X-RAY BURSTS

George W. Clark
Department of Physics and Center for Space Research
Massachusetts Institute of Technology, Cambridge, Massachusetts

Most of the variable phenomena of high-luminosity ($\gtrsim 10^{36}$ erg s^{-1}) stellar X-ray sources can be explained, at least qualitatively, within the general framework of binary accretion models in which thermal X-rays are emitted in the vicinity of a neutron star or blackhole by plasma that has flowed downhill from the surface of a nuclear burning companion and been heated by conversion of its gravitational potential energy. The yield of X-ray energy in this process is so high, exceeding in some cases $0.1c^2$ per unit mass, that X-ray luminosities in excess of $10^4 L_\odot$ can be generated with accretion rates of only $\sim 10^{-8}$ $M_\odot$ per year. Since the transfer process depends strongly on many parameters that specify the relevant properties of two stars and their interaction, one finds a remarkable variety and range of X-ray phenomena. If the compact object is a magnetized neutron star, rotation will cause its X-ray emission pattern to sweep over a distant observer and thereby produce regular pulsations like those observed with periods in the range from 1 to 10^3 seconds. Orbital motions can cause regular eclipses and absorption dips like those observed with periods in the range from hours to days. Changes in the rate of mass loss by the nuclear burning star or in the transfer efficiency can account for the variations in intrinsic X-ray luminosities that appear as flares, novae and on-off transitions. Irregularities in the flow of plasma near the compact star can also affect the intrinsic luminosity and appear as erratic fluctuations, spikes and shot-noise in the observed intensity.

Recently Babushkina et al. (1975) discovered a new and qualitatively distinct kind of X-ray variation that may also fit within the general binary accretion model, though it was entirely unpredicted and is, indeed, a most surprising phenomenon. In data obtained by the Kosmos 428 satellite in 1971 they found two brief, intense "bursts" of X-rays recorded by detectors sensitive above 40 keV from two different sources lying within about 20 degrees of the galactic center. In both bursts the intensities rose to peak values in about 1s and decayed in $\lesssim$10s, and the total energy fluxes at the detector were of the order of 3×10^{-6} ergs cm^{-2}. The bursts differed from typical gamma ray bursts in having much softer spectra and much smaller energy fluxes.

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part I, 101-110.

In December of 1975 Grindlay and Heise (1975), working with data obtained in September of 1975 by the ANS satellite and without prior knowledge of the earlier Russian work, reported two brief bursts of 1-30 keV X-rays from a source at a position within a 1'x30' error box which includes the X-ray source 3U1820-30 in the globular cluster NGC6624. Given the known distance of the cluster, the total energy released per burst was found to be in excess of 10^{39} ergs. Subsequently, a search of data recorded in May 1975 by the SAS-3 X-ray observatory revealed ten bursts from the same source, and showed that they recurred at intervals which fluctuated by 4% about a mean value of $0^{d}18$ (Clark 1976a).

During the past nine months there have been many discoveries of X-ray "bursters" and their peculiar properties, both from the currently operating X-ray satellites SAS-3, OSO-8, ANS and Ariel-5, and from the data banks of the Vela and UHURU satellites. The purpose of this review is to give a general account of the status of observations and theories of "bursters" as of August 26, 1976 without attempting to duplicate the comprehensive review prepared recently by Lewin (1976a).

Figure 1 shows the ten bursts from NGC6624 recorded by SAS-3, and

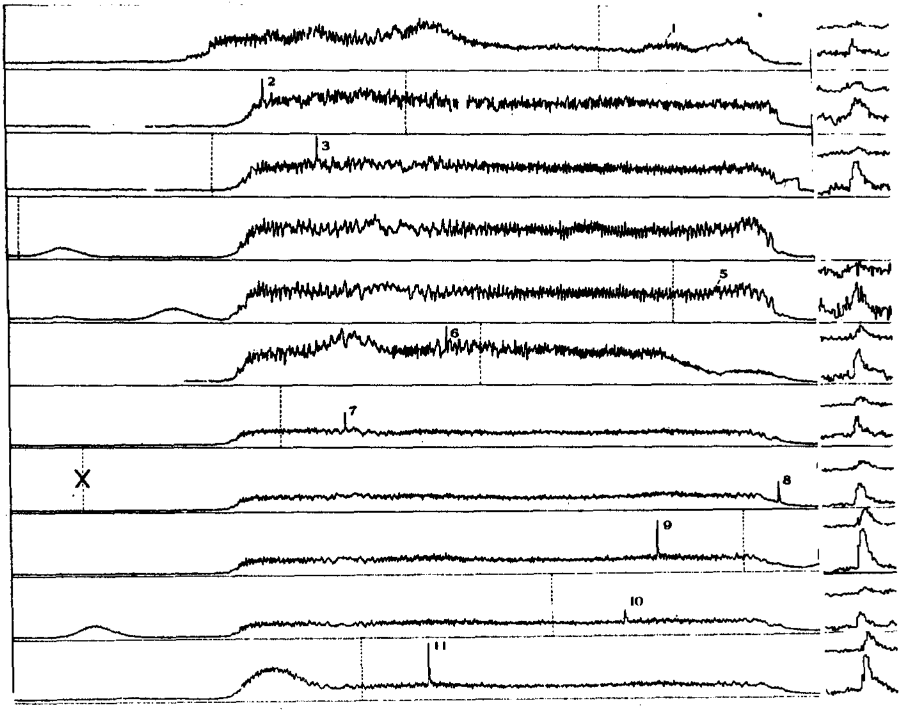

Fig. 1. - Ten X-ray bursts numbered 1 to 11 (number 4 missing, presumably due to Earth occultation) observed with modulation collimator detectors on the SAS-3 (Clark et al. 1976). Dashed lines show times in the sequence $t_0 + 0.1822k$ ($k = 1,2,...11$). Expanded light curves of each burst are shown on the right (2-6 keV below, 6-11 keV above).

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

Figure 2 is a composite of the last five bursts which shows their average temporal structure and spectral evolution (Clark et al. 1976). As in the case of the Kosmos 428 bursts, these rose in ~1 sec and decayed in $\lesssim$10 sec. Their spectra, however, are much softer than the Kosmos 428 bursts. They show a progressive hardening as noted earlier in the ANS data by Grindlay et al. (1976), and as is clearly seen in the hardness ratio plot of Figure 2. A similar hardening is shown by one of the Kosmos 428 bursts (Babushkina, et al. 1975). Probably the most significant fact about the NGC6624 bursts is, however, their quasi-periodic recurrence with phase jitter. Together with the temporal structure of the bursts themselves it reveals the actions of a mechanism on four widely different time scales. The bursts rise in ~1s, decay in ~10s, and recur in 15000s with a phase jitter of 600s.

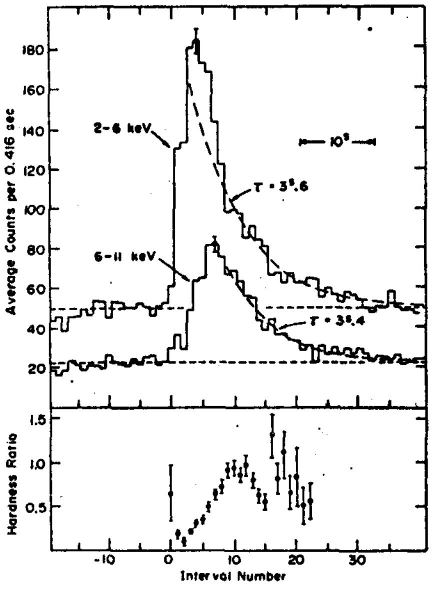

Fig. 2 - Co-added light curves of bursts 7-11, and plot of the hardness ratio (6-11 keV) ÷ (2-6 keV).

When the recurrence phenomenon came to light the question immediately arose as to whether the bursts were produced by a precisely periodic rotational or orbital mechanism with a superposed phase jitter like that implied by the model of Bahcall and Ostriker (1976) in which an orbiting neutron star crashes through the accretion disc of a massive black hole. Alternatively, it seemed the bursts could be the product of some kind of stellar relaxation oscillator, and therefore subject to the vagaries of phase and period one expects in such devices, both terrestrial and cosmic.

In an effort to learn more about the NGC6624 bursts the y-axis detectors of SAS-3 were pointed at NGC6624 for a period of one week during the latter part of January 1976. The persistent source 3U1820-30

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

was found to be in a state of high luminosity and no bursts were detected from the cluster. This added to the evidence for a correlation between bursts and the intensity of 3U1820-30 that had been suggested by the ANS investigators who observed NGC6624 twice, once in a high state of 3U1820-30, and once in a low state, and found bursts in only the low state.

During this same January observation bursts were detected by the "slat collimator" detectors which have long and narrow rectangular fields of view. During the observation of NGC6624 these fields of view crossed the galactic equator in the vicinity of the galactic center. A similar configuration occurred during the next scheduled observation which was a study of the X-ray pulsations of GX1+4. Again bursts were detected, not from the region of GX1+4, but, as before, from 2 of the long and narrow slat collimators that crossed the galactic equator, this time at a different angle. Shortly thereafter the y-axis was moved to the galactic center as originally scheduled, and bursts with a variety of shapes and recurrence patterns were detected. When these were sorted out three new burst sources were found within ~0.5 degrees of $\ell^{II} = 0°$, $b^{II} = 0°$, (Lewin 1976b,c; Clark, 1976b; Hoffman 1976; Lewin et al. 1976b). No previously reported globular cluster lies within their error boxes. Each source produced bursts with characteristic shapes, spectrum, recurrence rate, and phase jitter. For example, bursts from MXB1743-29 were double peaked and had a 1.46-day recurrence interval with a 6.2% rms phase jitter.

The SAS-3 observatory was later moved to point the y-axis detectors at a nearby region in Scorpio where intersections of several slat collimator patterns had indicated the presence of another burst source. Suddenly an astonishing phenomenon appeared in all four detectors which have fields-of-view that overlap in a ~1 deg^2 region around the y-axis. Bursts were detected in rapid fire sequences with separations ranging from ~6 to 400 seconds, and sizes ranging over nearly two orders of magnitude (Lewin, 1976d; Hearn, 1976; Lewin et al. 1976a). Typical data are shown in Figure 3. Observations during the next several days established the following properties of these bursts from MXB1730-335, the "rapid burster":

1) The total energy in a burst is proportional to the time to the next burst, i.e., after every burst the source "recovers" for a time proportional to the size of the burst

2) The peak intensity is approximately the same for all bursts

3) The recurrence patterns are highly variable and change qualitatively on time scales of hours, e.g., long sequences of nearly equal bursts may change within a few hours to short series of small bursts terminated by a very large one.

We note that a few of the bursts from MXB1730-335 do not conform to 1) and 2) above. These anomolous bursts are the subject of a forthcoming paper (Ulmer et al. 1976).

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

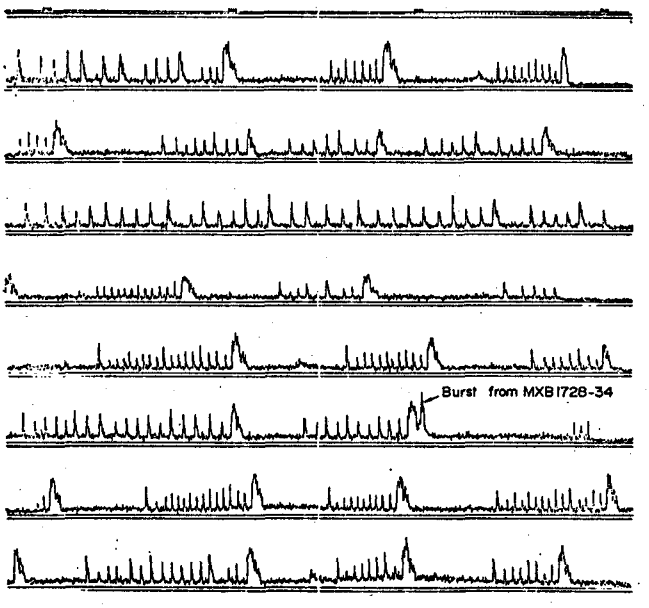

Fig. 3 - 24-Minute snapshots from eight orbits of SAS-3 during pointed-mode observation of MXB1730-335, the rapid burster, on March 2/3, 1976. In the sixth orbit there is a burst from a slow burster, MXB1728-34, (Hoffman et al. 1976) which was also in the field of view.

Immediately after the discovery and the approximate position of the rapid burster were announced (IAU Circulars 2922 and 2925) a previously unrecorded, highly obscured cluster, "probably globular", was found in the error box on a far red, deep sky plate by Liller, and refined measurements of positions were made by ANS and Ariel-5 (IAU Circular 2929). Subsequent IR scans by Kleinman, Kleinman and Wright (1976) have since confirmed the identification of the object as a globular cluster. Thus a second source of X-ray bursts, albeit unique in their rapid recurrence, is apparently located within a globular cluster. The recurrence characteristics of the rapid burster clearly suggest that it is a cosmic relaxation oscillator which must "recharge" to a critical trigger level after each burst before it can produce the next one. In this way its action resembles that of a neon-bulb flasher with a variable depth of discharge and not that of a water tank that empties every time it is flushed.

In the course of investigating the rapid burster, several bursts of a different and distinct form were also recorded from another new burst source, MXB1728-34, (Lewin, 1976d) which lies less than 1° away. One of its bursts can be seen on top of a large burst from the rapid burster in Figure 3. In contrast to bursts from NGC6624, the spectra of the bursts from MXB1728-34 soften with time. In addition the average recurrence interval changed significantly from week to week (Hoffman et al. 1976). This variability of the recurrence interval again suggests the action of a relaxation oscillator, in this instance with

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

a variable power supply. As in the cases of the three sources near the galactic center, no globular cluster has been detected at the position of MXB1728-34 on the same plate on which Liller found the faint globular cluster associated with the rapid burster.

Returning once more to NGC6624, an 8-day observation by SAS-3 was carried out from March 11 to 19 of 1976, and during the first four days 22 bursts were recorded in a series with an apparent mean interval which was not the old $0^{d}.18$ but $0^{d}.12$ (Clark 1976c). Moreover, the intervals between bursts decreased from $\sim 0^{d}.14$ to $0^{d}.09$ before the bursts ceased on the fourth day at which time the intensity of 3U1820-30, the highly variable and persistent source in NGC6624 had risen from a low level to about one-third of the peak values it achieved on the sixth and subsequent days. This established that the burst mechanism is, like that of both the slow and rapid bursters in Scorpio, a relaxation oscillator driven by a variable power supply. Furthermore it proved that the burst source is identical with the persistent and highly variable source 3U1820-30.

The position of 3U1820-30 within the globular cluster and the possible identification of an optical or other counterpart is clearly a matter of the greatest interest. If its mass is much greater than the average mass of cluster members ($\sim 0.6 M_{\odot}$) then it should be very close to the center. The error area of the Uhuru position (Giacconi, et al. 1974) was only 2.4 square arc minutes and it included the center of the globular cluster NGC6624 with which it was tentatively identified. The preliminary SAS-3 position, derived from rotation modulation collimator data, reduced this by half to an error circle of radius 40 arc seconds (Jernigan et al. 1975) within which lies the center of the cluster and, for that matter, most of the stars of the cluster. A further reduction is anticipated when final calibration and reduction of the SAS-3 measurements are completed in the near future. The next major improvement should come from the HEAO-B telescope which will give ~1 arc second accuracy, sufficient to measure the possible displacement of all but a possible super-massive body from the gravitational center of the cluster.

The original discovery that one of the five previously known variable X-ray sources located in globular clusters is also a source of bursts itensified interest in the problems of the nature and the origin of the cluster sources. The discovery of an obscured globular cluster at the site of the rapid burster further intensified it.

It is clear that cluster sources cannot be binaries with massive nuclear burning components like most of the bright X-ray sources found in the spiral arms since all globular cluster stars more massive than $0.8 M_{\odot}$ have already burned out. On the other hand one can reasonably assume that some of the neutron star or blackhole remnants of the original massive stars remained in the shallow gravitational wells. Therefore, to explain the existence of X-ray sources in globular clusters it may suffice to show how a few of these remnants

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

in special clusters can be supplied with material to generate X-rays by the accretion mechanism. These clusters are, indeed, special, being highly condensed at their centers as shown by prior data, particularly that of Peterson and King (1975), and by the recent studies of Bahcall (1976) and Bahcall and Hausman (1976). In the case of NGC6624 short exposures show a bright unresolved region, about 4" in size, near the cluster center. The blob appears to be unresolved stars in a region of very great stellar density amounting to $\sim 10^5 M_{\odot} pc^{-3}$. It seems possible that this high concentration is an important clue to the nature of the supply of accretion material for the X-ray source.

Two divergent lines developed from the start in efforts to explain the cluster X-ray sources. Clark (1975) suggested they are, like the disc sources, close binaries formed through capture of field stars by compact remnants in the central regions of high stellar density. Several capture processes have been suggested of which the more plausible are tidal friction in close two-body encounters (Fabian, Pringle and Rees 1975), and exchange collisions between compact remnants and primordial Population II close binaries (Hills 1976). Speculations along the other line were stimulated by earlier work concerned with the possible formation of massive black holes by gravitational collapse of the central regions of condensed globular clusters. Bahcall and Ostriker (1975) and Silk and Arons (1975) suggested that such an object would be supplied with accretion material if it lay at the center of a cluster with sufficiently high central escape velocity to retain matter ejected as stellar winds by stars of the general population. The matter would fall toward the center of the cluster to feed the X-ray generating accretion process of the black hole.

The discovery of bursts and their property of quasi-periodic recurrence stimulated further elaboration of both these ideas. Seeking an explanation for the ~10 second decay and progressive spectral hardening of the NGC6624 bursts, Grindlay and Gursky (1976a) suggested a reverberation theory of the burst tails which, in their analysis, implied that the source is a massive blackhole. In this theory X-rays produced in a brief ($\lesssim 2$ s) primary burst, are multiple scattered by the electrons in a hot plasma cloud surrounding the source, thereby giving rise to a reverberation "tail". Attributing the spectral hardening of the tail to an average energy shift which is proportional to $kT/m_e c^2$ per scattering, they found the required plasma temperature is so high that the cloud could be gravitationally bound only by a central body with a mass $> 10^2 M_{\odot}$, i.e. a supermassive black hole. A more complete treatment by Canizares (1976) has shown, however, that the observed hardening can be accounted for as the spread in the spectral distribution produced by Doppler shifts in scattering from a much cooler plasma cloud, and that the necessary cloud could be retained by a neutron star. Thus the spectral and temporal properties of the NGC6624 bursts themselves do not lend new support to the massive blackhole hypothesis. Moreover, spectral hardening itself is not a general property of bursts since, as noted above, the spectra of

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press

bursts from MXB1728-34 soften in their decay phase as do bursts from numerous other sources (Lewin, 1976a).

The positions of the sources provide the most direct evidence bearing on the relation of burst sources to globular clusters. Only two of the 15 or so known burst sources are definitely located within the limits of known clusters (Lewin, 1976a). No clusters are found within the error boxes of the three bursters at the galactic center, two of the three burst sources found in the Aquila-Serpens region by OSO-8 (Swank et al. 1976) and SAS-3 (Lewin et al. 1976c,d; Li and Lewin 1976), MXB1728-34 discussed above, the Norma burster discovered by Vela (Belian et al. 1976; Grindlay and Gursky 1976b), and two poorly positioned sources detected by SAS-3 of which one is in Pupis (Doty 1976) and the other probably in Taurus (Lewin 1976a). To maintain the hypothesis that all of these are in previously unknown and highly obscured globular clusters one would have to accept the implication that burst sources are perfect markers of a previously unrecognized subclass of highly obscured globular clusters. In addition, the apparent concentration of the burst sources toward the plane of the galaxy, is qualitatively different from the nearly spherical distribution of clusters about the galactic center. Thus there is little doubt that X-ray burst sources occur outside as well as inside globular clusters as do ordinary variable X-ray sources. Moreover, considering that two burst sources are in clusters, it seems likely that burst sources, like variable X-ray sources in general, occur more frequently in globular clusters in proportion to other stars than elsewhere in the galaxy. Finally, in one certain case (3U1820-30) and at least in three probable cases (MXB1728-34, MXB1906+00 and MXB1837+05) there is a persistent source associated with the burst source (Lewin 1976a). All of this points to the conclusion that X-ray bursts are a phenomenon of ordinary high-luminosity variable X-ray sources, in effect, a peculiar, but not rare, mode of X-ray emission.

In January of 1976, during private discussions on bursts at the Cambridge (Mass.) AAS Symposium on High Energy Astrophysics, F. Lamb suggested to us that bursts were caused by plasma instabilities in the magnetospheres of accreting neutron stars in binary systems. The general problem of such instabilities has been explored in the context of accretion flows by Arons and Lea (1976) and by Elsner and Lamb (1976). Following discovery of the rapid burster and its behavior suggestive of a relaxation oscillator, the idea of bursts as plasma instabilities has been worked out in more detail by Baan (1976) and by Lamb et al. (1976). At the present time this model appears promising with a range of possible phenomena that may prove sufficient to encompass all the complex behavior recorded so far. In this model, plasma, trapped in the magnetosphere of an accreting star, rains to the surface, either continuously in small bits or spasmodically in giant blobs, depending upon the particular combination of circumstances defined by the magnetic field, the accretion rate, the rotation rate and, presumably, the recent history. Thus X-ray bursts may prove to be a new and powerful probe of the plasma physics around neutron stars.

REFERENCES

Arons, J. and Lea, S.M.: 1976, Ap.J. 207, 914.
Baan, W.: 1976, Ap.J. to be published.
Babushkina, O.P., Bratolyubova-Tsulukidze, L.S., Kudryavtsev, A.S., Melioranskii, A.S., Savenko, I.A., and Yushov, B.Yu.: 1975, Sov. Astron. Lett. 1, 32.
Bahcall, J.N. and Ostriker, J.P.: 1975, Nature 256, 23.
Bahcall, J.N. and Ostriker, J.P.: 1976, Nature 262, 37.
Bahcall, N.A.: 1976, Ap.J. (Letters) 204, L83.
Bahcall, N.A. and Hausman, M.A.: 1976, Ap.J. (Letters) 207, L181.
Belian, R.D., Conner, J.P. and Evans, W.D.: 1976, Ap.J. (Letters) 206, L135.
Canizares, C.: 1976, Ap.J. (Letters) 207, L101.
Clark, G.W.: 1975, Ap.J. (Letters) 199, L143.
Clark, G.: 1976a, I.A.U. Circular, No. 2907.
Clark, G.: 1976b, I.A.U. Circular, No. 2922.
Clark, G.: 1976c, I.A.U. Circular, No. 2932.
Clark, G.W., Jernigan, G.W., Bradt, H., Canizares, C., Lewin, W.H.G., Li, F.K., Mayer, W., and McClintock, J.: 1976, Ap.J. (Letters) 207, L105.
Doty, J.: 1976, I.A.U. Circular, No. 2922.
Elsner, R.F. and Lamb, F.K.: 1976, Ap.J., to be published.
Fabian, A.C., Pringle, J.E. and Rees, M.J.: 1975, Mon. Not. R. Astr. Soc. 172, 15p.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., and Tannenbaum, H.: 1974, Ap.J. Suppl. 27, 37.
Grindlay, J. and Heise, J.: 1975, I.A.U. Circular, No. 2879.
Grindlay, J., Gursky, H., Schnopper, H., Parsignault, D.R., Heise, J., Brinkman, A.C. and Schrijver, J.: 1976, Ap.J. (Letters) 205, L127.
Grindlay, J. and Gursky, H.: 1976a, Ap.J. (Letters) 205, L131.
Grindlay, J. and Gursky, H., 1976b, preprint # 550.
Hearn, D.: 1976, I.A.U. Circular, No. 2925.
Hills, J.G.: 1976, Mon. Not. R. Astr. Soc. 175, 1p.
Hoffman, J.H.: 1976, I.A.U. Circular No. 2946.
Hoffman, J.A., Lewin, W.H.G., Doty, J., Hearn, D., Clark, G.W., Jernigan, G. and Li, F.K.: 1976, Ap.J. (Letters), November 15.
Jernigan, J.G., Canizares, C., Clark, G., Doxsey, R., Epstein, A., Matilsky, T., Mayer, W. and McClintock, J.: 1975, B.A.A.S. 7, 443.
Kleinman, D.E., Kleinman, S.G. and Wright, E.L.: 1976, preprint.
Lamb, F., Fabian, A.C., Pringle, J.E. and Lamb, D.Q.: 1976, preprint.
Lewin, W.H.G.: 1976a, Mon. Not. Roy. astr. Soc., in print.
Lewin, W.H.G.: 1976b, I.A.U. Circ. 2911.
Lewin, W.H.G.: 1976c, I.A.U. Circ. 2918.
Lewin, W.H.G.: 1976d, I.A.U. Circ. 2922.
Lewin, W.H.G., Doty, J., Clark, G.W., Rappaport, S.A., Bradt, H.V.D., Doxsey, R., Hearn, D.R., Hoffman, J.A., Jernigan, J.G., Li, F.K., Mayer, W., McClintock, J., Primini and J. Richardson: 1976a, Ap.J. (Letters), 207, L95.
Lewin, W.H.G., Hoffman, J.A., Doty, J., Hearn, D.R., Clark, G.W.,

Jernigan, J.G., Li, F.K., McClintock, J.E., and Richardson, J.: 1976b, Mon. Not. R. astr. Soc., December.
Lewin, W.H.G., Hoffman, J.A., Doty, J., Buff, J., Clark, G.W., and Rappaport, S., 1976c, Mon. Not. R. astr. Soc., December.
Lewin, W.H.G., Doty, J., Hoffman, J.A. and Li, F.K.: 1976d, I.A.U. Circ. 2984.
Li, F.K. and Lewin, W.H.G.: 1976, I.A.U. Circ. 2983.
Peterson, C.J. and King, I.R.: 1975, A. J. 80, 427.
Silk, J. and Arons, J.: 1975, Ap.J. (Letters), 200, L131.
Swank, J.H., Becker, R.H., Provado, S.H. and Serlemitsos, P.J.: 1976, I.A.U. Circ. 2963.
Ulmer, M.,Lewin, W.H.G., Hoffman, J.A. and Doty, J.: 1976, submitted to Ap.J. (Letters).

DISCUSSION

J.F. Dolan - I would like to point out that the "relaxation oscillator" behavior of a repetitive burster (the time between bursts is linearly proportional to the intensity of the preceding burst) is reminiscent of the behavior of optical flares from U Geminorum type systems. Perhaps this may indicate that the repetitive X-ray burster is also a close binary with a dwarf primary, although the secondary would have to be a compact object.

https://doi.org/10.1017/S1539299600002446 Published online by Cambridge University Press