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POSITION AND PULSE PROFILE OF THE X-RAY TRANSIENT 4U 0115+63

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ABSTRACT

The celestial position of the 3.6 s X-ray pulsar, 4U 0115+63, has been measured to a precision of 12″ in one dimension with the scanning modulation collimator experiment on *HEAO 1*. This result, together with a position obtained with *SAS 3*, has led to the identification of an early-type star as the optical counterpart. We infer an X-ray luminosity of $\sim 3 \times 10^{37}$ ergs s^{-1} (3–13 keV) from our observed flux of about 30% that of the Crab and an estimated distance of 5 kpc. The pulse profile over the energy range 3–13 keV is similar to that of Cen X-3.

Subject headings: pulsars — X-rays: sources

I. INTRODUCTION

The transient X-ray source 4U 0115+63, first observed with the *Uhuru* satellite in 1971 January (Forman, Jones, and Tananbaum 1976), again entered a bright state in 1978 early January. This event was detected independently with *SAS 3* (Cominsky *et al.* 1978*a*) and the *Ariel 5* All-Sky Monitor (Holt and Kaluzienski 1978). The *SAS 3* observation showed that the source is pulsing with a period of 3.6 s and yielded a celestial position precise to 30″. On 1978 January 16 (1300 UT), the $+Y$ axis detectors of the *HEAO 1* satellite were pointed at the source for $\sim$3 hours. We present here an improved position for the source, accurate in one dimension to $\sim$12″, and also the pulse profile in three energy bands. The data were obtained with the scanning modulation collimator experiment on *HEAO* 1 (Gursky *et al.* 1978; Schwartz *et al.* 1978).

II. OBSERVATIONS AND RESULTS

The detection system consists of two four-grid modulation collimators of FWHM 30″ (MC1) and 120″ (MC2), with fields of view limited by square coarse collimators of $4° \times 4°$ FWHM. The modulation collimators are oriented so that the celestial lines of position from MC1 are inclined 20° to those of MC2. The instantaneous orientation of the instrument is determined from star-tracker and gyro data.

During the present pointed observation, the drifts in the spacecraft orientation about the mean pointing direction (by $\pm 0\overset{\circ}{.}5$ at typical rates of 1″–20″ s^{-1}) caused the source to repeatedly cross the modulation collimator planes of maximum transmission. There were 145 and 35 crossings of duration 4–15 s and 12–60 s in MC1 and MC2, respectively, during the 75 minutes of data presently available for analysis. The 3.6 s pulsations are clearly visible in the data.

Celestial lines of position were determined from the portion of the observation (19 minutes) for which star-tracker data were available. The data from each collimator were superposed modulo the collimator periodicity, yielding 1.7×10^4 source counts and 5.5×10^3 background counts during the source transits. Each set of data yields multiple lines of position which, in turn, define multiple intersections on the sky. Only one of these intersections falls within the $3' \times 5'$ *Uhuru* error region (Forman *et al.* 1978). This intersection also falls within the 30″ radius *SAS 3* error circle.

The celestial position we obtain for 4U 0115+63 is $\alpha(1950) = 1^h15^m13\overset{s}{.}7$, $\delta(1950) = 63°28'40''$. The corners of the error region, given by the intersection of the 90% confidence lines of position, are $\alpha = 1^h15^m10\overset{s}{.}9$, $\delta = 63°29'47''$; $\alpha = 1^h15^m15\overset{s}{.}0$, $\delta = 63°28'53''$; $\alpha = 1^h15^m16\overset{s}{.}6$, $\delta = 63°27'33''$; $\alpha = 1^h15^m12\overset{s}{.}4$, $\delta = 63°28'28''$. The 90% confidence interval includes contributions from photon-counting statistics as well as systematic errors in the aspect determination and collimator alignment. The latter are based on previous observations of Sco X-1, and have been verified on identified sources during both scanning and pointed observations. An additional small systematic error has been included due to a 7° C decrease in the temperature of the instrument prior to the present observation. Ground calibrations show that the relative alignment of the collimators and the star-trackers changes by less than 3″ over this temperature range. A pointed observation of GX 301−2/WRA 977 on 1978 January 25 showed no detectable change in the alignment.

A finding chart taken from POSS E (red) print (Fig. 1, Pl. L4) shows the *HEAO 1* and *SAS 3* error regions (90% confidence). The blue print is reproduced by Cominsky *et al.* (1978*a*). One relatively bright star (star 1) lies within both the *SAS 3* and *HEAO 1* error regions. Astrometry to $\sim$2″ yields a position for this star of $\alpha = 1^h15^m13\overset{s}{.}8$, $\delta = 63°28'38''$ (1950.0). We measure the magnitude from the image diameters on the POSS prints (King and Raff 1977) to be $m_v \approx 15.2 \pm 0.5$. This star has subsequently been identified as the optical counterpart (Johns *et al.* 1978) on the basis of Hα emission in its spectrum. Optical observations are consistent with a B-type star with about 5 mag of visual extinction. To be within the Galaxy ($d \lesssim 7$ kpc in the direction $l^{II} = 126°$), the absolute magnitude

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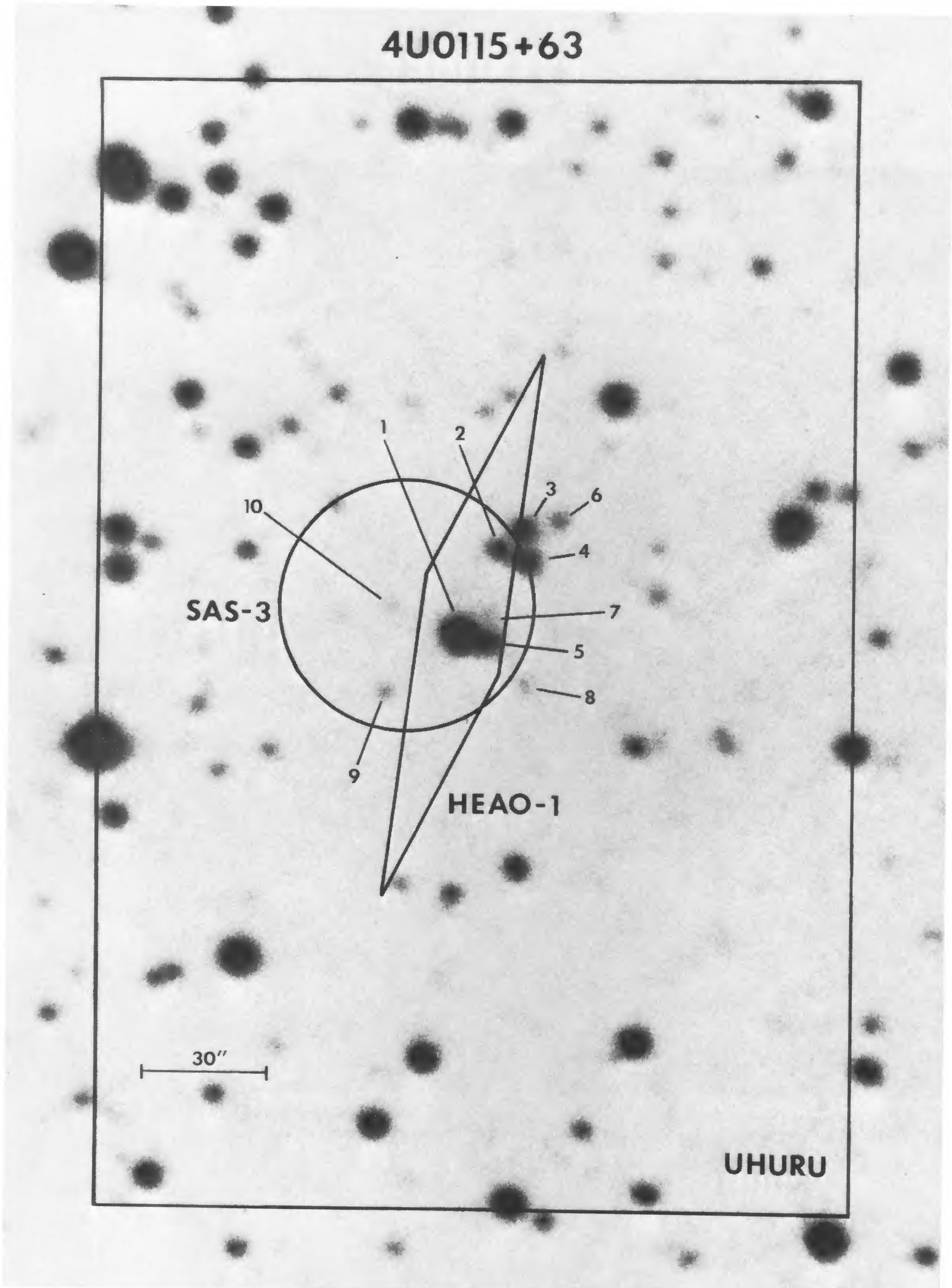

FIG. 1.—Finding chart for 4U 0115+63 taken from the POSS E (red) print (©)National Geographic Society) showing the *Uhuru* (Forman *et al.* 1978), *SAS 3* (Cominsky *et al.* 1978*a*), and *HEAO 1* error regions (90% confidence).

JOHNSTON *et al.* (*see* page L71)

must be $M_v \gtrsim -4$. This is consistent with a main-sequence or giant B-type star, but not a supergiant. To account for the observed extinction we estimate a distance of at least 5 kpc, placing the star $\sim$100 pc from the galactic plane. At 5 kpc, the observed X-ray luminosity was 3×10^{37} ergs s^{-1} (3–13 keV). We estimate a low-energy cutoff of at least 1.5 keV on the basis of the relation between visual extinction and X-ray absorption (Gorenstein 1975; Ryter, Cesarsky, and Audouze 1975).

Detailed pulse shapes (Fig. 2) were obtained from the MC2 data folded modulo the precise *SAS 3* pulse period for January 16 (3.61355 s; Rappaport 1978). We used only those data accumulated when the collimator transmission exceeded 10% of its maximum value (6.6×10^4 source and 1.9×10^4 background counts in 1100 s). The MC2 counts, telemetered every 160 ms, were folded into 30 time bins, each of duration 120 ms. The combined modulation and coarse collimator response was also binned to determine the correction to the pulse shape caused by the variable transmission during the individual transits. The variation in this correction factor from the average is no more than 1% for any bin. The pulse profiles in Figure 2 have had background subtracted and have been corrected for the collimator response.

The 0.9–13.3 keV profile (Fig. 2*d*) exhibits a single

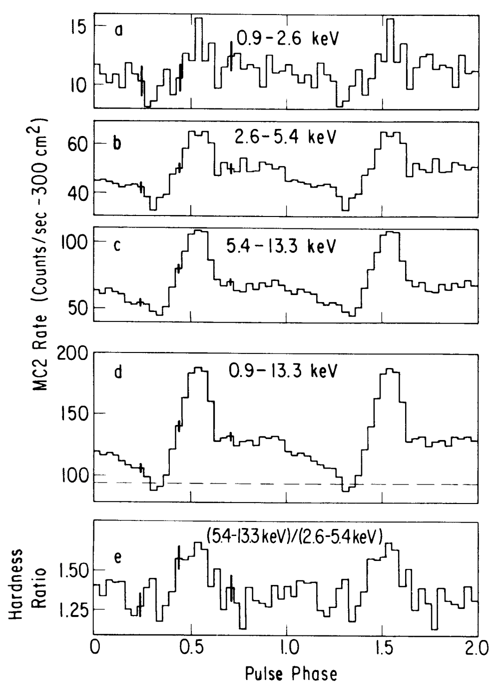

FIG. 2.—Pulse profiles for 4U 0115+63 after background subtraction and correction for the 120″ and 4° × 4° FWHM collimator responses. The vertical scale is adjusted to suppress the steady flux. The data, telemetered every 160 ms, are folded into 30 bins of duration 120 ms. Two cycles of the folding period (3.61355 s; Rappaport 1978) are shown. The dashed line in (*d*) indicates the steady count rate (94 counts s^{-1}) used to calculate the pulse fraction. The ratio of the 5.4–13.3 keV to the 2.6–5.4 keV flux is shown in (*e*). Note the increase in hardness during the pulse maximum. Typical 1 σ errors are shown.

sharp maximum, more than doubling in intensity in 0.72 s. It decays rapidly to two-thirds of maximum in 0.36 s and more slowly to a narrow minimum. We have divided the data into three segments, each of duration $\sim$25 minutes, and find no evidence for variability of the pulse shape. Finally, we note a hardening of the spectrum above 2.6 keV at the peak of the pulse (Fig. 2*e*).

The pulsed fraction of the total (0.9–13.3 keV) flux is 27% ± 2%. We define the pulsed fraction to be (total rate–steady rate)/(total rate), and take the steady rate to be the average over the 360 ms before the pulse begins to rise. The pulsed fraction for each energy channel is given in Table 1. There appears to be an increased pulsed fraction at higher energy.

Compared with other pulsars (cf. Rappaport and Joss 1977), the pulse shape of 4U 0115+63 is remarkably similar to that of Cen X-3 (Ulmer 1976). We note that among the known X-ray pulsars, the period of Cen X-3 (4.8 s) is the closest to that of 4U 0115+63 (3.6 s). Spectral hardening near pulse maximum has been reported for both Cen X-3 (Ulmer 1976) and Her X-1 (Pravdo *et al.* 1977).

The energy spectrum of the source is extremely hard. The MC2 count rates, relative to the Crab, are 0.09 ± 0.02, 0.23 ± 0.03, and 0.64 ± 0.10 for the 0.9–2.6, 2.6–5.4, and 5.4–13.3 keV energy bands, respectively. We have attempted to fit both power-law and thermal bremsstrahlung energy spectra, with interstellar cutoff terms, to the time-averaged data. The spectrum is so hard that the optically thin thermal bremsstrahlung model is inappropriate. The power-law fit yields an energy spectrum rising with energy: $\alpha = -0.4 \pm 0.3$, where we include possible systematic errors. Jones (1977) obtained $\alpha = -0.1 \pm 0.2$ and a low-energy cutoff of 2.7 ± 0.7 keV from the 1971 *Uhuru* data. The spectral hardening during the 30% of the pulse centered on the pulse maximum (Fig. 2*e*) amounts to $\Delta\alpha = -0.18 \pm 0.05$.

III. DISCUSSION

Galactic X-ray transients have been discussed by a number of authors (e.g., Pringle 1976; Avni, Fabian, and Pringle 1976; Kaluzienski *et al.* 1977; Cominsky *et al.* 1978*b*). In spite of dissimilarities, transients may be divided into two classes based on spectral hardness (Maraschi *et al.* 1976; Kaluzienski *et al.* 1977; Cominsky *et al.* 1978*b*). X-ray pulsations have been observed only from two members of the high-temperature class ($kT >$

TABLE 1

PULSED FRACTION ON 1978 JANUARY 16

Energy Band	Pulsed Fraction
0.9–2.6 keV........	12% ± 7%*
2.6–5.4 keV........	25% ± 2%
5.4–13.3 keV.......	30% ± 2%
Average (0.9–13.3 keV)........	27% ± 2%

* The error is not Gaussian: the probability of zero pulsed fraction in this channel is less than 0.1%.

15 keV): A0535+26 (Rosenberg *et al.* 1975; Bradt *et al.* 1976) and A1118−61 (Eyles *et al.* 1975; Ives, Sanford, and Bell Burnell 1975), which have pulse periods of 104 s and 405 s, respectively. Except for the transient nature of their outbursts, these sources appear to be similar to persistent pulsing sources known to be in binary systems (Coe *et al.* 1975; Avni, Fabian, and Pringle 1976; Jones 1977; Kaluzienski *et al.* 1977; Rappaport and Joss 1977).

Several models have been proposed for these systems which involve an early-type star in a binary system with a rapidly spinning neutron star. The accreting material can be supplied by the stellar wind of a massive early-type star (possibly excited by X-rays from the neutron star; Basko *et al.* 1977), or by material ejected by a rapidly spinning Be star (Maraschi, Treves, and van den Heuvel 1976). The pulsing transients A0535+26 and A1118−61 have both been tentatively identified with Be stars (Chevalier and Ilovaisky 1975; Stier and Liller 1976). The persistent pulsing sources SMC X-1 and Cen X-3, which have hard spectra and irregular, extended high and low states, have been identified with massive post–main-sequence stars (Webster *et al.* 1972; Liller 1972; Krzeminski 1974).

The transition from a low to a high state might be caused by instabilities in the matter surrounding a rotating Be star, an increase in a stellar wind (see, e.g., Pringle 1976), or instabilities in an accretion disk (Amnuel and Guseinov 1976). Alternatively, a transition could arise when X-rays from the neutron star sufficiently ionize a surrounding dense cloud of accreting material which up till then has smothered the X-ray emission (Pringle 1973; McCray 1975; Schreier *et al.* 1976).

Current optical and X-ray observations do not yet exclude any of the above possibilities. The only known high-temperature, pulsing transients are A0535+26, A1118−61, and 4U 0115+63. The data so far have been inadequate for determining unique orbits for the former two sources (Rappaport *et al.* 1976; Ives, Sanford, and Bell Burnell 1975). The mass function (5 $M_\odot$) and orbital period (24^d) of 4U 0115+63 have already been determined from recent *SAS 3* observations (Rappaport *et al.* 1978). Further understanding of the 4U 0115+63 system must await classification of the optical counterpart and a determination of the optical mass function.

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