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SIMULTANEOUS X-RAY AND RADIO OBSERVATIONS OF GX 13+1

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ABSTRACT

The results of simultaneous X-ray and radio observations of GX 13+1 are presented and possible models are discussed in light of these observations. We find no evidence for correlated X-ray and radio flux density variations. The 6 to 20 cm wavelength spectral index varies from $\alpha = +0.5$ to -1.0 ($S_\nu \propto \nu^\alpha$), indicating that the radio flux is most probably produced by a nonthermal emission mechanism. Application of an equipartition synchrotron model to the data suggests that the radio emission originates in a region with a magnetic field of ~ 1 gauss. If the radio flux density variations are due to injection of relativistic electrons the equivalent nonthermal particle energy is 10^{36}–10^{41} ergs s^{-1}.

Subject headings: radiation mechanisms — radio sources: variable — stars: individual (GX 13+1) — stars: radio radiation — X-rays: binaries

I. INTRODUCTION

GX 13+1 is a relatively poorly studied galactic bulge X-ray source. It is intrinsically one of the brightest, being near the Eddington luminosity for a 1.4 $M_\odot$ neutron star if it is located near the galactic center (assumed herein to be at 7 kpc [Grindlay 1985; Ebisuzaki, Hanawo, and Sugimoto 1984]). Based on its location in the galactic bulge, and the similarity of its X-ray and optical properties to those of the other galactic bulge sources, we would expect it to be a low mass X-ray binary (LMXRB) (see Brakt and McClintock [1983] for a review of the properties of LMXRB). The high extinction to the galactic center precludes the identification of an optical counterpart, but radio (Grindlay and Seaquist 1986) and infrared (Garcia and Grindlay 1987) counterparts have been found. Its X-ray variability is unusual among the LMXRBs in that the source spectrum sometimes becomes harder, and other times becomes softer, as the luminosity increases (Stella, White, and Taylor 1985; Garcia and Grindlay 1987). Flux density variations on time scales as short as ~ 50 ms and the unusually soft spectrum (among the galactic bulge X-ray sources) revealed by an *EXOSAT* observation in 1983 September (Stella, White, and Taylor 1985) suggest a possible analogy with black hole candidates in their "high" state (White and Marshall 1984). Despite extensive high-sensitivity searches, the rapid quasi-periodic oscillation (QPO) often seen in LMXRB (van der Klis 1986) has not been found in GX 13+1.

The radio counterpart to GX 13+1 was discovered at a flux density of 1.8 mJy at 6 cm wavelength (Grindlay and Seaquist 1986), but prior to this work no information on variability or the radio spectrum was available. Our goals for these radio observations were threefold: (1) to investigate the radio variability, if any, and its relation to the X-ray variability, (2) to measure the radio spectrum, thereby constraining possible emission mechanisms, and (3) to search for associated radio lobes or jets as in Sco X-1 (Hjellming and Wade 1971; Geldzahler *et al.* 1981) and Cir X-1 (Haynes *et al.* 1986). We report here the results of ~ 11 hours of radio observations made with the VLA,[2] 6 of which were simultaneous with X-ray observations made with the *EXOSAT* Medium Energy Array (ME) (Taylor *et al.* 1981).

II. OBSERVATIONS AND ANALYSIS

a) Radio

The radio observations were obtained during part of a program to measure the radio spectra and variability of a number of galactic bulge X-ray sources. The observations of GX 13+1, which took place in 1985 from 06:54 to 11:13 UT May 1 and 06:50 to 13:24 UT May 2, were therefore often interrupted to observe other sources. The VLA (Thompson *et al.* 1980; Hjellming 1983) was in the B configuration; the standard VLA calibrators 1741−038 and 1908−202 were used to calibrate the complex antenna gains throughout the observations. The absolute flux density was ascertained with observations of 3C 286. The low elevation of GX 13+1 causes the phases to drift rather quickly, so the phase calibrators were observed at ~ 20 minute intervals. Approximately twice as much observing time was spent at 6 cm as at 20 cm wavelength. The VLA phase center was at a position 8″ to the south of GX 13+1 in order to avoid artifacts which can occur at the center of VLA maps. The data were calibrated at the VLA and then analyzed at the Center for Astrophysics using the Astronomical Image Processing System (AIPS).

The 6 and 20 cm light curves (Fig. 1) were derived by averaging the flux density received from the position of GX 13+1 in ~ 30 minute segments. This averaging time was chosen as a reasonable compromise between the desire for high signal-to-

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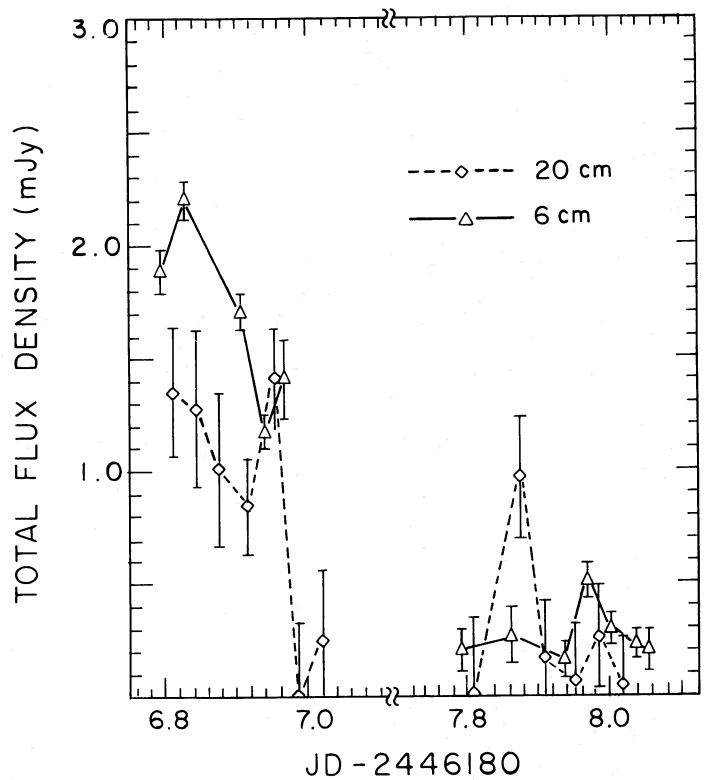

FIG. 1.—The light curve of GX 13+1 at 6 and 20 cm as seen from the VLA on 1985 May 1 and 2. The source is above the horizon for ~8 hr a day, hence the large gap in the coverage. The integration times are ~30 minutes, and the vertical bars indicate the 1 σ errors.

noise ratio and high time resolution. The averaging was done by first shifting the phase center of the data to the position of GX 13+1, and then averaging the real and imaginary parts of the data. Assuming the data are accurately described by a single point source at the phase center, the average of the real parts measures the source flux density. Similarly, the error on the flux density is the measured rms of the real parts. We note that this technique is much more computer efficient than measuring the flux density in a series of time-resolved maps. In order to exclude the effects of nearby extended sources (Altenhoff *et al.* 1978; Downes *et al.* 1980), we have spatially filtered the data by excluding baselines less than 20000 λ (where λ is the observing wavelength). We tested the reliability of the light curves by shifting the phase center to a blank position nearby GX 13+1. When data at baselines less than 20000 λ are excluded, the flux density measured at this blank position is consistent with a mean of zero and no significant variations. The average of the imaginary parts provides an additional check on the reliability of the light curves, as they should be consistent with a mean of zero and no significant variations (and in this case are) if the above assumptions are correct. This is a particularly strong test as the imaginary parts have been processed in a fashion identical to the real parts, therefore retaining any possible systematic errors. Also, contamination by other sources is the most likely cause of errors in the computed light curve for sources in the crowded galactic plane region—and such contamination would almost certainly cause a nonzero mean in the imaginary parts if it were present. We are thus assured that the light curves (Fig. 1) are truly representative of the source.

The variability at 6 and 20 cm is very pronounced. The most rapid fluctuation is the drop in the 20 cm flux density by a factor of ~3 in 45 minutes (at JD 2,446,186.98) and the largest fluctuation is the drop in the 6 cm flux density by a factor of ~10 over the 2 days of observation. The spectral index α ($S_\nu \propto \nu^\alpha$) is $0.49^{+0.17}_{-0.13}$ at the start of these observations, drops to $\sim 0.06^{+0.22}_{-0.21}$ within 5 hr, and a day later is briefly $-1.23^{+0.60}_{-0.69}$. There is no indication of circular or linear polarization in the flux. The 2 σ upper limits (variations from zero) to the polarization at the highest flux density levels reached are 10% and 60% at 6 and 20 cm, respectively.

We tested for the presence of a correlation between the 6 and 20 cm flux densities on hour time scales by subtracting the mean flux density on each day and computing the linear regression coefficient (under the hypothesis of no correlation) on the residuals (Press *et al.* 1986). The correlation coefficient $r = 0.12$, which has a 73% chance of being exceeded by uncorrelated data sets. Thus the hypothesis that the data are *not* correlated is clearly allowed. The very low value of the correlation coeffiicent suggests that it would be interesting to test the inverse hypothesis—that the data are completely correlated. We therefore constructed many artificial "perfectly correlated" 20 cm data sets by interpolating between the 6 cm measurements and adding Gaussian noise at the measured levels. The resulting histogram of correlation coefficients indicates the probability of $r < 0.12$ from perfectly correlated data is 2.1%. While this indicates the data sets are not perfectly correlated, substantial partial correlations are allowed. On daylong time scales the 6 and 20 cm flux densities appear to be correlated as the mean flux at both wavelengths dropped on May 2. However, with only two data points we cannot make a strong case for the existence of a long-term correlation.

Maps were made from all the data in order to search for any associated radio lobes (as seen in Sco X-1 [Fomalont *et al.*

1983]) or extended emission (as in Cir X-1 [Haynes *et al.* 1986]). As the lobes of Sco X-1 are only slightly resolved, similar emission regions associated with GX 13+1 would be unresolved. Hence maps made using all available antenna baselines and natural weighting would be most sensitive to detecting them. Such maps set a 2 σ upper limit to the flux density of any Sco X-1 like lobes with 1′ of GX 13+1 of 0.1 mJy at 6 cm, and 1.0 mJy at 20 cm. The lower of these limits is set by the noise level of the map and is approximately equal to the integrated flux density expected from the lobes of Sco X-1 (Fomalont *et al.* 1983) if their distance (taken to be 0.7 kpc [Bradt and McClintock 1983]) were increased to that of GX 13+1.

The observations at 20 cm are more sensitive to detecting extended emission (as seen around Cir X-1) because its flux density rises toward longer wavelengths, and because the increased beam size at longer wavelengths is more sensitive to detecting extended emission. We further increased the beam size to 8″.4 × 8″.2 (FWHM) by tapering the map at baselines greater than 20000 λ. We find extensive extended emission in the area around GX 13+1 but this is mainly due to galactic H II regions and is not associated with GX 13+1. We note the existence of a north–south extended feature which is approximately centered on GX 13+1 (see Fig. 3), but caution that this is probably background emission. Our ability to detect extended emission from GX 13+1 is limited both by source confusion and by the sensitivity of the map (1.0 mJy per beam at 2 σ, or equivalently, $T_B = 12$ K). This limit is substantially above the level of the diffuse emission surrounding Cir X-1 ($\sim$0.1 mJy per beam at 20 cm; Haynes *et al.* 1986).

b) X-Ray

We observed GX 13+1 with the *EXOSAT* ME detector from 07:30 UT to 15:40 UT on 1985 May 2. As in previous observations of GX 13+1 with the ME (Stella, White, and Taylor 1985), the spectrum is well fitted by a two-component model consisting of blackbody and an unsaturated Compton spectrum, along with a low-energy cutoff due to photoelectric obsorption. The fitted equivalent column density on May 2 was $\sim 2 \times 10^{22}$ cm^{-2}, and the 1–20 keV luminosity was $\sim 5 \times 10^{37}$ ergs s^{-1} for an assumed 7 kpc distance.

In order to search for correlations between the X-ray and radio flux densities, we integrated the X-ray data on a time scale comparable to the integration time of the radio data and then compared the two light curves (Fig. 2). We have tested for the presence of a correlation with a first order linear regression and a nonparametric Spearman-rank test (Press *et al.* 1986). The linear correlation coefficient is 0.03, which has a 52% probability of being exceeded by uncorrelated data sets. The Spearman rank-order correlation coefficient is 0.8, which has a 87% probability of being exceeded by random data sets. Once again, these low values of the correlation coefficient prompt us to test the inverse hypothesis. In a manner similar to that described above, we find that the probability of $r < 0.03$ for perfectly correlated data sets is 0.04%. We therefore have fairly strong evidence that the 1–12 keV X-ray and 6 cm radio flux densities are not perfectly correlated.

III. DISCUSSION

While not explicitly mentioned in the discovery paper (Grindlay and Seaquist 1986) the probability of detecting an unrelated radio source with flux >1 mJy in the GX 13+1 error region is $\sim 2 \times 10^{-4}$ (Taylor and Seaquist 1986). As the majority of such unrelated sources are extragalactic, the rapid variability reported herein strengthens the identification of this radio source with GX 13+1. The shortest duration radio flares observed at 6 and 20 cm limit the size of the radio emitting region to be less than 2×10^{14} cm and 0.7×10^{14} cm, respectively. These size scales are equal to the light travel distance for 1/2 of the duration of a flare (the duration of a flare is the time

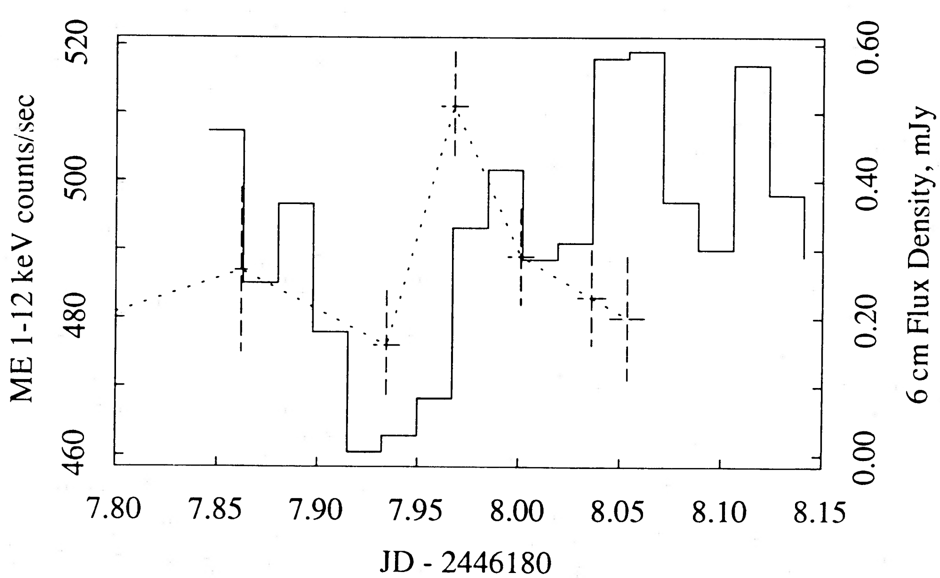

FIG. 2.—The simultaneous X-ray (*solid line*) and radio (*dotted line*) light curves on 1985 May 2. The 1–12 keV X-ray data have been binned in 25 minute intervals in order to match the integration time of the 6 cm radio data. The horizontal bars on the radio points indicate the beginning and end of each integration. The error bars on the X-ray data points are approximately equal to the thickness of the solid line, and the 1 σ error bars on the radio points are plotted.

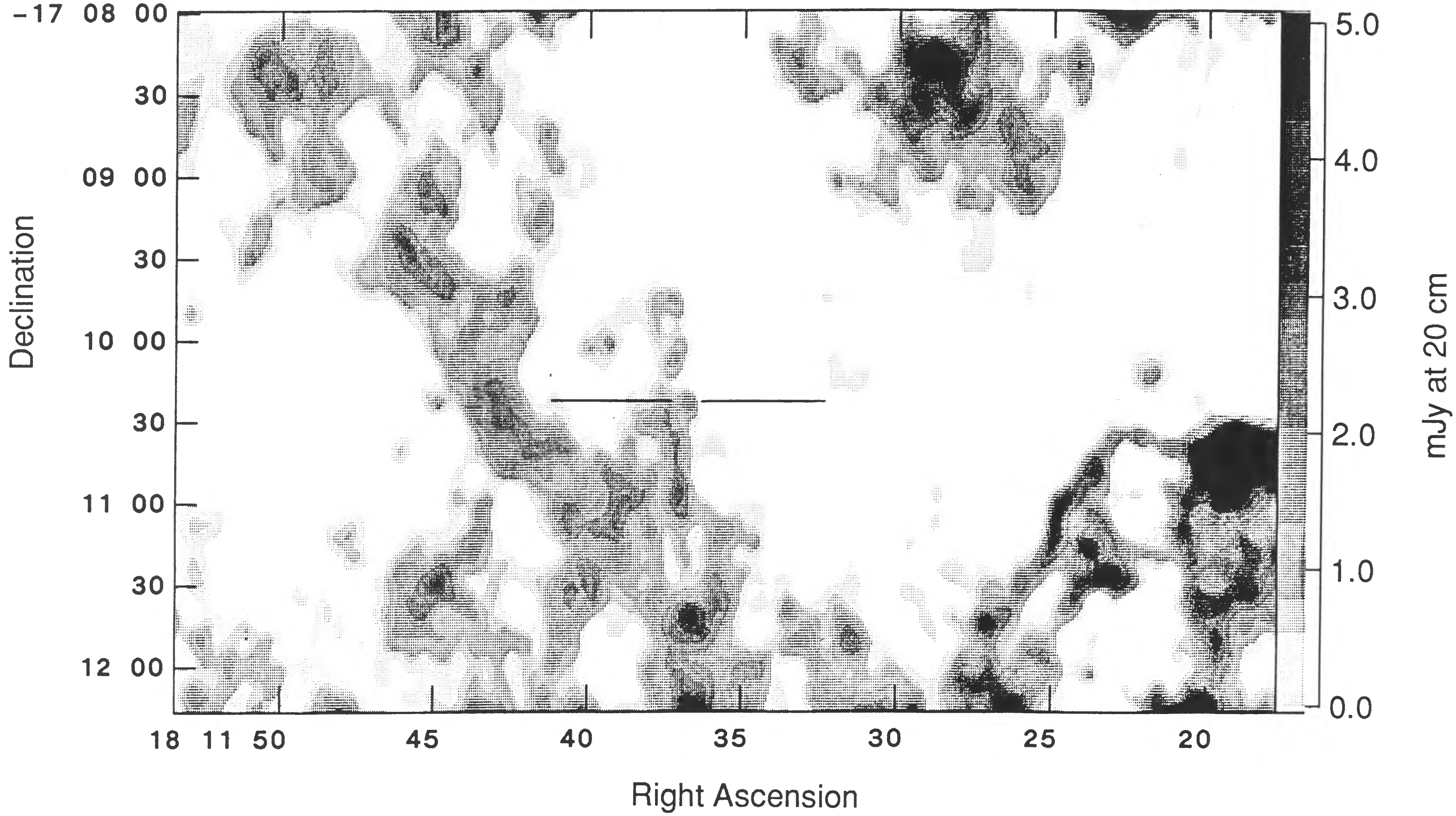

FIG. 3.—Map at 20 cm wavelength of the region around GX 13+1. The solid bars indicate the position of GX 13+1. Because of the extensive emission due to galactic H II regions, it is not clear if the extended emission near GX 13+1 is associated with this X-ray source.

between local extrema). The brightness temperatures implied by these flares are greater than $10^{6.7}$ K and greater than $10^{9.1}$ K, respectively, which by themselves do not require a nonthermal emission mechanism. However, the spectral index, which ranges from $+0.5$ to -1.0, strongly suggests a nonthermal emission mechanism.

It is possible that the radio flux is due to coherent emission mechanisms. Such mechanisms would produce extremely high T_B without the relativistic bulk motions often seen in synchrotron emitting regions (cf. Hjellming and Johnston 1981 and Molnar 1986). We would expect coherent emission to be highly polarized, but the low flux density observed from GX 13+1 does not allow strong constraints on the degree of polarization.

Synchrotron emission from a region with variable optical depth may be a more likely emission mechanism, as it has been observed in several other accreting binaries (e.g., Cyg X-3: Molnar, Reid, and Grindlay 1984; Cir X-1: Haynes, Lerche, and Murdin 1980; LSI+61 303: Taylor and Gregory 1984; and SS 433: Seaquist *et al.* 1982). In Cyg X-3 and Cir X-1, the optical depth is believed to vary due to the adiabatic expansion of a cloud of synchrotron electrons. The expanding synchrotron model (van der Laan 1966) predicts that for each flare, the flux density should peak sooner, decay more rapidly, and reach a greater value at higher frequencies. This is indeed the behavior seen in Cyg X-3 and Cir X-1 but is not the behavior we see here from GX 13+1. The rapid drop in the 20 cm flux density at JD 2,446,186.98 clearly is not consistent with this model. This implies that the radio flux density variations are due (at least in part) to the variable injection (and spectrum) of relativistic electrons. The apparent lack of a correlation between the 6 and 20 cm flux densities may also be consistent with a model of variable particle injection.

These variations bear more resemblance to those of Sco X-1, which also show variable α with the most negative values at times of low flux density levels. There is no systematic time delay between the short and long wavelength radio flux density from Sco X-1 (Hjellming and Wade 1971). Similarly, there is no clear indication of the long wavelength flux density from GX 13+1 leading or trailing the short wavelength flux density, although the sense of any time delay is difficult to discern from the present data (due in part to the small number of data points).

We apply the standard equipartition synchrotron model (Kellermann 1974) in order to help determine the physical conditions in the radio-emitting region of GX 13+1. We first solve for the optically thin case, since the derived quantities are then much less sensitive to the assumed input parameters, and the spectral index during the decay of the flares ($\alpha < 0$) is consistent with optically thin emission. The lack of a systematic delay in the long and short wavelength flux densities also argues for the applicability of the optically thin case, as optically thick emission (as in the van der Laan model) would most naturally produce a preferred time delay. The variable spectral index is a natural consequence of variable particle injection in this model. Assuming that the size of the emitting region is on the order of the upper limit determined by the fastest 20 cm flare, we find

$$B \gtrsim 0.4(\theta/0.7\ \text{mas})^{-6/7}(d/7\ \text{kpc})^{-2/7}(S/1\ \text{mJy})^{2/7}\ \text{gauss} \quad (1)$$

where B is the equipartition magnetic field, θ is the angular diameter of the emitting region in milliarcseconds (mas), d is the distance to the source, S is the flux density in mJy, and $\alpha = -0.6$. The corresponding energy in relativistic electrons, $(B^2/8\pi)[(4/3)\pi R^3]$, is less than or $\sim 3 \times 10^{39}$ ergs. If we estimate the energy input in relativistic electrons by assuming the flux density variations are due to injection of new electrons, the energy required is less than or $\sim 10^{36}$ ergs s^{-1}, which is relatively modest compared to the energy in X-ray photons. As the energy is relatively weakly dependent ($\propto R^{9/7}$) upon the source radius, the true luminosity is probably $\sim 10^{36}$ ergs s^{-1}.

It is instructive to also solve the optically thick, synchrotron self-absorbed case, as it may be appropriate during the rise of the flares (with $\alpha > 0$). From Kellermann (1974) (see also Jones, O'Dell, and Stein 1974),

$$B < 2.3 \times 10^{-5} S_A{}^{-2} \nu_A{}^{5} \theta^4\ \text{gauss} \quad (2)$$

where ν_A is the self-absorption frequency in GHz, and S_A is the flux density in Janskys at ν_A. Taking $S_A = 2$ mJy, $\nu_A = 3$ GHz, and $\theta < 0.7$ mas, we find $B < 3.3 \times 10^2$ gauss. The equivalent energy, $(B^2/8\pi)[(4/3)\pi R^3]$, scales like $\nu_A{}^{10}\theta^{11}$, and is less than 10^{45} ergs. In this case, if we assume the flux density variations are due to injection of relativistic electrons, the energy input is less than 10^{41} ergs s^{-1}, a factor of $\sim 10^3$ higher than the X-ray luminosity. We note that a firm lower limit to the source size (0.01 mas) can be set by the requirement that T_B not exceed the "Compton catastrophe" limit of $\sim 10^{12}$ K. The corresponding lower limit on the energy injected in relativistic electrons is $\sim 10^{24}$ ergs s^{-1}.

How does the apparent lack of a correlation between the X-ray and radio flux densities compare to the correlations (or lack thereof) found in other binaries? In Cir X-1 (Haynes, Lerche, and Murdin 1980) and LSI+61° 303 (Taylor and Gregory 1982), radio flaring occurs on the orbital time scale and is believed to be due to increases in the mass transfer rate (e.g., Band and Grindlay 1984). Changes in the viewing geometry or mass transfer rate modulate the X-ray flux on the same time scale, so the two are correlated. Similar effects modulate the X-ray and radio flux densities of Cyg X-3, but due to the difference in the radio and X-ray periods (Molnar, Reid, and Grindlay 1985) the character of the correlation between the two is not fixed. In Sco X-1, despite several searches, there is no clear correlation between the radio and X-ray on hour time scales. However, there is a correlation on longer time scales. The radio flares seen in Sco X-1 occur only on a specific branch of its bimodal "hardness ratio" diagram. A possible explanation of this bimodal behavior has recently been suggested (Priedhorsky 1986). In this scenario, a fast spinning weakly magnetized neutron star acts like a flywheel in the energy balance of the LMXRB. At high accretion rates most of the source luminosity is powered by accretion, whereas for lower accretion rates the energy stored in the spinning neutron star is released in the inner part of the disk, and this "spin down" luminosity dominates. Enhanced radio emission is likely associated with the latter intervals since most of the source luminosity is supplied electrodynamically by the fast rotating neutron star and is therefore expected to be largely nonthermal. The radio luminosity is then not correlated with the total X-ray luminosity, but only with that part due to the spin down luminosity. As the radio fluctuations of GX 13+1 resemble those seen in Sco X-1, we suggest that a similar mechanism is responsible for the radio flux. Since the bimodal hardness ratio diagram is caused by the presence of these two different energy generation mechanisms, the observation that the hardness ratio diagram of GX 13+1 (Garcia and Grindlay 1987) has a bimodal, V-shaped structure similar to that seen in Sco X-1 (Priedhorsky *et al.* 1986) lends support to the above suggestion. A possibly relevant difference between the hardness ratio diagrams is that the bimodal structure in GX 13+1 occurs relatively infrequently.

IV. CONCLUSIONS

We have detected radio variations from GX 13+1 which strongly suggest the presence of a nonthermal source in this X-ray binary. A possible source of this emission is synchrotron emission from relativistic electrons which are sporadically injected into a region with a magnetic field of ~ 1 G. An adiabatically expanding synchrotron source, as discussed by van der Laan (1966), is not consistent with the data. There is no evidence for a correlation between the 6 cm radio and 1–12 keV X-ray flux densities. The calculated energy in nonthermal particle production is strongly dependent upon poorly constrained parameters. Assuming the source size is on the order of the upper limit set by the light travel time, this energy could range from 10^{36} to 10^{41} ergs s^{-1}.

If the model of Priedhorsky (1986) is applicable to GX 13+1 the radio flux should be correlated with that part of the X-ray flux produced by the coupling of the neutron star spin down energy into the accretion disk. Analysis of the present X-ray data is continuing in order to deconvolve the X-ray spectrum into its constituent parts and test this prediction. Future coordinated observations of radio emitting LMXRB with sufficient spectral resolution to unambiguously deconvolve the X-ray spectrum would also be useful to test the applicability of model of Priedhorsky (1986). Radio observations with larger beam sizes and increased sensitivity would be useful in order to search for extended emission of the type recently found surrounding Cir X-1 (Haynes *et al.* 1986).

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