RevMexAA (Serie de Conferencias), **6**, 105–107 (1997)

MICRO-Jy RADIO GALAXIES: STARBURSTS AT $z < 1$?

James D. Lowenthal[1]

RESUMEN

Con el telecopio Keck de 10-m, se obtuvieron espectros e imágenes $BRIK$, en tres campos, de una muestra completa de las fuentes μJy del VLA. El 93% de las fuentes con $I \sim 26.5$ ha sido identificada y se tiene el 70% de los corrimientos al rojo en un campo (100% para $I < 24$), con una mediana de $z_{med} \sim 0.5$. El $\sim$ 50% de las fuentes parecen estar dominadas por galaxias azules luminosas con formación estelar, con una fracción grande de sistemas de pares cercanos e interactuantes. Cerca del 25% son QSOs con altos corrimientos al rojo y el otro 25% muestra emisión debida a formación estelar y líneas de absorción de poblaciones evolucionadas. Los colores de las fuentes son consistentes con los de las galaxias de campo, dominadas por tipos Sbc, aunque las fuentes son más luminosas por al menos 1 mag. Las morfologías de las imágenes en K, $K_{med} = 17.2$, son consistentes con las imágenes ópticas. Pareciera que la fuente μJy típica es similar a M82, alejada a $z \sim 0.5$. Las fuentes parecen estar evolucionando.

ABSTRACT

We have obtained $BRIK$ broad-band images and optical spectra, with the 10-m Keck telescope, of a complete sample of μJy sources detected in three fields at the VLA. About 93% of the sources are identified down to $I \sim 26.5$, and redshifts in one field are 70% complete (100% for $I < 24$), with a median value $z_{med} \sim 0.5$. Some $\sim$ 50% of the sources appear to be dominated by star-forming galaxies with a large fraction of interacting and close-pair systems. About 25% are high-z QSOs (one has Mg II absorption at $z_{abs} = z_{em} = 1.8$), and the remaining 25% show signs of both star-formation-induced emission and absorption lines characteristic of evolved stellar populations. The colors of the sources are consistent with those of field galaxies (dominated by Sbc galaxies), though the μJy sources are at least 1 mag brighter than field galaxies. The K-band images reveal morphologies consistent with the optical appearances and $K_{med} = 17.2$; we find no dust-enshrouded "monsters". It appears that the typical μJy source is similar in most respects to M82. Evolution of the sources now appears inevitable.

Key words: **GALAXIES: ACTIVE — GALAXIES: INTERACTIONS — GALAXIES: STARBURST — INFRARED: GALAXIES**

1. THE FAINTEST RADIO GALAXIES

Millions of times fainter than classical double-lobed radio monsters, μJy radio sources are the distant analogs of *IRAS* galaxies. Just as number counts of optical galaxies and *IRAS* sources show excesses at faint levels that imply evolution, so too do counts of the faintest radio sources exceed simple no-evolution models (Condon 1989; Windhorst 1990; Wall 1994). Below 1 mJy, radio sources are dominated by blue galaxies generally identified with starbursts, similar to the ones dominating the *IRAS* Faint Source Survey (FSS), in contrast to the old red ellipticals that host the classical double-lobed sources at the bright end of the radio luminosity function (Benn et al. 1993; Rowan-Robinson et al. 1993). But what are the μJy sources? Are they low-luminosity local sources, are they more distant versions of the sub-mJy galaxies, or do they trace activity of a different sort altogether? Only recently have optical identifications and redshifts become available for a handful of μJy sources (Hammer et al. 1995; Windhorst et al. 1995), but the results are not conclusive.

2. OBSERVATIONS

We obtained deep optical images and spectra with the Low Resolution Imagining Spectrograph and near-IR images with the Near-Infrared Camera (NIRC) at the 10-m Keck telescope of a complete sample of μJy sources discovered with the VLA. We studied three fields: Lynx.2 and SA68 from the Leiden-Berkeley Deep

[1]UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA.

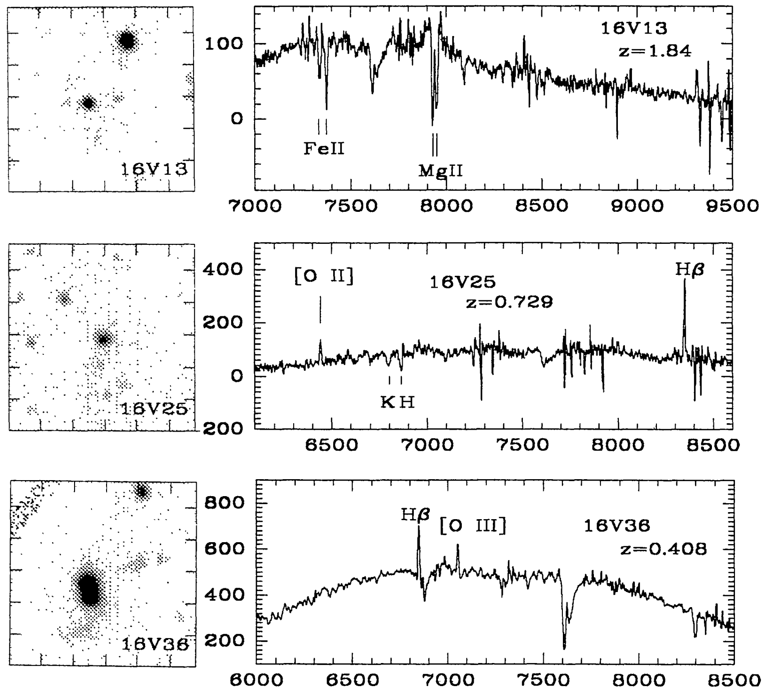

Fig. 1. Three $B+R+I$-band images and spectra of μJy sources from the Lynx.2 field. Each image is 30″on a side, and centered on the source's VLA coordinates. 16V13 is a QSO with strong Mg II absorption at $z_{abs} = z_{em}$. The source is extended in both the radio ($\theta \sim 13''$) and the optical. 16V25 has radio and optical properties similar to those of M82. 16V36 is associated with an interacting pair of galaxies; note the tidal tails.

Survey (Windhorst et al. 1984) and a field studied with the VLA and *HST* in the course of the *HST* Medium Deep Survey (Windhorst et al. 1995 —the "Lilly field"). With 1σ levels of 3, 60, and 2 μJy, the complete radio catalogs comprised 14, 9, and 16 sources, respectively. Using both multi-object slit masks and long-slit pointings we obtained 14 new redshifts from the complete samples (as well as several more for objects in the incomplete samples), bringing the total numbers of redshifts in the Lynx.2, SA68, and Lilly fields to 11 (80%), 2 (22%), and 10 (63%), respectively. Since optical identifications were only 64% complete for the Lynx field, we obtained deep *BRI* images of the same part of the Lynx field containing the objects we studied spectroscopically, and summed all the images to create a deep identification image. The 3σ levels were $B \sim 26.2, R \sim 26.9,$ and $I \sim 25.4$ in 3″ apertures. In most cases there is a bright object within 3″ of the VLA coordinates; in several cases there is evidence for interacting systems. In only two cases in the Lynx.2 sample is there no optical object within 3″ of the VLA coordinates, and no obvious candidate nearby. To test for contamination from field galaxies we randomized the positions and repeated the identification exercise. This indicates that at most about 15-20% identifications could be due to unrelated field galaxies. Most objects are detected in the NIRC images at $K < 22.5$ but $I - K_{med} = 2.8$; we do not find dust-enshrouded "monsters" underneath the faint radio emission.

3. WHAT ARE THE μJy RADIO SOURCES?

Morphologically, many of the optical sources correspond to galaxies in close pairs or groups, often with clear signs of interactions such as tidal tails; this is consistent with the predictions and preliminary results of Windhorst et al. (1993) and Windhorst (1995). Most of the sources show the strong Hβ and [O III] λ5007 emission lines characteristic of star formation; the source 16V36 ($z = 0.408$) in Lynx.2 (Fig. 1) is a good example. About 25% of the sources also show the Ca H&K, Fe, and/or Balmer series absorption lines characteristic of evolved stellar populations. These appear to be similar to the "S+A" galaxies identified as mJy sources by Benn et al. (1993), although most spiral and starburst galaxies with any evolved underlying stellar population will also show such emission plus absorption spectra (cf., Kennicutt 1992). Only one spectrum has a featureless continuum that yields no redshift or spectral type. Due to our short spectral coverage, we lack sufficient emission line data to discriminate between star formation and AGN as the cause of the emission. Hammer et al. (1995) have attempted this with their sample of μJy sources from the Canada France Redshift Survey (CFRS), and have concluded that AGN *dominate* the sources. However, 40% of the μJy sources are extended in the radio at $\theta > 5''$ while only 20–30% are variable (Windhorst et al. 1995), which argues against their being AGN, and also that discriminating among emission processes with even the line fluxes used by Hammer et al. is difficult and not entirely secure. Furthermore, the CFRS group finds a significant number of ellipticals in their μJy sample; we find none. As Hammer et al. point out, their field may be affected by a large structure at $z \sim 1$, which could weight the tally heavily towards ellipticals. Approximately 25% of the sample consists of high-redshift ($z > 1.5$) QSOs. One of these, at $z = 1.8$, shows strong Mg II and Fe II absorption at the emission redshift of the QSO (see Fig. 1). The median redshift of the sample is $z = 0.5$, with no chance of bringing it higher than $z \sim 0.7$ even if all the missing redshifts are filled in at $z > 1$. This is in contrast to the suggestion by Hammer et al. that 40% of the μJy sources are at $z > 1$. It has been shown (Wall et al. 1986) that only if the median redshift of the μJy sources were less than 0.1 could we avoid the conclusion from the number counts that the sources are an *evolving* population. Our measured median $z \sim 0.5$ forces us to infer that evolution has been detected. This is consistent with the strong evolution derived from FSS counts (e.g., Lonsdale et al. 1990), which are presumably sampling a parent population similar or identical to the one seen by the VLA (except for the VLA's much more sensitive detection limits, which probes deeper into cosmological space).

4. FIELD GALAXIES AND μJy RADIO SOURCES

The $B - R$ and $R - I$ colors of the sources are consistent with those of field galaxies in the same images: $B - R \sim 1$ and $R - I \sim 0.7$. However, the μJy sources, with $I_{\rm med} \sim 20$, are 1–2 magnitudes brighter than the typical field galaxy down to our photometric limits. We note that the field galaxy population is generally dominated by moderate-luminosity late-type spirals (e.g., Driver et al. 1995). With redshifts, we calculate intrinsic colors and luminosities of our galaxy sample. These also are consistent with Sbc galaxies over the observed range of redshifts of our sample, with a typical luminosity close to L* ($M_B \sim -20.1$ for $h = 0.75$) —again, somewhat brighter than a typical field galaxy. The median radio power is $P_{\rm med} \sim 10^{22}$W Hz^{-1}, similar to M82, the prototypical starburst galaxy. This echoes the results of Windhorst et al. (1995). It is interesting that the surface density of radio counts extrapolated down to 300 nJy matches that of optical field galaxies to $V < 28$ ($1.5 - 3 \times 10^5$deg^{-2}; Windhorst et al. 1993). Unless some radically new population of bizarre sources has appeared in one or the other spectral band, we should expect the bulk of sources to appear in both ultra-faint radio and optical surveys on an almost one-to-one basis. Star formation could provide the common link, producing faint blue galaxies that dominate the optical counts and thermal bremsstrahlung and non-thermal synchrotron radiation (via supernovae) to power the radio emission. There may also be strong implications for merging models of field galaxy evolution (e.g., Broadhurst et al. 1992), since it is mergers that drive the starbursts that figure so prominently in the *IRAS* and μJy samples (Rowan-Robinson et al. 1993).

REFERENCES

Benn, C. R., Rowan-Robinson, M., McMahon, R. G., Broadhurst, T. J,. & Lawrence, A. 1993, MNRAS, 263, 98

Broadhurst, T. J., Ellis, R. S., & Glazebrook, K. 1992, Nature, 355, 55

Condon, J. J. 1989, ApJ, 338, 13

Driver, S. P., Windhorst, R. A., Ostrander, E. J., Keel, W. C., Griffiths, R. E., & Ratnatunga, K. U. 1995, ApJ, 449, L23

Hammer, F., Crampton, D., Lilly, S. J., Le Fevre, O., & Kenet, T. 1995, MNRAS, 276, 1085

Kennicutt, R. C. J. 1992, ApJS, 79, 255

Koo, D. C., & Kron, R. G. 1992, ARA&A, 30, 613

Lonsdale, C. J., Hacking, P. B., Conrow, T. P., & Rowan-Robinson, M. 1990, ApJ, 358, 60

Rowan-Robinson, M., Benn, C. R., Lawrence, A., McMahon, R. G., & Broadhurst, T. J. 1993, MNRAS, 263, 123

Wall, J. V. 1994, AustrJPhys, 47, 625

Wall, J. V., Benn, C. R., Grueff, G., & Vigotti, M. 1986, in Highlights of Astronomy, Vol. 7 (Dordrecht: D. Reidel), 345

Windhorst, R. A., Fomalont, E. B., Kellermann, K. I., Partridge, R. B., Richards, E., Franklin, B. E., Pascarelle, S. M., & Griffiths, R. E. 1995, Nature, 375, 471

Windhorst, R. A., Mathis, D., & Neuschaefer, L. 1990, in Evolution of the Universe of Galaxies; Proceedings of the Edwin Hubble Centennial Symposium (Astr. Soc. Pac.), 389

Windhorst, R. A., van Heerde, B. M., & Katgert, P. 1984, A&AS, 58, 1

Windhorst, R. A., Fomalont, E. B., Partridge, R. B., & Lowenthal, J. D. 1993, ApJ, 405, 498