

EVIDENCE FOR THE BINARY NATURE OF 2U 1700–37

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ABSTRACT

Analysis of *Uhuru* data on the X-ray source 2U 1700–37 has revealed the presence of regular occultations. The period is 3.4 days with an occultation duration of 1.1 days. The source is highly variable on a time scale of minutes. Significant intensity variations have also been observed on a time scale of 0.1 second with a 3σ upper limit of 17 percent on the percentage periodically pulsed. The energy spectrum is flat and shows a large amount of low-energy absorption. The data indicate that 2U 1700–37 is an X-ray source in a binary system. The 6.6-mag O7f star HD 153919 is suggested as the optical candidate.

Subject headings: binaries — X-ray sources

I. OBSERVATIONS

The X-ray source 2U 1700–37 was first detected by the *Uhuru* satellite in 1970 December. The most extensive *Uhuru* observations of this source were made in 1972 May. The 2–6 keV intensity measured for 7 days during this set of observations is shown in figure 1. These data show two complete cycles of the source. Transitions from the high-intensity state to the low state are clearly visible on May 11.7 and May 15.1. Two upward transitions from states of low intensity to states of high intensity are seen on May 12.8 and May 16.2. Combining these observations with others ranging over a year and a half, we have determined a period of 3.412 ± 0.002 days. The occultation is centered on UT 1972 May 15.64 ± 0.04 (JD = 2,441,453.14).

We have examined data for 70 days on which 2U 1700–37 was surveyed between 1970 December and 1972 May and have determined that its behavior is always consistent with the derived period and phase. Observations obtained over this time are shown in figure 1 folded with the 3.412-day period. The data are plotted twice for illustration.

The eclipse duration determined from the data in figure 1 is 1.10 ± 0.07 days. We can set a 3σ upper limit of 6 counts per second on the intensity observed during the occultation of 2U 1700–37. At times the occultation appears to be somewhat longer than 1.10 days, as in the first cycle in figure 1. It is possible that the large variability in intensity described below could account for this behavior or that the eclipse duration actually does vary.

The data in figure 1 also show a second minimum at phase 0.5. When all the available sightings are folded with the 3.412-day period and averaged into 25 intervals, the average intensity in the center bin of the high state is half that of the adjacent bins. The intensity at phase 0.5 is 10 standard deviations below that of the bins on either side, although it is not particularly meaningful to consider the difference in terms of standard deviations since statistically significant fluctuations in intensity are so prevalent in the data. There are, however, no substantial upward fluctuations

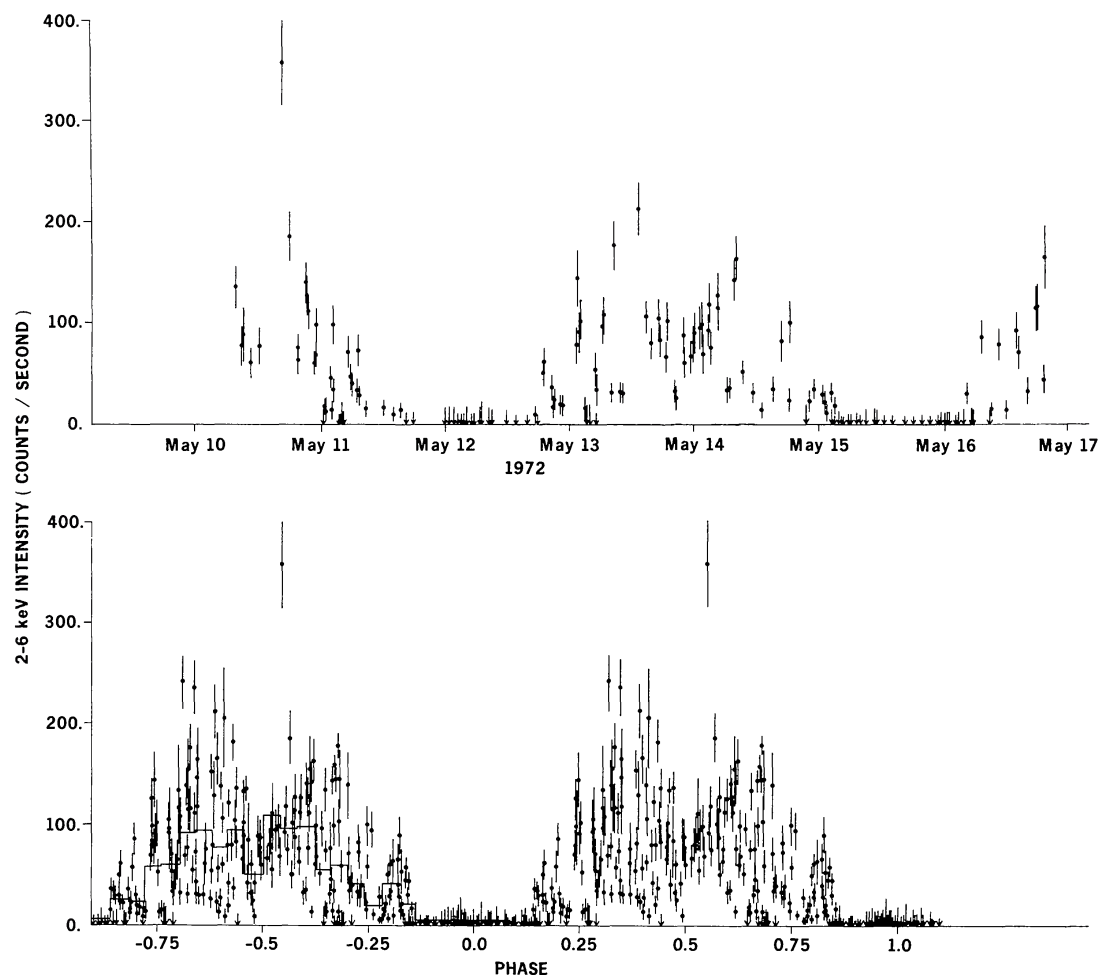


FIG. 1.—The 2–6 keV intensity of 2U 1700–37 corrected for elevation in the field of view and shown with $\pm 1\sigma$ error bars. The upper portion shows seven days of data from 1972 May. Plotted below are observations obtained between 1970 December and 1972 May folded with the 3.412-day period. A histogram of the intensity averaged in 25 equal intervals is also shown.

yet observed at phase 0.5. The intensity averages without error bars are shown in the lower portion of figure 1.

There is a large degree of variability in the intensity during the 2.3-day on time, as can be seen in figure 1. Since the data in the top portion of figure 1 were obtained after the failure of the *Uhuru* star sensors, only rough aspect information was available to correct the source intensity for the location of the source within the collimator field of view, so that the error bars on the intensities are necessarily large. However, the large uncertainties do not mask the fluctuations in which the intensity changes by as much as a factor of four in times of 10 minutes. Variability on the time scale of seconds also has been observed. On several occasions the intensity has more than doubled from one second of observations to the next. All of this variability has also been detected during observations made when the *Uhuru* star sensors yielded good aspect information.

Rapid intensity changes on time scales of a tenth of a second are also present in the 2U 1700–37 data. These fluctuations are not so striking as those seen in Cyg X-1, perhaps owing to the lower intensity of 2U 1700–37. However, even when no significant flares on times of seconds are visible, the fits of the data to a constant

intensity are not good, implying that there is variability on even shorter time scales. When the intensities are averaged over a few tenths of a second, the fit is improved for about half the cases. For example, analysis of the center 7 seconds of one 30-second pass with the data taken every tenth of a second gave a χ^2 per degree of freedom of 1.47 with a sigma of 0.16; the same measurement summed in 0.3-s bins gave a χ^2 per degree of freedom of 1.04 with a sigma of 0.28. We interpret these results as indicating that the rapid changes occurred on times of a tenth of a second or less. We have Fourier-analyzed and performed autocorrelations on several 20–30-second observations of 2U 1700–37 with a time resolution of 0.096 to search for a periodicity in the short-term variability. We can set a 3σ upper limit of 17 percent on the percentage of the flux that is periodically pulsed with a period ranging from 0.1 to about 10 seconds.

The 2–20 keV spectrum of 2U 1700–37 is flat and shows a large amount of low-energy absorption. The spectrum is variable with a power-law energy index ranging from -0.4 to $+1.0$ and a cutoff varying between 2.1 and 5.5 keV, corresponding to hydrogen densities of 4×10^{22} and 4×10^{23} atoms per cm^2 (Brown and Gould 1970). Thermal spectra with temperatures greater than 10^8 °K and substantial low-energy cutoffs are also consistent with many of the observations.

The position of the X-ray source (90 percent confidence level contours) is shown in figure 2 (plate L1). The large box is the position from the 2U catalog, and the small box is a new position obtained from additional source sightings not included in the 2U catalog. The new box has an area of 0.009 square degrees and is centered at $\alpha(1950) = 17^{\text{h}}00^{\text{m}}29^{\text{s}}$ and $\delta(1950) = -37^\circ46'4''$, with the corners located at

$\alpha(1950)$	$\delta(1950)$
$17^{\text{h}}00^{\text{m}}51^{\text{s}}$	$-37^\circ48'0''$
$17^{\text{h}}00^{\text{m}}51^{\text{s}}$	$-37^\circ44'7''$
$17^{\text{h}}00^{\text{m}}6^{\text{s}}$	$-37^\circ44'7''$
$17^{\text{h}}00^{\text{m}}6^{\text{s}}$	$-37^\circ48'0''$

II. DISCUSSION

The most conspicuous object at the new X-ray location is a 6.6-mag O7f (Crampton 1971) star HD 153919 ($\alpha_{1950} = 17^{\text{h}}00^{\text{m}}32.7^{\text{s}}$, $\delta_{1950} = -37^\circ46'29''$). Rappaport, Doxsey, and Zaumen (1972) have communicated that data from a rocket flight on 1971 May 1 have yielded an independent X-ray location for 2U 1700–37. Their observations with a modulation collimator show a 4σ peak centered at $\alpha(1950) = 17^{\text{h}}00^{\text{m}}29.5^{\text{s}}$ and $\delta(1950) = -37^\circ46'44''$ with a radius of uncertainty of $1'5''$ (90 percent confidence). This position, which includes the candidate star, is also shown in figure 2.

The high correlation of bright stars in X-ray error boxes noted by Gursky (1972) provides further reason for considering this star as the optical candidate. Also Heap (1971) has found that compared to O stars, Of stars have low surface gravities, which would fit well with a model in which X-rays result from the accretion of mass from the binary companion, in this case the O7f star, onto the compact X-ray source. Compactness is inferred from the short-timescale pulsations. Spectra recently obtained by Koo and by Liller and Forman show interesting features that appear to come and go on time scales less than 10 minutes. Further optical observations of HD 153919 are needed to test the identification with the X-ray source.

Henry (1972) has suggested that for binary systems containing X-ray sources, the amount of X-ray radiation absorbed by the optical companion and reradiated at ultraviolet and optical frequencies is proportional to the duration of the X-ray eclipse. For 2U 1700–37, the maximum observed X-ray luminosity from 2 to 10 keV is 3×10^{36} ergs per second, based on a distance of 1.7 kpc to the optical candidate. However, the luminosity of the optical candidate is about 10^{38} ergs per second, so

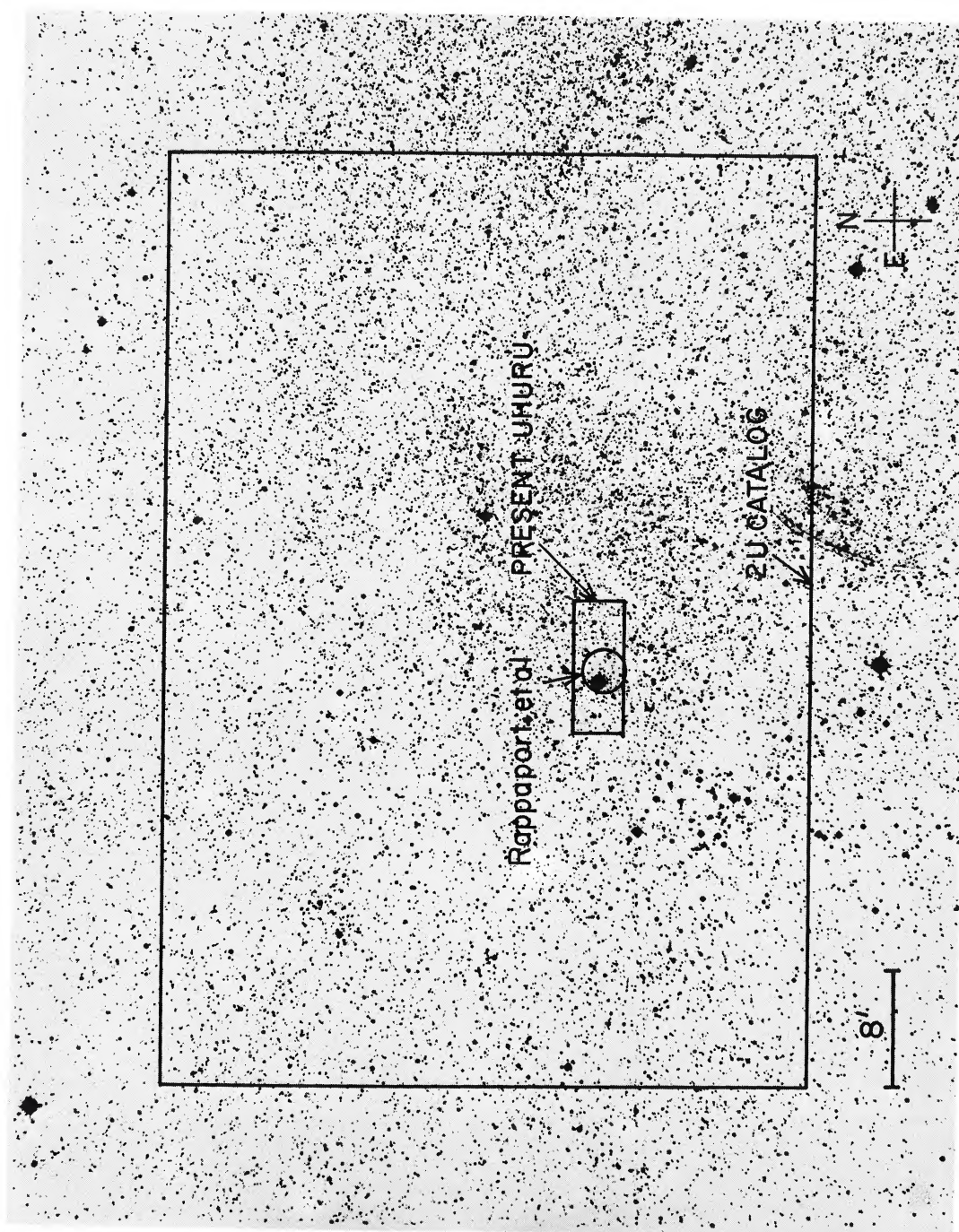


FIG. 2.—Location of 2U 1700—37 shown on an enlargement from the *Palomar Sky Survey*. Both the old location from the 2U catalog and the new *Uhuru* position are shown. In addition, a location recently determined by Rappaport *et al.* (1972) is given. The bright star contained within all three location determinations is HD 153919, the suggested optical candidate.

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TABLE 1
CHARACTERISTICS OF X-RAY BINARIES

Source	Binary Period (Days)	Short-Term Variability	Long-Term Variability	Power-Law Energy Index	Cutoff (keV)	Optical Candide date	Distance (kpc)	Peak Luminosity (2-10 keV ergs per second)
2U 1700-37	3.412 ±0.002	Nonperiodic pulsations as short as 0.1s	No extended lows	-0.4 +1.0	2.1 +5.5	HD 153919	1.7	3×10^{36}
2U0900-40 (GX 263+3)	8.96 ±0.05 ^{a,b}	Nonperiodic ^a pulsations on time of seconds	No extended lows ^a	-0.2 ⁺ +0.7 ^a	2.5 ⁺ 4.4 ^a	HD 77581 ^{c,d,e,t}	1.3 ^{d,e}	4×10^{36}
SMC X-1 (2U 0115-73)	3.8927 ±0.0010 ^f	Nonperiodic ^f pulsations on time of minutes	Extended lows ^f	0.0 ⁺ 0.3 ^f	1.5 ⁺ 3.0 ^f	Sanduleak ^u No. 160	61 ^f	3×10^{38}
Her X-1 (2U1702+35)	1.700167 [±] 0.000006 ^{g,h}	1.23782-s ^{g,h} pulsations	Extended lows ^{g,h} average cycle of 35.3 days	-1.3 ⁺ +0.2	1.5 ⁺ 3.2	HZ Her ^{i,j,k}	5.8 ^k	1×10^{37}
Cen X-3 (2U1119-60)	2.08712 [±] 0.00004 ^l	4.842-s ^l pulsations	Extended lows ^l	-0.4 ⁺ +0.6	1.5 ⁺ 4.2	None	?	?
Cyg X-1 (2U1956+35)	5.600±.003 from ^{m,n,o} optical. Not ob- served in X-ray	Quasi-periodic ^{p,q,r} pulsations as short as 50 ms	Single low-energy transitions ^s	2.8 ⁺ 4.1 before transition 0.45 after transition	≤1.5	HDE 226868 ^{m,n}	2 ^{n,o}	1×10^{37} before transition; 3×10^{36} after transition
^a Forman et al. 1972 ^b Ulmer et al. 1972 ^c Kellogg and Murray 1971 ^d Brucato and Kristian 1972 ^e Hiltner, Werner, and Osmer 1972 ^f Schreier et al. 1972b ^g Stanbaum et al. 1972a ^h Forman et al. 1972 ⁱ Ulmer 1972a ^j Bahcall and Bahcall 1972 ^k Forman, Jones, and Liller 1972 ^l Schreier et al. 1972a ^m Bolton 1972a ⁿ Webster and Murdin 1972 ^o Bolton 1972b ^p Rappaport et al. 1971 ^q Oda et al. 1971 ^r Schreier et al. 1971 ^s Stanbaum et al. 1972b ^t Bradt and Kunkel 1971 ^u Liller 1972b								

even if a large fraction of the X-ray energy were absorbed and reradiated, there would be only a small ($\lesssim 1$ percent) effect on the observed optical luminosity.

Six X-ray sources—Cen X-3, Her X-1, SMC X-1, Cyg X-1, 2U 0900—40, and 2U 1700—37—are now believed to belong to binary systems. Of the six, all except Cyg X-1 show X-ray occultations. As for the other occulting binaries, the energy spectrum of 2U 1700—37 is flat and has a large low-energy cutoff. Interstellar absorption cannot account for the large cutoff and certainly not for the variability observed in the amount of absorption. In fact, this source has the greatest amount of absorption of any of the X-ray binaries observed so far. The eclipse duration of 2U 1700—37 is also the longest of any of the six binaries, lasting about 30 percent of the entire period. Schreier *et al.* (1972*b*) have suggested that the large low-energy cutoff observed in occulting X-ray binaries is due to an accretion disk or circumbinary matter concentrated in the orbital plane. Also the presence of a second intensity minimum, when combined with the compactness required by the time variability and the parameters of the system that might be determined from an optical identification, could be very important in understanding the nature of the emission process.

A comparison of some of the properties of 2U 1700—37 with those of the other X-ray binaries is given in table 1. For the power-law energy index and the low-energy cutoff, the extremes in variability are given for each source. In several respects, in addition to their both being in binary systems, 2U 1700—37 is similar to Cyg X-1. For both sources the X-ray energy is pulsed on short time scales requiring compactness of the X-ray source, although neither shows periodic pulsations. Neither source exhibits extended lows during which it is not observed above the X-ray background. In addition, the peak X-ray luminosity of 2U 1700—37 and Cyg X-1 (post transition) are about the same if the optical identifications and hence the distances are correct. The close similarity in the X-ray properties of Cyg X-1 and 2U 1700—37 suggests that 2U 1700—37 might be a black hole, as has been advocated for Cyg X-1 (Webster and Murdin 1972; Bolton 1972*a, b*; Tananbaum *et al.* 1972*b*). In that case, as for Cyg X-1, the mass of the X-ray source would be considerable and the mass ratio therefore would not be very different from unity. Hence a search for radial velocities in the proposed optical candidate could prove most informative.

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