AGN and starbursts at high redshift: High resolution EVN radio observations of the Hubble Deep Field.

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VLBI now has the capability of imaging relatively large fields-of-view ($\sim$ 5 arcmin^2) with sub-mJy detection limits. In principle such observations can distinguish between starburst and AGN activity in cosmologically distant sources. We present the first deep, wide-field European VLBI Network (EVN) 1.6 GHz observations of faint radio sources in the Hubble Deep Field (HDF) region. The EVN clearly ($> 5\sigma$) detects 2 radio sources in a field that encompasses the HDF and part of the Hubble Flanking Fields (HFF). The sources detected are: VLA J123644+621133 (a z=1.01, low-luminosity FR-I radio source located within the HDF itself) and VLA J123642+621331 (a dust enshrouded, optically faint, z=4.424 starburst system). A third radio source, J123646+621404, is detected at the 4σ level. The observations presented here, suggest that the radio emission in the dusty starburst, VLA J123642+621331, arises mainly from AGN activity, suggesting that in this system, both AGN and starburst activity co-exist. The prospects for future VLBI deep fields are briefly discussed.

1. Introduction and Data Analysis

With the recent implementation of both wide-field (Garrett et al. 1999) and phase-referencing techniques (*e.g.* Beasley & Conway 1995), VLBI now has the capability of imaging relatively large fields-of-view ($\sim$ 5 arcmin^2) with sub-mJy detection limits. It is thus possible for VLBI to begin to contribute to our understanding of the nature of the faint, sub-mJy and microJy radio source population. Hitherto such investigations have been limited to connected element interferometers such as the VLA (Richards et al. 1998, R98), MERLIN (Muxlow et al. 1999, M99) and the WSRT (Garrett et al. 2000a). These observations show that the radio structure of these faint sources is usually sub-galactic in size, the emission has a steep spectrum and identifications via optical, infrared and sub-mm instruments suggest the vast bulk can be identified with cosmologically distant starburst galaxies (often with distorted optical morphologies). These deep radio surveys are thus crucially important to some hot-topics of the day, including galaxy formation and evolution in the early universe. There are many important questions in this area that can benefit from high sensitivity VLBI observations. In particular, there is accumulating evidence that both starburst and AGN activity (in the early universe) are related to galaxy interactions and mergers. It seems possible that both starburst and AGN activity often co-exist in the same system.

VLBI, with its ability to provide milliarcsecond angular resolutions can, in principle, distinguish between the two phenomena. In starburst galaxies the radio emission is believed to arise from relatively extended star formation processes (such as radio emission from relic SNR, young SNR, HII regions) whereas in AGN the compact radio emission is usually associated with a powerful central engine, regulated by a super-massive black hole. Fortunately, the starburst and AGN phenomena present (with high angular resolution) very different radio morphology (c.f. Pedlar and Gabuzda - these proceedings).

In this paper, we present the first VLBI observations of faint radio sources in the Hubble Deep Field (Williams et al. 1996). The observations were made using the European VLBI Network (EVN) utilising the new, high sensitivity MkIV Data Acquisition System. EVN Observations of the HDF region were made on 12-14 November 1999 at 1.6 GHz. A total of 32 hours observing time was split into two, 16 hour runs. Seven EVN telescopes successfully participated, including the (DSN/NASA) 70-m telescope at Robledo, Spain. The observations were made in phase-reference mode and correlated at the NRAO VLBA correlator in Socorro, USA. In order to image the entire HDF and part of the Flanking Fields (a region spanning ~ 6 arcmin^2), the data were maintained in their original form (1 second integrations, 512×0.125 MHz channels). After applying the standard VLBI calibration techniques, these data were Fourier transformed to the image plane, and six dirty images were simultaneously generated, targeting known areas of radio emission detected via earlier 1.4 GHz MERLIN observations (with MERLIN peak flux $> 60\mu$Jy/beam). In order to check the robustness of our data and imaging routines, one of the six fields was centred on an "empty" region of radio sky located within the HDF. It should be noted that the brightest source in the HDF has a total WSRT flux density of only 1.6 mJy (Garrett et al. 2000a) – the EVN observations (with a beam size area that is 1 million times smaller than the WSRT) might best be considered as the *first VLBI observations of blank radio sky!*

The naturally weighted, dirty images of the HDF and HFF sources are shown in Fig 1. The images are restored with a Gaussian elliptical beam (26×20 mas in PA= $-31°$). The r.m.s. noise levels (as measured by IMEAN over the entire image) range from 41μJy/beam (in a field with a clear detection) to 33μJy/beam (in a field with no detection).

2. EVN Detections in the central HDF region

At the 5σ detection level, the EVN observations clearly detect VLA J123642+621331 (at the phase centre) and VLA J123644+621133 (located within the HDF itself). Both sources are detected independently in both left and right-hand circular polarisations. *Note that these two sources, imaged and detected via the same data set are separated by ~ 2 arcminutes on the sky - simultaneous detection of multiple sources in a single VLBI field of view will soon be the "rule" rather than the exception!* There is a 4σ detection of J123646+621404, located within 20 mas of the measured MERLIN position. Two other sources were not detected: J123646+621448 and J123652+621444.

2.1. *VLA J123644+621133 and VLA J123642+621331*

VLA J123644+621133 is identified with a bright ($I \sim 21.05^m$) z=1.013, red elliptical galaxy (R98), with a radio luminosity and large scale radio structure that classify it as an FR-I (R98). The EVN (see Fig. 1) detects a compact core component (c) with an estimated size < 26 mas, implying a brightness temperature, $T_b > 1.8 \times 10^5$ K. There also appears to be a clear 5σ detection of an additional component located ~ 60 mas south of the core component (note that the MERLIN position lies roughly half-way between components (c) and (j) – the EVN thus provides *the* most accurate (ICRF) source positions associated with the HDF. The traditional VLBI structure observed in VLA J123644+621133 supports the view (see M99) that the rare "classical" radio sources detected in the HDF and HFF, are simply related to the mJy tail of the AGN radio source population.

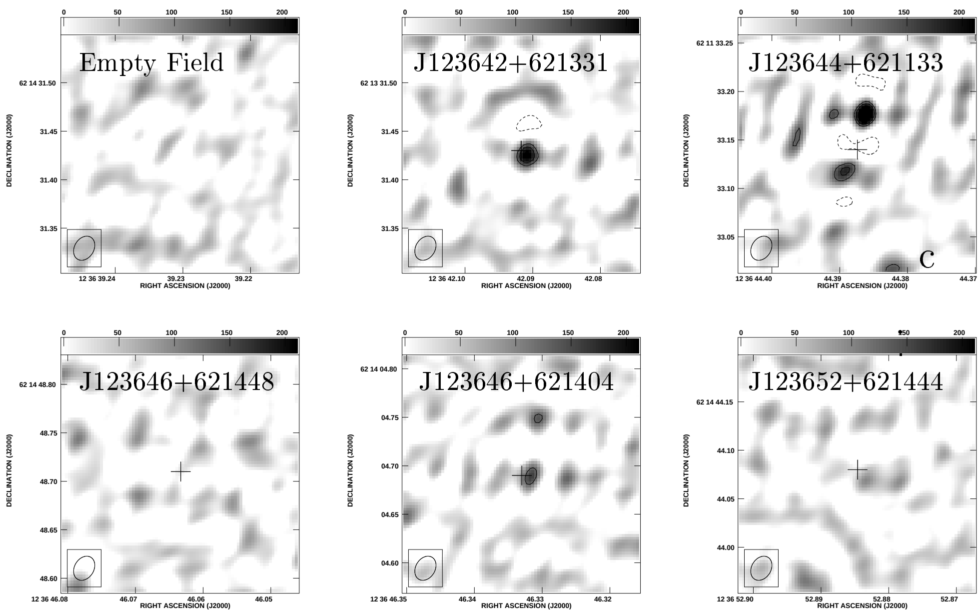

FIGURE 1. EVN 1.4 GHz dirty images of the six MERLIN targets. The MERLIN source positions are identified by crosses. Contours are drawn at -3, 3, 4, 5, 6, 7, 8, 9 times the rms noise level $\sim 40\mu$Jy per beam.

VLA J123642+621331 lies just outside the HDF, in an adjacent HFF. It is a relatively bright, steep spectrum radio source ($S_{1.4GHz} \sim 470\mu$Jy) with no optical counterpart to $I \leq 25^m$ (R98). Deep HST NICMOS 1.6μm imaging clearly detects an extremely red 23.9^m counterpart to the radio source (Waddington et al. 1999, hereafter W99), and spectra obtained by the Keck II telescope show a single strong emission line, which is identified with Ly α at z=4.424. W99 interpret the source as a dust obscured, star-forming galaxy with an embedded active nucleus.

The high resolution $0.15''$ 1.4 GHz VLA-MERLIN observations (M99) show that approximately 10% of the total radio emission in VLA J123642+621331 resides in an extended component, lying to the east of an unresolved core. It is the core which is detected by the EVN at 1.6 GHz. The main question is whether the radio emission arises due to star-formation processes or AGN activity. The EVN limit on the measured core size ($<$ 26 mas) implies a brightness temperature $> 10^5$K. The detection of this compact radio source, together with its high luminosity of $\sim 10^{25}$W/Hz ($\sim$ 100 times more luminous than the luminous starburst Arp 220), argues strongly for an AGN interpretation for most of the radio emission. A higher resolution (21×15 mas), uniformly weighted image of VLA J123642+621331 suggests that the core is resolved on the longer EVN baselines, although it should be noted that the noise in this image is twice as high as that in the naturally weighted case (see Fig. 1). Further, high resolution, global VLBI observations are clearly required to confirm an AGN interpretation for this radio source.

3. Conclusions

3.1. *Results*

We have clearly (5σ) detected two radio sources within the HDF region. One of these lies within the HDF itself (VLA J123644+621133) and shows all the usual properties of a low luminosity, classical FR-I radio source. The second, perhaps more interesting source is VLA J123642+621331. The EVN detection of a compact core supports the suggestion that this is a dusty, star-forming galaxy in which the bulk of the radio emission is associated with an embedded AGN.

3.2. *Future VLBI Deep Fields*

Further high sensitivity Global VLBI observations of this source and other sources in the HDF region are planned. It may be noted that significant short-term improvements in VLBI deep field imaging can be expected. A 2-fold increase in sensitivity is anticipated from the MkIV system running at its full 1 Gbit/sec capacity. This, coupled with multiple correlator passes associated with a judiciously chosen target field (see Garrett 2000b), will permit VLBI r.m.s. noise levels to routinely approach those currently enjoyed by connected element arrays. *VLBI observers might want to bear in mind that embedded within every typical continuum VLBI data set, there are, in addition to the brighter target, 3 eminently detectable sub-mJy sources - all trying to get out!*

Global VLBI observations with 3 times the resolution and 4 times the sensitivity of the pilot observations presented here, are now achievable. With a linear resolution of $\sim$ 30 pc at cosmological distances, only Global VLBI can resolve nuclear star-forming regions like those observed in Arp 220 (Smith et al. (1998)). Targeted observations of the optically faint radio source population (of which VLA J123642+621331 is just one example) may throw new light on the nature of the associated population of dusty sub-mm sources, recently discovered by SCUBA (Hughes et al. 1998). In the absence of near-infrared, optical, ultraviolet and even X-ray emission (due to dust obscuration), future VLBI observations will be a crucial diagnostic in distinguishing between AGN and starburst activity in these systems.

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