Galaxies and Their Constituents at the Highest Angular Resolutions
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High Resolution Studies of mJy and μJy Radio Sources

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Abstract.
VLBI observations can now be used to examine the milliarcsecond properties of mJy and sub-mJy radio sources. Here we describe a snapshot survey of compact mJy sources selected from the FIRST survey and the first EVN observations of a 6 arcmin square field centred on the Hubble Deep Field. At the few mJy level, a significant number of steep-spectrum sources appear to be very young low-luminosity radio galaxies. Older and fainter examples of this type of source are seen in the HDF, and are detected by the EVN. The VLBI observations of the HDF support the view that at least one of the putative distant, dusty starbursts harbours an AGN.

1. Introduction

Radio observations are playing a key role in understanding the evolution and formation of galaxies, their star-formation histories and the incidence of AGN. They can provide estimates of the star-formation rate free from dust extinction, they provide the highest angular resolution and the most accurate positions. High resolution radio observations can distinguish between nuclear activity and star-formation, and the radio-submm spectral index provides a powerful redshift estimator for distant, optically faint galaxies.

The increasing sensitivity of VLBI, provided by the large antennas of the EVN and the MkIV bandwidth upgrade, along with the technique of phase-referencing means that we can now attack the mJy and even μJy radio population at milli-arcsecond resolution.

2. An Unbiased VLBI Survey of mJy radio sources

Initially, 127 sources were selected from the VLA FIRST survey, above 10 mJy, discarding about 20% which were clearly resolved. For efficient phase-referencing, the sources were chosen in a 3×4 degree box surrounding the calibrator J1159+291. To select the compact sources, MERLIN snapshots at 5

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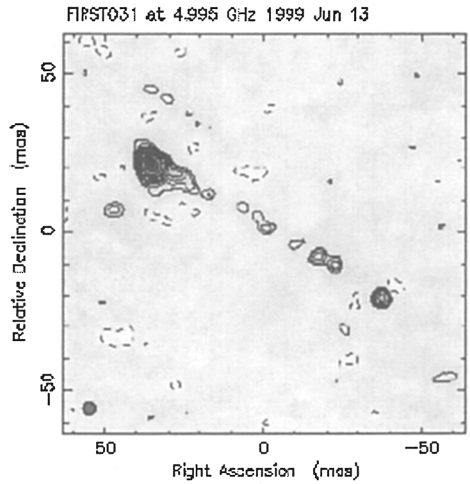

Figure 1. Global VLBI 5 GHz map of a 70-mas steep spectrum source with a total flux density of 25 mJy at 5 GHz.

GHz provided a 2 mJy detection threshold at 50 mas resolution. Perhaps surprisingly, over half the sources were detected: most were barely resolved, except for a few small double sources and the more compact lobes of larger sources, which the blind selection had not excluded.

The detected sources were observed with Global VLBI snapshots at 5 GHz with 2 mas resolution. Apart from a few obviously extended sources, any source which was compact on MERLIN scales was detected by these brief global VLBI snapshots, implying that perhaps 30% of all sources brighter than 10 mJy at 1.4 GHz are easily accessible to VLBI (Garrington et al 1999).

The detected sources show a broad range of radio spectral indices. The steep spectrum sources are almost all empty fields on the POSS. Although some also have extended radio emission, a number remained barely resolved in these brief VLBI snapshots and were followed-up by more intensive Global VLBI observations. In 4/5 cases, these objects have compact, linear structures ~ 10 mas across. One source, which had initially attracted attention because it appeared as an isolated 5-mas diameter ring (Garrington et al 1999), turned out to be a 70-mas compact steep-spectrum object.

The expansion of brighter examples of such sub-kpc steep-spectrum sources has recently been measured directly, giving kinematic ages of order 1000 yrs (Owsianik & Conway 1998) and confirming the view that these are the progenitors of large 'classical' radio galaxies (Readhead et al 1999). Since the radio source luminosity declines rapidly at it expands, the very faint sources found here are expected to develop into much fainter FR1 radio galaxies. Two examples of older, larger and fainter FR 1 radio galaxies with flux densities of ~ 1 mJy are seen in the HDF (see below). The number of these young sources found in this survey may imply that the these nascent FR1 sources fade faster with time than their more powerful counterparts.

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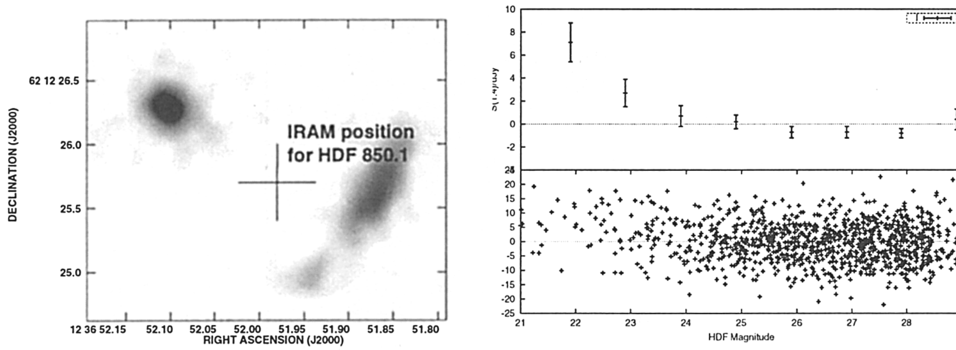

Figure 2. Left: The IRAM position for the sub-mm galaxy HDF850.1 and the accurate astrometry of the HDF using MERLIN suggest that this sub-mm source is not identified with any of the surrounding galaxies. Right: 1.4 GHz flux densities for all the optically catalogued galaxies in the HDF, vs I-magnitude (lower) and in magnitude bins (upper). Detections above 25μJy are excluded, but the positive bias is clear.

3. MERLIN/VLA Observations of the Hubble Deep Field

Below about 1 mJy, the radio source population becomes increasingly dominated by star-forming galaxies. The most complete investigation of this population has been carried out using MERLIN and VLA observations of the Hubble Deep Field, led by Richards (2000 and references therein) and Muxlow et al (1999).

The angular resolution of MERLIN has been essential, since the majority of sources detected are not resolved by the VLA alone and MERLIN has been used to accurately register the radio and optical images to within 20 mas.

The majority of the radio sources are due to the integrated emission from relic SNR in relatively bright disk galaxies at $z = 0.4 - 1.0$, indicating star-formation rates of $> 100 M_{\circ}$ yr^{-1}. However, as many as 15% of the radio detections are optically undetected (Richards et al 1999). Some are clearly very red objects and the natural interpretation is that these are powerful, distant and heavily obscured star-forming galaxies. However, we note that one of these, J3651+1221, (eg Muxlow et al 1999) is detected by *Chandra* (Hornschemeier et al 2000) and the photometric redshift implies an X-ray luminosity appropriate for a quasar.

The position of the brightest sub-mm source in the HDF (850.1) has now been determined to within 300 mas with respect to the ICRF using the IRAM interferometer (Downes et al 1999). Using the accurately aligned optical image, it would now appear that this source is associated with a galaxy which is below the HDF limit - another distant dusty starburst, perhaps (see Fig. 2)

Finally, a statistical comparison of the radio and optical images in the central HDF itself can be used to probe much deeper than the 8σ level used for detection (Fig. 2). It appears that at the few μJy level most of the brighter galaxies show radio emission (cf the WSRT results of Garrett et al 2000a).

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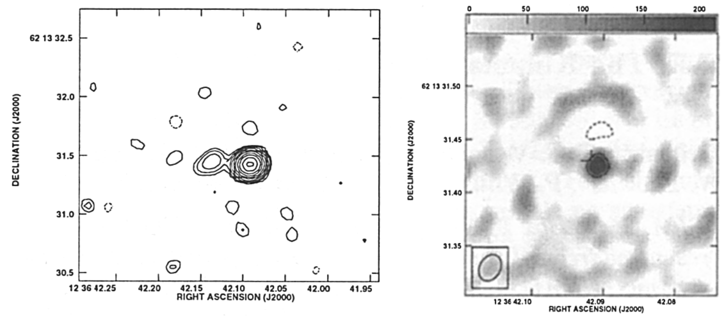

Figure 3. MERLIN+VLA (left,200 mas beam) and EVN (right, 25 mas beam) images of the $z = 4.4$ HFF galaxy 3642+1331.

4. EVN Observations of the Hubble Deep Field

VLBI observations of the HDF, capitalising on the large collecting area and sustained 256 Mb/s recording capability of the EVN, have been led by Garrett et al (2000b). Individual fields around MERLIN detections above 60 μJy within 3.5 arcmin of the field centre were imaged with a sensitivity of 35 μJy rms.

Two sources were clearly detected: 3644+1133 is an FR 1 radio galaxy with a total extent of 30 arcsec and a total flux of 0.6 mJy. The EVN image detects the core and a knot in the southern jet. This is just the type of source which the steep-spectrum mJy sources discussed above might evolve into. 3642+1331 is one of the optically faint sources, perhaps a distant starburst. Waddington et al (1999) place this galaxy at $z = 4.4$ based on a single spectral line, implying a radio luminosity of $L_{1.4} = 3.5\,10^{25}$ W/Hz. The EVN image (Fig. 3) shows that more than half of the radio flux arises in a single component < 20 mas in size. The high brightness temperature ($T_b > 10^5$K) suggests that this is an AGN. A further AGN, 3646+1404, also detected by *Chandra* is detected at the 3σ level.

References

Downes, D. et al 1999 A&A, 347, 809
Garrett et al. 2000a A&A, 361, L41
Garrett et al. 2000b A&A, submitted
Garrington, S. et al. 1999 NewAR, 43, 629
Hornschemeier, A. et al. 2000 ApJ, 541, 49
Muxlow, T et al. 1999 NewAR, 43, 623.
Owsianik I. & Conway J.E. 1998 A&A, 337, 69
Readhead, A.C.S. et al. 1996 ApJ, 463, 95
Richards, E.A. 2000 ApJ, 533, 611
Richards, E.A. et al 1999 ApJ, 526 L73
Waddington, I. et al 1999 ApJ 526, L77

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