ABSTRACT

We have observed the starburst dwarf galaxy VII Zw 19 at subarcsecond resolution with MERLIN and MERLIN+European VLBI Network (EVN) at 18 cm, with MERLIN at 6 cm, and with the Very Large Array (VLA) in the A configuration at 6 and 2 cm. The galaxy is detected at all VLA wavelengths and is resolved. It is also resolved at 18 cm by MERLIN but is not detected by the EVN or by MERLIN at 6 cm. VII Zw 19 has a complex structure of nonthermal radio emission at 18 cm extended over \( \sim 1200–1800 \) pc \( (4''–6'') \). That the EVN did not detect this emission indicates that there are no obvious point sources that could be radio supernovae. The 2 cm emission, predominantly thermal free-free emission, has a markedly different spatial distribution from the nonthermal emission. The radio colors show that the galaxy contains numerous supernova remnants, as well as many young H \( \alpha \) regions, many of which are optically thick at 6 cm. Two extended regions of 2 cm emission have little 18 cm flux and are probably emission from young star clusters. VII Zw 19 resembles M82 in its radio and infrared spectrum, but the starburst region in VII Zw 19 is twice the size of the one in M82 and twice as luminous.

Key words: galaxies: dwarf — galaxies: individual (VII Zw 19) — galaxies: peculiar — galaxies: starburst — galaxies: star clusters — radio continuum: general

1. INTRODUCTION

VII Zw 19 is a dwarf galaxy at a distance of 64 Mpc (Conti 1991), with the optical-UV spectrum of a young starburst. It is classified as a blue emission-line galaxy and a Wolf-Rayet galaxy (Schaerer et al. 1999). The optical image of the galaxy is dominated by a strong central source, with the plumes and jets suggesting starburst winds (Zwicky & Zwicky 1971). The Wolf-Rayet feature in the spectrum of a galaxy is a sign that many massive stars have formed within the past 2–3 Myr. Dwarf Wolf-Rayet galaxies are particularly interesting, because they have less continuous, “background” star formation than do large spiral galaxies and therefore are less processed, have lower metallicity, and can be a local laboratory for studying earlier epochs of the universe. When dwarf galaxies undergo a starburst, it is an event isolated in both space (as dwarf galaxies have no large-scale structural forces) and time, i.e., not confused by the ongoing star formation: the starburst emission is more “pure” than in spiral galaxies. The radio emission of dwarf galaxies is usually dominated by thermal emission from the current crop of H \( \alpha \) regions rather than the nonthermal emission from cosmic rays generated by supernovae from older stars, perhaps, in part, because of the episodic nature of their star formation activity (Deeg et al. 1997; Beck et al. 2000; however, magnetic fields may also play a role: cf. Turner et al. 1998).

VII Zw 19 was observed at H 0 with the Wise Observatory and with the Very Large Array (VLA)\(^1\) at 20, 6, 3.6, and 2 cm at \( \sim 1'' \) resolution by Beck et al. (2000), who found that the galaxy at all wavelengths has a strong central source in a weak envelope of emission. VII Zw 19 has an unusually strong nonthermal radio component for a Wolf-Rayet dwarf galaxy. The total fluxes in the VLA maps (Beck et al. 2000) result in spectral indices of \(-0.45\) between 20 and 6 cm and \(-0.24\) between 6 and 2 cm, indicating that there is both thermal (spectral index \(-0.1\)) and nonthermal (typical spectral index \(-0.4\) to \(-1.4\)) emission present. VII Zw 19 looks, in its radio spectrum, as if it could be a transition object between the very young starburst dwarf galaxies, with their completely thermal or optically thick thermal spectra, and the older starburst galaxies, with their plentiful supernovae. There was some indication in the Beck et al. (2000) images that the thermal emission came from the outer regions of the galaxy. However, the arcsecond resolution of the images corresponds to \( \sim 500\) pc at 65 Mpc, which is inadequate to resolve much structure within the starburst.

We have taken another look at the radio emission from VII Zw 19, this time at subarcsecond resolution, with the hope of

\(^1\) The VLA telescope of the National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.
distinguishing thermal from nonthermal emission regions and radio supernovae or supernova remnants (SNRs) from extended regions of diffuse synchrotron emission. We observed VII Zw 19 at 18 cm with the MERLIN+European VLBI Network (EVN) in 2000 November, at 6 cm with MERLIN alone in 2001 August, and at 20, 6, and 2 cm with the VLA in the A configuration in 2002 March. These images allow us to distinguish regions that are only ~50–60 pc across.

2. OBSERVATIONS AND NONDETECTIONS

VII Zw 19 was observed on 2000 November 10 with the MERLIN+EVN2 array, including the Cambridge, Jodrell, Westerbork, Effelsburg, Medicina, and Noto antennae, and in 2001 August with the MERLIN array alone at 6 cm (specifics are given in Table 1). The data were reduced in the usual way with AIPS,3 including phase referencing. Two calibrators (J0426+6825 and J0427+6821) were observed, and the MERLIN data were reduced twice, independently, such that each reduction used only one or the other of the two calibrators. The differences in the fluxes from the two reductions are less than 1 σ pixel−1. Images made from the two reductions are essentially identical, which argues strongly for the reality of the complex structures observed.

The EVN maps show a few sources in the field, with peak fluxes up to 0.25 mJy beam−1, but none of them are anywhere near the peaks seen in the MERLIN 18 cm maps. We conclude that they are either background radio sources or noise. The nondetection with EVN of a source easily detected in MERLIN argues that the emission from VII Zw 19 is so extended as to be resolved out by the EVN beam (0′′17 × 0′′126 beam of a robust = 1 map).

compact emission. There are no very bright compact (<10–12 pc) sources, such as radio supernovae or giant compact H ii regions, detected in VII Zw 19.

The VLA observations were performed in the A configuration on 2002 March 25. The weather was good, and 27 antennas were employed in the observations. For the 2 cm observations we used reference pointing and fast-switching, with a cycle time of 2 minutes. Fluxes at 6 cm were based on observations of 3C 48, following the VLA 1999.2 values with adopted fluxes of 7.91 and 7.98 Jy for the two intermediate frequency bands. For the 2 cm observations, which resolve out 3C 48, we adopted a flux of 0.67 Jy for the polarization calibrator 0713+438, based on the fluxes at 6, 3.6, and 1 cm measured by S. Myers and G. Taylor on 2002 March 20.4 5 days before our run. We estimate that the uncertainty in the 2 cm flux of the A configuration data is ~5%, based on the power-law fit to the spectrum; the variability of this calibrator, for which the flux is tracked every two weeks, was less than 2% for all of 2002, so the power-law fit dominates the uncertainty in the 2 cm flux scale. The uncertainty in the flux scales based on the standard flux calibrator 3C 48 is similar or less. Beam sizes and rms noise levels for the maps are presented in Table 1.

These A configuration data are ideal for detecting small sources but do not reveal extended emission well. We therefore added to them the lower resolution VLA data from Beck et al. (2000). The 6 cm data of that run were obtained in the B configuration and the 2 cm data in the C configuration; those data were combined with these new A configuration data sets to produce maps that are sensitive to structures up to 20′′ in extent. The short 20 cm “snapshot” data that we obtained for VII Zw 19 in this run are consistent with, but noisier than, the longer integration observation in Beck et al. (2000). The older data (from 1997) in Beck et al. (2000) were also obtained in the A configuration, so the 20 cm map derived from those data is shown here.

VII Zw 19 is not a very well known radio source, and there are few archival data that can tell us whether or not the galaxy is time variable. Condon et al. (1996) measured the same 20 cm flux in 1993 with the VLA in the A configuration as Beck et al. (2000) did in 1997. The only previous VLA measurement is from 1984 and was generously given to us by G. Wynn-Williams. That program observed the galaxy at 20, 6, and 2 cm but used configurations with lower resolution than did Beck et al. (2000). The spatial details are not comparable, but the

### Table 1

| λ      | Telescope | rms (mJy beam−1) | Beam (arcsec) | P.A. (deg) | θmax (arcsec) | Peak Flux (mJy beam−1) | Total Mapped Fluxa (mJy) |
|--------|-----------|------------------|---------------|------------|---------------|------------------------|--------------------------|
| 18 cm  | MERLIN    | 0.11             | 0.30          | ...        | 6.5           | 1.06                   | 10 ± 4                   |
| 18 cm  | MERLIN    | 0.10             | 0.18 × 0.18   | 0′          | 6.5           | 0.9                    | 14 ± 4                   |
| 6 cm   | MERLIN    | 0.09             | 0.046 × 0.14  | −35        | 1.2           | 0.4                    |                          |
| 20 cm  | VLA       | 0.08             | 1.17 × 0.97   | 14         | 35            | 5.4                    | 24 ± 2                   |
| 6 cm   | VLA       | 0.04             | 0.45 × 0.34   | 15         | 10            | 0.91                   | 11 ± 1                   |
| 2 cm   | VLA       | 0.03             | 0.27 × 0.22   | 25         | 4             | 0.35                   | 8.8 ± 2                  |

a The value θmax is the maximum size scale that is well sampled by these images. Fluxes and peak fluxes are therefore lower limits to the total flux.

b Total fluxes are obtained by integrating over a circular aperture centered on the peak. The large uncertainties at 18 cm are due to the use of two different flux calibrators, as discussed in the text.

c The two 18 cm maps were made with different constraints in the mapping. The larger beam is naturally weighted, and the smaller beam was imposed in the AIPS utility IMAGR to be a symmetric beam close to the 0′′17 × 0′′126 beam of a robust = 1 map.

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2 The European VLBI Network is a facility of European, Chinese, and other radio astronomy institutes funded by their national research councils.

3 The Astronomical Image Processing System (AIPS) was developed by the NRAO.

4 See http://www.vla.nrao.edu/astro/calib/polar/2002/.
3. IMAGES AND RADIO COLORS

MERLIN detected emission from VII Zw 19 at 18 cm and the VLA detected the galaxy at all wavelengths: 20, 6, and 2 cm. The radio images are shown in Figure 1. For the VLA data we show two views of the radio emission at each wavelength. The gray contours represent images with beams of 1""-2"" (FWHM) and increased sensitivity to extended emission; the weighting (Gaussian taper of 400 kλ) for these maps favors the shorter VLA baselines within the combined data set. The black contours represent the high-resolution images, which were made by giving more weight to the new A configuration data (setting AIPS mapping parameter “robust” = 1 or 2) and that are sensitive to compact sources (and less so to extended emission at lower intensity levels). The low-resolution 20 cm image in Figure 1 (top left) is from Beck et al. (2000), and the high-resolution image is from the 18 cm MERLIN data. The MERLIN and VLA runs were, unfortunately, on two different astrometric systems (J2000 at the VLA and B1950 at MERLIN), so the B1950 (∇, ∇) data were converted to J2000 using the AIPS utility UVFIX. Experience has shown that the converted data should be accurate at the 10–20 mas level, which is only one tenth of the beam size in the highest resolution images. Consistent with the MERLIN and EVN images, there are no point sources in the VLA maps, even at beam sizes of 0"15 (47 pc). Total fluxes obtained using the AIPS utility IRING are listed in Table 1. The 20, 6, and 2 cm fluxes from these new VLA data sets agree (to within 5%) with the 1997 fluxes from Beck et al. (2000), as do the fluxes from the combined 6 and 2 cm data sets in Table 1.

3.1. The Emission Mechanisms

The different radio wavelengths observed are sensitive to different emission mechanisms and physical conditions, and
the spectral index, \( \alpha \), can in theory be used to separate nonthermal sources from \( \text{H} \alpha \) regions (Turner & Ho 1994). The 18 and 20 cm maps are probably dominated by nonthermal emission, the 2 cm by thermal, and the 6 cm should be sensitive to both. Of all the observations, the 18 cm MERLIN and 2 cm VLA have the most nearly matched beam sizes, \(~0.2^{\prime}\)\( ^{-1} \) for the 2 cm map and \( 0.24 \text{ mJy beam}^{-1} \) for the 18 cm map, with levels \( \pm 2\sigma \) where \( n = 0, 1, 2, \ldots \) times the given contour unit. The VLA map contains short-spacing information and is sensitive to structures up to \(~0.15^\circ\); the MERLIN map is sensitive only to structures less than \(~0.4^\circ\) in extent.

The southeast and southwest thermal filaments that are suggested by Figure 2 are evident here. There are other possible thermal-free-free sources, including the source to the south, which have been blanked because of weakness in the 6 cm map.

The overall spectral index of the galaxy from the total fluxes is \(~0.42\) between 18 and 2 cm and \(~0.2\) between 6 and 2 cm. The 2 cm flux is inconsistent with a model of a uniform nonthermal component of spectral index \(~0.7\) and an optically thin free-free component. Either the nonthermal component has a very steep spectral index of \(~-1.5\), or the 2 cm free-free emission has a significant component with a rising flux.

When we fold in the spatial information contained in the 6–2 cm spectral index map in Figure 1, we see that the nonthermal spectral index is not as steep as \(~-1.5\). There are indeed spatially distinct regions of emission with a rising spectrum. The radio flux from this galaxy thus appears to have a significant contribution from optically thick thermal emission at 2 cm and from nonthermal emission at 18 cm, and the thermal emission is found preferentially at the outer edges of the radio source and to the south. The spatial variation of the spectral index also suggests that there may be thermal emission in the center, but that it is confused with synchrotron emission within our 310 pc beam.

The final considerations constraining the nonthermal emission mechanism are that there is no very bright point source and that the flux from the central region has not changed with time since 1984. These points make it very unlikely that VII Zw 19 contains any very luminous radio supernovae, similar to SNe 1986J or 1988Z (Weiler et al. 1990; Williams et al. 2002). The nonthermal emission must instead be produced by remnants of supernovae.

3.2. An Extended and Mature Starburst Region

The compact nonthermal emission, as traced by the 18 cm MERLIN map, which had \( \theta_{\text{max}} = 6.5^{\prime} \), is confined to less than \( 1^\circ \) (310 pc) and has a total mapped flux of 7.5–12.5 mJy, depending on which calibrator was used (see above). The total mapped flux in the 20 cm VLA maps \( (\theta_{\text{max}} = 38^{\prime}\prime) \) is 24 mJy, which corresponds to 22 mJy at 18 cm for a spectral index of \(~-0.7\). Thus, about half to two thirds of the total 20 cm flux from VII Zw 19 is extended emission from outside the central source. The high spatial resolution MERLIN observations have resolved out the most extended component of the long-wavelength emission.

The radio emission in VII Zw 19 differs from the young star formation sources in the dwarf galaxies NGC 5253 (Turner et al. 1998) and II Zw 40 (Beck et al. 2002), which have almost no nonthermal emission. The 18 cm flux of the central region corresponds to the equivalent of 2500 Cas A SNRs (Baars et al. 1977), comparable to what is deduced for the starburst in M82. The starburst in VII Zw 19 has evolved into the stage of plentiful supernovae and/or the means of expressing this state in the form of synchrotron emission. The thermal emission at 2 cm, adjusted for distance, is about 100 times as strong as that from the purely thermal, optically thick \( \text{H} \alpha \) region excited by the super star cluster in NGC 5253 (Turner et al. 1998). Therefore, what roughly emerges is a picture of the central 310 pc of VII Zw 19 containing a few thousand SNRs and a few hundred dense young \( \text{H} \alpha \) regions.

3.3. The Extranuclear Thermal Sources: Bright Star Clusters?

These high-resolution maps of VII Zw 19 paint a remarkable picture of a galaxy where star formation is simultaneously extended and compact. The total extent of the starburst is
1.2 kpc, yet there are distinct regions of nonthermal and thermal emission, of which the nonthermal are the older and more evolved and the purely thermal the youngest. We now consider in detail the thermal sources, which are the youngest and thus the current starburst regions. We use the predominance of emission at 2 cm as the signpost for thermal sources, although this may be an oversimplification; the central core of the galaxy has a nonthermal spectral index, yet it probably contains both thermal and nonthermal emission.

We therefore isolate the current starburst regions from the high-resolution 2 cm map (Fig. 1, bottom left). In the southeast there is a clear peak at R.A.(J2000) = 04h40m47.369, decl. (J2000) = +67°44′09″13, with a peak flux of 0.3 mJy beam$^{-1}$ and total flux of 0.4 mJy, which corresponds to $N_{1_{24}} \sim 1.5 \times 10^{31} \, \text{s}^{-1}$ in a region roughly 110 pc × 40 pc in size. (The peak is clearly extended; the source is assumed to be Gaussian and deconvolved from the beam.) A weaker peak is found at R.A. = 04h40m47.45, decl. = $+67°44′09″10$, with peak 0.24 mJy beam$^{-1}$ and total flux 0.3 mJy, which corresponds to $N_{1_{24}} \sim 1.0 \times 10^{32} \, \text{s}^{-1}$ in a region roughly 75 pc × 30 pc. The total flux at 2 cm in the southeast portion of the source (which appears as a single source in the lower resolution image of Fig. 1, bottom right) is 0.9 mJy, or $N_{1_{24}} \sim 3.3 \times 10^{35} \, \text{s}^{-1}$, in a region about 150 pc (≈0.5″) across.

The filament in the southwest is extended and thermal. The total flux in this filament is about 0.5 mJy, corresponding to $N_{1_{24}} \sim 2 \times 10^{35} \, \text{s}^{-1}$, covering a total extent of ~350 pc with no clear structures down to our smallest 2 cm beam of 0.2″ (~60 pc).

There are also regions of thermal emission, indicating starburst activity, quite distant from the center. Roughly 600 pc to the south of the main radio source is an extended region containing 0.3 mJy of thermal flux, for a total $N_{1_{24}} \sim 1.1 \times 10^{32} \, \text{s}^{-1}$, or the equivalent of $1.1 \times 10^{4} \, \text{O} \, \text{stars}$. A compact source is visible about 0.5 kpc to the northeast of the central source, at R.A. = 04h40m47.59, decl. = $+67°44′10″3$. This compact source has a peak of 0.24 mJy beam$^{-1}$. It is unresolved and therefore less than 45 pc × 34 pc in size, with $N_{1_{24}} \sim 8.5 \times 10^{35} \, \text{s}^{-1}$. This source by itself is an impressive center of star formation, containing the equivalent of 8500 $\text{O} \, \text{stars}$.

The thermal radio emission we estimate for all the sources we have identified as being true starbursts corresponds to a total ionization of $N_{1_{24}} \sim 7.3 \times 10^{32} \, \text{s}^{-1}$, or the equivalent of $7.3 \times 10^{4} \, \text{O} \, \text{stars}$. Using the relation $L_{\text{O}} = (2-3 \times 10^{-44}) N_{1_{24}}$, we find the expected luminosity of the OB stars to be $1.4-2.2 \times 10^{10} \, L_{\odot}$. The total infrared luminosity of this galaxy from the $\text{IRAS}$ fluxes is $7.3 \times 10^{10} \, L_{\odot}$, so we see that a substantial fraction of the total luminosity comes from the compact starburst sources listed here.

4. CONCLUSIONS: TWICE THE M82 STARBURST AT 64 Mpc

We have emphasized what is unusual about VII Zw 19: that it is a dwarf galaxy with a nonthermal spectrum, that it contains an extended and highly structured region of nonthermal emission, and that it also holds regions of optically thick thermal emission that are spatially distinct from the nonthermal sources. Although unusual, VII Zw 19 is not unique. In many respects it is remarkably similar to the well-known starburst galaxy M82 (Golla et al. 1996). If M82 were at 64 Mpc instead of 3.3 Mpc, it would have fluxes of 22 mJy, 4.5 mJy, and 0.15 Jy at 20 cm, 2 cm, and 12 μm, respectively, which are quite similar to the 24 mJy, 9 mJy, and 0.29 Jy of VII Zw 19, and it would have about half the linear extent in the radio—700 pc as opposed to 1200 pc. VII Zw 19 is bluer in the infrared than M82, and it has about twice the thermal flux (i.e., twice the $N_{1_{24}}$ or number of equivalent $\text{O} \, \text{stars}$). The main observational difference between the two galaxies is that the starburst region in M82 is more dominated by synchrotron emission. M82 does not have the equivalent of the two extended regions of optically thick thermal emission regions seen at 2 cm in VII Zw 19.

If M82 were at the distance of VII Zw 19, then its thermal sources could not be separated from the nonthermal at the resolution of the images presented here. The two giant thermal clusters are probably responsible for the excess at 2 cm and for the infrared flux in VII Zw 19, as compared with M82. The two giant thermal clusters may indicate that the star formation process in VII Zw 19 is not coeval (i.e., with the entire central region the same age), but that star formation began at an earlier epoch in the main complex and only more recently in the thermal clusters. However, there may be other reasons that VII Zw 19, overall, but particularly in the outer “thermal” regions, is deficient in synchrotron emission as compared with M82.

One possible difference between M82 and VII Zw 19 is the environment. M82 is part of a group of galaxies, interaction with which has apparently triggered the starburst activity (Yun et al. 1994), whereas VII Zw 19 is isolated. What, then, triggered the starburst in VII Zw 19? A possible explanation is that VII Zw 19 accreted another dwarf galaxy that is no longer visible as a separate object. This is the process believed to have started the activity in He 2-10, for example (Kobulnicky et al. 1995). If VII Zw 19 underwent such an accretion event in the last 100 Myr, it would have disturbed the kinematics of the molecular and atomic gas in a fashion that should still be observable.

VII Zw 19 is a challenge to map and study properly. Its distance of 64 Mpc reduces the effective spatial resolution by a factor of 20 and the measured fluxes by a factor of 400, compared with M82. The active region covers 1.2 kpc, but it contains regions of distinct properties and histories on size scales down to our resolution limit of 45 pc. It is a tribute to current subarcsecond imaging methods that we have been able to study the structure at all. This galaxy is much more complicated than most starburst dwarf galaxies, and its evolution and star formation history remain mysterious.

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Conti, P. S. 1991, ApJ, 377, 115
Deeg, H.-J., Duric, N., & Brinks, E. 1997, A&A, 323, 323
Golla, G., Allen, M. L., & Kronberg, P. 1996, ApJ, 473, 244
Kobulnicky, H. A., Dickey, J. M., Sargent, A. I., Hogg, D. E., & Conti, P. S.
1995, AJ, 110, 116
Schaerer, D., Contini, T., & Pindao, M. 1999, A&AS, 136, 35
Turner, J. L., Beck, S. C., & Ho, P. T. P. 1998, AJ, 116, 1212
Turner, J. L., & Ho, P. T. P. 1994, ApJ, 421, 122
Weiler, K. W., Panagia, N., & Sramek, R. A. 1990, ApJ, 364, 611
Williams, C. L., Panagia, N., Van Dyk, S. D., Lacey, C. K., Weiler, K. W., &
Sramek, R. A. 2002, ApJ, 581, 396
Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1994, Nature, 372, 530
Zwicky, F., & Zwicky, M. 1971, Catalogue of Selected Compact Galaxies and
of Post-Eruptive Galaxies (Gümlingen: Zwicky)