Near-Infrared Light Curves of the Black Hole Binary A0620–00

Cynthia S. Froning
froning@stsci.edu

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

and

Edward L. Robinson
elr@astro.as.utexas.edu

Department of Astronomy, University of Texas at Austin, Austin, TX 78712

ABSTRACT

We measured the near-infrared orbital light curve of the black hole binary A0620–00 in 1995 and 1996. The light curves show an asymmetric, double-humped modulation with extra emission in the peak at orbital phase 0.75. There were no significant changes in the shape of the light curve over the one-year observation period. There were no sharp dips in the light curves nor reversals of the asymmetry between the two peaks as seen in earlier observations. The light curves are well fit by models incorporating ellipsoidal variations from the mass-losing K-type star plus a beamed bright spot on the accretion disk around the compact star. The long-term stability of the light curve shape rules out superhumps and star spots as sources of asymmetry when we observed A0620–00. The ellipsoidal variations yield a lower limit $i \geq 38^\circ$ on the orbital inclination. The light curves show no eclipse features, which places an upper limit $i \leq 75^\circ$. This range of inclinations constrains the mass of the compact object to $3.3 < M_1 < 13.6 M_\odot$. The light curves do not further constrain the orbital inclination because the contribution of the accretion disk to the observed flux is unknown. We argue that a previous attempt to measure the near-infrared flux from the accretion disk using the dilution of the $^{12}$CO(2,0) bandhead in the spectrum of the K star is not reliable because the band strength depends strongly on surface gravity.

Subject headings: binaries: close — infrared: stars — stars: individual (A0620–00) — stars: variables: other

1. Introduction

The bright X-ray nova A0620–00 (V616 Mon) was discovered when it erupted in 1975 (Elvis et al. 1975). Observations obtained after its return to quiescence revealed that A0620–00 is an
interacting binary system with a K star donating mass to a compact star via an accretion disk (Oke 1977; McClintock et al. 1983). Early fits to the radial velocity variations of the K star gave a semi-amplitude of $K_2 = 457$ km s$^{-1}$, which, when combined with the orbital period ($P_{\text{orb}} = 7.75$ hr), yielded a mass function $f(M) = 3.17 M_\odot$. The mass function equals the minimum dynamical mass of the compact star. Since the mass function for A0620–00 is greater than the theoretical maximum mass for a neutron star, A0620–00 became a strong candidate for a black hole binary (McClintock & Remillard 1986). Follow-up observations have refined the velocity semi-amplitude and determined the mass ratio of the binary: $K_2 = 433 \pm 3$ km s$^{-1}$ and $q = M_2/M_1 = 0.067 \pm 0.01$ (Marsh, Robinson & Wood 1994; Orosz et al. 1994 found similar binary parameters). With these values, the masses of the stars are $M_1 = (3.09 \pm 0.09) \sin^{-3} i M_\odot$ and $M_2 = (0.21 \pm 0.04) \sin^{-3} i M_\odot$, lacking only a determination of the orbital inclination to be fully determined.

One method for obtaining the orbital inclination of A0620–00 is to measure the ellipsoidal variations of the Roche-lobe-filling K star. Two studies of the ellipsoidal variations have resulted in non-overlapping estimates of the inclination and, consequently, non-overlapping estimates of the mass of the compact star. Haswell et al. (1993) fit models including a Roche-lobe-filling star and an accretion disk to simultaneous UBVR light curves of A0620–00 and found an inclination range for $q = 0.067$ of $65.75 \leq i \leq 73.75$. This corresponds to a compact star mass of $3.40 \leq M_1 \leq 4.20 M_\odot$ (the compact star masses given here and elsewhere in this manuscript were calculated by us using the mass function determination from Marsh, Robinson & Wood 1994). Shahbaz, Naylor & Charles (1994) fit a K-band light curve of A0620–00 with a model including only the lobe-filling star and derived a best-fit inclination of 37$^\circ$, with a range of inclinations $30^\circ \leq i \leq 45^\circ$ (90% confidence limits for $q = 0.067$; their Fig. 2). This corresponds to $M_1 = 14.2 M_\odot$, and a range of $8.49 \leq M_1 \leq 25.4 M_\odot$. All authors agree that the compact star should be a black hole.

The orbital light curves of A0620–00 have shown clear evidence that the ellipsoidal variations are distorted: the light curve minima and maxima have varied in relative height and depth, the light curve minima have on occasion shown sharp features rather than smooth troughs, and the asymmetry between the two peaks has reversed (Haswell 1996 and sources therein). The ellipsoidal variations can be distorted by star spots on the K star; by a non-axisymmetric distribution of light across the accretion disk, such as the bright spot where the mass stream impacts the accretion disk; by superhumps caused by a precessing, elliptical accretion disk; and by dilution of the star light by non-variable flux from other components of the binary system, such as an axisymmetric accretion disk. The presence of variable sources of flux in the system can confuse attempts to isolate the ellipsoidal component of the variations, and if a non-varying flux is present in the binary system but not in the models, the models will underestimate the true amplitude of the ellipsoidal variations and, in turn, underestimate the orbital inclination. The difference between the derived inclinations for A0620–00 stems in part from uncertainty about the magnitude of these distortions.

The light curve of A0620–00 has been monitored at R and I wavelengths (e.g., Leibowitz, Hemar & Orio 1998), but few observations have been published at longer wavelengths. Since the contribution of the K star to the observed flux is maximized in the near-infrared, that wavelength
region provides a good window to target the ellipsoidal modulation. In order to investigate the remaining uncertainties concerning the mass of its compact star and to measure the long-term behavior of its orbital light curve, we have reobserved the orbital light curve of A0620–00 in the J, H and K bandpasses. This paper reports the results of our observations.

2. Observations and Data Reduction

We observed A0620–00 on 1995 December 15 – 17, 1996 January 27 – 29 and 1996 December 7 – 12 on the 2.7-m telescope at McDonald Observatory using ROKCAM, a near-infrared imaging camera (Colomé & Harvey 1993). In all three observing runs, we observed extensively in the H filter (1.45 – 1.85 \( \mu \)m), where our S/N was maximized, and we supplemented these data with observations in the thermal K (2.05 – 2.4 \( \mu \)m) in 1996 January and in the J-band (1.1 – 1.4 \( \mu \)m) in 1996 December. The dates and total exposure times of the observations are summarized in Table 1. Individual exposure times were 20 seconds in J and H and 10 seconds in K, with telescope nods between integrations to sample the variable sky background. After subtracting sky and dark current, we calibrated the images using dome flats (constructed from images taken with the dome lights off subtracted from images taken with the lights on). We aligned the individual frames and coadded them in groups of four, from which we extracted the instrumental magnitudes of A0620–00 and three nearby comparison stars. The positions of the comparison stars relative to A0620–00 and their NIR colors are given in Table 2.

The two brighter comparison stars were averaged and used to correct the observations for seeing and extinction variations. The third, fainter star is comparable in brightness to A0620–00 in the near-infrared. We used the scatter in its measurements to assign an uncertainty to the relative photometry in each filter on each night. We flux calibrated the H and K data using observations of four standard stars from 1996 January 27 (Elias et al. 1982). The J-band observations were flux calibrated using a single standard star observed on 1996 December 8; the uncertainty in the J-band flux calibration was estimated by using the same standard star to calculate a H-band calibration and comparing that result to the calibration from 1996 January 27. Because of the paucity of K-band observations of the A0620–00 field, the transformation equations for each filter were fit with a fixed extinction coefficient (Allen 1976) and no color terms. The mean colors for each observing run are shown in Table 3. The mean H magnitude of the A0620–00 lightcurve was stable over the one-year baseline of our observations, changing by less than 0.05 mag. In the final step, we converted the data from magnitudes to fluxes (Mégeessier 1995).

The observations from each run were combined into mean light curves using the linear ephemeris of McClintock & Remillard (1986). The combined fluxes and error bars were determined from weighted means of the data, where the weights were based on the uncertainties assigned each night from the scatter about the mean for the third field star. The bin sizes in the combined light curves are 0.01 in orbital phase for J and H and 0.05 for K, corresponding to time intervals of 4.65 min and 23.3 min, respectively. The orbital phases conform to the standard convention: phase 0 corresponds
to inferior conjunction of the K star. There is no substantial drift in the phasing of the light curve relative to the 1986 ephemeris (nor with respect to the refined ephemeris of Orosz et al. 1994; the two orbital solutions differ by an amount smaller than the bin size of our points): the light curve minima occur at phases 0 and 0.5, and the maxima at phases 0.25 and 0.75.

The H-band light curves of A0620–00 are shown in Figure 1, and the observations in J from 1996 December and in K from 1996 January are shown in Figure 2. The light curves all show an asymmetric, double-humped modulation. There were small fluctuations over the orbit from one observation to the next, but there was no gross variability in the shape or overall flux of the H light curve over the one-year course of our observations. The minimum at \( \phi = 0.5 \) is deeper than the primary minimum at \( \phi = 0 \) and the peak at \( \phi = 0.75 \) higher than the peak at \( \phi = 0.25 \) in all of the H-band light curves, and the same appears to be true in the (noisier) K light curve. The J-band light curve is too poorly sampled to determine the relative amplitudes of the peaks and troughs. The peaks and troughs in the data are smooth, showing no evidence of the sharp dips seen in B light curves circa 1986–1989 (Bartolini et al. 1990; Haswell et al. 1993; Haswell 1996). The shape of the light curves is very similar to that of a K-band light curve obtained in 1990 by Shahbaz, Naylor & Charles (1994). The phasing of the light curve peaks and troughs and the sense of the asymmetry in the peaks is the same in both observations. Our mean K and (J–K) colors are also close to the colors they found.

The shapes of the near-infrared light curves of A0620–00 are generally consistent with ellipsoidal modulation in a system of moderate to high inclination, but there are two clear deviations from a pure ellipsoidal modulation. First, there are small fluctuations (\( \approx 0.05 – 0.1 \) mJy) among the three observations in the amplitudes of the peaks relative to the troughs, indicating a variable source of flux in addition to the ellipsoidal modulation. The second deviation is the unequal maxima, which an ellipsoidal variation cannot produce. The bright spot is a plausible source for this asymmetry. It is seen in Doppler tomograms of the accretion disk in A0620–00 (Marsh, Robinson & Wood 1994) and would be expected to boost the peak at \( \phi = 0.75 \) relative to the \( \phi = 0.25 \) peak, as we observe. Superhumps from a precessing, non-circular disk or star spots on the K star could also cause asymmetries but, as we will show, they are less plausible sources for the asymmetries in our light curves.

3. Modeling the Light Curves

We modeled the near-infrared light curves of A0620–00 with a rewritten, updated version of the light curve synthesis code described in Zhang, Robinson & Nather (1986). The code simulates the light curves of binary systems and includes the equipotential geometry, limb and gravity darkening for the stars, and a limb-darkened, flared accretion disk with a bright spot on its edge and top surface. A significant improvement to the code is the use of specific intensities and quadratic limb darkening coefficients for cool stars obtained from fits to model stellar atmospheres of late-type stars (Allard & Hauschildt 1995; the fits to the model atmospheres are presented in Froning 1999b).
We fit three sets of models to the A0620–00 light curves. In the first set we assumed that only the K star contributes to the observed flux. For the second set we added an accretion disk with a bright spot on its edge. The third set was a series of models to estimate the effect of a non-varying source of diluting flux on the derived orbital inclinations. We modeled the H light curves only; the J and K data are of lower quality and do not warrant detailed modeling.

3.1. Models Including Only the K Star

We initially assumed that the K star is the only source of the observed flux. We assumed that the asymmetry in the observed light curve is caused by extra flux added to the peak at $\phi = 0.75$ and, to avoid this extra flux, we fit the models to the light curves only over phases from $\phi = 0$ to 0.51. We generated model light curves of the K star, varying each of the parameters that affect the shape of the ellipsoidal modulation in turn, and fit the light curves to the observed data by least squares.

The parameters that affect this model are: the orbital inclination, $i$, the mass ratio, $q$, the temperature of the K star at the pole, $T_2$, the quadratic limb-darkening coefficients and the gravity darkening coefficient, $\beta$. We varied the inclination from $i = 1^\circ - 89^\circ$ in $1^\circ$ steps and the K star temperature from $T_2 = 4000 - 4500$ K in increments of 100 K. The mass ratio in A0620–00 is known to be $q = 0.067$ (Marsh, Robinson & Wood 1994). We calculated models for this mass ratio but also for $q = 0.056$, 0.083 and 0.10 to check the dependence of our results on mass ratio. The limb darkening was modeled using quadratic limb darkening coefficients obtained from the model stellar atmospheres discussed above. We calculated models for gravity darkening coefficients of 0.05 and 0.08 (Sarna 1989) and we assumed that the K star fills its Roche lobe.

Figure 3 shows the best-fit models for each of the H-band light curves. The parameters for the models are given in Table 4. For the 1996 December light curve, the best-fit model for $q = 0.067$ has an inclination of $i = 44^\circ$; for the 1996 January light curve, $i = 38^\circ$ gives the best fit; and for the 1995 December light curve, models with $43^\circ - 45^\circ$ give good fits. The models are largely insensitive to variations in the mass ratio and are only weakly dependent on the temperature of the K star and the value of the gravity darkening coefficient. The best fits were typically obtained for $T_2 = 4100$ K and $\beta = 0.08$. More important, changes in these parameters had virtually no effect on the value of the best-fit inclination. For the 1996 January light curve, for example, the reduced $\chi^2$ of the best fits for each combination of the other parameters tested range from $\chi^2_{\nu} = 1.06 - 1.58$, but the inclinations for these models vary only from $i = 38^\circ - 41^\circ$. Similarly, the models calculated for the 1996 December light curve had $\chi^2_{\nu}$ between 2.62 and 3.01 and inclinations from $i = 45^\circ - 50^\circ$, while for the 1995 December light curve, $\chi^2_{\nu} = 1.13 - 1.18$ and $i = 43^\circ - 48^\circ$.

If the K star is the sole contributor to the near-infrared emission from $\phi = 0 - 0.51$, then the orbital inclination in A0620–00 is $i = 38^\circ - 45^\circ$ ($i = 38^\circ - 50^\circ$ for the extreme range of parameter values). This range is consistent with the results of Shahbaz, Naylor & Charles (1994), who found
a best fit to their K light curve of $i = 37^\circ$ for $q = 0.067$ and a 90% confidence interval of $i \simeq 30^\circ - 45^\circ$ for that mass ratio (their Fig. 2).

The assumption that the modulation of the light curve at these orbital phases is purely ellipsoidal is not correct, however. The amplitude of the $\phi = 0.25$ peak relative to the light curve minima is smaller in the 1996 January light curve than in 1995 December or 1996 December light curves. This leads to a lower value for the orbital inclination based on the 1996 January data ($i = 38^\circ$) and a range of possible inclinations ($38^\circ - 41^\circ$) that does not overlap those determined from the 1995/1996 December light curves ($i = 43^\circ - 50^\circ$). This change in the amplitude of the modulation even at $\phi = 0.25$ indicates that there is some source of variable contamination of the ellipsoidal modulation. It also gives a measure of the uncertainty in any determination of the inclination based on just one observation epoch: the inclinations derived from our three light curves have a range of 7$^\circ$. In summary, models including only the effect of ellipsoidal variations of the K star give a lower limit to the inclination of $i \geq 38^\circ$ and show that there is a variable distortion of the ellipsoidal variations even at $\phi = 0.25$.

3.2. Models Including the K Star and an Accretion Disk with a Bright Spot

We next modeled the light curves over the full binary orbit, adding an accretion disk and a bright spot to the K star. We have complete orbital coverage only in the H band, so we cannot constrain system parameters such as the temperature of the accretion disk and bright spot with our models. Rather, our goal was to find simple models with reasonable parameter values that fit the observed light curves in order to determine the range of possible values for the orbital inclination.

Since the derived orbital inclinations do not depend strongly on the mass ratio, the temperature of the K star, nor the gravity darkening coefficient, we fixed their values at $q = 0.067$, $T_2 = 4100$ K and $\beta = 0.08$. The inner radius of the accretion disk was fixed at 0.001 $R_{L1}$ and the outer radius at 0.5 $R_{L1}$, which is the outer radius in visible light found by Marsh, Robinson & Wood (1994). To allow for a beamed bright spot on the disk rim, we set the flare half-angle of the disk to a small but non-zero value of 1$^\circ$. The bright spot also extends onto the top surface of the disk from 0.45 – 0.5 $R_{L1}$ (Marsh, Robinson & Wood 1994). Since the bright spot is not eclipsed and since the disk has only a small flare, the spot component on the top of the disk merely adds to the constant disk flux and is otherwise irrelevant. The bright spot and accretion disk were each assumed to emit as single-temperature blackbodies, with the linear limb-darkening coefficients for the accretion disk obtained from Claret (1998). Previous observations of A0620–00 in quiescence have found no evidence for significant irradiation of the K star by the disk, so we did not include irradiation in our models.

The parameters we varied were: the orbital inclination, $i$, the temperature of the accretion disk, $T_{disk}$, the temperature of the bright spot, $T_{spot}$, the azimuthal position of the spot on the disk, $\phi_{spot}$ and the azimuthal full width of the spot, $\Delta \phi_{spot}$. We varied the inclination from $i = 1^\circ - 89^\circ$, ...
$T_{\text{disk}}$ from 2000 K – 5000 K, $T_{\text{spot}}$ from 5000 K – 25,000 K, $\phi_{\text{spot}}$ from 80° – 115° (measured with respect to the line connecting the centers of the stars and increasing in the direction of the orbital motion) and $\Delta \phi_{\text{spot}}$ from 5° – 15°.

Figure 4 shows the H light curves and the models with the lowest $\chi^2$ for the parameter values we tested. The output model parameters are given in Table 4. The fits demonstrate that simple models incorporating ellipsoidal variations from the K star and a two-component — constant flux plus a beamed bright spot — accretion disk can fully account for the near-infrared light curves of A0620–00. We reiterate that the models summarized above are not intended to provide real constraints on the properties of the accretion disk (the temperature of the bright spot, for example, is dependent on its assumed size and on the assumed temperatures of the K star and the accretion disk). Moreover, the fits presented above are definitely not unique. Virtually any model with $i > 38^\circ$ will fit the light curves equally well if $T_{\text{disk}}$ is increased with inclination. For example, a model with $i = 44^\circ$ and $T_{\text{disk}} = 2000$ K fits the 1996 January light curve as well as the model with $i = 70^\circ$ and $T_{\text{disk}} = 5000$ K shown in Figure 4.

Our light curves show no evidence of an eclipse, which does set an upper limit to the inclination. For the assumed disk size, $R_{\text{disk}} = 0.5 R_{L_1}$, we found that inclinations above 75° introduced eclipse features in the models inconsistent with the data. Marsh, Robinson & Wood (1994) found a similar limit, $i < 76^\circ$, based on the lack of observed rotational disturbance in the H$\alpha$ emission line. Our agreement with their upper limit is reassuring but not unexpected, as we used their values for the mass ratio and accretion disk radius in our models.

The sense of the asymmetry of the H-band light curve and the orbital phasing of the light curve peaks was stable over the one year covered by our observations. This long-term stability argues against a precessing, non-circular disk or star spots as sources of the asymmetry in the light curve peaks, as both are likely to produce a variable asymmetry. When the asymmetry is modeled by a bright spot on the edge of the disk, both the phase and the extent of the bright spot are the same in all three H-band light curves and, with less confidence, in the K-band light curve: $\phi_{\text{spot}} = 100^\circ – 110^\circ$ and $\Delta \phi_{\text{spot}} = 5^\circ – 10^\circ$. These results strongly support identifying the bright spot as the source of the extra flux at $\phi = 0.75$. The location of the bright spot in our models is not the same as the location of the spot in the Doppler maps of Marsh, Robinson & Wood (1994), who found $\phi_{\text{spot}} \simeq 55^\circ$ (their Figure 7). The position of a bright spot as seen in optical line emission will not necessarily coincide with the location of peak spot emission in the near-infrared (see, e.g., Littlefair et al. 2000, Froning et al. 1999) ; the difference between the two suggests that the near-infrared bright spot emission in A0620–00 originates downstream from the initial mass stream impact point.
3.3. Models with a K Star and a Constant Extra Flux.

Since there is a direct tradeoff between extra constant flux from the accretion disk (or any other source) and the orbital inclination inferred from the amplitude of the ellipsoidal variations, we ran a final set of models to determine how the inclination changes as disk flux is added to the light curve. To do this, we fit a K star model ($T_2 = 4100$ K, $\beta = 0.08$) to the 1996 January data and added increasing amounts of disk flux, specified in the light curve synthesis program as a fraction of the total light curve flux at $\phi = 0.25$. Table 5 shows the derived orbital inclination as the disk contribution increases. For no disk contribution, we recover the $38^\circ$ inclination found in Section 3.1. To allow orbital inclinations approaching $75^\circ$ – the upper limit set by the lack of eclipses – the disk would need to be contribute 55% of the H-band flux. Table 5 also shows that if the accretion disk contribution in the H-band is low, large fluctuations in the disk flux are needed to explain the change in the amplitude of the $\phi = 0.25$ peak discussed in Section 3.1: the 6–7$^\circ$ difference in the inclinations of our secondary star model fits to the three H light curves implies fluctuations of 20–25% in the contaminating flux at the $\phi = 0.25$ peak.

4. The Mass of the Compact Star

Based on our fits to the H-band light curves, we can constrain the inclination in A0620-00 to $38^\circ \leq i \leq 75^\circ$. The upper limit on the inclination is quite strict, as light curve models with $i \geq 75^\circ$ show both primary and secondary eclipse features not seen in the data. The lower limit on the inclination is also a fairly strict limit. The amplitude of the light curve modulation was larger in 1996 December and 1995 December than in 1996 January, indicating that the $38^\circ$ lower limit on the inclination derived from the latter is a probable underestimate of the true binary inclination caused by dilution of the ellipsoidal modulation by an accretion disk flux component.

From determinations of the orbital period, mass ratio and radial velocity semi-amplitude of the K star, Marsh, Robinson & Wood (1994) derived a mass $M_1 = (3.09 \pm 0.09) \sin^3 i \, M_\odot$ for the compact star in A0620-00. Combined with our limits on the inclination, this limits the mass of the compact star to lie in the range $3.3 \leq M_1 \leq 13.6 \, M_\odot$. The lower limit is close to, but remains larger than, the maximum mass of a uniformly rotating neutron star with the stiffest equation of state, $\sim 3.2 \, M_\odot$ (Friedman, Ipser & Parker 1986), and it is well above the maximum mass of a nonrotating neutron star, $1.8 - 2.5 \, M_\odot$ (Akmal, Pandharipande & Ravenhall 1998).

Haswell et al. (1993) identified a sharp dip in their UBVR light curves of A0620-00 as an eclipse of the K star by a large accretion disk (at or near the maximum radius for a circular disk inside the Roche lobe around the compact star). If this identification is correct, the inclination of A0620-00 is $65.75 \leq i \leq 73.5$ and the mass of the compact star is $3.40 \leq M_1 \leq 4.20 \, M_\odot$ (using the inclination range found by Haswell et al. 1993 for $q = 0.067$ and masses from the Marsh, Robinson & Wood 1994 equation for $M_1$ given above). Johnston et al. (1989) also invoked a large accretion disk to model 1986 spectroscopic observations of A0620–00. Haswell (1996) explained the large disk and
the grazing eclipse in the context of a non-circular, precessing accretion disk model for A0620–00: as the orientation of the non-circular disk changes over the long ($\gg P_{\text{orb}}$) precession period, eclipses appear and disappear and superhumps move through the light curve, causing changes in the shape of the light curves as was, indeed, seen from 1981 – 1989 in A0620–00.

Leibowitz, Hemar & Orio (1998) found that A0620–00 exhibited slow fluctuations in its mean optical brightness between 1991 and 1995 with a peak-to-peak amplitude of 0.3 – 0.4 mag in the R band. They did not find any periodicities in the fluctuations. Specifically, they found no evidence of a superhump period nor of a beat period between the superhump and orbital periods. The shape of the orbital light curve varied somewhat with brightness, but the sense of the asymmetry between the two peaks never reversed. There is, therefore, no evidence for current or recent superhumps in A0620–00. Haswell (1996) concluded that, after 1989 the accretion disk had shrunk below the radius necessary to trigger the tidal interactions that drive superhumps.

The most serious challenge to the superhump model comes from Marsh, Robinson & Wood (1994), who re-analyzed the 1986 observations of Johnston et al. (1989) and concluded that both the 1986 and the 1991/92 data sets—which straddle the observations of Haswell et al. (1993)—are consistent with a smaller accretion disk, $R_{\text{disk}} = 0.5 – 0.6 R_{L1}$, one too small to drive superhumps. They note, however, that their accretion disk radius is based on the radius of $H\alpha$ emission and could be smaller than the radius of the optically thick accretion disk used by Haswell et al. (1993).

Shahbaz, Naylor & Charles (1994) also narrowly constrained the derived inclination for A0620–00 to $30^\circ \leq i \leq 45^\circ$, corresponding to $8.49 \leq M_1 \leq 25.4 M_\odot$. Their best-fit value for $q = 0.067$ was $i = 37^\circ$, which corresponds to $M_1 = 14.2 M_\odot$. Their analysis was predicated on the assumption that the accretion disk does not contaminate the K-band flux from the K star. To test this, Shahbaz, Bandyopadhyay & Charles (1999) obtained a K-band spectrum of A0620–00 to which they fit scaled template spectra of stars of known spectral type. From this, they concluded that the K star provides $75\pm17\%$ of the K-band flux. They noted that a 27% accretion disk contribution (their maximum likely disk fraction) would increase the minimum inclination in A0620–00 by $7^\circ$ and decrease the mass of the compact star by $3.6 M_\odot$. If the accretion disk does contribute $\sim 25\%$ of the near-infrared flux, their three observations would indicate an inclination of $i = 46^\circ – 53^\circ$ and a corresponding mass of $5.9 < M_1 < 8.5 M_\odot$.

To determine the contribution of the disk to the infrared spectrum, Shahbaz, Bandyopadhyay & Charles (1999) fit the template spectra to just the $\lambda 2.29 \mu m ^{12}\text{CO}(2,0)$ bandhead. The use of this feature to estimate the disk contribution is problematic for several reasons. First, the CO molecular line strengths are both temperature and gravity dependent (e.g., Kleinman & Hall 1986). While the spectrum of the K star in A0620–00 is clearly inconsistent with that of a giant star (luminosity class III), its effective gravity could still be significantly lower than the gravity of a main-sequence star (Oke 1977; Murdin et al. 1980). Shahbaz, Bandyopadhyay & Charles (1999) used only dwarf stars for their template spectra, so their results could not distinguish gravity dependent changes in the $\lambda 2.29 \mu m ^{12}\text{CO}(2,0)$ line strength. Second, observations of cataclysmic variables have shown
that in some systems, $^{12}$CO absorption is weaker relative to the strengths of the atomic absorption lines than expected for their donor star spectral types (Harrison, Szkody & Johnson 1999). In addition, the ratio of the $^{12}$CO bandhead equivalent width to those of the atomic lines can vary with time (Ramseyer et al. 1993). The reason for these abnormalities in the CO absorption line strengths is not yet understood. Thus, using the strength of the $\lambda 2.29 \mu m$ $^{12}$CO(2,0) bandhead to measure the contribution of the disk to the infrared flux gives unreliable results. The measurements by Shahbaz, Bandyopadhyay & Charles (1999) do not settle the question of how much flux the disk contributes to the light curve of A0620-00 at infrared wavelengths. The orbital inclination could, therefore, be significantly higher than the lower limit set by the ellipsoidal variations ($i > 38^\circ$) and the mass of the compact star much less than the upper limit ($M_1 < 13.6 M_\odot$).

5. Conclusions

1. The infrared light curves of the black hole binary A0620–00 show an asymmetric, double-humped modulation with extra emission in the peak at phase $\phi = 0.75$. There were no gross changes in the morphology of the light curves over a one year period from 1995 December to 1996 December. The mean infrared colors and the shape of the light curve are also the same as observed in 1990 January. There were no sharp dips in the light curve nor reversals of the asymmetry between the two humps as were seen in observations circa 1986 – 1989.

2. The light curves are consistent with ellipsoidal variations from the K star plus beamed flux from a spot on the accretion disk. A precessing disk is an unlikely source of light curve modulation during the observation period. Star spots are also ruled out unless the spot is fixed in location and size on the K star surface.

3. Based on fits to the lower peak in the light curve (between $\phi = 0$ and 0.51), the minimum inclination in A0620–00 is $i \geq 38^\circ$. From the absence of eclipse features in the light curves, models including an accretion disk of radius $R_d = 0.5 R_{L_1}$ give an upper limit to the inclination of $i \leq 75^\circ$. The mass of the compact star in A0620–00 is $3.3 < M_1 < 13.6 M_\odot$.

4. Ellipsoidal variations provide only a lower limit to the inclination of non-eclipsing binary systems when the contribution of the accretion disk is unknown. A previous attempt to determine the relative contribution of the accretion disk and K star to the near-infrared flux used the strength of the $\lambda 2.29 \mu m$ $^{12}$CO(2,0) bandhead. This method is not reliable.

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Table 1. Observations of A0620–00

| Date (UT)    | Filter(s) | Total Exposure Time (ksec) |
|--------------|-----------|----------------------------|
| 1995 Dec 15  | H         | 3.72                       |
| 1995 Dec 16  | H         | 3.46                       |
| 1995 Dec 17  | H         | 1.92                       |
| 1996 Jan 27  | H,K       | 3.60, 0.25                 |
| 1996 Jan 28  | H         | 0.70                       |
| 1996 Jan 29  | H,K       | 4.40, 0.35                 |
| 1996 Dec 7   | H         | 2.96                       |
| 1996 Dec 8   | J,H       | 1.16, 0.72                 |
| 1996 Dec 9   | J,H       | 1.34, 1.48                 |
| 1996 Dec 10  | J,H       | 1.16, 1.40                 |
| 1996 Dec 12  | J,H       | 0.20, 3.56                 |
Table 2. Reference Stars in A0620–00 Field

| Star  | Position\(^a\) | J     | H     | K     |
|-------|----------------|-------|-------|-------|
| Star 1 | 18"N, 18"W     | 13.4±0.1 | 12.92±0.02 | 12.78±0.03 |
| Star 2 | 19"N, 5"W      | 15.0±0.1 | 14.34±0.02 | 14.06±0.03 |
| Star 3 | 37"N, 14"E     | 15.4±0.1 | 14.79±0.02 | 14.57±0.03 |

\(^a\)Relative to A0620–00.

Note. — The error bars given are the uncertainties in the flux calibration only. In J and H, this is the dominant uncertainty, but in K, where little data was acquired, the standard deviation about the mean for each star’s measurements is of order the flux calibration uncertainty.
Table 3. NIR Colors of A0620–00

| Date         | Filter | Mean color |
|--------------|--------|------------|
| 1995 December| H      | 14.80±0.02 |
| 1996 January | H      | 14.83±0.02 |
| 1996 January | K      | 14.49±0.03 |
| 1996 December| J      | 15.6±0.1   |
| 1996 December| H      | 14.84±0.02 |

Note. — The error bars shown are the uncertainties in the flux calibration only.
Table 4. Parameters of best fit light curve models.

| Light Curve       | $\chi^2$ | $i$  | $T_{disk}$ | $T_{spot}$ | $\phi_{spot}$ | $\Delta\phi_{spot}$ |
|-------------------|----------|------|------------|------------|-----------------|----------------------|
| Secondary star only |          |      |            |            |                 |                      |
| 1996 December     | 2.62     | 44°  | ...        | ...        | ...             | ...                  |
| 1996 January      | 1.06     | 38°  | ...        | ...        | ...             | ...                  |
| 1995 December     | 1.13     | 43° – 45° | ...    | ...        | ...             | ...                  |
| Secondary star plus accretion disk and bright spot |          |      |            |            |                 |                      |
| 1996 December     | 1.88     | 74°  | 5000 K     | 25,000 K   | 100°            | 5°                   |
| 1996 January      | 0.83     | 70°  | 5000 K     | 20,000 K   | 100°            | 10°                  |
| 1995 December     | 1.32     | 53°  | 2000 K     | 25,000 K   | 115°            | 10°                  |

Note. — For all models listed, $q = 0.067$, $T_2 = 4100$ K, $\beta = 0.08$. For the models including an accretion disk, the disk extends from $0.001 \, R_{L_1}$ to $0.5 \, R_{L_1}$. The radial extent of the bright spot is $0.45 – 0.5 – R_{L_1}$, and the disk has a flare half-angle of $1°$. 
Table 5. Best fit inclination vs. fractional disk contribution for 1996 January lightcurve.

| $i$ (°) | $f_{\text{disk}}$ | $i$ (°) | $f_{\text{disk}}$ |
|---------|-------------------|---------|-------------------|
| 38      | 0                 | 54      | 0.4               |
| 39      | 0.05              | 58      | 0.45              |
| 41      | 0.1               | 64      | 0.5               |
| 42      | 0.15              | 72      | 0.55              |
| 44      | 0.2               | 89      | 0.6               |
| 46      | 0.25              | 89      | 0.65              |
| 48      | 0.3               | 89      | 0.7               |
| 51      | 0.35              |         |                   |
Fig. 1.— The 1996 December, 1996 January and 1995 December H-band light curves of A0620–00, plotted over one and a half cycles in orbital phase. The data are binned to 0.01 in orbital phase. Orbital phase zero corresponds to inferior conjunction of the mass-losing star.
Fig. 2.— The 1996 December J-band light curve and the 1996 January K-band light curve of A0620–00, plotted over one and a half cycles in orbital phase. The J observations are binned to 0.01 in orbital phase. The K observations are binned to 0.05 in orbital phase. Orbital phase zero corresponds to inferior conjunction of the mass-losing star.
Fig. 3.— The H-band light curves of A0620–00 and the best-fit model including only the K star ellipsoidal variations. The models were fit to the light curves from $\phi = 0 - 0.51$ only, assuming that the K star is the sole source of flux at those orbital phases. The orbital inclinations of the models are $i = 44^\circ$, $38^\circ$ and $45^\circ$ for 1996 December, 1996 January and 1995 December, respectively.
Fig. 4.— The H-band light curves of A0620–00 with an example of a successful K star plus accretion disk and bright spot model overplotted for each. For 1996 December, the model shown has $i = 74^\circ$ and $T_{\text{disk}} = 5000$ K. For 1996 January, $i = 70^\circ$ and $T_{\text{disk}} = 5000$ K and for 1995 December, $i = 53^\circ$ and $T_{\text{disk}} = 2000$ K.