Simultaneous radio and X-ray observations of the low-mass X-ray binary GX 13+1

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Abstract. We present the results of two simultaneous X-ray/radio observations of the low-mass X-ray binary GX 13+1, performed in July/August 1999 with the Rossi X-ray Timing Explorer and the Very Large Array. In X-rays the source was observed in two distinct spectral states; a soft state, which had a corresponding 6 cm flux density of \(\sim 0.25\) mJy, and a hard state, which was much brighter at 1.3–7.2 mJy. For the radio bright observation we measured a delay between changes in the X-ray spectral hardness and the radio brightness of \(\sim 40\) minutes, similar to what has been found in the micro-quasar GRS 1915+105. We compare our results with those of GRS 1915+105 and the atoll/Z-type neutron star X-ray binaries. Although it has some properties that do not match with either atoll or Z sources, GX 13+1 seems more similar to the Z sources.

Key words. Accretion, accretion disks - Stars: individual: GX 13+1 - Stars: neutron - ISM: jets and outflows - X-rays: stars - Radio continuum: stars

1. Introduction

Based on their correlated spectral and variability properties, the brightest persistent neutron star low-mass X-ray binaries (LMXBs) are often divided in two groups: the atoll and Z sources (Hasinger & van der Klis 1989; van der Klis 1995a), after the tracks they trace out in X-ray colour-colour diagrams (CDs). Although atoll and Z sources share some variability and spectral properties (in the X-ray band), there are significant differences between the two groups: atoll sources are less luminous, have harder X-ray spectra and show stronger rapid time variability than the Z sources (van der Klis 1995a). Atoll sources are also less luminous in the radio (Fender & Hendry 2000). Although some of the observational differences can be accounted for by differences in the mass accretion rate, with the Z sources probably accreting near the Eddington rate and atoll sources at rates ranging from near Eddington to less than 10% of it, it is generally believed that additional differences, e.g. in the neutron star properties, are required to explain all observational differences (Hasinger & van der Klis 1989).

The nature of GX 13+1, one of the brightest neutron star LMXBs, is still ambiguous. Schulz et al. (1989) grouped it with the high luminosity sources (Schulz et al. 1989), which included the six sources that were later labeled as Z sources. Hasinger & van der Klis (1989) classified it as a bright atoll source, although they noted that of all atoll sources it showed properties which were closest to those seen in the Z sources, most notably its far branch-like appearance in the CD and the featureless power law noise in the power spectrum that is typical for that spectral state. Although the EXOSAT observations analyzed by Hasinger & van der Klis (1989) only showed the source in the so-called ‘banana branch’ state, the bimodal behavior of the source reported by Stella et al. (1985) strongly suggests that the source occasionally enters a different state. The latter seemed to be confirmed by the first observations of the source with the Rossi X-ray Timing Explorer (RXTE), in which a clear two branched structure was found in the CD (Homan et al. 1998). Although the pattern in the CD resembled both Z and atoll source tracks, the resemblance to Z sources was
strengthened by the discovery (in the same observations) of a 57–69 Hz quasi-periodic oscillation (QPO), which had properties similar to that of the horizontal branch QPO in the Z sources. The CD of GX 13+1 in a recent paper by Muno et al. (2001), which for the first time displays a 'complete' pattern, shows a sharp vertex, similar to the normal branch/flaring branch vertex seen in the Z sources and quite unlike the rather smooth curves seen in atoll sources. More recently, Schnerr et al. (2003) analyzed a large set of RXTE data and conclude that many of the source's properties do not fit within the atoll/Z framework, although they favor the option of an atoll source. They suggest that part of its unusual behavior can be explained with the presence of a relativistic jet, that is almost pointing directly towards us.

Observations in the infrared suggest the presence of a K giant secondary (Garcia et al. 1992; Bandopadhyay et al. 1999) and a possible orbital or precessional modulation with a period of ~20 days (Bandopadhyay et al. 2002); these are properties that are thought to be more typical for Z sources than for atoll sources. GX 13+1 also shares a common mean radio luminosity (Grindlay & Seaquist 1986; Garcia et al. 1988) with the Z sources and black hole candidates (Fender & Hendry 2000), suggesting a similar origin for the quiescent radio emission from persistent black hole and Z source X-ray binaries, and GX 13+1. None of the (other) atoll sources is consistent with this relation. Although the source is variable in radio on time scales of less than an hour, no clear relation between X-ray and radio luminosities was found (Garcia et al. 1988).

In this paper we present the results of a coordinated X-ray/radio campaign, which had as its principal aim to investigate the possibility that GX 13+1 shows a similar X-ray state dependence of its radio emission as is found in the Z sources. In most of those sources the radio luminosity decreases from the horizontal branch to the flaring branch. We find similar behavior in GX 13+1.

2. Observations and analysis

2.1. X-ray observations

Our X-ray data were obtained simultaneously with the Proportional Counter Array (PCA; Zhang et al. 1993; Jahoda et al. 1994) and the High Energy X-ray Timing Experiment (HEXTE; Gruber et al. 1996; Rothschild et al. 1998) onboard RXTE (Bradt et al. 1993). The observations were performed in 1999 between July 31 23:52 UTC and August 1 10:39 UTC (obs. 1), and on August 04 between 02:44 and 12:05 UTC (obs. 2). The total exposure times for the two observations were, respectively, ~22.5 ks and ~18.3 ks. The PCA and HEXTE data were obtained in several different modes; the spectral and timing properties of these modes are given in Table 1. For all modes we discarded data taken during Earth occultations and passages through the South Atlantic Anomaly.

The Standard 2 data were used to produce light curves, colour curves, a colour-colour diagram (CD), and a hardness-intensity diagram (HID), and to perform a spectral analysis. Only data from Proportional Counter Units (PCUs) 0 and 2 were used (all layers), since these were the only two that were active during all our observations. The data were background subtracted; dead time corrections (~3–3.5%) were only applied for the spectral analysis. A soft colour was defined as the ratio of count rates in the 4.2–7.5 keV and 2.5–4.2 keV energy bands, and a hard colour as the ratio of count rates in the 10.0–18.5 keV and 7.5–10.0 keV energy bands (these four energy bands correspond, respectively, to Standard 2 channels (running from 1 to 129) 7–14, 3–6, 21–40, and 15–20). A CD and a HID were produced by, respectively, plotting hard colour versus soft colour and hard colour versus the 2.5–18.5 keV count rate, for each 16 s data point. The soft and hard colour curves, which had an initial time resolution of 16 s, were rebinned to a time resolution of 1024 s, to allow a better study of their variations on long time scales. The PCA spectra were created using the standard FTOOLS V5.2 routines. Systematic errors of 0.6% were added and response matrices were produced using PCARSP (V8.0). The details of the models used to fit the spectra of GX 13+1 are discussed in Section 3.1.

HEXTE light curves were produced by running the FTOOLS V5.2 script hxtlcurs (which automatically corrects for background and deadtime) on the E_Sus_256_DX1F mode data of cluster A. Additional rebinning was applied, resulting in 1024 s time bins, to achieve better statistics.

The rapid X-ray time variability of the source was studied in terms of power spectra. For this analysis we performed fast fourier transforms (FFTs) of the high time resolution (1/8192 s) data. Power spectra were produced with frequencies of 1/1024–512 Hz (2–26.5 keV band) and 1/16–2048 Hz (2–26.5 keV, 2–6.3 keV, and 6.3–26.5 keV bands). No background or dead time corrections were applied to the data prior to the FFTs; the effects of dead time were accounted for by our fitting method. The power spectra were selected on time, count rate and/or colour and subsequently rms normalized according to a procedure described in van der Klis (1995). The resulting power spectra were fitted with a constant, to account for the deadtime modified Poisson level, a power law, a zero-centered time modified Poisson level, a power law, and a zero-centered time modified Poisson level, a power law, and a zero-centered time modified Poisson level, a power law, and a zero-centered time modified Poisson level, a power law, and a zero-centered time modified Poisson level.

| Mode | Time res. (s) | Energy range (keV) | Energy channels |
|------|--------------|--------------------|-----------------|
| Standard 1 | 1/8 | 2–60 | 1 |
| Standard 2 | 16 | 2–60 | 129 |
| SB_125us_0_13_1s | 1/8192 | 2–5.9 | 1 |
| SB_125us_14_17_1s | 1/8192 | 5.9–7.6 | 1 |
| E_125us_64M_18_1s | 1/8192 | 7.6–60 | 64 |
| E_Sus_256_DX1F | 1/131072 | 10–250 | 256 |
Fig. 1. The evolution of GX 13+1 during the observations on 1999 August 1 (left column) and 1999 August 4 (right column).  

2.2. Radio observations

The radio data were obtained with the Very Large Array (VLA) radio observatory in its most extended (A) configuration. GX 13+1 was observed at 6 cm on 1999 August 1 between 00:33 and 09:31 UTC (obs. 1), and on 1999 August 4 between 00:22 and 08:51 UTC (obs. 2). During the observations, the radio flux density was measured using a Lorentzian, to account for the deviations from the power law noise, and a Lorentzian for a weak QPO in the second observation. Errors on the fit parameters were determined using $\Delta \chi^2 = 1$. Upper limits on QPOs were determined by fixing the frequency and FHWM to (a range of) values and using $\Delta \chi^2 = 2.71$ (95% confidence).
the first observation 25 of the 27 VLA antennas were used; 26 were used during the second observation. Due to technical problems ∼39% (obs. 1) and ∼8% (obs. 2) of the total observing time was lost. Observations were made simultaneously in both circular polarizations in each of two independent 50 MHz bands centered on 4885.1 and 4835.1 MHz. Flux densities, which are all Stokes I, were referenced to those of 1328+307 (3C 286), taken to be 7.462 and 7.510 Jy at 4885.1 and 4835.1 MHz respectively (Perley et al., priv. comm.). The overall flux density scale is probably good to at least ∼5%. To calibrate the complex antenna gains the standard calibration source 1817-254 was observed at 30 minute (obs. 1) or 6 minute (obs. 2) intervals; the reason for the denser sampling of the calibration source in obs. 2 was that during obs. 1 a large part of the data was rendered useless due to a combination of bad weather conditions and too long intervals between calibration observations. The data were reduced and analyzed using the Astronomical Image Processing System (AIPS). For each day, images were first made using the entire data sets, ignoring any variability of GX 13+1. These images were used to find nearby confusing sources, which were then subtracted from the original uv-data. These uv-data were then split into 15-minute bins (or longer, in the case of weak signals) and imaged to give the flux density history of GX 13+1. This procedure allows the full synthesis mapping of confusing sources, while retaining the best possible sensitivity to fluctuations of GX 13+1. The flux densities are the average of the of maximum flux density and the integrated flux density in the region containing the source in the cleaned image. Note that because of calibration and other "dead" time, the amount of data in each bin is usually less than the sampling time. Errors on the flux density were conservatively calculated as the sum of the squares of (1) the difference of the maximum and the integrated flux density and (2) the measured off-source rms. Early in obs. 1 and during the beginning and end of obs. 2 the source wandered away from the image center, probably because the elevations of GX 13+1 and the calibrator were rather different there - the effects of these problems can clearly be seen in the increase of the error bars at the end of the radio light curve in Fig. 1.

3. Results

3.1. X-ray observations

From Figs. 1, 3 it is clear that the X-ray properties of the source changed between the first to the second observation. The second observation has a higher count rate, both in the 2–25 keV (Fig. 1a and b) and 20–100 keV bands (Fig. 1c and d) and shows more variability in the 2–25 keV band. Also, the second observation tends to be spectrally harder; while the PCA count rates increased only by a factor of ∼1.3, the HXTE count rates increased by a factor of ∼3.2. The spectral difference is most clearly seen in the CD and HID shown in Fig. 2, where the two observations show up as distinct patches, and Fig. 3 which shows the ratio of the spectra of obs. 2 and 1. Note that the small bridge between the two patches in the HID (Fig. 2b) does not represent a real connection between the two patches, but corresponds to the upper right part of patch traced out during obs. 1 in the CD. It is not clear from our observations how the source bridges the gap between the two patches in HID - we refer to Schnerr et al. (2003) for an observation that shows a transition between the two patches. Although type I X-ray bursts have been observed from GX 13+1 (Fleischman 1985; Matsuba et al. 1995), none were seen during our observations.

3.1.1. X-ray spectra

X-ray spectral fits were performed with XSPEC [Arnaud 1996, V11.2] to the 3-25 keV PCA spectra using two different models. The first model is based on the continuum model used by Ueda et al. (2001), for their ASCA 1–10 keV spectra of GX13+1, and Sidoli et al. (2002), for their 2–10 keV XMM-Newton spectra. It consists of a black body (bbody in XSPEC), and a disk black body (diskbb). Galactic neutral hydrogen absorption (phabs) was fixed at $N_H = 2.9 \times 10^{22}$ atoms cm$^{-2}$ (Ueda et al.
For the second observation the addition of the line (gauss) around 6.4 keV and an absorption edge (edge) around 8 keV [Ueda et al. 2001] did not lead to acceptable fits. The second model we tried was a thermal Comptonization model (comptt, Titarchuk 1994; Hua & Titarchuk 1995), which has recently been applied successfully to the broad band continuum of several bright neutron star LMXBs (see, e.g., di Salvo et al. 2000; Iaria et al. 2001). The $N_H$ was again fixed to $N_H = 2.9\times10^{22}$ atoms cm$^{-2}$. For the second observation a reasonable fit was obtained ($\chi^2_{\text{red}} = 1.35$), but the first observation showed large residuals between 5 and 10 keV ($\chi^2_{\text{red}} = 15.6$). Adding a line around 6.4 keV and an edge around 9 keV greatly improved the fit ($\chi^2_{\text{red}} = 0.6$). For the second observation the addition of the line and edge led to a small improvement ($\chi^2_{\text{red}} = 0.9$), with the two components not being detected significantly. The best-fit results with the four-component model are given in Table 2. Some caution should be taken with interpreting the spectral results, as the low line energy (which tended to decrease when not fixed) and the high edge energy indicate different ionization stages of Fe. Also the large spectral changes within obs. 1 may have been partly responsible for the observed residuals. For both observations no black body component was needed, as the Comptonization component provided good fits at low energies.

For a more model independent comparison of the spectra of the two observations we plot the ratio of observations 2 and 1 in Fig. 3. While below 7 keV the ratio is rather constant, above that energy the spectrum of obs. 2 becomes increasingly hard.

Table 2. Spectral fit results. Errors on the fit parameters are 68% confidence limits, upper limits represent 95% confidence limits. The 3–10 and 10–25 keV fluxes are unabsorbed.

| Parameter          | Obs. 1                  | Obs. 2                  |
|--------------------|-------------------------|-------------------------|
| $N_H$ (atoms cm$^{-2}$) | $2.9\times10^{22}$ (fixed) | $2.9\times10^{22}$ (fixed) |
| $kT_W$ (keV)       | 0.98±0.02               | 0.92±0.01               |
| $kT_e$ (keV)       | 2.88±0.06               | 3.04±0.04               |
| $\tau$             | 7.2±0.2                 | 8.10±0.15               |
| $R_W$ (kAU)        | 21.7±0.9                | 27.2±0.7                |
| $E_{FE}$ (keV)     | 6.42 (fixed)            | 6.42 (fixed)            |
| FWHM (keV)         | 0.78±0.13               | 0.4±0.2                 |
| Fe EW (eV)         | 223                     | <96                     |
| $E_{\text{edge}}$ (keV) | 9.1±1.0                | 9.1 (fixed)             |
| $\tau_{\text{edge}}$ | 0.12±0.03              | <0.03                   |
| $F_{\text{3–10}}$ (ergs cm$^{-2}$ s$^{-1}$) | 1.50±8.0               | 2.00±8.0                |
| $F_{\text{10–25}}$ (ergs cm$^{-2}$ s$^{-1}$) | 1.80±9.0               | 3.60±9.0                |
| $\chi^2_{\text{red}}$ (dof) | 0.6 (40)               | 0.9 (41)                |

Fit parameters of the comptt model - $kT_W$: input soft photon (Wien) temperature - $kT_e$: plasma temperature - $\tau$: plasma optical depth - $R_W$: effective Wien radius for the soft seed photons [in ‘t Zand et al. 1999], here derived for an assumed distance of 7 kpc.
Table 3. Power spectral fit results. As a model independent measure of the variability we also include the total fractional rms in the 0.001–1 Hz and 1–100 Hz ranges. FWHM stands for full-width-at-half-maximum.

| Parameter                              | Obs. 1     | Obs. 2     |
|----------------------------------------|------------|------------|
| Power law rms \( a \) (%)             | 5.15±0.12  | 7.71±0.11  |
| Power law index                        | 1.09±0.01  | 1.09±0.01  |
| Lorentzian rms \( a \) (%)             | 2.99±0.01  | 3.4±0.6    |
| Lorentzian FWHM (%)                    | 0.45±0.04  | 100±30     |
| Lorentzian freq. (Hz)                  | 0 (fixed)  | 0 (fixed)  |
| QPO rms \( c \) (%)                   | <1         | 2.1±0.4 (3.2\( \sigma \)) \( d \) |
| QPO FHWM (Hz)                          | 18 (fixed) | 18±6       |
| QPO frequency (Hz)                     | 60 (fixed) | 60±2       |
| rms [0.001–1 Hz] (%)                   | 6.6±0.02   | 9.15±0.02  |
| rms [1–100 Hz] (%)                     | 3.17±0.10  | 5.93±0.06  |
| \( \chi^2_{red} (d.o.f) \)            | 1.07 (209) | 1.01 (210) |

\( a \) Integrated between 0.001 and 1 Hz, \( b \) Integrated between 0 and +\( \infty \) Hz, \( c \) Integrated between –\( \infty \) and +\( \infty \) Hz, \( d \) Significance is calculated from the power, not the fractional rms.

4.1. Outflow

It is generally believed that the radio emission from neutron star and black hole X-ray binaries is produced by highly relativistic electrons that interact with magnetic fields to produce synchrotron radiation. High resolution radio observations of a handful of X-ray binaries show that these electrons reside in powerful, collimated outflows, commonly referred to as jets. It is assumed that in the X-ray binaries for which jets have not (yet) been directly observed the radio emission originates in a similar outflow. To see whether this could also be the case for GX 13+1, we estimate the size of the emission region. If, for an assumed spherical region, this size is larger than the binary separation, the highly relativistic synchrotron plasma cannot be contained in the system and the most plausible option would then be that we are dealing with an outflow. Assuming a maximum brightness temperature \( T_B \) of \( \leq 10^{12} \) K (see e.g. Kellermann & Pauliny-Toth 1969 and a distance of 7 kpc \( K = 11.2 \) cm, suggesting an outflow is also present in GX 13+1.

4.2. X-ray/radio connection

Although the exact mechanism for producing jet outflows in X-ray binaries is still not clear, the energy needed to achieve the inferred observed high bulk velocities suggests that they form in the inner parts of the accretion flow, where also most of the X-rays are produced. Simultaneous X-ray and radio observations of GRS 1915+105 seem to confirm such a direct link between the outflow and inner accretion disk \( K \). Clear patterns of X-ray/radio behavior are also observed in other black hole and Z source X-ray binaries; in general the spectrally hard X-ray states have a higher radio luminosity than the spectrally soft states.

Our observations of GX 13+1 reveal a similar pattern, with the second observation being both more luminous in the radio and showing a harder energy spectrum (Figs. 11).
Table 4. Observed mean and maximum radio flux densities and estimated distances for the six Z sources and GX 13+1. This table is reproduced from Tables 2 and 3 in Fender & Hendry (2000), with updated values for GX 13+1.

| Source      | Mean\(^a\) | Max\(^b\) | distance | Refs |
|-------------|------------|-----------|----------|------|
|             | (mJy)      | (mJy)     | (kpc)    |      |
| Sco X-1     | 10 ± 3     | 22        | 2.0 ± 1.0| 1.2  |
| GX 17+2     | 1.0 ± 0.3  | 13.4      | 7.5 ± 2.3| 1.3  |
| GX 349+2    | 0.6 ± 0.3  | 1.3       | 5.0 ± 1.5| 4.5  |
| Cyg X-2     | 0.6 ± 0.2  | 3.4       | 8.0 ± 2.4| 1.67 |
| GX 5-1      | 1.3 ± 0.3  | 1.6       | 9.2 ± 2.7| 1    |
| GX 340+0    | 0.6 ± 0.3  | 0.6       | 11.0 ± 3.3| 8    |
| GX 13+1     | 1.8 ± 0.3  | 7.7       | 7 ± 1     | 9-13 |

\(^a\) Mean cm radio flux density
\(^b\) Maximum radio flux density at 6 cm

References: 1: Penninx (1989), 2: Bradshaw et al. (1999), 3: Penninx et al. (1988), 4: Cooke & Ponman (1991), 5: Christian & Swank (1997), 6: Hjellming et al. (1990a), 7: Cowley et al. (1979), 8: Penninx et al. (1993), 9: Grindlay & Seymour (1980), 10: Garcia et al. (1988), 11: Berendsen et al. (2000), 12: Bandyopadhyay et al. (1999), 13: this work.

4.3. Comparison with Z and atoll source observations

Before discussing the nature of GX 13+1 in view of the atoll/Z source classification we compare its X-ray/radio behavior with that of sources from both classes. Although Schnerr et al. (2003) concluded that GX 13+1 is neither a Z nor an atoll source, one could, purely based on its appearance in the CD, argue that the source was in the atoll source banana branch and island state, during obs. 1 and 2 respectively, or the Z source flaring branch and normal branch.

Based on observing campaigns of the Z sources GX 17+2 (Penninx et al. 1988), Cyg X-2 (Hjellming et al. 1990a), Sco X-1 (Hjellming et al. 1990b), and GX 5-1 (Tan et al. 1992), Penninx (1989) suggested that all Z sources share a common radio, UV, and X-ray luminosity on their normal branch. Subsequent detections of GX 349+2 (Cooke & Ponman 1991) and GX 340+0 (Penninx et al. 1993) at approximately the predicted radio brightness seemed to confirm this idea. Penninx (1989) derived a normal branch luminosity of \( \sim 1.6 \cdot 10^{38} \) erg s\(^{-1}\) in the 1.5-15 keV band. In the same energy band we obtain (extrapolating our fit to lower energies) \( \sim 1.7 \cdot 10^{38} \) erg s\(^{-1}\), which is remarkably close the value of Penninx (1989).

The assumption of Penninx (1989) might be not completely valid; using the distance estimates and average flux densities from Fender & Hendry (2000) (see Table 4) it seems that there is a considerable spread in the average...
radio luminosity of the six Z sources. Moreover, none of them has a higher value than GX 13+1. However, this average radio luminosity depends strongly on the time a source spends in a radio bright state. Taking the maximum radio flux densities (at 6 cm) reported in the literature (see references in Table 2) should partly correct for this, which results in GX 17+2 being the most luminous with GX 13+1 being second. The overall behavior of the radio brightness along the track in the CD is also similar to that observed in several of the Z sources (Penninx et al. 1988; Diehlming et al. 1990a,b).

The only atoll source for which a clear pattern in the X-ray/radio emission has been found is 4U 1728–34 (Migliari et al. 2003). In that source the radio flux density was highest in the island state; it increased by a factor ~6 from the hard part of the island state toward the transition between the island state and, what seemed to be, the banana branch. After this transition it dropped sharply by a factor of ~6. While the decrease of radio flux with spectral hardness (in the island state) is opposite to overall behavior in GX 13+1 and several Z sources (where we see an increase with spectral hardness along the track in the CD), the factor of ~6 difference between the island state and banana branch is similar in sign and magnitude to the difference between our second and first observation. The average X-ray luminosity of 4U 1728–34 (assuming a distance of 5.2 kpc (Galloway et al. 2002)) is more than a factor 10 lower than that of GX 13+1, whereas the 6 cm flux density is probably more than a factor 100 lower.

4.4. Z or atoll?

The nature of GX 13+1 and its place in the Z/atoll classification scheme have recently been extensively studied and discussed by Schnerr et al. (2003). They found that its motion through the HID is in the opposite sense to that in the CD, with the X-ray count rate increasing again when the source moves into the spectrally hard state, contrary to most atoll and Z sources (see our Fig. 2 and also Wijnands et al. 1997 for similar behavior in the Z source Cyg X-2). Moreover, the strength of the very low frequency variability also changes in the opposite sense to that observed in Z and atoll sources.

In an attempt to fit GX 13+1 within the Z/atoll scheme as an atoll source, Schnerr et al. (2003) tried to explain the source’s peculiar behavior with the presence of a relativistic jet with an axis nearly aligned to our line of sight. The radio emission could then be boosted by more than an order of magnitude, putting the radio emission of GX 13+1 in accordance with measurement and upper limits of other atoll source; the unusual X-ray phenomena could be the consequence of a better view of the X-ray emitting regions associated with the base of the jet, possibly assisted by Doppler boosting.

As we showed above, the X-ray and radio luminosities of GX 13+1 are actually in the range expected for Z sources, without requiring any unusual jet geometries, making a Z source nature more likely in our opinion (the atoll sources GX 9+1, GX 9+9 and GX 3+1 have also similar X-ray luminosities but much lower radio luminosities). This is supported by our spectral fit parameters, which are quite similar to those found in the Z sources (see e.g. Di Salvo et al. 2000; Di Salvo et al. 2001) and less like those in the atoll sources (see e.g. Di Salvo et al. 2006; Barret et al. 2000; Barret & Olive 2002), and by the fact that GX 13+1 rarely shows type I X-ray bursts. Based on the morphology in our CD GX 13+1 was probably observed in the normal branch and flaring branch. Although no clear indications for normal branch oscillations are found, the band limited noise measured by Schnerr et al. (2003) has properties similar to the normal branch oscillations found in GX 5-1 (Jonker et al. 2002) and GX 340+0 (Jonker et al. 2000) close to the normal branch/flaring branch vertex, where it is very broad (Q < 1) and rather weak (≤2% rms). In GX 5-1 and GX 340+0 this broad bump evolves into a strong 6 Hz QPO as the spectrum hardens - this is not observed in GX 13+1. There are additional differences with the other Z sources, in particular with respect to the behavior of the low frequency variability.

Finally, we note that although the source was more similar to the Z sources than to the atoll sources during our observations (at a luminosity three times as high as during the EXOSAT era), this does not exclude that at lower luminosities it behaves more atoll-like.

5. Summary

Our simultaneous X-ray/radio observations of GX 13+1 revealed a strong dependence of the radio brightness on the X-ray state of the source. In the hard spectral state, which was at least 4 times brighter in the radio than the soft state, we also found a correlation between the X-ray and radio properties on a short time scale, with changes in radio having a delay of ~40 minutes with respect to those in X-rays. We attribute this delay to the time it takes for the flow to become optically thin in the radio. The absence of strong dips in the X-ray light curve during the radio flare suggests that only a small amount of the matter is redirected from the inflow to the outflow. On the basis of a comparison with atoll and Z sources we conclude that the source is more similar to the Z sources, although several properties of GX 13+1 remain unexplained.

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