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A PRECISE POSITION AND OPTICAL IDENTIFICATION FOR 4U 2129+47: X-RAY HEATING AND A 5.2 HOUR BINARY PERIOD

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ABSTRACT

We present a precise (20″) position and an optical counterpart for the weak X-ray source 4U 2129+47. The optical counterpart shows weak but distinct He II λ4686 and C III–N III λλ4640–4650 emission. Both Hβ and Ca II H and K are sometimes visible in absorption. Numerous plates and spectrophotometric observations from the 1978 observing season show that the blue magnitude varies from 16.7 to 18.0 on a period of 5.2382 hours. The light curve is sinusoidal in appearance, but with sharply defined V-shaped minima. We propose that most of the optical emission from this system originates at the X-ray heated face of the normal star and hence that this system is analogous to HZ Her/Her X-1. This is one of the few intrinsically faint optical counterparts of X-ray sources that show clear evidence of binary nature. Our observations suggest a distance of 1.2–1.6 kpc for the source, and a consequent X-ray luminosity $\sim 10^{34.8}$ ergs s^{-1}.

Subject headings: stars: variables — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The HZ Her/Her X-1 system has been unique in X-ray astronomy in that it displays a large X-ray heating effect in the optical spectrum and light curve of the primary star. This effect is a particularly valuable diagnostic tool for investigating this system and has enabled detailed models of an X-ray irradiated stellar atmosphere to be developed (see Anderson 1977, and references therein). One might have expected many other dwarf X-ray binaries to show similar X-ray heating effects (Joss, Avni, Rappaport 1978; Joss and Rappaport 1978), but only weak optical modulation (if any!) is generally observed (as in Sco X-1; see Gottlieb, Wright, and Liller 1975). We now present 4U 2129+47 as a second dwarf X-ray system that shows immediately apparent binary behavior. We report a precise X-ray location for this weak, variable (~10–20 *Uhuru* counts; Forman *et al.* 1978) source and the subsequent optical identification, and discuss the binary parameters as derived from our optical measurements.

II. OBSERVATIONS

X-ray.—*HEAO 1* observations of 4U 2129+47 were carried out from 1977 December 9–17. A precise position for the source was determined from a superposition of 54 orbits of scanning modulation collimator data. The source was detected at the 10 σ level in both collimators at an intensity equivalent to 5 *Uhuru* counts. Only one of the multiple modulation collimator positions falls near the *Uhuru* position for the source (Forman *et al.* 1978). The error box is plotted in Figure 1 (Plate L1).

Optical.—We undertook a photographic search of this error box in 1978 July; a highly variable star was immediately apparent. Its 1950 position is $\alpha = 21^h29^m36^s.2$, $\delta = +49°04'08''$, and it is marked in Figure 1. We discuss below our extensive observations of this star.

Spectrophotometry.—We observed the source on 11 different nights in 1978 using the Lick Observatory 3 m Shane telescope and Image Tube Scanner (ITS; Robinson and Wampler 1972). Typical observations covered a range of 2500 Å with a resolution of 10 Å; central wavelengths ranged from 4200 Å to 5800 Å. Our main results are presented below.

a) *Photometry and Ephemeris*

As the ITS is a photoelectric device, our data contain accurate photometric information, provided large enough measurement apertures are used. We reduced our spectrophotometric scans to absolute fluxes by observing Oke (1974) standard stars, and using reduction techniques similar to those of Smith (1975). We find a range of variability in V from 16.2 to 17.4, with a $B - V$ color ranging from 0.5 at maximum light to 0.8 at minimum light. There is considerable ultraviolet excess, with $U - B$ showing a stronger variation with magnitude than $B - V$; $U - B$ varies from a rather uncertain value of -0.1 at minimum light to -0.7 at maximum. Our uncertainties are dominated by systematics of about 0.1 mag.

On the night of September 8 UT, we observed the

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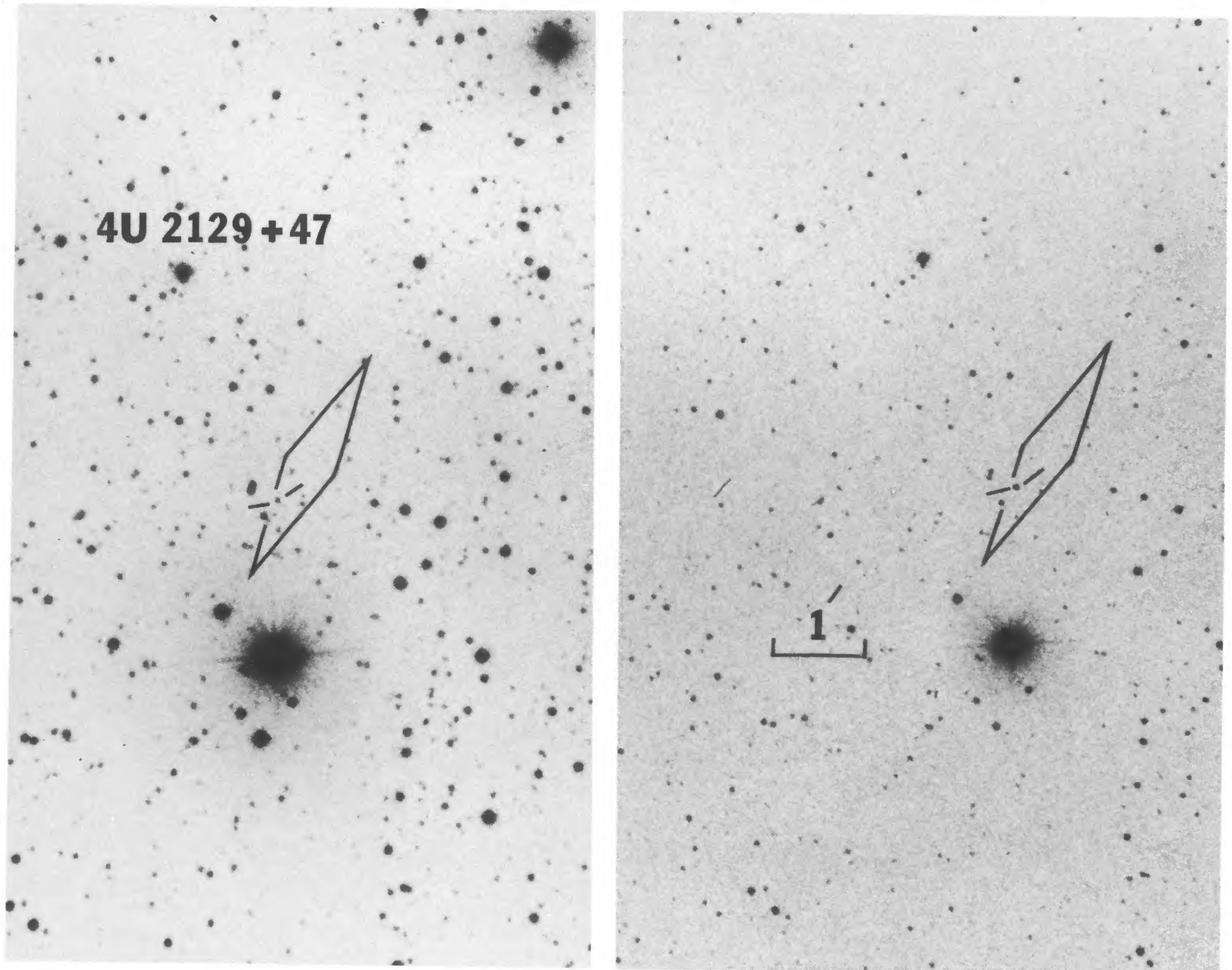

FIG. 1.—Finding charts for the 4U 2129+47 field. *Left*, Crossley blue (103-a0 + GG385) plate taken 1978 July 6 at binary phase 0.01; *right*, ultraviolet (103-a + UG2) plate taken 1978 July 5 at phase 0.51. North is at the top and east is to the left. Our 90% confidence error box and the optical counterpart are indicated on each plate. The large difference in brightness of the counterpart between the plates is due to both the binary phase and the different passbands.

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star continuously for 5.2 hours. The count rate data, which cover the range 3600–5900 Å, are shown in Figure 2, plotted as a function of phase. Notice the well-defined minimum in the light curve, which provides an excellent fiducial mark for period determination. A similar sharp minimum was observed the next night, and yet another one on October 26. These data provide the photometric ephemeris,

$$T_{\rm min} = 2443760.755(\pm\ 0.003) + 0.21826(\pm\ 0.00003)E\ ,$$

where $T_{\rm min}$ is the heliocentric Julian date of minimum light. The errors quoted are derived from conservative estimates of the uncertainty in the times of minimum light. Photographic photometry from 11 nights between 1978 July and October confirms the reality of this periodicity.

b) *Spectral Features*

Figure 3 shows averaged spectra of this object. In most of our spectra, He II λ4686 and/or the C III–N III λλ4640–4650 blend appear in emission. These features are typical of galactic X-ray sources (McClintock, Canizares, and Tarter 1975), but are seldom found in normal stars. Taken together, the unusual optical modulation and the detection of these features secure the identification.

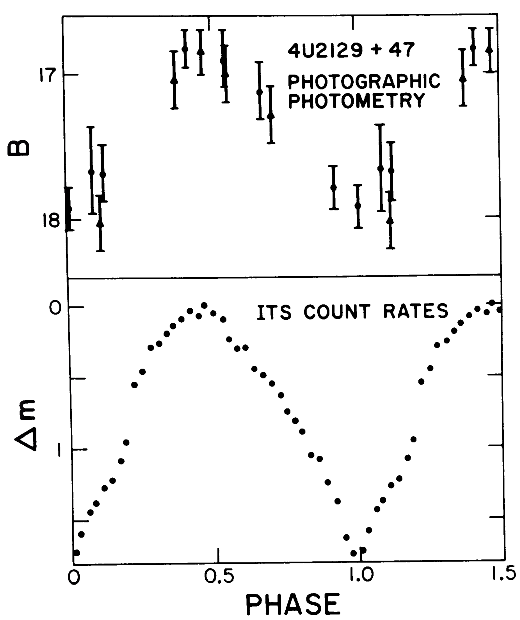

FIG. 2.—*Upper*, photographic blue magnitudes of 4U 2129+47 obtained in the interval 1978 July 6–October 29 folded using the ephemeris discussed in the text. Errors shown are estimated relative 2 σ errors. *Lower*, ITS total count rates (sky subtracted) from 1978 September 8 UT, expressed in relative magnitudes. Each point represents one 8 minute integration. The observation started at phase 0.6 with 3".5 × 4" apertures. The apertures were changed at phase 0.2 to 4".9 × 6" because of worsening observing conditions at large air mass. The apparent discontinuity at this phase may therefore be due to a change in the fraction of light entering the aperture.

A number of other features appear in our spectra. We often detect Hβ absorption, which sometimes appears to be filled in with emission. The Ca II H and K lines appear frequently in absorption, but are variable by a factor of at least 3 in equivalent width, precluding an entirely interstellar origin. On many spectra, the NaD lines are detected weakly. The H and K absorption appears strongest at minimum light, while the Hβ absorption is generally strongest at maximum light.

c) *Studies of Field Stars*

In order to estimate the reddening in the field, we obtained spectrophotometric scans of several nearby stars. One was a K star, and hence of little use, but two were useful. The first, 15" southeast of the counterpart, is between spectral types B8 and A5, with $V = 16.0$ and $B - V = 0.51$; the second, 71" due north, is between F1 and F5, with $V = 15.4$ and $B - V = 0.84$. These spectral types were determined by comparison with spectral type standards observed with the same instrument. Interpreting these numbers according to typical main-sequence values given by Allen (1973), we find that 1.2–1.6 mag of extinction (in A_V) occurs in the nearest 1.5 kpc along the line of sight, with very little additional reddening out to 4 kpc, the distance of the A star. At $b = -3\overset{\circ}{.}1$, the A star is at least 200 pc from the galactic plane, and hence little reddening is expected beyond it. We adopt a firm maximum extinction A_V of 1.9 for this field.

III. DISCUSSION

In what follows, we assume that the strong 5.2 hour modulation in the optical flux arises from the changing aspect of the X-ray heated face of a normal star in a binary system, and not from an eclipse. The light curve is modulated smoothly and approximately symmetrically over the entire cycle, while an eclipse would occupy less than half the cycle. Although some cataclysmic variables, such as U Gem, exhibit grossly asymmetric modulation throughout the light curve because of the changing aspect of a "hot spot" on an accretion disk (Robinson 1976*a*, and references therein), the symmetry of the 4U 2129+47 light curve argues against application of that model here. The spectrum also has no strong emission features, which is similar to HZ Her but dissimilar to most cataclysmic variables, the only systems in which accretion disks have been unambiguously observed.

If the normal star is on the main sequence and fills its Roche lobe, the binary period allows us to estimate its mass M_N and radius R_N in the manner described by Robinson (1976*b*).[5] The results are nearly independent of the mass assumed for the X-ray source, M_X, unless $M_X \ll M_N$; a more important uncertainty is the correct

[5] His expression for M_N must be generalized in the case that the compact star is much more massive than the normal star. We do so using expressions given by Paczynski (1971).

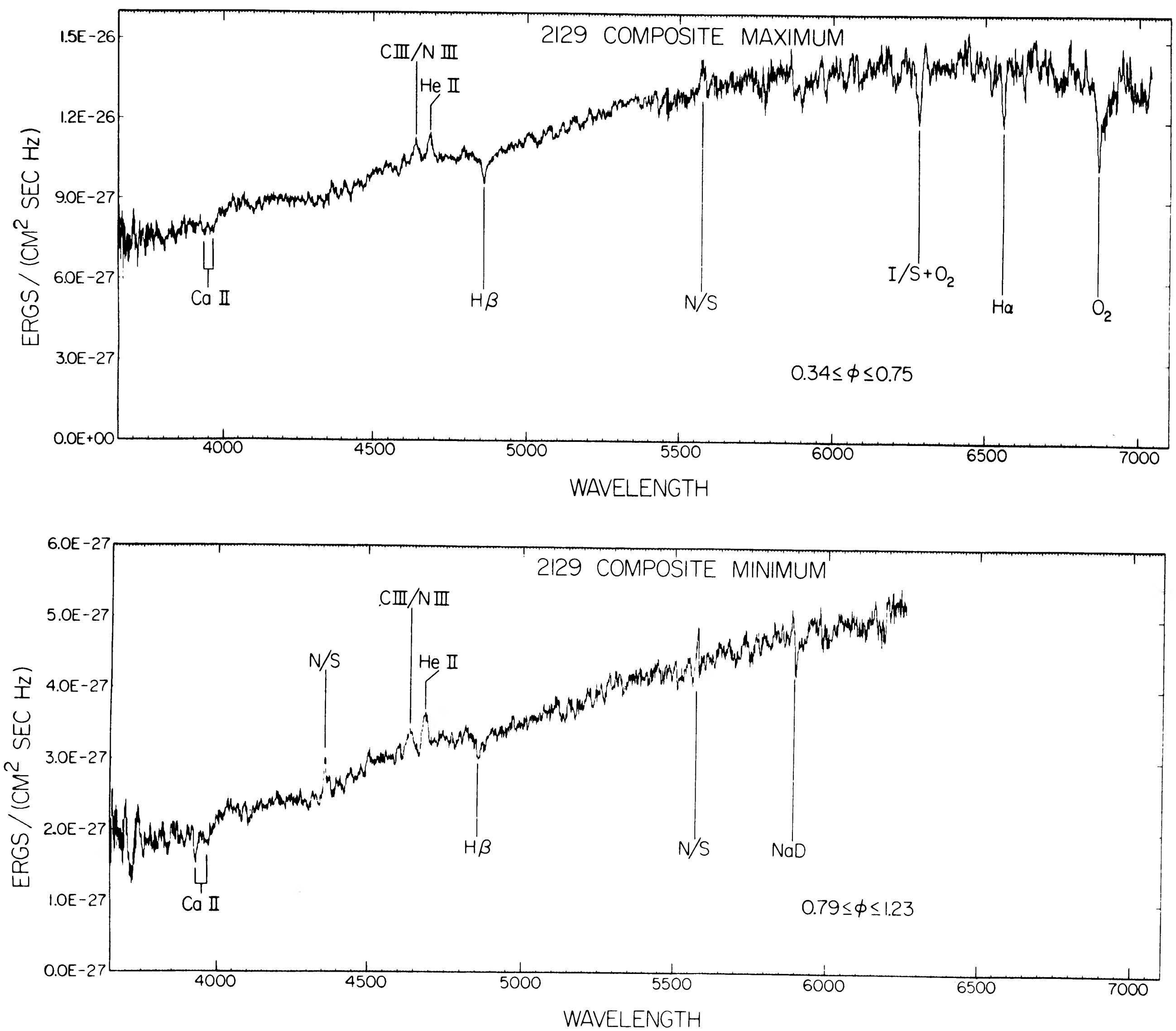

FIG. 3.—(*a*) Averaged ITS spectrum of 4U 2129+47 around maximum light (binary phase 0.34–0.75). A total of 4.7 hours of data from 1978 July 12, September 8, October 25, and October 26 was summed. Features marked *N*/*S* are imperfectly subtracted night-sky emission features; those marked O_2 are telluric molecular oxygen bands. The feature near λ6280 may be blended with a diffuse interstellar band. (*b*) Similar to (*a*), but around minimum light (phase 0.79–1.23). We display the sum of 5.6 hours of data obtained 1978 July 13, 14, 15, September 8, October 25 and 26.

mass-radius relation for the lower main sequence. Allowing for these uncertainties, we find $0.59 \leq M_N \leq 0.80$, and $0.59 \leq R_N \leq 0.68$, provided $M_X \geq M_N$. If the normal star is evolved, but has at least the radius appropriate to its mass on the main sequence, these numbers are upper limits for its mass and radius. Only in the unlikely case that the normal star is *smaller* than its main-sequence radius could these numbers be substantially incorrect.

A star of this mass should be an early M star (Bopp 1974) with $B - V \sim 1.3$. Assuming that the color at minimum light arises from a combination of light from the hot side ($B - V = 0.5$) and the cool side, we find that the cool side may contribute up to 40% of the light in V at minimum light. The rather weak H and K and NaD lines observed may thus easily arise on the cool side, and hence may not be used to analyze the X-ray heated atmosphere. Unfortunately, the fraction of the light contributed by the cool side at minimum light and the spectral type of the normal star are not sufficiently well determined to allow an accurate spectroscopic distance estimate; the allowed range includes the distances derived below from observations at maximum light.

If we adopt an assumption regarding the heated face of the normal star, we may estimate the distance to the source. We assume that the V surface brightness is related to the intrinsic $B - V$ color in the same manner as for normal stars, as calibrated by Barnes, Evans, and Moffett (1978). As we discuss above, the binary period gives (with some assumptions) a very strong constraint on the physical size of the normal star. We may thus calculate an absolute magnitude, and hence a distance. The reddening does not enter this calculation, because of a fortunate coincidence between the slope of the surface brightness–color relation and the ratio of total to selective extinction. Complicated aspect effects (see, e.g., Margon *et al.* 1977) will not be important at maximum light, as the heated face is turned almost directly toward the observer, filling a large fraction of the stellar disk. The distance we derive is only weakly dependent on the size of the normal star; we take R_N to be $0.6\ R_\odot$, and find a distance of 1.4 kpc for our nominal $B - V$ of 0.5. Assuming $B - V$ to be 0.6 and 0.4, respectively, gives distances of 1.2 and 1.6 kpc; thus this method is somewhat sensitive to both our observational uncertainties and our assumptions. Taking the X-ray flux to be 15 *Uhuru* counts s^{-1}, we obtain an isotropic luminosity of $L_X = 6 \times 10^{34}$ ergs s^{-1} at 1.4 kpc. Our reddening measurements suggest that $A_V \geq 0.7$ at this distance, implying an intrinsic color $(B - V)_0 \leq 0.3$.

If the normal star fills its Roche lobe, the fraction of the X-radiation it intercepts is determined by the mass ratio of the system and the radiation pattern of the X-rays. If this pattern is isotropic, we may compute the mass ratio of the system from the observed ratio of X-ray to optical flux $F_X/F_{\rm opt}$. We have done so for several assumed values of $(B - V)_0$, on the assumption that, for each value, the bolometric correction is the same as for a normal star of that color. In doing so, we use a relation derived from Margon *et al.* (1977, 1978):

$$\frac{F_{\rm opt}}{F_X} = \frac{2R_N^2}{3\pi a^2}\left[\cos i + \left(\frac{\pi}{2} + i\right)\sin i\right],$$

where a is the binary separation, i the inclination, and $F_{\rm opt}/F_X$ is the observed bolometric optical to X-ray flux ratio at maximum light, corrected for interstellar extinction. Taking i to be $\pi/2$, and an X-ray flux of 15 *Uhuru* counts s^{-1}, we find $M_X/M_N = 2.7$ for $(B - V)_0$ of 0.3, with rapidly decreasing values as one assumes bluer intrinsic colors. For $(B - V)_0 = 0$, we obtain $M_X/M_N = 0.14$. The rapid decrease results from the rapidly increasing bolometric and extinction corrections, and the consequent requirement that the normal star intercept a large fraction of the X-ray flux. Although this estimate is quite uncertain, it suggests that M_X is likely to be less than $3\ M_\odot$. The bluest intrinsic colors we have assumed seem unlikely, as they imply extremely small masses for the X-ray star.

Why is this system qualitatively so different from all other faint X-ray stars? One possibility is that the compact object is a degenerate dwarf, a suggestion supported by the low X-ray luminosity and the low nominal mass of the compact star. Kylafis and Lamb (1979) predict that degenerate dwarfs accreting well below their Eddington limits should be efficient sources of hard X-rays. If the X-ray star is a degenerate dwarf, however, one is left with two questions. First, why is this system so different from cataclysmic variables, which it should resemble? Second, how does one explain the $\sim 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ mass-transfer rate necessary to power the X-ray star? If the X-ray star is a neutron star, both these problems are alleviated; a much lower mass-transfer rate ($\sim 10^{-11}\ M_\odot\ {\rm yr}^{-1}$) is required, which could be provided by the slow main-sequence evolution of the normal star. However, how such a system would remain bound after the formation of the neutron star remains problematic.

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Note added in proof.—We observed a fourth photometric minimum of the source 1979 July 30 with the Lick 3 m telescope. This gives a refined ephemeris, $T_{\rm min} = 2{,}443{,}760.755\ (\pm 0.003) + 0.218259\ (\pm 0.000007)E$, where the notation and error estimation are as above.

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