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INFRARED SPECTROSCOPY OF GX 1+4/V2116 OPHIUCHI: EVIDENCE FOR A FAST RED GIANT WIND?

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ABSTRACT

We present infrared spectroscopy of the low-mass X-ray binary GX 1+4/V2116 Ophiuchi. This symbiotic binary consists of a 2 minute accretion-powered pulsar and an M5 III red giant. A strong He I 1.083 μm emission line with a pronounced P Cygni profile was observed. From the blue edge of this feature, we infer an outflow velocity of 250 ± 50 km s^{-1}. This is an order of magnitude faster than a typical red giant wind, and we suggest that radiation from the accretion disk or the neutron star may contribute to the acceleration of the outflow. We infer a wind mass-loss rate of $\sim 10^{-6}$ $M_\odot$ yr^{-1}. Accretion from such a strong stellar wind provides a plausible alternative to Roche lobe overflow for supplying the accretion disk that powers the X-ray source. The H I Paβ and He I 1.083 μm emission lines show no evidence for the dramatic variability previously reported in some optical lines and no evidence for pulsations at the 2 minute pulsar period.

Subject headings: binaries: symbiotic — pulsars: individual (GX 1+4) — stars: individual (V2116 Ophiuchi) — stars: mass loss — stars: neutron — X-rays: stars

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) consist of a late-type star or degenerate dwarf transferring matter to a neutron star or black hole via an accretion disk. The mass donor generally fills its Roche lobe. The optical emission in LMXBs is usually dominated by reprocessing in the X-ray–heated disk. However, in those systems with late-type donors and wide ($P_{\rm orb} \gtrsim 1$ day) orbits, the infrared luminosity of the donor is comparable to that of the disk, allowing direct study of the donor. The infrared emission is also less affected by interstellar absorption, which is generally a significant hindrance in optical studies of LMXBs.

The most luminous known LMXB mass donor is V2116 Ophiuchi, the M5 III giant companion of the 2 minute accretion-powered pulsar GX 1+4 (Glass & Feast 1973; Davidsen, Malina, & Bowyer 1977; Chakrabarty & Roche 1997, hereafter CR97). The system is exceptional in a number of ways. It is a symbiotic binary (see Kenyon 1986 and Iben & Tutukov 1996 for reviews), the only one known with a confirmed neutron star companion. Its binary period is unknown but must be $\gtrsim$100 days, making it the widest known LMXB by an order of magnitude. The dense emission-line nebula surrounding the binary is powered by ultraviolet radiation from an accretion disk. Dramatic 100% variability on a timescale of minutes was observed in the optical emission fluxes of selected He I and Fe II lines, while the continuum and all other lines remained constant (CR97). Coherent optical pulsations at the 2 minute X-ray pulsar period are intermittently detected in the broadband, blue continuum (Jablonski et al. 1997). GX 1+4 (=4U 1728−247) is one of brightest hard X-ray sources in the Galactic center region. X-ray timing of the pulsar has revealed remarkable bimodal accretion torque transitions between long intervals of steady, rapid spin-up and equally rapid spin-down (Chakrabarty et al. 1997). This may indicate that the dipole magnetic field strength at the neutron star surface is extraordinarily strong ($\sim 10^{14}$ G) or that the accretion disk alternates between states of prograde and retrograde rotation and is fed by the red giant's wind rather than by Roche lobe overflow (Makishima et al. 1988; Chakrabarty et al. 1997; Nelson et al. 1997).

We report here on infrared observations of the GX 1+4/V2116 Oph binary. Besides the characterization of the infrared spectrum of V2116 Oph, one of our primary goals was to exploit the bright infrared emission from the star in order to search for the rapid emission-line variability reported by CR97 in the optical. An unanticipated result of our observations was the detection of a fast outflow from the M giant, which has important implications for understanding the mass transfer in this binary.

2. OBSERVATIONS

We observed V2116 Oph on 1995 May 10 using the new near-infrared long-slit spectrometer (Larkin et al. 1996) at the f/70 Cassegrain focus of the Palomar Observatory 5 m Hale telescope. The two available gratings yield wavelength resolutions $R \equiv \lambda/\Delta\lambda \approx 1000$ and $R \approx 4000$, when used with a 0.″7 slit width. We made two types of observations: (1) relatively long exposures (several pulsar periods) in order to get time-averaged spectra of the object and (2) rapid time sequences to look for time variability in selected emission lines.

For the long exposures, five $R \approx 1000$ spectra were taken. These included four 1 minute observations at different grating angles to cover the entire K bandpass (2.0–2.4 μm) and a 2 minute observation within the J band, centered on the H I 1.2818 μm (Paβ) line. Also, a high-resolution ($R \approx 4000$) spectrum of the He I 1.083 μm line was obtained with a total integration time of 6 minutes.

All of the observations were made in pairs using a 0.″75 × 40″ slit. The first exposure of a pair was taken with the target 10″ from one end of the slit, and the target was then moved 20″ along the slit for the second exposure. The spectra were reduced by subtracting image pairs and then dividing by a sky-subtracted standard star frame. Bad pixels were removed by linear interpolation. To remove a slight curvature along the spatial axis, a star was moved in 5″ intervals along the slit,

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and its position was fitted with a third-order polynomial. For all our observations, the seeing was $\lesssim 1''$ at 2 μm, and the sky was photometric. A nearby star was simultaneously observed with an offset guider that controlled a tip-tilt secondary. With this guiding system in place, tracking errors ($\lesssim 0''.1$) were insignificant compared with the seeing.

Wavelength calibration was achieved by fitting atmospheric OH airglow emission lines with a quadratic polynomial. We obtained the OH line wavelengths from Oliva & Origlia (1992) and Maihara et al. (1993). A conservative estimate of the absolute wavelength calibration uncertainty is roughly 1 pixel, corresponding to 70 km s^{-1} for $R \approx 1000$ and 15 km s^{-1} for $R \approx 4000$. This includes the systematic uncertainty due to curvature of the spectral lines and the line-fitting procedure. The observed wavelengths of V2116 Oph were corrected for the Earth's motion with respect to the solar system barycenter. Air wavelengths are quoted for all spectral features discussed in this Letter.

The flux calibration was performed in the following way. For the relative calibration, we used observations of the G3 IV standard star HR 6441, for which we assumed a blackbody temperature of 5725 K. Since we only observed through a narrow slit, absolute calibration using HR 6441 was not possible. Instead, we normalized our spectra to the typical infrared photometric magnitudes of V2116 Oph, which have been fairly constant over the 1990s except during the bright X-ray flare of 1993 September (CR97).

The time variability of the Paβ and He I 1.083 μm lines was investigated by obtaining six sequences of time-resolved spectra of each line. Each sequence consisted of eight exposures with an integration time of 8 s. Due to overhead in reading out and storing the data, exposures were actually separated by 14.43 s, and the total duration of a sequence was 115.455 s (close to the 2 minute pulse period of GX 1+4). Between sequences (i.e., every 2 minutes), the object was moved to the opposite end of the slit, as described above. The sequences were reduced in pairs, with the average spectrum of one sequence being used for the sky subtraction of the individual spectra in the other. For each line, a total of 48 exposures (each 8 s long) was obtained, covering a total time span of about 1000 s. The resolution was $R \approx 1000$ for the Paβ spectra and $R \approx 4000$ for the He I 1.083 μm spectra.

3. RESULTS

Figure 1 shows our combined *K*-band spectrum of V2116 Oph. In addition to strong H I 2.1655 μm (Brγ) emission and absorption band features due to ^{12}CO and ^{13}CO, there are several weaker absorption features due to neutral metal species. The He I 2.06 μm line may also be detected in emission, but telluric contamination shortward of 2.1 μm prevents a secure identification. The spectrum longward of 2.1 μm is similar to one obtained contemporaneously from UKIRT (at somewhat lower resolution) by Bandyopadhyay et al. (1997) on 1995 June 29. Except for the Brγ emission line, both observations are consistent with the spectrum expected from an isolated late-M giant (Kleinmann & Hall 1986). Comparing our CO absorption band measurements with the synthetic spectra of Lazaro et al. (1991), we estimate that the [C/H] $\approx$ 0.0 and that the ^{12}C/^{13}C $\approx$ 5. The latter quantity is consistent with an independent estimate of ^{12}C/^{13}C $\approx$ 8 by Bandyopadhyay et al. (1997). By comparison, both single M giants and M giants in symbiotics generally have relative and isotopic abundances of carbon somewhat below the solar value (Lazaro et al. 1991; Schild, Boyle, & Schmid 1992).

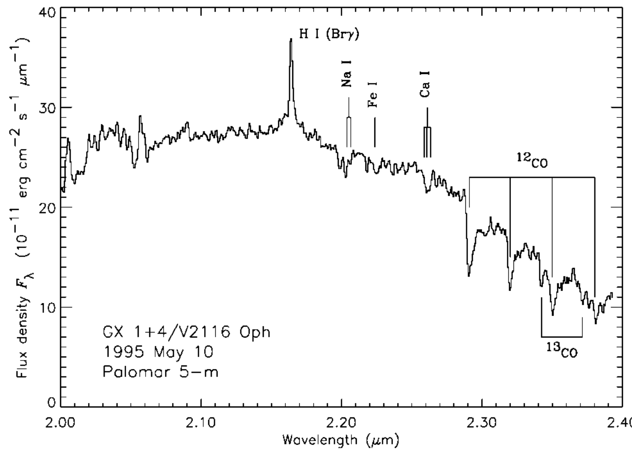

FIG. 1.—Medium-resolution *K*-band spectrum of V2116 Oph. Except for the hydrogen Brγ emission line, the spectrum is typical of an isolated M5 III giant. The He I 2.06 μm line may be detected in emission, but telluric contamination shortward of 2.1 μm prevents a secure identification.

Time-resolved emission-line photometry of the Paβ and He I lines showed no evidence for the dramatic 100% variability on a 10 minute timescale previously reported for some optical He I and Fe II emission lines (CR97). The two lines showed fractional rms variations of about 15%, which is consistent with Poisson counting statistics. We folded the IR spectrophotometric data at the X-ray pulse period of the neutron star (122.169 s on 1995 May 10.44; Chakrabarty et al. 1997) to look for coherent pulsations. No pulsations were detected in either the emission lines or the continuum. The 2 σ upper limits on the pulsed fractions were less than 5% for the He I line and less than 13% for the adjoining continuum, and less than 9% for the Paβ line and less than 5% for the adjoining continuum. For comparison, pulsation searches in optical emission lines set upper limits of less than 1.7% (3 σ) in Hα (Krzeminski & Priedhorsky 1978) and less than 1% (3 σ) in O I λ8446 (Deutsch, Margon, & Bland-Hawthorn 1998). However, optical pulsations from V2116 Oph have been intermittently detected in the broadband blue continuum with 2% amplitude (Jablonski et al. 1997). Since the pulsed fraction of the X-ray emission is known to be high ($\gtrsim$50%), the absence of pulsations in the emission lines is consistent with the conclusion of CR97 that the emission lines are powered by ultraviolet radiation from the accretion disk rather than X-rays from the accreting pulsar. The cause of the rapid optical line variability reported by CR97 remains a puzzle.

We attempted to use the observed line features to measure the radial velocity of V2116 Oph. The Paβ line gave a velocity of -255 ± 70 km s^{-1}, and the Brγ line gave a velocity of -190 ± 70 km s^{-1}. Velocity measurements with the weak absorption features in the *K*-band spectrum were difficult, because the lines are inherently asymmetric (Kleinmann & Hall 1986) and were measured at low resolution; however, the Na I and Fe I features gave velocities ranging from -120 to -370 km s^{-1}. In principle, the strong CO band features can provide an excellent velocity measurement. However, we did not attempt this since our wavelength calibration redward of about 2.3 μm is uncertain, because of the lack of OH airglow lines in that region. For comparison, the Hα 6563 Å emission line has a velocity of ≈ -150 km s^{-1} (CR97).

Figure 2 shows the line profile for the He I 1.0830 μm emission feature. Weak emission (equivalent width $-W_\lambda \sim$ 30 mÅ) in this line has been observed in several M giants,

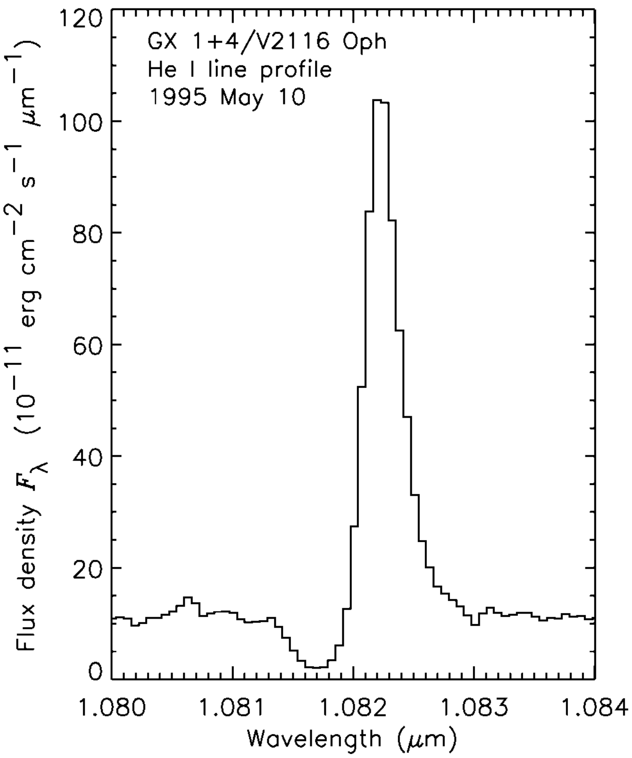

FIG. 2.—High-resolution P Cygni profile of the He I 1.083 μm emission line in V2116 Oph. Relative to the laboratory air wavelength of 1.08303 μm, the blue edge of the absorption core has a velocity of -473 ± 15 km s^{-1}, and the red edge of the emission line has a velocity of -5 ± 15 km s^{-1}. Adopting -220 ± 50 km s^{-1} (the average of the Paβ and Brγ velocities) as the velocity of the star, we infer a wind speed of 250 ± 50 km s^{-1}.

three of which are in binaries (O'Brien & Lambert 1986). However, in V2116 Oph, this line is 3 orders of magnitude stronger ($-W_\lambda = 31$ Å) and is probably powered by photoionization of the red giant's wind by the accretion disk. A pronounced P Cygni profile is evident in Figure 2. The blue edge of the absorption core has a velocity of -473 ± 15 km s^{-1}, and the red edge of the emission line has a velocity of -5 ± 15 km s^{-1}. P Cygni profiles are caused by an expanding shell around a star (e.g., Mihalas 1978). The absorption core is due to material in front of the stellar disk, while the emission line is due to material on either side of the star. The maximum outflow velocity of the material is given by the velocity difference of the blue edge of the absorption core and the rest frame of the star. (The red edge of the emission line cannot be used, since the star occults the material moving at maximum velocity.) We do not know the velocity of V2116 Oph securely. However, adopting the average of the Paβ and Brγ velocities, -220 ± 50 km s^{-1}, we infer an outflow velocity of 250 ± 50 km s^{-1} from V2116 Oph. If we instead adopt the Hα velocity of -150 km s^{-1} for V2116 Oph, then the inferred outflow velocity is $\approx$320 km s^{-1}. No clear evidence for a P Cygni profile was found in the hydrogen Paschen or Brackett lines.

Late-M giants generally have relatively strong Si I 1.0827 μm and Ti I 1.0828 μm absorption lines (O'Brien & Lambert 1986). We now consider whether these features could distort the intrinsic P Cygni profile of the He I 1.083 μm line. If we shift these features by our assumed radial velocity of -220 km s^{-1} for V2116 Oph, then they would overlap the red edge of the P Cygni absorption core but would leave the blue edge of the absorption core unaffected. Also, the Si I and Ti I features have a combined equivalent width of $W_\lambda \approx 0.33$ Å and a central depth of 25% relative to the continuum in late-M giants (O'Brien & Lambert 1986), compared with $W_\lambda = 3.3$ Å and a central depth of 80% for our P Cygni absorption core. Thus, we are confident that our outflow velocity is unaffected by the blended lines.

4. DISCUSSION

It is widely believed that red giants have slow winds (10–30 km s^{-1}; e.g., Reimers 1981; Dupree 1986). Since these winds are much slower than the photospheric escape velocity $v_{esc} = (2GM_g/R_g)^{1/2}$, the wind acceleration mechanism must be operating in the extended atmosphere of the giant. However, the outflow velocity we observe from V2116 Oph is an order of magnitude larger than a typical red giant wind velocity. Most existing measurements of wind velocities in late-type giants were made in large stars on the asymptotic giant branch (AGB), with $R_g \gtrsim 100\ R_\odot$. Since we expect the wind velocity to scale roughly as $R_g^{-1/2}$, a smaller star might have a somewhat faster wind. Indeed, a fast (~100 km s^{-1}) wind was observed from the metal-poor G9.5 III Fe-2 star HD 6833, which has roughly solar mass and a radius of 30–45 $R_\odot$ (Dupree, Sasselov, & Lester 1992). Based on luminosity and extinction arguments, CR97 concluded that V2116 Oph is probably near the tip of the first-ascent red giant branch, with a radius $R_g \lesssim 100\ R_\odot$. However, this argument seems unable to account for an order of magnitude increase in the wind velocity, since V2116 Oph is certainly not a factor of 100 smaller in radius than an AGB star.

It is possible that the observed outflow is due to a wind from the accretion disk rather than the red giant. The X-ray–timing behavior of the pulsar (Chakrabarty et al. 1997), the optical emission line spectrum (CR97), and the optical pulsations in the broadband blue continuum (Jablonski et al. 1997) all point to the presence of an accretion disk in this binary. However, our observed velocity seems too *small* for mass loss from the disk, since accretion disk winds are radiatively driven and supersonic (see, e.g., Warner 1995 and references therein).

Although isolated late-M giants may be unable to produce fast winds, it is possible that the energy for accelerating the outflow is provided by the hot component in a symbiotic binary. In the case of V2116 Oph, either the ultraviolet radiation from the neutron star's accretion disk or X-rays from the neutron star itself certainly possess sufficient energy to power a fast wind. While direct radiative acceleration of the wind is inconsistent with our data, illumination of the red giant's atmosphere might lead indirectly to enhanced acceleration of an outflow. It is interesting to note that a strong He I 1.083 μm P Cygni profile indicative of a fast ($\approx$150 km s^{-1}) wind was also observed from the symbiotic star CI Cyg, an M5 II giant (Bensammar et al. 1988). The cool component in this eclipsing symbiotic binary is an AGB star, while the hot component is thought to be an ~0.5 $M_\odot$ main-sequence star with an accretion disk (Kenyon 1986; Kenyon et al. 1991). The observed wind is probably from the cool component, however, since it is only observed during eclipse. As in V2116 Oph, the hydrogen Brackett and Paschen emission lines in CI Cyg did show P Cygni profiles. This is not particularly surprising, though, since the metastability of the lower state of the He I 1.083 μm transition makes it a particularly sensitive probe of bulk mass motion in the atmospheres of cool stars (O'Brien & Lambert 1986; Lambert 1987; Dupree et al. 1992).

Whatever the acceleration mechanism, a fast wind has important consequences in the GX 1+4/V2116 Oph binary. CR97 pointed out that V2116 Oph probably does not fill its Roche lobe, since there is no evidence for the highly super-Eddington mass transfer that would then be expected from such a large star. Instead, they prefer the suggestion of Makishima et al. (1988) that the neutron star is accreting from the red giant wind. Interpreting the marginal detection of 6 cm radio continuum emission from V2116 Oph (Marti et al. 1997) as thermal bremsstrahlung due to ionization of the red giant wind by the accretion disk and/or the X-ray pulsar, CR97 inferred a wind mass-loss rate of

$$-\dot{M}_w \approx 1 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1} \left(\frac{v_w}{10\ \mathrm{km\ s^{-1}}}\right)\left(\frac{D}{10\ \mathrm{kpc}}\right)^{3/2}, \quad (1)$$

where v_w is the wind velocity and D is the distance to the source. For a 10 km s^{-1} wind, at least 1% of the wind would have to be accreted by the pulsar in order to explain the $\gtrsim 10^{37}$ ergs s^{-1} X-ray luminosity observed from GX 1+4. However, the required capture fraction drops to ∼0.1% if the wind velocity is an order of magnitude higher. Low capture efficiencies are typical of wind accretion in X-ray binaries (see Frank, King, & Raine 1992).

We can use the P Cygni profile to make an independent estimate of the wind mass loss from V2116 Oph. Naively assuming that the outflow consists of ionized hydrogen, and adopting the characteristic density and scale size of the symbiotic nebula enshrouding the giant (CR97), the continuity equation yields

$$-\dot{M}_w \approx 2 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}\left(\frac{n_e}{10^9\ \mathrm{cm^{-3}}}\right) \times \left(\frac{v_w}{250\ \mathrm{km\ s^{-1}}}\right)\left(\frac{r_{\mathrm{out}}}{1\ \mathrm{AU}}\right)^2, \quad (2)$$

where n_e is the electron density and r_{out} is the effective radius of the outflow. This is roughly consistent with the rate inferred from the radio flux in equation (1), assuming $v_w = 250$ km s^{-1}. With such a high mass-loss rate from the red giant, only a very small fraction of the wind need be accreted by the pulsar to explain the observed X-ray luminosity. Thus, it seems plausible that the accretion disk in GX 1+4 is supplied by the red giant's wind rather than by Roche lobe overflow. If this is the case, then V2116 Oph is the only known LMXB donor that does not fill its Roche lobe.

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