical estimates) to $\leq$12%.

Subject headings: binaries: close — black hole physics — stars: individual (GS 2000+25) — X-rays: stars

1. INTRODUCTION

The study of quiescent X-ray novae has been directly responsible for the recent success in finding Galactic black holes (see van Paradijs & McClintock 1995 for a review, as well as Bailyn et al. 1995 and Remillard et al. 1996 for additional systems). The primary datum is the mass function determined from radial velocity studies of the secondary star, but in the majority of cases these observations are feasible only after the X-ray nova fades from outburst to quiescence. Knowledge of the mass function allows one to place a *lower* limit on the mass of the compact object (M_X); if this limit is $\geq$3.2 $M_\odot$, the system is classified as a strong black hole candidate.

A more accurate determination of M_X requires knowledge of the mass of the secondary star (M_2), together with either the mass ratio ($q = M_X/M_2$) or the orbital inclination (i) of the system. The value of q can sometimes be determined from the rotational broadening of absorption lines in the spectrum of the secondary (e.g., Wade & Horne 1988). Alternatively, M_2 and i can be constrained by modeling the ellipsoidal variations of the secondary as a function of i and q (e.g., McClintock & Remillard 1986). A potentially serious source of error using the latter technique arises from contamination due to emission from the accretion disk; for example, it is known that the disk can contribute ~50% of the total flux in the V band (e.g., McClintock & Remillard 1986). However, since the continuum of the accretion disk is substantially bluer than that of the secondary (typically $f_\lambda \propto \lambda^{-1.8}$; see Garcia et al. 1996 for a compendium of estimates), photometry at 1–2 μm should be considerably less sensitive to accretion disk contamination (e.g., Shahbaz, Naylor, & Charles 1993, 1994). Here we present J and K' (1.95–2.35 μm) photometry of the quiescent X-ray nova GS 2000+25, obtained in an attempt to measure the true ellipsoidal light curve of the secondary and to constrain more accurately the mass of the compact object.

GS 2000+25 was discovered by the *Ginga* satellite as a 12 crab X-ray nova on 1988 April 26 UT (Tsunemi et al. 1989). The X-ray, optical, and radio properties of GS 2000+25 during and after outburst were typical of the "canonical" properties of the black hole X-ray novae (especially A0620−00). An 8.25 hr orbital period was determined once the object had returned to quiescence (Callanan & Charles 1991; Chevalier & Ilovaisky 1993). Because of the faintness of this system (R = 21.2 mag), the radial velocity curve of the secondary has only recently been measured by Filippenko, Matheson, & Barth (1995; hereafter FMB) and by Casares, Charles, & Marsh (1995). The derived mass function is 4.97 ± 0.10 $M_\odot$, placing GS 2000+25 firmly in the class of strong black hole candidates.

2. OBSERVATIONS

We observed GS 2000+25 with the UCLA twin-channel infrared camera on the Lick Observatory 3 m Shane telescope during 1995 August 11 and 12 UT. A dichroic beam splitter allows simultaneous imaging in both a short-wavelength channel (using a NICMOS3 HgCdTe array) and a long-wavelength channel (InSb array); we used J and K' filters, respectively. Each detector is a 256 × 256 pixel array, with a scale of 0″.675 pixel^{-1}. For further details see McLean et al. (1993, 1994).

Conditions during the first night were characterized by seeing of 2″–3″ and a highly variable background in both J and K' (primarily due to large excursions in the outside temperature). Detector backgrounds were much more stable during the second night, with seeing in the range 1″.5–2″. We note that good seeing is especially important for this object, since there is an unrelated star only ~2″.1 from GS 2000+25 (e.g.,

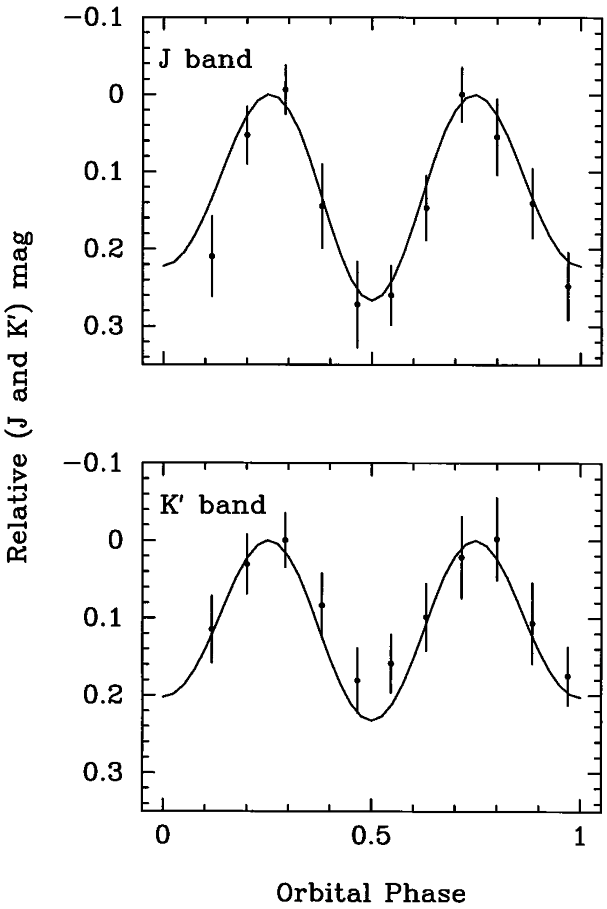

FIG. 1.—Light curves of GS 2000+25, showing J and K' ellipsoidal variability, obtained on 1995 August 12 UT. Phase 0.0 corresponds to inferior conjunction of the secondary star.

Callanan & Charles 1991). For the rest of this paper we focus on the data acquired from the second night of observations.

The data were obtained using a 9 point raster scan of the field, with 4 minutes per exposure. For each image, a median filtered background was generated using the nearest (in time) nine exposures. These backgrounds were subtracted, and the images (in both J and K') were flat-fielded, coaligned, and co-added (nine at a time) using a shifted pixel mask to produce the final sequence of images for the photometry. The total integration time per summed image was 36 minutes.

Relative photometry was then performed on the 11 summed, final images using DAOPHOT (Stetson 1987). A sample of relatively isolated stars distributed throughout the image was used to characterize the variation of the point-spread function across the image. The error bars for the GS 2000+25 light curve were calculated from the observed rms in comparison stars of similar magnitude, and therefore account for both counting statistics and systematic errors. Most of the second night was photometric, and we calibrated the field using UKIRT faint standard stars (Casali & Hawarden 1992).

We detected GS 2000+25 at a K' magnitude of 16.8 ± 0.1 and $J - K' = 1.4 \pm 0.12$. Figure 1 illustrates the J- and K'-band light curves, folded on the orbital ephemeris; we used the period of Chevalier & Ilovaisky (1993; $P_{\rm orb} = 0.344098$ days) and the spectroscopic T_0 of FMB (Heliocentric Julian Day [HJD] = 2,449,920.9409; note that Julian Days in FMB were incorrectly listed as HJDs), yielding a photometric T_0 = HJD 2,449,920.8549 corresponding to inferior conjunction of the secondary star. Also shown on this plot is the best-fit model assuming zero accretion disk contamination, which we describe below.

3. MODELING THE DATA

In order to constrain the orbital inclination and mass ratio of this system, the data were fitted to a model consisting of a Roche lobe filling secondary (Avni 1978). A simple blackbody approximation was assumed, with limb-darkening coefficients taken from Al-Naimiy (1978) and a gravitational darkening coefficient of 0.08 (Lucy 1967), appropriate for an early to mid-K secondary (FMB).

Simulations show that the use of Kurucz stellar atmospheres instead of a blackbody approximation changes the amplitude of the ellipsoidal variation by 1%–2% at most, an effect much smaller than the uncertainty in the data. We also varied both the gravitational and limb-darkening coefficients, using values appropriate for K0–K7 dwarfs (FMB), and found no significant effect on our light-curve models.

We assume for the moment that the accretion disk contribution is negligible at J and K' (see § 4 for further discussion of this point). The assumption that the secondary fills its Roche lobe is an essential one, since the ellipsoidal amplitudes are strongly dependent on this; however, we believe this to be correct, because the Doppler maps of Casares et al. (1995) show Hα emission occurring in the disk consistent with the location of a hot spot caused by continued accretion from the secondary, even in this quiescent state.

The combined J- and K'-band data were fitted to this model for a variety of mass ratios and orbital inclinations. We plot in Figure 2 the 90% confidence contours (for 2 degrees of freedom) for this data set. The best-fit models (i.e., for the combined J and K' fit) have a reduced χ^2 of ~0.6. Rather than force the reduced χ^2 to equal unity, we chose instead to leave the uncertainties as they are, and hence the black hole mass constraints derived below will be somewhat conservative. We believe this approach to be the most prudent one, considering the possibility of residual systematic effects, especially in our K' data.

Using the mass function of FMB, we have also calculated lines of constant M_X and drawn them in Figure 2. The location of these lines is *independent* of the mass of the secondary. The upper bound to the inclination derived from the lack of an eclipse by the secondary is also plotted (e.g., Callanan & Charles 1991). Finally, the hatched area corresponds to the region of allowed solutions of inclination and mass ratio; its vertical extent is dominated by the range of likely secondary masses. Here we assume a secondary mass of 0.4–0.9 $M_\odot$, suitable for a main sequence, or a slightly evolved, Roche lobe filling K dwarf secondary (FMB; Popper 1980).

We see from Figure 2 that, regardless of the assumed mass of the secondary and the orbital inclination, the mass of the black hole in GS 2000+25 is less than 11 $M_\odot$ for $4 < q < 30$, at the 90% confidence level. Assuming negligible flux from the accretion disk in both the J and K' bands, we derive $i = 65° \pm 9°$ and $M_X = 8.5 \pm 1.5\ M_\odot$ (1 σ uncertainties). We note that our value for the inclination agrees with the optical estimates of Chevalier & Ilovaisky (1993); however, our result is much less sensitive to accretion disk contamination (see below). Also, we recently became aware of the work of

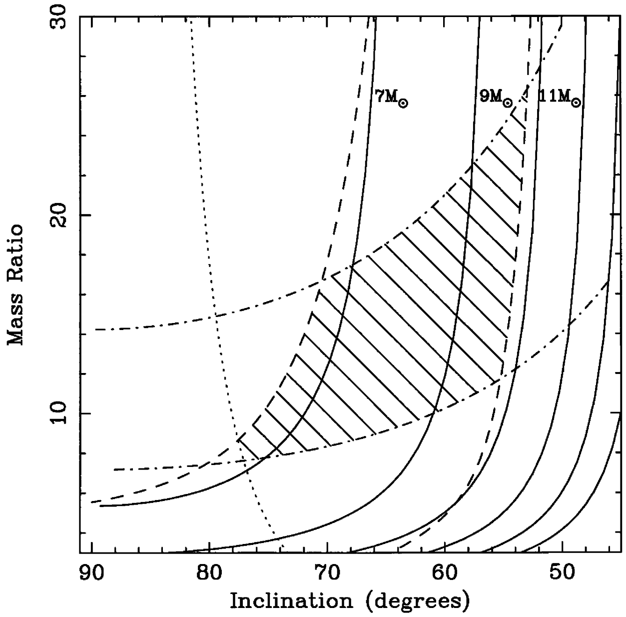

FIG. 2.—GS 2000+25 Mass ratio (q) and inclination (i) constraints estimated from the data in Fig. 1. The 90% confidence contours derived from the fit to the combined J and K' light curves are shown as dashed lines: q and i must lie within this region. The upper bound to the inclination derived from the lack of eclipses is shown as the dotted line on the left. Contours of constant M_X (*solid lines*) are also plotted. Finally, the hatched region denotes the values of q and i allowed for a mass function of 4.97 $M_\odot$ (FMB). The upper and lower bounds of this region, shown as dot-dashed lines, correspond to masses of 0.4 and 0.9 $M_\odot$, respectively, appropriate for a K dwarf secondary.

Beekman et al. (1996); their mass constraints for GS 2000+25 are consistent with ours.

One caveat is that the light curves of low-mass X-ray binaries often exhibit flickering superimposed on the ellipsoidal variations, especially at optical wavelengths and prior to quiescence (e.g., V404 Cyg [Casares et al. 1993]; GRO J0422+32 [Chevalier & Ilovaisky 1995]). If this is also the case for GS 2000+25, the ellipsoidal variation deduced from data taken over a single night may be erroneous. Although this effect is likely to be small in our study, which uses infrared data obtained in quiescence, it cannot be ignored; a recent H-band study of V404 Cyg shows considerable variability not associated with the ellipsoidal modulation (Sanwal et al. 1996).

4. DISK CONTAMINATION AND DISTANCE TO GS 2000+25

As might be expected, accretion disk contamination of the ellipsoidal modulation will reduce the upper bound to the mass of the black hole. We have attempted to quantify the possible accretion disk contamination independently of any optical estimate, as follows. We assume that the spectral slope of the accretion disk can be approximated as $f_\lambda \propto \lambda^{-1.8}$ (Garcia et al. 1996) out to the K' band, and fit both the J and K'-band data sets simultaneously over a range of J and K'-band contaminations, keeping the ratio of the accretion disk flux in each passband fixed (at 2.8). We find that a K' contamination as large as 12% is formally excluded at the 90% confidence level.

The optical spectra, however, provide more stringent upper limits. It has been estimated (FMB) that the contamination due to the disk at 6300 Å is less than 20%; for the accretion disk spectral slope assumed above, this implies a maximum contamination at K' of ~2% (and ~6% at J). Our modeling shows that such a contribution will decrease our M_X estimate by ≤8%, well within our measurement error.

Assuming a K dwarf secondary with $J - K = 0.45-0.85$ mag (e.g., Johnson 1966), we estimate $A_V = 3.0-5.2$ mag (using the interstellar extinction relations of He et al. 1995), in good agreement with optical estimates of the extinction toward GS 2000+25 (e.g., Charles et al. 1991). Moreover, we use Patterson (1984, his Fig. 4) and Johnson (1966) to derive $M_K(\text{secondary}) = 5.1 \pm 1.2$ mag. For $3.0 \text{ mag} < A_V < 5.2$ mag, we have $0.3 \text{ mag} < A_K < 0.5$ mag (He et al. 1995); applying this to the observed magnitude and comparing with the absolute magnitude, we estimate a distance $D = 2 \pm 1$ kpc to GS 2000+25.

5. CONCLUSIONS

Under the assumption of a negligible, or at least constant, accretion disk contribution in our J and K' data, we constrain the mass of the black hole in GS 2000+25 to be $8.5 \pm 1.5 M_\odot$. As the sample of Galactic X-ray novae increases with the current generation of all-sky monitors (BATSE and the XTE ASM), a true measure of the Galactic black hole mass distribution will be possible for the first time, which can then be compared to theoretical models for the formation of black holes in binaries (e.g., Verbunt & van den Heuvel 1995).

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Note added in proof.—A reanalysis of the FMB Keck optical spectra of GS 2000+25 by E. T. Harlaftis, K. Horne, & A. V. Filippenko (PASP, 762 [1996]) gives a mass ratio $q = 23.8 \pm 6.8$ from their measured semiamplitude ($K = 519.9 \pm 5.1$ km s^{-1}, consistent with FMB) and rotational broadening ($v \sin i = 86 \pm 8$ km s^{-1}) of the secondary star. In conjunction with our Figure 2, this implies $M_X \approx 10\ M_\odot$. A Doppler map of the system shows evidence for a bright spot in the accretion disk, as also found by Casares et al. (1995).