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DYNAMICAL EVIDENCE FOR A BLACK HOLE IN X-RAY NOVA OPHIUCHI 1977

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ABSTRACT

We have conducted spectral and photometric observations of the quiescent optical counterpart of X-ray Nova Ophiuchi 1977 (H1705-250; V2107 Oph) at CTIO. Fifty hours of photometry during 1994 July reveal a typical double-wave modulation of ± 0.2 mag with a period of 12.51 ± 0.03 hr. The mean brightness was $V \sim 21.5$. Forty spectra (2000 s exposures) were obtained in 1994 July and 13 similar spectra were obtained in 1993 May. We derived the absorption-line radial velocities using two conventional cross-correlation techniques. Both of them suggest a velocity semiamplitude (K) in excess of 400 km s^{-1}, but only half or less of the spectra could be utilized because the signal-to-noise ratio is so low. Consequently, we devised a new and powerful "restframe search" technique that uses all of the available data. For each of several million binary ephemerides, we summed all of the spectra in a trial restframe of the secondary star, and each restframe spectrum was cross-correlated against a template spectrum with a well-known velocity. We then searched for the set of orbital parameters that produced the strongest cross-correlation value. The results confirmed the photometric period and the best restframe spectrum has a highly significant correlation ($r \sim 6$) against a broad range of K star templates. The best value for the velocity amplitude is $K = 420 \pm 30$ km s^{-1}. The corresponding mass function is $f(M) = 4.0 \pm 0.8$ $M_\odot$. The probability is high that the compact object exceeds the maximum mass (~ 3 $M_\odot$) for a neutron star. Furthermore, this nova is very similar in many respects to the dynamical black hole binaries, A0620−00 and *X*-ray Nova Muscae 1991. We conclude that X-ray Nova Oph 1977 is the sixth confirmed example of an X-ray binary with a black hole primary. The estimated magnitude of the secondary star is $V \sim 22.0$. This distance to the binary system is 6 kpc, if the companion is a K3 star near the main sequence. Double-peaked Hα emission suggests low levels of accretion ~ 17 yr after outburst, similar to the behavior seen in A0620−00. Unusual structure in the Hα line profile was observed during 1994 July, and its cause remains unexplained. The most straightforward interpretations of the light curves confine the binary inclination angle to the range of 60°–80°. In that case, the mass of the black hole primary is 6 ± 1 $M_\odot$, if the companion is a K3 star on the main sequence.

Subject headings: binaries: spectroscopic — black hole physics — novae, cataclysmic variables — stars: individual (Nova Ophiuchi 1977) — X-rays: stars

1. INTRODUCTION

Dynamical evidence for the existence of stellar-mass black holes has depended exclusively on studies of particular X-ray binary systems. Three lines of evidence combine to make the case that these binaries contain black holes: (1) A luminous and variable X-ray source establishes the presence of an accreting compact object at least as dense and massive as a neutron star. (2) Measurements of the orbital period and the radial velocity of the secondary star determine that the mass of the compact object exceeds 3 $M_\odot$. (3) According to general relativity, a neutron star more massive than ~ 3 $M_\odot$ is unstable and will collapse to form a black hole (Rhoades & Ruffini 1974; Chitre & Hartle 1976). There are five cases for which these conditions have been established with a high degree of probability; these systems are accordingly known as "black hole binaries." They include two persistent X-ray sources with massive companion stars: Cyg X-1 (Bolton 1975) and LMC X-3 (Cowley et al. 1983), and three X-ray novae with low-mass companions A0620−00 (McClintock & Remillard 1986), V404 Cyg (Casares, Charles, & Naylor 1992), and X-ray Nova Muscae 1991 (hereafter XN Mus91; Remillard, McClintock, & Bailyn 1992). These X-ray novae are particularly exciting because their low-mass companions have high orbital velocities, leading to large values of the mass function (> 3 $M_\odot$), which is an absolute lower limit on the mass of the compact object. Thus, for these X-ray novae straightforward radial velocity measurements alone have clinched the argument that their compact objects are too massive to be neutron stars, irrespective of the presumed mass of the companion star or the inclination angle of the binary system.

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Considering all five black hole binaries, the estimates of the binary inclination angles and the likely masses of the secondary stars have yielded black hole masses in the range 4–20 $M_\odot$ (Gies & Bolton 1986; Cowley et al. 1983; Haswell & Shafter 1990; Wagner et al. 1992; Orosz et al. 1995). These values are far above the measured masses of neutron stars, which cluster in the range 1–2 $M_\odot$ (Phinney & Kulkarni 1994; McClintock & Remillard 1990; Kelley et al. 1983; Primini, Rappaport, & Joss 1977; Hutchings et al. 1977). Unfortunately, for a large majority of X-ray binaries it is impossible to measure the radial velocity of the companion star, either because the accretion disk is too bright, or because the interstellar extinction is too great.

Many researchers have explored the possibility of distinquishing between accreting neutron stars and black holes by characterizing their temporal and spectral X-ray properties. In this regard, the most intriguing characteristic is the shape of the X-ray spectrum. In the black hole binaries, the high-energy spectrum often appears to have two components: a bright, thermal component (~ 1 keV), and a "hard tail" that extends with a power-law shape out to many hundreds of keV (White & Marshall 1984; Tanaka 1989; Sunyaev et al. 1992; Tanaka & Lewin 1994). However, this phenomenology is fraught with exceptions (e.g., Hellier 1994), and there are additional complications due to spectral variability, small sample sizes, and relatively poor spectral coverage at high photon energies. Thus, the effort to distinguish accreting black holes and neutron stars has given way to inconclusive statistical evaluations based on combinations of several emission properties (Tanaka & Lewin 1995).

An X-ray Nova in Ophiuchus (hereafter "XN Oph77"), which was observed with the *Ariel V* and *HEAO-1* satellites during 1977 August, reached a maximum X-ray flux (2–18 keV) of ~ 3.5 Crab (Watson, Ricketts, & Griffiths 1978). The associated optical nova ($V \sim 15.8$) was identified by Griffiths et al. (1978), who noted a 21st mag object near the nova position on the Palomar Sky Survey plates. A variable, hard X-ray component was seen in XN Oph77 which extended to photon energies above 100 keV (Wilson & Rothschild 1983; Cooke et al. 1984). The composite appearance of the X-ray spectrum and the temporal profile of the nova decay in soft X-rays have prompted frequent comparisons of XN Oph77 with the emerging class of black hole X-ray novae (see references above).

The present paper provides optical evidence that XN Oph77 is the sixth member of the class of black hole binaries established via dynamical measurements of the secondary star. We report the recovery of the X-ray nova in its quiescent state and the discovery of its 12.51 hr binary period, which we derive from optical photometry and spectroscopy. The radial velocities of the secondary star were not easily extracted, owing to the extreme faintness of the quiescent system; nevertheless, our conclusions regarding the high value of the binary mass function are consistently confirmed using a variety of analysis techniques performed on two different data sets.

2. OBSERVATIONS AND THE RECOVERY OF XN OPH77 IN QUIESCENCE

The recovery of the quiescent optical counterpart of XN Oph77 began in 1992 April with CCD imaging observations using the 1.5 m telescope at CTIO. The details of the observations are described in Remillard et al. (1992). We accumulated 46 exposures of XN Oph77 (900 s each) with a Corning No. 9780 ("$B+V$") filter after our primary target, XN Mus91, had set. A single faint object, which is located nearest to the position of the optical nova (Griffiths et al. 1978), clearly varied in intensity with maxima that appeared to recur at a period of 6.4 hr. However, poor phase coverage prevented the determination of a unique photometric period.

A more intensive observing program was undertaken during 1993 May at CTIO. Imaging CCD measurements, again with the $B+V$ filter, were performed with the 1.5 m telescope using the CFCCD camera with the TI No. 3 detector, which has 800 pixels along each axis and a pixel size of 0ʺ16 square. A series of 1000 s exposures were made of XN Oph77 on the nights of 1993 May 17–18 (UT), along with exposures of several standard stars (Landolt 1992). Routine processing of the images was done to eliminate the electronic bias and to correct for pixel-to-pixel sensitivity variations using images of the twilight sky. The sky conditions were clear with image profiles averaging 1ʺ1 FWHM. The averaged image for the observations during May 17 is displayed in Figure 1; the optical counterpart of XN Oph77 in quiescence is indicated with an arrow.

Spectral observations of XN Oph77 were obtained with the CTIO 4 m telescope on 1993 May 23 (UT), using the RC spectrograph, the folded Schmidt camera, the Tek 1024 No. 2 CCD, and the KPGL-3 grating. This instrumental configuration produced a dispersion of 2.0 Å per pixel over our chosen wavelength range of 4700–6700 Å. We obtained 13 exposures of 2000 s each with a 1ʺ5 entrance slit. The slit was aligned in the east–west direction, which for XN Oph77 was nearly optimum for minimizing light loss due to atmospheric dispersion (Filippenko 1982). Observations of XN Oph77 were interspersed with exposures of wavelength calibration lamps (He-Ne-Ar). We observed flux calibration stars as well as several dwarf stars (G, K, and M types) that have well-determined systemic velocities. The wavelength calibrations were interpolated dispersion solutions scaled according to the time of an observation relative to the times of adjacent lamp exposures. All of the spectral reductions were performed with IRAF. The average of the 13 spectra is shown in the bottom panel of Figure 2. The spectrum is very similar to the quiescent spectra of A0620−00 (X-ray Nova Mon 1975) and XN Mus91, with broad and double-peaked Hα emission superposed on a flat optical continuum (e.g., Orosz et al. 1994). The wings of the Hα line are detected to ± 2000 km s^{-1}, while the FWHM is 2200 km s^{-1} and the equivalent width is 110 Å. The broad and double-peaked profile is a signature of a Keplerian accretion disk orbiting a compact star (Smak 1981; Horne & Marsh 1986). This spectrum is compelling evidence that XN Oph77 has been recovered in its quiescence state. Thus, emission from the accretion disk is evident more than 16 yr after the X-ray nova event; the same is true of A0620−00 (Orosz et al. 1994).

Our most extensive photometric and spectral observations were made with the CTIO 1.5 and 4 m telescopes during 1994 July. The data yields were significantly higher than in 1993 due to stable weather conditions. The instruments, the CCD detectors, the calibration observations, and the data reduction procedures were all very similar to those described above for the 1993 May observations. At the 1.5 m telescope we used 2 × 2 on-chip binning, which gave a pixel size of 0ʺ32 square. Using the $B+V$ filter, we accumu-

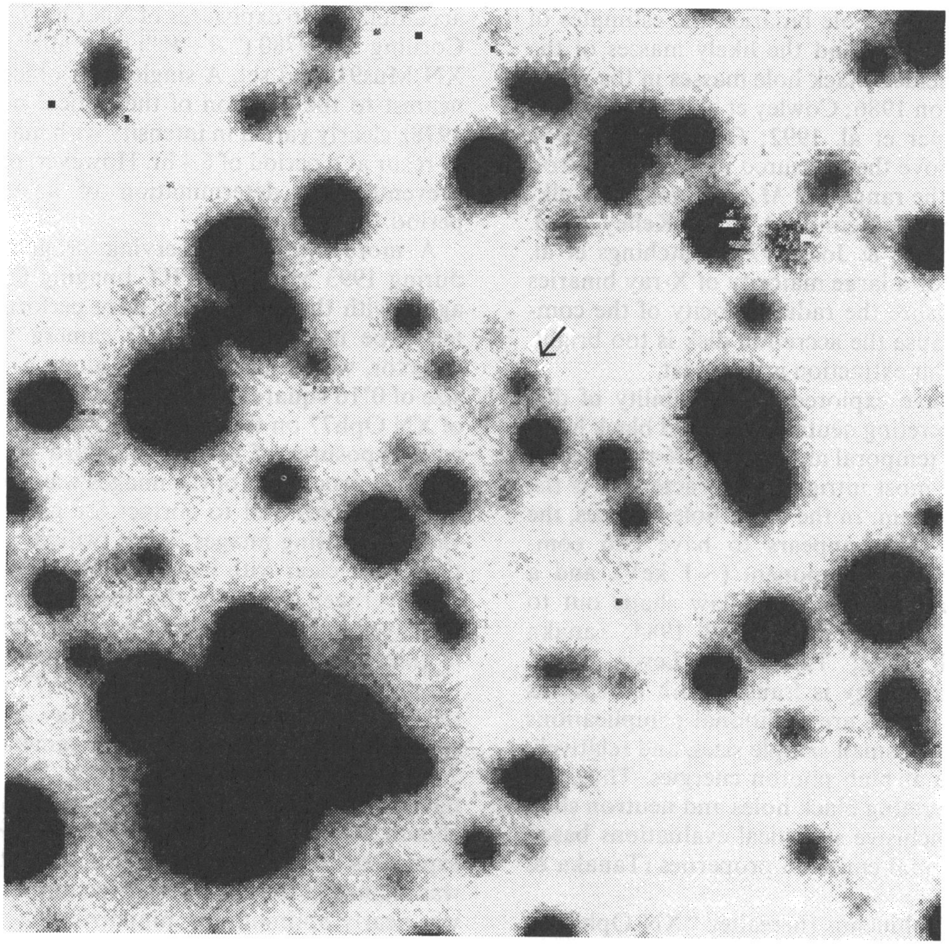

FIG. 1.—Image ("$B+V$" filter) of XN Oph77 in its quiescent state ($V \sim 21.5$). The total exposure time is ~6 hr. The coordinate of the optical counterpart (epoch J2000 ± 1″), which is marked with an arrow, is 17:08 14.2, −25°05′32″. The angular width of the image is 43″ along each axis; north is toward the top and east is to the left.

lated 50 hr of photometric data (typically 900 s exposures) during six nights: July 9–14, UT. The 4 m observations yielded 40 spectra (2000 s exposures) distributed over three nights: July 4–6 UT. The average spectrum for the 1994 data set is shown in the top panel of Figure 2. Although the average flux level during 1994 July is very similar to that of 1993 May, a distinct change occurred in the profile of the Hα line, as shown in Figure 2. The line profile as observed in 1994 is extraordinary for its strong asymmetry and its central depression that plunges to the continuum level (see Orosz et al. 1995). We note that the average spectrum obtained on each of the three nights during 1994 July (which individually sample ~75% of an orbital period) have this same appearance. A second difference in the 1994 spectrum is the reduced flux in the Hβ emission line; this effect may be intimately related to the changes in the Hα profile.

3. PHOTOMETRIC ANALYSIS AND RESULTS

The relative intensities of XN Oph77 and selected field stars were computed using DAOPHOT (Stetson 1987), which fits the stellar profiles to a point spread function derived for each CCD image. The 1994 July data provide superior constraints on the photometric period, and we discuss these results first. The light curves on each night display brightness waves with full amplitudes of several tenths of a magnitude in the $B+V$ band. We searched for periodic modulations using the variance minimization technique of Stellingwerf (1978), applied with 25 phase bins. The results are shown in Figure 3. Significant dips in the variance statistic represent trial periods in which the normalized variance is reduced, compared to the variance in the total data set. The six deepest minima in Figure 3 imply the following periodicities: 6.3 hr, the 1 day aliases of this period, twice 6.3 hr and the 2 day aliases of the latter period. Since the photometric light curves of quiescent X-ray novae are dominated by the ellipsoidal variability of the secondary star (e.g., McClintock & Remillard 1986; Remillard et al. 1992; Wagner et al. 1992; Shahbaz et al. 1994), we conclude that the orbital period is 12.51 ± 0.03 hr. The uncertainty is estimated from the profile of the variance minimum, and it is slightly larger than an alternative estimate based on a Monte Carlo redistribution of deviations between points on the light curve and the smoothed profile of the folded light curve. In Figure 4, we display the folded photometric data of 1994 July at the period of 12.51 hr. All of the data points are plotted in the top panel, while the bottom panel shows the same data averaged in 16 phase bins. The photometric observations obtained during 1992 April and 1993 May also showed evidence for a fundamental modulation in the range of 6.0 to 6.5 hr, but these data are sparse and have poor phase coverage.

The $B+V$ magnitudes were calibrated to the standard V mag scales via synthetic aperture analysis (10″ aperture),

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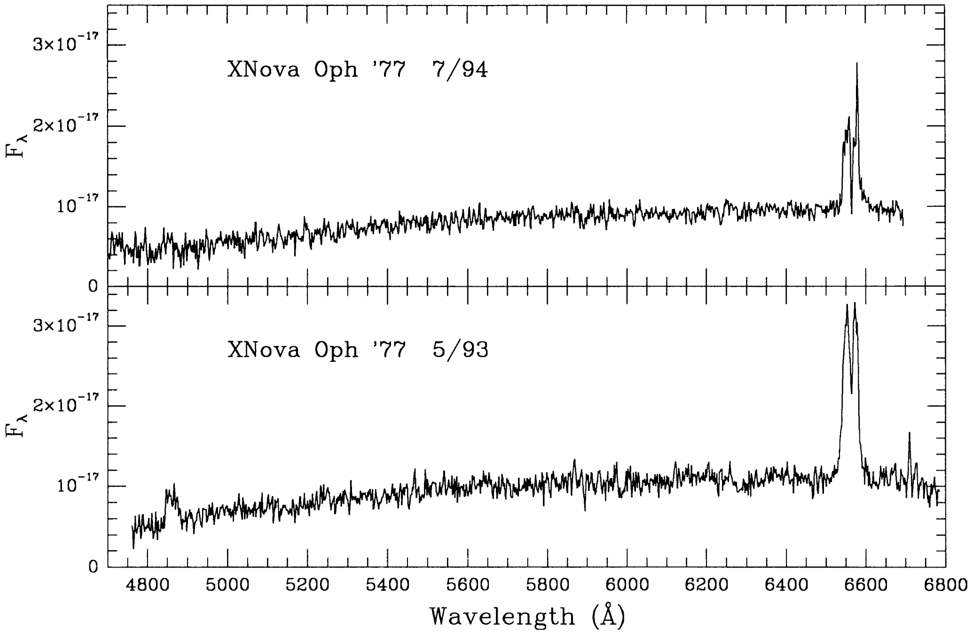

FIG. 2.—Average spectrum of XN Oph77 obtained during the 1994 July and 1993 May CTIO observing runs, respectively. No Doppler corrections have been applied. The Hα profile in the 5/93 spectrum is typical of quiescent X-ray novae, while the asymmetric and peculiar structure in Hα during 1994 July, which is evident throughout each of the three nights of observations, remains unexplained.

using the designated "point spread" stars and selected standard stars of Landolt (1992). The V mag calibration, which includes a color dependence, was computed for XN Oph77 assuming a color index, $B - V \sim 1.4$. The average V mag is 21.5, with a net calibration uncertainty of ~ 0.1 mag. The average brightness of XN Oph77 over the 3 yr of observations appears nearly constant. Possibly the quiescent nova was brighter by 0.1 mag in 1993; however, this conclusion is uncertain because the changes in the phase coverage from year to year could artificially produce a similar result.

4. SPECTRAL ANALYSIS AND RESULTS

The central question for our spectral analysis is whether it is possible to extract radial velocities of the companion star in order to evaluate the mass function and thereby constrain the mass of the compact object. Extraordinary efforts are required to track the absorption lines of a 21st mag star that is located in a crowded galactic field and furthermore is diluted by emission from an accretion disk. We describe three methods used to determine the radial velocity curve of XN Oph77. These methods utilize increasing percentages of the 40 spectra obtained during 1994 July. The third method, which successfully makes use of all the data, was devised for this study of XN Oph77.

4.1. *Conventional Radial Velocity Analysis*

In a conventional analysis for the orbital elements of a spectroscopic binary, each spectrum in a series of measurements is cross-correlated against the spectrum of an appropriate template star, thereby producing a time series of radial velocities which exhibit the binary period and yield the value of the mass function. In the cases of A0620−00

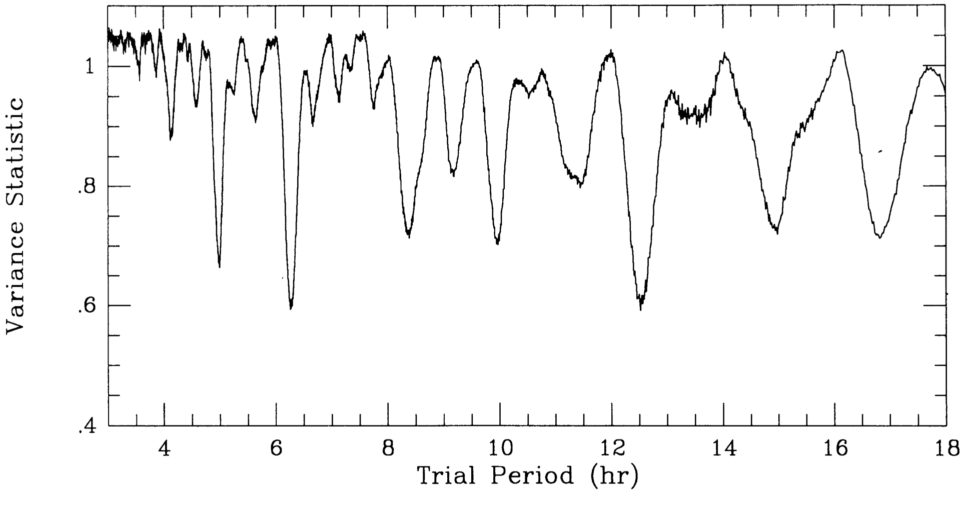

FIG. 3.—The search for the orbital period of XN Oph77 in six nights of photometry obtained during 1994 July. The two deepest minima correspond to the binary period (12.51 hr) and the half-period ($\sim$6.3 hr). The latter is evident because the "ellipsoidal variations" in the brightness of the secondary star cause two maxima and two minima per binary period.

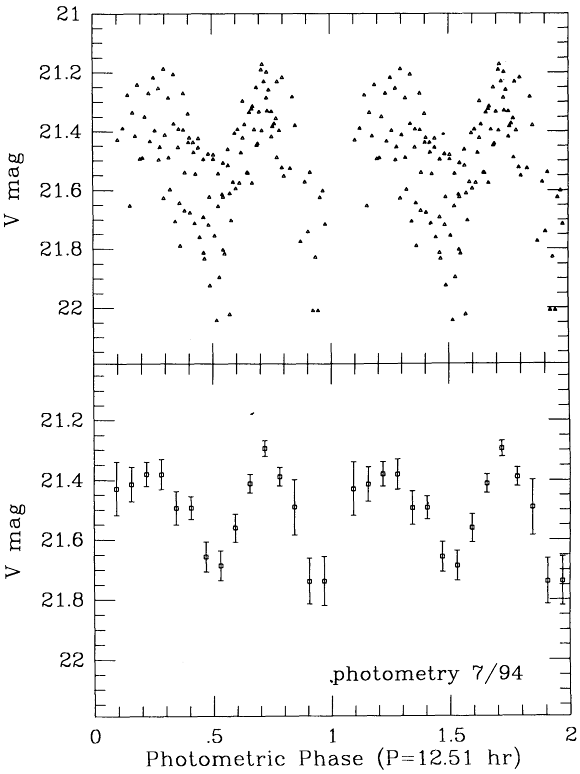

FIG. 4.—Photometric data for XN Oph77 folded at a period of 12.51 hr. In the top panel all of the individual measurements ($B+V$ filter) from 1994 July are displayed, while the bottom panel shows the average magnitudes and rms errors in 16 phase bins. Photometric phase 0.0 is the time of brightness minimum associated with the binary conjunction in which the companion star is closer to the observer.

and XN Mus91 (McClintock & Remillard 1986; Remillard et al. 1992; Orosz et al. 1995), we used a Tonry & Davis (1979) significance threshold, $r > 2.6$, and we typically restricted ourselves to a wavelength range from about 4900 to 6500 Å. The rest frame spectra of the secondary stars in these systems were determined to be K5 V and K4 V, respectively, and the cross-correlation results were quite robust over the range of reference templates with spectral types from late G to early M.

To compensate for the faintness of XN Oph77, we modified our earlier approach by decreasing the significance threshold to $r > 2.4$, and also by computing cross correlations in three ranges of wavelength. Specifically, we adopted the following procedures: (1) the K3 V spectrum of HD 9770, which was observed with the same instrumentation as the nova, was chosen as the primary cross-correlation template because on average it gave the strongest correlations with the spectra of XN Oph77. (2) Each XN Oph77 spectrum was cross-correlated with the spectrum of HD 9770 over the wavelength range 4900–6400 Å. If the correlation significance exceeded $r = 2.4$, then the corresponding radial velocity was assigned to that observation, and the spectrum was eliminated from further consideration. (3) Step two was repeated for the range 5000–6000 Å, which contains a higher density of K star absorption lines. (4) the second step was again repeated for the range 5100–5600 Å, which contains the densest region of absorption lines. The order of these steps favors velocity measurements that are based on the widest bandwidth and the greatest number of absorption lines.

The above analysis yielded 15 radial velocity measurements with $r > 2.4$. The remaining 25 spectra failed to produce r values >2.4 for any of the three wavelength regions. In the top panel of Figure 5, all 15 velocities are plotted, folded at the photometric period of 12.51 hr with an arbitrary epoch. To determine whether these velocity measurements are consistent with the orbital motion of the companion star, we successively fitted sine curves to the data, each time removing the most deviant velocity point until all of the surviving measures were within 3 σ of the revised fit. The resulting model and data are shown in the lower panel of Figure 5; the rejected points (five of the 15 velocities) are denoted by an open box symbol. The model parameters for the conventional method are given in Table 1B. The velocity semiamplitude derived for the secondary star is large ($K = 480$ km s^{-1}); however, only 10 of the 40 spectra were used to derive this result. On the positive side, the velocity variations lend support to the photometric period: the accidental probability that 10 of 15 velocities can be fitted with a sine wave at the photometric period is extremely small.

4.2. *Radial Velocities from Phase-binned Spectra*

In order to utilize more of the radial velocity data, we used the photometric period to bin the spectra in discrete intervals of orbital phase. We chose to distribute the 40 spectra, which span a range of 0.79 in binary phase, as

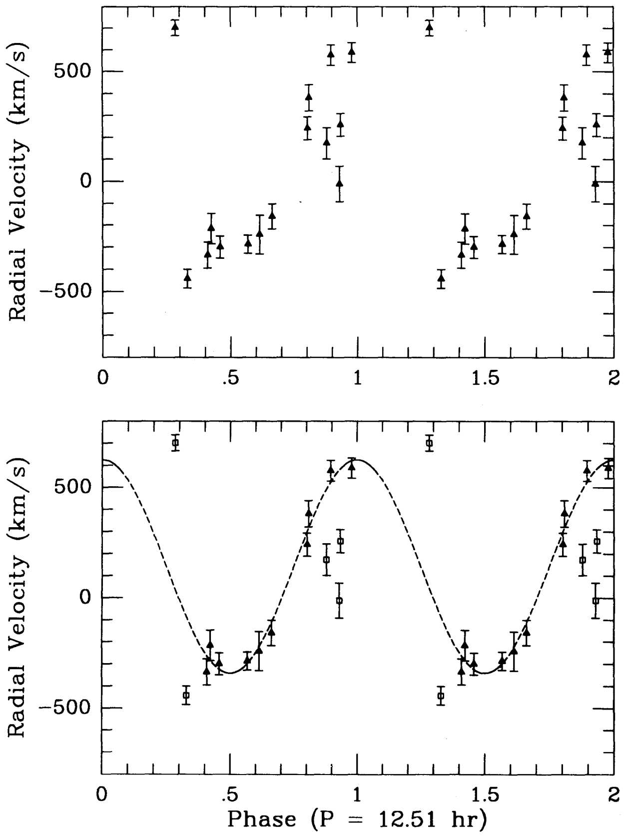

FIG. 5.—Radial velocities obtained from a cross-correlation analysis of 40 individual spectra of XN Oph77 obtained during three consecutive nights in 1994 July. The cross correlation template star is of spectral type K3 V. Fifteen of the spectra yielded a correlation significance of $r > 2.4$, and their velocities are displayed in the top panel in binary phase relative to the photometric period (12.51 hr). In the bottom panel the same data are shown, along with an iterated fit to a sine wave, which agrees with 10 of the 15 measurements. The deviant points are plotted as open squares.

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TABLE 1

Several Determinations of the Orbital Parameters

A. Orbital Period

Parameter	Value 1	Value 2
Photometric period (days)[a]	0.5213 ± 0.0013	
T_0 (photometric minimum;[b] UT & HJD)[c]	1994 July 9.288 ± 0.005	9542.793
T_0 (photometric minimum; UT & HJD)	1993 May 18.280 ± 0.010	9125.785
T_0 (photometric minimum; UT & HJD)	1992 Apr 7.360 ± 0.008	8719.863
Spectroscopic period, time series analysis	0.523 ± 0.015	
Spectroscopic period, rest frame search	0.509 ± 0.009	

B. Radial Velocities[d]

Parameters	Value			
Data set	1993 May	1994 Jul	1994 Jul	1994 Jul
Analysis method	Rest frame search	Time series	Phase-binned	Rest frame search
Number of spectra, final model	13 of 13	10 of 40	22 of 40	40 of 40
K velocity (km s^{-1})	470 ± 50	483 ± 27	470 ± 28	406 ± 30
γ velocity (km s^{-1})	0 ± 40	142 ± 22	77 ± 20	20 ± 20
T_0 (K max; UT days)	23.585 ± 0.025	6.368 ± 0.010	6.322 ± 0.008	6.318 ± 0.008
T_0 (K max; HJD)[c]	9131.091	9539.873	9539.827	9539.823

[a] The photometric period was determined from the CTIO data set of 1994 July.

[b] We derive the time of photometric minimum, assuming a period of 0.5213 days. The photometric epoch for phase 0.0 is the time of binary conjunction, with the secondary star closer to the observer. Since there are two photometric minima per orbital cycle and the period uncertainty is too large to span the time interval between data sets, the 1992 T_0 time may correspond with either phase 0.0 or 0.5.

[c] All HJD results are given as heliocentric Julian day −2,440,000.0.

[d] Radial velocity analyses assume $P = 0.5213$ days.

uniformly as possible. Thus, we used variable bin widths with a maximum width of 0.045, thereby populating 16 bins with two to three spectra each. The spectra in each bin were averaged. We then followed the cross-correlation procedures described in § 4.1, again using the spectrum of HD 9770 (K3 V) as a velocity template. Radial velocities with $r > 2.4$ were obtained for 11 of the 16 phase-binned spectra. As before, we iterated a fit to a sine curve; the results are shown in Figure 6. Only two velocities deviate significantly from the iterated sine wave; again, they are denoted by an open box symbol. The nine velocities that agree with the sine wave (Fig. 6) correspond to 22 of the 40 individual spectra. Therefore, phase binning allows us to use more than twice as many spectra as the conventional time series method described above. The radial velocity curve has a semiamplitude, $K = 470 \pm 28$ km s^{-1}, which implies a mass function of $5.6 \pm 1.0\ M_\odot$.

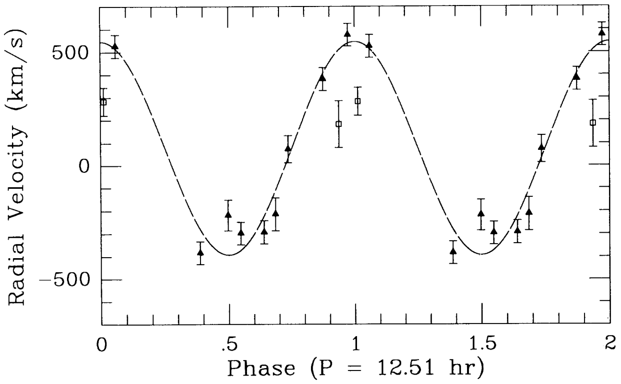

Fig. 6.—Radial velocities obtained from a cross-correlation analysis of XN Oph77 spectra that were first averaged in 16 phases bin. There are two or three spectra contributing to each data point, and the photometric period of 12.51 hr has been assumed. Eleven of the phase-averaged spectra produce a correlation significance of $r > 2.4$, and all but two of these (*open boxes*) lie along the fitted sine wave (see text) which corresponds to a velocity amplitude of 470 km s^{-1}.

In an attempt to improve further the results obtained by phase binning, we averaged the spectra in each phase bin in two-dimensional form. Then we extracted and calibrated the 16 phase-binned spectra and cross-correlated them with the template spectrum as described previously. The results appeared similar to those shown in Figure 6 and were no better than before. In particular, there was no increase in the number of useful velocity measurements compared with the results derived from spectral averaging in one-dimension. We further repeated the phase-binned analysis using template stars of spectral types G8 V, K0 V, and K5 V, but none of these choices led to improvements over the results obtained with the K3 V template.

4.3. *Radial Velocities from a General Rest Frame Search*

In the conventional analysis, only 10 of the 40 spectra could be utilized in determining the radial velocity curve (Fig. 5). In the phase-binned analysis, only 22 of the spectra were useful (Fig. 6). As a third method for computing the radial velocities, we offer a strategy that is not limited by the signal-to-noise ratio of one or a few spectra. For each of several million assumed binary ephemerides, we summed *all* of the spectra in a trial rest frame of the secondary star, and we cross-correlated the trial rest frame spectrum against the template spectrum. We then searched for the set of binary parameters that produced the strongest correlation value, thereby determining the binary parameters using all of the data at once.

The free parameters for a trail rest frame are the period (P), epoch (i.e., time of maximum velocity, T_0), velocity semiamplitude (K), and the binary systemic velocity (γ). We investigated a four-dimensional grid of rest frames in which

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P ranged from 3 to 24 hr, T_0 was searched in steps of 0.02 P, K ranged from 0 to 600 km s^{-1} in steps of 10 km s^{-1}, and the interval in γ was -20 to $+50$ km s^{-1} in steps of 10 km s^{-1}. The trials in γ were confined to orbital periods near 12.5 hr, while we assumed $\gamma = 0$ at other trial periods. We again chose the K3 V template star, HD 9770, and a cross-correlation region 4900–6400 Å. All of the spectra were normalized to the local continuum value prior to this analysis. For each grid point, we Doppler corrected each of the 40 XN Oph77 spectra to the rest frame of the secondary star, computed the average rest frame spectrum rebinned to a standard output format, renormalized the rest frame spectrum to an average flux of unity, and then cross-correlated this spectrum against the template spectrum. This analysis method was implemented using both personal software and IRAF-based routines; similar results were obtained in both cases.

As a collateral application of the rest frame search technique, we made a spectroscopic determination of the binary period. We tracked the maximum value of the cross correlation as a function of P, while permitting K and T_0 to vary at each trial period. The results, shown in Figure 7, imply a spectroscopic period of 12.22 ± 0.22 hr, which confirms the more precise photometric period (12.51 ± 0.03 hr) derived in § 3.

To evaluate the K-velocity of the companion star, we fixed the binary period at $P = 12.51$ hr and computed the cross correlation values as a function of K and T_0 in the plane $\gamma = 0$ km s^{-1}. The results are displayed in Figure 8, which shows a substantial correlation peak centered at $K = 406$ km s^{-1} and $T_0 =$ 1994 July 5.28, UT (see Table 1).

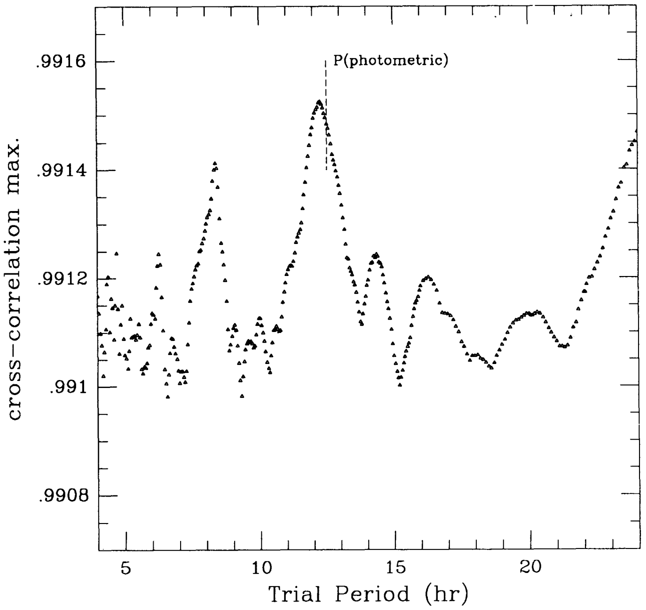

FIG. 7.—A search for the binary period of XN Oph77 using the "rest frame search" technique applied to 40 spectra obtained during 1994 July. The cross correlation template was a K3 V star, and all of the spectra were normalized to the local continuum values prior to analysis. The plot shows the maximum cross correlation value as a function of trial period, allowing variations in both the K velocity (0 to 600 km s^{-1} in steps of 10 km s^{-1}) and the epoch of the velocity sine wave (steps of 0.02 in binary phase). Only the systemic velocity of the binary system was held fixed ($\gamma = 0$) in this analysis. The derived spectroscopic period of 12.22 ± 0.22 hr agrees with the more accurate photometric period (12.51 hr). The cross correlation peaks near 8.4 hr and beyond 24 hr represent 1 day aliases of the orbital period.

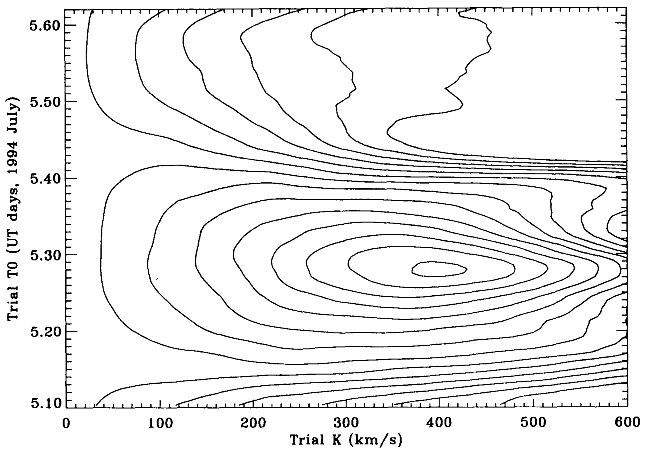

FIG. 8.—Rest frame search for T_0 and K using all 40 spectra of XN Oph77 obtained during 1994 July. The contours of cross correlation values are shown for trial rest frame spectra and a K3 V template. In this case, the period is fixed at 12.51 hr, and $\gamma = 0$ km s^{-1}.

A less significant, but basically similar result is shown in Figure 9 for the 13 spectra obtained during 1993 May. In the latter plot the maximum correlation is near $K = 470$ km s^{-1}. We arrived at a final K value by weighting these results by the respective exposure times. We first estimated the uncertainty in K as the uncertainty in fitting a parabola to determine the cross-correlation peak along the K axis at the best value of T_0. We further investigated the uncertainty due to systematic effects by measuring the deviations in K as we varied the choice of template spectrum and the continuum normalization method. Considering both of these effects, the conclusion of the rest frame analysis is: $K = 420 \pm 30$ km s^{-1}. The binary mass function is then

$$f(m) = PK^3/(2\pi G) = (M_x \sin i)^3/(M_x + M_c)^2$$
$$= 4.0 \pm 0.8\ M_\odot .$$

A summary of the best orbital parameters for XN Oph77 is given in Table 2.

Since there were no X-ray eclipses observed during the nova outburst (Watson et al. 1978), the binary inclination angle is limited to $i < 80°$. If we further adopt a reasonable lower limit for the mass of the companion star of $M_c > 0.2$ $M_\odot$ (for the case of an evolved companion), then $M_x > 3.5$

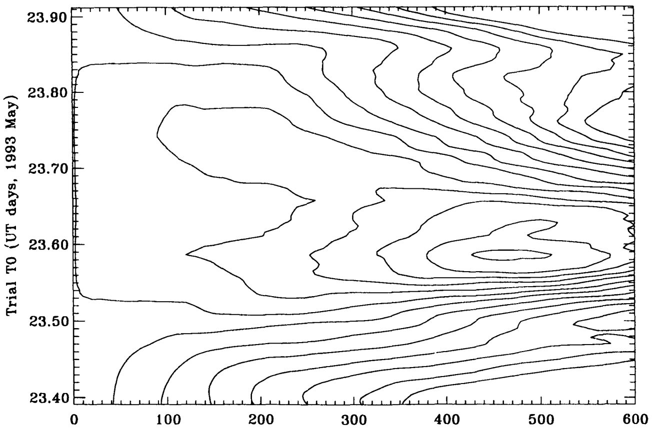

FIG. 9.—Rest frame search applied to the 13 spectra of XN Oph77 obtained during 1993 May. All other parameters are the same as those used for the analysis reported in Fig. 8.

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TABLE 2

ORBITAL PARAMETERS FOR XN OPH77

Parameter	Value
Orbital period (days)	0.5213 ± 0.0013
T_0 (photometric minimum; UT)	1994 Jul 9.288 ± 0.005
T_0 (photometric minimum; heliocentric)	HJD 2,449,542.793 ± 0.005
K velocity (km s^{-1})	420 ± 30
γ velocity (km s^{-1})	10 ± 20
T_0 (K max; UT days)	1994 Jul 6.318 ± 0.008
T_0 (K max; HJD)	HJD 2,449,539.823 ± 0.008

$M_\odot$ at 95% confidence. Thus, for nearly all of the available parameter space, the compact object is too massive to be a neutron star. As an example, if one assumes that the secondary star is a main-sequence K3 V star ($M_c = 0.75\ M_\odot$), and the inclination angle is moderate (e.g., $i = 60°$), then our best value for the mass function would imply $M_x = 8\ M_\odot$. We therefore propose that XN Oph77 be considered the sixth "dynamical" black hole binary.

The 1994 spectra of XN Oph77 were converted to the secondary rest frame with the overall "best" ephemeris: $P = 12.51$ hr, $K = 420$ km s^{-1}, $T_0 = 1994$ July 5.28 (UT), and $\gamma = 10$ km s^{-1}. The spectrum is shown in Figure 10, along with the spectrum of the K3 V template star used in the cross-correlation analysis. All of the most prominent K-star absorption features can be seen in the secondary rest frame, except for the complex near Mg $b(\sim 5175$ Å), which we believe is partially filled by Fe II emission, an effect that has been seen in other quiescent X-ray novae (Marsh, Robinson, & Wood 1994; Orosz et al. 1995). The rest frame spectrum of the secondary star produces a correlation significance of $r > 6.0$ against several template stars with spectral types in the range of K0–K5.

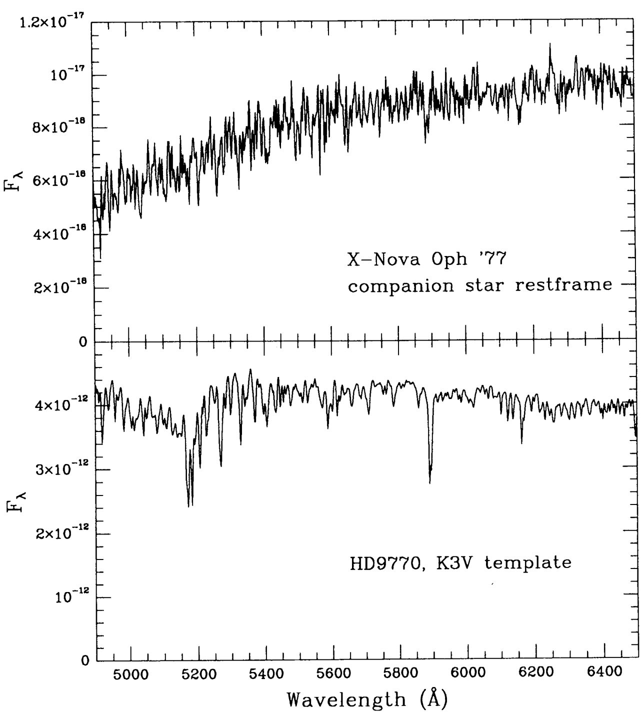

FIG. 10.—(*top*) A section of the optical spectrum of XN Oph77 that has been Doppler-corrected to the rest frame of the secondary star using the photometric period and a K-velocity of 420 km s^{-1}. The correlation significance of the net rest frame spectrum is $r = 6$. All of the strongest K star absorption lines are evident, except for the complex near Mg $b(\sim 5175$ Å), which is filled in by an emission line. (*bottom*) The spectrum of HD 9770 (K3 V), which was used as the cross correlation template.

5. DISCUSSION AND SUMMARY

There are striking similarities between XN Oph77 and both A0620−00 and XN Mus91, which include the following: the orbital period, type of companion star, X-ray spectrum in outburst, X-ray to optical flux ratio in outburst, nova decay timescales (X-ray and optical), optical light curve in quiescence, and broad Hα emission in quiescence (see references in § 1). These similarities foster the inclusion of XN Oph77 among the black hole binaries, in addition to the dynamical evidence presented above.

The agreement between the photometric and spectroscopic determinations of the orbital period is an important check on our results, given the difficulties of tracking the motion of such a faint star. We must also examine the phase relationship between these independent data sets. The zero point for the spectroscopic phase is the time of maximum radial velocity, while photometric phase (as defined here) is the brightness minimum associated with inferior conjunction of the companion star (i.e., spectroscopic phase $= 0.75$). The photometric epoch (see Table 2) occurs at a spectroscopic phase of 0.698 ± 0.023, where the uncertainty includes contributions for both epoch times and also for the propagation of the period across the six-orbit gap between the data sets. The phase offset therefore deviates by 2.3 σ from the expected value of 0.75. More stringent measurements of this quantity for other black hole binaries have not revealed any significant offsets (McClintock & Remillard 1986; Remillard et al. 1992; Wagner et al. 1992). This result raises the possibility of a mild phase offset between the spectroscopic and photometric data sets, perhaps induced by an additional source of light that also causes the differences in the photometric maxima (see also McClintock & Remillard 1990). The observations of 1993 May have an even longer gap (11 orbits) between spectroscopic and photometric data sets, and the spectroscopic phase of the photometric epoch time is 0.823 ± 0.058. This result is consistent with the expected value of 0.75, but the uncertainty here is relatively large.

Studies of the companion stars of accreting white dwarfs in some dwarf nova systems have shown that the measured radial velocities may exhibit systematic offsets that are believed to be caused by the heating of the companion's photosphere in the hemisphere facing the accretion disk (e.g., Hessman et al. 1984; Wade & Horne 1988). While we cannot fully evaluate the effects of heating in the case of XN Oph77, we do note that this problem appears to be insignificant in studies of the other black hole X-ray novae. Direct measurements of the high-energy emission from A0620−00 deep into quiescence reveals a luminosity $\sim 6 \times 10^{30}$ ergs s^{-1} (McClintock, Horne, & Remillard 1995), which is too low to cause significant heating of the companion star (see arguments in McClintock & Remillard 1986). Furthermore, as noted above, the optical light curves of these systems show their deepest minima (as predicted by the ellipsoidal variations model) at just the times when the disk-heated hemisphere of the companion star would be most visible, implying a negligible level of heating (McClintock & Remillard 1986; Haswell et al. 1993; Remillard et al. 1992; Orosz et al. 1995). The various measure-

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ments of the radial velocities of A0620−00 (McClintock & Remillard 1986; Johnston, Kulkarni, & Oke 1989; Marsh et al. 1994; Orosz et al. 1994) and XN Mus91 (Remillard et al. 1992; Orosz et al. 1995) have produced highly consistent results, and there is no evidence that the absorption-line systems fail to deliver an accurate record of the companion star motions in these binaries.

The spectrum of XN Oph77 in the rest frame of the companion star exhibits K star absorption lines that are somewhat weaker than the lines of a normal K dwarf. The weaker lines are presumably due to dilution of the stellar spectrum by continuum emission from the accretion disk. Using the technique described by Orosz et al. (1995), we estimate that the *K* star represents 60% ± 20% of the total light at 5500 Å. Thus the estimated magnitude of the secondary star is $V \sim 22.0$. Adopting the reddening estimate, $E(B-V) \sim 0.5$, obtained during the nova outburst (Griffiths et al. 1978), we deduce a corrected and dereddened magnitude for the companion star (isolated from the estimated disk component), $V_0 \sim 20.5$. If the companion is a K3 main-sequence star ($M_v = 6.6$), then the implied distance to XN Oph77 is ∼6 kpc, with considerable uncertainty for each of the above assumptions.

As noted above, the lack of X-ray eclipses during the nova outburst restricts binary inclination angle to $i < 80°$. On the other hand, the optical photometric modulations in quiescence (Fig. 4) are sufficiently large that they provide a lower limit for i, if it is assumed that the primary effect underlying this light curve is ellipsoidal variations in the secondary star. For high values of the mass ratio (e.g., $q > 5$), the amplitude of ellipsoidal modulations is primarily dependent on the binary inclination (see McClintock & Remillard 1990). A minimum value for i can be derived by applying the ellipsoidal model to fit both minima but only the lesser maximum in the $B+V$ light curve, while implicitly assuming that all of the light (except for the excess light near phase 0.75) arises from the secondary star. This produces a minimum inclination since the correction for the accretion disk contribution would increase the ellipsoidal modulations and hence require a larger inclination angle. The results of this analysis implies: $i > 60°$. For the case $i = 70° \pm 10°$, and $M_c \sim 0.7\ M_\odot$, then the black hole mass is estimated to be $6 \pm 1\ M_\odot$.

The peculiar Hα line profile observed in XN Oph77 during 1994 July is different from the usual asymmetry that is correlated with binary phase and can be attributed to a "hot spot" where the accretion stream impacts the edge of the disk (e.g., Marsh et al. 1994; Orosz et al. 1994). We note that some symbiotic stars show phase-independent, asymmetic Hα profiles (Robinson et al. 1994; van Winckel, Duerbeck, & Schwarz 1993), but the cause in these cases is also unexplained.

In summary, we have demonstrated that a 4 m telescope can be used to measure the radial velocities of a binary system for which the estimated magnitude of the secondary star is $V \sim 22$. However, to achieve this goal one must make use of all of the available data. The conventional techniques provided only an indication of the radial velocity curve, and they gave results that are affected by systematic error, as exhibited by the variations in γ and T_0 in Table 1B. Consequently, we devised the "rest frame search" method, which explores a multidimensional grid of binary ephemerides. For each trial ephemeris, all of the spectra were summed in the rest frame of the secondary star, and the rest frame spectrum was cross-correlated against a template spectrum. Thus all of the available signal was present during each correlation calculation.

In our study of XN Oph77, both the spectroscopy and photometry are consistent with an orbital period of 12.5 hr, and the photometry exhibits the double-wave modulations attributed to the rotation of a secondary star whose shape is gravitationally distorted by a massive compact object. The rest frame search yields a radial velocity curve with a semi-amplitude of 420 km s^{-1}, from which we deduce a mass function of $4.0 \pm 0.8\ M_\odot$, and a high probability that the compact object in this binary system is a black hole. Further, model-dependent interpretations of the rest frame spectrum and $B+V$ light curve lead to an estimated mass for the black hole of $6 \pm 1\ M_\odot$.

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Note added in proof.—A recent publication by Martin et al. (MNRAS, 274, L46, [1995]) shows photometric modulations in XN Oph77 that are similar to those reported here. Their analysis prefers the 8.4 hr value as the fundamental period (i.e., half the orbital period), which is a 1 day alias of the 6.2 hr period selected in our case. The spectroscopic analysis presented here (e.g., Fig. 7) provides confirmation that our interpretation for a binary period near 12.5 hr is correct.