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THE DISCOVERY OF RAPIDLY REPETITIVE X-RAY BURSTS FROM A NEW SOURCE IN SCORPIUS

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ABSTRACT

Rapidly repetitive X-ray bursts have been observed from a new X-ray source in Scorpius. More than 2000 bursts were observed during the ~4 day continual SAS-3 observations of this source which we designated MXB 1730−335. The time interval between bursts varied from a minimum of ~6 s to a maximum of ~5 minutes. The energy in a given burst is approximately linearly proportional to the time interval to the next burst. The largest bursts observed last for ~60 s and represent an energy release of $\sim 10^{40}$ ergs for an assumed distance to the source of 10 kpc. The smallest bursts observed last only for a few seconds. We suggest that the bursts are caused by sporadic precipitations of plasma from a reservoir in the magnetosphere of a neutron star. The reservoir is replenished at a nearly constant rate by mass transferred from a binary companion.

Subject headings: X-rays: sources — X-rays: transient sources

I. INTRODUCTION

Several groups have now reported X-ray burst sources which were detected with satellite-borne experiments (Babushkina *et al.* 1975; Grindlay *et al.* 1976; Clark *et al.* 1976; Lewin 1976*a;* Belian, Connor, and Evans 1976). At present there are known to be at least nine X-ray burst sources which typically exhibit a rapid rise time ($\lesssim 1$ s), peak brightness of the order of magnitude of the Crab Nebula, exponential decay time of a few seconds, and repetition rates of a fraction of a day to several days. With one exception these sources are located near the galactic plane with $|b^{\text{II}}| \lesssim 14°$ and with $263° \lesssim l^{\text{II}} \lesssim 45°$ (Clark *et al.* 1976; Grindlay *et al.* 1976; Jones and Forman 1976; Belian, Connor, and Evans 1976; Clark 1976; Doty 1976; Lewin 1976*a*, *b;* Hoffman 1976).

While investigating a region which we knew from previous observations to contain at least one of these sources, we pointed the *Y*-axis detectors of the SAS-3 observatory (see next section) in the vicinity of 3U 1727−33. A source of rapid repetitive X-ray bursts was immediately apparent from the first data we received, and from the aspect solutions it was clear that the source was not 3U 1727−33 (Lewin 1976*b*). This new and unique source was designated MXB 1730−335.

During the ~4 day continual observations of MXB 1730−335 more than 2000 X-ray bursts were observed from this source. Here we discuss some of the salient features of this source and, in particular, a relation between burst-energy and burst-spacings which implies a relaxation-oscillator model.

II. OBSERVATIONS

The new source in Scorpius (MXB 1730−335) was observed by the SAS-3 X-ray observatory simultaneously in independent detector systems with four different fields of view. The counting rate data from the four systems are shown in Figure 1 for an ~40 min period of pointed observations near 1976 March 2.3 (UT). Forty-six bursts can clearly be distinguished. The smallest and largest time intervals between the bursts during this portion of the observations are ~13 s and ~6.5 min, respectively.

The detection systems are labeled, in Figure 1: (*a*) left slat, (*b*) center slat, (*c*) right slat, and (*d*) horizontal tube. The center slat has a 1° × ~40° FWHM field of view; its direction is perpendicular to the equatorial plane of the satellite. The left and right slat have $0\overset{\circ}{.}5 \times \sim 40°$ FWHM fields of view which are inclined ±30° with respect to the center slat. The horizontal tube has a circular field of view of $1\overset{\circ}{.}7$ FWHM. These four detection systems and a star camera are coaligned to within 6′ (the alignment is known to better than $\sim 0\overset{'}{.}5$) on the equatorial plane of the satellite. The four different fields of view have an area of ~1.1 square degrees in the sky in common. The effective area of each of the four systems is ~80 cm². The energy range of the left and right slat detectors is ~1.3–15 keV, while the energy range of the center slat and the horizontal tube is ~1.3–50 keV.

The position of the source was first determined by a careful comparison of the burst counting rates in the various systems using some of the data from seven orbits. The position of the source obtained in this was is in an ~50 arcmin² area in the sky (Hearn 1976). It is centered on $l^{\text{II}} = 354\overset{\circ}{.}80$, $b^{\text{II}} = -0\overset{\circ}{.}22$; $\alpha(1950) = 17^{\text{h}}30\overset{\text{m}}{.}2$, $\delta(1950) = -33°25'$.

Counting-rate plots for five energy channels of the horizontal tube detection system, for an ~170 s period near 2 March $7^{\text{h}}39^{\text{m}}$ (UT), are shown in Figure 2. During this period (also shown in Fig. 1) six bursts

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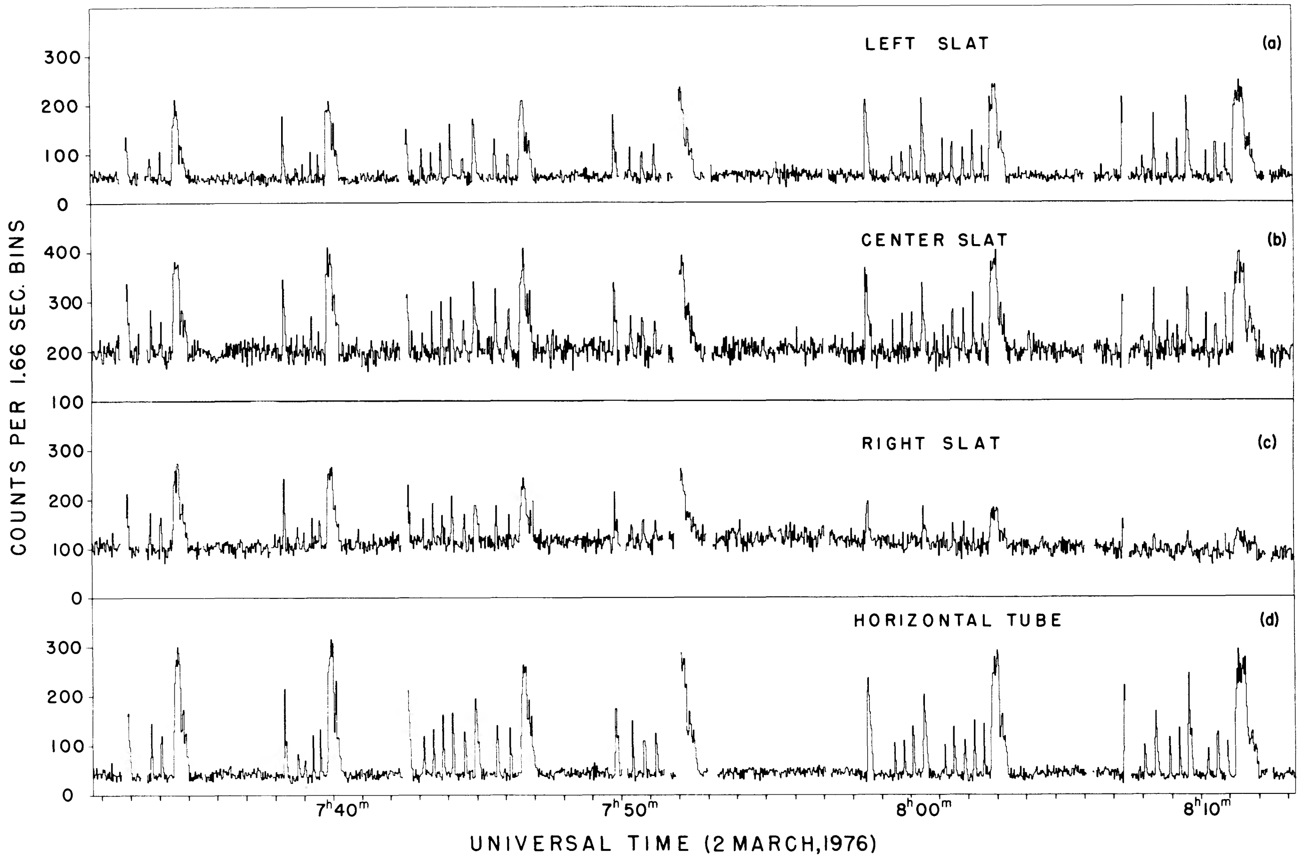

FIG. 1.—Counting rate data ($\sim$1.5–10 keV) from MXB 1730−335 which illustrates the burst activity typical of the observations near 2.3 March 1976 (UT). The source was within the fields of view of four of the collimated proportional counter systems of SAS-3. Toward the end of the data segment in (*c*), small motions of the satellite ($\sim$10′) caused the source to drift toward the edge of the field of view of the right slat collimator. Occasional small gaps in the data are due to losses in the transmission link via telephone line. The non-burst counting rate in (*a*), (*b*), and (*c*) is due largely to (i) other X-ray sources which are simultaneously in the fields of view of the extended slat-type collimators, (ii) isotropic X-ray background, and (iii) non–X-ray background. In (*d*) the non-burst counting rate could be due to (i) the known X-ray source 3U 1727−33 which was in the circular field of view of the horizontal tube detection system, (ii) a non–X-ray background, and (iii) possibly, a more or less steady component of MXB 1730−335.

of widely varying magnitude were observed. It is apparent from this figure that the spectra of individual bursts are about the same, although the energy in the bursts varies by about a factor of 30. There seems to be one burst near $7^{\rm h}39^{\rm m}30^{\rm s}$ which appears only in the 1.3–3 keV energy channel. We have no way of knowing, however, whether this burst comes from MXB 1730−335. In general, the largest bursts (one is shown in Fig. 2) show a multiple-peak structure.

The burst patterns sometimes change significantly in less than half an hour; we give two examples only. On March 3 between $02^{\rm h}10^{\rm m}$ and $02^{\rm h}40^{\rm m}$ (UT) the time separations between bursts varied very little from a minimum of $\sim$40 s to a maximum of $\sim$80 s; very small bursts and very large ones were not observed. About half an hour later an entirely different pattern, similar to the one shown in Figure 1, was observed. On March 4, from $10^{\rm h}00^{\rm m}$ to $10^{\rm h}20^{\rm m}$ (UT) the burst pattern was again similar to the one in Figure 1; however, about half an hour later from $10^{\rm h}55^{\rm m}$ to $11^{\rm h}40^{\rm m}$ the bursts were almost equal in size and their time separations were typically $\sim$35 s.

An area of the sky which includes MXB 1730−335 was also observed by SAS-3 (*right slat*) between 1976 February 1.3 and 6.8 (UT), and no repetitive bursts were observed at that time.

A striking feature is evident from Figure 1. The larger the energy in a burst, the longer it takes for the onset of the *next* burst. In Figure 3 we show the approximate energy ($\sim$1.5–10 keV) in $\sim$250 bursts versus the time separation to the following burst. The bursts were taken from horizontal tube data of six orbits which showed significantly different burst patterns as discussed above. If the energy in a given burst were linearly proportional to the time separation between it and the following burst, then the points would fall on a straight line which is inclined at 45° (one such line is shown). Near the low-energy end of the scale the time intervals are uncertain by $\sim$40 percent. The data in Figure 3 have not yet been corrected for effective exposure to the source, which varied during the six orbits by about

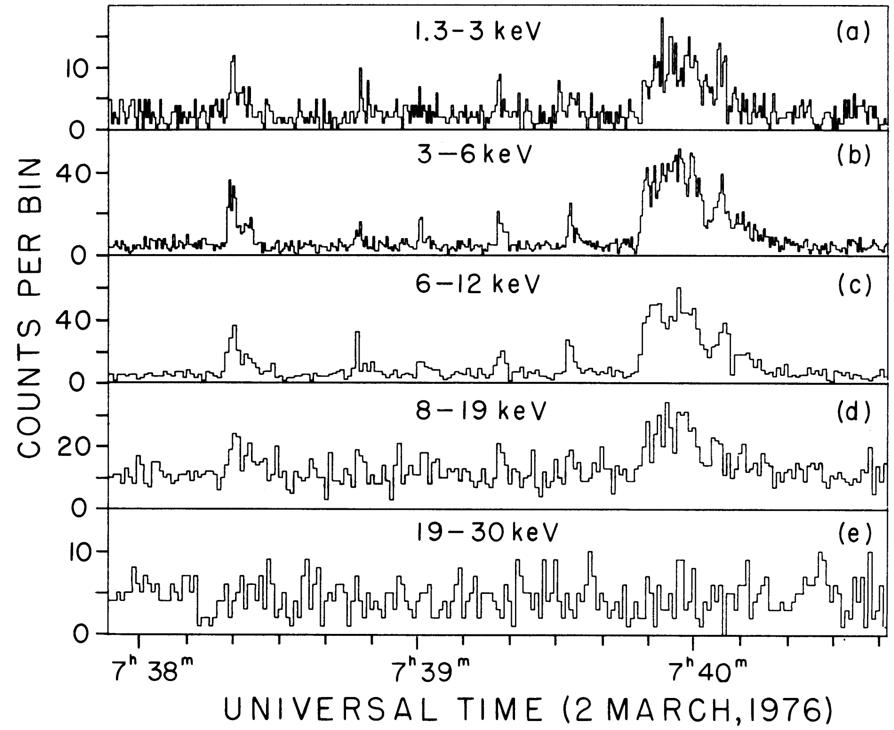

FIG. 2.—Counting rate data from the burst source MXB 1730−335 in five energy intervals. The time-bin size in (*a*) and (*b*) is 0.416 s while for (*c*), (*d*), and (*e*) the bin size is 0.832 s. The spectra for the bursts are similar. Note the multiple peak structure in the largest burst which occurs near 7h40m (UT).

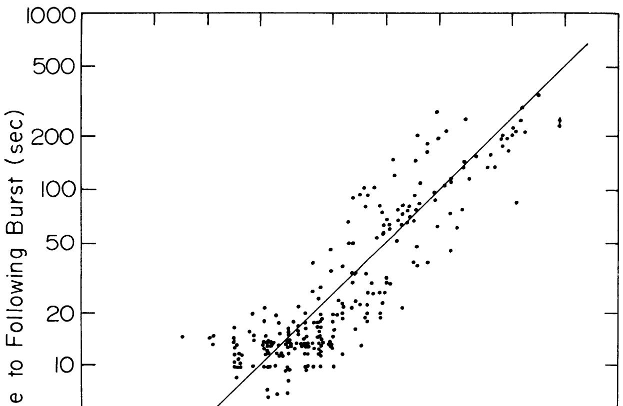

FIG. 3.—The relation between the X-ray energy in a burst and the time interval to the following burst. The burst energy (~1.5–10 keV) is normalized to an assumed source distance, *D*, of 10 kpc. If the energy in the first burst were linearly proportional to the time separation between this and the following burst, then the points would fall on a straight line which is inclined at 45° (one such line is drawn). Uncertainties in the time intervals could be ~40% (only at the low end of the scale). Uncertainties in the relative burst energies are ±20% (see text).

±20 percent from a mean value. As a result, there is a ±20 percent jitter in the relative energies in the data points.

As can be seen from Figure 3, the approximate linear relation between the energy in a burst and the time interval to the next burst holds quite well for bursts in the range ~2×10^{38} ergs to ~6×10^{39} ergs (for an assumed distance of 10 kpc). One can see from Figure 3 that no bursts were observed with energies either larger than ~10^{40} ergs or with energies less than ~10^{38} ergs. Also, time intervals between bursts of less than ~6 s were not observed.

There is a maximum peak luminosity for the X-ray bursts (regardless of whether they last 5 s or 60 s). This luminosity is equivalent to about 150 counts s^{-1} (horizontal tubes) and amounts to ~2×10^{38} ergs s^{-1} for an assumed source distance of 10 kpc. All of the six giant bursts shown in Figure 1 have reached this maximum level.

When MXB 1730−335 is Earth occulted, the measured X-ray intensity in the horizontal tube system is about half the non–X-ray burst intensity when the source is not occulted. The difference between these two levels of X-ray intensity can be due to (i) a steady luminosity from 3U 1727−33 (only ~0°.7 from MXB 1730−335); (ii) a non–X-ray background; (iii) a possible steady luminosity (not in X-ray bursts) from MXB 1730−335. We have no knowledge of the contributions of (i) and (ii); therefore, we can only set an upper limit to (iii). This upper limit is ~18 counts s^{-1}

in the horizontal tube which represents about 4×10^{37} ergs s^{-1}. The time averaged X-ray burst luminosity of the source is about 2×10^{37} ergs s^{-1} (for an assumed distance to the source of 10 kpc).

III. DISCUSSION

The following appear to be the salient properties of these rapidly repetitive bursts: (1) Their rise times are almost always $\lesssim 1$ s. (2) The repetition rate is highly and irregularly variable. (3) The burst patterns can change significantly in about half an hour. (4) The interval between a given burst and the next burst is approximately proportional to the total energy of X-rays in the given burst. (5) The energy release in the bursts varies by ~ 2 orders of magnitude from $\sim 10^{38}$ to $\sim 10^{40}$ ergs (for an assumed distance to the source of 10 kpc). (6) The X-ray luminosity during a burst does not exceed a certain level ($\sim 2 \times 10^{38}$ ergs s^{-1} for the same assumed distance). (7) The average X-ray luminosity in bursts amounts to $\sim 2 \times 10^{37}$ ergs s^{-1} for the same assumed distance. (8) The average non-burst luminosity is less than 4×10^{37} ergs s^{-1} for the same assumed distance. (9) The burst spectrum does not exhibit a substantial low-energy cutoff. (10) Rapid repetitive bursts were not detected during extended observations of the same region several weeks earlier.

The short rise times suggest that the energy in a burst is released in a region small compared to the diameter of a normal nondegenerate star. The large and irregular variability of the repetition rate implies that the bursts are not controlled by a periodic mechanism such as an orbiting or rotating system, or by a mechanical oscillator with one or more characteristic frequencies. Rather, the approximately proportional relation between the burst energy and the time interval to the following burst is the behavior that one expects of a relaxation oscillator powered by a steady flow of energy.

It seems to us that the most likely source of this energy is accretion of matter onto a compact star. The high value of the average luminosity in the bursts suggests that the energy released in bursts, per unit of accreted mass, is large compared to nuclear binding energies, i.e., that it is a substantial fraction of mc^2 as is the case for accretion onto a neutron star or black hole. In particular, the bursts probably cannot be the result of nuclear burning (hydrogen flashes) on the surface of either a neutron star or a white dwarf. In the case of a neutron star, the steady X-ray emission would dominate the time-averaged burst emission by more than an order of magnitude because of the higher energy yield in the accretion process. Nuclear burning on a white dwarf would lead to a (recurrent) nova phenomenon with known temporal properties which do not resemble those of the present source.

With these considerations in mind, we suggest that the bursts are caused by plasma instabilities in an orderly magnetosphere such as may exist in the neighborhood of a magnetized neutron star. (This mechanism was suggested to us by F. K. Lamb [1976] in connection with previously detected burst phenomena.) Matter falling toward the star is arrested in a reservoir at a distance from the surface that is large compared to the radius of the neutron star. Only a small fraction of the gravitational energy is released up to that point. The matter piles up in the reservoir until its total mass exceeds a critical value, whereupon the reservoir springs a leak and some matter falls toward the surface, releasing most of its gravitational potential energy as a burst of thermal X-rays. The leak heals, and the source is relatively quiet until the reservoir fills up again to the point of instability, whereupon another burst occurs. If such a process emptied the reservoir during each burst, then the size of a burst would be correlated with the time interval to the previous burst. In contrast, the observed correlation of burst size with the succeeding interval suggests that the reservoir is partially drained whenever its level reaches a critical upper limit.

The absence of rapid repetitive bursts only a few weeks earlier indicates that the material for accretion is likely to be drawn not from a large cloud of interstellar material but rather from a binary companion. The latter source of accretion, as we know from other binary systems, can be highly variable or even intermittent.

The conditions for the stability of plasma in the magnetosphere of a neutron star have been examined by Lamb (1974; 1975), Elsner and Lamb (1976), and Arons and Lea (1976). They showed that a plasma cloud supported by magnetic pressure is subject to a Rayleigh-Taylor instability if its temperature falls below a critical value. They discuss only the onset of the instability (which is expected to allow plasma to penetrate over most of the magnetosphere boundary except near the poles) and steady mass flows. We note that our observations indicate that the critical parameter for stability is not temperature but total mass. Furthermore, the data show that stability is frequently restored before the reservoir is emptied.

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