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X-ray observations of Circinus X-1 in its low state

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Summary. *Ariel V* experiment C repeatedly observed Cir X-1 in the low-intensity portion of its 16.6-day light curve. The spectrum of the source is found to be a power law with photon spectral index ~ 2.3–3.0 and hydrogen column density $N_\mathrm{H} \sim 10^{22}\,\mathrm{cm}^{-2}$. A weak iron feature may be present. The observation of such a low column density for the low-intensity state runs counter to previous assumptions; the significance of this observation for the current model of the source, in which the modulation is explained by absorption of X-rays in the primary's stellar wind, is discussed. A spectrum of 4U1510 – 59, in the same field as Cir X-1, is also reported.

1 Introduction

Circinus X-1 was discovered by Margon *et al.* (1971), although it is possible that the source had been previously detected (MacGregor, Seward & Turiel 1970; Harries *et al.* 1971). A point radio source associated with Cir X-1 was discovered by Clark, Parkinson & Caswell (1975), who suggested the system to be a runaway, high-eccentricity binary ejected from the nearby supernova remnant G321.9 – 0.3, a few arcmin to the south. The identification of a highly reddened 20-mag star as the optical counterpart is due to Whelan *et al.* (1977). Discovery of a common 16.6-day periodicity in the X-ray (Kaluzienski *et al.* 1976), radio (Whelan *et al.* 1977) and infrared fluxes (Glass 1978) secured the identification.

A black hole candidacy has been suggested on the basis of the detection of millisecond X-ray bursts (Toor 1977). The general similarity of the short-term temporal behaviour of Cir X-1 and Cyg X-1 (the latter being the only well-established black hole candidate, e.g. Oda 1977) has also been noted (Jones *et al.* 1974; Buff *et al.* 1977; Sadeh *et al.* 1979) although, in the absence of a determination of the mass function of the system, the argument is not conclusive.

The X-ray light curve is highly asymmetric (Kaluzienski *et al.* 1976; Wilson & Carpenter 1976; Buff *et al.* 1977; Bignami *et al.* 1977), and is characterized by a sharp drop marking phase 0. This is followed by the abrupt onset of a flare in the radio and infrared bands. The radio flare generally has a double-peaked structure (Thomas *et al.* 1978; Haynes *et al.* 1978). The current model for Cir X-1 (Haynes *et al.* 1979; Murdin *et al.* 1980; Haynes, Lerche & Murdin 1980) consists of a compact companion orbiting a massive supergiant. The asymmetric light curve is explained by a highly eccentric orbit with consequent modulation of both the mass transfer rate and the absorption of the low-energy X-rays in the stellar wind.

Mention of 'extended lows' (e.g. Kaluzienski *et al.* 1975, 1976; Baity, Ulmer & Peterson 1975) occur in the literature prior to the discovery of the periodicity, but they could possibly be explained by insufficient phase coverage. We examined a comprehensive list of published observations (at energies $< 20\,\mathrm{keV}$) and found no conflict between the observations and an explanation of the variations as due only to the 16.6-day periodic modulation. The peak value of the light curve could nevertheless be highly variable (as observed, for example, by Kaluzienski *et al.* 1976).

2 Observations and results

Circinus X-1 was observed five times by MSSLs proportional-counter spectrometer (experiment C) on *Ariel V*; the observations were distributed between quadrant and multiscaler modes. A journal of quadrant-mode observations is given in Table 1. In quadrant mode the time resolution is one orbit of the satellite (~ 100 min), but 31 channels of spectral information are available. The energy range at launch was 1.5–15 keV in high gain and 3–30 keV in low gain, and drifted to 0.6 of these values by the end of the observations reported here. In multiscaler mode, counts are collected in 64-s bins, with no spectral information. A fuller description of experiment C and its mode of operation is given by Sanford & Ives (1976). Observations where the satellite pointing was such that Cir X-1 was seriously confused by 4U 1556 – 60 and 1543 – 62 have been discarded, as have observations at the time of a flare, possibly of A 1542 – 62, in 1975 February.

The source 4U 1510 – 59, only 1°.5 to the SW of Cir X-1, is always in the field of view. Its intensity in the *Uhuru* catalogue is six *Uhuru* counts although *Copernicus* observations (Zarnecki *et al.* 1975) put a (point source) upper limit on its flux of ~ 4 *Uhuru* counts. When Cir X-1 is in the centre of the field of view of experiment C, it is seen equally in all four quadrants and its contribution to the signal is therefore removed along with that of the background. Observations made in this way have permitted an independent determination of the spectrum of 4U 1510 – 59, shown in Fig. 1(c); we estimate the flux of the source at the time of our observations to be ~ 5 *Uhuru* counts. 4U 1510 – 59 is a point source within the boundary of the SNR MSH 15 – 5$\underline{2}$, probably associated with it (Murdin 1982, private communication). The hard spectrum observed (Fig. 1c) is consistent with it being a compact source.

All sets of observations of Cir X-1 correspond to phases of low flux, with the exception of the 1977 April multiscaler observations. The two sets of observations taken during 1976 February (day numbers 36.7–45.4 and 51.1–53.4) correspond to the two major gaps in the ASM observations of Kaluzienski *et al.* (1976). The first set is simultaneous with the RMC (Wilson & Carpenter 1976) and ST observations (Coe, Engel & Quenby 1976). The second one follows immediately after a transition reported by Kaluzienski *et al.* (1976).

Discrimination against confusion by other sources is difficult for multiscaler-mode observations, but analysis of observations made in this mode on adjacent and overlapping fields of view indicate that the signal is predominantly that of Cir X-1. By folding the data at a trial period and determining χ^2 against the hypothesis of constant flux, the data have been searched for periods up to 100 min. No significant periods were found. Within each

Table 1. Journal of observations and summary of results. (A line feature is included in the spectral fits where shown.)

Mid-time of observations (UT days)	Phase+	Normalization factor	Photon spectral index	Hydrogen column density (10^{22} cm^{-2})	Red. χ^2		Integral flux (10^{-2} ph cm^{-2} s^{-1}) in§ selected bands (energies in keV) 2-4	4-5	5-8	8-10	2-10
40.7 1975	.41	.96±.61	2.6±.4	2.5±1.9	1.5		5.9±.5	1.7±.2	1.6±.3	<.8	9.6±.6
41.3 1975	.47	.31±.07	2.3±.2	*	1.0		2.2±.1	.7±.1	.3±.1	.4±.1	4.0±.2
37.1 1976	.22	.64±.07	2.2±.1	(0.5)	.7		12.0±.5	2.8±.3	3.9±.3	1.2±.3	19.9±.7
36.7 1976	.20	1.36±.15	2.6±.1	1.9±.9	.7		-	-	-	-	-
39.0 1976	.34	.77±.06 .33±.02	3.3±.1 2.7±.1	(1.0) *	1.3 2.4	a	4.0±.1	.5±.1	.7±.1	.2±.1	5.5±.10
40.1 1976	.40	.71±.07 .35±.03	3.3±1. 2.8±.1	(1.0) *	2.0 2.8	b	3.2±.1	.4±.1	.7±.1	.2±.1	4.4±.1
41.1 1976	.46	.87±.33 .26±.02	3.4±.3 2.5±.1	1.6±.6 *	.8 1.2	c	3.7±.1	.5±.1	.8±.1	.3±.1	5.3±.2
42.0 1976	.52	.20±.17	2.0±.4	.4±1.9	1.1		3.0±.2	.6±.1	1.3±.2	<.4	5.2±.3
45.0 1976	.70	.17±.02	1.8±.1	1.6±.5	1.0		3.2±.3	.8±.1	1.9±.2	<.5	6.1±.3
51.3 1976	.08	.55±.12	3.1±.2	*	1.9		4.4±.2	<.4	<.5	<.5	4.6±.3
52.5 1976	.15	.57±.10 .30±.04	3.1±.2 2.7±.1	(1.0) *	1.9 2.1	d	2.9±.1	.4±.1	.7±.1	<.2	4.1±.1
248.2 1976	.98	.23±.08	2.3±.2	.9±.9	.6		2.7±.1	.6±.1	.8±.1	.3±.1	4.4±.1
250.1 1976	.11	.31±.09	2.2±.2	.7±.8	.9		4.4±.2	1.0±.1	1.6±.1	.4±.1	7.3±.2

+ Phase is computed according to the ephemeris of Kaluzienski and Holt (1977).

* N_H could not be determined from the fit.

§ from direct deconvolution; upper limits are 3 sigma

a + line at 7.44 ± .19 keV, intensity .21±.05x10^{-2} cts cm^{-2} s^{-1}

b + line at 7.27 ± .27 keV, intensity .19±.06x10^{-2} cts cm^{-2} s^{-1}

c + line at 6.66 ± .38 keV, intensity .27±.16x10^{-2} cts cm^{-2} s^{-1}

d + line at 7.03 ± .38 keV, intensity .18±.10x10^{-2} cts cm^{-2} s^{-1}

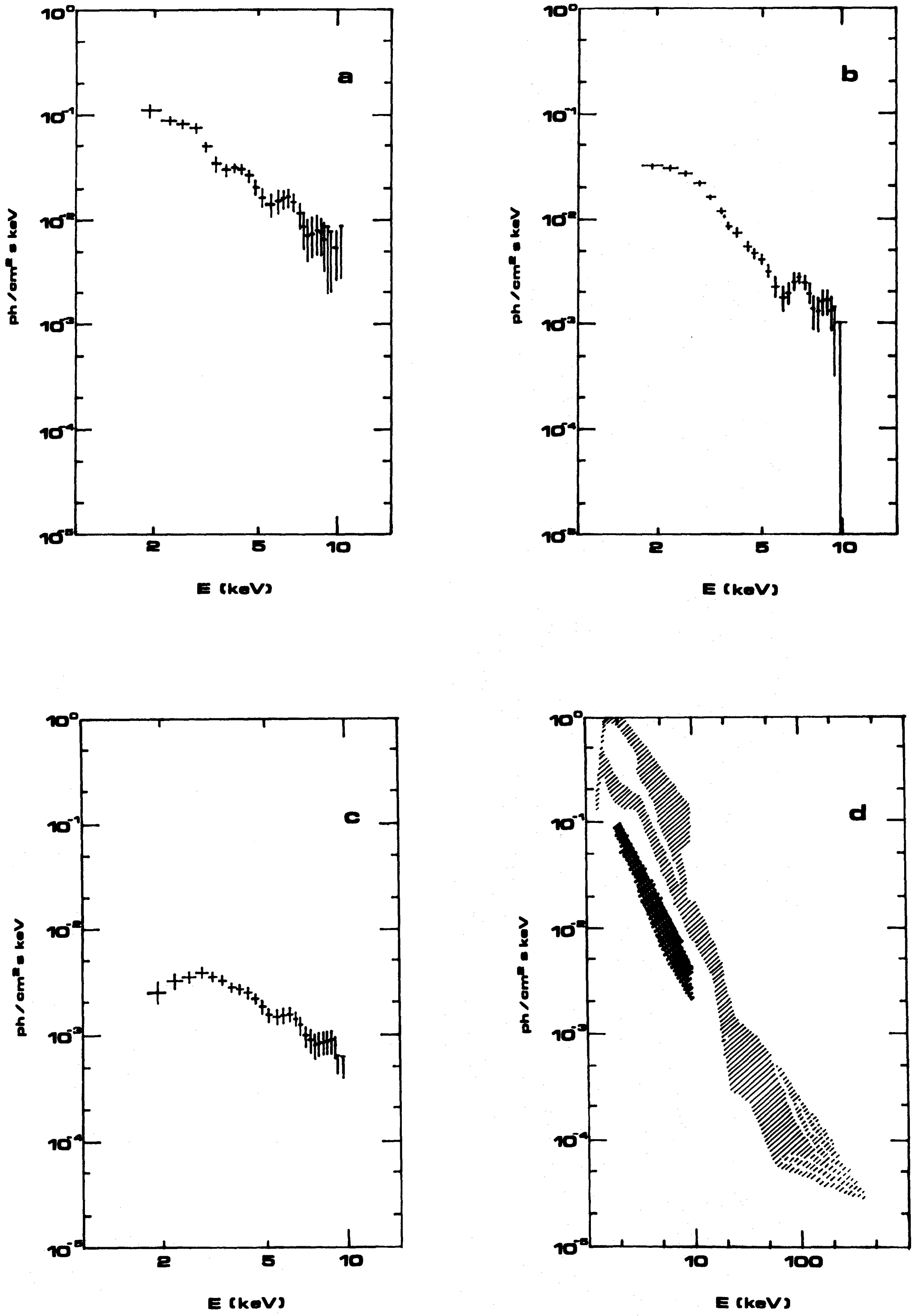

Figure 1. (a) Spectrum of Cir X-1, 1976 February 5.7–6.4. (b) Spectrum of Cir X-1, 1976 February 7.5–8.5. (c) Spectrum of 4U 1510 – 59, 1976 February 6.5–7.5. (d) High- and low-state spectra of Cir X-1: heavy shading indicates the range of the low-state spectra observed (this paper); light shading indicates the range of high-state spectra observed (after Baity *et al.* 1975, incorporating the data of Wilson & Carpenter 1976).

observing period the count rate is approximately constant and all the individual count rates were within 10 per cent of the mean.

On account of the low flux level a number of orbits were combined before attempting spectral analysis. Spectra shown in Fig. 1 have been restored with the Blissett & Cruise (1979) direct-deconvolution method. A weak spectral feature at ~ 7 keV is apparent in many spectra. Raw spectra were also fitted by a least-squares technique for non-linear functions (Bevington 1969) with a power-law continuum plus a line feature; results are given in Table 1, together with broad-band integrals. We stress that the direct-deconvolution method and the fitting procedure are completely independent; nevertheless a very good agreement exists between the restored spectra and the best-fitting spectral shapes. We note that when we include a line in the fit we obtain a steeper power law. We note also that some spectra are unusually flat (~ 2); this is probably due to the contamination by other, harder sources in the field of view.

3 Discussion

The most important result of our observations of Cir X-1 is that the spectrum in the low state appears to be very similar to that found in the brighter state, although scaled down in intensity by an order of magnitude or so (see Fig. 1d). Especially striking is the moderate absorption ($N_H \sim 10^{22}\,\mathrm{cm}^{-2}$) found in our data, compatible with the interstellar column density for a distance of 8–9 kpc (Goss & Mebold 1977). This result contradicts the suggestion (e.g. Murdin *et al.* 1980) that the low-intensity states are caused by increased absorption of the low-energy X-rays by column densities of up to $2.5 \times 10^{24}\,\mathrm{cm}^{-2}$. The evidence in support of such large absorption is limited; Jones *et al.* (1974) report low-energy absorption equivalent to column densities of $3 \times 10^{22}\,\mathrm{cm}^{-2}$ to $2 \times 10^{23}\,\mathrm{cm}^{-2}$ with a 'preliminary indication' that the spectrum is more cut-off at times of lower intensity. Coe *et al.* (1976) find a 12-keV cut-off (i.e. $N_H \sim 2.5 \times 10^{24}\,\mathrm{cm}^{-2}$) but we note that the energy range of the ST is 26 to 1200 keV. This cut-off is deduced by combining ST data with a point of Baity *et al.* (1975), taken at least 3 years previously, and a simultaneous RMC upper limit which has been incorrectly derived from the RMC count rate (Coe & Skinner, private communications). This should be a factor of approximately 2 higher. We note further that the ST data, although having the same spectral slope, consistently lie above the extrapolation of the experiment-C data, whereas there is good agreement between the (correctly converted) RMC data and simultaneous experiment-C data.

Careful consideration has been given to the possibility of contamination of our spectrum of Cir X-1 (especially at lower energies) by 4U 1510 – 59. Comparison of Fig. 1(c) with Fig. 1(a) or 1(b) shows that the intensity of this source is less than 15 per cent of Cir X-1 at low energies, although larger at higher energies. Thus the only explanation of the unexpectedly strong signal detected from Cir X-1 at low energies is a model with moderate rather than large absorption.

3.1 A POSSIBLE MODEL FOR CIR X-1

In the current model of Cir X-1 (Murdin *et al.* 1980), the primary, a massive supergiant, is the optical and infrared source; the compact companion is the X-ray source. An inverse square law for the density of the primary's stellar wind is assumed; the motion of the compact companion in a highly eccentric orbit through the wind causes the apparent high- and low-intensity states as the amount of absorbing material along the line-of-sight varies. (Note, however, that although the primary is usually taken to be a reddened OB supergiant, its nature is not well established (Nicolson, Feast & Glass 1980). The parameters of the system therefore have large uncertainty, but in these models the masses and radii are not critical.)

We consider here (a) the consequences of extending this model to take account of the variation of the accretion rate on to the compact object around its orbit, and (b) what constraints are imposed on the model by the lower value of the hydrogen column density reported here.

The luminosity at a distance r from the primary is given by

$$L_\mathrm{x}(r) \propto \dot{M}_\mathrm{accr}(r) \exp\left[-\tau(r)\right].$$

$\tau(r)$ is computed by Murdin *et al.* (1980), while the accretion rate is

$$\dot{M}_\mathrm{accr}(r) = \dot{M}_* \pi r_\mathrm{a}^2/(4\pi r^2)$$

and the accretion radius r_a (if we neglect the sound velocity in the wind) is

$$r_\mathrm{a} = 2GM_\mathrm{x}/(v_\mathrm{rel})^2,$$

where

$$(v_\mathrm{rel})^2 = (v_\mathrm{orb})^2 + (v_\mathrm{wind})^2$$

(Lamers, van den Heuvel & Petterson 1976). The orbital velocity v_orb is given by the equations of motion. The wind velocity is given by (Lamers *et al.* 1976):

$$(v_\mathrm{wind})^2 = \frac{16GM_*}{R_*}\left(\frac{r}{R_*} - 1\right)\frac{R_*}{r}.$$

We note that, under these assumptions, the asymmetry of the light curve (and thus any variation of its shape due to possible orbital precession) derives from $\tau(r)$ alone; $\dot{M}_\mathrm{accr}(r)$ is symmetric with respect to the line of apsides.

In comparison with the model of Murdin *et al.* (1980), this extended model gives light curves with more pronounced peaks (Chiappetti & Bell Burnell 1981). The parameter τ_0 (the optical depth at the surface of the primary) is critical; for example $\tau_0 = 5$ corresponds to $n_{(r=R_*)}R_* = 10^{24}\ \mathrm{cm}^{-2}$, the maximum X-ray cut-off assumed by Murdin *et al.* (1980). Our observation of $N_\mathrm{H} \sim 10^{22}\ \mathrm{cm}^{-2}$ would force us to use a smaller τ_0, but then the light curve would be determined very largely by $\dot{M}_\mathrm{accr}(r)$, and would become symmetric. To maintain a sufficient amount of asymmetry in the light curve, but also accommodate $N_\mathrm{H} \sim 10^{22}\ \mathrm{cm}^{-2}$, we suggest a less eccentric orbit. For $e \sim 0.5$, τ_0 can be greater than the maximum observed X-ray cut-off, since at periastron the compact object is no longer grazing the primary. An optical depth at the surface of the primary of 0.5 would ensure significant modulation with non-zero residual flux at minima.

We finally note that in such accretion models the high-energy X-rays should be (symmetrically) modulated as $\dot{M}_\mathrm{accr}(r)$, and the width of the peak in the light curve centred at phase 0 should give an indication of the eccentricity.

Further study of the source is certainly required. High-resolution X-ray spectroscopy will clarify the nature and origin of the 7-keV feature. Simultaneous soft and hard X-ray observations will also be useful for studying possible differences in the orbital modulation.

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Note added in proof

Since submitting this paper we have learnt of the work of Argue & Sullivan (1982, *Observatory*, **102**, 4) which suggests that the optical counterpart of Cir X-1 cannot be an early-type object.