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SIMULTANEOUS X-RAY AND RADIO OBSERVATIONS OF GX 5−1

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ABSTRACT

Simultaneous X-ray (*Ginga*) and radio (VLA) observations of the Z-type low-mass X-ray binary GX 5−1 were made during 1989 September 1–6. The radio flux of GX 5−1 was less than 1 mJy when the X-ray source was in the horizontal branch. In the normal branch, the radio flux increased up to ~6 mJy, and its variations were anticorrelated with those of the X-ray flux during time intervals of tens of minutes. This radio behavior is opposite to the X-ray/radio correlation found before in the Z sources GX 17+2, Cyg X-2, and Sco X-1. We conclude that the radio properties of GX 5−1 are different from those of these three Z sources, at 99.5% and 96.5% levels of confidence, for the horizontal branch and the normal/flaring branches, respectively.

Subject headings: binaries: spectroscopic — radio continuum: stars — X-rays: stars

1. INTRODUCTION

The bright low-mass X-ray binaries (LMXB) can be divided into two groups, the so-called "Z sources" and "atoll sources" (Hasinger & van der Klis 1989). Sources in both groups show a strong correlation between their X-ray spectral and fast variability properties; however, the nature of the correlation is different for the two groups.

The X-ray spectral variations of the Z sources are characterized by a Z-shaped track in X-ray color-color and color-intensity diagrams (see, e.g., Hasinger & van der Klis 1989), in which three so-called spectral branches can be distinguished. In the "horizontal branch" (HB), high-frequency quasi-periodic oscillations (QPOs) are observed in the power spectrum of the X-ray intensity variations, whose centroid frequency is strongly correlated with the X-ray intensity. At its high-intensity side, the HB is connected to the "normal branch" (NB), along which there is a positive correlation between X-ray intensity and the hardness of the X-ray spectrum. As the source moves from the HB to the NB, the high-frequency QPOs become weak and disappear; when the source occupies the middle part of the normal branch, another type of QPO appears, whose frequency is always in the range 5–7 Hz. At the "soft" side the NB is connected to the "flaring branch" (FB), along which the source intensity may show large variations. As the source moves onto the FB, the centroid frequency of the (~6 Hz) NB QPO increases, and the power of the QPO spreads out over a very wide frequency range.

Recent simultaneous radio and X-ray observations of the Z sources GX 17+2, Cyg X-2, and Sco X-1 (Penninx et al. 1988; Hjellming et al. 1990a, b) have shown a connection between the radio brightness and the X-ray spectral states (and therefore with the properties of the X-ray QPOs); these sources appear to be "radio-quiet" when they are in the FB and NB state, and the radio flux is high and variable in the HB state. Penninx (1990) found that the ratio of the average radio flux to the average NB X-ray flux is quite similar for these three sources.

In this paper we report on the results of simultaneous X-ray and radio observations of the Z source GX 5−1, which were made to see whether the above X-ray/radio correlation also holds for the Z source GX 5−1. Some radio observations (not simultaneous with X-ray observations) have previously been made of GX 5−1. The radio flux measured by Grindlay & Seaquist (1986) in 1982 June was ~1.3 mJy at 20 cm. This is comparable to the 20 cm flux measured by Geldzahler (1983) in 1982 February, but much lower than the 21 cm radio flux (~10 mJy) reported by Braes, Miley, & Schoenmakers (1972); clearly the radio flux is variable. In addition to these published results, GX 5−1 was detected in 1987 June with the VLA by R. L. White (private communication); the source flux then was 1.62 ± 0.06 mJy and 3.57 ± 0.16 mJy at 4.8 and 1.5 GHz, respectively. In § 2 we describe our own (1989 September) observations, and the results of the data analysis. These results are discussed in § 3. We formulate our conclusions in § 4.

2. OBSERVATIONS AND RESULTS OF DATA ANALYSIS

The X-ray observations of GX 5−1 were made with the Large Area Counter (LAC) of *Ginga* (Makino et al. 1987; Turner et al. 1987) during 1989 September 1–2 and September 4–6. The X-ray data were accumulated in 12 energy channels with a time resolution of 7.8 m; the data were corrected for spacecraft attitude, background, and dead time. X-ray color-color diagrams for these observations (Lewin et al. 1992), i.e., plots of a low-energy hardness ratio, calculated as the count rate ratio of the 3.5–6.9 keV band to the 1.2–3.5 keV band, versus a high-energy hardness ratio (6.9–18.4 and 3.5–6.9 keV bands), are shown in Figure 1. From these diagrams, and from the properties of the power spectra of the X-ray intensity variations Lewin et al. (1992) found that GX 5−1 was in the HB

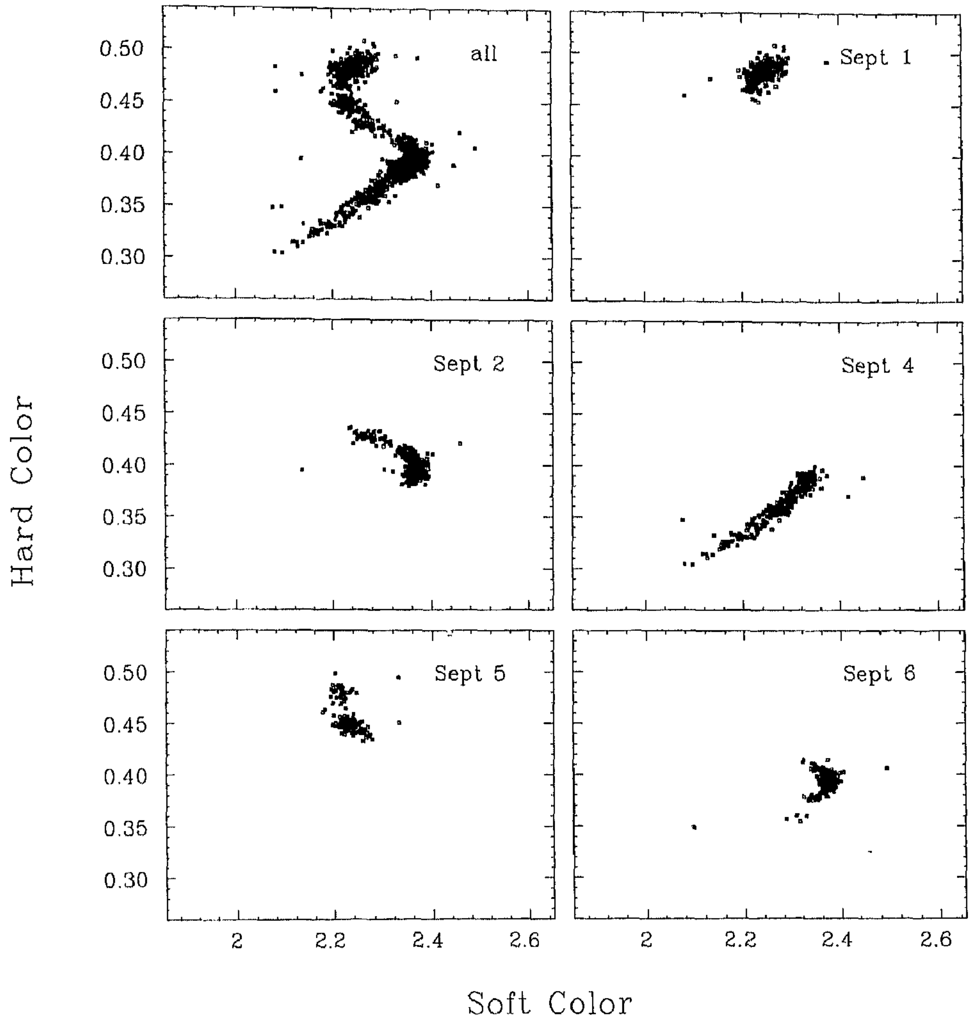

FIG. 1.—X-ray color-color diagrams for 5 days and for the combined X-ray observations (*upper left*). The "hard color" is the counting rate ratio for the energy channel 6.9–18.4 keV to the 3.5–6.9 keV channel; the "soft color" is the ratio for the 3.5–6.9 keV channel to the 1.2–3.5 keV energy channel. For more details, see Lewin et al. (1992).

state on 1989 September 1, 2, 5, and 6 and in the NB state on September 4 (see Fig. 1). The X-ray fast-timing characteristics of GX 5−1 on these branches (Lewin et al. 1992) were similar to those observed earlier for this source (van der Klis et al. 1985, 1987; Mitsuda, Dotani, & Yoshida 1988; Mitsuda & Dotani 1989), and for other Z sources in the same spectral state (see Hasinger & van der Klis 1989).

The radio observations of GX 5−1 were made with the NRAO Very Large Array (VLA). The VLA was in the 3.3 km C configuration with minimum beam sizes of 10″, 3″, and 1″.5 at observing frequencies of 1.49, 4.9, and 8.4 GHz, respectively. During the observations 26 or 27 telescopes were used with two adjacent 50 MHz bands at each of the three frequencies, with average system temperatures of 60, 50, and 40 K, respectively. Phase and amplitude calibrations were determined from interleaved observations of the calibrator 1741−038, and the flux calibration was obtained from daily observations of 3C 286. Normal calibration procedures were used. Flux densities during weak-source states were obtained from deconvolved images in AIPS; however, the highly time variable flux densities during 1989 September 4 were determined using a special program, with which we imaged and deconvolved the data in 3 minute intervals, resulting in data cubes with one temporal and two spatial dimensions. See Table 1.

The field near GX 5−1 is too crowded with confusing emission at 1.49 GHz to allow high enough dynamic range imaging to determine radio fluxes of GX 5−1 at this frequency. The results for 4.9 and 8.5 GHz are plotted as a function of time in Figures 2*a* and 2*b*, respectively, together with the (1.2–18.4 keV) X-ray count rate (Fig. 2*c*) and the X-ray spectral hardness defined as the count rate ratio for the 6.9–18.4 keV and 3.5–6.9 keV bands (Fig. 2*d*). For the spectral shape we observed for GX 5−1 one count corresponds to 4.8×10^{-12} ergs cm^{-2} (this calibration is fairly insensitive to the detailed spectral shape). During three of the four days, GX 5−1 was a very weak radio source (see Fig. 2). The average fluxes between roughly 2:00 and 6:00 UT on September 2, 5, and 6 were 1.0 ± 0.1, 0.72 ± 0.1, and 0.78 ± 0.1 mJy at 4.9 GHz, and 0.87 ± 0.1, 0.49 ± 0.1, and 0.81 ± 0.1 mJy at 8.4 GHz. On September 4, the radio emission varied in the range of 1.5 to 6 mJy; the radio intensity curve is displayed in detail in Figure 3, where the flux densities at 4.9 GHz are indicated by filled circles, and those at 8.4 GHz with crosses. The error limits were estimated from the peak-to-peak noise in the images and are consistent with

TABLE 1
RADIO FLUXES (mJy) OF GX 5−1 ON 1989 SEPTEMBER 4

UT	S (4.9 GHz)	S (8.4 GHz)
02:02:20.........	3.69 ± 0.50	
02:05:10.........	3.75 ± 0.50	
02:24:10.........		3.93 ± 0.30
02:27:40.........		4.07 ± 0.30
02:36:05.........	3.73 ± 0.60	
02:39:35.........	3.82 ± 0.60	
02:42:25.........	3.78 ± 0.60	
02:45:15.........	3.91 ± 0.60	
02:48:03.........	4.34 ± 0.60	
02:51:34.........	4.30 ± 0.60	
02:54:22.........	4.64 ± 0.60	
02:57:11.........	5.07 ± 0.60	
03:00:00.........	5.26 ± 0.60	
03:03:30.........	5.28 ± 0.60	
03:06:20.........	5.24 ± 0.60	
03:31:40.........	5.40 ± 0.60	
03:35:10.........	5.80 ± 0.60	
03:37:58.........	5.54 ± 0.60	
03:40:47.........	5.70 ± 0.60	
03:43:35.........	5.80 ± 0.60	
03:45:00.........		6.05 ± 0.30
03:48:31.........		5.50 ± 0.30
03:51:20.........		4.90 ± 0.30
03:54:08.........		4.42 ± 0.30
03:57:40.........		4.13 ± 0.30
04:06:48.........	4.10 ± 0.50	
04:09:37.........	4.10 ± 0.50	
04:13:08.........	3.90 ± 0.50	
04:15:56.........	3.70 ± 0.50	
04:18:45.........	3.55 ± 0.50	
04:21:34.........	3.50 ± 0.50	
04:25:05.........	3.61 ± 0.50	
04:27:54.........	3.34 ± 0.50	
04:30:42.........	3.40 ± 0.50	
04:33:31.........	3.00 ± 0.50	
04:37:02.........	3.10 ± 0.50	
04:39:50.........	3.50 ± 0.50	
04:42:39.........	3.30 ± 0.50	
04:45:28.........	3.30 ± 0.50	
04:48:59.........	2.90 ± 0.50	
05:10:47.........	2.50 ± 0.50	
05:13:36.........	2.60 ± 0.50	
05:17:07.........	2.50 ± 0.50	
05:19:55.........	2.60 ± 0.50	
05:22:44.........		1.53 ± 0.20
05:26:15.........		1.53 ± 0.20
05:29:04.........		1.59 ± 0.20
05:31:52.........		1.40 ± 0.20
05:42:25.........	1.70 ± 0.40	
05:45:134........	2.10 ± 0.40	
05:48:03.........	2.20 ± 0.40	
05:51:34.........	2.40 ± 0.40	
05:54:22.........	2.90 ± 0.50	
05:57:11.........	3.00 ± 0.50	
06:00:42.........	3.00 ± 0.50	

thermal noise. With the exception of September 5, at all times (even during the rapid variations observed on September 4) the radio spectrum of GX 5−1 had a spectral index, α, consistent with 0, i.e., it was flat. On September 5 the spectrum was that of a nonthermal radio source with a spectral index of −0.7, which is typical for optically thin synchrotron emission (Hjellming 1988). On September 4 the radio flux of GX 5−1 varied on time scales as short as ~5 minutes, i.e., close to the separation between the points plotted in Figure 3, with the bulk of the variability occurring on a time scale of hours. The shortest time scale of variability of radio emission hitherto seen in the other Z sources was about 20 minutes; however, radio flux variations on time scales of a few minutes were often seen in the unusual X-ray transient GS 2023+336 (V404 Cyg; see Han & Hjellming 1990).

Figure 2 suggests that there is a correlation between the radio flux and the X-ray spectral state of GX 5−1. On 1989 September 2, 5, and 6, the radio flux of GX 5−1 was below 1 mJy; the X-ray source was then in the HB state. On September 4, when GX 5−1 was in the NB state the radio flux was much higher, up to 6 mJy. A comparison of the variations of the X-ray flux (and spectral hardness) and that of the radio flux on September 4 shows that although the two fluxes did not follow the same relation throughout the observation, during time intervals of tens of minutes they were generally anticorrelated (see Fig. 4).

3. DISCUSSION

3.1. *General Characteristics of the X-Ray Emission*

The X-ray flux of GX 5−1 during our 1989 September observations ranged between $\sim 3.6 \times 10^{-8}$ and $\sim 6.2 \times 10^{-8}$ ergs cm^{-2} s^{-1}; this is similar to the fluxes observed previously for this source (Forman et al. 1978; Warwick et al. 1981; Wood et al. 1984). Likewise, the color-color diagram (Fig. 1), which shows a horizontal and a normal branch, and the correlated fast-variability behavior, are very similar to those obtained in previous observations (see, e.g., Hasinger & van der Klis 1989). For more details on our X-ray observations we refer to Lewin et al. (1992).

3.2. *General Characteristics of the Radio Emission*

The time scale, τ, of significant radio flux variations on September 4 was as short as ~5 minutes, which implies an upper limit to the size of the emitting region of $c\tau \sim 10^{13}$ cm if we assume that the radiation mechanism is incoherent. If the radiation mechanism is coherent, the size is smaller. For a distance of ~6.4 kpc (Penninx 1990) the corresponding upper limit to the angular diameter is ~0.1 mas for incoherent emission, and less if it is coherent. This can be transformed into a lower limit on the brightness temperature T_B (in kelvins) according to the expression (Hjellming 1988)

$$S_\nu = T_B \theta^2/(1970\lambda^2)\ \text{Jy}\ , \tag{1}$$

where θ and λ are the angular diameter (in arcseconds) and the wavelength (in cm), respectively; the numerical constant (i.e., 1970) is not dimensionless. From this we find $T_B > 3 \times 10^{10}$ K.

The short time scale of the intensity variations and the high brightness temperature are both consistent with the often used model (see, e.g., Hjellming 1988) that the radio flux originates in small synchrotron-emitting regions containing a mixture of relativistic electrons and magnetic fields. In this case a lower limit on the size can be obtained from the inverse Compton limit for an incoherent synchrotron source, for which $T_b < 10^{12}$ K. For a uniform source with $S_\nu \sim 5$ mJy this limit on the brightness temperature leads to $\theta > 0.02$ mas. This limit, and the inferred size scales and brightness temperature limits based on the shortest time scale of significant variation, indicate that the brightness temperature is within about an order of magnitude of the inverse Compton limit, and the angular scale of the radio source in the range 0.02–0.1 mas. These results are consistent with the inferences for the radio emission from other X-ray binaries (Hjellming et al. 1990a, b).

The flat spectrum seen in the September 4 radio event in GX

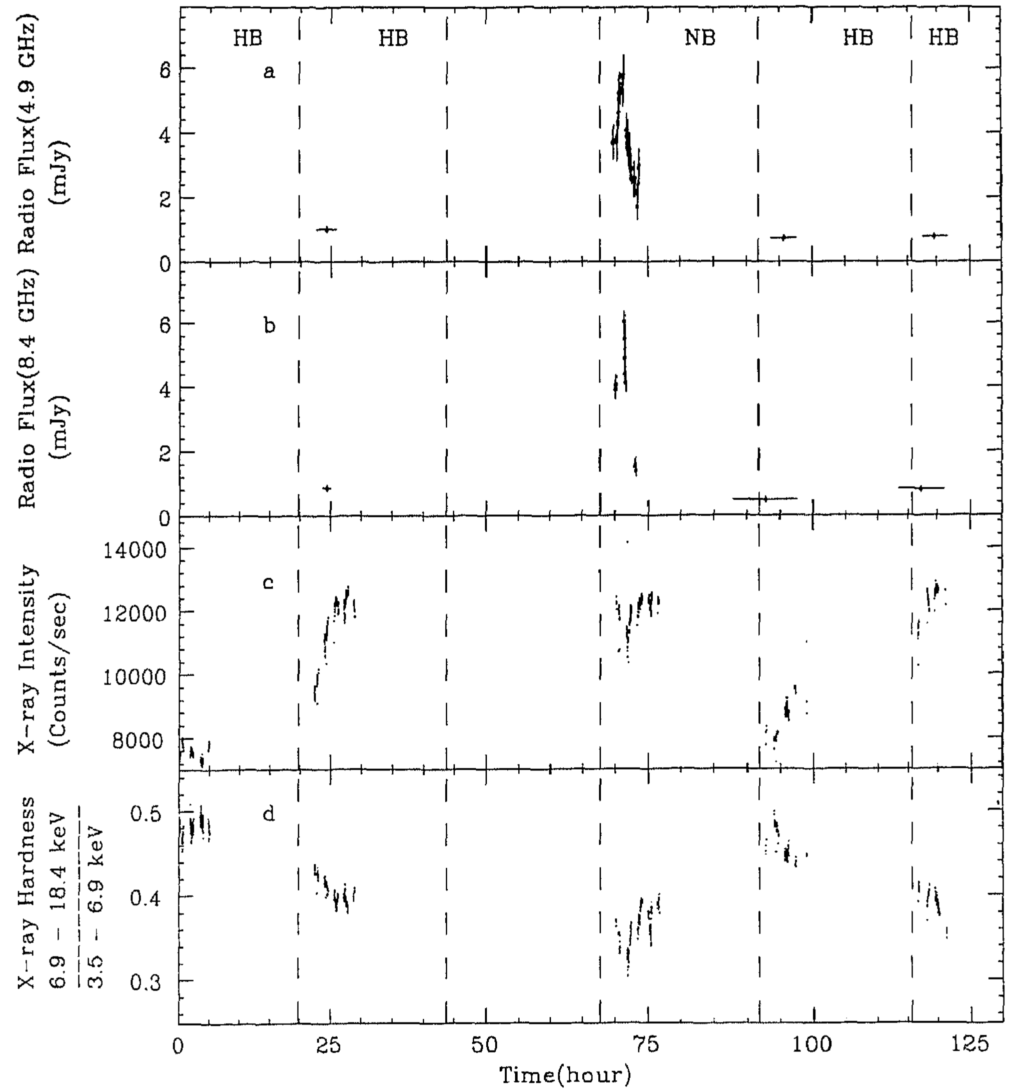

FIG. 2.—The radio fluxes from GX 5−1 at (*a*) 4.9 GHz and (*b*) 8.4 GHz, (*c*) the (1.2–18.4 keV) X-ray count rate, and (*d*) X-ray hardness ratio are plotted as a function of time. On 1989 September 2, 3, 5, and 6, the radio flux was below 1 mJy while the X-ray source was in the horizontal branch, but the radio flux increased up to ~6 mJy on 1989 September 4 while the X-ray source was in the normal branch. It is noticed that the radio flux was highly variable and anticorrelated with the X-ray count rate as well as with the X-ray hardness when the X-ray source was in the normal branch. One count corresponds to 4.8×10^{-12} ergs cm^{-2}. Time 0 = UT 1989 September 1, 04:16:53.

5−1 indicates that this was not caused by a single adiabatically expanding "synchrotron bubble" (Hjellming & Johnston 1988). The flat spectrum can be explained, however, with either an inhomogeneous radio source structure, or by a large optical depth with a turnover in the radio spectrum between 4.9 and 8.4 GHz. The former explanation is the most likely when a flat spectrum occurs with a range of flux variations as large as that observed on September 5.

In most earlier radio observations of Z sources, the spectral index was negative, with typical values near −0.6. However, for a given source on a given spectral branch large variations of α have been observed; e.g., for Cyg X-2 on the NB, α has been observed to vary between ~0.0 and < −1.0 (Hjellming et al. 1990a). The interpretation of fairly isolated observations of the spectral index is not straightforward (see Hjellming & Johnston 1988).

3.3. *Comparison with Other Z Sources*

The X-ray/radio behavior which we observe for GX 5−1 is very different from that found for the Z sources GX 17+2, Cyg X-2, and Sco X-1 (Penninx et al. 1988; Hjellming et al. 1990a, b). In GX 5−1 the radio flux was found to be lowest when the source was on the HB, and highest on the NB. In the three other Z sources, the radio flux was lowest when they were on the FB, and highest on the HB. In order to put this difference into perspective and to address the question whether the X-ray/radio connection found earlier for GX 17+2, Cyg X-2, and Sco X-1 is perhaps the result of a chance coincidence in sampling uncorrelated X-ray and radio properties, we will discuss the results in some detail.

GX 17+2 was observed simultaneously in X rays and radio on six different days between 1988 March 28 and April 5. Each

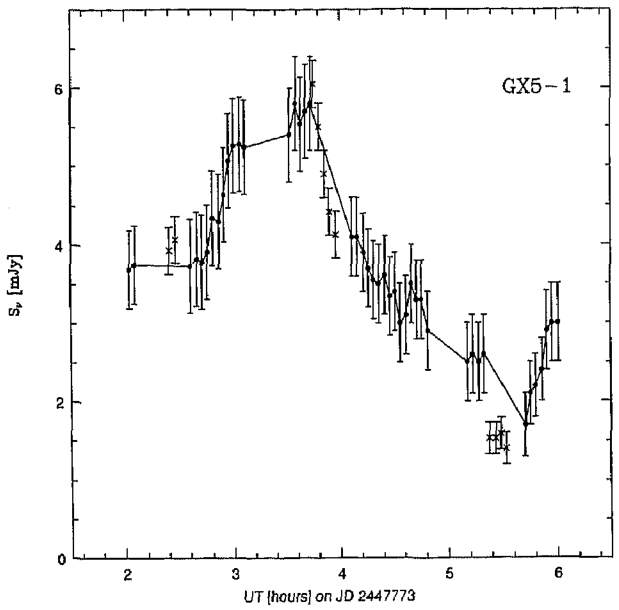

FIG. 3.—Plot of the radio event on 1989 September 4 in the form of flux density (in mJy) as a function of UT; the filled circles and crosses indicate measurements at 4.9 and 8.4 GHz, respectively.

of the simultaneous observations lasted for about two hours or longer. The source was found once on the FB, 3 times on the NB, and twice on the HB. The 6 and 20 cm flux from GX 17+2 increased by factors ~30 and ~40, respectively, as the X-ray state changed from the FB and NB to the HB (Penninx et al. 1988). When the radio flux was high, the radio spectral index ($\alpha \sim -0.6$) was consistent with that of an optically thin synchrotron emitter.

During simultaneous *Ginga*/VLA observations of Cyg X-2 made in 1988 June (Hjellming et al. 1990), the X-ray spectral state alternated from the HB to the NB/FB twice in a 5 day

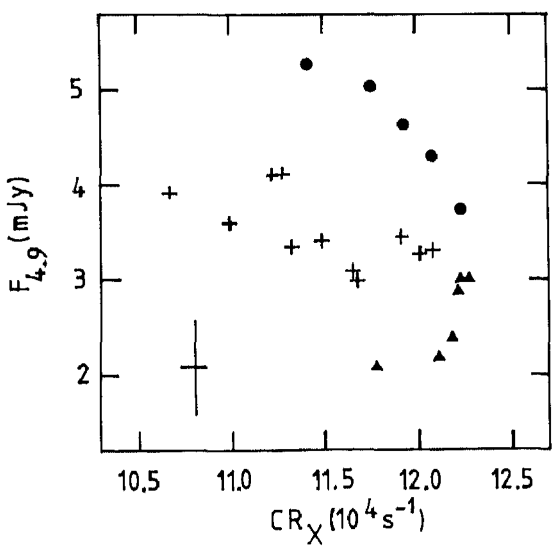

FIG. 4.—Relation between the 4.9 GHz radio flux (in mJy) and the X-ray count rate of GX 5−1, as observed on 1989 September 4 when the source was on the normal branch. Different symbols indicate different time intervals, as follows: UT 02:48–03:03 (*filled circles*); UT 04:04–04:45 (*plus signs*); UT 05:45–06:02 (*filled triangles*). Typical errors on the points are indicated by the large cross in the lower left corner.

period. On all three occasions that Cyg X-2 was found on the HB or the uppermost part of the NB (defined by the presence of high-frequency HB-QPO), its radio flux was relatively high (2–5 mJy) and variable. On three other occasions, and also twice during similar observations in 1988 October, Cyg X-2 was in the FB or (lower) NB state; its radio flux was then low (<1 mJy; Hjellming et al. 1990a). The spectral index α (as measured between 4.9 and 8.4 GHz) was generally negative; however, both on the HB and NB large variations in α, typically between ~0.0 and ~ −1.0, were observed.

Hjellming et al. (1990b) observed Sco X-1 simultaneously in X rays and radio during 2 days in 1989 March. During this observation, Sco X-1 was observed once on the FB and once on the NB. The radio flux was very low (~1 mJy at 1.49, 4.9, and 8.4 GHz) when the source was on the FB. On the NB the radio flux ranged between ~9 and 5.5 mJy for frequencies between 1.49 and 8.4 GHz. Taking into account that the distance to Sco X-1 is smaller than that of GX 17+2 and Cyg X-2 by at least a factor of 3 (see Penninx 1990, and references therein), this result implies that on both the NB and FB the radio state of Sco X-1 was similar to the radio quiet states in GX 17+2 and Cyg X-2. According to Penninx (1990) the results of extensive radio and X-ray observations of Sco X-1 made during the 1970s are consistent with this picture.

Since the time scale in which the spectral state of Z sources changes is of the order of a day (van der Klis et al. 1991), we assume that in a comparison of the radio properties of different sources and different spectral states, radio observations on different days can be considered independent. (Note that such a comparison is only meaningful if the relation, if any, between the radio and X-ray properties is instantaneous, without delays between changes in the X-ray state and the related radio emission). Counting the number of such independent observations we find that GX 17+2, Cyg X-2, and Sco X-1 have been observed 5 times in the HB state, 6 times in the NB state, and 5 times in the FB state. During all HB observations the sources were in a radio "high" state, and during all NB and FB observations they were in a radio "low" state.

In comparing the radio properties of GX 5−1 with those of the other three Z sources, we make a simplifying initial assumption that the underlying radio properties of Z sources can be described by a bimodal distribution of radio intensity, i.e., a "low" and a "high" state (see the above description of the radio observations of GX 17+2, Cyg X-2, and Sco X-1); we assume that they are the same for all Z sources, i.e., both in the HB, and in the NB/FB the probability q_L to encounter the source in a low state is the same for GX 5−1 and for the other three sources.

The first question is whether or not there is a difference in the radio properties between the HB and the NB/FB. With the above description of the radio properties in terms of q_L this question can be phrased as follows: what is the probability P that a sample of five (or more) "high" states out of eight trials have been drawn from the same population as a sample of one (or less) out of 11 trials? Using the binomial distribution we find that the probability that this happens by chance coincidence is at most 6.6×10^{-3} (for $q_L = 0.68$). Thus, we conclude that there is some, but not overwhelming, evidence that the radio properties of Z sources in the HB state differ from those in the NB and FB states. (We note that before adding GX 5−1 to the group of Z sources the probability to encounter zero "high" states out of 10 trials on the NB and FB, and five out of five on the HB, was less than 7×10^{-5} [for $q_L = 0.66$]).

On the basis of the above we now allow q_L to be different for the HB and NB/FB (we indicate its value on these branches by $q_{L,h}$ and $q_{L,nf}$, respectively). Then the next question is what is the probability, P, that for GX 5−1 we find the radio state to be low in three out of three HB observations, whereas in the other three sources the score is zero out of five such observations. This probability is given by $P = (1 - q_{L,h})^5 q_{L,h}^3$, which has a maximum value $P_{\max} = 5 \times 10^{-3}$ for $q_{L,h} = 0.38$. Similarly, for the NB/FB we have to compare 10 out of 10 "hits" with 0 out of 1; the probability for this to happen is at most 3.5×10^{-2}, for $q_{L,nf} \sim 0.09$. Combining these upper limits, we find that the probability that GX 5−1 and the other three Z sources follow the same relation between X-ray and radio properties, is at most $\sim 2 \times 10^{-4}$. From this we conclude that, under the assumptions made, it is very likely that the relation between the X-ray and radio properties of GX 5−1 is different from that of the other Z sources.

4. CONCLUSION

From simultaneous X-ray (*Ginga*) and radio (VLA) observations of GX 5−1, we have found that its radio flux was below 1 mJy when the X-ray source was in the HB, and it increased up to ~6 mJy when the X-ray source was in the NB. This X-ray/radio behavior is opposite to the correlation found in GX 17+2, Cyg X-2, and Sco X-1. Using a simple model for the radio behavior of Z sources involving two radio states ("high" and "low") we have made a quantitative analysis of this difference in radio behavior. We find that the correlation between the radio flux and the X-ray spectral state, found for the sources GX 17+2, Cyg X-2, and Sco X-1, is significant; on the HB these Z sources are in a radio "high" state, whereas on the NB and FB they are in a radio "low" state. The radio properties of GX 5−1 are different from those of these three Z sources, at 99.5% and 96.5% levels of confidence, for the HB, and the NB/FB, respectively.

There is one possibility that would make the X-ray–to–radio correlation of GX 5−1 consistent with the other Z sources. Little is known about the range of possible delays between changes in X-ray states and the related radio emission. If the strong and variable radio emission on September 4 was a sampling of a strong radio event preceding the NB state observed in both X-ray and radio, this event could have occurred during an unobserved HB state that evolved to a NB state leaving a residual strong radio source. In other words, all of the sampled radio emission during this campaign could have *originated* during HB X-ray states, and the sampling was not sufficient to see the evolutionary connections between these states in the radio and in X-ray. Under these circumstances the quiescent FB–NB radio states would not yet have been observed in GX 5−1. This possibility exists because we have very sparse sampling of the transitions between X-ray states, and even poorer measurement of possible delays between the changes in X-ray and radio states. Some delay is expected because changes must propagate from the compact X-ray–emitting environment to the larger radio-emitting regions.

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