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A three-year record of the branch behaviour of the Z source GX $5-1$ ($4U\ 1758-25$)

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SUMMARY

We present a three-year random sample of the X-ray flux variations of the bright Galactic Bulge source GX $5-1$ obtained with the *Ginga* All-Sky Monitor. The data allow us, for the first time, to perform a statistical study of the branch behaviour of a Z source. They cover 98 per cent of the branch pattern displayed by the source (90 per cent confidence). The pattern remained remarkably stable over the three years of observation. The horizontal branch (HB) extends over a factor of 2 in X-ray intensity, the source spends about equal time in the HB and in the normal branch (NB), and no flaring branch is detected. The branch behaviour is random and uncorrelated on time-scales longer than several days. Consequences of these results for near-critical accretion rate models of the NB, and for the magnetic field strength of GX $5-1$ relative to other Z sources are discussed.

1 INTRODUCTION

GX $5-1$ ($4U\ 1758-25$) is, after Sco $X-1$, the brightest of the low-mass X-ray binaries (LMXB). In X-ray hardness versus intensity and X-ray colour–colour diagrams the source exhibits characteristic elongated structures or 'branches' (Shibazaki & Mitsuda 1984). The source shows intensity-dependent quasi-periodic oscillations (QPOs; van den Klis *et al.* 1985a) which are believed to be magnetospheric in origin (Alpar & Shaham 1985). The occurrence of these QPOs is correlated with the spectral branches (van der Klis *et al.* 1985b; van der Klis *et al.* 1987). The source is now recognized as a member of the class of the 'Z sources', LMXB characterized by three-branched, roughly Z-shaped X-ray hardness–intensity and colour–colour diagrams (see Hasinger & van der Klis 1989, hereafter HK89). Z sources show two different types of quasi-periodic oscillations (QPOs) and three additional noise components in their X-ray intensity variations, whose occurrence and properties strongly correlate with the position of the source in the Z. Radio, optical and UV properties also depend on position in the Z (see Penninx 1989; Hasinger *et al.* 1989).

Z sources move along the three branches of the Z in an irregular fashion on time-scales of about a day and never 'jump' from one branch to the other without passing by the branch junction. It seems very likely therefore that it is the accretion rate $\dot{M}$ that determines the position of the source in the Z. Because of the Z shape seen in hardness–intensity diagrams, this directly implies that there is no simple relation between $\dot{M}$ and the X-ray intensity I_x. The three branches which together make up the Z are called horizontal branch (HB; upper branch in the Z), normal branch (NB; middle branch) and flaring branch (FB; lower branch); for various reasons (e.g. HK89; Hasinger *et al.* 1989), $\dot{M}$ is believed to increase in this order. The HB–NB junction is called the 'apex'.

Z sources tend to be more luminous than the other LMXB, many of which belong to the class of the 'atoll sources' (HK89), which *also* exhibits correlated behaviour between X-ray spectra and X-ray variability, but one that is quite different from that of the Z sources. The two known orbital periods of Z sources are both longer than 10 hr, those of the atoll sources are all shorter than 5 hr. It has been hypothesized (HK89) that the differences between the Z and the atoll sources are due to differences in both the neutron-star magnetic field strength B and the accretion rate $\dot{M}$, evolutionary differences resulting in the correlated occurrence of evolved companion stars, higher accretion rates, and higher fields in the Z sources. It should be noted that the distinction between Z and atoll sources is based on the properties of a sample of 16 persistently bright LMXB; it is not yet clear in what way faint or transient LMXB fit in. If the above interpretation is correct, then the existence of additional types of sources (high-B, low-$\dot{M}$ and vice versa) might be expected.

Until now, our knowledge of the branch behaviour of the Z sources has been based on 'snapshots' of a couple of days at most (Branduardi *et al.* 1980; Shibazaki & Mitsuda 1984; Priedhorsky *et al.* 1986; van der Klis *et al.* 1987; Hasinger 1987; Penninx *et al.* 1988; Ponman, Cooke & Stella 1988;

Van Paradijs *et al.* 1988; Hasinger *et al.* 1989; Penninx *et al.* 1990a,b; Schulz, Hasinger & Trümper 1989; HK89; Tan *et al.*, in preparation). In this paper, we report results from the *Ginga* All-Sky Monitor which allow us to study the branch behaviour of GX 5 − 1 over a period of three years. As the observations extend over many times the typical time-scale of the source motion through the branches, our data allow us, for the first time, to statistically study the branch behaviour of a Z source.

2 OBSERVATIONS AND RESULTS

The *Ginga* All-Sky Monitor (ASM; Tsunemi *et al.* 1989) is a proportional-counter array with an effective area of 420 cm^2. The instrument is operated to allow, within a 20-min interval each day, 18 s of observation of each point in the sky at an average effective area of 70 cm^2. Two energy channels are available in the present analysis of the ASM data: 1–6 and 6–20 keV. Over the interval 1987 March to 1990 March, a total of 118 observations were made of GX 5 − 1 which were acceptable from the point of view of background, Earth occulation and aspect. The detection limit of the ASM is about 0.18 $cs^{-1}\,cm^{-2}$ (1–20 keV); GX 5 − 1 was above this limit in all our measurements. Thirty per cent of the measurements were made with intervals less than 1.5 d, and another 30 per cent had intervals in the range of 1.5 and 4.5 d. The data contain 21 gaps longer than 10 d. The observed total count rates from GX 5 − 1, after subtraction of a ~0.15 $cs^{-1}\,cm^{-2}$ background and corrected for aspect, varied between about 1.7 and 3.3 $cs^{-1}\,cm^{-2}$.

A hardness–intensity diagram of the data (Fig. 1) displays the characteristic pattern of HB and NB, the upper two branches of the Z; no FB is visible. The branches are, within the uncertainties, narrow, implying that the pattern remained stable to within 10 per cent in intensity and 0.1 in hardness over the three years of observation.

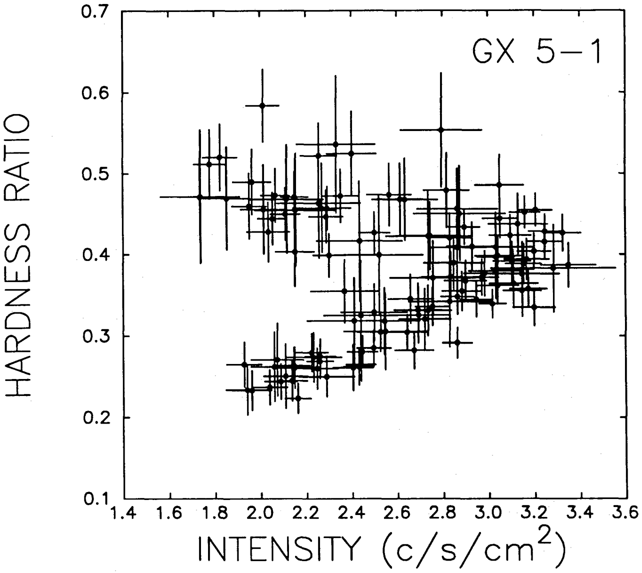

Figure 1. X-ray hardness–intensity diagram of GX 5 − 1 from the three years of *Ginga* ASM data. Hardness ratio is (6–20 keV/1–6 keV) count rate ratio, intensity is over the 1–20-keV range. Error bars include 1 σ counting statistics as well as systematic uncertainties in background correction and aspect solution. The upper two branches of the Z pattern (horizontal branch and normal branch) are seen; there is no evidence for the lowest ('flaring') branch.

There is no evidence that GX 5 − 1 ever entered the FB state during our observations (although we obviously cannot exclude an FB that exactly retraces the NB in the hardness–intensity diagram). The HB extends to an X-ray intensity a factor of 2 below that in the apex. Assuming that our data is a random sample of the possible positions of GX 5 − 1 in the hardness–intensity diagram, we find that the source spends less than 2 per cent of its time (90 per cent confidence) in the FB or in an even lower intensity part of the HB.

The time spent on each branch is approximately equal. Excluding a region near to the apex where HB and NB cannot be distinguished (defined by two lines perpendicular to the branches and intersecting near $I_x = 2.6$ $cs^{-1}\,cm^{-2}$), we find that the fraction of the time spent on the remaining part of HB and NB, respectively, is 29 ± 5 and 33 ± 5 per cent.

We studied the distribution of the points over the branches. A one-dimensional Kolmogorov–Smirnov test for deviation from uniformity (e.g. Press *et al.* 1988) applied to the distribution of the points projected on a line describing each branch ($H = 0.561 - 0.044 I_x$ for the HB and $H = -0.020 + 0.129 I_x$ for the NB, where H is the hardness ratio) yields probabilities of 23 and 84 per cent, respectively, to obtain the observed distribution by random sampling from a uniform distribution.

The motion of the source through the branches is entirely consistent, on the time-scales considered, with being random and uncorrelated. Epoch-folding searches reveal no evidence for periodicity, nor is there evidence for any other correlation in the position of the source in the diagram on time-scales of days to weeks. If we consider the locations in the hardness–intensity diagram of all data points obtained within a given fixed interval (which we chose to be 1, 2, 4, 8 and 16 days in successive trials) of the source being in the HB, NB or apex region, respectively, we find that these locations are always consistent with being a random sample of the total obesrved branch pattern. Absolute deviations of 20 per cent in the fraction of the time spent in a given region of the diagram would have been detectable from our data within 4 d; of 10 per cent, in 16 d.

3 DISCUSSION

Models for the branch pattern of Z sources (Lamb 1989; Hasinger, Priedhorsky & Middleditch 1989; see also van der Klis *et al.* 1987) have mostly relied on the effects of radiation pressure near to the Eddington limit to influence the accretion flow and thereby affect the emerging radiation. In some of these models the mass-transfer rate is close to the critical Eddington value $\dot{M}_{\rm Edd}$ on the NB, whereas on the FB supercritical mass-transfer occurs. The most quantitatively developed model (Lamb 1989) requires $\dot{M}$ to be within 10 per cent of $\dot{M}_{\rm Edd}$ everywhere on the NB.

If the mass-transfer rate is an independent variable, changing through external causes such as atmospheric variations in the companion star, then there is no particular reason for it to remain close to $\dot{M}_{\rm Edd}$. A Z source would in the above near-critical models be expected to spend only a small percentage of its time on the NB. Our data strongly contradict this, as the time spent on the NB is about equal to that in the HB, whereas the observed range in X-ray intensity (and also QPO frequency; see Tan *et al*., in preparation) on the HB strongly suggests a large range in accretion rate on that branch. So, for near-critical models for the NB to remain viable, they should be supplemented with a mechanism that can keep the accretion flow near to the neutron star close to the critical value for extended intervals of time while the external mass transfer varies. Such a mechanism might, for example, involve X-ray irradiation of the companion, the accretion stream or the outer disc.

As quantified in Section 2, it is likely that our data covers practically the entire branch pattern displayed by GX 5 − 1. The stability of the pattern over a period of three years is at variance with the considerable shifts and shape changes in branch pattern observed in the Z source Cyg X-2 (Hasinger 1987). Apparently, such changes are not fundamental to the mechanism causing the Z pattern. The HB extends to lower X-ray intensities relative to the apex in GX 5 − 1 than in any other Z source. The intensity variation on the HB is accompanied by a factor of 3.7 change in QPO frequency (Tan *et al*., in preparation). This, combined with the absence of an FB, suggests that compared to other Z sources GX 5 − 1 covers a relatively low-accretion-rate range with, in particular, no super-Eddington mass-transfer rate episodes. Assuming a near-critical accretion model for the NB, and assuming that the neutron stars in Z sources spin at rates similar to the equilibrium spin rate $\nu_{\rm eq} \propto \bar{\dot{M}}^{3/7}\ \mu^{-6/7}$ (e.g. Ghosh & Lamb 1979), where μ is the neutron star magnetic moment and $\bar{\dot{M}}$ some appropriate time average of the accretion rate, this allows, within the beat-frequency model (Alpar & Shaham 1985), to constrain the magnetic field strength of GX 5 − 1 relative to some other Z sources. In the beat-frequency model, the HB QPO frequency is given by $\nu = \nu_{\rm K} - \nu_{\rm S}$, where $\nu_{\rm K}$ is the Kepler frequency at the magnetospheric radius and $\nu_{\rm S}$ is the neutron star spin frequency. If the accretion rate at the apex is a fixed fraction (e.g. 0.9) of the Eddington rate $\dot{M}_{\rm Edd}$, then $\nu_{\rm K}$ there is $\propto \dot{M}_{\rm Edd}^{3/7}\mu^{-6/7}$. Combining these equations, we have $\mu^{6/7} \propto (\dot{M}_{\rm Edd}^{3/7} - \alpha\bar{\dot{M}}^{3/7})/\nu_{\rm APEX}$, where $\nu_{\rm APEX}$ is the QPO frequency at the apex, and α a constant of order unity determined by the details of the interaction between the inner disc and the magnetosphere. From the fact that $\nu_{\rm APEX}$ is not higher in GX 5 − 1 than in the Z sources Cyg X-2 (Hasinger *et al.* 1989) and GX 340 + 0 (Penninx *et al.* 1990b), and as by hypothesis $\bar{\dot{M}}$ is lower in GX 5 − 1 than in other Z sources, we may now conclude that the magnetic moment of the neutron star in GX 5 − 1 is larger than in Cyg X-2 and GX 340 + 0. Note that this argument holds even if the powers of μ and $\dot{M}$ on which the frequencies depend are different from the values of − 6/7 and 3/7 adopted here (e.g. White & Stella 1988). A similar argument cannot be made with respect to GX 17 + 2, as in that source the QPO frequency at the apex is considerably lower than in GX 5 − 1.

4 CONCLUSION

GX 5 − 1 seems to preferably occupy the regions of the Z pattern which are associated with lower mass-transfer rates. If neutron stars in Z sources spin at their equilibrium rates and the beat-frequency model for HB QPO is current, then this might indicate that its magnetic field strength is higher than in the Z sources Cyg X-2 and GX 340 + 0.

There is no evidence for strongly non-linear mapping between accretion rate and locus in the Z pattern. This requires models for the NB which rely on near-critical accretion rate values there, to be supplemented with a flow control mechanism that can keep the accretion rate close to the Eddington limit irrespective of changes in the mass-transfer rate.

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