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INFRARED SPECTROSCOPY OF SYMBIOTIC STARS. IV. V2116 OPHIUCHI/GX 1+4, THE NEUTRON STAR SYMBIOTIC

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ABSTRACT

We have computed, using 17 infrared radial velocities, the first set of orbital elements for the M giant in the symbiotic binary V2116 Ophiuchi. The giant's companion is a neutron star, the bright X-ray source GX 1+4. We rule out the previously proposed period of 304 days and instead find an orbital period of 1161 days, by far the longest of any known X-ray binary. The orbit has a modest eccentricity of 0.10, with an orbital circularization time of $\lesssim 5 \times 10^6$ yr. The large mass function of the orbit significantly restricts the mass of the M giant. Adopting a neutron star mass of $1.35 M_{\odot}$, the *maximum* mass of the M giant is $1.22 M_{\odot}$, making it the less massive star. Spectrum synthesis analysis of several infrared spectral regions results in slightly subsolar abundances for most metals. Carbon and nitrogen are in the expected ratio resulting from the red-giant first dredge-up phase. The lack of ^{17}O suggests that the M giant has a mass less than $1.3 M_{\odot}$, consistent with our maximum mass. The surface gravity and maximum mass of the M giant result in a radius of $103 R_{\odot}$, much smaller than its estimated Roche lobe radius. Thus, the mass loss of the red giant is via a stellar wind. These properties argue that the M giant is near the tip of the first-ascent giant branch. Although the M-giant companion to the neutron star has a mass similar to the late-type star in low-mass X-ray binaries, its near-solar abundances and apparent runaway velocity are not fully consistent with the properties of this class of stars. Thus, in many ways this symbiotic X-ray binary system is unique, and various scenarios for its possible evolution are discussed.

Subject headings: binaries: symbiotic — infrared: stars — stars: individual (V2116 Oph) — stars: late-type

1. INTRODUCTION

The star V2116 Ophiuchi = GX 1+4 ($\alpha = 17^{\text{h}}32^{\text{m}}02^{\text{s}}.16$, $\delta = -24^{\circ} 44' 44''.0$ [J2000.0], $V = 18.4$ mag) is unique among currently known symbiotic stars because the companion to the late-type giant is a neutron star rather than a white dwarf or main-sequence star. Lewin et al. (1971) identified the object as a very bright, hard X-ray source, GX 1+4. Doty (1976) found GX 1+4 to be an X-ray variable with a period of 2 minutes, suggesting that it is a slow pulsar. Early observations of its period changes led to the suggestion that the variations resulted from Doppler shifts associated with orbital motion (Becker et al. 1976). However, it was later determined that the spin-up and spin-down of the neutron star resulted from variable mass accretion (Doty et al. 1981; Ricketts et al. 1982; Makishima et al.

1988). While the present paper is only indirectly concerned with the neutron star at the heart of GX 1+4, we note that it is an extraordinary object. The rate of change of its rotation period is the greatest of any known pulsar, and the magnetic field, perhaps as large as $B_0 \sim 3 \times 10^{13}$ G, is among the largest measured in any astronomical object (Cui 1997).

Confirmation of the GX 1+4 optical counterpart with an 18th visual magnitude star came from both a precise *ROSAT* position (Predehl et al. 1995) and the detection of optical pulsing and flickering from the candidate star (Jablonski et al. 1997). Glass & Feast (1973) had previously shown that the suspected optical counterpart is an infrared source. The system is situated in the direction of the galactic center ($l = 1^{\circ}94$, $b = 4^{\circ}79$) and is significantly reddened, with $A_v \sim 5$ mag (Davidsen et al. 1977; Shahbaz et al. 1996; Chakrabarty & Roche 1997). Distance estimates, depending on the evolutionary state of the red giant, range from 3 to 15 kpc (Chakrabarty & Roche 1997). On the basis of optical spectra, Davidsen et al. (1977) suggested

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TABLE 1
RADIAL VELOCITIES OF V2116 Oph

| Heliocentric Julian Date (HJD - 2,400,000) | Wavelength (μm) | Phase | Velocity (km s^{-1}) | $O - C$ (km s^{-1}) | Source |
|---|---------------------------------|-------|------------------------------------|-----------------------------------|------------|
| 51,362.778..... | 1.5612-1.5682 | 0.500 | -162.5 | 1.4 | KPNO 4 m |
| 51,363.736..... | 1.5612-1.5682 | 0.501 | -163.9 | -0.0 | KPNO 4 m |
| 51,677.953..... | 1.5534-1.5606 | 0.771 | -174.3 | -0.2 | KPNO 4 m |
| 51,737.750..... | 1.5590-1.5662 | 0.823 | -178.3 | 0.6 | KPNO 2.1 m |
| 51,982.019..... | 1.6536-1.6610 | 0.033 | -194.2 | -1.4 | KPNO 4 m |
| 52,048.137..... | 1.6190-1.6250 | 0.090 | -190.5 | 0.7 | MSO |
| 52,098.932..... | 1.6275-1.6330 | 0.134 | -188.0 | 0.4 | MSO |
| 52,133.982..... | 1.6275-1.6330 | 0.164 | -186.3 | -0.3 | MSO |
| 52,155.957..... | 1.6275-1.6330 | 0.183 | -184.3 | 0.1 | MSO |
| 52,357.272..... | 1.6275-1.6330 | 0.356 | -170.1 | -0.2 | MSO |
| 52,399.268..... | 1.6275-1.6330 | 0.393 | -168.2 | -0.5 | MSO |
| 52,447.177..... | 1.6275-1.6330 | 0.434 | -165.5 | 0.2 | MSO |
| 52,502.980..... | 1.6275-1.6330 | 0.482 | -165.0 | -0.8 | MSO |
| 52,749.900..... | 2.2212-2.2315 | 0.695 | -167.8 | 0.5 | Gemini S |
| 52,771.672..... | 2.3304-2.3413 | 0.714 | -170.7 | -1.2 | Gemini S |
| 52,849.503..... | 2.2900-2.2980 | 0.781 | -174.9 | 0.0 | Gemini S |
| 53,098.811..... | 2.2212-2.2315 | 0.995 | -191.8 | 0.5 | Gemini S |

that GX 1+4 = V2116 Oph² (Kholopov et al. 1981) is a symbiotic star. They also noted that the emission-line strengths indicate the presence of a circumstellar envelope of radius $\sim 860 R_{\odot}$ ($\sim 6 \times 10^8$ km). In addition, Davidsen et al. (1977) concluded that if the orbital separation is the size of the circumstellar envelope, the orbital period would be years.

Shahbaz et al. (1996) observed the optical spectrum at a resolving power of ~ 800 and found strong emission lines of hydrogen, neutral helium, and neutral oxygen, as well as O III, Fe VII, and Fe X forbidden emission. Absorption bands of TiO and VO are conspicuous in the red, leading to an M5 III spectral type classification for the late-type star in the system (Shahbaz et al. 1996; Chakrabarty & Roche 1997). Because of the large amount of reddening and the energy distribution of the M giant, V2116 Oph is much brighter in the infrared, $K \sim 8$ mag, than at optical wavelengths. Bandyopadhyay et al. (1997) and Chakrabarty et al. (1998) observed the near-infrared spectrum of V2116 Oph at resolving powers of up to 4000. In contrast to the complex optical spectrum, except for strong emission lines from H I Brackett γ and He I 10830 Å, the infrared spectrum is typical of a cool M giant. Chakrabarty et al. (1998) interpreted the He I line as an outflow of $\sim 300 \text{ km s}^{-1}$ from the M giant. However, Kotani et al. (1999) noted similar line widths for optical-region emission lines and argued that the broad emission lines arise in gas that is gravitationally bound to the neutron star.

Binary systems containing a red giant are required to have a long orbital period. Doty et al. (1981) noted that a period of at least 120 days is necessary for $a \sin i$ to exceed the stellar radius, which places V2116 Oph in a unique X-ray binary niche. There have been several attempts to determine the orbital period by making the assumption that mass transfer from the M giant to the neutron star is enhanced at periastron. This mass transfer will alter the rotation period of the neutron star and hence the pulse rate, so a statistical analysis of the X-ray pulses should show peaks at the orbital period. From such analyses Cutler et al. (1986) and Pereira et al. (1999) concluded that the orbital period is ~ 304 days.

In this paper we exploit the typical M-giant near-infrared spectrum first described by Bandyopadhyay et al. (1997). Our high-resolution, infrared spectra of V2116 Oph span nearly 5 yr, enabling us to determine the first spectroscopic orbit of the red giant. We also present an evaluation of the surface abundances of the M giant. The neutron star in the V2116 Oph binary system is the remnant of a supernova. The survival of the binary is remarkable, given that the supernova must have been catastrophic for both the star we now see as the M giant as well as the surviving remnant. Our results enable us to further investigate the properties of the system and improve our understanding of the red-giant member, as well as the evolution of this neutron star binary.

2. OBSERVATIONS AND REDUCTIONS

Our 17 spectroscopic observations of V2116 Oph were obtained with four telescopes at three different observatories (Table 1). From 1999 July through 2001 March we obtained spectra at the Kitt Peak National Observatory (KPNO) with the Phoenix cryogenic echelle spectrograph at the $f/15$ focus of both the 2.1 m and the 4 m Mayall telescopes. A complete description of the spectrograph can be found in Hinkle et al. (1998). The widest slit was used, which results in a resolving power of $\sim 50,000$. The KPNO observations were centered at several wavelengths between 1.55 and 1.66 μm .

From 2001 May through 2002 August spectra were obtained in the southern hemisphere with the 1.88 m telescope and coude spectrograph system at the Mt. Stromlo Observatory (MSO). The detector was an infrared camera, NICMASS, developed at the University of Massachusetts. We obtained a 2 pixel resolving power of 44,000 at a wavelength of 1.63 μm . A more complete description of the experimental setup may be found in Joyce et al. (1998), as well as in Fekel et al. (2000b). The detector and electronics were previously used for our survey of northern symbiotics, carried out with the coude feed telescope at KPNO.

The devastating bush fire of 2003 January destroyed both the 1.88 m telescope at MSO and our infrared NICMASS camera. As a result, from 2003 April through 2004 April we obtained additional observations with the 8 m Gemini South telescope, Cerro Pachón, Chile, and the Phoenix cryogenic echelle spectrograph.

² In this paper we refer to the symbiotic system as V2116 Oph and reserve the name GX 1+4 for the X-ray source. However, V2116 Oph is classified by the GCVS as a variable X-ray source and the names are fully synonymous.

The first and last spectra had spectral resolving power of $\sim 70,000$, while the other two had resolving power of $\sim 50,000$. Although V2116 Oph was very challenging to find and observe at KPNO and MSO, observations with the Gemini South telescope were straightforward because the target was acquired with the help of a guide star. At $K \sim 8$ mag V2116 Oph is a relatively bright star for an 8 m telescope. The spectra obtained with Phoenix on Gemini South are of excellent quality and were useful in abundance analysis as well as the determination of the orbit.

Standard observing and reduction techniques were used (Joyce 1992). Wavelength calibration posed a challenge, because the spectral coverage was far too small to include a sufficient number of ThAr emission lines for a dispersion solution. Our approach was to utilize absorption lines in a K III star to obtain a dispersion solution. Several sets of lines were tried, including CO, Fe I, and Ti I. These groups all gave consistent results.

Radial velocities of the program star were determined with the IRAF cross-correlation program FXCOR (Fitzpatrick 1993). The reference star was δ Oph, an M-giant IAU velocity standard, for which we adopted a radial velocity of -19.1 km s^{-1} from the work of Scarfe et al. (1990).

3. ORBITAL ELEMENTS

To determine the orbital period, we first fit a sine curve to our 17 velocities for trial periods between 100 and 1500 days, with a step size of 0.1 days. For each period the sum of the squared residuals was computed, and the period with the smallest value of that sum, 1154.5 days, was identified as the preliminary value of the orbital period. We note that a phase plot of our velocities, determined with the previously suggested orbital period of 304 days (Cutler et al. 1986; Pereira et al. 1999), shows that both maximum and minimum velocities occur at the same phases. Thus, the 304 day period is clearly excluded. Chakrabarty & Roche (1997) speculated that the 304 day period was in fact an artifact of the strong $1/f$ torque noise in the pulsar's spin behavior.

Adopting the 1154.5 day period and unit weight for all velocities, initial orbital elements were computed with BISP, a computer program that implements a slightly modified version of the Wilsing-Russell method (Wolfe et al. 1967). The orbit was then refined with SB1 (Barker et al. 1967), a program that uses differential corrections. The best-fitting period is 1160.8 days or 3.18 yr. Because of the relatively low orbital eccentricity of 0.101 ± 0.022 , we computed a circular-orbit solution with SB1C (D. Barlow 1998, private communication), which also uses differential corrections. The tests of Lucy & Sweeney (1971) indicate that the eccentric solution is to be preferred. Orbital phases for the

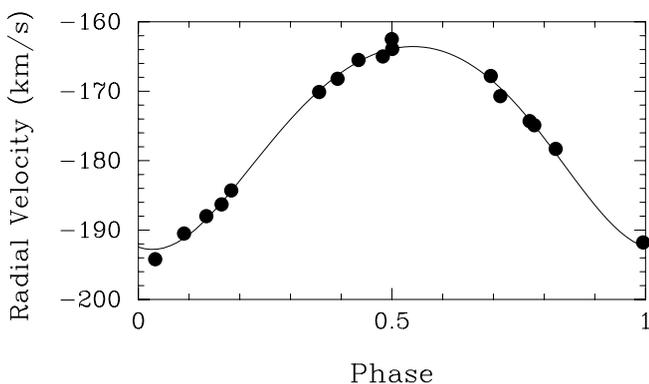


FIG. 1.—Computed radial velocity curve of V2116 Oph compared with our infrared velocities. Zero phase is a time of periastron passage.

TABLE 2
ORBITAL ELEMENTS OF V2116 Oph

| Parameter | Value |
|--|-----------------------------|
| Orbital period, P (days)..... | 1160.8 ± 12.4 |
| Orbital period, P (yr)..... | 3.18 ± 0.03 |
| Time of periastron passage, T (HJD)..... | $2,451,943 \pm 53$ |
| Systemic velocity, γ (km s^{-1})..... | -176.73 ± 0.22 |
| Orbital velocity semi-amplitude, K_g (km s^{-1})..... | 14.62 ± 0.34 |
| Eccentricity, e | 0.101 ± 0.022 |
| Longitude of periastron, ω_g (deg)..... | 168 ± 17 |
| Projected semimajor axis, $a_g \sin i$ (km)..... | $232.2 \pm 6.0 \times 10^6$ |
| Projected semimajor axis, $a_g \sin i$ (R_\odot)..... | 334 ± 9 |
| Mass function, $f(m)$ (M_\odot)..... | 0.371 ± 0.026 |
| Standard error of observation of unit weight (km s^{-1})..... | 0.85 |

NOTES.—When applicable only to the red-giant component of the binary orbit the parameters are subscripted “ g ” The six orbital elements have the standard definitions of Sterne (1941). Definitions for $a \sin i$ and $f(m)$ are given by Batten et al. (1989).

observations and velocity residuals to this final solution are given in Table 1. In Figure 1 the velocities and computed velocity curve are compared, where zero phase is a time of periastron passage.

The period of 3.18 yr has resulted in large phase gaps since only 1.5 orbital periods have been covered. Nevertheless, the elements, listed in Table 2, are reasonably well determined. The mass function, which is the minimum mass of the unseen star, is quite large, $0.371 M_\odot$, and thus consistent with the secondary being a neutron star. The center-of-mass velocity of -177 km s^{-1} is within the range of emission-line velocities of -120 to -370 km s^{-1} that Chakrabarty et al. (1998) found for this system. The standard error of an individual velocity is 0.85 km s^{-1} , which is in good agreement with uncertainties derived in our work on other S-type symbiotic systems (Fekel et al. 2000b). V2116 Oph is classified as a variable X-ray source, not a late-type variable star, in the GCVS, and there is no indication of intrinsic velocity variation in the M III star. The orbital elements presented here supersede the preliminary results of Hinkle et al. (2003). The ephemeris for a possible eclipse of the neutron star is

$$T_{\text{conj}} = \text{HJD } 2,452,235.8(\pm 53) + 1161(\pm 12)E,$$

where E is the integer number of 1161 day cycles after the given time of conjunction. This ephemeris predicts an upcoming mid-eclipse on UT date 2008 March 31.

4. ABUNDANCES

The high-resolution infrared spectra from which radial velocities were determined were also used to derive abundances for a small number of elements. With limited spectral coverage, the following atomic and molecular species were analyzed: Fe I, Na I, Sc I, Ti I, $^{12}\text{C}^{16}\text{O}$, $^{12}\text{C}^{17}\text{O}$, $^{12}\text{C}^{14}\text{N}$, ^{16}OH , and H^{19}F , with resulting abundances for Fe, ^{12}C , ^{14}N , ^{16}O , ^{17}O , ^{19}F , Na, Sc, and Ti. The line selection (with these lines being largely unblended and measurable in terms of equivalent widths) is listed in Table 3, along with excitation potentials, gf-values, and equivalent widths. Although equivalent widths are listed in this table, all abundances were derived ultimately from spectrum synthesis.

In a stellar abundance analysis, the model atmosphere parameters of effective temperature (T_{eff}), surface gravity (parameterized by $\log g$, with g in units of cm s^{-2}), microturbulent velocity (ξ), and metallicity must be specified. Because V2116 Oph has a very large and uncertain reddening, photometric colors cannot

TABLE 3
ABUNDANCE SPECTRAL-LINE DATA

| Species | Wavelength (Å) | χ (eV) | $\log gf$ | EW (mÅ) |
|------------------------------------|------------------------|-------------|-----------|---------|
| Fe I..... | 22,257.098 | 5.06 | -0.770 | 296 |
| | 22,260.186 | 5.09 | -1.000 | 271 |
| Na I..... | 23,378.945 | 3.75 | +0.731 | 594 |
| Sc I..... | 23,266.729 | 1.43 | -1.280 | 539 |
| | 23,404.756 | 1.44 | -1.278 | 581 |
| | 22,232.957 | 1.74 | -1.621 | 617 |
| Ti I..... | 22,309.961 | 1.73 | -2.086 | 534 |
| | 15,563.376 | 1.15 | -1.141 | 119 |
| $^{12}\text{C}^{14}\text{N}$ | 23,351.438 | 0.42 | -5.104 | 897 |
| $^{12}\text{C}^{16}\text{O}$ | 23,384.467 | 0.38 | -5.165 | 859 |
| | 23,389.146 | 2.20 | -4.790 | 163 |
| | 23,396.305 | 0.37 | -5.187 | 833 |
| | 23,398.275 | 1.73 | -4.458 | 444 |
| | 23,406.389 | 0.00 | -6.583 | 682 |
| | ^{16}OH | 15,560.271 | 0.30 | -5.307 |
| ^{16}O | 15,568.807 | 0.30 | -5.270 | 574 |
| | 15,572.111 | 0.30 | -5.183 | 555 |
| H^{19}F | 23,358.412 | 0.48 | -3.955 | 463 |

NOTE.—Molecular dissociation constants are taken to be $D_0(\text{CN}) = 7.65$ eV, $D_0(\text{CO}) = 11.09$ eV, $D_0(\text{OH}) = 4.39$ eV, and $D_0(\text{HF}) = 5.82$ eV.

be used to derive an accurate T_{eff} . We rely instead on the spectral type, as discussed by Chakrabarty & Roche (1997), and use this as an initial temperature estimator. Chakrabarty & Roche (1997) determined a range of spectral classes from M3 to M6; however, their various spectral indicators peak near M4 to M5. This suggests that the effective temperature for V2116 Oph falls near $T_{\text{eff}} = 3400$ K, with an uncertainty of about ± 200 K.

A series of model atmospheres, covering a range of effective temperatures ($T_{\text{eff}} = 3200\text{--}3600$ K) and gravities ($\log g = 0.1\text{--}1.0$), was generated with a version of the MARCS code (Gustafsson et al. 1975). The $^{12}\text{C}^{16}\text{O}$ lines span a range of excitation potential and line strength. Thus, they can be used to constrain both T_{eff} and the microturbulent velocity (ξ) by requiring no trends in the derived carbon abundance with both χ and

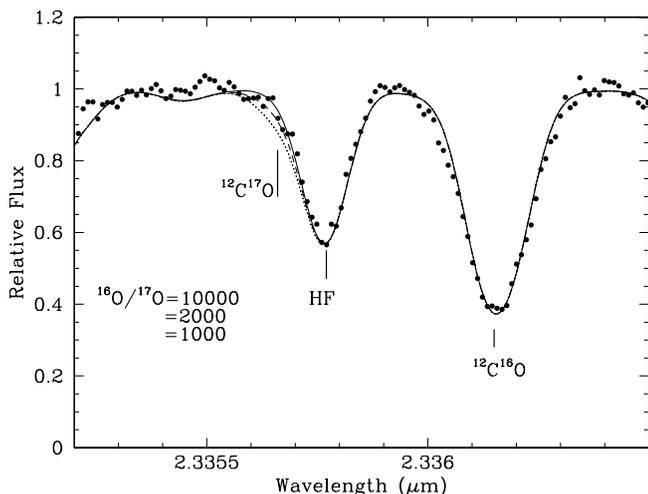


FIG. 2.—Sample illustration of synthetic spectra compared to the observed spectrum of V2116 Oph. This region shows the 1–0 R9 HF line, along with a strong $^{12}\text{C}^{16}\text{O}$ blended feature (3–1 R24+R76), as well as the expected location of a clean $^{12}\text{C}^{17}\text{O}$ line (2–0 R26) that is not detected. If V2116 Oph were a first-ascent red giant more massive than about $1.3 M_{\odot}$, the $^{12}\text{C}^{17}\text{O}$ should be visible.

TABLE 4
ABUNDANCES

| Species | V2116 Oph | Sun | [X/H] |
|-------------------------------------|-----------------|------|-------|
| Fe..... | 7.45 ± 0.26 | 7.50 | -0.05 |
| ^{12}C | 8.03 ± 0.18 | 8.45 | -0.42 |
| ^{14}N | 8.97 ± 0.25 | 7.80 | +1.17 |
| ^{16}O | 8.47 ± 0.29 | 8.77 | -0.30 |
| $^{16}\text{O}/^{17}\text{O}$ | ≥ 1500 | 2660 | ... |
| ^{19}F | 4.55 ± 0.22 | 4.55 | 0.00 |
| Na..... | 6.00 ± 0.18 | 6.33 | -0.33 |
| Sc..... | 3.18 ± 0.15 | 3.17 | +0.01 |
| Ti..... | 4.58 ± 0.22 | 5.02 | -0.44 |

NOTE.—Format for V2116 Oph and Solar abundances are $A(X) = \log [N(X)/N(\text{H})] + 12.0$, and $[X/H] = A(X)_{\text{Star}} - A(X)_{\text{Sun}}$.

reduced equivalent width. This exercise indicates that the most consistent set of stellar parameters to describe V2116 Oph, based on the infrared lines, is $T_{\text{eff}} = 3400$ K, $\log g = 0.5$, and $\xi = 2.4$ km s $^{-1}$. These parameters are typical for a cool, low- to intermediate-mass, first-ascent giant or asymptotic giant branch (AGB) star.

A near-solar metallicity is indicated, so final model atmospheres were generated with solar metallicities. A sample comparison of synthetic spectra with the observed spectrum is shown in Figure 2, where the HF 1–0 R9 line, a $^{12}\text{C}^{17}\text{O}$ line, and a $^{12}\text{C}^{16}\text{O}$ line are shown. Abundances are listed in Table 4, with the uncertainties estimated by changing stellar parameters by ± 100 K in T_{eff} , ± 0.3 dex in $\log g$, and ± 0.3 km s $^{-1}$ in ξ . As can be seen, the abundances of Fe, ^{16}O , ^{19}F , Na, Sc, and Ti are slightly subsolar, while ^{12}C is somewhat lower in abundance and ^{14}N is enhanced.

The lowered ^{12}C and elevated ^{14}N are the expected result of the red-giant first dredge-up phase. Indeed, the ^{12}C and ^{14}N do not fall far from a CN-mixing line of nitrogen versus carbon starting from initial solar-like C and N abundances. These results also agree with the lower limits derived for the $^{16}\text{O}/^{17}\text{O}$ ratios of ≤ 1500 , which is a value expected for a low-mass ($M \sim 1.0\text{--}1.3 M_{\odot}$), first-ascent giant (see the review of Smith 1990). The indication from the ^{17}O abundance that V2116 Oph is a low-mass giant is in agreement with the result derived from the mass function.

5. DISCUSSION

5.1. Evolutionary State of the M Giant

Based on X-ray and infrared observations, Chakrabarty & Roche (1997) constrained the basic properties of the M giant and the distance to the V2116 Oph system. Chakrabarty & Roche (1997) then discussed the evolutionary state of the giant, concluding that it is either a low-mass star near the tip of the first-ascent giant branch or a low- or intermediate-mass star beginning its ascent of the AGB. Using luminosity and extinction arguments, they suggested that the giant is near the tip of the first-ascent red giant branch.

Our results enable us to place additional observational constraints on the late-type giant. The large value of the mass function significantly restricts the mass of the M giant because of constraints on the neutron star mass. The upper limit to the mass of a neutron star is $\sim 3 M_{\odot}$, when the internal sound speed reaches the speed of light. A maximum neutron star mass of $3 M_{\odot}$ results in a maximum mass of $5.5 M_{\odot}$ for the M giant (Fig. 3). However, such a large mass for the neutron star seems unlikely. The masses of neutron stars in binary radio-pulsar systems are all very close to $1.35 M_{\odot}$ (Thorsett & Chakrabarty 1999), and so we adopt a

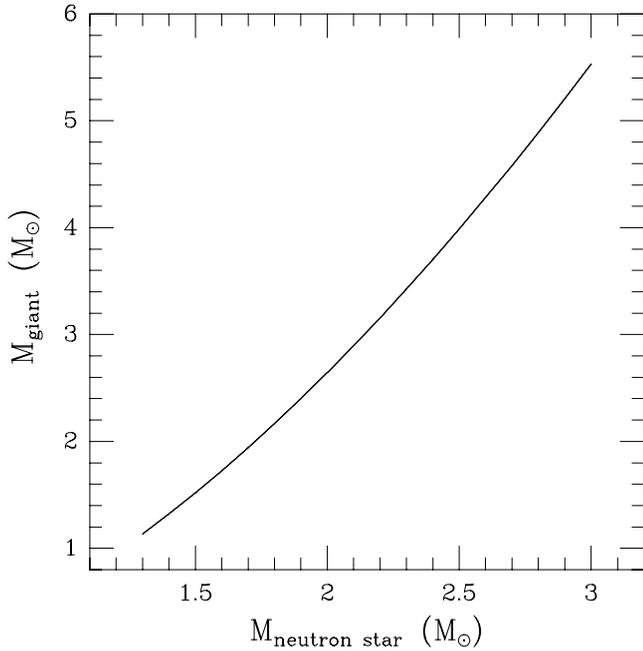


FIG. 3.—Line shows the relation between the masses, in solar units, of the M giant and the neutron star for an orbit seen edge-on. The neutron star mass ranges from the Chandrasekhar limit to black hole collapse. For a given neutron star mass, decreasing the orbital inclination decreases the mass of the M giant. Additional constraints (see text) suggest a neutron star mass near $1.35 M_{\odot}$ and a nearly edge-on orbital inclination.

mass of $1.35 M_{\odot}$ for the neutron star component in V2116 Oph. With a neutron star mass of $1.35 M_{\odot}$, the value of the mass function requires that the mass of the M giant be $\leq 1.22 M_{\odot}$, consistent with a low-mass star. A mass of $1.22 M_{\odot}$ requires an edge-on orbital inclination. The requirement that the lower mass star have time to evolve to a giant implies that the inclination cannot be near to face-on. For example, as the inclination is decreased from edge-on (90°), a neutron star mass of $1.35 M_{\odot}$ and an inclination of 70° result in a mass of $1.0 M_{\odot}$ for the M giant, while an inclination of 60° results in an M-giant mass of $0.72 M_{\odot}$.

Chakrabarty & Roche (1997) examined a number of optical and near-infrared spectra of V2116 Oph. They suggested that optical flux from the neutron star accretion disk and from X-ray heating of the red giant weakens the TiO band strengths much of the time, making the spectral class appear as early as M3. They determined a mean spectral class of M5, while a calculation of the X-ray luminosity suggests a M6 spectral class, corresponding to $T_{\text{eff}} = 3380$ K. This result is in excellent agreement with our value of 3400 K, determined from spectrum synthesis of our infrared spectra.

Using $T_{\text{eff}} = 3400$ K and $R = 103 R_{\odot}$ (§ 5.2) with the equation $L = 4\pi\sigma R^2 T_{\text{eff}}^4$, we derive a luminosity of $1270 L_{\odot}$ for the M giant. This luminosity puts the red giant very near the tip of the first-ascent giant branch, or on the lower portion of the AGB (Charbonnel et al. 1996). A first-ascent giant is in agreement with the C and N elemental abundances and the oxygen isotopic abundances. The above temperature and luminosity combined with an $A_v = 5$ mag (§ 1) results in a distance of 4.3 kpc. In spite of its position in the sky, which is quite near the direction to the Galactic center, V2116 Oph is clearly not an object associated with the center of the Milky Way.

The models of Charbonnel et al. (1996) indicate that the current mass of $\leq 1.22 M_{\odot}$ corresponds to a main-sequence mass of $\leq 1.34 M_{\odot}$ and that such a star with solar metallicity takes $\sim 5 \times 10^9$ yr to reach the first-ascent giant branch tip. Assuming

the neutron star resulted from a core-collapse supernova with a $M \geq 10 M_{\odot}$ progenitor, the progenitor lifetime up to core collapse was a few times 10^7 yr. If true, the neutron star would be 5 billion years old, a point we return to below.

5.2. Synchronization and Circularization

Zahn (1977) has shown that tidal forces in binaries cause rotational synchronization and orbital circularization, and that the time required for synchronization is shorter than that for circularization. Both the synchronization and circularization times are principally dependent on the ratio of the semimajor axis of the relative orbit, a , to the giant star radius, R . The circularization time scales as $(a/R)^8$, while the synchronization time scales as $(a/R)^6$ (Soker 2000). The orbit of the red giant in the V2116 Oph system provides the value for the semimajor axis of the red giant times the sine of the inclination, $a_g \sin i$. Designating the semimajor axis of the neutron star's orbit as a_n , the semimajor axis of the relative orbit is $a = a_g + a_n$. The masses of the components are approximately equal, so for this system we assume $a = 2a_g$.

On the basis of the work of Zahn (1977), Schmutz et al. (1994) and Mürset et al. (2000) have argued that in most S-type symbiotics, the giant is synchronously rotating. Indeed, with the orbital parameters and masses derived for V2116 Oph, the tidal synchronization time (the time required to spin up the red giant to synchronous rotation with the orbit) is only $\sim 10^4 \sin^{-6} i$ yr, according to the formulae in Soker (2000). The orbit of V2116 Oph has a modest eccentricity. Thus, the rotational angular velocity of the M giant will synchronize with that of the orbital motion at periastron to achieve pseudosynchronous rotation (Hut 1981). With equation (42) of Hut (1981) we calculated a pseudosynchronous period of 1075.5 days. Although the synchronization and circularization calculations involve raising the ratio (a/R) to large powers, it is very unlikely that these times can be a factor of 10 larger. The semimajor axis is known to 2%. As discussed below, our value for the radius of the giant, $103 R_{\odot}$, is uncertain by $\sim 30\%$.

If, as suggested by theory, the M giant is pseudosynchronously rotating, its projected rotational velocity can be used to estimate its minimum radius. To determine $v \sin i$ of the M giant, we measured the FWHM of a few atomic features at $2.2 \mu\text{m}$. We also measured the same lines in several late-type giants with known $v \sin i$ values. With the latter set of stars, we produced an empirical broadening calibration similar to that of Fekel (1997). Using the calibration and an adopted macroturbulence of 3 km s^{-1} , we determined $v \sin i = 8 \pm 1 \text{ km s}^{-1}$ for the M giant. The pseudosynchronous period and the $v \sin i$ value result in a *minimum* radius (i.e., $\sin i = 1$) of $170 \pm 21 R_{\odot}$.

Another way of estimating the red-giant radius is to use the results of Dumm & Schild (1998). They computed radii for a sample of nearby M giants that have relatively well-determined *Hipparcos* parallaxes. They found a median radius of $\sim 150 R_{\odot}$ for the M6 giants in their sample, but their Figure 6 shows that the radius of a given spectral type is mass-dependent. Our orbital and abundance results indicate that the M giant has a mass $\leq 1.2 M_{\odot}$. Figure 6 of Dumm & Schild (1998) shows that the M6 giants with the lowest masses, $1.0 M_{\odot} \leq M \leq 1.6 M_{\odot}$, have a mean radius of $118 R_{\odot}$, significantly smaller than the minimum radius for pseudosynchronous rotation.

The best determination of the M giant radius is computed from our spectroscopic determination of $\log g = 0.5 \pm 0.3$ and a maximum mass for the red giant of $1.22 M_{\odot}$, which result in a radius of $103 R_{\odot}$. The estimated uncertainty of $\log g$ results in a radius range of $73\text{--}145 R_{\odot}$. Decreasing the mass of the red giant decreases its radius. So the mean radius from the low-mass

M6 giants of Dumm & Schild (1998) is consistent with our spectroscopic determination. Contrary to theoretical expectations, both those values argue that the M giant is not rotating pseudosynchronously. Paul et al. (1997) find a value for the angle between the observer line of sight and the neutron star spin axis of $56^\circ \pm 8^\circ$. Since the M giant is not rotating pseudosynchronously, we are unable to present arguments that the spin axis of the neutron star should be normal to the orbital plane.

The V2116 Oph orbit has significant eccentricity. The timescale for circularization of the orbit caused by tides induced in the red giant by the companion is $\sim 5 \times 10^6 \sin^{-8} i$ yr from the relations given by Soker (2000). Since mass loss and transfer as well as tides tend to circularize orbits (Hurley et al. 2002), a kick from the supernova explosion that formed the neutron star is one way to produce a noncircular orbit. The apparent lack of ejecta seems to exclude a relatively recent supernova explosion, although the reddening toward V2116 Oph is large and it is possible that supernova ejecta surrounding the system have not been detected. However, there are many red giants currently in very close binary systems that appear to be in eccentric orbits (Soszyński et al. 2004). Thus, the eccentricity of the V2116 Oph orbit does not necessarily limit the time since the supernova event. Soker (2000) has argued that the eccentricity in such evolved systems is caused by an enhanced mass-loss rate during periastron passage. Indeed, other articles of this series (Fekel et al. 2000a, 2000b, 2001) have found symbiotic systems with eccentric orbits for periods as short as 450 days; however, these systems contain a white dwarf rather than a neutron star companion to the M giant and are less massive.

The X-ray flux and its behavior require the presence of an accretion disk around the neutron star. Chakrabarty & Roche (1997) favored a stellar wind rather than Roche-lobe overflow to form the accretion disk. Placing V2116 Oph on the first-ascent giant branch implies that the M giant does not fill its Roche lobe. This is in agreement with less direct but powerful arguments presented by Chakrabarty & Roche (1997) based on the stellar radius and luminosity as determined from the V2116 Oph reddening, variability, and stellar wind and the GX1+4 X-ray luminosity and accretion torque. The optical variability of V2116 Oph and the cessation of flickering from the presumed accretion disk during faint intervals suggest that the mass transfer from the red giant to the X-ray source is time-variable (Jablonski et al. 1997), as would be the case for a non-Roche-lobe-filling system. Although the orbit of V2116 Oph is not circular, the eccentricity is low, and we can determine an approximate Roche-lobe radius. With Kepler's third law and the formula of Eggleton (1983), we find a Roche-lobe radius = $236 R_\odot$. Comparison with our derived giant radius of $103 R_\odot$ indicates that like most S-type symbiotic binaries (Mürset & Schmid 1999), the M giant is far from filling its Roche lobe. Thus, the mass transfer to the neutron star does indeed result from the M-giant stellar wind rather than Roche-lobe overflow.

5.3. Evolution of the Binary System

The existence of X-ray binaries is proof of what might seem an unlikely proposition, that a binary system can survive a supernova explosion. In the case of V2116 Oph the current M giant not only survived the explosion but did so with no obvious change in the surface abundances. Surprisingly, there is no reason to expect the abundances of what is now the M giant to be altered significantly by the supernova explosion. If the stars had been in contact, the area subtended by the then main-sequence star was on the order of 0.001% of the surface area of the supernova precursor. Even if the supernova ejecta exceeded

several solar masses of oxygen, the amount accreted by the main-sequence star would have resulted in undetectable surface abundance changes after the main-sequence surface has been subducted in the giant stage.

Defining characteristics of high- and low-mass X-ray binaries are given by Verbunt & van den Heuvel (1995). In low-mass X-ray binaries, the companion to the compact object has a mass $\lesssim 1.0 M_\odot$. These systems belong to a very old stellar population and do not show runaway characteristics. Solely on the basis of our upper limit to the mass of the red giant, V2116 Oph/GX 1+4 would marginally meet the criteria for a low-mass system. However, the abundances of the red giant are nearly solar, and hence the system does not belong to a very old population. The center-of-mass velocity of the system is quite large, -177 km s^{-1} . While the V2116 Oph system fits the mass criteria for low-mass systems, the near-solar abundances make V2116 Oph a deviant member.

Furthermore, the large velocity of V2116 Oph suggests that it is a runaway system. On 2003 February 16 the $1.564 \mu\text{m}$ spectrum of a star separated from V2116 Oph by $19''$, Star 6 in Chakrabarty & Roche (1997, Table 2), was observed with a spectral resolving power of 50,000 with Phoenix at Gemini South. This star, which has a similar visual magnitude to V2116 Oph, proved to be an M star with a velocity of $+118 \text{ km s}^{-1}$. The observation of one star of unknown distance does not demonstrate the kinematics of the V2116 Oph field, but the 295 km s^{-1} velocity difference between the two systems suggests that a significant velocity was imparted to the V2116 Oph system by the supernova explosion, giving it a runaway velocity.

Considerable discussion exists in the literature on ways to produce X-ray binaries. As reviewed by Canal et al. (1990), Iben et al. (1995), Verbunt & van den Heuvel (1995), and others, while there is consensus that high-mass systems are the result of massive star evolution, four schemes have been advanced for the formation of low-mass X-ray binary systems. These four are (1) capture of a neutron star by another star in a dense stellar system (e.g., globular cluster), (2) the direct evolution of one star of a primordial binary into a neutron star, (3) triple-star evolution of a system including a massive star binary, and (4) a low-mass binary, where one member first becomes a white dwarf then undergoes mass accretion resulting in collapse to a neutron star.

For a field star, tidal capture by a neutron star is unlikely. The neutron star must approach the star to be captured by 2–3 times the target star radius, although the odds may be increased by involving a binary system (Canal et al. 1990). Since the neutron star and the M giant have nearly equal masses, the capture conditions are very limited. The tidal capture mechanism is most likely for stars in the cores of globular clusters. The abundances of V2116 Oph do not rule out a scenario in which V2116 Oph was formerly a member of a low-mass globular cluster and escaped as the result of being captured by a runaway neutron star. Achieving escape velocity from a globular cluster is a major difficulty, but this scenario is remotely possible (Krolik et al. 1984). Nonetheless, we discount tidal capture for the formation of the V2116 Oph system.

Evolution of V2116 Oph from a massive-star–low-mass star binary is tightly constrained by the requirement that a bound binary system survive a supernova event. Standard models show that systems ejecting half or more of their total mass in a supernova explosion become unbound (Dewey & Cordes 1987). The production of a neutron star remnant from a main-sequence star requires a $\sim 9 M_\odot$ main-sequence star. Without any velocity kick, keeping the system bound during a supernova with a massive star

and a $1.3 M_{\odot}$ companion requires that the neutron star progenitor have a mass no greater than $\sim 4 M_{\odot}$ at the time of the supernova event. Certainly considerable mass loss can occur before the supernova progenitor explodes. Calculations by Maeder & Meynet (1988) for single-star mass loss indicate that a $9 M_{\odot}$ star could be reduced to $3.5 M_{\odot}$ before the star explodes. Furthermore, Hills (1983) suggests that in unusual conditions of orbital phase and eccentricity a system losing more than half of the total mass can survive. The presence of a velocity kick from the supernova further constrains the mass loss to keep the system bound, and this scenario for V2116 Oph seems unlikely.

A modification to the direct evolution scheme invokes common envelope evolution (Taam & Sandquist 2000), which would allow a binary with high- and low-mass members to survive the supernova phase. A common envelope stage when the massive star becomes a supergiant can lead to the ejection of the common envelope, resulting in a binary composed of an evolved stellar core and a main-sequence companion. The reduced mass difference between the evolved core and the main-sequence star allows the system to remain bound. The orbit following the supernova explosion would be highly eccentric (Dewey & Cordes 1987), but tidal interaction would rapidly circularize the orbit.

Canal et al. (1990) and Iben & Tutukov (1999) note that it is possible to form a V2116 Oph-like binary through common envelope evolution and merger starting with a triple system. One such scenario invokes a massive close binary with a distant dwarf companion. The massive binary undergoes mass transfer and a supernova. The remaining massive star–neutron star system then undergoes common envelope evolution and a merger forming a Thorne-Zytkov object, i.e., a red giant with a neutron star core. This is followed by a common envelope phase with the dwarf during which the neutron star envelope is ejected leaving a neutron star–dwarf system. Starting from either a binary or a triple system and by invoking various special conditions, it does appear possible to evolve a high-mass–low-mass binary into a neutron star–low-mass binary.

The last scenario is accretion-induced collapse (AIC) of a white dwarf. The more massive member of a low-mass binary system initially becomes a white dwarf. Mass transfer then takes place from the initial secondary, resulting in collapse of the white dwarf to a neutron star. The appeal of the model is that small mass ejection is involved and hence minimal disruption to the orbit. An initially massive white dwarf and a high rate of mass accretion are required. Broad objections to AIC concern the details of the mass transfer and the requirement that the supernova event leave a remnant. The accretion-induced collapse scenario is reviewed at length by Canal et al. (1990). A consequence of the AIC is that the stars in the system can have similar ages.

Objections are possible when applying any of these scenarios to the V2116 Oph system. However, in many aspects V2116 Oph appears to be a perfect example of a AIC system as suggested by van den Heuvel (1984). The secondary is only now on the giant branch. If the dwarf in the prior dwarf-white dwarf star system had nearly filled its Roche lobe, a high-rate mass transfer episode would have taken place as post-main-sequence evolution commenced. The accretion rate from a $1.2 M_{\odot}$ secondary is optimal for AIC (van den Heuvel & Taam 1984). Van den Heuvel & Taam (1984) also point out that a precursor white dwarf $\sim 10^9$ yr old would have the optimal interior structure for AIC. A binary of the age of V2116 Oph could have a white dwarf this old. Furthermore, the current evolutionary state of V2116 Oph, i.e., a first-ascent red giant and a neutron star companion, would be the product of a relatively recent AIC event. The evolution of the binary orbit following the supernova results from the ex-

plosive ejection of $\sim 0.2 M_{\odot}$. This enlarges the binary orbit but does not disrupt the system. The ejecta from such a supernova would likely be mainly helium (Nomoto 1982) and would not impact the measured abundances of the current M III.

The massive star and AIC scenarios produce neutron stars with ages differing by billions of years. If it were possible to date the neutron star, it would be possible to exclude certain classes of models. The neutron star spin rate does not provide any insight since, as noted in § 1, the neutron star rotation rate of V2116 Oph is linked to the mass transfer. The surface temperature of the neutron star reflects the interior structure and hence age (Baym & Pethick 1979). This measurement would be difficult to carry out due to mass transfer in the V2116 Oph system. However, Taam & van der Heuvel (1986) proposed that the surface magnetic fields of neutron stars decay on a timescale measured in 10^6 yr. The neutron star in V2116 Oph has a magnetic field that is among the strongest known, implying youth. At odds with Taam & van der Heuvel (1986), Phinney & Verbunt (1991) noted evidence that neutron star fields do not undergo massive decay but did find that field decay of at least a factor of 4 over a period of $\sim 10^{10}$ yr is required to match neutron star field statistics. The field of V2116 Oph is near the maximum limit supportable in a neutron star (Flowers & Ruderman 1977) and cannot possibly be the age of the M-giant component in the system.

Given the nature of the V2116 Oph system, with the extraordinary presence of a neutron star in a 3 yr orbit, near solar abundances of the M giant, and the large radial velocity, the binary is the only system of its type known in the Milky Way galaxy. This suggests either a very rapid evolutionary state or a highly unusual formation mechanism. While the giant phase is not short-lived, it is possible that the system is currently undergoing a short-lived phase of high mass transfer associated with the late-type star's evolution to the red-giant tip. The probabilities associated with the formation mechanism are best summarized by Iben et al. (1995), who note that a binary evolving to this end must escape both the hazards of merger and disruption from supernova explosion.

The future evolution of V2116 Oph is an interesting topic for speculation. When the current red giant becomes an AGB star in $\sim 10^8$ yr, single-star evolution predicts that it will be much larger in size than its current orbit (Charbonnel et al. 1996). Furthermore, tidal interaction and perhaps magnetic braking will reduce the current separation. Thus, expansion of the giant will result in the V2116 Oph system becoming a contact binary. An AGB star does not contract as a result of mass loss, so as the AGB star continues to expand the neutron star will be engulfed in the envelope of the AGB star and co-rotation, the requirement for escaping common envelope evolution, will be lost. Common envelope systems rapidly eject mass and the evolutionary end-product will be a neutron star–white dwarf binary similar to PSR 0655+64 or PSR 0820+02 (van den Heuvel & Taam 1984). The existence of these objects suggests, as do arguments about the lifetime of the mass transfer stage, that the evolutionary path of V2116 Oph is not extremely rare in the Milky Way. V2116 Oph is notable because the current mass transfer rate makes it highly visible.

6. CONCLUSIONS

The determination of a time series of infrared radial velocities of the M giant V2116 Oph have confirmed the association of this star with the neutron star/X-ray source GX 1+4. The single-line spectroscopic binary orbit is now well determined and, at 1161 days, exceeds the orbital period of any other low-mass X-ray binary by a factor of nearly 50 (Liu et al. 2001).

While the inclination is unknown, on the basis of other X-ray binary systems the mass of the neutron star is probably $\sim 1.35 M_{\odot}$. The plane of the orbit must lie close to the line of sight, implying that eclipses of at least part of the mass transfer flow or accretion disk are possible. The next predicted date of “mid-eclipse” is 2008 Mar 31. The abundances of the M giant, as well as the mass function of the orbit combined with the adopted mass of the neutron star, indicate a mass of $\sim 1.2 M_{\odot}$ for the M giant. The abundances of the M giant also suggest that it is a first-ascent giant, in agreement with arguments presented in the detailed study of the system by Chakrabarty & Roche (1997). Our radius of the M giant and the X-ray behavior of the system indicate that the giant does not fill its Roche lobe, a conclusion consistent with its identification as a first-ascent giant. The fact that the giant does not fill its Roche lobe makes V2116 Oph very different from other low-mass X-ray binaries.

The evolutionary history of this and other neutron star binaries is an area of continued speculation. Should the neutron star have originated with the supernova explosion of a $\sim 10 M_{\odot}$ star, the neutron star is ancient, having coexisted with the progenitor of the current M giant for nearly 5 billion years. However, the activity of the V2116 Oph neutron star strongly suggests that it was formed 10^7 yr ago or less. Since we know that the age of the M giant is $\sim 5 \times 10^9$ yr, this implies that a massive star never existed in this system. This strongly suggests that the neutron star resulted from accretion-induced collapse. The precollapse system consisted of a white dwarf and the first-ascent giant nearly filling its Roche lobe.

If the accretion-induced collapse scenario is correct, the V2116 Oph neutron star is a fairly recent remnant from a single degenerate Type I supernova event. To an observer prior to the

V2116 Oph supernova, the white dwarf–red-giant system would have appeared as a symbiotic system. There are few symbiotic systems known that contain high-mass white dwarfs and none that also contain a companion close to filling its Roche lobe. However, the fraction of symbiotic binaries that have been fully characterized is small. Continued exploration of these systems may reveal a pre-accretion-induced collapse system.

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