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Published in:
Astrophysical Journal Letters

THE ASTROPHYSICAL JOURNAL, 360:L19–L22, 1990 September 1

CORRELATION OF X-RAY BURST PROPERTIES WITH SOURCE STATE IN THE "ATOLL" SOURCE 4U/MXB 1636−53

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Received 1990 May 2; accepted 1990 June 19

ABSTRACT

A series of *EXOSAT* observations of the "atoll" source 4U/MXB 1636−53 shows that duration and temperature of the X-ray bursts strongly correlate with the X-ray spectral and fast variability characteristics of the persistent emission of the source. We suggest that this implies that spectral shape, fast variability, and burst duration and temperature all correlate well with accretion rate $\dot{M}$. This provides a strong argument that in the atoll sources, source-state is determined by $\dot{M}$, just as in the Z sources. Our observations also show that the persistent X-ray intensity can vary independently from the other mentioned characteristics. Therefore, we conclude that intensity is probably *not* a good measure for the accretion rate.

Subject headings: stars: individual (4U/MXB 1636−53) — stars: neutron — X-rays: binaries — X-rays: bursts — X-rays: spectra

I. INTRODUCTION

It has become evident over the last few years that bright low-mass X-ray binaries (LMXB) show systematic, correlated variations in their X-ray spectral and X-ray fast variability characteristics (see Lewin, van Paradijs, and van der Klis 1988 and van der Klis 1989 for reviews). Recently, Hasinger and van der Klis (1989, hereafter HK89) showed that two distinct classes of LMXB can be distinguished on the basis of these correlated variations. They are named, after the shapes of their X-ray color-color diagrams, the Z sources and the atoll sources.

Z sources tend to be more luminous than atoll sources. They show two different types of quasi-periodic oscillations and three different source states, corresponding to the three branches of the rough Z shape they exhibit in an X-ray color-color diagram. Atoll sources include X-ray burst sources such as 4U/MXB 1636−53, as well as some of the sources that have traditionally been called "bright Galactic bulge sources," such as GX 13+1 and GX 9+1. They show two states. In the "island" state, there is a strong (10%–20% rms) stochastic variability component in the power spectrum extending to high (∼100 Hz) frequencies called high-frequency noise (HFN). This state is characterized by very little X-ray spectral variation on time scales of a day, which for short observations leads to the formation of isolated patches (islands) in the color-color diagram. In the "banana" state, the HFN is much weaker (<8% rms) and considerable X-ray spectral changes take place on time scales of hours to days that show up as a curved (banana) branch in the color-color diagram. In both states a <1%–2% rms power-law noise component called very low frequency noise (VLFN) is also present, which tends to be stronger in the banana state. On time scales longer than several days, the islands extend themselves into branches and gradual transitions occur between the two states, which are apparently two extremes of a continuous range. The characteristic types of QPO seen in the Z sources have not been observed in the atoll sources.

HK89 proposed that the difference between Z and atoll sources might be related to different evolutionary histories for the members of the two classes, leading to the presence of evolved companion stars and relatively strong ($\sim 10^{10}$ G) neutron star magnetic field strengths in the Z sources only. For the Z sources it seems clear (e.g., Hasinger *et al.* 1989) that it is the accretion rate $\dot{M}$ that determines the source state, which implies that the X-ray intensity I_X is not monotonically related to $\dot{M}$ in these sources. It has been suggested (HK89) that for atoll sources, a similar situation applies.

In this *Letter* we report results of the first investigation into the relation between source state (banana or island) and X-ray burst properties in an atoll source, 4U/MXB 1636−53. We make use of the results of an exhaustive homogeneous analysis of the burst properties of this source by Damen *et al.* (1990*a*) and follow the methods of HK89 for the analysis of the persistent emission. We find that some burst properties strongly correlate with atoll state, whereas the X-ray intensity I_X does not. We conclude that this strengthens the idea that in atoll sources, as in the Z sources, it is the accretion rate $\dot{M}$ that determines the source state, and that, contrary to what has up to now been nearly universally assumed, there is no simple relation between $\dot{M}$ and I_X. A preliminary report of part of this work appeared in van der Klis (1990).

II. ANALYSIS AND RESULTS

4U/MXB 1636−53 was observed with the *EXOSAT* Medium Energy instrument (Turner, Smith, and Zimmermann 1981) on five occasions (in 1983 July, 1984 May and September, and 1985 August and September). The total observing time was ∼180 hr; during this time 61 X-ray bursts were observed. We classified source state according to the methods outlined in HK89, using 0.001–100 Hz power spectra of the X-ray variability to determine the strength of the HFN and VLFN components, and X-ray color-color diagrams to parameterize the X-ray spectral shape. For all observations, including the four not previously analyzed in this respect, a good correspondence was found between the morphology of the color-color diagram, and the fast variability, with, as expected, strong

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HFN correlating to an "island" in the color-color diagram and weak HFN to a "banana" branch.

We studied the relation between source state and the various burst properties described in Damen *et al.* (1990*a*). Strong correlations with source state were found for the burst duration τ (defined as the ratio of total energy emitted in the burst and burst peak luminosity), and for the burst temperature $T_{0.1}$, the fitted blackbody temperature of the X-ray spectrum at the point in the burst decay where the luminosity reaches a level of 10% of the Eddington luminosity. $T_{0.1}$ is known to vary from burst to burst, indicating that the burst decay is not simply due to the cooling of a blackbody of constant size, and to be well correlated with τ (Damen *et al.* 1989).

The correlation of τ and $T_{0.1}$ with source state is illustrated in Figure 1 for the observations (Lewin *et al.* 1987) obtained in 1985 August. The small symbols (*dots* and *crosses*) in Figure 1 each represent a 200 s measurement of the X-ray colors; together, they make up a characteristic "atoll" color-color diagram. The large open circles each represent an X-ray burst. The position of each circle indicates "where the source was," i.e., what its X-ray colors were, when the burst occurred; the size of the circle is a measure for the temperature (*top*) or duration (*bottom*) of the burst, according to the key given in each frame. During the observations, the source gradually moved from the island state (*crosses*), down into the left end of the banana branch (*dots*), and then to the right and up into this branch, with the usual changes in the strengths of HFN (8.8% $\pm$ 0.7% rms in the island state to $<3.0\%$ at the hard end of the banana branch) and VLFN ($<0.8\%$–2.4% $\pm$ 1% rms). A surprisingly good correlation of source state with the burst properties is evident, with typical temperatures $kT_{0.1}$ of 1.3 keV and burst durations of >20 s in the island state, and 1.1 keV and $\lesssim 10$ s in the banana state. The only discrepant burst (*hatched*) is the exceptional "triple-peaker" (van Paradijs *et al.* 1986). The data obtained during all four other observations closely reproduce parts of this pattern, with colors and burst properties narrowly matching those in the 1985 August observation. During the 1984 and 1985 September observations (*not shown*), the source was in the banana state; during the 1983 observation, it was in the island state. If we rank all bursts according to their position in the diagram approximately according to the arrow in Figure 1 (*top*), a Spearman rank correlation test gives probabilities for chance occurrence of the observed correlations of 1.0×10^{-5} and 1.5×10^{-6} for the burst temperature and duration (excluding the triple-peak burst), respectively.

Figure 2 (*top*) shows the 1983 data (pluses) superposed on the 1985 August results; the match with the 1985 island data is very good, both with respect to the position in the color-color diagram and HFN (10.1% $\pm$ 0.6% rms) and VLFN (0.7% $\pm$ 0.2% rms) strengths, and with respect to burst temperature (and duration, not shown). However, the X-ray hardness versus intensity diagram of the same data presents a quite different picture (Fig. 2, *bottom*; cf. Damen *et al.* 1990*b*). The 1983 island state data (*pluses*) do not at all coincide with the 1985 island state data (*crosses*), as is the case in the color-color diagram. Instead, they are at much higher X-ray intensity, and form a fuzzy branch located above the 1985 banana state data (the lower, slightly curved branch [*dots*]). There is a gradual increase in the X-ray intensity during the 1983 observation which is accompanied by small variations in the hard X-ray color (see Breedon *et al.* 1986, for a more detailed analysis of the spectral variations in this observation). So, position in the

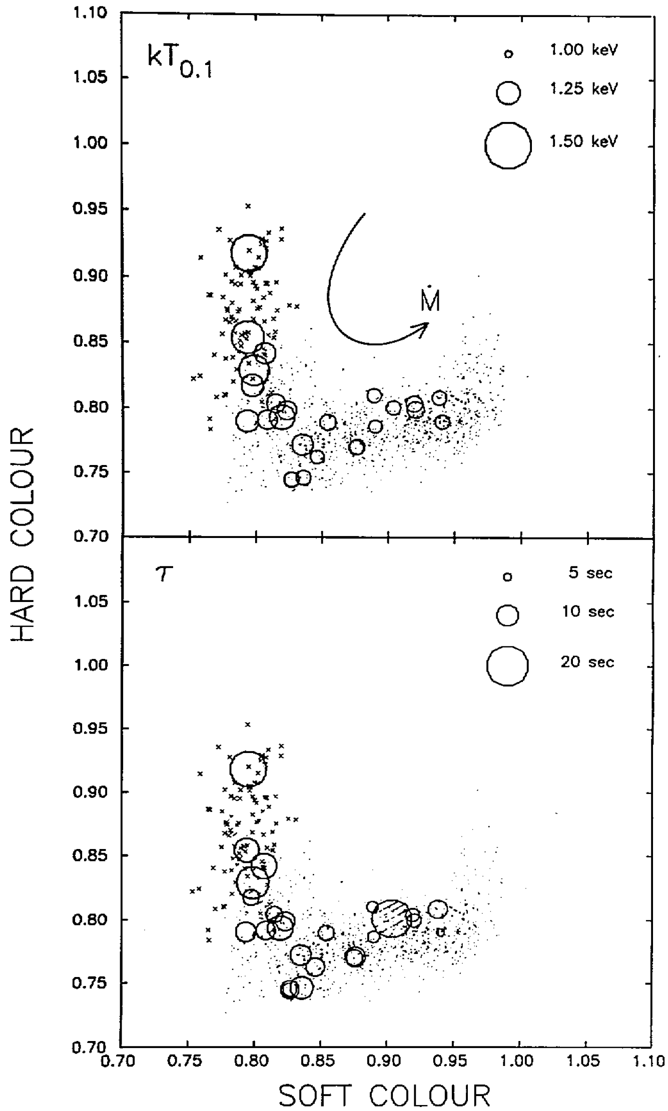

FIG. 1.—X-ray color-color diagrams (*small symbols*) with X-ray bursts (*large circles*) superposed. Each color measurement corresponds to 200 s of data; hard color is the ratio of the 6.1–20.5 to 4.5–6.1 keV and soft color that of the 2.9–4.5 to 0.9–2.9 keV count rates. Typical statistical uncertainties in the color measurements are 0.01 and 0.02 in the soft and hard colors, respectively. Crosses and dots indicate island and banana states, respectively, as determined from the X-ray variability characteristics (see text). The position of a large circle indicates the average of the colors of the persistent emission just before and after the X-ray burst; the size of the circle represents the burst temperature (*top*) or duration (*bottom*) as indicated. The hatched circle in the lower frame corresponds to the triple-peaked burst (van Paradijs *et al.* 1986); apart from this one instance, there is a strong correlation between source state and both burst temperature and duration. The direction in which we conclude $\dot{M}$ to increase is indicated in the top frame.

X-ray color-color diagram, HFN and VLFN strengths, burst duration, and burst temperature all correlate very well with each other, but at least on one occasion, X-ray intensity strongly deviates.

III. DISCUSSION

It was shown by van Paradijs, Penninx, and Lewin (1988, hereafter PPL88), that for several burst sources, there exists a general correlation between the level of the persistent X-ray emission, and the burst duration. Damen *et al.* (1989) found in

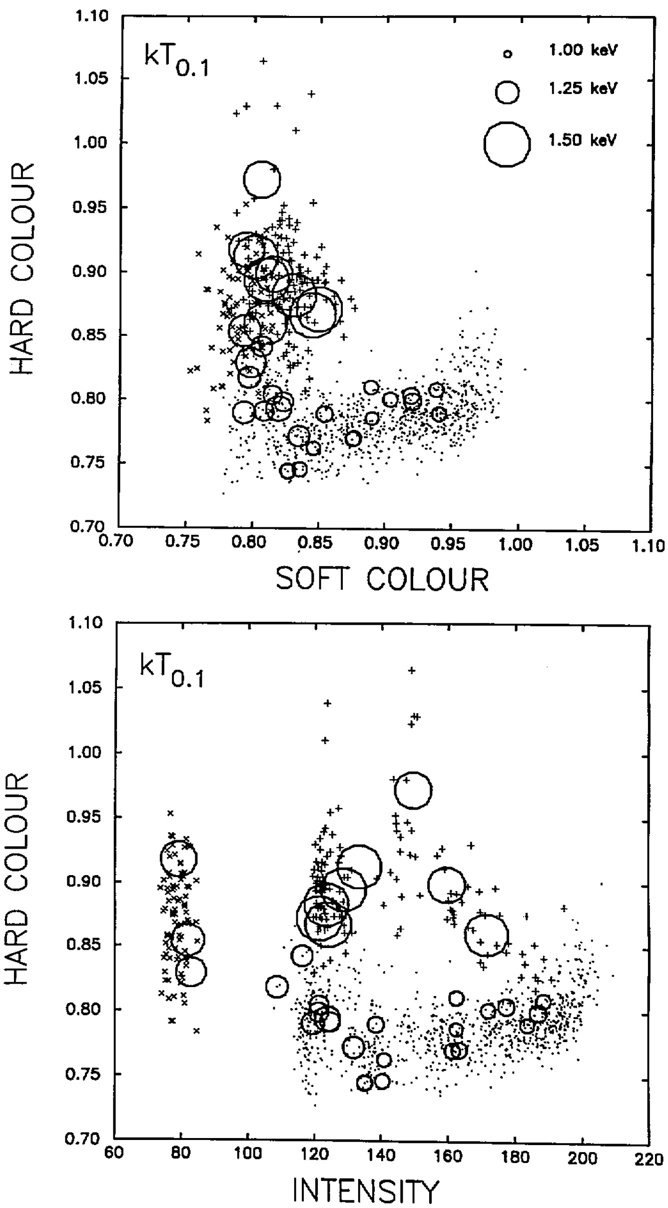

FIG. 2.—X-ray color-color (*top*) and hardness vs. intensity (*bottom*) diagrams with X-ray bursts superposed. Intensity is the count rate in the 0.9–20.5 keV band. The pluses correspond to the 1983 island state observation (see text), and the size of a circle indicates the burst temperature in both frames; all other conventions are as in Fig. 1. The 1983 and 1985 August island state data coincide in the color-color diagram and exhibit similar burst temperatures (and durations, not shown), but are far apart in the hardness vs. intensity diagram.

4U/MXB 1636−53 that for small variations in the intensity of the persistent emission, this correlation does not strictly hold. Implicitly assuming that I_X is a measure for $\dot{M}$, they concluded that the burst duration is determined to first order by the accretion rate, but that on a more detailed scale unknown additional parameters are involved in determining τ.

HK89 proposed that $\dot{M}$ is in atoll sources more reliably diagnosed through determination of source state from the properties of the X-ray color-color diagram and the power spectrum, than from I_X. Combined with the present analysis, this idea leads to an alternative explanation for the observed deviations from a strict correlation between τ (and $T_{0.1}$) and I_X, namely, that burst duration (and temperature) *do* correlate strictly with $\dot{M}$ and therefore with position in the color-color diagram and HFN and VLFN strengths, but that I_X *does not*. In this interpretation, the large variations in I_X discussed by PPL88 reflect variations in $\dot{M}$, but smaller variations, such as those in the 1983 island observation discussed here, often do not. It is not clear from our data whether deviations from a strict $\dot{M}$-I_X proportionality occur continuously or only occasionally, but we suggest that they happen sufficiently frequently to cause the scatter in the observed (PPL88) τ-I_X relation. The reason that I_X does not strictly track $\dot{M}$ (a possibility already mentioned in a slightly different context by PPL88), may be that, similar to the idea for the Z sources, I_X is affected by changes in the geometry of the accretion flow, causing changes in the spectral or directional distribution of the emitted flux.

It has sometimes been noted (Turner and Breedon 1984; Damen *et al.* 1989), that the bursts observed during the 1983 observation are somehow exceptional. With the benefit of the classification of the atoll source state of the 1983 data (based on the X-ray color-color diagram and the fast variability characteristics) as a typical island state, we are now directed to see that the 1983 burst properties are not very different from those seen in the 1985 August island state. As suggested previously by PPL88 and Damen *et al.* (1989) on the basis of the work of, e.g., Fujimoto, Hanawa, and Miyaji (1981) and Ebisuzaki and Nakamura (1988), long burst durations and high burst temperatures might be caused by a high hydrogen content of the bursting layers, which in turn would be the consequence of less efficient steady nuclear burning at lower accretion rates. With the demise of persistent intensity as a strict measure of $\dot{M}$, there is now no need for unknown additional parameters affecting these burst properties: the data are consistent with τ and $T_{0.1}$ being a function of accretion rate only. If we accept this interpretation of the longer and higher temperature bursts in the island state, then the accretion rate must increase from the island to the banana state, in accordance with the fact the X-ray intensity usually increases in that sense (HK89).

IV. CONCLUSION

The assumption that atoll source state, as determined from the properties of the X-ray colors and the fast X-ray variability measures accretion rate $\dot{M}$, turns a complicated relationship between X-ray burst duration (and temperature), and the properties of the persistent emission into a simple monotonic dependence of these burst properties on $\dot{M}$. This assumption, however, forces us to accept that in the atoll sources, like in the Z sources, the persistent X-ray intensity is *not* a good measure of $\dot{M}$.

E. D. is supported by the Netherlands Foundation for the Advancement of Research (NWO) through ASTRON under grant 782-371-019. J. v. P. acknowledges support from NATO through grant 0331/88. W. H. G. L. acknowledges support from NASA under grants NAG8-674 and NAG8-700.

Note added in manuscript.—Analysis of the *EXOSAT* data of 4U 1705 − 44 shows a similar correlation between burst temperature and duration, and atoll source state as reported in this paper for 4U/MXB 1636−53. In both sources, the waiting times between bursts are more stable in the island state than in the banana state.

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