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# ORBITAL ELEMENTS OF 4U 0115+63 AND THE NATURE OF THE HARD X-RAY TRANSIENTS*

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## ABSTRACT

Precise elements of the first measured orbit of a transient X-ray source (4U 0115+63) are presented. The projected semimajor axis of the X-ray star (140.1 lt-s) and the orbital period ($24^{\mathrm{d}}3$) yield a mass function of 5.00 $M_{\odot}$. The orbit is moderately eccentric, with $e = 0.34$. We propose that the relatively wide orbit is the cause of the slow rate of circularization and also precludes steady mass transfer, thereby resulting in the transient nature of the source.
*Subject headings:* X-rays: binaries — X-rays: sources

## I. INTRODUCTION

Transient X-ray sources have been the subject of much study with several satellites, including *Uhuru*, *OSO 7*, *Ariel 5*, *SAS 3*, and *OSO 8* (see, e.g., Kaluzienski *et al.* 1977; Cominsky *et al.* 1978*b*). It is often argued that these sources are accreting compact stars in binary systems. However, because no binary orbit has heretofore been measured for any of these transient sources, it has not been possible to test conclusively the validity of the binary hypothesis or the models for these sources that are based on this hypothesis. Orbital periods of ~8 d and $\gtrsim$20 d have been suggested for two of the transient sources (Matilsky *et al.* 1976; Rappaport *et al.* 1976), but these are unconfirmed, and, in any case, no reliable information is available on the size of the orbits.

Recently, the "hard" transient X-ray source 4U 0115+63 (Forman *et al.* 1978) was observed to undergo a new outburst (Clark and Cominsky 1978; Holt and Kaluzienski 1978). Shortly thereafter, 3.6s X-ray pulsations were discovered (Cominsky *et al.* 1978*a*), and precise positional determinations (Cominsky *et al.* 1978*a*; Johnston *et al.* 1978) led to a probable identification with a heavily reddened early-type star (Johns *et al.* 1978). The discovery of short-period X-ray pulses from a transient source presented a unique opportunity to determine a precise binary orbit for a system of this type.

In this *Letter*, we report extended *SAS 3* timing observations of pulsations from 4U 0115+63 and present the first definitive measurement of the binary orbit of a transient X-ray source. Constraints on the nature of the optical companion star are given and a model for mass transfer in this system is considered. We also discuss the relation of 4U 0115+63 to other hard transient X-ray sources.

## II. OBSERVATIONS AND ANALYSIS

Observations of the arrival times of the pulsations from 4U 0115+63 were made with *SAS 3* during the 26 day interval 1978 January 12.8–February 7.8 (UT). Most of the observations were made with the center slat collimator detector (Lewin *et al.* 1976; Buff *et al.* 1977) in the energy range 1.5–13 keV. During the intervals 1978 January 12.8–13.6, 18.1–19.6, and January 27.9–February 7.8, this detector was pointed continuously at the source except for a 1500 s Earth occultation during each satellite orbit. Additional timing data were obtained with the rotation modulation collimator detectors (Doxsey *et al.* 1978) between 1978 January 15.1 and 16.7. It was during the latter observation that the celestial location of 4U 0115+63 was measured (Cominsky *et al.* 1978*a*). The timing resolution for all the observations was 0.416 s.

The data from each satellite orbit were folded modulo a trial pulse period of ~3.615 s. The arrival time of an arbitrary fiducial point on the pulse profile was determined by cross-correlating the folded data against a fixed reference pulse template. The pulse template was produced from one orbit of data with particularly good counting statistics. The procedure followed for 4U 0115+63 was very similar to that used for 4U 0900−40 and SMC X-1 (Rappaport, Joss, and McClintock 1976; Primini, Rappaport, and Joss 1977). In all, the arrival times for the fiducial point on 121 pulse profiles were measured during the 26 day interval.

We carried out a least-squares fit of pulse arrival times to a function of the form

$$t_n = t_0 + nP + \tfrac{1}{2}P\dot{P}n^2 + \frac{a_x}{c}\sin i\, F(\theta, e, \omega)\,. \quad (1)$$

Here, $t_n$ is the arrival time of the $n$th pulse, $t_0$ is a constant, $P$ is the intrinsic pulse period, $\dot{P}$ is the rate of change of the intrinsic pulse period, $a_x \sin i$ is the projected semimajor axis of the orbit of the X-ray star, and $i$ is the orbital inclination angle. The quantity $F(\theta,e,\omega)$ is a function representing an orbit with eccentricity $e$, longitude of periastron $\omega$, and mean anomaly

$$\theta = \frac{2\pi}{P_{\mathrm{orb}}}(t - \tau)\,, \quad (2)$$

where $P_{\mathrm{orb}}$ is the orbital period and $\tau$ is the time of periastron passage. The fit has eight free parameters

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($t_0$,$P$,$\dot{P}$,$a_x \sin i$,$e$,$\omega$,$P_{\rm orb}$, and $\tau$); none of these has been determined from previous X-ray or current optical observations. The error analysis for our fitting procedure has been discussed previously (Rappaport, Joss, and McClintock 1975; see also Avni 1976).

We found that the quality of the fit could be substantially improved by including a pulse phase shift between the first part of the observation ($t$ < JD 2,443,530.0) and the second part. This indicates that the pulse period changes during the entire observation were more erratic than can be described by equation (1) with a constant value for $\dot{P}$. We attempted to fit more complex variations in the pulse period (e.g., a term proportional to the second time derivative of $P$ in eq. [1]) but found that the added terms were highly correlated with the orbital parameters and did not improve the fit. We therefore caution that the error bars in Table 1 are *formal* 95% confidence limits and that the systematic uncertainties due to erratic changes in the pulse period may be somewhat larger.

The observed variation in pulse arrival time due to orbital motion is displayed in Figure 1. Also shown on the figure is a curve representing the best-fit eccentric orbit. It is immediately apparent from Figure 1 that 4U 0115+63 is in a long orbit ($P_{\rm orb} \approx 24\overset{d}{.}3$) that is that is moderately eccentric ($e \approx 0.34$). The value of $a_x \sin i$ (~140 lt-s) together with the orbital period yield a mass function of ~5 $M_\odot$. The exact values of the best-fit orbital parameters and their associated uncertainties are given in Table 1. A schematic diagram of the orbit is given in Figure 2.

## III. DISCUSSION

Our results demonstrate that the X-ray star in 4U 0115+63 is a member of a binary stellar system that is wider than any other known X-ray binary. Some evidence has previously been presented that other spectrally "hard" X-ray transients, including the pulsing transients A1118−61 and A0535+26, are members of binary systems (Chevalier and Ilovaisky 1975; Stier and Liller 1976; Rappaport *et al.* 1976). In view of the present results, it now appears almost certain that all of these sources are binaries.

The mean value of the rate of decrease of the pulse period ($\dot{P}$) is consistent with the expected spin-up of a

TABLE 1

PARAMETERS FOR THE 4U 0115+63 BINARY X-RAY SYSTEM*

| | |
|---|---|
| $a_x \sin i$...... | $140.13 \pm 0.16$ lt-s |
| $P_{\rm orb}$......... | $24\overset{d}{.}309 \pm 0\overset{d}{.}021$ |
| $K_x$.......... | $133.65 \pm 0.20$ km s$^{-1}$ |
| $f(M)$........ | $5.007 \pm 0.019$ $M_0$ |
| $e$........... | $0.3402 \pm 0.0004$ |
| $\omega$........... | $47\overset{\circ}{.}66 \pm 0\overset{\circ}{.}17$ |
| $\tau$........... | JD 2,443,540.951 $\pm$ 0.006 |
| $P$†.......... | $3.6145737 \pm 0.0000009$ s |
| $\dot{P}/P$........ | $(-3.2 \pm 0.8) \times 10^{-5}$ yr$^{-1}$ |

* Quoted uncertainties are approximate single-parameter 95% confidence limits.

† The pulse period is referred to an epoch of JD 2,443,521.00.

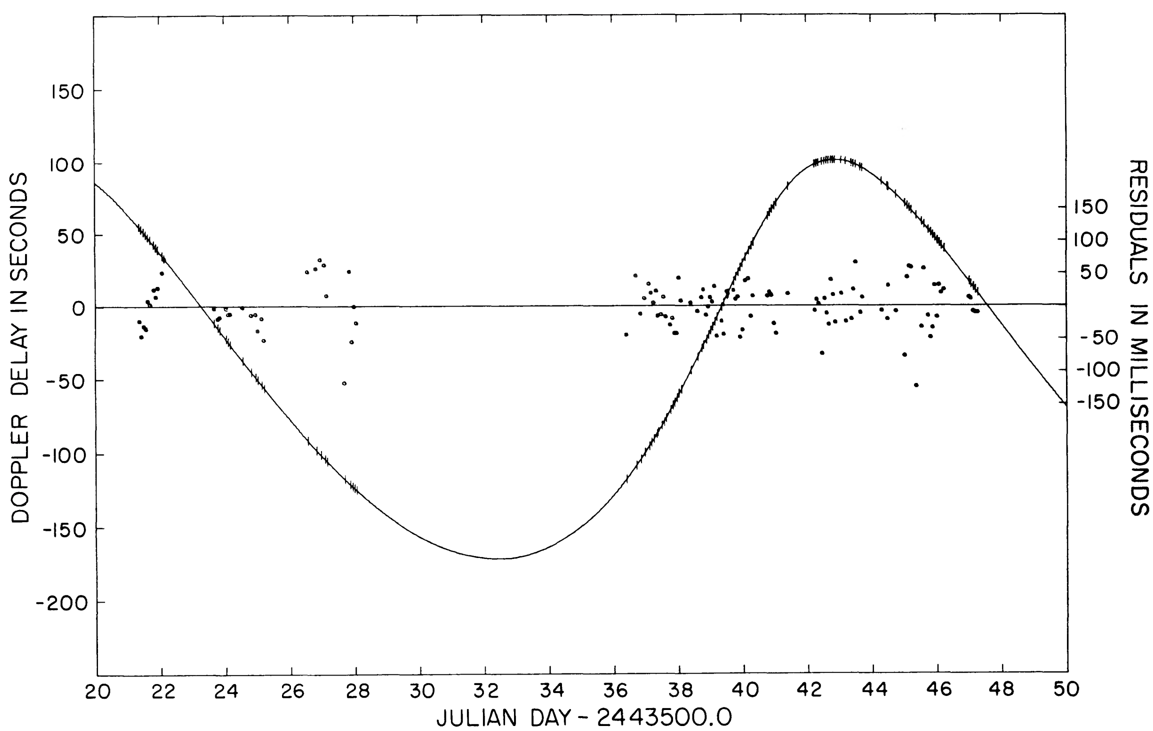


FIG. 1.—Doppler delay data for 4U 0115+63. The vertical bars are the measured delays in pulse arrival time (*left-hand scale*); the length of each bar is considerably larger than the uncertainty in the measurement. The solid curve represents the expected delays for the best-fit orbital parameters given in Table 2. Small open circles (*right-hand scale*) indicate the residual differences between the measured delays and the best-fit curve.

rotating neutron star that is accreting from a disk (Rappaport and Joss 1977, and references therein). The apparent fluctuations in $\dot{P}$ may be related to the secular decline in the source intensity (by a factor of $\sim$5) and in the associated accretion torque on the neutron star during the interval of observation (see Rappaport and Joss 1977). Alternatively, they may result from the character of the viscous coupling between the fluid core and solid crust of the neutron star following the sudden increase in the accretion torque at the start of the outburst (see Lamb, Pines, and Shaham 1978).

The average value of $\dot{P}/P$ during the observation corresponds to an absolute X-ray luminosity of $\sim 2 \times 10^{36}$ ergs$^{-1}$ (see Rappaport and Joss 1977). From the mean X-ray intensity of the source during the observation ($\sim 3 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$), we infer a distance of $\sim$2.5 kpc. This result implies that the B star optical counterpart discovered by Johns *et al.* (1978) has $M_v \sim -1.5$ and is fairly near the main sequence.

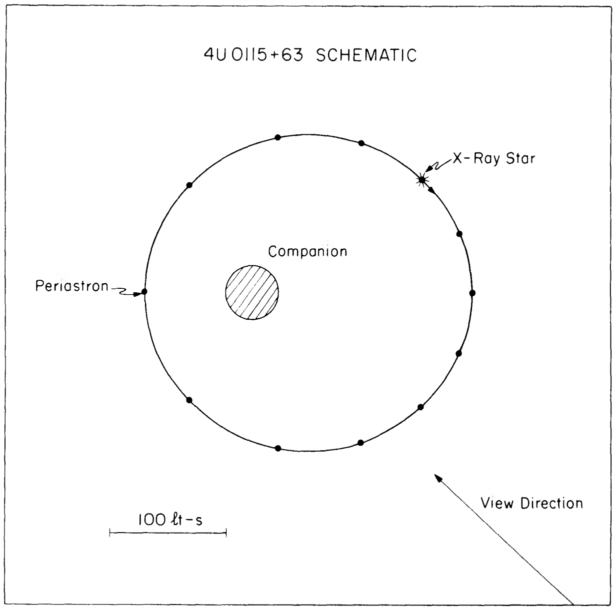


FIG. 2.—Orbital schematic for the 4U 0115+63 binary system. For orbital inclination angles, $i$, less than 90°, the size of the orbit scales as 1/sin $i$. The heavy dots represent the position of the compact X-ray star in increments of 30° in the mean anomaly. The corresponding time interval between these points is 2.0 days. The companion star is placed at the center of mass of the system; its radius is chosen to have an illustrative value of 10 $R_\odot$.

The mass function of 5.0 $M_\odot$ that we obtained implies a companion mass of $\geq 5\ M_\odot$, which is consistent with the mass expected for a main-sequence B star. The inferred radius of the companion ($\sim$5–10 $R_\odot$), together with the large value of $a_x$ sin $i$, predict a small *a priori* probability for eclipses in this system; in fact, the X-ray star is not observed to eclipse at superior conjunction, which occurred near JD 2,443,542.3 (see Fig. 1). We suggest that the companion star is a Be star, as are the proposed counterparts of a few other "hard" X-ray transients (Chevalier and Ilovaisky 1975; Stier and Liller 1976; see also Maraschi, Treves, and van den Heuvel 1976). As discussed below, the mass loss that gives rise to the Be spectral characteristics may be intimately related to the transient nature of these sources.

The present accurate determination of the longitude of periastron ($\pm 5'$) should allow a measurement of the apsidal motion if the source undergoes another outburst in a few years. Most of the apsidal motion will be due to the tidal and/or rotational distortion of the companion star; the general-relativistic contribution should be negligible. Together with refined optical observations, a determination of the apsidal motion would place significant constraints on the radius, rotation rate, and internal structure of the companion.

The object 4U 0115+63 is the sixth X-ray pulsar for which the orbital elements have been determined by measurements of the variations in pulse period or pulse arrival time. The values of the projected semimajor axes ($a_x$ sin $i$) and eccentricities ($e$) of the orbits of these six sources are given in Table 2; 4U 0115+63 has the largest values of both $a_x$ sin $i$ and $e$ among these sources. This finding may lead to an understanding of the transient character of 4U 0115+63 and the other hard X-ray transients.

TABLE 2

ORBITAL PARAMETERS FOR SIX X-RAY BINARIES

| Source | $a_x$ sin $i$* (lt-s) | $P_{orb}$ (d) | $f(M)$ ($M_\odot$) | $e$* | Ref. |
|---|---|---|---|---|---|
| Her X-1......... | 13.19±0.03 | 1.700 | 0.85 | <0.003 | a |
| Cen X-3......... | 39.73±0.03 | 2.087 | 15.5 | 0.0008±0.0002 | b |
| 4U 1538−52..... | 55.2 ±7 | 3.730 | 13 | ... | c |
| SMC X-1....... | 53.46±0.05 | 3.892 | 10.8 | <0.0007 | d |
| 4U 0900−40..... | 111.40±3.3 | 8.966 | 18.5 | 0.13±0.04 | e |
| 4U 0115+63..... | 140.13±0.2 | 24.31 | 5.00 | 0.3402±0.0004 | f |

* Wherever possible, we have given 95% confidence limits for the error bars.
[a] Tananbaum *et al.* 1972; Schreier and Fabbiano 1976; Fechner and Joss 1977.
[b] Schreier *et al.* 1972; Schreier and Fabbiano 1977.
[c] Becker *et al.* 1977; Davison, Watson, and Pye 1977.
[d] Primini, Rappaport, and Joss 1977.
[e] Rappaport, Joss, and McClintock 1976.
[f] Present *Letter*.

Among the other five X-ray pulsars with measured orbits, one (Her X-1) is believed to be undergoing accretion by critical-lobe overflow of a late-type companion star (Tananbaum *et al.* 1972). Each of the remaining four (Cen X-3 4U 0900−40, SMC X-1, and 4U 1538−52) is thought to be accreting from a stellar wind, the strength of which may be enhanced by the proximity of an early-type companion to its critical potential lobe (Basko *et al.* 1977; Avni 1978; Conti 1978; Ziolkowski 1977).

In the case of 4U 0115+63, the relatively large value of $a_x \sin i$ would require an extremely large mean radius of the companion ($R \gtrsim 30\ R_{\odot}$) to allow critical-lobe overflow, even at periastron. Such a large radius appears to be excluded by the observations of the optical counterpart (Johns *et al.* 1978) and the distance estimate given above, which together indicate that $R \lesssim 10\ R_{\odot}$. Thus, the companion apparently underfills its critical lobe by a wide margin at all times.

We suggest that the large value of $e$ is not a direct cause of the intermittent character of the mass transfer, but rather that both the eccentricity and the transient character of the source result from the large orbital separation. The circularization time scale of a close binary due to tidal dissipation is proportional to $(R/D)^{-5}$, where $R$ is the mean radius of the companion and $D$ is the mean orbital separation (Lecar, Wheeler, and McKee 1976, and references therein). This time scale could well be $10^3$ times larger for the 4U 0115+63 system than for any of the other binaries listed in Table 2. Moreover, due to the large orbital separation, the mass-transfer rate may be low except during episodes of enhanced spontaneous mass loss from the companion. In this picture, the intervals between outbursts are governed by the intervals between the active episodes of the companion, and the mass transfer may occur along any portion of the orbit. The outburst lasts as long as the enhanced activity of the companion and the subsequent exhaustion of material that may become stored in an accretion disk. The value of $a_x \sin i$ for 4U 0115+63 is so large, compared to the probable size of the companion, that the mass-transfer rate is probably not substantially enhanced at periastron.

To summarize: We believe that the nature of the hard X-ray transients is revealed in the properties of 4U 0115+63. They are collapsed stars (perhaps all neutron stars) in binary systems that are substantially wider than the more persistent X-ray binaries. The large orbital separation and/or the small radius of the companion star result in episodic, rather than continuous, mass transfer onto the X-ray star.

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