THE ASTROPHYSICAL JOURNAL, 227:294–298, 1979 January 1

X-RAY BURSTERS AND "SOFT" X-RAY TRANSIENTS: DIFFERENT PHENOMENA FROM THE SAME OBJECTS

G. FABBIANO AND G. BRANDUARDI
Harvard-Smithsonian Center for Astrophysics
Received 1978 May 10; accepted 1978 July 17

ABSTRACT

A statistically significant association is found between X-ray bursters and "soft" X-ray transients. Some of the observational evidences about galactic X-ray sources are reviewed. The data support the picture of galactic X-ray sources as due to compact objects in a variety of binary system environments.

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

I. INTRODUCTION

The long-term behavior of H1608−522 (Fabbiano *et al.* 1978) led the authors to suggest the association of X-ray bursters with X-ray transients. The possibility of such an association for two of the galactic center bursters with the X-ray transients A1742−28 and A1743−29 had been noted by Lewin *et al.* (1976*a*). The recent discovery of a transient X-ray source at the location of the burster MXB 1659−29 (Lewin *et al.* 1978; Share *et al.* 1978; Griffiths *et al.* 1978*b*) seems to confirm the validity of the suggestion that X-ray bursters and X-ray transients are closely related phenomena. The weight of the recent development has led us to review all of the available data which bear on the hypothesis that transients and bursters are different states of galactic variable X-ray sources. The results of this analysis indicate that this association is statistically significant and further unifies the picture of galactic X-ray sources as due to compact objects in a variety of binary system environments.

II. DATA

For our analysis we considered all the X-ray bursters reported in the literature for which a reasonably good positional determination exists (maximum error box size of a few square degrees). We then reviewed the X-ray observations since 1964 at the locations of these X-ray bursters. In particular, we looked for evidence which indicated transient-like behavior.

The results of our search are given in Table 1, along with the references; six bursters were found to be associated with longer-term transient X-ray emission. Two of these, XB 1608−52 and Aql MXB, are associated with well-known transients, MX 1608−52 (Kaluzienski *et al.* 1975; Fabbiano *et al.* 1978 and references therein) and Aql X-1 (Buff 1975; Kaluzienski *et al.* 1976, 1977*a*), respectively. Two, MXB 1742−29 and MXB 1743−29, have error boxes which include the positions of the transients A1743−29 and A1742−28, respectively (Lewin *et al.* 1976*a*). Evidence of bursting activity in the galactic center region was also present in earlier *Copernicus* data, while monitoring the decay of the transient A1742−28 (Branduardi 1977). A fifth burster, MXB 1659−29, has recently been associated with a transient X-ray source (Lewin *et al.* 1978; Share *et al.* 1978; Griffiths *et al.* 1978*b*). The sixth one is MXB 1636−53, which is associated with the source 4U 1636−53. This source is not listed as a transient in the 4U catalog, where its intensity is reported to be between 125 and 250 counts s^{-1}. However, Parsignault and Grindlay (1978) report that the source appeared to be below the threshold of detectability when it was observed by *ANS* in 1975 March. Their 3σ upper limit is equivalent to 22 *Uhuru* counts s^{-1}. Six months later *ANS* observed an average flux equivalent to 95 ± 1 *Uhuru* counts s^{-1}. The *Uhuru* data are not inconsistent with 4U 1636−53 being a recurrent transient. In fact, this source was observed in high intensity in 1971 March for a month and then again in 1972 October–December. Another possible association between an X-ray burster and a transient is found if we consider the pre-*Uhuru* data. This involves the transient Cen XR-4 (Evans, Belian, and Conner 1970) and a long burst that was observed from the same area of the sky 2 days before the transient appeared. Even if the error boxes are rather large (a few square degrees), the two events are likely to be associated with the same object due to the low density of sources in that region of the sky. The burst lasts longer (10 minutes) than most of the observed X-ray bursts but its time behavior and spectral evolution are those characteristic of an X-ray burst.

III. ANALYSIS

To calculate the number of chance coincidences between X-ray bursters and transient-like sources, we restrict ourselves to the region of sky where most of the bursters are observed, namely, between $-10° < b^{\text{II}} < +10°$ and $320° < l^{\text{II}} < 40°$. Fifteen bursters are located in this area. Since the density of X-ray sources is higher in the vicinity of the galactic center, we divide the area in three bins: (1) $10° < l^{\text{II}} < 40°$ and $320° < l^{\text{II}} < 350°$; $-10° < b^{\text{II}} < 10°$; (2) $350° < l^{\text{II}} < 10°$;

TABLE 1

X-Ray Bursters, Associated Transients, and Their Steady X-Ray and Optical Counterparts

Burster	X-Ray "Steady" Source	Associated Transient	Optical Counterpart	Burster Error Box* (sq. deg.)	References
MXB 0512−40	4U 0513−40	...	Globular cluster NGC 1851	0.0001	a
0615+09	4U 0614+09	...	...	0.13	b,c,d,e
Cen XR-4	...	Cen XR-4	Globular cluster NGC 5824?	16	f,g,h
XB 1608−52[1]	MX 1608−52	H1608−522	Reddened object	3.0	i,j,k
MXB 1636−53[1]	4U 1636−53	4U 1636−53	blue star	0.1	a
MXB 1659−29[2]	...	1659−29	...	0.1	a,l,m,n
MXB 1728−34[2]	4U 1728−33	...	...	0.1	a
MXB 1730−335[2]	...	...	Reddened globular cluster	0.1	a
MXB 1735−44[1]	4U 1735−44	...	Blue star	1.5	a
MXB 1742−29[3]	GCX	A1743−29	...	0.34	o
MXB 1743−28[3]	GCX	...	...	0.28	o
MXB 1743−29[3]	GCX	A1742−28	...	0.18	o
1 square degree containing 4U 1746−37[1]	4U 1746−37	...	Globular cluster NGC 6441	1.0	p
4U 1820−30[2]	4U 1820−30	...	Globular cluster NGC 6624	0.1	a
MXB 1837+05[1]	4U 1837+04	...	Blue star	0.1	a
MXB 1906+00[1]	A1905+00	...	...	0.1	a
Aql MXB[1]	4U 1908+00	Aql X-1	K0 star	2.4	q,c,r
MXB 1916−05[1]	4U 1915−05	...	...	0.1	a

* The values used in the probability calculation have been modified as discussed in the text.

References.—[a] Lewin and Joss 1977 and references therein; [b] Lewin 1976; [c] Forman *et al.* 1978; [d] Lewin, Hoffman, and Doty 1976; [e] Davidsen *et al.* 1974; [f] Belian, Conner, and Evans 1972; [g] Evans, Belian, and Conner 1970; [h] Seward and Liller 1977; [i] Grindlay and Gursky 1976; [j] Fabbiano *et al.* 1978; [k] Grindlay and Liller 1978; [l] Lewin *et al.* 1978; [m] Share *et al.* 1978; [n] Griffiths *et al.* 1978*b*; [o] Lewin *et al.* 1976*a*; [p] Li and Clark 1977; [q] Lewin 1977; [r] Thorstensen, Charles, and Bowyer 1978.

$-10° < b^{II} < 10°$, with the exclusion of a 16 square degrees region at the galactic center, which we take as bin 3; and (3) $358° < l^{II} < 2°$, $-2° < b^{II} < 2°$. The bursters in Table 1 are labeled with a superscript 1, 2, or 3, to designate to which one of the bins they belong. Since we have no way of correcting the number of observed bursters for coverage, we calculate the upper limit for the number N of chance coincidences, multiplying the density of transients in each bin by the total burster uncertainty area and adding together the contributions of the three bins:

$$N = \sum_{i=1}^{3} \frac{NT_i{}^*T}{A_i} \sum_{j=1}^{n_i} A_j$$

where

- A_i is the area of the bin under consideration.
- NT_i is the yearly rate of transients in that bin ($NT_i = 1.64, 0.65, 0.26$ for $i = 1, 2, 3$).
- T is the total time interval in which we find systematic X-ray observations. This covers the period since the *Uhuru* launch up to now (7.5 years).
- n_i is the number of bursters in the bin under consideration ($n_i = 7, 5, 3$ for $i = 1, 2, 3$).
- A_j is the uncertainty area around each burster (Lewin 1977; Lewin and Joss 1977; Li and Clark 1977; Lewin, Hoffman and Doty 1976). For bursters whose error box is less than 0.1 square degrees we take $A_j = 0.1$ square degrees; otherwise we use the burster error box area. We do this to make the burster error boxes comparable to those of the 4U sources.

To obtain NT_i we use the upper limit for the yearly rate of transients estimated by Cominsky *et al.* (1978) over all the galactic plane and we correct it according to the distribution in galactic longitude of the 4U sources within $\pm 10°$ of the galactic plane. The correction factor for each bin is given by the fraction of 4U sources in that bin with respect to the total number of 4U sources within $\pm 10°$ of galactic latitude. The underlying assumption is that the galactic plane X-ray transients belong to the same population as the generality of the galactic plane X-ray sources, which is confirmed by X-ray observations and optical identifications (see, e.g., Cominsky *et al.* 1978). The 4U coverage of the galactic plane region is quite uniform, especially near the galactic center.

The *Uhuru* satellite did not have enough spatial resolution to resolve the galactic center region. For this reason, to calculate the number of expected transients for bin 3 we use the latest results of Cruddace *et al.* (1978), who detected six sources at the galactic center.

Since the actual coverage is less than the 7.5 years we use, and since NT_i is an upper limit, we are abundantly overestimating the number of expected coincidences.

The number of chance coincidences we obtain is $N = 0.19$, which corresponds to a greater than 5σ result for the six coincidences here considered ($7.5 \times 10^{-6}\%$ probability of chance coincidence). Because of the conservative assumptions used in the above calculation, what we obtain is really a lower limit to the significance of the result.

IV. DISCUSSION

The result of § III indicates that there is a statistically significant association of X-ray bursters with X-ray transients. This leads to the hypothesis that X-ray bursters and X-ray transients are not distinct classes of objects, but just represent different responses of the same system to different physical conditions (Fabbiano *et al.* 1978). We will discuss this hypothesis in the context of our understanding of the nature of the X-ray bursters and of the place that they occupy in the more general picture of the galactic X-ray sources. To this end we will review some of the facts about the galactic X-ray sources in general and X-ray bursters and transients in particular.

One of the most relevant characteristics of the galactic X-ray sources is their spectral classification into two general categories: the "hard" ones, which can be fitted by thermal spectra with $kT > 15$ keV, and the "soft" ones, with $kT \leq 15$ keV. In the first category belong the pulsating X-ray binaries, often highly massive systems, whose optical counterparts are early-type stars; in the second one belong the great majority of the unidentified galactic bulge sources, the low-mass binaries like Sco X-1 and Cyg X-2, and the globular cluster sources. The steady counterparts of X-ray bursters are also among the "soft" galactic X-ray sources.

Since the discovery of the X-ray bursts (Grindlay *et al.* 1976), different interpretations have been proposed for the nature of this phenomenon. The main issue is whether the X-ray bursts are the signature of a different kind of X-ray source (e.g., the giant black hole hypothesis; Grindlay and Gursky 1976), or whether they are produced in more traditional binary systems, like low-mass black holes, neutron stars, or white dwarfs accreting matter from "normal" companions (see, e.g., Lamb *et al.* 1977; Baan 1977). While no bursts have yet been detected from an eclipsing X-ray source, there is indirect evidence to support the binary hypothesis. This evidence rests mainly upon the resemblance of the steady counterparts of X-ray bursters to the generality of the "soft" galactic X-ray sources and to the low-mass binaries in particular (Lamb and Lamb 1977).

The X-ray transients are a class of X-ray sources defined by their peculiar temporal behavior. The definition of transient is somewhat controversial, since it is dependent on the sensitivity of the instrument and on the available coverage (Cominsky *et al.* 1978). In some cases of transient X-ray sources there is no detectable "steady" low-level emission, while in other cases, like 4U 1608–52 (Forman *et al.* 1978), the source appears to be for quite a long time in a state of moderate intensity, similar to other galactic X-ray sources. Nevertheless, the same spectral classification in "hard" ($kT > 15$ keV) and "soft" ($kT \leq 15$ keV) applies to the transients as to the generality of the galactic X-ray sources (Pounds 1976 and references therein). Pulsations have been observed only in the "hard" X-ray transients, most of which are identified with early-type stars. It must be added that most of the galactic X-ray sources show a certain amount of variability (a factor of 2 to 5) in their X-ray luminosity (Forman *et al.* 1978). All of these considerations led to the suggestion that transient X-ray sources are intrinsically of the same nature as the "normal" X-ray sources (Cominsky *et al.* 1978 and references therein).

All of the associations reported in Table 1 are with "soft" X-ray transients. Further evidence for the correlation of X-ray bursters with "soft" X-ray transients is given by their optical counterparts. Five "soft" X-ray transients (A1524–61, A0620–00, Aql X-1, MX 1608–52, Nova Oph) have been optically identified with late-type stars or red objects (Murdin *et al.* 1977; Oke 1977; Thorstensen, Charles, and Bowyer 1978; Grindlay and Liller 1978; Griffiths *et al.* 1978*a*). Of the bursters that are not associated with globular clusters, four have a blue Sco X-1–like optical counterpart and two have a red counterpart (see Table 1), if the identifications of the bursters with Aql X-1 and MX 1608–52 are correct. While the red counterpart is directly suggestive of a late-type star, the Sco X-1–like optical counterpart is also explainable in terms of X-ray heating of a late-type low-mass star (Milgrom and Katz 1976). None of the bursters so far has been identified with an early-type supergiant, in agreement with the X-ray observations that associate the bursters with the "soft" galactic sources.

The binary nature of the "soft" X-ray transients has been demonstrated by their optical identification with objects showing starlike spectra (which we have discussed above) and by the presence of periodicities that indicate an orbital motion (the 7.9 day period in A0620–00 and the 3.9 day and 7.9 day periodicities in its optical counterpart; Chevalier, Ilovaisky, and Mauder 1976; Duerbeck and Walter 1976; Matilsky *et al.* 1977; the 1.3 day period in Aql X-1; Watson 1976). The association of the X-ray bursters with the "soft" transients, together with the evidence related to both the steady X-ray counterparts of the former and their optical identifications, gives more strength to the hypothesis that X-ray bursts also originate in binary systems and not from massive black holes accreting interstellar clouds.

A binary system which can show at different times low-level steady-like emission, bursts, or transient-like outbursts must be characterized by a variable mass exchange. This is indeed the case of low-mass binary systems where the "normal" companion is a late-type star. As discussed by Kaluzienski *et al.* (1977*b*), this type of binary system could be responsible for the "soft" X-ray transients. It is possible that similar systems could produce the whole range of phenomena observed in the galactic X-ray sources with "soft" thermal spectra, i.e., "steady" X-ray emission, X-ray bursts, and transient outbursts.

The globular cluster X-ray sources are also of the "soft" kind. Both X-ray bursts and transient outbursts have been observed from these sources. This is consistent with the globular clusters being rich in late-type binaries (van den Heuvel 1977) and does not require the presence of a central giant black hole to explain the X-ray emission.

The "soft" X-ray transients are not a homogeneous class because of differences in their luminosities and light curves. An occurrence-frequency/energy-release relation similar to the one observed for the optical cataclysmic variables appears to be valid also for these X-ray transients. The most energetic outbursts have been observed only once per source (e.g., A0620−00), while less energetic outbursts can be repetitive (e.g., Aql X-1, MX 1608−52). We would then expect bursters to be associated with not very energetic transients. This is indeed the case for five of the seven burster/transient associations mentioned in § II (XB 1608−52/H1608−522, MXB 1636−53/4U 1636−53, MXB 1659−29/1659−29, MXB 1742−29/A1743−29, Aql MXB/Aql X-1). On the basis of this we would expect bursts from the recurrent transient 4U 1630−47, as already suggested by Grindlay and Liller (1978).

As we have already mentioned, no X-ray burster has ever been associated with a "hard" X-ray source. Maraschi, Treves, and van den Heuvel (1977) pointed out that the "hard" X-ray sources are associated with pulsed emission and with high-mass optical companions. They explain the lack of observed pulsations in the "soft" sources as due to Compton scattering of the hard radiation in a cloud surrounding the compact object. The existence of the cloud is likely in a low-mass system where the accretion is mainly due to Roche lobe overflow. All accretion models for burst formation require the presence of some accumulation of matter around the X-ray source. As discussed by Lamb and Lamb (1977), bursting behavior is not expected to occur with accretion from a high-velocity wind or a geometrically thin accretion disk: this is the case of the high-mass binaries. Variations in the density of the wind, but not in its velocity, could still give rise to transient events.

V. CONCLUSION

We have shown evidence for a statistically significant association between X-ray bursters and "soft" X-ray transients. The obvious implication is that the same object can be responsible for both types of behavior. Furthermore, the presence of steady 4U counterparts of transients and bursters and the similarity of these in spectra, luminosity range, and flux variability to the majority of the galactic plane X-ray sources (Forman *et al.* 1978; Jones 1977) suggest a uniqueness and continuity in the nature of most of the galactic X-ray sources, consistent with them originating in binary systems. Differences in the nature of each component could account for all the different kinds of behavior observed. In particular, X-ray bursters are associated with "soft" sources, in agreement with the fact that such a behavior is not likely to occur in a high-velocity stellar wind regime.

We thank Ethan Schreier for his comments and criticism and Riccardo Giacconi for his interest in this work. We acknowledge useful discussions with Fred Seward and Josh Grindlay and we thank the anonymous referee for comments. We also wish to thank Olga Messina for help in preparing the manuscript.

Note added in manuscript, 1978 August.—Analysis of *SAS 3* data has shown that the rapid burster (MXB 1730−335) is also a recurrent transient (Lewin 1979).

REFERENCES

Baan, W. A. 1977, *Ap. J.*, **214**, 245.
Belian, R. D., Conner, J. P., and Evans, W. D. 1972, *Ap. J. (Letters)*, **171**, L87.
———. 1976, *Ap. J. (Letters)*, **206**, L135.
Branduardi, G. 1977, Ph.D. thesis, University of London.
Buff, J. 1975, *IAU Circ.*, No. 2788.
Chevalier, C., Ilovaisky, S. A., and Mauder, H. 1976, *IAU Circ.*, No. 2957.
Cominsky, L., Jones, C., Forman, W., and Tananbaum, H. 1978, *Ap. J.*, **224**, 46.
Cruddace, R. G., Fritz, G., Shulman, S., Friedman, H., McKee, J., and Johnson, M. 1978, *Ap. J. (Letters)*, **222**, L95.
Davidsen, A., Malina, R., Smith, H., Spinrad, H., Margon, B., Mason, K. O., Hawkins, F. J., and Sanford, P. W. 1974, *Ap. J. (Letters)*, **193**, L25.
Duerbeck, H. W., and Walter, K. 1976, *Astr. Ap.*, **48**, 141.
Evans, W. D., Belian, R. D., and Conner, J. P. 1970, *Ap. J. (Letters)*, **159**, L57.
Fabbiano, G., Bradt, H., Doxsey, R. E., Gursky, H., Schwartz, D. A., and Schwarz, J. 1978, *Ap. J. (Letters)*, **221**, L49.
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, *Ap. J. Suppl.*, **38**, in press.
Griffiths, R. E., *et al.* 1978*a*, *Ap. J. (Letters)*, **221**, L63.
Griffiths, R., Johnston, M., Bradt, H., Doxsey, R., Gursky, H., Schwartz, D., and Schwarz, J. 1978*b*, *IAU Circ.*, No. 3190.
Grindlay, J., and Gursky, H. 1976, *Ap. J. (Letters)*, **205**, L131.
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. E., and Liller, W. 1978, *Ap. J. (Letters)*, **220**, L127.
Jones, C. 1977, *Ap. J.*, **214**, 856.
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., and Serlemitsos, P. J. 1975, *IAU Circ.*, No. 2859.
———. 1977*a*, *Nature*, **265**, 606.
———. 1977*b*, *Ap. J.*, **212**, 203.
Kaluzienski, L. J., Holt, S. S., Esfandiari, M., Boldt, E. A., and Serlemitsos, P. J. 1976, *IAU Circ.*, No. 2965.
Lamb, F. K., Fabian, A. C., Pringle, J. E., and Lamb, D. Q. 1977, *Ap. J.*, **217**, 197.
Lamb, D. Q., and Lamb, F. K. 1977, *Ann. NY Acad. Sci.*, **302**, 261.
Lewin, W. H. G. 1976, *IAU Circ.*, No. 2914.
———. 1977, *M.N.R.A.S.*, **179**, 43.
———. 1979, IAU/COSPAR Symposium on X-ray Astronomy, *Adv. Space Exploration*, **3**, in press.
Lewin, W. H. G., Hoffman, J. A., and Doty, J. 1976, *IAU Circ.*, No. 2994.
Lewin, W. H. G., *et al.* 1976*a*, *M.N.R.A.S.*, **177**, 83p.
Lewin, W. H. G., and Joss, P. C. 1977, *Nature*, **270**, 211.
Lewin, W. H. G., Hoffman, J., Marshall, H., Primini, F., Wheaton, W., Cominsky, L., Jernigan, G., and Ossman, W. 1978, *IAU Circ.*, No. 3190.
Li, F., and Clark, G. 1977, *IAU Circ.*, No. 3095.
Maraschi, L., Treves, A., and van den Heuvel, E. P. J. 1977, *Ap. J.*, **216**, 819.
Matilsky, T., *et al.* 1977, *Ap. J. (Letters)*, **210**, L127.
Milgrom, M., and Katz, J. I. 1976, *Ap. J.*, **205**, 545.
Murdin, P., Griffiths, R. E., Pounds, K. A., Watson, M. G., and Longmore, A. J. 1977, *M.N.R.A.S.*, **178**, 27p.

Oke, J. B. 1977, *Ap. J.*, **217**, 181.
Parsignault, D., and Grindlay, J. 1978, *Ap. J.*, **225**, 970.
Pounds, K. A. 1976, *Commetns Ap.*, **6**, 145.
Seward, F. D., and Liller, W. 1977, *Pub.A.S.P.*, **89**, 696.
Share, G., *et al.* 1978, *IAU Circ.*, No. 3190.
Thorstensen, J. R., Charles, P. A., and Bowyer, S. 1978, *Ap. J.* (*Letters*), **220**, L131.
van den Heuvel, E. P. J. 1977, *Ann. NY Acad. Sci.*, **302**, 14.
Watson, M. G. 1976, *M.N.R.A.S.*, **176**, 19p.

G. BRANDUARDI and G. FABBIANO: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138