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A BLACK HOLE GREATER THAN 6 $M_\odot$ IN THE X-RAY NOVA XTE J1118+480[1]

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ABSTRACT

Observations of the quiescent X-ray nova XTE J1118+480 with the new 6.5 m Multiple Mirror Telescope have revealed that the velocity amplitude of the dwarf secondary is 698 ± 14 km s^{-1} and the orbital period of the system is 0.17013 ± 0.00010 days. The implied value of the mass function, $f(M) = 6.00 \pm 0.36\ M_\odot$, provides a hard lower limit on the mass of the compact primary that greatly exceeds the maximum allowed mass of a neutron star ($\sim 3\ M_\odot$). Thus, we conclude that the compact primary is a black hole. Among the 11 dynamically established black hole X-ray novae, the large mass function of XTE J1118+480 is rivaled only by that of V404 Cyg. We estimate that the secondary supplies 34% ± 8% of the total light at 5900 Å and that its spectral type is in the range from K5 V to M1 V. A double-humped *I*-band light curve is probably due to ellipsoidal modulation, although this interpretation is not entirely secure because of an unusual 12 minute offset between the spectroscopic and photometric ephemerides. Assuming that the light curve is ellipsoidal, we present a provisional analysis that indicates that the inclination of the system is high and the mass of the black hole is correspondingly modest ($M_1 \lesssim 10\ M_\odot$). The broad Balmer emission lines (FWHM = 2300–2900 km s^{-1}) also suggest a high inclination. For the range of spectral types given above, we estimate a distance of 1.8 ± 0.6 kpc.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (XTE J1118+480) — X-rays: stars

1. INTRODUCTION

The X-ray nova XTE J1118+480 was discovered with the *Rossi X-Ray Timing Explorer* All-Sky Monitor on 2000 March 29 (Remillard et al. 2000). In outburst the optical counterpart brightened by about 6 mag to $V \approx 13$ (Uemura et al. 2000). Extensive optical data in outburst reveal that the orbital period is ≈4.1 hr (Patterson 2000; Uemura et al. 2000; Garcia et al. 2000; Dubus et al. 2001). XTE J1118+480 has one truly exceptional attribute: its low reddening, $E(B-V) \approx 0.013$ mag ($N_{\rm H} \approx 1.0 \times 10^{20}$ cm^{-2}; Hynes et al. 2000). It is the least reddened of all known X-ray binaries.

Including XTE J1118+480, very strong evidence now exists for black hole primaries in 11 X-ray novae (McClintock 1998; Filippenko et al. 1999; Orosz et al. 2001). Since XTE J1118+480 was known to be optically bright in quiescence ($R \approx 18.8$; Uemura et al. 2000), the source appeared to be a good prospect to become the 11th black hole X-ray nova. Thus, we monitored the brightness of the optical counterpart closely when it first appeared in the night sky in late October, and we found that it had returned to its preoutburst brightness (e.g., $V = 19.0$ on 2000 October 29.48 UT). In early December, using the new 6.5 m Multiple Mirror Telescope (MMT), we obtained the spectroscopic observations detailed herein.

2. OBSERVATIONS AND ANALYSIS

Spectroscopic observations of XTE J1118+480 were obtained with the new 6.5 m MMT at the F. L. Whipple Observatory (FLWO) on the nights of 2000 December 1 and 4 (UT). The blue channel spectrograph was used with the Loral CCD (3072 × 1024) detector and the 500 groove mm^{-1} grating. This configuration yielded ≈3.6 Å resolution (FWHM) for a slit width of 1″.0, which approximately matched the seeing on the two observing nights. The sky conditions were clear. Two exposures of XTE J1118+480 (900 s each) were obtained on December 1, and six additional exposures (900–1200 s each) were obtained on December 4. Immediately before and after each observation of the object, an exposure was obtained of a wavelength calibration lamp (He-Ne-Ar). We also observed BD +12447, an M2 dwarf with a well-determined systemic velocity, and the flux standard Feige 34. In our data analysis, we also made use of spectra of six additional dwarf stars, which were obtained with precisely the same focal-plane instrumentation in earlier MMT observing runs. The wavelength calibrations were interpolated dispersion solutions scaled according to the time of an observation relative to the time of the lamp exposures. Cross correlations between the flux-calibrated spectra of XTE J1118+480 and the template spectra of the G/M dwarfs were computed for the range 4900–6500 Å. The spectral reductions and cross-correlation analysis were performed using the software package IRAF.[5]

Photometric monitoring observations were performed using the 1.8 m Vatican Advanced Technology Telescope (VATT) located at the Mount Graham International Observatory on the nights of 2000 November 30 and December 1 (UT). These observations were conducted using the VATT CCD camera and Loral CCD detector (2048 × 2048 pixels) and a Harris *I* filter ($\lambda_0 = 8105$ Å; FWHM = 1624 Å). The CCD was binned at 2 × 2 pixels providing a scale of 0″.4 pixel^{-1}. Ninety-six consecutive images were obtained on November 30, and an additional 53 images were obtained on December 1. The typical integration time was 120 s, and the time between consecutive

[1] Observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

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[5] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

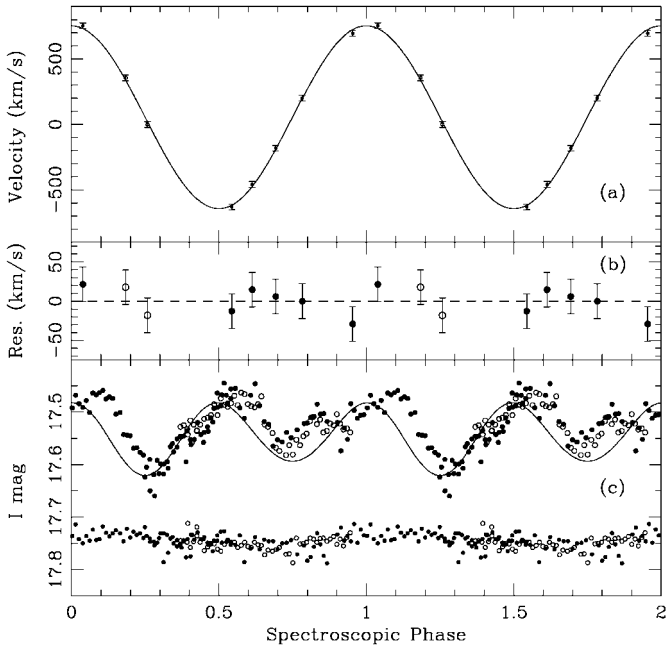

FIG. 1.—Spectroscopic and photometric data folded on the orbital period and the ephemeris given in Table 1. (*a*) Radial velocity measurements of the secondary star. The smooth curve is a fit to a circular orbit based on the velocity amplitude and phase given in Table 1. (*b*) The residual differences between the data and the fitted curve. Open and filled symbols are for December 1 and 4, respectively. (*c*) The top trace is the *I*-band light curve of XTE J1118+480 with a superposed ellipsoidal model. Filled and open symbols are for November 30 and December 1, respectively. The bottom trace shows the intensity of a nearby comparison star of magnitude $I = 17.0$; the trace is shown here offset by 0.75 mag for convenience of display. The rms variation in the star's intensity is 0.015 mag.

observations was typically 3 minutes. On both nights, seeing was 2″ at the start of the observations due to high air mass but quickly improved to 1″ thereafter. There was light cirrus on the first night, and the second night was clear. Images were processed to eliminate the electronic bias, correct for pixel-to-pixel sensitivity variations, and remove significant interference fringes in the images. The relative intensities of XTE J1118+480 and selected field stars were computed using DAOPHOT photometry. The photometric calibration was performed using Landolt standard stars.

3. SPECTROSCOPIC RESULTS

We used the spectra of the velocity standards as cross-correlation templates to derive a radial velocity curve for the secondary star. The eight individual spectra of XTE J1118+480 were cross-correlated against each of our seven template stars, which ranged in spectral type from G8 V to M2 V. Comparable velocity curves were obtained with each template spectrum. However, based on the Tonry & Davis (1979) *R*-value, which is a measure of signal-to-noise ratio achieved in a cross-correlation, we found that the K3 V, K5 V, and K5/8V templates yielded the best correlations. The eight velocities derived using the K5/8V template star, GJ 9698, are shown in Figure 1*a*. The velocity data imply that the secondary star in XTE J1118+480 is orbiting a compact object with a velocity amplitude of approximately 700 km s^{-1}. The large velocities of the secondary contrast sharply with the behavior of the night-sky lines, which show an rms variation of less than 10 km s^{-1}.

Assuming a sine function, the velocities are well fitted by the orbital parameters given in Table 1, where T_0 is the time of maximum velocity, V_0 is the systemic velocity, K_2 is the velocity semiamplitude of the secondary, and P is the orbital period. These four parameters were fitted simultaneously using the interactive data language routine CURVEFIT. A preliminary account of these dynamical results (McClintock et al. 2000) and the consistent results obtained by a second group (Wagner et al. 2000) appeared earlier in the IAU circulars. In § 4 we argue that the period given in Table 1 is the correct orbital period, not an alias. In fitting the velocities, we have assumed that the eight velocity errors are all the same because the *R*-values are all comparably high (≈7–12). We have adjusted this error to the value 24 km s^{-1} in order to give $\chi^2_\nu = 1.0$. The orbital parameters in Table 1 define the velocity ephemeris, which is represented by the solid line in Figure 1*a*. The postfit residuals are shown in Figure 1*b*. The mass function may be derived from the above results:

$$f(M) \equiv \frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \frac{PK_2^3}{2\pi G} = 6.00 \pm 0.36\ M_\odot.$$

Since the mass of the compact primary necessarily exceeds the value of the mass function, our results imply that the primary is much too massive to be a neutron star within general relativity and is therefore a black hole (Rhoades & Ruffini 1974).

An average of the six spectra taken on December 4 in the rest frame of the secondary star is shown in Figure 2*a*. Before averaging the individual spectra, they were Doppler shifted to zero velocity using the velocities predicted by the ephemeris in Table 1. The spectrum of the template star, GJ 9698, is shown in Figure 2*b* for comparison. Most of the stronger absorption lines of GJ 9698 are evident in XTE J1118+480. The most prominent features are the continuum discontinuity at Mg *b* (~5175 Å) and the Na I 5890–96 Å doublet. As noted above, the cross-correlation analysis favors template stars of mid-K spectral type over those with spectral types of M0 V or later. However, an inspection of the rest-frame spectrum itself suggests that it is somewhat later than mid-K. Given our limited signal-to-noise ratio, we conclude that the spectral type of the secondary is in the range K5–M1. Since the orbital period and mass estimates imply a binary separation of ~3 $R_\odot$, the secondary is presumed to be luminosity class V.

Because of the very low column depth to the source (§ 1), the Na I line is quite free of interstellar contamination. We therefore use its equivalent width to estimate the relative contributions of the secondary star and the accretion disk to the total light at 5900 Å. For the spectrum of XTE J1118+480 (Fig. 2*a*) we find EW = 2.8 ± 0.2 Å. For five comparison stars with spectral types ranging from K5 V to M1 V, we find EW = 6.6–10.8 Å. From these results, we conclude that the K/M dwarf secondary

TABLE 1
SPECTROSCOPIC ORBITAL PARAMETERS

Parameter	Value
T_0 (UT)[a]	2000 Dec 1.6476 ± 0.0010
T_0 (heliocentric)[a]	JD 2,451,880.1485 ± 0.0010
V_0 (km s^{-1})	26 ± 17
K_2 (km s^{-1})	698 ± 14
P (days)	0.17013 ± 0.00010
$a_2 \sin i$ ($R_\odot$)[b]	2.35 ± 0.05
$f(M/M_\odot)$	6.00 ± 0.36

[a] Time of maximum redshift.
[b] Projected orbital radius of the secondary.

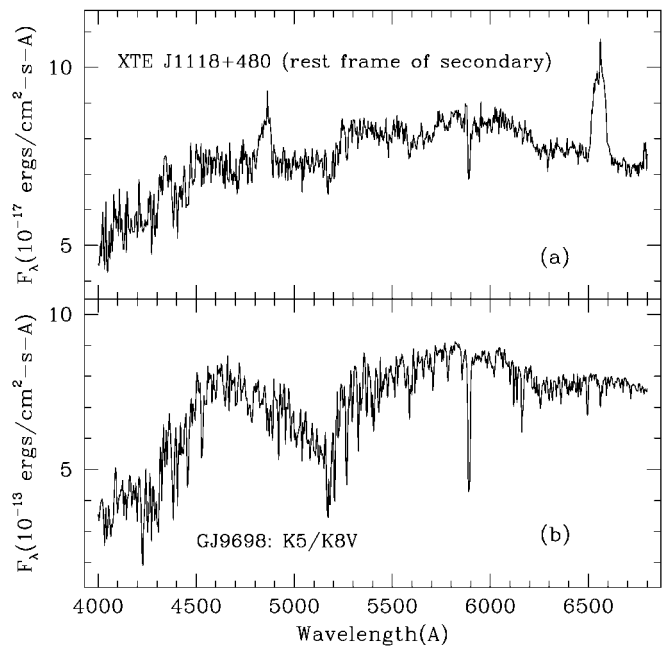

FIG. 2.—(*a*) Spectrum of XTE J1118+480 in the rest frame of the secondary star. The photospheric absorption features are most apparent in this frame; however, the prominent Balmer emission lines are significantly distorted. (*b*) The spectrum of GJ 9698, which was used as a velocity template for the cross-correlation analysis.

contributes 34% ± 8% of the total light at 5900 Å, a result we use in § 4 to analyze the ellipsoidal light curve and we now use to estimate the distance to the source.

We estimate the distance to XTE J1118+480 using "method 2" described in Barret, McClintock, & Grindlay (1996). For the secondary, we compute an average density of $\rho = 6.9$ g cm^{-3} from the orbital period and assume $M_2 = 0.4\ M_\odot$, which is very probably correct to within a factor of 2 (e.g., van Paradijs & McClintock 1994). With these inputs we calculate $R_2 = 0.45\ R_\odot$. We use the total magnitude of the optical counterpart, $V = 19.0$ (§ 1), and the fraction of the light contributed by the secondary, to estimate the magnitude of the secondary: $V = 20.1 \pm 0.3$. Finally, for the range of spectral types in question, K5 V–M1 V, we obtain an estimate of the distance: $d = 1.8 \pm 0.6$ kpc. There are two nearly equal (~25%) contributions to the error: the uncertainty in the spectral type of the secondary and the (assumed) factor of 2 uncertainty in the mass of the secondary.

The spectrum of XTE J1118+480 shows strong Balmer emission lines, which indicate the presence of an accretion disk. In individual exposures, the Balmer lines are often double-peaked and quite broad with widths in the range 2300–2900 km s^{-1} (FWHM).

4. PHOTOMETRY RESULTS

The *I*-band light curve of XTE J1118+480 folded on the spectroscopic ephemeris is shown in Figure 1*c*; data for a comparison star of comparable magnitude are plotted just below. The light curve shows two maxima and two minima per orbital cycle. This behavior is the hallmark of an ellipsoidal light curve, which is commonly observed for quiescent black hole X-ray novae. However, the light curve deviates significantly from an ideal ellipsoidal light curve, which is represented by the solid line (see § 5), in several ways. For example, there is extra light near phase 0.8, which may be due to the bright spot (Warner 1995). A more problematic deviation from the ellipsoidal model is the apparent phase lag of the light curve relative to the spectroscopic ephemeris. Fitting the light curve to a sinusoid gives a phase lag of 0.050 ± 0.008, which corresponds to a time delay of 12.2 ± 2.0 minutes. In contrast, studies of other quiescent X-ray novae indicate good agreement between the photometric and spectroscopic phases (e.g., McClintock & Remillard 1986; Shahbaz et al. 1994; Orosz & Bailyn 1997). Consequently, this 12 minute phase lag calls into question the ellipsoidal nature of the light curve. Possibly XTE J1118+480 was not yet fully quiescent during our observations, even though our dynamical results (Table 1) are entirely consistent with those obtained more than a month earlier by Wagner et al. (2000). Possibly our light curve is dominated by eclipse effects, which can effectively shift the phase of a light curve. An example of this phenomenon is the set of light curves observed for GRO J1655−40 as it approached quiescence in early 1995 (see Fig. 1 in Bailyn et al. 1995). Future observations in deep quiescence can be expected to resolve these issues. In the meantime, we assume below in § 5 that the light curve is ellipsoidal.

Could this 12 minute phase difference be due to an error in the data clock at either the VATT or the MMT? We believe that the answer to this question is "no," despite the fact that the performance of these clocks was not rigorously checked at the time of the observations. The time base for both observatories is Network Time Protocol (NTP) via SUN computers, which routinely provides reliable and precise time to these observatories. Moreover, both observatories also use their NTP connection for the precise (~1″) pointing of their telescopes. If the NTP-based time had been in error by even 10 s during the observations, the telescope operator and observer would have noted gross errors in the telescope pointing; none was observed. Finally, independent and simultaneous photometry of XTE J1118+480 was obtained by P. Groot using the FLWO 1.2 m telescope; the light curve derived from these data agrees in phase with our VATT light curve to within 0.010 in phase or 2.4 minutes in time. We conclude that a terrestrial origin of the 12 minute phase offset appears very unlikely, and we believe that the offset is due to the source itself.

We searched the photometric data shown in Figure 1*c* for periodicities by computing the variance statistic of Stellingwerf (1978) for trial periods between 0.01 and 0.5 days. Deep minima in the Θ-statistic occur only at $P_{\rm phot} = 0.170 \pm 0.006$ days and at half that period. The statistical uncertainty in the period determination was estimated using a Monte Carlo method (Silber et al. 1992). The adopted *spectroscopic* period is approximately $P = 0.1701 \pm 0.0001$ days (Table 1), and its two closest aliases are $P_- = 0.1610$ days and $P_+ = 0.1803$ days. We now give four reasons for rejecting these alias periods and adopting $P = 0.1701$ days as the orbital period: (1) The light curves obtained by folding the photometric data on P_- and P_+ are complex and much less compelling than the light curve shown in Figure 1*c*, as expected since they differ from the best photometric period by greater than 1.5 σ. (2) A superhump modulation (Warner 1995) was repeatedly observed during outburst; its period decreased from 0.1708 ± 0.0001 days (Patterson 2000) to 0.1703 ± 0.0001 days (Uemura et al. 2000) over the course of several weeks. These results argue very strongly in favor of $P = 0.1701 \pm 0.0001$ days and against the aliases (e.g., Bailyn 1992; Kato, Mineshige, & Hirata 1995). (3) The T_0 given by Wagner et al. (2000) agrees with our T_0 for $P = 0.1701 \pm 0.0001$ days but disagrees if one adopts P_- or P_+. (4) Wagner et

al. (2000) independently found $P = 0.1699 \pm 0.0001$ days with spectroscopic observations separated by 10 nights. We therefore conclude that $P = 0.17013 \pm 0.00010$ days is the correct orbital period.

5. ON THE MASS OF THE BLACK HOLE

We now use the absence of X-ray eclipses and a preliminary analysis of the light curve to further constrain the mass of the black hole. Despite very extensive X-ray observations of XTE J1118+480 in outburst, no X-ray eclipses have been reported. We can use this result to place an upper limit on the inclination angle, which boosts somewhat the $6.0\ M_\odot$ mass limit that is set by the mass function. We consider two models for the secondary: (1) First is an $0.5\ M_\odot$ star with a radius of $0.5\ R_\odot$ that just fills its Roche lobe. In this case, we find that an absence of eclipses implies $i < 79.^\circ5$ and $M_1 > 7.2\ M_\odot$. (2) Second is a very low mass secondary, $M_2 = 0.2\ M_\odot$, which we assume just fills its Roche lobe radius of $0.35\ R_\odot$. In this case, we find $i < 81.^\circ8$ and $M_1 > 6.5\ M_\odot$. Here we have used the mean radius of the Roche lobe in calculating the eclipse condition.

We modeled the *I*-band light curve (Fig. 1*c*), which we assume to be ellipsoidal (but see § 4), using a computer code written by Avni (1978; see also Orosz & Bailyn 1997). We assumed a K7 V stellar atmosphere, a limb-darkening coefficient of $u = 0.60$ (Al-Naimiy 1978), and a gravity-darkening exponent of $\beta = 0.08$. We assumed that the star fills its Roche lobe and that its rotation period is the orbital period. We further assumed that $M_1/M_2 = 20$, although the light curve is very insensitive to the choice of this parameter for $M_1/M_2 \gtrsim 10$. The biggest uncertainty is the fraction of the light at 8100 Å that is nonstellar; we call this component the "disk fraction." For the purposes of this approximate analysis, we assume that the disk fraction at 8100 Å is 66%, the same as the value we derived at 5900 Å in § 3. We computed a set of ellipsoidal models for the star for $i = 40^\circ$ to $i = 90^\circ$ in steps of 5°. To each model, we added a constant component of the flux corresponding to the 66% contribution of the accretion disk.

The model that best matches the folded light curve is shown in Figure 1*c*. This model corresponds to a very high inclination, $i = 80^\circ$, and a value for the mass of $M_1 = 7.2\ M_\odot$ (for $M_2 = 0.5\ M_\odot$). This result is consistent, but just barely, with the limits obtained above from the absence of X-ray eclipses. There are several caveats on this preliminary analysis, the most important of which concerns our use of the disk fraction at 5900 Å as a proxy for the unknown disk fraction at 8100 Å. The available evidence indicates that the disk fraction decreases with increasing wavelength (e.g., Oke 1977; Casares et al. 1993; Marsh, Robinson, & Wood 1994). Consequently, we have very likely added too much disk light to our models. As a hypothetical example, consider the effect of adding a disk fraction of only 40% (instead of 66%) to our models. In this case we would have found $i = 52^\circ$ and $M_1 = 13.2\ M_\odot$ (for $M_2 = 0.5\ M_\odot$). A very strong upper limit on the mass is obtained by making the extreme assumption that the disk contributes no light at all in the *I* band. In this case we find $i > 40^\circ$ and $M_1 < 24\ M_\odot$. Despite the overriding uncertainty in the *I*-band disk fraction, our provisional light curve results suggest that the orbital inclination is relatively high, $i \gtrsim 55^\circ$, and that the black hole mass is correspondingly modest $M_1 \lesssim 10\ M_\odot$. The broad Balmer emission lines (§ 3) also suggest a high inclination.

6. CONCLUSION

With XTE J1118+480, there are now 11 X-ray novae that have been dynamically confirmed to contain black hole primaries. For XTE J1118+480, we find an exceptionally large mass function, $6.00 \pm 0.36\ M_\odot$, which is rivaled only by that of V404 Cyg (Casares, Charles, & Naylor 1992). XTE J1118+480 is additionally distinguished by having the shortest orbital period (4.08 hr) of the black hole binaries. Finally, the extraordinarily low column depth ($N_{\rm H} \approx 1.3 \times 10^{20}$ cm^{-2}) and modest distance (~1.8 kpc) of XTE J1118+480 make this system central to the study of Galactic black holes.

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