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A RADIAL VELOCITY STUDY OF 4U 2129+47: A LOW MASS X-RAY BINARY SYSTEM

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ABSTRACT

We have detected radial velocity variations of the He II λ4686 line in the low luminosity X-ray binary 4U 2129+47, in phase with the 5.24 hour binary period. The observed K velocity of 216±70 km s^{-1} implies a mass for the compact object of 0.53(+1.0, −0.4) solar masses. This confirms that the system mass is low; the compact object may be a degenerate dwarf. The λ4686 line is quite broad and may originate in an accretion disk. By contrast, the λ4640 feature is relatively narrow and may originate at the heated face of the normal star; its radial velocity tends to support this conclusion.

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

I. INTRODUCTION

The X-ray source 4U 2129+47 has a remarkable optical counterpart (Thorstensen *et al.* 1979, hereafter Paper I) in that the optical light from this star shows an ~1.7 mag modulation on a period of 5.2 hours with a corresponding variation in the X-ray region (Ulmer *et al.* 1980). The optical color is bluest at maximum light, and the light curve closely resembles that of HZ Her (although the period of 4U 2129+47 is shorter). Much of the modulation is apparently caused by anisotropic X-ray heating of an otherwise faint normal star in a binary system, a model long accepted for HZ Her (see, e.g., Gerend and Boynton 1976).

The 4U 2129+47 system is only the second X-ray system to show this behavior. Although both Sco X-1 (Gottlieb, Wright, and Liller 1975) and 2S 1822−371 (Mason *et al.* 1980) both show binary-period modulations, these are comparatively small in amplitude (~0.3 mag) and are not accompanied by color changes; an insignificant fraction of the light must therefore arise at the normal star.

In Paper I it was shown that several parameters of the system may be derived given minimal assumptions. If the normal star follows a main-sequence mass-radius relation and fills its Roche critical lobe, it must have a mass M_N (in solar units) between 0.59 and 0.80 and a radius R_N (in solar units) between 0.59 and 0.68, provided only that the X-ray source mass $M_X \geq M_N$. If the observed color of the heated face is a good indicator of its surface brightness, one may compute a distance of ~1.4 kpc for the source from its magnitude at maximum light. At this distance the isotropic X-ray luminosity L_X is relatively small, of order 6×10^{34} ergs s^{-1}. Similar conclusions were reached by McClintock, Remillard, and Margon (1981) in an extensive photometric study.

If the X-ray star is a neutron star, the slow main-sequence expansion of the normal star easily explains the small (~10^{-11} $M_\odot$ yr^{-1}) mass transfer rate necessary to power the X-ray source. The evolutionary scenario leading to this state, however, remains unclear. If the X-ray source is a degenerate dwarf, a possibility allowed by its low X-ray luminosity, the mass transfer rate must be nearly three orders of magnitude larger, which presents a problem. Also, one would expect in this case that the system would resemble a cataclysmic variable, which it does not.

Since this is one of the few optically faint X-ray systems with a known binary period, it is a prime candidate for a radial velocity study. The usefulness of such a study is greatly enhanced by the known interpretation of the binary phase; the X-ray source is behind the normal star at photometric phase zero (Paper I). Thus we can expect to determine where in the system the various emission features arise and to clarify the nature of the compact object.

II. OBSERVATIONS

We observed 4U 2129+47 on the nights of 1980 June 12, 13, and 14 UT, using the Kitt Peak National Observatory (KPNO) 4 m telescope and Intensified Image Dissector Scanner (IIDS). A 400 lines mm^{-1} grating used in the second order gave a spectral resolution of 5 Å FWHM (determined from strong comparison lines) over the useful spectral range from 3820 to 5180 Å. The raw data channels were approximately 1.3 Å wide. We

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used 1″.8 observing apertures during the first night and 1″.4 apertures for the second and third. These small apertures made photometric estimates unreliable but were necessary to ensure good radial velocity accuracy. As it was, the full width of the larger 1″.8 aperture projected to a width of 260 km s^{-1} on the spectrum. Thus centering and guiding were crucially important. The telescope tracked the source with an offset autoguider; we checked the centering of this autoguider about every 40 minutes using the aperture-viewing TV. The TV was red-sensitive and the spectral region covered was blue, which can cause a centering drift as the source changes air mass. Accordingly, we filtered the guiding TV field with a Schott BG-23 filter which passed a wavelength range similar to that recorded. To calibrate wavelength shifts due to spectrograph flexure and other causes, helium-neon-argon wavelength calibration scans were taken every 40 minutes. The standard KPNO reduction software interpolates between these scans when deriving the wavelength scale for each observation, thereby removing any slowly varying terms in the calibration. These effects were in any case rather small (less than a few angstroms). Because of all these precautions, the velocities derived should be intercomparable to better than 50 km s^{-1}, given adequate signal to noise.

We observed the source for a total of 6.9 hours over the 3 nights; all binary phases were covered, although not uniformly. The sum total spectrum is shown in Figure 1. All the spectral features were very weak; it was necessary to superpose data from all 3 nights before meaningful conclusions could be drawn. The observed features were as follows.

a) *Calcium* II

The Ca II H and K lines were present at all phases, and no clearly significant variation in equivalent width was observed. Thus the earlier conclusion of variable equivalent widths requires confirmation. The centroid of the K line shows no variation in radial velocity; its equivalent width in the sum of all the data is 1.1 ± 0.3 Å (error is estimated). The apparent centroid of the H line shows variations of radial velocity, but this is probably due to varying contamination by Hϵ. Thus, the evidence supports the conclusion that the H and K lines in this data set are primarily of interstellar origin. Given the probable 1.4 kpc distance of 4U 2129+47 (Paper I), the equivalent width is somewhat larger than one would expect; however, the equivalent width of the interstellar H and K lines has a large scatter at a given distance and is not well correlated with reddening (Münch 1968, and references therein).

b) *Balmer Lines*

These are barely detected, with Hβ and Hγ intermittently visible, and Hβ especially appears to be filled in with emission. This interpretation is tentative given the signal-to-noise ratio. No reliable radial velocities can be measured using these lines.

c) *Helium* II λ*4686*

This is the most interesting feature in the spectrum. It is virtually invisible at maximum light due to the strong continuum, but it is detected at all other phases. There are clear variations in its radial velocity (Figs. 2 and 3). Maximum radial velocity occurs around phase 0.7 and 0.8, and minimum near 0.2 or 0.3, in the photometric phase convention used above. In this convention, zero phase corresponds to the closest approach of the normal star. Hence, the λ4686 emission arises on the X-ray star's side of the center of mass. The apparent amplitude of the motion is quite large (Fig. 3). Summing all the data from phases 0.15–0.35 and comparing this with phases 0.65–0.85, the apparent motion of the centroid of the line is 6.3 ± 2.2 Å (conservative estimated error), from 4684.4 Å to 4690.7 Å (after heliocentric correction). This implies a K velocity of 216 ± 70 km s^{-1},[2] if it is due to orbital motion, and a systemic velocity of 120 ± 100 km s^{-1}.

[2]The K velocity is estimated here using a small correction (about 8%) for the phase mixing in the bins employed. This correction assumes a sinusoidal velocity curve with maxima and minima exactly at quadrature phase in the photometric ephemeris.

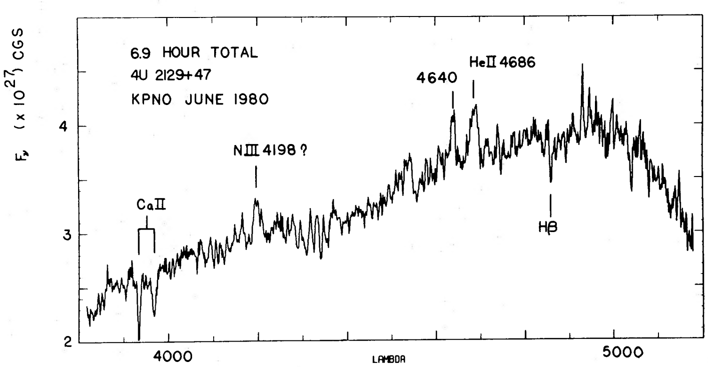

FIG. 1.—Total of 6.9 hours of data obtained 1980 June 12, 13, and 14 UT with the Kitt Peak 4 m reflector and IIDS. Features discussed in the text are marked. Note the strong continuum (the zero point is offset).

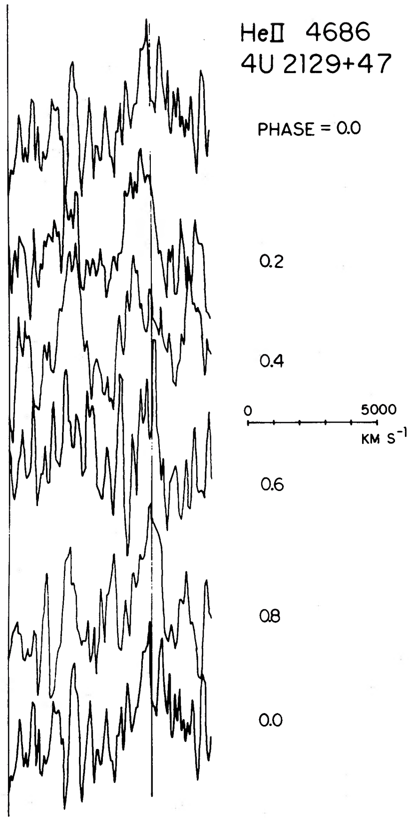

FIG. 2.—Averages of the Kitt Peak 4 m data near λ4686, folded on the photometric period. The fine vertical line marks the rest wavelength of He II λ4686. Although the signal to noise is variable (due to nonuniform phase coverage) and often poor, a shift in the λ4686 feature can be clearly discerned.

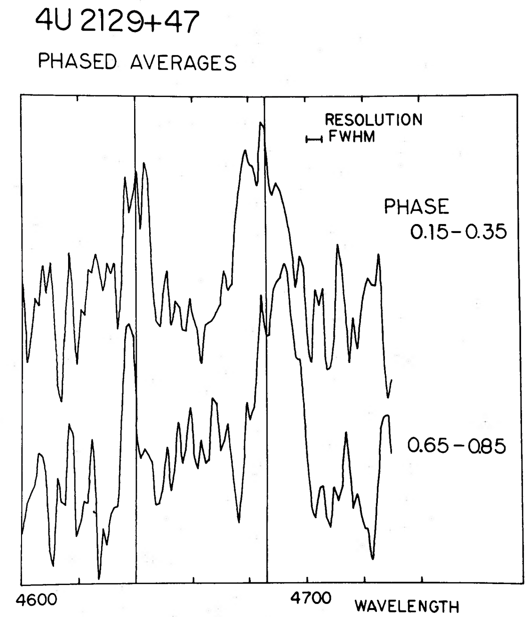

FIG. 3.—Same as Fig. 2, but with bins taken around quadrature phases. Since observations were concentrated near these phases, the signal to noise is not as poor as for Fig. 2. Note the considerable motion of He II λ4686 and the apparent antiphased motion of the N III λ4640 blend. The contrast between the width of λ4686 and that of λ4640 is apparent.

The line is quite clearly resolved; in the phase averages above it has a mean width (corrected for the instrumental profile) of 1060 km s^{-1} FWHM. The profile is steep-sided, so the full width at zero intensity is only slightly larger.

d) *Other Features*

The N III complex near λ4640 appears intermittently. It is unusually sharp and might be due to only one line. The apparent centroid of the feature moves in antiphase to the λ4686 line, with a full motion of 3.2 Å (205 km s^{-1}), however, this is not a secure result. The change in the apparent width of the feature (see Fig. 3) suggests that this may be a noise effect or that it may be due to a change in the relative contributions of the different lines in this blend (McClintock, Canizares, and Tarter 1975).

The data from the first and second nights show an apparently significant emission feature near λ4198. This may be identified with N III features at λλ4195.7 and 4200.0 (Meinel, Aveni, and Stockton 1975). However, the N III features at λ4097.7, which is sometimes seen in X-ray stars (McClintock, Canizares, and Backman 1978), are not detected. The λ4198 feature is too weak and intermittent to provide useful radial velocities.

III. DISCUSSION

a) *Mass Estimates*

The shift of the λ4686 lines gives information about the nature of the compact object. Its phasing and its considerable breadth suggest that it arises in an accretion disk around the X-ray emitting object. We assume that the centroid of the λ4686 line accurately reflects the motion of the compact object; this is true provided that the emission arises symmetrically in the disk. We may then compute the mass of the compact star to be

$$M_X = \frac{P M_N^{3/2} \sin^{3/2} i}{(a_X \sin i)^{3/2}} - M_N,$$

where P is the period in years, $a_X \sin i$ is in AU and is derived from the λ4686 velocities, and M_N is the mass of the normal star (both M_X and M_N are in solar masses). We take M_N from above to be 0.70 (+0.10, −0.11). Taking $i = 90°$, we find $M_X = 0.53$ for our nominal M_N and $a_X \sin i$. Our conservative limits on $a_X \sin i$ give an M_X of 0.11 and 1.51, with all other parameters held constant. Changing M_N while holding $a_X \sin i$ constant changes M_X by ±0.2. Decreasing i to 70° (a conservative lower limit if the X-ray modulation observed by Ulmer *et al.* 1980 is due to an eclipse) decreases the nominal M_X to 0.42. In sum, the large amplitude observed favors a rather low mass for the compact star ($\lesssim 1$ solar mass), but it does not completely exclude larger masses. We stress that the small derived M_X does *not* depend critically on our assumption that the normal star fills its Roche lobe on the main sequence. That assumption gives the value used for M_N above, but M_N is in any case very unlikely to be significantly larger than the above values, since the secondary's spectrum is not clearly seen and since the system's optical luminosity is quite modest. If the secondary is slightly evolved and is *less* massive than our estimate, then our M_X becomes even smaller.

Supporting evidence for a moderately low mass comes from the rather long eclipse observed by Ulmer *et al.* (1980). They estimate an eclipse half-width of 18°–27°; in a Roche geometry (Kopal 1959; Chanan, Middleditch, and Nelson 1976) this implies that $M_X/M_N \leq 2.2$, even for $\sin i = 1$. Thus from our M_N we have $M_X \leq 1.8$. The 27° eclipse would imply an M_X/M_N of only 0.5. In view of the signal to noise available, their estimates must of course be used with caution.

b) *Other Deductions*

The narrowness of the λ4640 blend implies that it arises in a region distinct from the λ4686 line. This, taken together with the possible motion in antiphase to λ4686, suggests that it comes from the heated face of the normal star. However, if this were so, one might expect it to be strongest at maximum light. These data are not extensive enough to illuminate this point; in the Lick data discussed above, it appears that the λ4640/λ4686 ratio is largest at maximum light.

IV. SUMMARY AND CONCLUSIONS

The X-ray stars of large L_X/L_{opt} are often thought to be low mass systems (see, e.g., Joss and Rappaport 1979). However, mass functions have only been determined for a handful of these systems (Crampton *et al.* 1976; Cowley, Crampton, and Hutchings 1979). In the case of 4U 2129+47, we have found that the mass is indeed quite low. In fact, our nominal mass of 0.53 solar masses for the compact star is considerably under the Chandrasekhar limit and suggests a degenerate dwarf model for the source, a possibility discussed above. We note that neutron star models are not completely ruled out, since some neutron stars may have masses below the Chandrasekhar limit and since our upper limit is slightly larger than the Chandrasekhar limit.

The model for the system outlined in § I is qualitatively unaffected by these observations. One revision should be made, however. If the dip in the X-ray light curve observed by Ulmer *et al.* is in fact an eclipse, and if the X-ray source is pointlike, then the entire heated face of the normal star must be invisible to us during an interval around minimum light. This follows from the fact that all stellar surfaces are convex. In spite of this, the spectrum does not change greatly during minimum light. Perhaps much of the light at minimum arises from other material in the system, such as an unocculted portion of the accretion disk. In either case, further work remains and insight into binary stellar evolution may be the reward.

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