High resolution radio imaging of the Hubble Deep and Flanking Fields

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42 hours of A-array VLA data and 18 days MERLIN data at 1.4GHz have been combined to image a 10 arcminute field centred on the Hubble Deep Field. This area encloses both the Hubble Deep and Flanking Fields. A complete sample of 91 sources have been detected with flux densities above 40 μJy. All these have been imaged with the MERLIN+VLA combination to produce images with 0.2, 0.3 and 0.5 arcsecond resolution. These are the most sensitive 1.4GHz images yet made with rms noise levels of 3.3 μJy/beam in the 0.2 arcsecond images. About 70% of the microJy sources are found to be starburst type systems associated with major disk galaxies in the redshift range 0.4 - 1. Some 20% are found to be low–luminosity AGN systems identified with field ellipticals at redshifts close to 1. The remaining 10% are associated with optically faint systems close to or beyond the HDF limit; many of these may be dust–shrouded starbursts at high redshift. Recent wide-field EVN observations of the HDF (Garrett et al, these procs.) confirm that one of these objects (J123642+621331) is probably a dust enshrouded starburst system at z=4.424 with an embedded AGN.

1. Introduction

The Hubble Space Telescope has been used to image a window on the distant universe to very high sensitivity. The central Hubble Deep Field (HDF) and surrounding Hubble Flanking Fields (HFF) are complete to 29$^{\rm th}$ and 25$^{\rm th}$ R magnitude respectively (Williams et al, 1996). The HDF region was selected to avoid bright objects in any observable waveband.

Studies of radio source surveys above the mJy level indicate that they are dominated by powerful AGN type systems at substantial redshifts. Below a few mJy, the 1.4GHz integrated source counts show an upturn implying the emergence of an additional population of objects (Windhorst et al, 1985). Many of these μJy radio sources are associated with optically blue disk galaxies which often appear disturbed or are part of merging systems (Thuan & Condon, 1987). Such galaxy types at low redshift are known to exhibit a strong far–infrared:radio flux correlation implying active star-formation (Helou, Soifer, & Rowan-Robinson, 1985). We report here the results from our high–resolution, high–sensitivity 1.4GHz MERLIN+VLA study of the μJy sources found in the HDF and HFF.

2. The Radio Observations

42 hours of A–array VLA and 18 days of MERLIN data at 1.4GHz have been combined to image the μJy radio sources in a field 10 arcminutes on a side, centred on the HDF. The VLA data were taken during November 1996, and the MERLIN observations were

made during February 1996 and in April 1997. Due to computing limitations, the images were combined and deconvolved in the sky-plane. The maps were restored with 0.2. 0.3, and 0.5 arcsecond beams. These are the most sensitive 1.4GHz radio images ever made with rms noise (at 0.2 arcsec) = 3.3 μJy/beam. Nearly all the radio structures are resolved at this resolution, and are essentially unresolved at the VLA–only resolution of 2 arcseconds. The VLA–only image was used to define a sample of 91 radio sources complete to 40μJy in the 10 arcminute field centred on the HDF.

32 hours of wide-field EVN observation were taken on 12-14 November 1999 at 1.6GHz. The data configuration allowing imaging within a 2 arcminute field of view centred on the optically faint HFF object J123642+621331.

3. Astrometry

The VLA and MERLIN radio positions agree independently to better than 40 mas across the 10 arcminute field. The phase calibrator used has a absolute astrometric position error of 17 mas in both RA and Dec. Each HST WFPC2 frame typically contains too few radio detections to unambiguously align the radio and optical images. We have thus aligned a ground–based CFHT deep I-Band image covering a 9 arcminute field centred on the HDF (Cowie, private communication) under the radio detections. Optically compact galaxies in each WFPC2 frame were then registered over the Cowie ground–based image. The WFPC2 frames were thus aligned with the radio with residual optical registration errors of order 50 mas in the HDF itself, rising to around 150 mas in the outer parts of the HFF.

4. Radio Source Structures

Although few μJy radio sources are resolved by the 2 arcsecond beam of the VLA A-array image, virtually all the objects are resolved by the MERLIN+VLA combination images showing that they have angular sizes in the range 0.2 to 2 arcseconds. There are very few 'classical' high luminosity radio structures, and those that are found are associated with the mJy tail of the population. The vast majority of μJy sources have radio structures on the sub–galactic scale size. Around half show extended emission often aligned with the optical isophotes of the parent galaxy. Many show compact structure in addition to the extended emission.

We have compared our 1.4GHz fluxes with those measured by the VLA at 8.4GHz (Richards et al. 1998) to derive radio spectral indices for our sample. By comparison with established lower redshift systems, we interpret a flat or inverted radio spectrum together with a compact core and one or two–sided extended structure to indicate AGN activity. Steep–spectrum objects extended on sub–galactic scales (often aligned with the galaxy major axis) are strong starburst candidates - especially when also detected by the Infrared Space Observatory (ISO) (Goldschmidt et al. 1997).

Most of the radio sources are associated with relatively bright (R$<$25mag) galaxies (Richards et al. 1998). For those identified, we find that around 30% are low–luminosity AGNs associated with field elliptical galaxies with redshifts around 1. Around 70% are starbursts or strong starburst candidates identified with major disk galaxies in the redshift range 0.4 to 1. Figure 1 shows two examples of starburst systems. Around 10% of the radio sources are not identified and are thus associated with optically faint systems. Such systems are typically steep spectrum and may be distant dust–shrouded starbursts. The source J123651+621221 is a particularly interesting example in the HDF itself (See Figure 2). This object is steep–spectrum and extended, and overlies some faint red emission close to the HDF limit around 1 arcsecond to the north of its first suggested identification of a 24mag spiral at redshift 0.299. A recent NICMOS detection (Dickinson

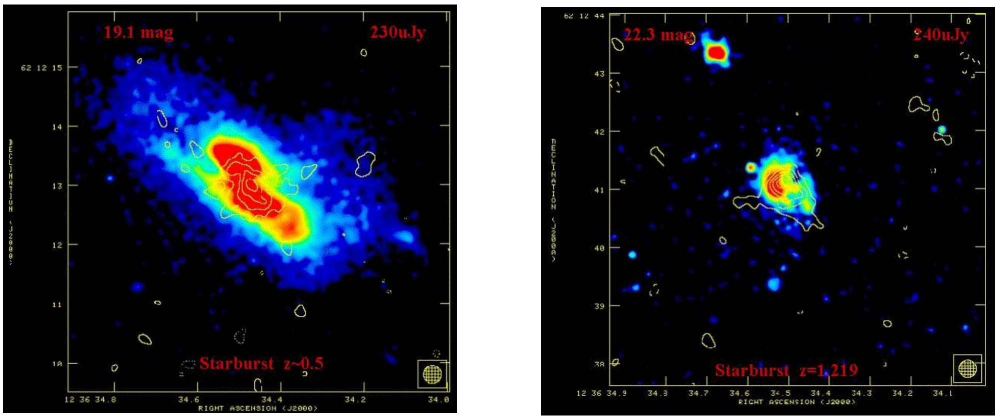

FIGURE 1. Two Starburst systems in the HFF. (a) Left J123634+621212 and (b) Right, J123634+621241. WFPC2 in false colour, MERLIN+VLA contoured linearly with CI=10 μJy/beam.

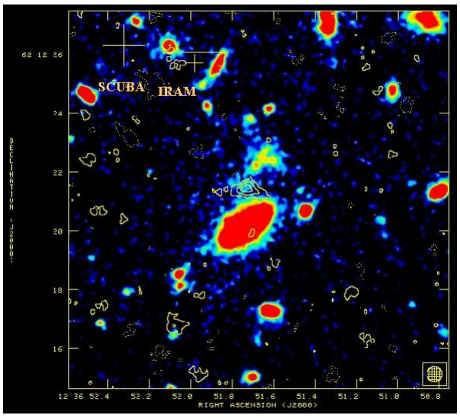

FIGURE 2. Optically faint system in the HDF, J123651+621221. WFPC2 in false colour, MERLIN+VLA contoured linearly with CI=10 μJy/beam.

2000), at the radio position shows an object with an unusual infrared spectrum whose photometry suggests a dust–shrouded starburst at a redshift of 2.6–2.7.

Figure 3 shows an enlargement of the top left-hand corner of Figure 2. This shows the original position of the brightest 850μm SCUBA source together with a revised position as measured by the IRAM telescope. Since the IRAM position is with respect to the radio reference frame, and the HST WFPC2 frames have been aligned over the same frame to better than 50 mas, it is clear that within measurement errors, this object is unidentified at the limit of the HDF (I<29^m).

5. J123642+621331 - A High Redshift Starburst With An Embedded AGN ?

This source lies just outside the HDF in an adjacent HFF frame. The MERLIN+VLA image at 0.2 arcsecond resolution shows a compact component embedded within an extended region of radio emission about 750mas in extent. It is a relatively bright, steep–spectrum radio source with no optical counterpart brighter than I=25^m. It is detected in a deep NICMOS 1.6μm exposure showing it to be an extremely red 23.9^m object. Two independent Keck II spectra show a single strong emission line, which is

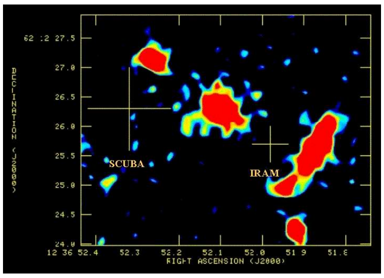

FIGURE 3. SCUBA detection 850.1, with original SCUBA and revised IRAM positions marked over the astrometrically aligned WFPC2 frame shown in false colour.

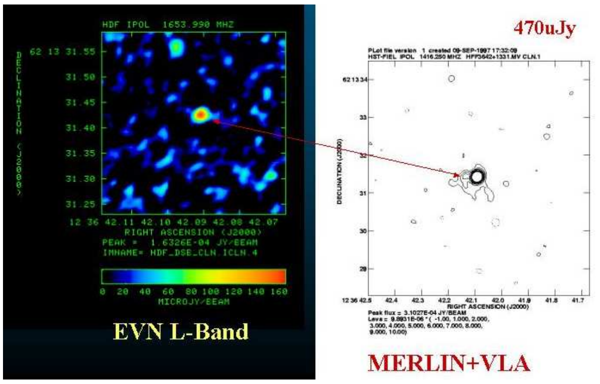

FIGURE 4. High redshift dust-shrouded starburst system J123642+621331 with a possible embedded AGN. MERLIN+VLA contoured at right with CI=10μJy/beam. EVN at left shown in false colour.

identified by Waddington et al. 1999 with Lyα at a redshift of 4.424. The source is also detected in the ISO supplementary list of sources and Waddington et al interpret the source as a dust obscured, starburst galaxy with an embedded AGN.

The EVN observations detect the compact component in J123642+621331 and show it to be smaller than 26 mas in size implying a brightness temperature greater than 10^5K (See Figure 4). This together with its high luminosity strongly supports the AGN interpretation, although further higher resolution global VLBI observations are required to confirm this.

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