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IN SEARCH OF A RADIO COUNTERPART FOR THE ULTRALUMINOUS X-RAY SOURCE AT THE NUCLEUS OF M33

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RESUMEN

Presentamos un análisis de observaciones de radiocontinuo del núcleo de la galaxia espiral M33, obtenidas del archivo del Very Large Array. La mayoría de estas observaciones fueron hechas con alta resolución angular ($\leq 1''$) en varias épocas y las hemos utilizado para buscar emisión de radio asociada con la fuente ultraluminosa de rayos X en el centro de M33. A 20 cm, con una resolución angular de $1\rlap{.}''3$, detectamos una fuente con densidad de flujo de 0.20 ± 0.02 mJy que coincide dentro de $0\rlap{.}''2$ con la posición del centro de M33 reportada por 2MASS. Adicionalmente, a 3.6 cm (con una resolución angular de $0\rlap{.}''3$), detectamos dos fuentes débiles, una de ellas con densidad de flujo de 0.04 ± 0.01 mJy y que coincide con la fuente a 20 cm (y por lo tanto con el centro de M33). La segunda fuente detectada a 3.6 cm, con densidad de flujo de 0.05 ± 0.01 mJy, está $\approx 0\rlap{.}''6$ al norte de la primera fuente. La posición para la fuente ultraluminosa de rayos X del satélite Chandra traslapa dentro del error con ambas fuentes de 3.6 cm.

ABSTRACT

We present an analysis of radio continuum observations of the nucleus of the spiral galaxy M33, taken from the Very Large Array archives. Most of these observations were made with high angular resolution ($\leq 1''$) at different epochs and we have used them to search for radio emission associated with the ultraluminous X-ray (ULX) source at the center of M33. At 20 cm, with an angular resolution of $1\rlap{.}''3$, we detect a source with flux density of 0.20 ± 0.02 mJy that coincides within $0\rlap{.}''2$ with the position of the center of M33 as reported by 2MASS. In addition, at 3.6 cm (with an angular resolution of $0\rlap{.}''3$), we detect two faint sources, one of them with a flux density of 0.04 ± 0.01 mJy that is coincident with the 20 cm source (and thus with the center of M33). The second 3.6 cm source, with a flux density of 0.05 ± 0.01 mJy, is $\approx 0\rlap{.}''6$ north of the first source. Within error, the Chandra position for the ULX overlaps with both 3.6 cm sources.

Key Words: **GALAXY: CENTER — GALAXY: INDIVIDUAL (M33) — RADIO CONTINUUM: GALAXIES**

1. INTRODUCTION

The existence of stellar-mass black holes, with masses in the range of $\sim 3 - 15\ M_{\odot}$, and produced by the collapse of massive stars, is now well established. On the other hand, supermassive black holes with M$\sim 10^{6} - 10^{10}\ M_{\odot}$ are found at the nuclei of active galaxies and quasars, with their formation mechanism remaining poorly understood.

The Eddington luminosity of an accreting object of mass M is $1.3 \times 10^{38}(M/M_{\odot})$ erg s^{-1}, which

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implies that luminosities below $\sim 10^{39}$ erg s^{-1} are expected for stellar-mass black holes. However, observations made over the last decades from X-ray satellites (see, for example Fabbiano 1989, Colbert & Mushotzky 1999, Colbert & Ptak 2002) have revealed the existence, in other galaxies, of X ray sources with luminosities in the range of $10^{39} - 10^{41}$ erg s^{-1}. If the X ray emission is isotropic, these results would appear to imply the existence of compact objects with masses of $10^2 - 10^4\ M_\odot$, between those of stellar-mass and of supermassive black holes. The possible existence of these intermediate mass black holes (IMBH) is of great relevance. However, there are problems with the IMBH explanation for ULXs. For example, Makishima et al. (2000) find that the observed innermost disk temperatures of seven ULXs studied by them are in the range of 1 to 2 keV, too high to be compatible with the required high black hole masses (disk temperature goes inversely with black hole mass), and characteristic of stellar-mass black holes. This and other difficulties discussed by King et al. (2001) have made astronomers search for other explanations for the high X ray luminosity observed in these extragalactic sources.

An alternative explanation uses the effect of beaming of the radiation of a stellar mass black hole, involving conventional high-mass X-ray binaries (King et al. 2001). In the model of these authors, the accretion disk around the black hole has a much lower scattering optical depth toward the rotational poles than in other directions. The emission would then be beamed in our direction like a lighthouse, and would account for the large fluxes observed.

In this paper we analyze archival Very Large Array observations of the region around M33-X8, the ULX at the center of M33 in an attempt to gain a better understanding of its nature. In particular, since some authors (Dubus & Rutledge 2002; Foschini et al. 2004) have suggested a link between galactic microquasars and extragalactic ULXs, we were interested in looking for a radio source with some of the radio characteristics of galactic microquasars (Mirabel & Rodríguez 1999). The ULX in M33 is the most luminous steady X-ray source in the Local Group with a 1-10 keV luminosity of $\sim 1.2 \times 10^{39}$ erg s^{-1}. Its relative proximity (795 kpc; van den Bergh 1991) makes it an ideal target for the search of a radio counterpart.

2. OBSERVATIONS

We analyzed radio continuum observations made on several epochs and wavelengths toward the center of M33. All observations were taken from the archives of the Very Large Array (VLA) of the NRAO[2]. In all cases, the on-source integration time at each epoch was over 2 hours. A summary of these observations is presented in Table 1. In this table we list the epoch and phase center of the observations, the phase calibrator used and its bootstrapped flux density, the VLA configuration and wavelength of the observations, and the rms noise of the final image. Most of the observations selected were in the A and B configuration, providing an angular resolution of about $1''$ or better. The data were analyzed following the standard VLA procedures using the NRAO AIPS software package. To obtain accurate absolute astrometry, the positions of the phase calibrators were corrected for the latest refined positions given in the list of VLA calibrators. In addition, all data were precessed to equinox J2000. The images were corrected for the primary beam response to obtain reliable flux densities.

The data correspond to ten different epochs, in which we detected a source at 20 cm within $1''$ of the center of M33 in three of them. In addition, at 3.6 cm we detected two sources within $1''$ of the center of M33 in one epoch. The flux densities or upper limits determined for these sources are given in Table 2.

3. RESULTS

3.1. *20 cm Observations*

At 20 cm, we detected a source on 1985 March 9, 1986 April 10, and 1987 November 30. The flux densities measured (0.17±0.03, 0.21±0.03 mJy, and 0.28±0.05 mJy), respectively) are consistent with a steady source at the 0.20 mJy level. The upper limit determined for 1983 November 14, ≤0.3 mJy, is also consistent with this conclusion.

Images of the surroundings of the center of M33 made at 20 and 6 cm with an angular resolution of $\sim 5''$ are shown in Figure 1. These data have been previously analyzed by Gordon et al. (1999) and the numbering of the sources follows their paper. Before this report, the only published 20 cm flux density for this region was a value of 0.6±0.1 mJy reported by Gordon et al. (1999) from these observations and others made at Westerbork. This apparent discrepancy in flux density disappears when we take into account that Gordon et al. (1999) reported the integrated total emission, while we report the peak emission for this image with an angular resolution of $\sim 5''$. We conclude that there is indeed a total flux

[2]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

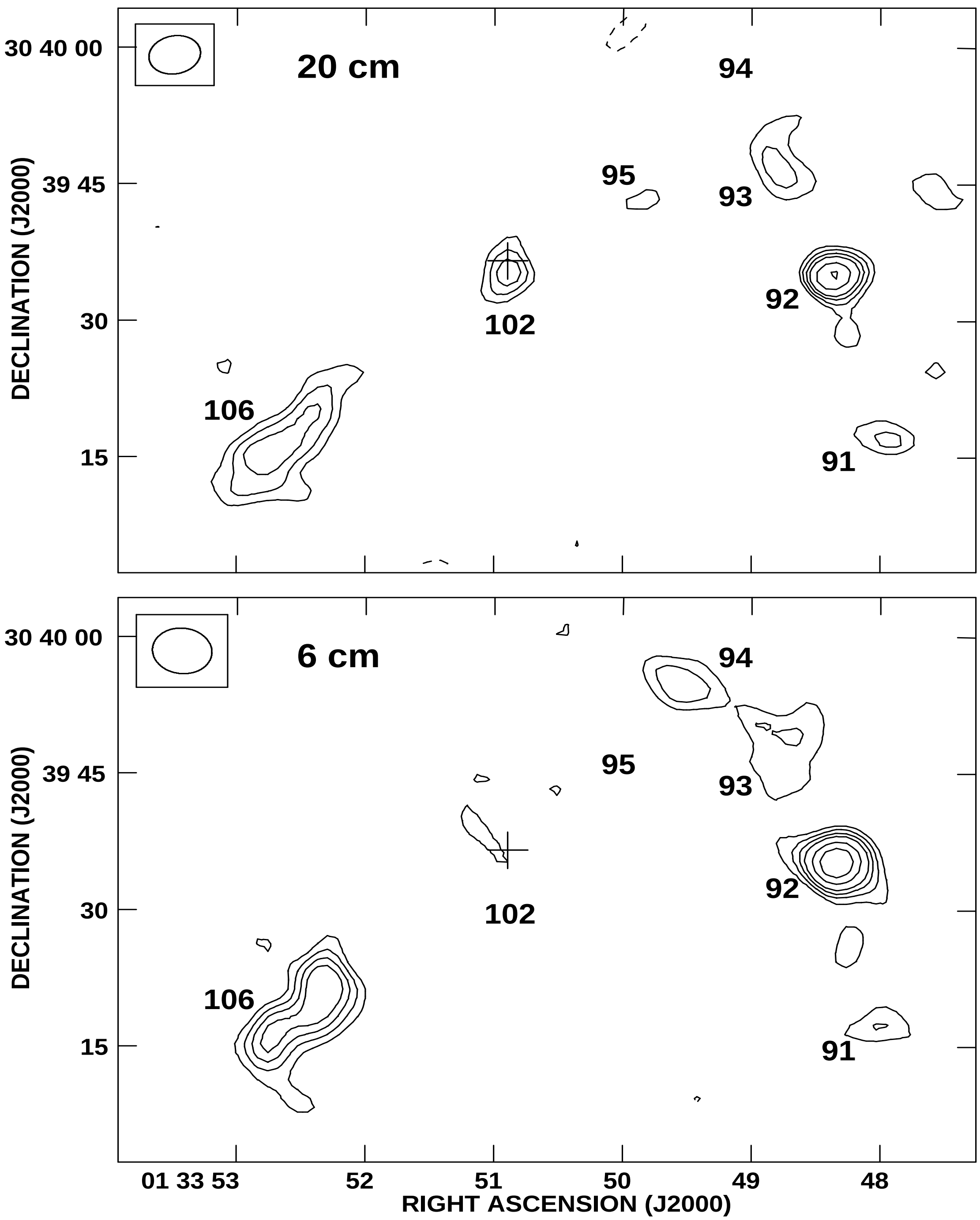

Fig. 1. (Top) Contour image of the surroundings of the center of M33 at 20 cm, made from the data taken on 1987 November 30. The levels are −4, −3, 3, 4, 5, 6, 8, and 10 times 47 μJy, the rms noise of the image. The beam ($5.''2 \times 4.''2; PA$ =-76°) is shown in the top left corner. (Bottom) Contour image of the surroundings of the center of M33 at 6 cm, made from the data taken on 1985 September 2, 8, and 13. The levels are −4, 4, 5, 6, 8, and 10 times 45 μJy, the rms noise of the image. The beam ($6.''0 \times 5.''0; PA = 82°$) is shown in the top left corner. The cross marks the 2MASS position of the center of M33. The numbers indicate the identifications of the sources made by Gordon et al. (1999). In this and the following figures the horizontal axis is right ascension, given in hours, minutes, and seconds, and the vertical axis is declination, given in degrees, arcminutes, and arcseconds.

TABLE 1

VERY LARGE ARRAY OBSERVATIONS OF M33

Epoch	Phase Center α(J2000)[a]	Phase Center δ(J2000)[a]	Phase Calibrator	Bootstrapped Flux Density (Jy)	VLA Configuration/ Wavelength (cm)	Rms noise (μJy)
1983 Nov 14	1 33 53.32	+30 39 27.1	0116+319	2.55±0.03	A/20	24
1985 Mar 09	1 33 47.22	+30 40 21.8	0133+476	1.13±0.01	A/20	27
1985 Jun 06	1 33 47.22	+30 40 21.8	0133+476	1.73±0.01	B/6	22
1985 Jun 08	1 33 47.22	+30 40 21.8	0133+476	1.86±0.01	B/6	32
1985 Sep 08[b]	1 33 53.59	+30 42 18.2	0137+331	5.54±0.01	C/6	58
1986 Apr 10	1 33 47.22	+30 40 21.8	0133+476	1.11±0.01	A/20	28
1987 Nov 30	1 33 53.22	+30 39 14.5	0137+331	15.5±0.1	B/20	45
1992 Nov 09	1 33 50.90	+30 39 36.6	0122+250	0.75±0.01	A/3.6	79
1997 Jul 16	1 33 50.80	+30 39 37.0	0137+331	3.15±0.01	C/3.6	26
2002 Jan 28	1 33 50.50	+30 38 21.8	0205+322	1.14±0.01	A/6	32

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.
[b]Refers to the concatenation of data taken on 1985 September 2, 8, and 13.

density of ~ 0.6 mJy within some $5''$ of the center of M33, but that the compact source, observed directly in the A configuration images with angular resolution of $\sim 1''$, has a flux density of only ~ 0.2 mJy. The remaining 0.4 mJy appear to be coming from a faint, extended component. Among the sources of Fig. 1, source 106 of Gordon et al. (1999) shows an interesting morphology that is reminiscent of a jet feature. Furthermore, the major axis of this structure points approximately to source 102 (coincident with the center of M33). However, source 106 is identified as an H II region by Gordon et al. (1999), based on its radio spectral index and by Boulesteix et al. (1974), based in its optical spectra. In addition, there are luminous stars, infrared sources, and molecular gas associated with this source (Massey et al. 1996; Kraemer et al. 2002; Engargiola et al. 2003), supporting its identification as a region of star formation. In any case, it is perplexing that the optical region is reported as approximately round (with diameter of $25''$) by Boulesteix et al. (1974) and Courtès et al. (1987), while the radio source is clearly elongated ($20'' \times 7''$, at a position angle of 142°).

An image made concatenating the high angular resolution ($\sim 1''$) 20 cm data taken on 1985 March 9 and 1986 April 10 is shown in Figure 2. This image clearly shows sources 92 and 102 of Gordon et al. (1999). The 20 cm position of source 102 from this image is $\alpha(2000) = 01^h33^m50\overset{s}{.}912$; $\delta(2000) = +30^\circ39'36\overset{''}{.}63$ (see Table 3). This position coincides within $0\overset{''}{.}2$ with the 2MASS position for the center of M33 (Cutri et al. 2003; see our Table 3) and we corroborate the association of source 102 with the center of this galaxy proposed by Gordon et al. (1999).

3.2. *6 cm Observations*

We analyzed data from four epochs at this wavelength (see Table 1). Only in the low angular resolution 6 cm data shown in Fig. 1 we find a hint of emission associated with the center of M33. Gordon et al. (1999) report a marginal detection of 0.2 ± 0.1 mJy at this wavelength. We did not detect a source associated with the galactic center of M33 at any epoch (see bottom panel of Fig. 2) in the high angular resolution data, with upper limits of the order of 0.1 mJy. Clearly, the lack of detectable emission at 6 cm indicates a non-thermal spectrum for the galactic center source.

3.3. *3.6 cm Observations*

At this wavelength we clearly detect two unresolved ($\leq 0\overset{''}{.}3$) sources in the 1992 November 9 data (see Figure 3). The south source has a flux density of 0.04 ± 0.01 mJy, and its position is coincident with our 20 cm source and with the center of M33 reported by 2MASS, $\alpha(2000) = 01^h33^m50\overset{s}{.}895$; $\delta(2000) = +30^\circ39'36\overset{''}{.}58$ (see Table 3). Since this 3.6 cm component coincides with the 20 cm emission source, we can derive a spectral index of $S_\nu \propto \nu^{-0.9\pm0.2}$ for it, concluding that this source clearly has a non-thermal nature.

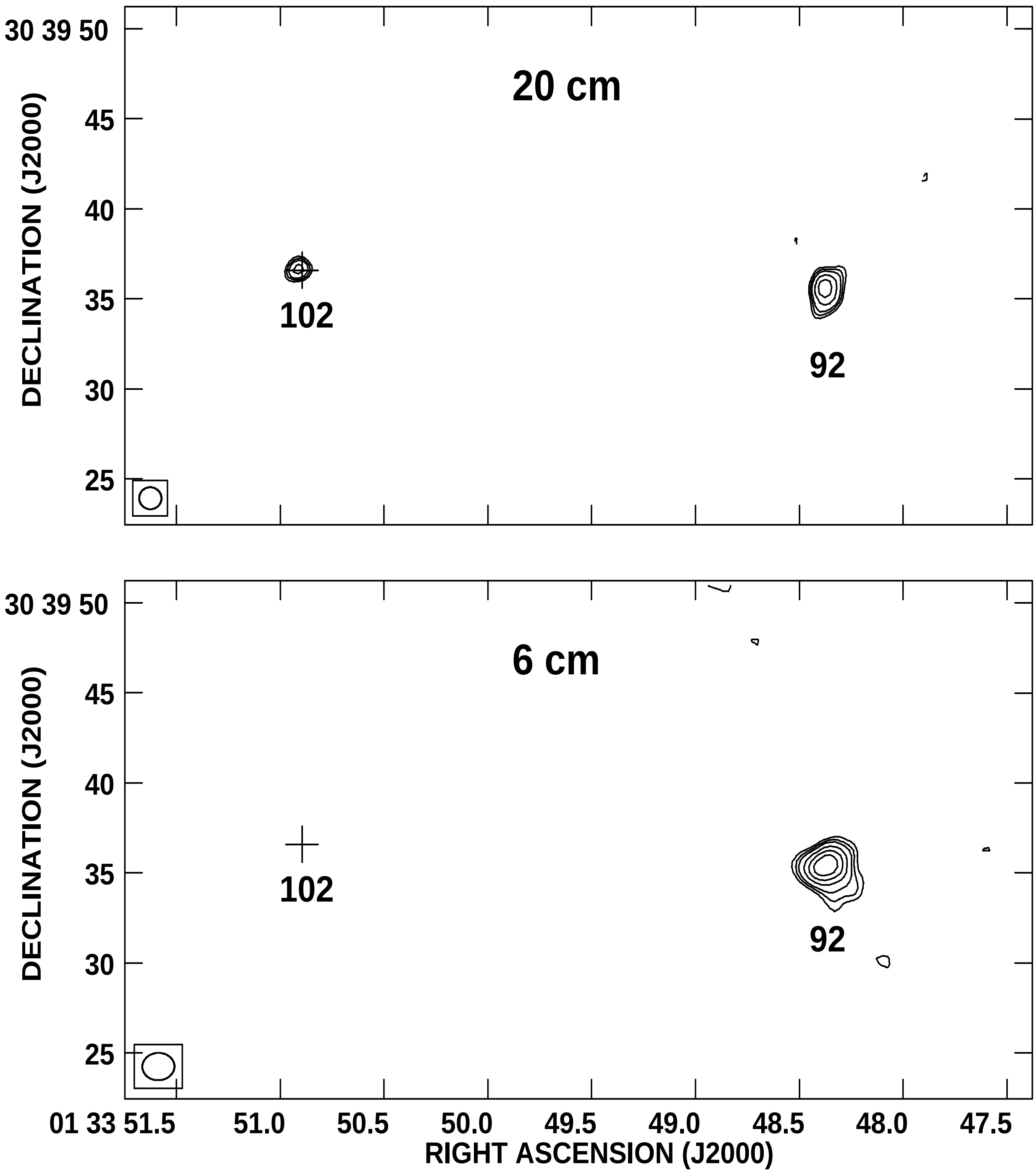

Fig. 2. (Top) Contour image of the central region of M33 at 20 cm, made from the data taken on 1985 March 9 and 1986 April 10. The levels are −4, 4, 5, 6, 8, 10, and 12 × 21 μJy, the rms noise of the image. The beam ($1''.4 \times 1''.2$; $PA = 88°$) is shown in the bottom left corner. (Bottom) Contour image of the central region of M33 at 6 cm, made from the data taken on 1985 June 6. The levels are −4, 4, 5, 6, 8, 10, 12, and 15 × 24 μJy, the rms noise of the image. The beam ($2''.0 \times 1''.5$; $PA = -89°$) is shown in the bottom left corner. The cross marks the 2MASS position of the center of M33. The numbers indicate the identifications of the sources made by Gordon et al. (1999).

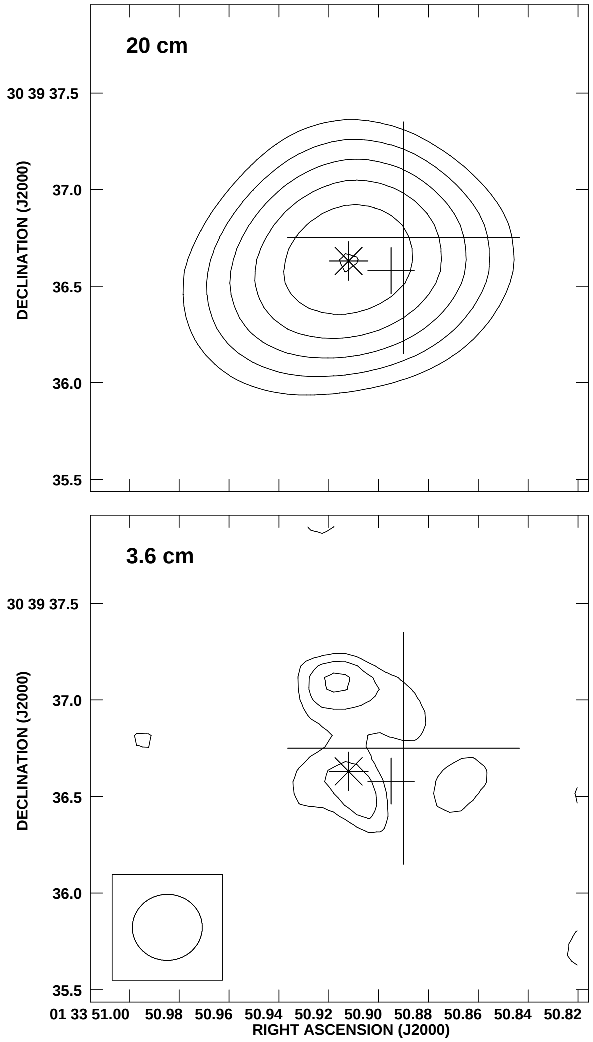

Fig. 3. (Top) Contour image of the center of M33 at 20 cm. The levels are 4, 5, 6, 7, 8, and 9 × 21 μJy, the rms noise of the image. The beam of this image is $1''.4 \times 1''.2; PA = 88^\circ$ (see Fig. 2). (Bottom) Contour image of the center of M33 at 3.6 cm. The levels are 2, 3, and 4 times 8 μJy, the rms noise of the image. The beam ($0''.36 \times 0''.34; PA = -88^\circ$) is shown in the bottom left corner. The small cross marks the 2MASS position of the center of M33. The asterisk marks the center of 20 cm emission. The large cross marks the Chandra position of the ULX, taken from Dubus & Rutledge (2002).

TABLE 2

FLUX DENSITIES OF THE SOURCES AT THE CENTER OF M33

Epoch	Wavelength (cm)	Flux Density (mJy)
1983 Nov 14	20	$\leq$0.3
1985 Mar 09	20	0.17±0.03
1985 Jun 06	6	$\leq$0.08
1985 Jun 08	6	$\leq$0.16
1985 Sep 08	6	$\leq$0.15
1986 Apr 10	20	0.21±0.03
1987 Nov 30	20	0.28±0.05
1992 Nov 09	3.6	0.04±0.01[a]
''	''	0.05±0.01[b]
1997 Jul 16	3.6	$\leq$0.12
2002 Jan 28	6	$\leq$0.13

[a]Corresponds to southern source.

[b]Corresponds to northern source.

The second 3.6 cm source has a flux density of 0.05 ± 0.01 mJy, and its location is $\approx 0''.6$ north of the first source. Within error, the Chandra position (Dubus & Rutledge 2002; see Table 3) overlaps both 3.6 cm sources (see Fig. 3).

What else can we say about the nature of this 3.6 cm northern source? It is clear that it cannot have the same spectral index of the southern source and be steady in time, since then the 20 cm emission would have to be centered between the northern and southern 3.6 cm components, which is not the case (see Fig. 3). We are then left with two possibilities: either the northern source is time variable or it has a flat spectrum. A time variable source could be associated with a microquasar or even with a radio supernova that exploded between 1986 (the last epoch of the 20 cm observations made in the A configuration) and 1992 (the epoch of the 3.6 cm observations). If the source has a flat spectrum (and no variability) it would probably be an H II region. Future monitoring of this region should discriminate between these possibilities. A more accurate X-ray position is needed to establish if the ULX is associated with one of the two 3.6 cm radio sources.

4. CONCLUSIONS

We presented multiepoch VLA observations made at various wavelenghts toward the center of the spiral galaxy M33. With an angular resolution

TABLE 3

DIFFERENT POSITIONS OF INTEREST

Telescope	α(J2000)	δ(J2000)	Error	Association
2MASS	$01^h33^m50\overset{s}{.}895$	$+30°39'36\overset{''}{.}58$	$0\overset{''}{.}06$	Center of M33
VLA (20 cm)	$01^h33^m50\overset{s}{.}912$	$+30°39'36\overset{''}{.}63$	$0\overset{''}{.}05$	Center of M33
VLA (3.6 cm)[a]	$01^h33^m50\overset{s}{.}917$	$+30°39'37\overset{''}{.}09$	$0\overset{''}{.}05$	ULX?
Chandra	$01^h33^m50\overset{s}{.}890$	$+30°39'36\overset{''}{.}75$	$0\overset{''}{.}6$	ULX

[a]Refers to the northern 3.6 cm source.

of $0\overset{''}{.}3$ at 3.6 cm, we detect two sources at the center of M33, separated by $0\overset{''}{.}6$ in the north-south direction. The southern 3.6 cm emission coincides with the center of the galaxy as determined by 2MASS. It has a 20 cm counterpart, implying a non thermal spectrum. The northern 3.6 cm component is either time variable (suggesting the presence of a microquasar or of a young radio supernova) or has a flat spectrum (suggesting it is an H II region). Future observations should clarify the nature of this radio source. Within error, the Chandra position for the ULX overlaps both 3.6 cm radio sources and a more accurate X-ray position is needed to establish if the ULX is associated with one of the 3.6 cm sources.

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REFERENCES

Boulesteix, J., Courtes, G., Laval, A., Monnet, G. & Petit, H. 1974, A&A, 37, 33
Colbert, E. J. M., & Mushotzky, R. F. 1999, AdSpR, 23, 847
Colbert, E. J. M. & Ptak, A. F. 2002, ApJS, 143, 25
Courtès G., Petit, H., Petit, M., Sivan, J.-P. & Dodonov, S. 1987, A&A, 174, 28
Cutri, R. M. et al., 2003, 2MASS All-Sky Catalog of Point Sources (University of Massachusetts and IPAC/California Institute of Technology).
Dubus, G., & Rutledge, R. E. 2002, MNRAS, 336, 901
Engargiola, G., Plambeck, R. L., Rosolowsky, E. & Blitz, L. 2003, ApJS, 149, 343
Fabbiano, G. 1989, ARA&A, 27, 87
Foschini, L., Rodriguez, J., Fuchus, Y. et al., 2004, A&A, 416, 529
Gordon, S. M., Duric, N., Kirshner, R. P., Goss, W. M., & Viallefond, F. 1999, ApJS, 120, 247
King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, 109
Kraemer K. E., Price, S. D., Mizuno, D. R., & Carey, S. J. 2002, AJ, 124, 2990
Makishima, K. et al., 2000, ApJ, 535, 632
Massey P., Bianchi, L., Hutchings, J. B., & Stecher, T. P. 1996, ApJ, 469, 629
Mirabel, I. F., & Rodríguez, L. F. 1999, ARA&A, 37, 409
van den Bergh, S. 1991, PASP, 103, 609

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