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OPTICAL OBSERVATIONS OF THE X-RAY NOVA EXO 0748−676 NEAR MAXIMUM LIGHT

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ABSTRACT

Photometric observations of the X-ray nova 0748−676 show that optical eclipses occur in phase with the X-ray eclipses. In addition, the light curve shows considerable modulation throughout the 3.8 hr orbital period. Spectra show emission lines of H and He II which vary in velocity, intensity, and profile throughout the orbital cycle. The phasing of the velocity variations suggests that the emission lines are formed in the vicinity of the compact star. However the lines are very weak, and accurate velocities cannot be determined from our data. Curiously, the emission lines have maximum flux near phase 0 (eclipse), indicating they cannot arise principally in the region which is eclipsed.
Subject headings: stars: eclipsing binaries — stars: individual — stars: novae — X-rays: binaries

I. INTRODUCTION

A bright (0.3 Crab) and previously unknown X-ray source displaying bursts, dips, and periodic eclipses was discovered by the *EXOSAT* on 1985 February 15 by Parmar *et al.* (1985*c*). Pedersen and Mayor (1985) and Wade *et al.* (1985) identified the X-ray source with a blue eclipsing variable star which showed an amplitude of 0.6 mag, with maximum light of $m_V \approx$ 16.9. Wade *et al.* find that the star is fainter than 23 mag on the SRC *J* plate, indicating that the object has had a large optical outburst as well. This suggests that the object is one of the class of "X-ray novae." Parmar *et al.* (1985*d*) also observed X-ray bursts and irregular intensity dips as the X-ray brightness slowly declined. Detailed X-ray observations of this nova have recently been presented by Parmar *et al.* (1985*b*).

Bradt and McClintock (1983) list only six X-ray novae which have previously been observed. Little is known about them as a class. Extensive optical and X-ray observations exist for only 0620−003 (V616 Mon) and 1908+005 (Aql X-1 = V1333 Aql), and some data are available for Cen X-4. These observations indicate that X-ray nova outbursts occur in binary systems consisting of a late-type (K) dwarf and a neutron star. Recently McClintock (1985) has found evidence that the compact star in V616 Mon has a mass of $\sim 4\ M_\odot$, making it a black hole candidate. When V616 Mon had declined considerably from its optical outburst, Oke and Greenstein (1977) were able to estimate the spectral type of the late-type component to be K5–K7 V. Later Oke (1977) confirmed this result from direct observations of the system near minimum light. For the secondary in Cen X-4, van Paradijs *et al.* (1980) give K3–K7 V, and Thorstensen, Charles, and Bowyer (1978) find K0 V for V1333 Aql. X-ray bursts have been observed in Cen X-4 and Aql X-1, as well as in the new nova EXO 0748−676. At maximum light, the optical and X-ray properties of the X-ray novae appear to be very similar to those of other low-mass X-ray binaries. However, why some binaries have large novalike outbursts when apparently similar systems (other disk-dominated galactic "bulge sources") do not, is unclear.

The outburst of EXO 0748−676 offered an unprecedented opportunity to study one of these X-ray novae since the eclipsing light curves define the period and strongly constrain models for the binary and its orbital inclination. Consequently, we obtained both spectroscopic and photometric observations of the system at CTIO shortly after its outburst.

II. PHOTOMETRIC OBSERVATIONS

Photometry of EXO 0748−676 was obtained during the period 1985 February 19–24 by two of us (J. S. and P. I.). The "Patch" photometer with a GaAs phototube was used on the CTIO 1.5 m telescope. Standard *BVRI* filters were used, and Landolt's (1983) equatorial standard stars were observed to transform the instrumental magnitudes to a standard system. However, since the primary program dealt solely with late-type stars, no standard stars as blue as EXO 0748−676 were observed (the bluest standard has $B-V = 0.49$). Therefore, the colors derived for the X-ray nova are somewhat uncertain.

Two sets of photometry of EXO 0748−676 were obtained. On February 21, a series of 50 second integrations through the *B*-band filter were taken during a half-hour period centered on the predicted time of eclipse. Sky measurements made at three times during that period showed little variation (the faintest

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and brightest sky measurements differed by 4%), and it was assumed during the data reduction that the sky was indeed constant during that interval. An internal error estimate for these observations can be made since the data were actually obtained as the sum of five individual 10 s integrations. The standard deviation among the individual 10 s integrations relative to the mean count rate was generally $\sim 3.0\%$. Therefore, the expected 1 σ error in the mean for the B band observations is ~ 0.015 mag. The external error will be larger because of variations in the sky during the observing period and because the transformation to the standard photometric system is uncertain.

The second data set consists of individual $BVRI$ observations of the X-ray nova obtained at random phases during February 19–24. Integration times were typically 20 s per filter for both the object and sky. The expected errors in the V magnitudes due to photon statistics for these observations is about ± 0.04. The derived $B-V$ colors generally have internal errors of $\sim 5\%$–6%, but the zero point could be in error by as much as 0.1 mag because of the lack of blue standards.

Table 1 provides a list of the photometric data obtained for EXO 0748−676. Figure 1 shows the data plotted against orbital phase, using the revised ephemeris given by Parmar *et al.* (1985*a*). This ephemeris is used throughout this paper. In Figure 1 the V-band observations have been converted to B-band estimates by assuming $B-V = 0.1$ mag. Not only is the ~ 0.6 mag eclipse apparent, but the system brightness appears to vary continuously throughout the cycle. The X-ray phase of optical minimum is determined from our data as $\phi = 0.003 \pm 0.006$. Pedersen *et al.* (1985) have pointed out that the light-curve "varies erratically from orbit to orbit," so it may not be worthwhile trying to model the system from a composite light curve, derived from several cycles. On the other hand, it may be that such a mean is the best way to reveal the repeating aspects of the light curve, which *can* be modeled.

TABLE 1

OPTICAL PHOTOMETRY FOR EXO 0748−676

HJD 2,440,000+	Phase	B	V	$B-V$
6117.618	0.927	17.30	...	...
6117.619	0.932	17.28	...	...
6117.622	0.953	17.36	...	...
6117.622	0.958	17.41	...	...
6117.623	0.962	17.41	...	...
6117.625	0.971	17.41	...	...
6117.626	0.980	17.45	...	...
6117.627	0.984	17.50	...	...
6117.628	0.993	17.58	...	...
6117.629	0.997	17.60	...	...
6117.629	0.001	17.63	...	...
6117.631	0.010	17.65	...	...
6117.632	0.019	17.56	...	...
6117.634	0.028	17.51	...	...
6117.635	0.036	17.50	...	...
6117.636	0.041	17.50	...	...
6117.637	0.049	17.50	...	...
6117.638	0.054	17.47	...	...
6117.638	0.058	17.44	...	...
6117.639	0.062	17.41	...	...
6117.640	0.067	17.31	...	...
6117.640	0.071	17.34	...	...
6115.556	0.992	...	17.54	...
6117.679	0.315	...	16.98	...
6118.602	0.103	...	17.19	0.19
6118.656	0.447	...	16.99	0.08
6118.731	0.914	...	17.27	0.09
6119.624	0.518	...	16.89	0.21
6119.633	0.575	...	16.91	0.19
6119.673	0.828	...	17.09	0.08
6120.609	0.698	...	16.91	0.14
6120.615	0.742	...	16.95	0.13
6120.732	0.474	...	17.04	0.10

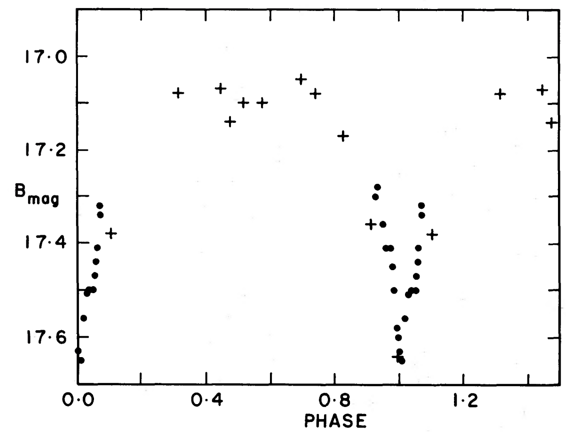

FIG. 1.—Light curve of EXO 0748−676. Filled dots represent observations taken during one cycle on 1985 February 21. Crosses represent observations taken during several cycles.

With these cautions, there are a few remarks that can be made about the light curve we do have. First, since the quiescent magnitude is fainter than 23 (Wade *et al.*), it is clear that all the luminosity we have recorded arises in some transient part of the system. There are two likely such elements: an accretion disk, and reprocessed X-rays on the facing side of the companion. The light curve in Figure 1 is similar to that of HZ Her in having an eclipse and distinct out-of-eclipse variations, and we suggest that *both* of the above luminous elements are found in EXO 0748−676, as in HZ Her. A rough division of the light curve into a sinusiodal variation and an eclipse suggests the relative amplitudes of these elements are 0.25 mag and 0.4 mag, respectively, in B-band light. This is not inconsistent with the lack of visibility of the main-sequence star spectrum at maximum light, in our spectra. It is also possible that the sinusoidal part of the light curve is due to the changing aspect of an inclined disk. We discuss these possibilities later in connection with the spectroscopic data.

Finally, we note that the duration of the part of the light curve that is clearly an "eclipse" is $\phi \approx 0.12$, compared with the $\phi \approx 0.036$ quoted for the X-ray eclipse by Parmar *et al.* (1985*b*). As pointed out by Wade *et al.*, this indicates the extended nature of the optical continuum region. In fact, these numbers indicate that the disk radius is ~ 2.5 times that of the companion star, assuming a main-sequence radius.

III. SPECTROSCOPIC OBSERVATIONS

Spectra of the optical counterpart of EXO 0748−676 were obtained with the CTIO 4 m RC spectrograph on five nights, 1985 March 13–17, 1 month after the nova was initially discovered by *EXOSAT*. The new "2D-FRUTTI" detector, constructed under the direction of S. Heathcote, was used to record the spectrum of the object and adjacent sky over a slit length of 50″. A slit width of 1″.3 was used for most of the observations. The spectra obtained cover the wavelength region 3675–5250 Å and were digitized at ~ 1 Å per pixel, yielding a resolution (FWHM) of 5 Å. All exposures were

TABLE 2

SPECTROSCOPIC OBSERVATIONS

HJD 2,440,000+	Phase[a]
6137.586...........	0.248
6137.604...........	0.361
6137.619...........	0.455
6137.634...........	0.549
6137.647...........	0.631
6138.622...........	0.750
6138.636...........	0.838
6138.651...........	0.932
6138.664...........	0.013
6138.678...........	0.102
6138.692...........	0.190
6139.675...........	0.359
6139.688...........	0.441
6139.702...........	0.529
6139.716...........	0.616
6139.729...........	0.698
6139.742...........	0.780
6140.643...........	0.434
6140.657...........	0.522
6140.670...........	0.604
6140.684...........	0.692
6140.697...........	0.773
6140.710...........	0.855
6140.723...........	0.937
6140.736...........	0.018
6141.576...........	0.290
6141.688...........	0.993
6141.703...........	0.087
6141.716...........	0.169
6141.729...........	0.250

[a] $\phi_0 = 2{,}446{,}111.57427 + 0.159338666E$ (Parmar *et al.* 1985*a*).

1000 s long, and wavelength comparison exposures were taken immediately before and after each integration. A journal of the spectroscopic observations is given in Table 2.

Flux standards and flat-field calibrations were obtained under identical conditions, but the narrow slit width precluded accurate transformation to fluxes. The flat-field procedure did not work well either, partially because the optimum procedures had not yet been defined at the time of our observing run. The preliminary reduction and extractions of sky-subtracted spectra were carried out at La Serena, with the final analysis being carried out at the Dominion Astrophysical Observatory. The wavelength stability of the detector was confirmed through cross correlation of comparison spectra taken before and after each object exposure. The shifts between such exposures were generally less than ~ 10 km s^{-1} (although shifts of 20–30 km s^{-1} occasionally occurred), and an average was taken of the comparison exposures for each object. The velocity errors from this effect are in any case much smaller than the measuring errors because of the weakness and asymmetry of the line profiles in the stellar spectra.

Altogether, 30 spectra of EXO 0748−676 were obtained. These were summed into 10 bins according to orbital phase, with three spectra in most bins, and the velocities and equivalent widths of all apparent features measured. The velocities of the emission lines were independently measured with the aid of a program which allowed a parabola to be fitted to an interactively selected region of the profile for each line, by cross-correlation of portions of the spectra against the sum of all observations and by visual positioning of a cursor on the line profile. The adopted velocities are a mean of these sets of

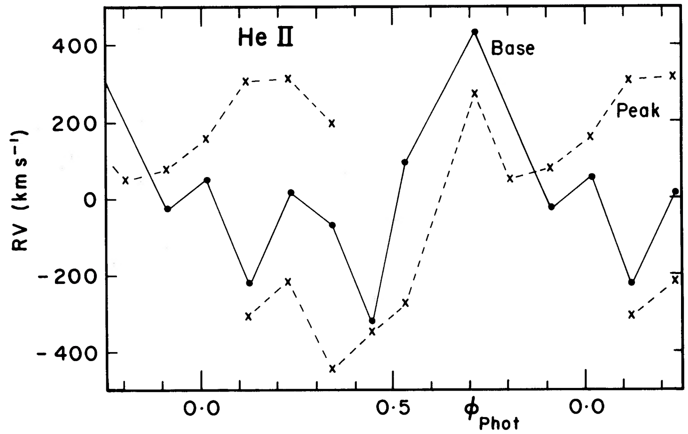

FIG. 2.—The He II λ4686 velocity curve. The velocity of the base, or lower portion of the line profile, is shown by the solid line and filled dots. The velocity of the peak(s) of the line is shown by the dashed line and crosses. The line is very weak through phases 0.25–0.75, and the velocities are much more uncertain. Scatter of independent measures typically is ± 75 km s^{-1} per point.

measures, weighted by the strength of the line, and the internal agreement of the measures. The velocities are shown in Figure 2.

IV. THE SPECTRUM AND LINE STRENGTH VARIATIONS

The sum of all spectra shows He II λ4686, the λ4640/50 blend (primarily N III and C III) and weak H Balmer lines superposed on a blue continuum. The line strengths vary greatly during the cycle, being strongest near the X-ray eclipse. In Figure 3 we show the average spectrum from four phase bins when the emission lines are strong (*top*) and four phase

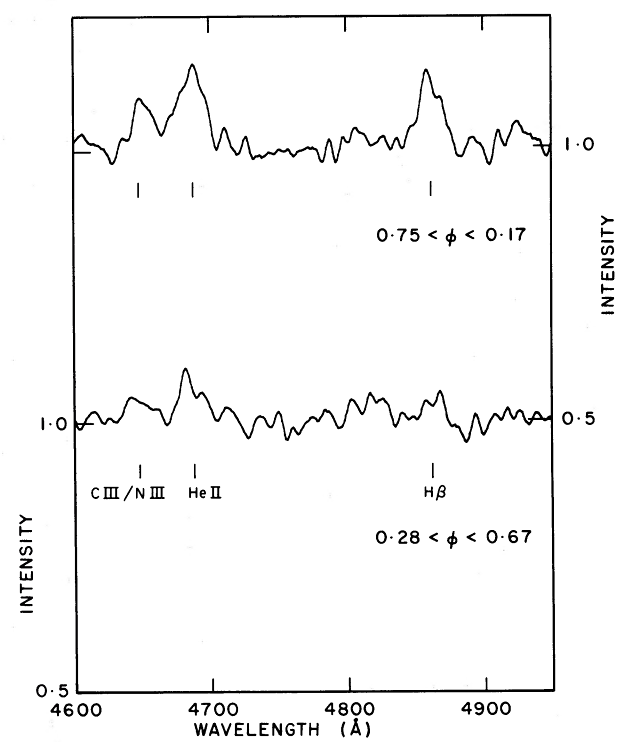

FIG. 3.—Portions of the average spectra observed in two phase bins near phase 0 (X-ray and optical eclipse), when the lines are stronger (upper), and near phase 0.5, when the lines are weak or absent.

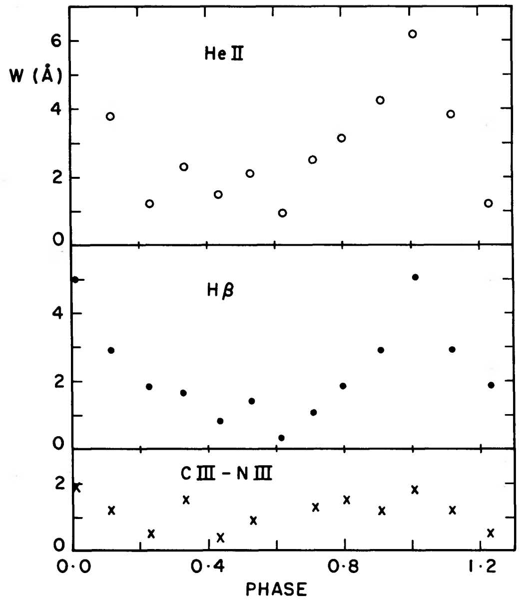

FIG. 4.—Variation of the equivalent widths of He II, Hβ, and the C III–N III blend at λλ4640–4650 as a function of phase.

bins when the lines are weak (*bottom*). Equivalent widths of all measurable features in the binned spectra are shown plotted as a function of orbital phase in Figure 4. The emission-line equivalent widths increase by about a factor of 5 near primary eclipse. This is very surprising since the velocities (if orbital) indicate that the emitting region is associated with the X-ray source and therefore might be expected to be eclipsed at phase 0. Only a small part of the observed equivalent width variation of the emission lines can be caused by the lowering of the continuum during the eclipse, since the eclipse depth is only 0.6 mag (and not, as far as we know, very variable). This factor of 5 change in the equivalent widths corresponds to a change in absolute flux in the lines of ~ 3 times. Therefore the emission region must lie at least partially out of the eclipse plane in order to still be visible (even enhanced!) at primary eclipse. Further, the region must be nearly hidden from our view during most of the orbital cycle (phases 0.2–0.8, approximately).

The emission lines are fairly broad, with full widths of ~ 2000 km s^{-1}. There is some suggestion that the profiles vary with phase, although this is difficult to separate from flux changes (Fig. 3). The lines are clearly double-peaked at some, if not all, phases (see Fig. 2). Near phase zero, both He II and H are clearly double with both components having nearly equal strength. Between phases 0.1 and 0.3 the shortward component is stronger, while from phases 0.8 to 0.9 the longward is stronger. In the phase interval when the lines are very weak it is almost impossible to tell if the lines are double or which component is stronger. The mean velocity separation of the components is ~ 700 km s^{-1} for both He II and H I, and it does not appear to vary with phase. The appearance of double-peaked profiles is typical of lines formed in an edge-on disk or ring. Similar profiles are frequently seen in dwarf novae with high orbital inclinations. The lines show no evidence of mass outflow (P Cygni profiles) as seen in classical novae: thus the optical analogy is again more closely to dwarf novae. Similar broad lines with no mass outflow were also seen in V616 Mon (Oke and Greenstein 1977) and in Cen X-4 (Canizares, McClintock, and Grindlay 1980).

V. VELOCITY VARIATIONS

The lines are very weak throughout a large portion of the orbital cycle, so that the resulting velocities are very uncertain. The average velocities for the base of the He II λ4686 line show that minimum velocity is reached near phase 0.25 and maximum near phase 0.75, as one would expect if the emission were formed near the compact star and moving with it (Fig. 2). A sinusoidal fit yields $\phi_0 = 0.76 \pm 0.16$, $K = 210 \pm 92$ km s^{-1}, and $V_0 = 20 \pm 64$ km s^{-1}. The Hβ measures are much less reliable, since the line is weaker, and show large scatter and no significant trend with phase. The He II velocity amplitude, if due to orbital motion, is higher than one might have expected. If this large velocity range is entirely due to orbital motion, and the primary is a 1.4 $M_\odot$ neutron star, then the unseen secondary must be a solar-type star just filling its Roche lobe. Since a solar-type star would be visible at minimum light and no star was in fact seen (see below), the companion star must be fainter and have a lower mass. The secondary stars in other X-ray novae appear to be much less massive than the Sun. The expected masses (~ 1.4 and ~ 0.4 $M_\odot$) *would* be obtained if the semiamplitude of the velocity variation of the X-ray source were only 120 km s^{-1}. Masses very close to these values were suggested by Parmar *et al.* (1985*b*) on the basis of the X-ray eclipse analysis. They also derive an orbital inclination of $\sim 75°$. Thus, it seems possible (but not certain) that some additional streaming motions in the gas combine with the orbital motion to produce the observed radial velocities. (To maintain the phasing, such motions would have to be parallel with the orbital motions of the compact star.) If so, then we are unable to use our velocities to determine the true nature of the component stars.

VI. DISCUSSION AND POSSIBLE MODELS FOR THE SYSTEM

Perhaps the most surprising feature observed in EXO 0748−676 is the marked intensity variation of the emission lines, reaching maximum strength near optical and X-ray eclipse. As discussed above, this variation cannot be accounted for by changes in the continuous light, but represents real changes in the line flux. A model which might explain both the variations in strength and velocity of the emission lines is pictured schematically in Figure 5. It contains a thick disk which is partially inclined to the orbital plane surrounding the neutron star. Emission lines are assumed to be formed on the inner edge of the disk. From the observer's orientation, when the X-ray star and the near part of the disk are eclipsed by the secondary star, the observer would still be able to see the illuminated inside edge on the far side of the disk. At other phases, the inside of the disk would be partially or wholly self-occulted because of the tilt and thus would be less visible to the observer. With this picture, the variations in strengths of the lines could then be explained by the particular angle from which we view the system. (We note that a disk which is substantially thicker on the side away from the companion star might also be used to explain the observed intensity variation of the emission lines. Again, self-occultation of the inner emitting region by the thicker side of the disk would give an observed phase-related variation of the emission line strengths.) Parmar *et al.* (1985*b*) suggest that the observed X-ray dips are due to azimuthal variations in the thickness of the disk, causing partial obscuration of the X-ray source. The cartoon shown in Figure

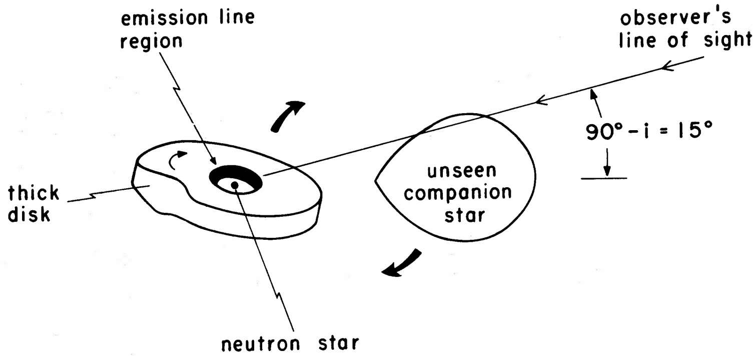

FIG. 5.—Schematic possible model for explaining the emission-line intensity and velocity variations in EXO 0748−676. The observer's inclination of 75° is adapted from Parmar *et al.* (1985*b*). The picture is drawn for a mass ratio of M_x/M_0 of 3, where the X-ray source is assumed to be a neutron star. The slightly tilted disk is postulated to "hide" the emission-line region from the observer except during the phases near X-ray eclipse.

5 tries to include these bulges in the disk at the approximate phases where they were expected to be during the time of our optical observations.

If the disk rotation is in the same direction as the orbital motion and if the emission is only observed from one side of the disk, the observed velocity curve from the emission lines will be the sum of the disk rotation and the orbital motion of the neutron star plus disk. In this case, we expect the velocity amplitude to be larger than that of the neutron star alone. This appears to agree with our observations, but we caution that a very specific orientation of the disk with respect to the secondary star is required! One might expect that such a disk would precess, and thus the observed phasing of the line flux maximum would change with time. Further spectroscopic observations could test this as long as the system stays bright. As pointed out before, if this picture (or something similar) is correct, it precludes the possibility of directly measuring the masses of the components of this interesting system from the radial velocities, even though we have the favorable case where both the period and orbital inclination are known in advance.

The modulation of the optical light curve outside of eclipse might also be explained as a result of the changing aspect of the disk with respect to the observer. However, little is known at present about the variations of the light curve from cycle to cycle, and this would have to be considered in any realistic model. No attempt has been made to interpret the complex X-ray dips or other intensity variations. Since simultaneous X-ray observations and optical photometry were not obtained during our spectroscopic run, we cannot realistically include these elements in a model.

If the mean velocity of the system (30 km s^{-1}) reflects the differential galactic rotation in this direction of the sky, a distance of ~ 6 kpc is derived. This estimate is of the same order of magnitude as the value of 20 kpc derived by Parmar *et al.* (1985*b*) on the assumption that the brightest X-ray bursts observed correspond to the Eddington luminosity of a neutron star. The galactic absorption in this direction ($l = 280°$, $b = -20°$) is likely to be low (~ 0.5 mag; Wade *et al.* 1985), and so these distance estimates correspond to an absolute magnitude of the accretion disk $M_v \approx +1.5$ to $+2.5$ mag. This can be compared to the luminosity of the accretion disk in V616 Mon. Using both the distance of 780 pc and the magnitude of the secondary found by Oke (1977), one derives $M_v \approx 0$ for the system at maximum light when the disk dominated the light. The apparent magnitude of EXO 0748−676 prior to its outburst was found to be fainter than 23 (Wade *et al.* 1985). If the companion is a late-type dwarf with an absolute magnitude of $\sim +9$ then one would expect the system to have an apparent magnitude of $m \approx 23$ in its low state, consistent with what was observed.

In summary, it appears that the system contains an accretion disk and a heated, low-mass star as principal luminous elements in its observed (high) state. The X-ray and optical high states presumably arise during a time of enhanced mass transfer analogous to dwarf novae. The bursting nature of the X-ray emission indicates that the accreting star is a neutron star, as is assumed to be present in most of the other X-ray novae, rather than the white dwarf present in ordinary dwarf novae or classical optical novae. The most probable masses of the components in EXO 0748−676 are ~ 1.4 and $\sim 0.4\ M_\odot$. Curiously, although the system appeared to fade rapidly in both X-rays and optical light for the first few months following the outburst, the system rebrightened in X-rays in approximately June 1985 (Parmar *et al.* 1985*b*). Recent observations by P. Schmidkte at CTIO in November 1985 show the optical magnitude still to be near 17th magnitude (!), although we do not know its behavior between March and November. Unfortunately, even when the system returns to minimum light, it is unlikely that we will be able to study the late-type companion as it will be too faint for detailed studies with present-day instrumentation.

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