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STUDIES OF THE AVERAGE PULSE SHAPE OF CENTAURUS X-3 IN THE 2–20 keV RANGE

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ABSTRACT

We report an analysis of the average pulse shape of Cen X-3 versus energy (2–20 keV) on time scales of hours to days derived from *Uhuru* observations during 1971 May 5–7 and 1971 December 18–20. The pulsed fraction varied with energy from 0.42 ± 0.02 to 0.80 ± 0.10 over the 2–20 keV range. The 2–6 keV pulsed fraction did not show statistically significant variations ($>2\ \sigma$) over the phase of the 2.087 day eclipse cycle. Individual measurements of the 2–6 keV pulsed fraction ranged from 0.45–0.56.

Subject heading: X-rays: sources

I. INTRODUCTION

We report here observations made with the *Uhuru* satellite of the energy and temporal dependence of the average pulse shape of the binary X-ray source Cen X-3. We have examined data from two full 2.087 day orbital cycles of the X-ray source. Extensive studies of the average or individual pulse shapes are being continued, and they are in part reported in Schreier *et al.* 1975. Our study of the pulse shape versus energy improves upon and extends previous measurements of Ulmer *et al.* 1974 and Long *et al.* 1975. These studies are of interest because of predictions about the energy dependence of the pulsations (e.g., Davidson 1973) or because of the possible existence of a weak, nonpulsed flux (Schreier *et al.* 1975; Giacconi 1974*a*). Also, as observed in Her X-1 (Giacconi 1974*a*; Joss 1974), we might expect changes in the average pulse shapes.

II. OBSERVATIONS AND RESULTS

We analyzed data accumulated during 1971 May 5–7 and 1971 December 18–20, concentrating on the May observations which were optimized for studying the pulsations. We then verified that the December data gave consistent results. In both cases, data recorded during the time of X-ray eclipse (see Schreier *et al.* 1972) were excluded from the analysis. The May observations were made with the satellite spinning at $\sim 0^\circ.1$ per second. This yielded about eight 4.8 s pulses during one sighting of the source in the 5° full width at half-maximum (FWHM) collimator. These pulses were folded modulo the pulsation period ($2\pi/\omega$) derived from the best fit to the data with the function

$$F = B + R\Delta[A_0 \sin(\omega t + \theta_1) + A_1 \sin(2\omega t + \theta_2) + A_2 \sin(3\omega t + \theta_3) + C]$$

(see Giacconi *et al.* 1971).

We computed the pulsed fraction for the 2–6 keV pulses averaged over each 40 s sighting of Cen X-3, and found no statistically significant ($>2\ \sigma$) variation over the 2.087 day eclipse cycle. The pulsed fraction values ranged from 0.45–0.56. These are lower than the 0.80–0.90 values reported by Schreier *et al.* 1972, because of variations in the pulse shape (cf. Ulmer *et al.* 1974). The shape of single pulses could not always be fitted by the "grand average" pulse shape discussed below, but we found no systematic variations in the pulse shape. Therefore, we present and discuss only average pulse shapes.

We combined the 40 s sighting average pulse shapes into a "grand average" pulse shape shown in Figure 1. Uncertainties in defining the 0.0 phase of the 4.8 s cycle resulted in a smearing of the "grand average" pulse by $\leqslant 0.24$ s. Along with this pulse shape in Figure 1, we show the spectral index (α) from a minimum χ^2 fit to $F = AE^{-\alpha} \exp[-(E/1.2)^{8/3}]$ keV/keV-s-cm^2 to the spectral data. We fixed the cutoff E_a at 1.2 keV (best fit for average spectrum given below), since E_a did not show any statistically significant ($>1.5\ \sigma$) variations in the range 2.2–1 keV. We used the 2–12 keV flux to determine the spectral index shown in Figure 1, because we could not find a good fit to the 2–20 keV flux with either a simple power law or exponential model ($\chi^2 > 20$, 4 degrees of freedom). We also show the "grand average" pulse versus energy in Figure 2. The "pulsed fraction," defined as (average flux–minimum flux)/(average flux), varied between 0.42 ± 0.02 and 0.80 ± 0.01 from the lowest to the highest energy channel.

The Cen X-3 spectrum derived from averaging all the May data was

$$F = AE^{+0.06 \pm 0.12} \exp[-(E/1.2 \pm 0.4)^{8/3}] \text{ keV} \quad (\text{keV-cm}^2\text{-s})^{-1}$$

in the 2–12 keV range ($\chi^2 = 0.5$, 2 degrees of freedom) and $\alpha \geqslant 3$ in the 12–20 keV range. Following Margon *et al.* 1975*a*, we used $\chi^2_{\min} + 3.5$ as the criterion for the 1 σ uncertainties when using three parameters and

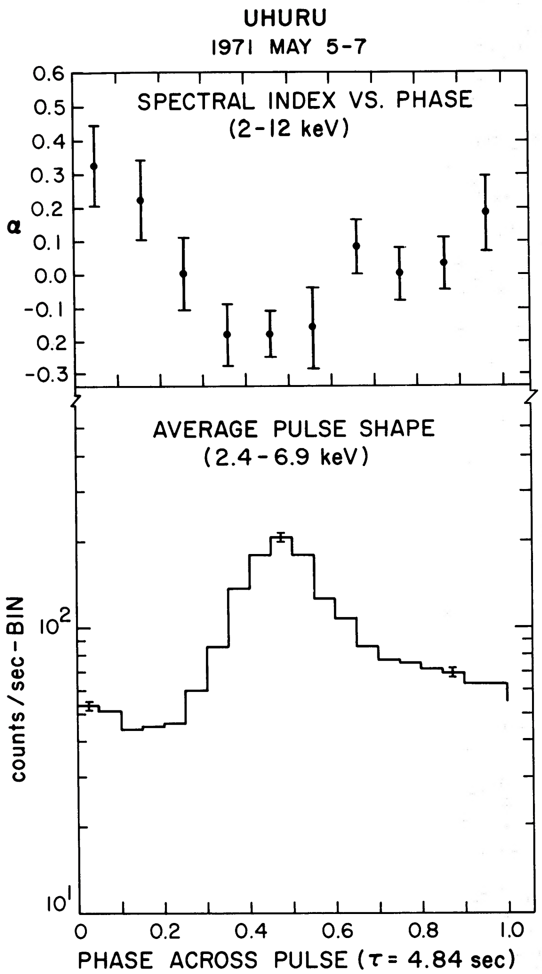

FIG. 1.—The "grand average" pulse shape of Cen X-3 and spectral index versus phase derived by fitting a power law to the 2–12 keV flux (see text). Earlier preliminary versions of this figure were given by Giacconi 1974*b* (2–20 keV data were fitted, spectral indices were averaged rather than the pulse being averaged and then fitting spectra, and the $\chi^2_{min} + 1$ criterion was used to determine the error bars) and Giacconi 1974*a* (the fixed value of E_a chosen was not that corresponding to the best fit value to the average spectrum).

$\chi^2_{min} + 2.3$ when using two parameters. Estimates of uncertainties in spectral fits corresponding to $\chi^2_{min} + 1$ or the 90 percent confidence level (as defined by Margon *et al.* 1975*a*) can be estimated for the data here by multiplying the quoted uncertainties by 0.5 and 1.3, respectively.

Except for the lowest energy channel (1.8–2.2 keV) the pulsed fractions derived from the 1971 December data were consistent with the 1971 May observations. In the 1.8–2.2 keV channel there was either contamination from a nearby X-ray source (see § III) or there was a low-temperature component present in the Cen X-3 spectrum giving rise to a 50 percent increase in flux in the 1.8–2.4 keV range (see Bleeker *et al.* 1973; conversely see Margon *et al.* 1975; Long *et al.* 1975) above the extrapolation of the best fit (in the 2.4–10 keV range) power-law spectrum

$$F = AE^{-0.07\pm0.14} \exp\,[-(E/1.1 \pm 1.0)]\ \text{keV}\ (\text{keV-cm}^2\text{-s})^{-1}.$$

III. DISCUSSION

The region of the sky near Cen X-3 contains 3U 1134−61, 3U 1145−61 (Giacconi *et al.* 1974), and A1118−61 (Eyles *et al.* 1975). These might have contributed to the nonpulsed portion of the flux we attributed to Cen X-3. All the sources but A1118−61 could be avoided by choosing portions of the scans of Cen X-3 2°–3° away from them. As for A1118−61, it has always been weak (Ives *et al.* 1975). Thus the contamination from any of these X-ray sources was probably less than 10 percent of the flux attributed to Cen X-3. Direct observational limits are 20 percent of the Cen X-3 flux.

For simplicity, we ignore the lowest energy 1971 December data and assume there was no contamination of the Cen X-3 flux by other X-ray sources. Then we can explain that a flux is always present throughout the 4.8 s cycle in at least three ways: (1) Cen X-3 has a steady nonpulsed component; (2) a portion of the X-ray beam from the rotating neutron star (cf. Davidson and Ostriker 1972) is always in our field of view; (3) some X-rays are always being scattered into our line of sight, even when the beam does not directly point at us. From the data in Figures 1 and 2, we see that, if (1) applies, the nonpulsed component has a softer spectrum than the pulse; if (2) applies, the X-ray beam is wider at lower energies; and if (3) applies, the lower energy photons must be preferentially scattered into our line of sight. Studies by Schreier *et al.* 1975 suggest the existence of a nonpulsed component, but direct or scattered flux from an X-ray beam cannot be ruled out, and as long as there is mass transfer in the system there must be some scattering of the Cen X-3 beamed X-ray flux (cf. Strittmatter 1974).

Changes in the average pulse shape during the 35 day ON-OFF cycle of Her X-1 have been observed (Joss 1974; Giacconi 1974*a*). Our 2 day observations of Cen X-3 were too short to detect similar variations if they exist. The work of Schreier *et al.* 1975 indicates that changes in pulse shape do occur, however, at times of transition between intensity states.

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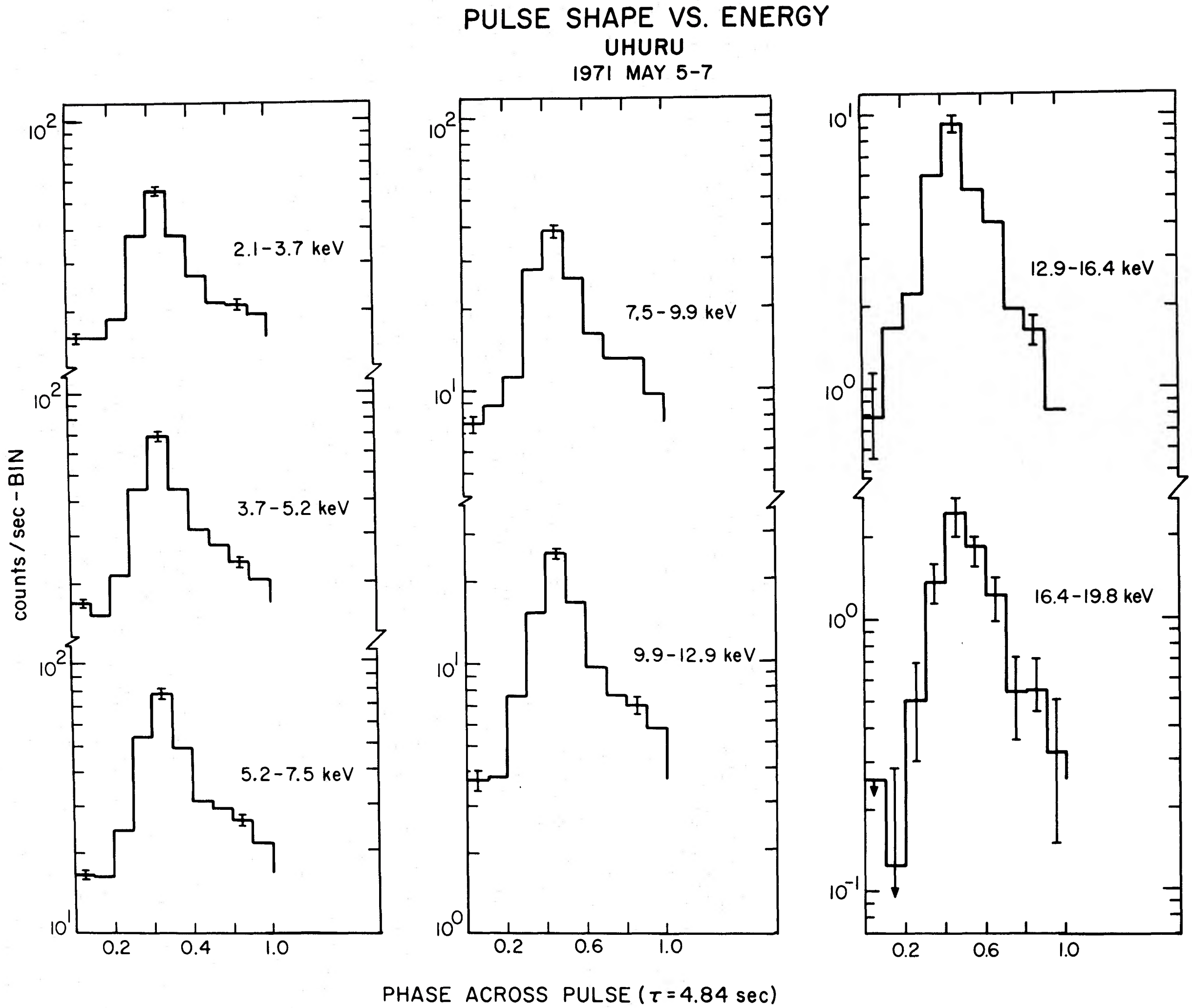

FIG. 2.—The "grand average" pulse shape of Cen X-3 shown as a function of energy

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