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A MODEL FOR 0921−63: A SECOND HALO X-RAY SOURCE

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ABSTRACT

Spectroscopic and photometric observations reveal the orbital period of 0921−63 is $8^{\mathrm{d}}.99$. The He II and H emission are formed near the degenerate neutron star. The secondary, weakly seen in the spectrum, appears to be an F–G giant of $\sim 1\ M_{\odot}$. The system eclipses so that ultimately precise radii and orbital inclination can be determined. The galactic location (~ 1.5 kpc below the plane) and its low mass (total mass $\sim 2\ M_{\odot}$) suggests 0921−63 is a halo object.

Subject headings: stars: eclipsing binaries — stars: individual — X-rays: binaries

I. INTRODUCTION

The optical counterpart of 0921−63 was first identified by Li *et al.* (1978) based on the presence of strong He II (λ4686) emission and a rather blue continuum. Later the spectrum was shown by Thorstensen and Charles (1980) to be composite with a weak late-type absorption spectrum sometimes present in addition to He II and H emissions. There are numerous observations of eclipses, or eclipse-like events (Chevalier and Ilovaisky 1981*a*; Mason 1981; Liller 1981; Charles and Thorstenson 1981; and Chevalier and Ilovaisky 1981*b*). It has been clear for some time both from radial velocities and photometry that the period is longer than a week, but because of the nature of short, widely spaced observing runs in the southern hemisphere, it has been difficult to obtain enough data to clearly define the period. In this paper we present spectroscopic results based on three observing runs at CTIO. In addition an attempt has been made to integrate the known photometry with our data in order to determine the geometry and hence the stellar masses.

II. OBSERVATIONS

Spectroscopic data were obtained with the RC image tube spectrograph of the CTIO 4 m telescope in 1980 February, 1980 November, and 1981 February–March. Exposures were taken in the blue spectral region (~ 3700–5200 Å) with a dispersion of ~ 47 Å mm^{-1} on baked IIIa-J plates. Typical exposures of ~ 30 minutes each were widened ~ 0.5 mm, with a few wider. All plates were measured for radial velocities and converted to direct intensities for equivalent width measurement. These velocities are given in Table 1. During 1981 March simultaneous *UBV* photometry was carried out by W. Liller on the 91 cm telescope at CTIO. Spectroscopy also done at CTIO by Charles and Thorstensen (1981) in 1979 December and 1980/1981 December/January is in good agreement with the data presented here.

III. DETERMINATION OF THE ORBITAL PERIOD

Although in a given observing run the radial velocities of the emission lines change from night to night, no individual spectroscopic run (five nights or less) was sufficient to show a complete cycle. Because these observing periods were often months apart, a number of acceptable periods could be found to fit the data. Ultimately using all the He II (broad base) velocities in the period finding program described by Morbey (1974) and comparing results with Charles and Thorstensen, a period of $8^{\mathrm{d}}.99$ was found to be by far the most significant one (an alternative period of $7^{\mathrm{d}}.7$ cannot entirely be ruled out, but it is less significant). This period is now confirmed by photometry of Chevalier and Ilovaisky (1981*c*). Other factors considered in verifying this period include other photometry available to us from the literature or private communication, the changing line profiles and intensities, and the apparent variation of the absorption line spectrum. The phase variation of all of these quantities will be shown in the §§ IV, V, and VI.

IV. THE SPECTRUM

Although on our plates the underlying absorption spectrum is weakly visible (most easily seen are the Ca II lines), the prominent features of the spectrum are a strong He II (λ4686) emission and a somewhat weaker Hβ emission. Weak C III/N III emission and higher Balmer emissions are present on some plates. Both He II and Hβ show a complex profile with a narrow peak which is variable in location on a weak broader base (He II width at continuum ~ 1300 km s^{-1}). The overall

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TABLE 1

RADIAL VELOCITIES IN 0921−63

HJD 2,440,000.4	ϕ^a	He II$_{base}$	He II$_{pk}$	H$_{base}$^{b}	H$_{pk}$
4289.74	0.606	+ 35	− 26	+108	+108
4289.79	0.612	+ 27	− 8	+ 19	− 16
4290.76	0.720	+ 44	− 19	+ 51	− 23
4290.81	0.725	+ 59	− 13	+ 45	+ 45
4291.54	0.807	+ 25	...	...	...
4291.74	0.829	+ 76	+ 39	− 32	− 8 (−206)
4291.83	0.839	+ 47	+ 47	...	−128:
4292.68	0.933	+137	...	...	+ 58
4292.83	0.950	+146	+146	+106	+ 74
4556.83	0.325	− 8	+ 54	+ 54	+196
4557.82	0.435	+ 2	+ 2	+ 15	+115
4558.82	0.546	+ 30	− 40	− 24	+ 38
4559.79	0.654	+ 28	− 48 (−624)	+172	+ 62
4662.72	0.107	+ 70	+121	+ 51	+ 57
4662.80	0.115	+ 71	+ 42 (+600)	+172:	...
4663.79	0.226	+ 74	+ 31	...	...
4664.61	0.317	+ 34	+ 92	+ 78	+118
4664.71	0.328	+ 66	+ 87	+ 87	+134
4665.57	0.423	− 18	+ 7	+200:	+155
4665.68	0.436	− 30	− 10	+ 8	+ 87
4666.59	0.537	− 38	+ 20	− 9	+ 69
4666.73	0.553	+ 6	− 15	+ 27	+ 80

[a]Phase based on $T_{\max\,vel} = 2{,}444{,}293.278$, $P = 8.987$ days.
[b]In most cases on Hβ used; occasionally other lines were averaged into quoted velocity.

appearance of the spectrum is remarkably similar to Cygnus X-2 (Cowley, Crampton, and Hutchings 1979), although the late-type spectrum is not so easily visible in 0921−63. It is not possible, in the blue region, to measure the velocities of individual absorptions, with the exception of Ca II, because they are so weak.

Both the equivalent width and the peak intensities of the emission lines show a large variation with phase, with an apparent maximum near 0.3–0.4 past maximum radial velocity (see Figs. 1 and 2). Unfortunately, poor phase coverage between 0.9 and 0.1 makes that part of the curve not well defined. We should also note that these quantities must reflect the continuum eclipse and light curve. Figure 2 shows composite tracings of 0921−63 in three phase bins, chosen to illustrate the principal spectral variations. Spectra are aligned to λ4686 emission velocities. The 0.9–0.3 bin contains only three weak spectra from a single observing run and includes the eclipse phases. Some moonlight contamination is probable, and it is not clear how much of what it shows is real, or truly phase-dependent, rather than spurious or dependent on the state of the system. It is clear that the emission is weaker, and the G band is stronger. The lower two tracings show more of interest: note particularly the emission line strength changes, including the C II, C III, N III lines, and the λ4541 He II line. We also see indication that He I exists in absorption, with velocities more negative in $\phi = 0.3$–0.6 than in $\phi = 0.6$–0.9.

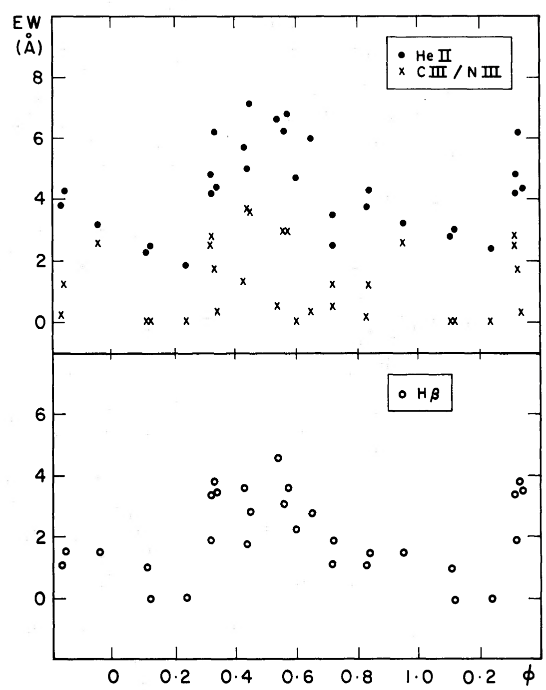

FIG. 1.—Equivalent widths of He II, C III/N III, and H as a function of orbital phase. All emissions show a strong eclipse between phases ~0.1 and ~0.3 and rise sharply after the eclipse. No overall light variation has been removed which might account for some of the slow variation outside eclipse.

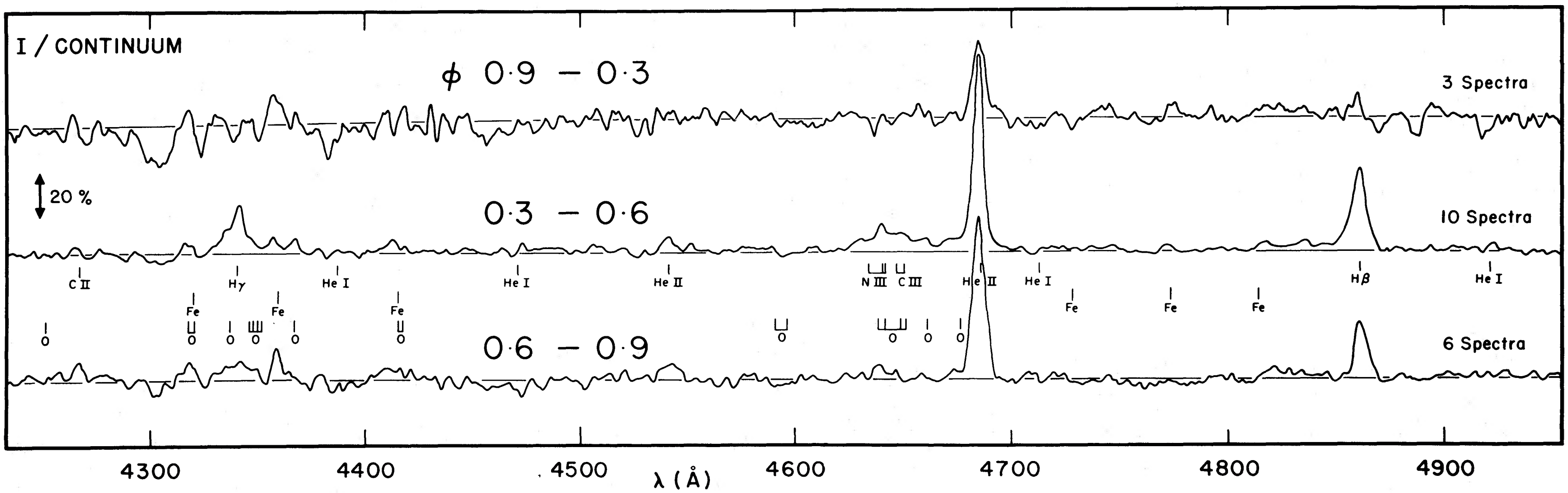

FIG. 2.—Mean spectra of 0921−63 averaged in the velocity frame of He II λ4686 emission. Principal emissions are identified. Possible identifications of very weak features with [Fe II] are shown by "Fe" and O II by "O". See text for discussion.

The spectrum also contains several weak emissions which may possibly be [Fe II]. Line positions are indicated in Figure 2. Some coincidences with O II are also shown, although we are unaware of these lines being present in emission in other objects. There is a broad emission at λ4167, and a weak emission at λ4836, for which we find no suitable identification. If properly identified, [Fe II] emissions would indicate a low density medium associated with the system. Two lines at λ4244 and λ4287 usually seen in objects showing [Fe II] are not present. There is no indication of a phase dependence of the proposed [Fe II] emissions.

The 0.9–0.3 phase bin data show absorption features characteristic of a late-type spectrum (although lunar contamination is possible). The G band is seen in all spectra, and a few weak line features (λ4233, 4383, 4530). These lines are not measurable on individual spectrograms.

V. RADIAL VELOCITIES AND STELLAR MASSES

In Figure 3 we show the radial velocities of the broad He II emission base as a function of phase, adopting the $8^{\mathrm{d}}.99$ period. Plotted in the two panels below it are the measures of the He II peak and Hβ peak. (Hβ base has large uncertainties because the line is quite weak.) In Table 2 we give the orbital elements, derived from the He II base measures as well as He II peak. We have allowed the period P to be a free parameter (starting with the value from the period finding routine). We adopt the spectroscopic period and phasing of He II base as our ephemeris, with T_0 being the time of maximum velocity in the circular (adopted) orbit:

$$T_{\mathrm{max\,vel}} = \mathrm{HJD}\ 2{,}444{,}293.28 + 8^{\mathrm{d}}.987E .$$

Although in most X-ray binaries the emission appears to be associated with the degenerate object (e.g., Sco X-1, the supergiant X-ray binaries, etc.), we know that in the spectroscopically similar system Cyg X-2 the emission is primarily formed on the heated face of the secondary star (Cowley, Crampton, and Hutchings 1979). In order to resolve that ambiguity we have looked into the phasing of the eclipses. The maximum strength of the late-type spectrum and weakening of the emission lines should occur when the degenerate object is hidden by the cool star. If the emission is formed on or near the neutron star, all these events should occur near $\phi = 0.25$ after maximum velocity. On the other hand, if the emission is formed on or near the secondary, the same events will occur at about $\phi = 0.75$ past maximum emission-line velocity. (We assume the center of mass to lie between the two objects.) From Figure 1 it is easily seen that the emission lines are weakest early in the orbital cycle, but the exact phase is difficult to say because of poor phase coverage. Similarly, by using all photometric minima known to us (see above references), we find that they also occur in the beginning of the cycle. Some photometric minima are centered on $\phi \sim 0.25$, but there is a scatter of observations of faint magnitudes from 0–0.3. Some of the scatter is due to the fact that we only know that the star was observed to be faint on a certain night but do not know the exact time of minimum light. We conclude, since the light minima occurred mainly from $\phi = 0.2$ to 0.3, the principal emission-line region lies near the degenerate star, rather than on or near the secondary.

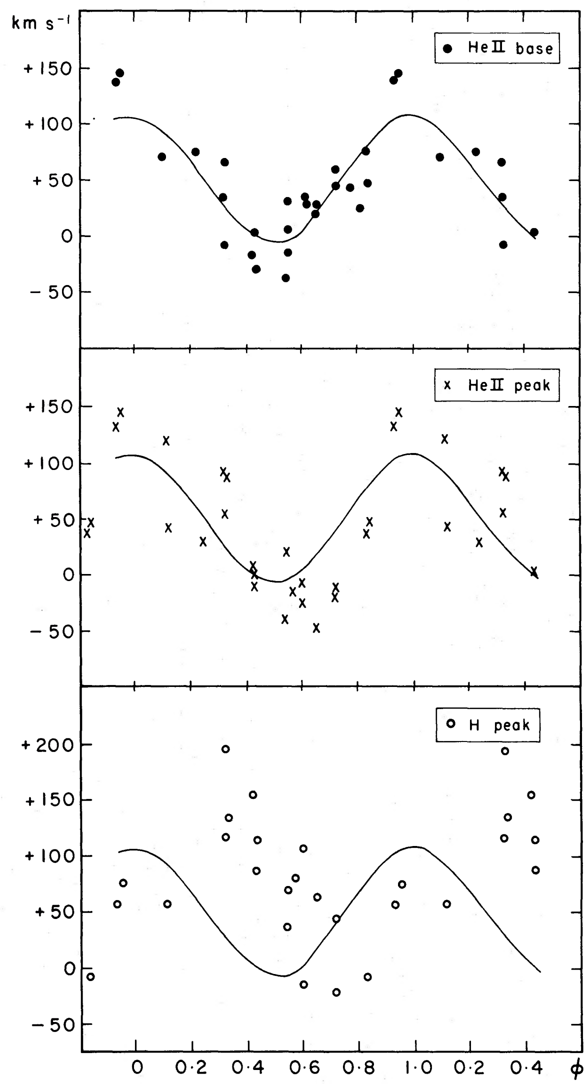

FIG. 3.—Velocity curves of emission lines in 0921−63. Top panel shows the velocity of the wide He II (base) together with the best orbital fit to a circular orbit (*smooth curve*). The lower two panels show the same orbital fit to He II base compared to He II narrow (peak) emission (*center panel*) and H (*lower panel*). Note that the He II peak shows both a larger amplitude and later phasing than He II base. H shows the same effect but with even later phasings of the velocity curve. This may be due to H being formed further from the neutron star along the accretion stream.

TABLE 2

ORBITAL ELEMENTS IN 0921−63

Element	He II$_{base}$	He II$_{peak}$
P	8.987±.023 days	9.00±.02 days
V_0	51.6±8.3 km s^{-1}	40.2±10.3 km s^{-1}
K	57.5±9.7 km s^{-1}	63.9±10.2 km s^{-1}
e	[0]	[0]
ω	[0]	[0]
T_{max}	JD 2,444,293.28±.39	JD 2,444,293.74±.44
SD of fit	27.8 km s^{-1}	32.9 km s^{-1}
$f(M)$	0.173 $M_\odot$	...
Observations	24	24

Further comments can be made regarding the eclipses. Photometry at CTIO by W. Liller (1981) on 1981 March 1–6 showed the system to be increasing in brightness on the first night and then fairly constant until the last night when it dropped by 0.4 mag. Chevalier and Ilovaisky (1981*b*) found the system to be dropping to a minimum on March 8. However, observations from South Africa from 1981 March 4–9, which are interlaced between the Chile observations, show a slight dip but no minimum (Mason 1981). Perhaps the deepest minimum has a very short duration ($<\sim 18$ hr). It is important to know the exact phasing of the minima to decide whether the emission-line velocities are purely orbital (minimum light expected $\phi \sim 0.25$) or whether some mass transfer stream contributes to the velocity curve (then minimum light is expected to occur nearer velocity maximum so that the eclipse phase would be $0<\phi<0.25$). The rise from minimum on 1981 March 1 overlaps our spectroscopic data and is thus least affected by uncertainties in the period. The faintest magnitude observed by W. Liller was $B=16.75$ on JD 2,444,664.60 ($\phi=0.32$) with the object continuing to rise. Since on March 1 the star was not observed at its faintest magnitude, the minimum must have occurred approximately half a day earlier, with an uncertainty of $\pm 0^{d}.5$, so that $\phi_{min} \sim 0^{d}.25 \pm 0.05$. Because of this phasing we assume the He II base velocities represent orbital motion of the degenerate star. This may not be strictly true, and better coverage of the eclipses will be important in establishing if any streaming motions contribute to the velocities. From this assumption about the phases we derive masses which will be upper limits *if* the eclipses occur nearer to the phase of maximum positive velocity.

From the orbital solution for the base He II emission velocities, we derive $f(M)=0.17\ M_\odot$, which represents the minimum possible mass for the secondary star. The resulting possible masses are plotted in Figure 4. Because the system eclipses, we are limited to $i>\sim 60°$ which results in a very narrow range of possible masses. If the primary is a neutron star and we adopt $M_x \sim 1.4$ $M_\odot$, then the secondary must lie between 1.0 and 1.2 $M_\odot$. This implies a mass ratio ($q=M_2/M_x$) between 0.7 and 0.9 from which the Roche lobe radius of the

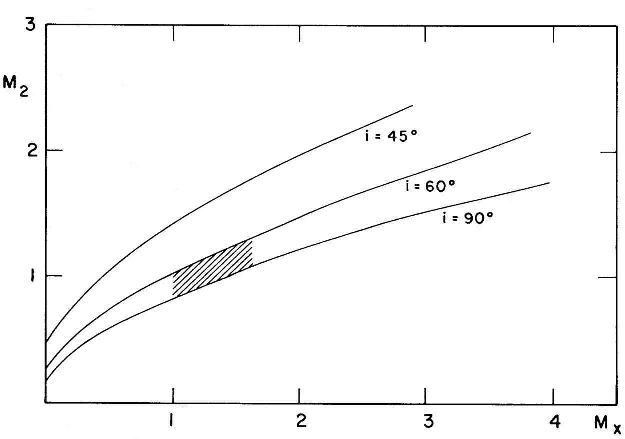

FIG. 4.—Possible masses for the secondary and X-ray star in 0921−63, assuming the He II emission represents the motion of the degenerate star. If any streaming motions add to the observed velocities, these masses are upper limits to the true masses. Since eclipses are observed, i probably lies between 70° and 90°. Assuming the primary is a 1.4 $M_\odot$ neutron star, the secondary's mass must be $\sim 1.1\ M_\odot$. The hatched region is the most likely region for both stars to lie.

secondary can be computed to be $\sim 7\ R_\odot$. This radius is consistent with an F or G giant, which is in reasonable agreement with what is observed. Unfortunately, most of the Ca II absorption velocities are complicated with some moonlight so that the amplitude and phasings of the late-type star cannot be determined from our data. Spectroscopic observations in the red, where the secondary should be more visible, would be important to determine the spectral type, luminosity class, and velocity of the star directly. The implied masses and types of the stellar components are very similar to what we see in Cyg X-2. In both systems the mass of the secondary turns out to be somewhat less massive than would be expected for a Population I giant ($\sim 2\ M_\odot$). However, mass loss from the system may have been important in the evolution of this object. Below (§ VII) we present arguments that the system probably belongs to the halo population (Population II) of the Galaxy.

In Figure 3, in addition to the velocity curve for He II emission base, we also show plots of He II peak and H peak velocities. The He II peak emission shows a larger amplitude and slightly later phasing than the base of the emission line (see Table 2). This is consistent with an S-wave phenomenon typically seen in cataclysmic variables and other interacting systems. The inference is that the narrow emission is formed in a stream from the secondary to the primary and/or in an excited region on the following hemisphere of the accretion disk. In either case the maximum velocity occurs after the quadrature, and the velocity amplitude is larger than the orbital motion (as observed here).

The H emission lines show maximum velocity near to what we consider to be the conjunction and a minimum half a cycle later. If there is stratification of the excitation along the stream, one might expect H to be formed nearer to the secondary (an effect also seen in CVs—e.g., U Gem; Smak 1976). In Figure 5 we show an approximate sketch of the system. Another argument that H emission is formed nearer the secondary is that it is very strongly eclipsed in $0.1 < \phi < 0.3$ (see Fig. 1), while He II is still partially visible. We conclude that the difference in velocity behavior of H and He II peaks is primarily due to the H being formed further from the degenerate star along the mass transfer stream from the secondary star.

VI. INTENSITY VARIATIONS OF THE EMISSION LINES

Figure 1 shows that all the emissions are strongly modulated with phase. The curves show at least two effects: (1) a noticeable minimum near $\phi \sim 0.25$ (optical eclipse), and (2) a more smoothly varying modulation which appears to peak near $\phi = 0.4$. Because of the eclipse and the small number of observations near $\phi = 0 \pm 0.1$, we are not sure where either the true maximum or minimum of this smoothly varying intensity curve lies. Further, if the out-of-eclipse light curve shows some regular modulation, it will be necessary to remove that before understanding how the emission intensities vary with phase.

VII. DISTANCE AND LUMINOSITY

It is possible to derive the approximate distance from several independent arguments. A first approximation can be derived by estimating the absolute magnitude.

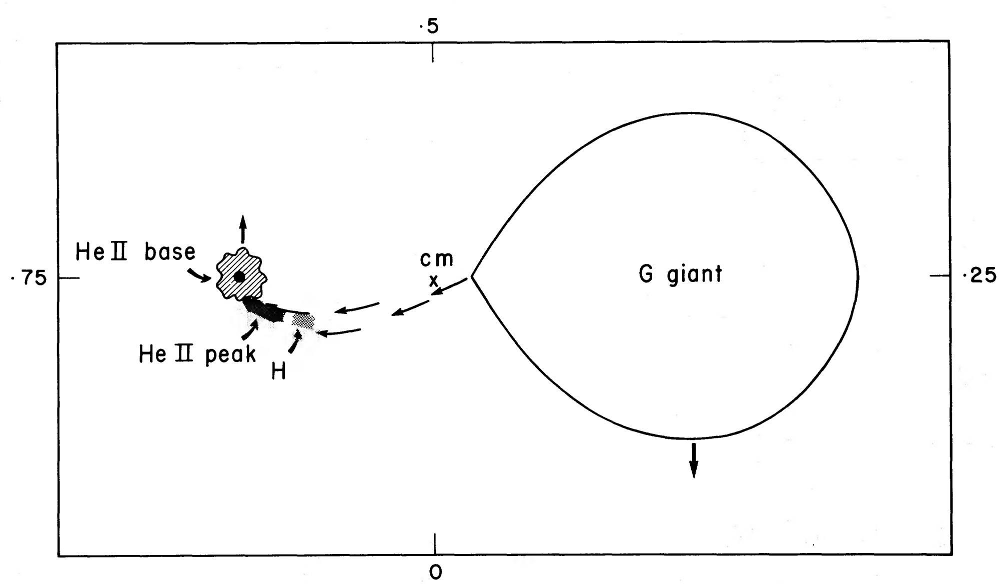

FIG. 5.—Schematic model of 0921−63 seen pole-on. The direction of orbital motion is clockwise. Eclipses occur at $\phi \sim 0.25$. The different phasing of He II and H sharp (peak) components can be explained by having them formed in different regions along the stream between the two stars.

An F–G giant is expected to have M_v in the range 0 to +2. Since the star is so poorly seen, most of the light must come from the disk. Thus we estimate $M_v \sim 0$. Chevalier and Ilovaisky (1981*a*) find the absorption to be ~1 mag. Liller's photometry shows mean (out-of-eclipse) light $m_v \sim 15.2$. From these quantities we derive a distance of ~7 kpc.

Secondly, from the systemic velocity ($V_0 = +57 \pm 10$ km s^{-1}), we can estimate the distance if the motion is due to differential galactic rotation. In this direction ($l = 282°$, $b = -9°$) for 50–60 km s^{-1} we derive a distance of 10–12 kpc. (For any positive value of V_0 the distance is >7 kpc.)

One could also estimate the distance from the X-ray luminosity, but this may be uncertain if eclipsing systems show systematically lower L_x due to obscuration by material in their accretion disks. However, we can turn the argument around and ask, for the assumed distance how does L_x compare to similar systems? Li *et al.* show $L_x \sim 6 \times 10^{35}$ ergs s^{-1} if the system lies at 10 kpc. This is two orders of magnitude smaller than L_x for the spectroscopically similar Cyg X-2. We note that in another low mass *eclipsing* system (1822−37) (Cowley, Hutchings, and Crampton 1981) the X-ray luminosity is also smaller than in systems like Sco X-1 or Cyg X-2.

If 0921−63 lies between 7 and 10 kpc away, it is approximately 1.5 kpc below the galactic plane (again, very comparable to the distance Cyg X-2 lies from the plane) and some 15 kpc from the galactic center. Its low mass (total mass <2) and distance from the galactic plane suggest that it may be an old system belonging to the galactic halo. The mass of the secondary is consistent with the turn-off mass in halo globular clusters, suggesting the secondary may have recently evolved to fill its Roche lobe.

VIII. CONCLUDING REMARKS

It appears that 0921−63 is a low mass system comprising a neutron star and an ~1 $M_\odot$ G giant. Although the rather long orbital period ($8^{\mathrm{d}}.99$) implies a separation of ~10 $R_\odot$, the secondary is expected to fill its Roche lobe and transfer matter to the degenerate star.

There is considerable evidence from existing photometry that the system may show bright and faint states (Chevalier and Ilovaisky 1981*b*). It would be particularly interesting to see if these states occur regularly and could be related to a precession of the disk, as in Her X-1.

Further spectroscopic observations are needed in the phase interval 0.9 to 0.3 to better define the intensity variation of the emission. Spectroscopic observation of the secondary at longer wavelengths might allow a direct determination of the mass ratio. Also, when the exact shape and duration of the eclipse are better known, the size, separation, and inclination of the system can be more precisely derived. If a longer disk precession period is present, the shape of the eclipse might vary, explaining differences which presently exist between photometric observations.

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Note added in proof.—G. Branduardi-Raymont, R. Corbet, A. N. Parmar, P. G. Murdin, and K. O. Mason (*Sp. Sci. Rev.*, **30**, 279 [1981]) have suggested a period of $17^{\mathrm{d}}.9$ from photometric data. They point out this is just double the value presented here. Our spectroscopic data rule out this longer period.

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