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PERIODIC PHOTOMETRIC VARIABILITY OF THE BLACK HOLE BINARY V404 CYGNI

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ABSTRACT

Recently, Casares, Charles, & Naylor (1992) reported the discovery of absorption lines characteristic of a late G- or early K-type star with a radial velocity curve of amplitude 211 km s^{-1} and a period of 6.473 days in the quiescent spectrum of the X-ray nova V404 Cygni. The mass function implied by these observations is $6.3 \pm 0.3\ M_\odot$ and can be considered as a lower limit to the mass of the compact object, which is then most likely a black hole. We have obtained CCD photometry, in the *I* band, of V404 Cyg during 1990, 1991, and 1992 and have discovered periodic variations having a period of 6.474 ± 0.005 days with a full amplitude of 0.2 mag, thus confirming the previously reported spectroscopic period. The light curve consists of two maxima and two minima per cycle, and the shape suggests that it is due to ellipsoidal variations of the secondary star which is tidally distorted by the presence of the massive compact object. We find that the hypothesis that the secondary star consists of a 4 $M_\odot$ K0 III star can be excluded. Instead, we propose that the secondary is a $\simeq 1\ M_\odot$ K0 IV star with $M_V \simeq 2.5$ mag at a distance of $\simeq 3.5$ kpc. Our results suggest that if the secondary star is nearly filling its Roche lobe, then the orbital inclination must be about 60°. If the inclination is as high as 80°, a plausible upper limit since no X-ray eclipses were observed, then the secondary star fills about 90% of the Roche lobe. Combining the spectroscopic and photometric results, we find that these limits imply a compact star mass of 8–12 $M_\odot$ and thus strengthen the evidence that the compact star is extremely massive and possibly a black hole.

Subject headings: accretion, accretion disks — binaries: spectroscopic — black hole physics — stars: individual: V404 Cygni — stars: variables: other — X-rays: stars

1. INTRODUCTION

X-ray novae comprise a subset of low-mass X-ray binaries (LMXRBs) which consist of a late-type optical companion star and a neutron star or black hole. In most LMXRBs, the intrinsic optical spectrum of the companion star is overwhelmed by the light of the accretion disk surrounding the compact object. In quiescent X-ray novae, however, the accretion disk contributes a much smaller fraction of the optical light and thus provides an opportunity to study the nature and orbital parameters of the companion star. For example, photometric and spectroscopic observations of another X-ray nova in quiescence, A0620−00 (V616 Mon), suggest that the binary system consists of a mid-K–type main-sequence companion star and a black hole (McClintock & Remillard 1986; Haswell & Shafter 1990) with a mass exceeding $\simeq 3.8\ M_\odot$.

A new X-ray nova, cataloged as GS 2023+338, was discovered by the Japanese *Ginga* X-ray satellite on 1989 May 21. On May 27, the X-ray source was identified optically with V404 Cygni (Marsden 1989; Wagner, Starrfield, & Cassatella 1989), a 12.5 mag optical nova whose last major outburst was in 1938. In contrast to other X-ray novae in outburst such as A0620−00, optical spectra of V404 Cyg exhibited a strong and rich emission-line spectrum superposed on a reddened continuum indicative of a high luminosity. Between 1989 June and 1990 June the mean visual brightness of V404 Cyg declined steadily, and since 1990 June, has remained relatively constant at $V \simeq 18$ mag, indicating that it had subsided into quiescence and, thus, had returned to near its preoutburst brightness (Szkody & Margon 1989).

Spectroscopic observations of V404 Cyg obtained in 1991 July and August by Casares, Charles, & Naylor (1992) revealed the presence of an absorption-line spectrum characteristic of a late G or early K star, superposed upon the spectrum of the accretion disk surrounding a compact object, with a radial velocity curve of amplitude 211 ± 4 km s^{-1} and a period of 6.473 ± 0.001 days. The mass function implied by this amplitude and period is $6.3 \pm 0.3\ M_\odot$ and represents a lower limit to the mass of the compact object. The most massive neutron stars predicted by general relativity have masses on the order of 3 $M_\odot$ and at most 5 $M_\odot$ for stiff equations of state, but all observationally determined neutron star masses lie near or below $\simeq 2\ M_\odot$ (Joss & Rappaport 1984) within the uncertainties. The best black hole candidates, Cyg X-1 and A0620−00, have compact star masses estimated to be at least 3.4 $M_\odot$ (Paczyński 1974) and 3.8 $M_\odot$ (McClintock & Remillard 1986; Haswell & Shafter 1980), respectively. Thus, the importance of V404 Cyg is that the orbital period and mass function measured by Casares et al. (1992) implies that the compact object must be extremely massive for any reasonable inclination of the system or mass of the secondary star.

2. OBSERVATIONS

As part of our continuing investigation of V404 Cyg, we obtained time-resolved differential CCD photometry of V404 Cygni on the nights of 1990 September 10–12; 1990 October 12–14 and 16–18; 1991 June 18, 20, 21, 23, and 27; and 1992 May 16, 17, and 18. The 1990 and 1991 observations were obtained using the Perkins 1.8 m telescope of the Ohio Wesleyan and Ohio State Universities at the Lowell Observatory and the Ohio State University Imaging Fabry Perot Spectrograph (IFPS) in direct mode. The 1992 observations were obtained

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with the J. S. Hall 1.1 m telescope of the Lowell Observatory. In both cases, the observations were made in the *I*-band using the combined response of a Texas Instruments, 800 × 800 pixel CCD and a RG-780 filter. This combination gave a passband with $\lambda_{\rm eff} \simeq 9000$ Å and a FWHM of $\simeq 1400$ Å. A total of 1318 exposures were obtained on 17 nights in generally good seeing (1″–2″) and transparency. Integration times were 3 and 5 minutes at the 1.8 m and 1.1 m telescopes, respectively. The average duration of the observations was 4.8 hr, with a minimum and maximum duration of 1.4 and 6.7 hr, respectively. The brightness of V404 Cyg with respect to two reference stars adjacent to it and of comparable brightness, was measured by two-dimensional digital aperture photometry. The differential photometric accuracy, as estimated by the relative magnitudes of the reference stars was $\simeq 0.008$ mag.

3. RESULTS

After the announcement by Casares et al. (1992) of a spectroscopic period, we examined our data for photometric periods greater than 0.5 days. Three period analysis tools were used: a discrete Fourier transform algorithm (Deeming 1975), the phase dispersion minimization technique (Stellingwerf 1978), and least-squares fitting to a cosine and evaluating the goodness-of-fit by the *F*-statistic. All three of these techniques showed the presence of four statistically significant periods in our data at 3.2, 3.0, 1.5, and 0.75 days. The two periods at 3.237 and 3.033 days are of nearly equal power and statistical significance ($\geq 99.9\%$), and thus we would not have been able to directly differentiate between these two periods based on our photometry alone. However, analysis of the sampling of our entire set of data and two independent halves of our data suggests that the 3.0 day period is an alias. In addition, the 3.0 day period and its aliases at 1.5 and 0.75 days are incompatible with the radial velocities obtained by Casares et al. (1992). The period at 3.237 ± 0.005 days is one-half of the spectroscopic orbital period of 6.473 ± 0.001 days within the errors. This suggests that, like many other X-ray binaries, the intrinsic light curve of V404 Cyg actually consists of two maxima and two minima per cycle but with a period of $2 \times 3.237 = 6.474 \pm 0.005$ days, and this value is in excellent agreement with the spectroscopic orbital period.

In Figure 1, we show our photometric data folded onto the spectroscopic period and ephemeris. The folded data confirm that there are two maxima and minima per cycle and also suggest that the maxima at phases 0.25 and 0.75 are of equal intensity but the minima at phases 0.0 and 0.5 are of unequal intensity with the minimum at phase 0.5 being about 0.04 mag brighter. The phasing of the photometric light curve is in excellent agreement with the radial velocity curve since the minima in the light curve occur at phases 0.0 and 0.5 which correspond to inferior and superior conjunction of the secondary star based on the radial velocity curve. Maxima in the light curve occur at the quadrature phases of the radial velocity curve. In addition, there is a considerable amount of short-time scale variability $\simeq 0.1$–0.2 mag at all phases of the 6.5 day period which arises from the fact that, even in the *I* band, the accretion disk still contributes a significant fraction of the total light of the system.

4. DISCUSSION

Three mechanisms might be responsible for the observed photometric variability in V404 Cygni: ellipsoidal light variations, X-ray heating, or eclipses. X-ray heating, of the side of the secondary facing the compact object, can be eliminated immediately as a source of the modulation. First, X-ray heating of the face of the secondary would predict that maximum brightness of the light curve should occur at superior conjunction (phase = 0.5) of the secondary star. The observed light curve is a minimum at superior conjunction. Second, from extrapolation of the X-ray light curve (Kitamoto 1990), we estimate that the quiescent X-ray luminosity of V404 Cyg should be $\simeq 10^{32}$ ergs s^{-1}. A Roche lobe–filling secondary

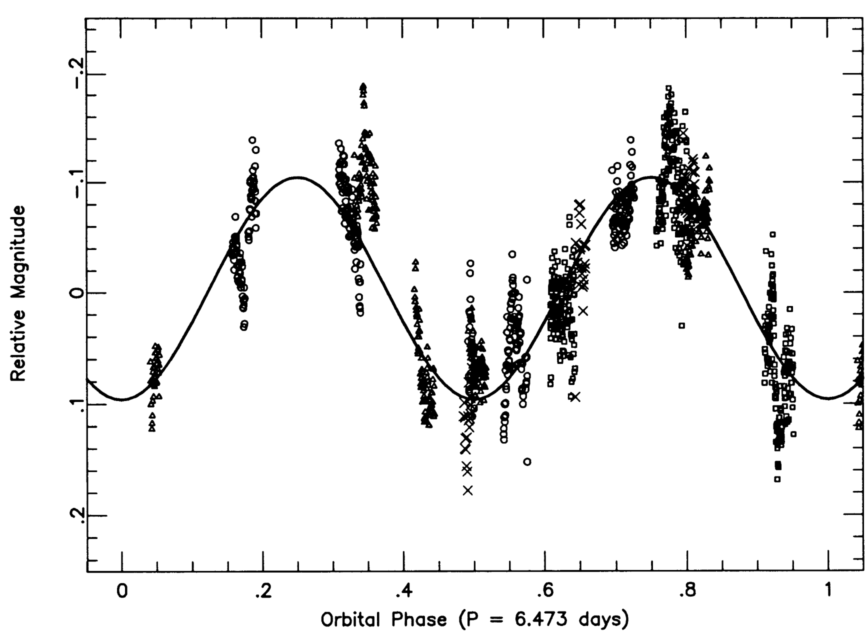

FIG. 1.—Ellipsoidal light curve and best cosine fit for the photometric variations of V404 Cyg. The data have been folded on the spectroscopic period and ephemeris. The 1990 September and October data are indicated by open squares and circles, respectively. The 1991 and 1992 data are indicated by open triangles and crosses, respectively.

would intercept about 1% of the X-ray flux emitted from the vicinity of the compact object, and the fraction of that emitted flux absorbed by the star would be less than 0.01% of the local surface thermal flux. Thus, X-ray heating would be negligible and cannot account for the observed amplitude of 0.2 mag.

Alternatively, the photometric modulation might be due to mutual eclipses of the secondary star and accretion disk; however, we feel that this is most unlikely for the following two reasons. First, the presence of an eclipse of a small accretion disk surrounding the compact object in quiescence would imply the presence of an eclipse of a hotter and more extended accretion disk during the outburst. An eclipse at that time would give rise to large-amplitude photometric modulations, but no such modulations were observed (Wagner et al. 1991). Second, if the observed light curve is due to mutual eclipses, we might expect that the amplitude of the short–time scale photometric variations arising from the accretion disk would decrease during an eclipse of the disk. Such an effect does not appear to be evident in our data, although we have not sampled the light curve completely near phase 0.0.

The most likely interpretation of the light curve is that it arises from ellipsoidal variations which result from tidal forces acting on the secondary star by a massive compact object. Ellipsoidal variations are observed in many X-ray binaries including black hole candidates such as Cyg X-1 (Lester et al. 1976) and A0620−00 (McClintock & Remillard 1986). A light curve arising from ellipsoidal variations generally has two roughly equal maxima and two somewhat different minima per cycle with a full amplitude of 0.04–0.2 mag (Avni & Bahcall 1975). The double-humped light curve of V404 Cyg strongly suggests that it is due to tidal distortion of the secondary star. An analysis of a light curve arising from ellipsoidal variations constrains three binary system parameters (Avni & Bahcall 1975): the radial fraction of the Roche lobe that is filled, f, the orbital inclination, i, and the mass ratio, $q = M_x/M_s$, where M_x and M_s are the mass of the compact object and secondary star, respectively.

It is difficult to accurately determine from the data the amplitude directly attributable to ellipsoidal variations since the accretion disk contributes a significant fraction of the total light of the system. Detailed constraints and conclusions must await modeling of the light curve based on full Roche geometry, and this work is in progress. However, we can draw some general conclusions regarding the nature of the binary system of V404 Cyg by combining the radial velocity and light curve results.

As pointed out by Casares et al. (1992), the secondary cannot be a main-sequence star because it would fill only $\simeq 15\%$ of its Roche lobe and could not transfer mass to the compact object and produce the outbursts. Instead, they have suggested that the binary system of V404 Cyg might consist of a 4 $M_\odot$ K0 III star and a black hole. We show below that such a secondary can be ruled out.

The mass function derived by Casares et al. (1992) can be rewritten as follows:

$$\frac{q^3 M_s \sin^3 i}{(1+q)^2} = 6.3 \pm 0.3\ M_\odot ,$$

and the constraint imposed by our ellipsoidal light variations can be expressed as

$$f^3 \simeq \frac{0.7(1+q)}{q \sin^2 i} ,$$

where in the latter equation we have combined the expression for the amplitude of ellipsoidal variations (Russell 1945; McClintock et al. 1983) and the expression for the mean radius of the Roche lobe (Paczyński 1971) with respect to the semi-major axis of the orbit, $R/a = 0.46(1+q)^{-1/3}$. We have evaluated the Russell (1945) law assuming an amplitude of 0.2 mag based on a best-fit cosine curve to the overall ellipsoidal light curve and have assumed gravity ($\tau_0 = 0.6$; Kopal 1959, Lucy 1967) and linearized limb ($u = 0.55$; Al-Naimiy 1978) darkening parameters appropriate for a K0 III star with an effective temperature of 4300 K and log $g \sim 2$–3. We find in this case that $f \approx 1$ and $i \simeq 70°$–$80°$. These limits predict the mass ratio in such a system to be $3 \leq q \leq 4$ implying a compact star mass of $12 \leq M_x \leq 16\ M_\odot$. However, a 4 $M_\odot$ K0 III star with a radial velocity semiamplitude of 211 km s^{-1} in a binary system with $q = 3$–4 would produce a radial velocity semiamplitude of 55–70 km s^{-1} for the compact object. Such an amplitude can be ruled out by our upper limit of $K_x \leq 34$ km s^{-1} and $q \geq 6$ obtained from our Hα emission-line radial velocities. These must originate from the accretion disk surrounding the compact object and thus provide a measurement of its orbital motion.

Instead, we propose that the binary system of V404 Cyg consists of a $\simeq 1\ M_\odot$ K0 IV star and a black hole. Adopting the gravity and limb-darkening parameters assumed above, we find that if $f \approx 1$, then the inclination must be $\simeq 60°$. We note that our lower limit for the inclination, based on the mass function *and* light curve is consistent with the double-peaked Balmer line profiles that require $i \geq 50°$ (Horne & Marsh 1986). At the other extreme, if i is as high as 80°, then the secondary fills about 90% of its Roche lobe. The limits imposed by the mass function and light curve constrain the mass ratio to be $8 \leq q \leq 12$ implying a mass for the compact star of 8–12 $M_\odot$.

The most probable limits that we have placed on the orbital inclination, radial fraction of the Roche lobe that is filled, and the mass ratio given above were based on the assumption that the best-fit amplitude of the observed light curve was entirely due to ellipsoidal variations, our best guess as to the nature of the secondary star, the mass function, and a simple model for the ellipsoidal light variations. Some of the uncertainties in the analysis of ellipsoidal light variations have been discussed by Avni & Bahcall (1975). The largest observational uncertainty in our results involves estimating the precise amplitude attributable to ellipsoidal light variations given the scatter of the data. If we assume that the ellipsoidal light amplitude could be as much as 0.05 mag in error around our mean value, then for $f \simeq 1$, the mass ratio could be as high as 19 and the inclination as low as 46° or as high as 73° for amplitudes of 0.15 and 0.25 mag respectively. If $i = 80°$, then f can be as low as 0.83 or as high as 0.98 for amplitudes of 0.15 and 0.25 mag, respectively. The mass of the X-ray star in this analysis is relatively insensitive to the values chosen for the gravity and limb-darkening coefficients assuming a luminosity class and range of effective temperature appropriate to the range of spectral types we believe characterize the secondary star.

A 1 $M_\odot$ K0 IV star also leads to a more reasonable estimate of the distance to V404 Cyg and the peak X-ray luminosity in outburst. The K0 III star suggested by Casares et al. (1992) placed V404 Cyg at a distance of $\simeq 11$ kpc, assuming $A_V \simeq 3.3$ mag, and led to a peak X-ray luminosity at maximum of 1.5×10^{40} ergs s^{-1}, a value that far exceeds the Eddington limit for any reasonable mass of the compact object. If we again assume that $T_{eff} \approx 4300$ K and that the radius of the secondary can be approximated by its Roche lobe radius of $\simeq 7$ $R_{\odot}$ (since it must be about this size to account for the outbursts) then its bolometric luminosity would be on the order of 5.7×10^{34} ergs s^{-1}. Such a star would have an absolute visual magnitude of about 2.5, and its apparent magnitude of 18.5 (assuming the disk and star both contribute about 50% of the light) plus 3.3 mag of visual extinction place V404 Cyg at a distance of about 3.5 kpc. This estimate for the distance to V404 Cyg is consistent with measurements of H I absorption (Han & Hjellming 1992) and the reddening of the optical spectrum (Casares et al. 1991; Wagner et al. 1991) which together give a distance of ~ 3 kpc. The peak X-ray luminosity would then be $\simeq 5.3 \times 10^{38}$ ergs s^{-1} and thus below the Eddington limit of an 8–12 $M_{\odot}$ black hole.

Our discovery of ellipsoidal light variations also eliminates the need to consider a triple star system model for V404 Cyg as was suggested by Casares et al. (1992). It has been shown from an analysis of ellipsoidal light variations for X-ray binaries (Avni & Bahcall 1975; Bahcall 1978; V616 Mon: McClintock & Remillard 1986) that the secondary or optical star fills or nearly fills its Roche lobe in every case where the evidence has been strong enough. Our analysis shows that the secondary star in V404 Cyg fills or nearly fills its Roche lobe as well. With a Roche lobe–filling secondary star, the outbursts, radial velocity variations, and ellipsoidal light variations can be accounted for, as in other X-ray novae and X-ray binaries, without appealing to a triple star system. In the absence of ellipsoidal light variations, a triple system might have been necessary to consider since an underfilling main-sequence star in a 6.5 day orbit would have been required to explain the radial velocity variations, and an inner binary with an orbital period of a few hours would have been required to account for the cataclysmic nature of the object and hourly time scale variations observed in the emission lines (Casares & Charles 1992). We admit that shorter time scale variations ($\simeq$4–6 hr) are present in the emission lines and continuum but feel that it is unlikely that these variations originate in an inner binary system within a triple system.

In summary, the radial velocity variations and period defined by Casares et al. (1992) in combination with our photometric data, indicate a high mass ratio and large mass for the compact object. Our results help to establish V404 Cyg as one of the strongest candidates for a black hole as compared to other binary systems such as Cyg X-1 and V616 Mon. We emphasize that, in constrast to other X-ray novae, the secondary in V404 Cyg is not on the main sequence but must be evolved. This result may also have important implications regarding the origin of lithium in the spectrum of the secondary of V404 Cyg (Wallerstein 1992; Martin et al. 1992). The large separation and evolved nature of the secondary must be two of the factors that make the outburst and decline of V404 Cyg unique among X-ray novae.

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REFERENCES

Al-Naimiy, H. M. 1978, Ap&SS, 53, 181
Avni, Y., & Bahcall, J. N. 1975, ApJ, 197, 675
Bahcall, J. N. 1978, ARA&A, 16, 241
Casares, J., et al. 1991, MNRAS, 250, 712
Casares, J., & Charles, P. A. 1992, MNRAS, 255, 7
Casares, J., Charles, P. A., & Naylor, T. 1992, Nature, 355, 614
Deeming, T. J. 1975, Ap&SS, 36, 137
Han, X., & Hjellming, R. M. 1992, ApJ, 400, 304
Haswell, C. A., & Shafter, A. W. 1990, ApJ, 359, L47
Horne, K., & Marsh, T. 1986, MNRAS, 218, 761
Joss, P. C., & Rappaport, S. A. 1984, ARA&A, 22, 537
Kitamoto, S. 1990, in Proc. North American Workshop on CV's and Low Mass X-ray Binaries, Accretion Powered Compact Binaries, ed. C. W. Mauche (Cambridge: Cambridge Univ. Press), 21
Kopal, Z. 1959, Close Binary Systems (New York: Wiley), 173
Lester, D. F., et al. 1976, ApJ, 205, 855
Lucy, L. B. 1967, Zs. Ap., 65, 89
Marsden, B. 1989, IAU Circ., No. 4783
Martin, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1992, Nature, 358, 129
McClintock, J. E., Petro, L. D., Remillard, R. A., & Ricker, G. R. 1983, ApJ, 266, L27
McClintock, J. E., & Remillard, R. A. 1986, ApJ, 308, 110
Paczyński, B. 1971, ARA&A, 9, 183
———. 1974, A&A, 34, 161
Russell, H. N. 1945, ApJ, 102, 1
Stellingwerf, R. F. 1978, ApJ, 224, 953
Szkody, P., & Margon, B. 1989, IAU Circ., No. 4794
Wagner, R., Starrfield, S. G., & Cassatella, A. 1989, IAU Circ., No. 4783
Wagner, R. M., et al. 1991, ApJ, 378, 293
Wallerstein, G. 1992, Nature, 356, 569