At the Edge of the Universe:
Latest results from the deepest astronomical surveys, 9-13 October 2006, Sintra (Portugal)
*ASP Conference Series, Vol. ***, 2006*
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High-z radio starbursts host obscured X-ray AGN

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Abstract. We use Virtual Observatory methods to investigate the association between radio and X-ray emission at high redshifts. Fifty-five of the 92 HDF(N) sources resolved by combining MERLIN+VLA data were detected by *Chandra*, of which 18 are hard enough and bright enough to be obscured AGN. The high-z population of μJy radio sources is dominated by starbursts an order of magnitude more active and more extended than any found at $z < 1$ and at least a quarter of these simultaneously host highly X-ray-luminous obscured AGN.

1. Radio-based classification

A region of 100 arcmin^2 around the Hubble Deep Field North (HDFN 10-arcmin field) was observed by the UK radio interferometer MERLIN and the USA VLA (Muxlow et al. 2005). 92 sources brighter than 40 μJy were found in the combined images, which reach a noise level of $< 4\mu$Jy using beam sizes of $0.''2 - 2''$. These are the only observations apart from the HST images which provide morphological information. 8.4-GHz data are also available for most of the field (Richards et al. 1998) allowing the radio spectral indices to be calculated.

We employed data access, crossmatching and manipulation tools now available via the AstroGrid Workbench and the EuroVO. These include the Vizier and Aladin services, TopCat and a cut-out extractor for radio images which uses the parselTongue scripting interface developed by RadioNet. We compare the radio data with the *Chandra* CDF(N) source list (Alexander et al. 2003) and other GOODS (Giavalisco et al. 2004) HDFN observations to investigate the properties of active galaxies at $z \gg 1$:

1. Can radio emission originate from a process different from the X-ray source in the same galaxy? If so, how much radiation has a common origin and how much is separate?

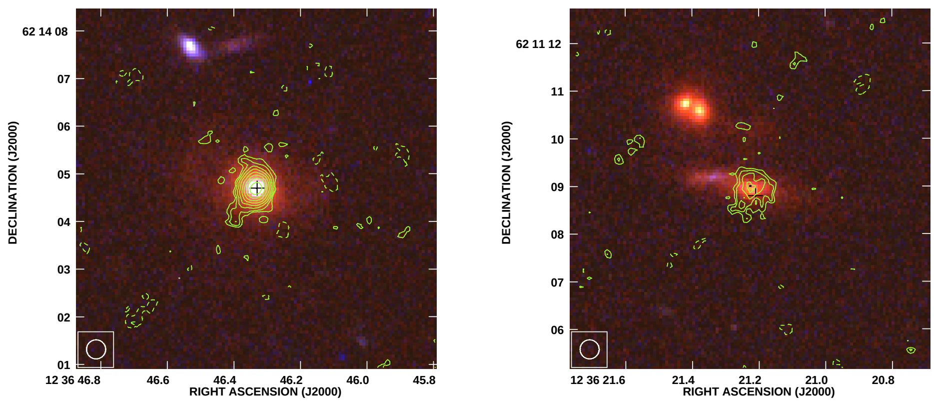

Figure 1. Radio contours overlaid on *HST ACS* images. The positions of the hard, obscured X-ray sources are marked with crosses. *Left:* J123646+621404 ($z = 0.96$) is a bright AGN with a compact core overlying the optical peak and lobes extending outside the host. It has a flat radio spectrum with $\alpha = -0.04$. *ISO*. *Right:* J123621+621109 ($z = 1.01$) is a radio starburst associated with a distorted optical system. It has a steep radio spectrum, $\alpha > 0.86$.

2. Are high-redshift starbursts just analogues of local ULIRGs or are they a distinct phenomenon only seen in the early universe?

The presence of rest-frame FIR emission (Garrett 2002; Elbaz et al. 2002), the HST images (Giavalisco et al. 2004) and other non-radio data were used for supporting information but not as the primary classification criteria. We were thus able to classify the specific origins of the radio emission in each galaxy, which may be different from the sources of optical and other radiation from the same object. Compact bright peaks with a flat radio spectrum are probably AGN, especially if radio lobes extend beyond the optical limits. Extended emission with a steep non-thermal spectrum is likely to be of starburst origin and in some cases optical knots of starformation can be seen. The latter are often associated with *ISO*, *Spitzer* or SCUBA sources (Serjeant et al. 2003; Borys et al. 2004; Chapman et al. 2005) and with interacting or distorted galaxies in the *HST* images. Figure 1. shows two typical sources. 3 out of every 4 μJy sources are starbursts, including those with X-ray counterparts. Three sources have both starburst and AGN radio characteristics.

2. Changes in the X-ray – radio relationship at high z

55 of the radio sources are among the 100 X-ray sources detected by *Chandra* in the same field (Alexander et al. 2003). A *Chandra* source with luminosity $L_{\rm X} > 10^{37}$ W is probably an AGN. If it has a hard photon index ($\Gamma < 1$), this indicates the presence of an obscured (type-2) AGN (Alexander et al. 2005). 64 type-2 AGN were identified in the 10-arcmin field (Padovani et al. 2004). Over half of the X-ray sources with MERLIN+VLA counterparts have $L_{\rm X} > 10^{35}$ W, 18 of which are classed as type-2 AGN. These are shown by a blue A in

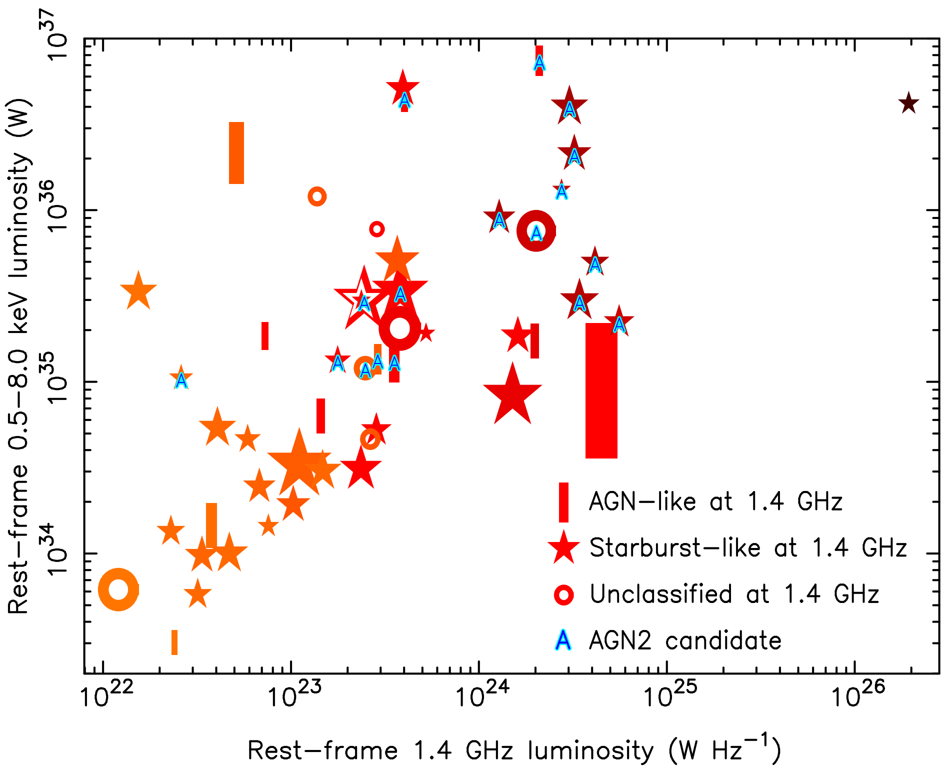

Figure 2. The distribution of the classes of radio-bright sources (see key) with respect to $L_{\rm R}$ and $L_{\rm X}$. The blue '**A**'s represent X-ray selected AGN2. The shade of the symbols is proportional to redshift, the darker sources being further away. Broadly, orange symbols represent $z < 1$; bright red symbols represent $1 < z < 2$ and browner symbols are more distant sources out to $z = 4.424$. The size of the symbols is proportional to the source largest angular size.

Fig. 2. The radio emission is starburst dominated in at least 11 of the radio counterparts. The redshift distribution of radio+X-ray source classifications is shown in Fig. 2.

At $z < 1.1$, under 1/3 X-ray sources in the HDFN have radio counterparts. This rises to over 1/2 at higher redshift and in most of these the high X-ray luminosity indicates the presence of an AGN. The $L_{\rm X} - L_{\rm R}$ relationship for starbursts at $z < 1.3$ (Bauer er al. 2002) breaks down at higher z where we see a dramatic increase in the scatter in Fig. 2. This is the case even if only the soft-band or the de-absorbed hard-band X-ray luminosity is considered.

Half of the 18 X-ray selected type-2 AGN with radio counterparts are at $z > 1.3$, all but one of which are radio starbursts. Two also have radio AGN cores. A large proportion of these objects are SCUBA sources, whose X-ray properties are discussed in detail by (Alexander et al. 2005). All 4 of the radio AGN identified with X-ray type-2 AGN, with no starburst signature, are at lower redshifts. The mean angular size of the radio sources in the HDFN is $1''.3$, corresponding to a typical extent of 8–10 kpc for starbursts and the inferred starformation rates are 1000–2000 $M_\odot$ yr^{-1} for the higher-redshift sources. This is an order of magnitude more exended and more vigourous than the behaviour of any objects at $z < 1$.

3. Conclusions

At $z > 1.3$, there is a strong association between the presence, but not the power, of faint radio and X-ray emission. The extended radio emission is starburst-dominated in 3/4 of the objects (Muxlow et al. 2005) whilst 18 of the X-ray sources are hard enough and bright enough to be AGN2 (Padovani et al. 2004). 11 of these X-ray AGN2 have radio starburst characteristics. Their radio emission mechanisms must be dominated by star-formation whilst the AGN provides most of the X-ray luminosity. The high-z population of μJy radio sources contains a significant fraction of starbursts an order of magnitude more active and more extended than local ULIRGS, and they simultaneously host highly X-ray-luminous obscured AGN.

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