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The discovery of X-ray bursts from Cir X-1

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Summary. A sequence of eight X-ray flares was detected during an *EXOSAT* observation of the low-state Circinus X-1 (=BR Cir). We identify these flares with X-ray bursts from Cir X-1. The recurrence time, ratio of persistent flux to the time-averaged flux and indications of cooling during the bursts are all consistent with these bursts being type I, although we cannot rule out the possibility that the bursts are type II. Type I bursts would be strong evidence that Cir X-1 is a neutron star and not a black hole.

1 Introduction

Circinus X-1 is a bright Galactic X-ray source that shows large variations. During its high-state it can become the second brightest X-ray source in the sky and often shows a very soft blackbody spectrum with a temperature of $kT<1$ keV. The count rate drops abruptly every 16.6 day (Kaluzienski *et al.* 1976) after which the spectrum becomes harder. The X-ray flux is highly variable and a correlation time-scale, given by the decay of the autocorrelation function, of a few seconds has often been observed (Dower, Bradt & Morgan 1982; Robinson-Saba 1983).

These general properties of Cir X-1 resemble those observed from the X-ray source Cygnus X-1 which is associated with a high-mass compact object that may be a black hole. The similarity of these two sources has led to the suggestion that Cir X-1 is itself a black hole (Samimi *et al.* 1979). In this paper we present *EXOSAT* X-ray observations of Cir X-1 showing X-ray bursts which, in other sources, have been taken as evidence of a neutron star.

The nature of the X-ray bursts, and in particular the short recurrence time, are discussed in Section 3. We identify the bursts as most likely of type I and thus due to thermonuclear burning of hydrogen and helium in the accreted matter. The relationship of the burst properties with the cyclic variability of Cir X-1 are explored in Section 4.

2 Observations

The *EXOSAT* observations of Cir X-1 reported here were obtained on 1984 day 335 when Cir X-1 was predicted to be roughly halfway through its 16.6-day cycle. Recent radio observations

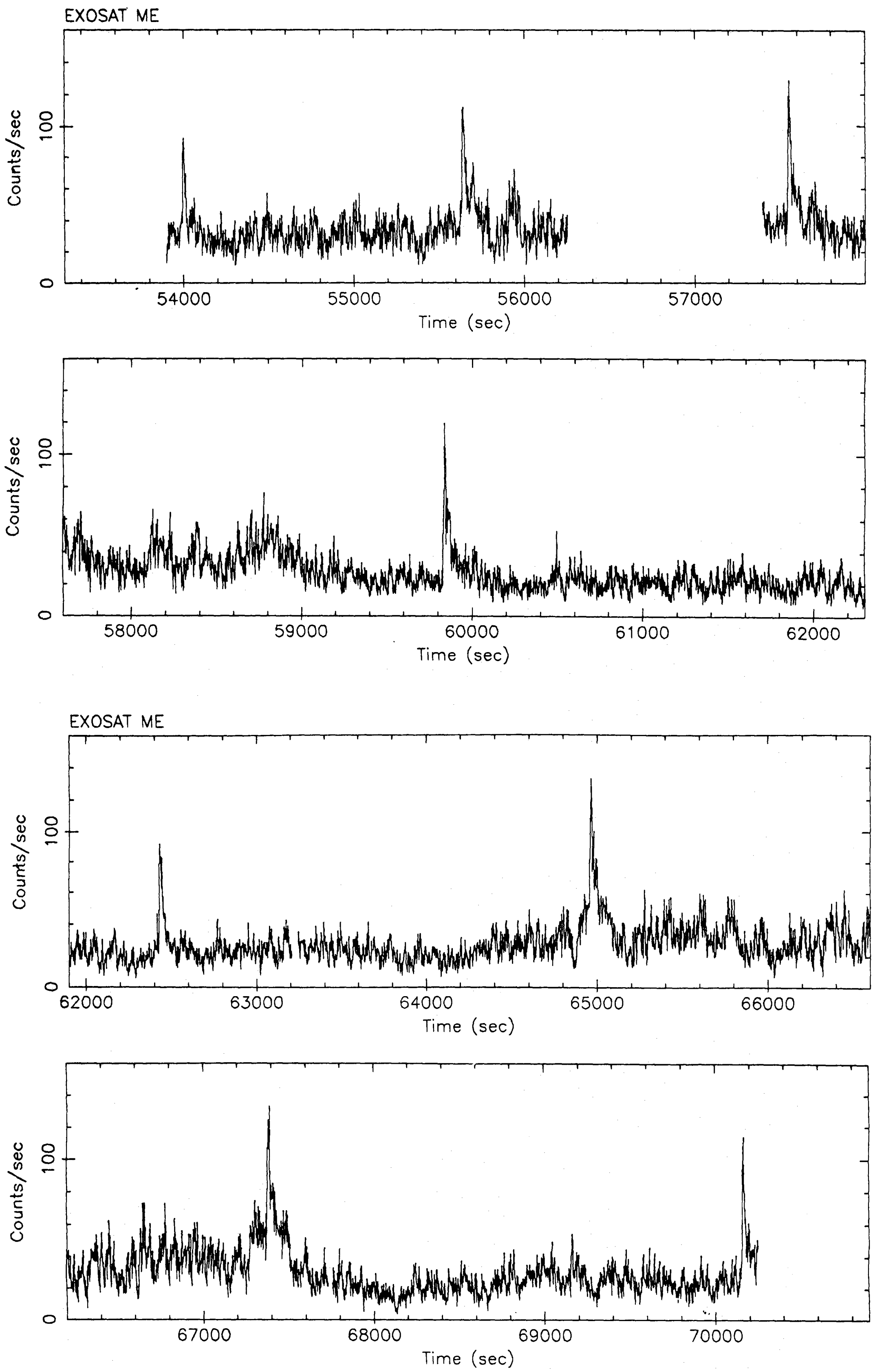

Figure 1. ME light curve of Cir X-1 covering the energy range 2–6 keV. The data have been binned every 2.5 s. A constant non-source background of 10.7 ct s^{-1} has been subtracted. For a typical burst spectrum, $N_H=5\times10^{22}$ atom cm^{-2}, $T_{bbody}=2$ keV, 1 ct $s^{-1}=1.1\times10^{-11}$ erg cm^{-2} s^{-1} over the 2–6 keV band.

(Nicolson, private communication) define the phase of the 16.6-day cycle to within 1 day, X-ray data were also obtained 8 day earlier, near the predicted time of the high-state/low-state transition. Data from that observation will not be discussed here other than to point out that a reduction of flux was observed near the time of predicted transition, although the source was not bright. There are indications of strong absorption which could have hidden a large fraction of the luminosity.

Fig. 1 shows the light curve for the entire day 335 observation from the Medium Energy (ME) proportional counter (Turner, Smith & Zimmermann 1981). Data from the Gas Scintillation Proportional Counter (GSPC: Peacock *et al.* 1981) reproduce all of the events seen in Fig. 1. The source was variable on all time-scales ranging from less than 1 s up to the length of the observation. Eight short flares are seen which greatly exceed the general level of flickering. Although it is possible that these flares are unusually large flickers, examination of Fig. 1 shows that the flares occur at semi-regular intervals whereas the level of flickering varies throughout the observation. In addition there are no flares with similar structure but, for example, with half the amplitude. These facts persuade us that the nature of the flares is distinct from that of the flickering.

Detailed examination of the flares show that in every case there is a sharp rise followed by a slower decline. The semi-regular spacing of the flares and the shape of each resemble the properties of bursts from X-ray bursters (see Joss & Rappaport 1984 for a review). In this paper we analyse the eight flares in greater detail and show that the data are consistent with their being bursts: we therefore refer to them as bursts from now on.

It is highly likely, but not certain, that these bursts originate in Cir X-1. There are only about 30 burst sources known, mostly within $\sim\pm 40°$ of the Galactic Centre (Cir X-1 is at $l=322°.1$, $b=0°.04$). An estimate of the probability that a new source would by chance lie in the $3/4\times 3/4°$ (FWHM) field of view of the ME is $\leqslant 5\times 10^{-3}$. Neither Cir X-1 nor any other source was detected in the low-energy (LE) telescope, presumably because of photoelectric absorption at the low-galactic latitude of Cir X-1. Future observations involving partial off-sets of the ME and a search for a possible correlation with the 16.6-day cycle should confirm our identification.

If our identification is correct and Cir X-1 is a high-mass X-ray binary (Whelan *et al.* 1977) then this would be the first time that bursts have been detected from a high-mass system. However, Nicolson, Feast & Glass (1980), have pointed out that the observed IR/optical emission is more likely to originate in a disc rather than an OB supergiant. Recent CCD astrometry (Argue *et al.* 1984) indicates that the earlier optical identification of Cir X-1 was in error. The new position suggests that Cir X-1 is more probably associated with a fainter object and thus with a low-mass system.

High-time-resolution light curves were constructed for each of the eight bursts. Each light curve was then divided into about six time intervals over which ME spectra were integrated and analysed. Background spectra were integrated for 90–800 s before the start of each burst. The observed flux, the best-fitting temperature, and the effective blackbody radius as a function of time during each burst, are displayed in Fig. 2. The fits included the effects of photo-electric absorption, with the amount fixed to an equivalent hydrogen column $N_H=5\times 10^{22}$ atom cm^{-2}, using the abundances and cross-sections from Morrison & McCammon (1983). This value of the column density was derived from fits to all the burst data. Model spectra based on a single temperature blackbody generally provided a good fit to the data, in contrast to the persistent flux for which more complicated models are required. A formally unacceptable value of χ^2 was obtained in a few cases, but a detailed examination of those spectra revealed that this was due to the non-Gaussian behaviour of spectra with few counts per bin, e.g. most of the excess χ^2 is due to a single bin (in the source spectra) containing zero counts. In order to calculate effective blackbody radii we assume that Cir X-1 is 10 kpc away (Goss & Mebold 1977).

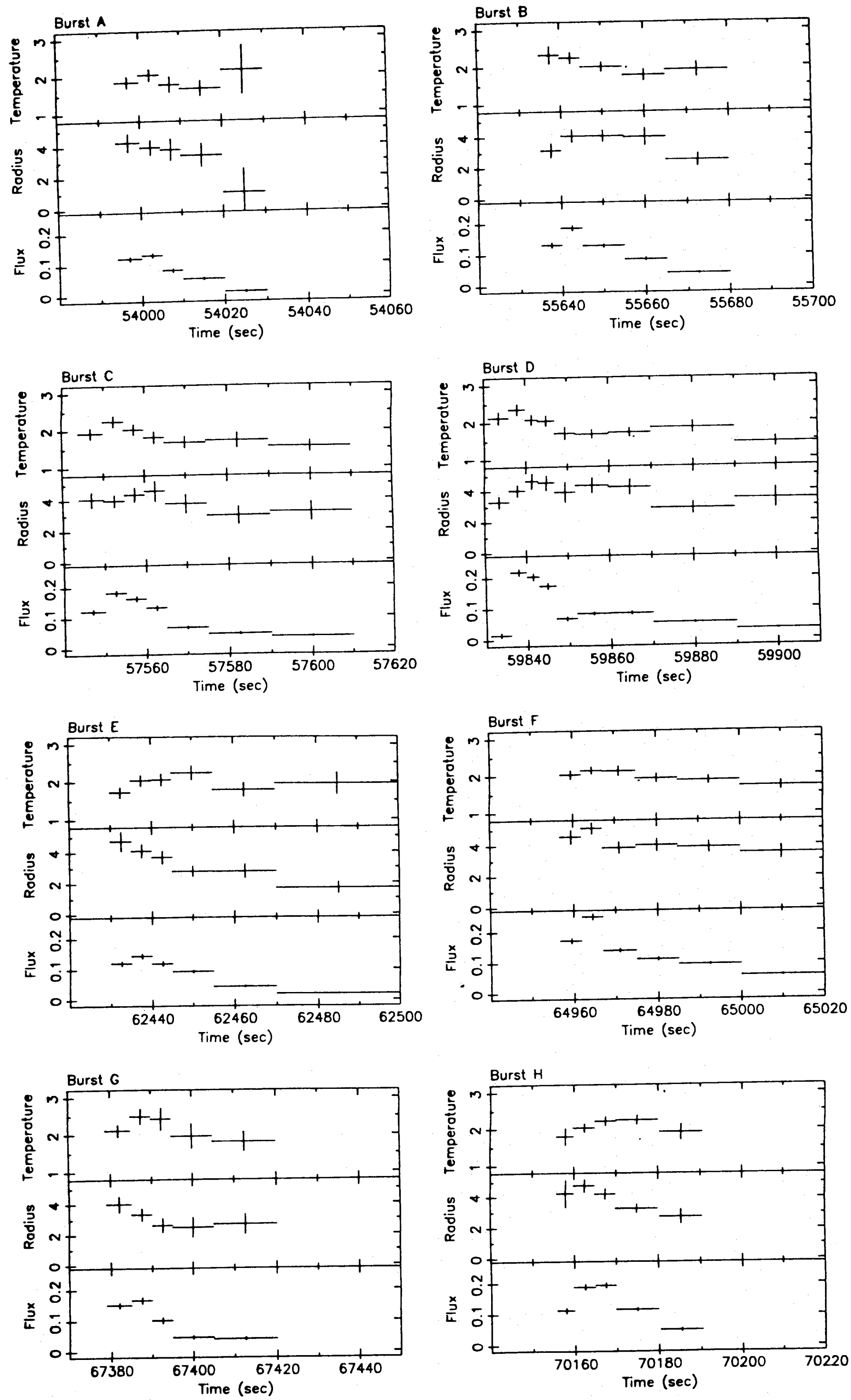

Figure 2. Parameter profiles of all eight bursts. For each burst the upper panel is the blackbody temperature in keV, the middle panel is the blackbody radius in km assuming a spherical emitting surface at a distance of 10 kpc and the lower panel is the ME integrated flux in ct cm^{-2} s^{-1}.

Some trends can be seen in the temperature profiles. A typical burst shows a peak temperature around 2.2 keV near the time when the flux is at a maximum which then declines by ~0.3 keV over the next 15 s. At later times the temperature no longer declines but is roughly constant at about 1.9 keV. The analysis of the temperature profiles is complicated by flickering of the underlying persistent emission. This can produce an excess count rate of up to ~40 ct s^{-1} for ~20 s, which compares with a peak rate during a burst of ~120 ct s^{-1}. Thus, detailed features of the separate temperature profiles are not to be trusted, although general trends should be reliable. In order to test whether the temperature profile declines or not, we fit the eight profiles to a straight line excluding points obtained before the peak but including all following data. A negative slope was preferred at the 90 per cent confidence level for five out of the eight profiles, and in all cases the best-fitting slope was negative.

We also considered the properties of a 'composite burst' produced by summing data from all eight bursts: a cross-correlation method was used to avoid bias. In brief a template burst was constructed by adding all eight bursts. At this stage some personal judgement was required in selecting the phase of each burst. In the following steps no such judgement was needed. A 10-knot spline was fitted to the template burst profile. This function called $S(t)$ is displayed in Fig. 3 and matches the global properties of the template; it also tends to remove high-frequency noise. Each burst was then separately fitted to the three-parameter function

$$f(C, A, t_0) = C + A^* S(t - t_0).$$

In this manner we forced the shape to remain constant but shifted the amplitude and phase (t_0) to minimize the χ^2. The value of t_0 for each burst gave us a reference time for the phase of each burst. Using this reference time we again added all the bursts to construct the composite burst. It is important to realize that this technique fits the entire burst profile and therefore is not expected to generate a very sharp rise.

The composite burst profile is displayed in Fig. 4. The rise time is ~3 s which is smaller than the ~5 s rise of the template burst. The decay can be fitted by the sum of two exponentials with decay times of 14 and ~100 s. It is possible that the second exponential is biased by a slight excess

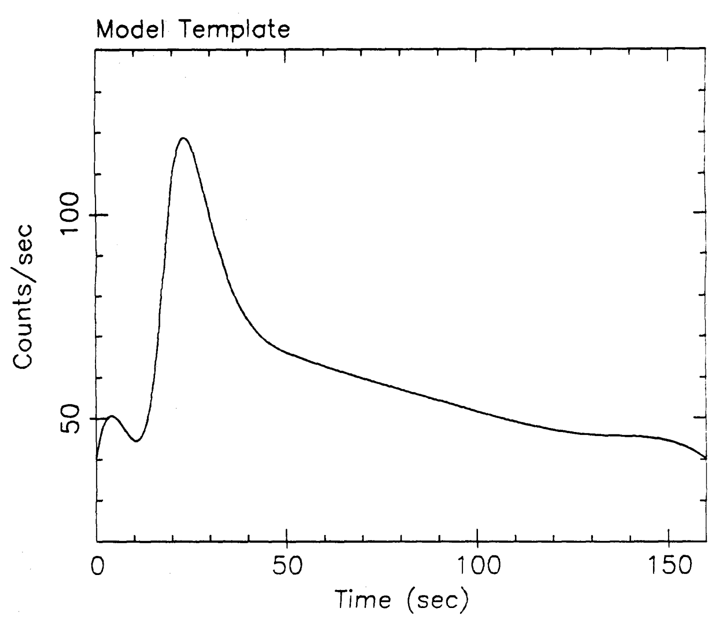

Figure 3. The template model of the template burst. The ripples before the rise are an artefact of the spline fit to the burst and exist at the noise level.

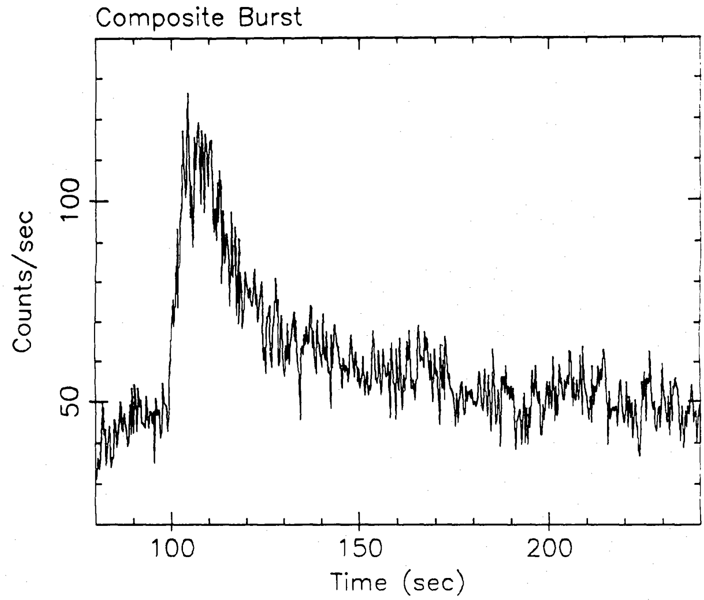

Figure 4. The composite burst time profile.

following the burst. Seven spectra were extracted from the composite burst. Again each spectrum was fitted to a single temperature blackbody. The spectral parameters are plotted in Fig. 5 which shows a clear indication of cooling with the best-fitting temperature dropping from 2.25 to 1.82 keV. This drop of 0.4 keV is consistent with the drop of ~0.3 deduced from inspection of the individual burst profiles. In Fig. 6 we show the composite burst in two energy bands.

Next we estimated the peak flux from each burst. In order to minimize the effects of the flickering we have fitted each burst profile to a smooth model of a burst. The data suggest the function

$$B(t)=Nt^P \exp(-t/\tau) \quad (1)$$

where t is measured from the start of the burst. The peak time is at $t=P\tau$ and so P determines how

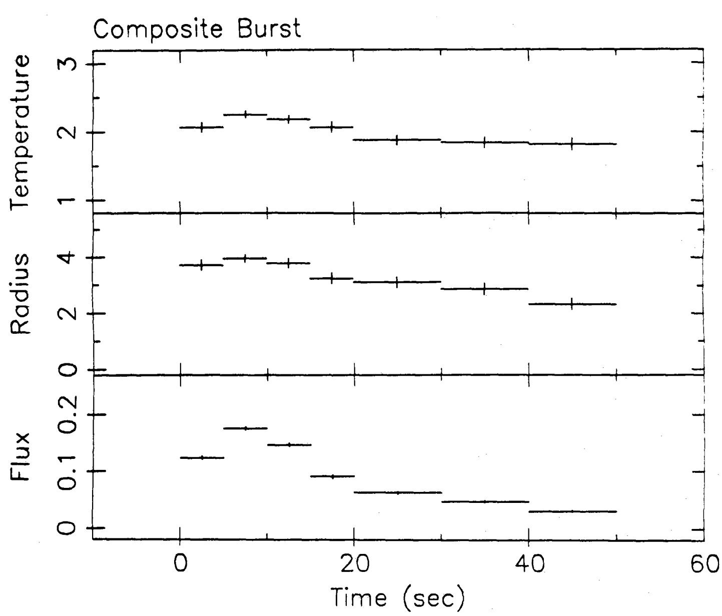

Figure 5. Parameter profile of the composite burst.

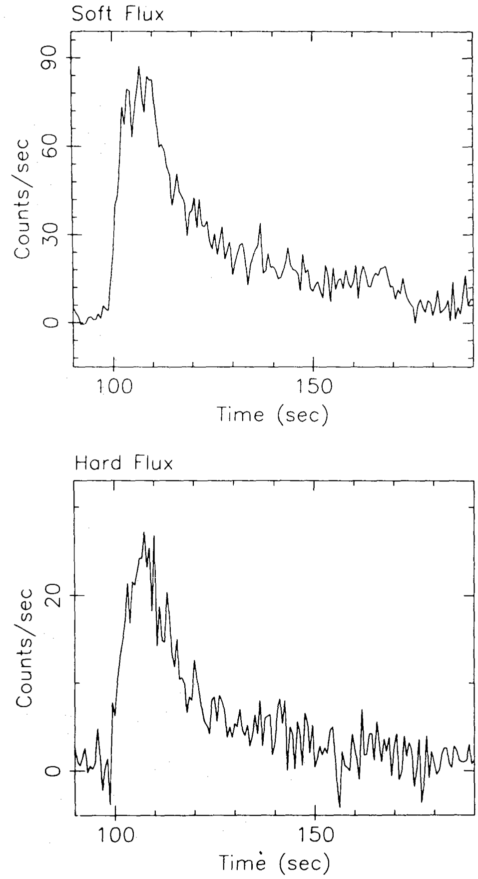

Figure 6. (Top) The composite burst in the 2–6.7 keV band. (Bottom) The composite burst in the 6.7–10 keV band. Notice that the decline is more rapid in the hard band as expected from cooling.

rapidly the count-rate rises. This model cannot be used to fit the entire burst profile since a single exponential will not fit the entire decay. The initial decay time is ~15 s but later increases to ~60 s. No attempt was made to fit the tails with the above model. In order to treat all bursts in a formal systematic manner a two-stage procedure was used. The peak time was initially estimated by fitting an entire burst with equation (1), then the burst was refitted over a 60-s interval extending from 40 s before this initial estimate of the peak to 20 s after. This allowed the background rate to be determined. Stopping the fit 20 s after the peak makes the results less sensitive to any long tails on the bursts. Flickering will bias individual results but there should be no systematic bias.

The peak fluxes are given in Table 1 and appear to be very similar. The mean peak rate is 0.124 ct s^{-1} cm^{-2} with a standard deviation of only 0.02 ct s^{-1} cm^{-2} (16 per cent of the mean). Two of the bursts are much fainter than the rest. The mean of the six brightest bursts is 0.134 ct s^{-1} cm^{-2} with a standard deviation of 0.01 ct s^{-1} cm^{-2} (8 per cent).

3 Nature of the X-ray bursts in Cir X-1

There are two classes of X-ray bursts whose properties are reviewed by Joss & Rappaport (1984). The first, type I, are probably due to a thermonuclear flash on the surface of a neutron star (Woosley & Taam 1976; Maraschi & Cavaliere 1977). All known X-ray burst sources have been shown to generate bursts which are consistent with this interpretation. Type II bursts tend to be more erratic and are explained as accretion instabilities. Present theory cannot rule out the

Table 1. Burst properties.

Burst	Start time UT s	Total Flux[a] counts	α_{max}	Peak Flux ct s^{-1} cm^{-2}	Peak L[b] 10^{37} erg s^{-1}
A	53990	1540	--	0.091	3.5
B	55636	2850	28	0.132	5.4
C	57545	3090	32	0.136	5.3
D	59830	2880	39	0.145	6.8
E	62429	2220	38	0.098	3.7
F	64958	2380	39	0.125	6.9
G	67368	2260	56	0.121	5.5
H	70155	2840	36	0.146	5.5

Notes:

(a) 1 ME count corresponds approximately to 1.4×10^{-11} erg cm^{-2} in the 2-10 keV band. The collecting area was 797 cm^2.

(b) Bolometric luminosity at a distance of 10 kpc.

possibility of instabilities in the accretion flow associated with a black hole. However, only the Rapid Burster is known to emit type II bursts and as it also emits type I bursts (Hoffman, Marshall & Lewin 1978) it is probably a neutron star. Thus all known burst sources are considered to be associated with neutron stars.*

In this section we will consider the observations from Cir X-1 and attempt to classify the bursts as either type I or II. Both burst types have spectra that can be fitted at least approximately with a blackbody. The main *observational* difference between the two burst types is that type I bursts cool after peaking whereas, for type II bursts, the temperature remains constant, although there have been few attempts to quantify this difference. Marshall *et al.* (1979) showed that the type II bursts had a constant temperature to within the measurement error of ±0.15 keV. Kawai *et al.* (1985) actually found an overall temperature increase from type II bursts that had been scaled before summing. Type I burst temperatures typically fall from slightly above 2 keV to less than 1 keV although there are examples of much smaller declines (see for example fig. 2 of Matsuoka 1985). As discussed in Section 2, the temperature of the bursts from Cir X-1 typically peaks near ~2.2 keV and then falls to ~1.8 keV. Although this change appears small it corresponds to a luminosity change of almost a factor of 2. There is little question that the burst temperature declines but it does not drop as rapidly as in other type I bursts.

There are several other properties of the observed bursts from Cir X-1 that resemble those attributed to thermonuclear flashes. First, the bursts are very regular. The eight bursts have a mean separation of 2300 s with an observed standard deviation of 400 s (17 per cent). A second

*Hoffman *et al.* (1978) have suggested that the irregular flares from the black hole candidate Cyg X-1 may be type II bursts. We are unaware of any quantitative study of this such as fitting an exponential to the decay or a blackbody model to the spectrum of the flares. These events (see, for example, the Cyg X-1 data of Canizares & Oda 1977) bear little resemblance to the events we are discussing.

property that resembles type I bursts is α, the ratio of the energy released as persistent flux to the energy released from the bursts, averaged over the same period of time, i.e., the ratio of release of gravitational to nuclear energy. The precise value of α is difficult to calculate for Cir X-1 because of the long tail to the bursts for which the integrated energy could easily exceed the energy released in the initial phase of the burst. We have used our fits to the early parts of the burst to estimate an upper limit to α. Table 1 gives the integrated flux from the early part of the burst. The mean value was ~2500 ct burst^{-1} whereas, on average, the persistent flux generated ~78 000 ct between bursts. This implies α~31 which is within the range predicted by theory (~100 for pure helium flash, down to ~30 if hydrogen burning is included, Hansen & Van Horn 1975; Taam & Picklum 1978). If the long tails are included then the value of α could be halved. The expected value of α can be lowered if the neutron star has a lower mass and/or a larger radius which thereby decreases the gravitational energy release. However, decreasing the mass will increase the magnitude by which the high-state flux, at times over 2×10^{39} erg s^{-1}, exceeds the hydrogen-rich Eddington luminosity. A second way in which the expected value of α can be reduced is to assume that the persistent emission is non-isotropic. For example, if the bulk of the persistent emission is coming from an accretion disc which happens to be highly inclined to our line-of-sight, then we will grossly underestimate the persistent luminosity and hence α. Finally, we note that bursting has been observed to stop if the luminosity of the persistent source is too high (Clark *et al.* 1977). The observed persistent luminosity of Cir X-1 during our observations is near 10 per cent of the Eddington limit (L_{ED}) for a 1 $M_\odot$ object which is in the range that allows bursting.

With our current data we are unable to rule out the possibility that the bursts are of type II. White *et al.* (1978) reported α~0.2 for type II bursts from the rapid burster, which is 100 times smaller than the value we find for the bursts from Cir X-1. It has been suggested that any persistent flux is generated by the type II bursts themselves, as the instability either permits accretion or stops it altogether. Type II bursts are rarely separated by more than 15 min (White *et al.* 1978; Marshall *et al.* 1979), including the unusual flat-top bursts (Inoue *et al.* 1980), and to see a sequence of eight separated by ~40 min would be unprecedented.

The bursts from Cir X-1 are weaker and recur more rapidly than bursts from typical type I sources. The authors suspect that in the past there was an observational bias against observing weak bursts separated by short intervals, due to the incomplete time coverage obtained by satellites in low Earth orbit. A long continuous *EXOSAT* observation of 4U1636−53 (Turner & Breedon 1984) found a burst recurrence time of roughly 60 min.

The peak flux from typical type I bursts is very close to (or in excess of) L_{ED} for a 1.4 $M_\odot$ object (Tanaka 1984), but for Cir X-1 the bursts peak at only 0.3 L_{ED}. If the entire surface radiates as a blackbody, then we infer a radius of less than 5 km, which is smaller than the 10 km typically reported. Radiation transfer effects (London, Taam & Howard 1984) mean that the inferred blackbody radii are about a factor of 2 smaller than the 'true' emitting radius. A small size would argue against the object being a black hole, as the surface of the disc would need to be even greater. It is worth noting that the peak temperature of the bursts, ~2.2 keV, is similar to that observed in more luminous type I bursts. There are arguments based on the Eddington limit (see Joss & Rappaport 1984) that the surface temperature should not exceed such values. This is consistent with the view that only a part of the neutron star surface is actually participating in the burst.

4 Discussion and conclusions

An object within 3/4° of Cir X-1, which is very probably Cir X-1 itself, emits X-ray bursts. The bursts resemble type I bursts but are weaker and recur more often than is common for other sources. It is likely that the cyclic high-state behaviour of Cir X-1 is responsible for the short recurrence time. During the high-state the luminosity of Cir X-1 greatly exceeds that of other burst sources. Consequently the temperature of the neutron star at the depth of a few metres where thermonuclear processes are important is relatively higher. Hydrogen and helium burning of the accreted gas presumably occurs smoothly during the high-state, but the declining temperature in the low-state allows the surface layers to pass into the bursting state. An application of the simple estimates for the cooling of freshly accreted matter in the work of Ayasli & Joss (1982) shows that it takes several days for the matter which was accreted during 12 hr in the high-state to cool below the helium-burning temperature of 2×10^8 K. It is assumed here that the high-state accretion rate corresponds to the Eddington limit and that the freshly accreted matter is initially much hotter.

The burst recurrence time is dependent upon the local accretion rate and surface temperature (see Ayasli & Joss 1982). There is some evidence in Fig. 1 that the recurrence time increases throughout the burst sequence. Fast bursting (i.e. more than 1 per hr) could be due to the accreted matter being funnelled on to part of the cooling neutron star surface. If the neutron star has a weak magnetic field then matter would tend to fall on the polar caps. If, on the other hand, the magnetic field is so negligible that the accretion disc extends to the surface, then matter would tend to fall on the equatorial region. As discussed in the last section, use of only part of the neutron star surface is consistent with the small inferred radius and luminosity. (It is not clear, however, whether the magnetic field prevents the matter from spreading over all the surface at the thermonuclear flash depth of metres.)

The Cir X-1 system is likely to be younger ($<10^8$ yr) than other burst sources if the 16.6-day cycle is due to an eccentric orbit (Murdin *et al.* 1980). It can then still possess a magnetic field strong enough to channel the accretion flow in the low-state (but perhaps not in the high-state). Typical type I bursters are in low-mass binaries that accrete fairly steadily for $>10^9$ yr. Thus typical type I burst sources would come from older neutron stars which may be more massive and have weaker magnetic fields than Cir X-1 (as suggested by models for the millisecond pulsar; van den Heuvel 1984). A low mass (e.g. $\sim 0.6\,M_{\odot}$) would help to explain the low observed value of α.

There are some similarities with Aquila X-1 (Buff *et al.* 1977). The X-ray light curve of both Cir X-1 and Aql X-1 show recurrent strong flares, although the time-scale of those in Aql X-1 is 12–16 month, more than an order of magnitude longer than Cir X-1 (Kaluzienski *et al.* 1976). The X-ray spectrum of the flares is soft, but not as soft as Cir X-1 during the high-state. X-ray bursts have been observed during the decline of Aql X-1 (Koyama *et al.* 1981).

If Cir X-1 is shown to emit type I bursts and hence is a neutron star then this would be proof that neither rapid variability nor biomodal spectral behaviour can be used as a reliable signature of a black hole. Stella *et al.* (1985) discovered Cyg X-1-like variability from the pulsar V0332+53, which already proves that rapid variability alone is not enough to indicate a black hole.

The possibility that the bursts in Cir X-1 respond in recurrence time and other properties to the accretion rate and surface temperatures suggest that further studies over a much larger interval may allow the start and end of the burst sequence to be observed. The simple discussion presented here indicates that the recurrence time increases as the neutron star cools following the high-state.

Acknowledgments

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