High Resolution Radio Imaging of Distant Submillimeter Galaxies

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Abstract. Using a combination of radio and optical imaging at 0.1″ to 0.2″ resolution with the VLA/MERLIN and HST has led to a breakthrough in our understanding of radio emission from distant (0.1 < z < 3) starburst galaxies. We have recently isolated a number of high redshift, dusty starburst galaxies that remain invisible in ground based images to $I_{AB}=25$ and $I_{AB}=28.5$ in the Hubble Deep Field. These galaxies appear as faint radio sources, often accompanied by very red counterparts ($I-K > 4-6$) and submillimeter sources with $S > 2$ mJy at 850 microns as measured with SCUBA on the JCMT. The far-infrared luminosities of these galaxies exceed even the most intense starbursts found in the local universe (e.g., Arp 220), suggesting they are in the process of converting the bulk of their gas mass into stars.

These galaxies, completely absent in optical surveys, constitute 50%-90% of the star-formation density in the distant Universe. Given the poor sub-mm resolution (15″) of the SCUBA/JCMT images, we use the 0.2″ radio imaging as a surrogate in order to understand the nature of the dominant emission mechanism driving the FIR luminosity (AGN vs. star-formation). Upcoming developments in radio instrumentation (the Expanded VLA Array and Square Kilometer Array) will soon increase sensitivity and resolution orders of magnitude, providing a natural complement to parallel developments in sub-mm facilities (e.g., ALMA). With dual radio continuum and sub-mm surveys of the distant Universe, a census of galaxy evolution to the earliest cosmic epochs ($z = 5-30$) will soon be possible.

Radio Emission from Distant Galaxies in the HDF

The diffuse radio emission observed in local starbursts is believed to be a mixture of synchrotron radiation (excited by supernovae remnants and hence directly proportional to the number of supernovae producing stars) and thermal radiation (from HII regions and hence an indicator of the number of O and B stars in a galaxy). As the thermal and synchrotron radiation of a starburst dissipates on a physical time scale of $10^7 - 10^8$ years, the radio luminosity is a true measure of the instantaneous star-formation rate (SFR) in a galaxy, uncontaminated by older stellar populations. Since supernovae progenitors are dominated by $\sim 8 M_\odot$ stars, synchrotron radiation has the additional advantage of being less sensitive to uncertainties in the initial mass function as opposed to UV and optical recombination line emission. However, the most obvious advantage of using the radio luminosity as a SFR tracer is its unsusceptibility to dust obscuration,
as galaxies and the inter-galactic medium are transparent at centimeter wave-lengths. The strong correlation between far-infrared and radio emission from local star-forming galaxies suggests that radio emission from distant, dust obscured galaxies should be visible at the microjansky level for luminous starbursts at redshifts less than 3-4.

We have recently completed a deep radio survey of the Hubble Deep Field using both the Multi-Element Microwave Linked Interferometer (MERLIN) and the Very Large Array (VLA) at 1.4 and 8.5 GHz (Richards et al. 1998, AJ, 116, 1039; Richards 1999a, ApJL, 511, 1; Richards 1999b, ApJ, 2000, in press, astro-ph/9908313; Muxlow et al. 2000, in prep.) in order to study the nature of microjansky radio galaxies, and in particular understand their implication for galaxy evolution at early epochs. The optical identifications of the 72 radio sources detected in a complete sample \( S_{1.4} \geq 40 \mu Jy \) or \( 6\sigma \) on the HST images in the HDF and flanking fields show that:

1. 70\( \pm 10\% \) of the optical identifications are associated with morphologically peculiar, merging and/or interacting galaxies, many with independent evidence for active star-formation (blue colors, infra-red excess, HII-like emission spectra).

2. The remaining identifications are composed of low-luminosity FR Is, Seyferts, LINERs, and luminous star-forming field spirals at low redshift (representative identifications are shown in Figure 1).

3. The radio spectral indices are in general steep \( (\alpha > 0.5 ; S \propto \nu^{-\alpha}) \) and the median radio angular size about 1-1.5'\( '' \), indicative of diffuse synchrotron emission in \( z = 0.2 - 1.3 \) galactic disks.

4. 20\% of the radio sources cannot be identified to \( I_{AB} = 25 \) in deep ground based images and to \( I_{AB} = 28.5 \) in the HDF itself. These radio sources are likely distant, extreme starburst systems enshrouded in dust. This 'new' population is discussed in more detail in Richards et al. (1999, ApJ, in press, astro-ph/9909251) and one source in particular, observed with HST-NICMOS by Waddington et al. (1999, ApJ, in press, astro-ph/9910069). Similar radio sources have recently been reported in the HDF-S (Norris et al. 1999, astro-ph/9910437).

Thus the cosmological faint radio population is dominated by the distant analogs of local IRAS galaxies with suggested star-formation rates of 10-1000 \( M_\odot \) yr\(^{-1}\). In principle this radio selected starburst population allows for a derivation of the star-formation history, independent of optical selection biases.

Detection of Distant Ultraluminous Radio Selected Starburst Galaxies

In March and June 1999, we obtained shallow JCMT/SCUBA images of 14 optically faint radio sources in the Hubble Flanking fields. We detected 5 of these sources above 6 mJy at 850 \( \mu m \). None of the 32 lower redshift \( (0.2 < z < 1.3) \) radio sources in our field of view were detected. Comparison of our source counts with those from previous sub-mm surveys (Eales et al. 1999; Hughes et al. 1999; Barger, Cowie & Sanders 1999), shows that our radio selection technique recovers essentially all of the bright \( S_{850} \geq 6 \) mJy sub-mm sources.
Thus there is an almost one-to-one correspondence between the bright sub-mm sky and the optically invisible microjansky radio sources ($S_{1.4} \gtrsim 40 \, \mu\text{Jy}$).

Based on the far-infrared to radio flux relationship observed in local starburst galaxies such as Arp 220, we modeled the redshifts of these optically faint, radio/sub-mm galaxies and found they likely lie at $1 \lesssim z \lesssim 3$ (Carilli & Yun 1999, ApJL, 1999, 513, 13). We can use the sub-mm flux alone to estimate the overall luminosity, only weakly dependent on redshift because of the offsetting effects of far-IR spectral index and cosmological dimming. These values imply we are detecting ultraluminous infrared galaxies with $10^{12-13}L_{\odot}$, substantially more luminous than Arp 220. In the volume probed by our survey between $1 \lesssim z \lesssim 3$, this corresponds to a volume averaged star-formation rate of $0.4 \, M_{\odot} / \text{yr}/\text{Mpc}^3$, equivalent to the dust corrected optical value obtained by Steidel et al. (1999, ApJ, 519, 1). Thus optically 'invisible' objects form an important constituent of the $z > 1$ star-formation history, as shown by Barger, Cowie and Richards (1999, AJ submitted). These high redshift radio selected starburst galaxies are completely missing from the optical samples, implying that optical surveys give a biased view of the distant star-forming Universe.

Our low redshift ($0.1 < z < 1.3$) sample contains important information on the star-formation history as well. Based on the optical identifications in our deepest radio surveys, we have attempted to make a first guess of the radio determined star-formation history. We use both the radio properties, such as spectral index and morphology, as well as the optical morphology provided by HST images to cull a clean sample of star-forming systems (Richards et al. 1998; Richards 1999b; Haarsma et al. 1999). Our preliminary results are in general agreement with the dust corrected estimates of Steidel et al., although systematically higher at all redshifts. We interpret this as evidence of missing star-formation is the optical studies due to underestimates of the dust extinction. We cannot completely rule out the possibility that our radio samples have some contamination by low-luminosity AGN (i.e., Seyferts) which could also bring the radio and optical surveys into better agreement.

Deeper high resolution radio observations, with complete spectroscopic coverage are needed to reveal the amount of 'hidden' star-formation in the distant Universe. Only by combining, optical, radio, and far-infrared/sub-mm measurements of distant galaxies can a reliable consensus of their star-forming properties be obtained.

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**Figure Caption 1:**
Montage of radio/HST flanking field overlays. Contours are 1.4 GHz fluxes drawn at 2, 4, 8, 16, 32, 64 $\sigma$ ($\sigma = 4 \, \mu\text{Jy}$). Greyscale is log stretch of HST I-band image 5'' on a side. **Upper Left:** $I = 19.5$ elliptical with weak radio AGN core at $z = 0.32$. Twenty percent of the IDs are AGNs. **Upper Right:** $I = 21.1$ disk galaxy is at $z = 0.96$ with a flat radio spectral index ($\alpha = 0.2$). The optical spectra shows broad high excitation lines, suggesting the presence of a Seyfert core. **Lower Left:** A dramatic $z = 0.5$ merger with a starburst
core. This galaxy has about 1/3 the luminosity of Arp 220. About 60% of the radio IDs are of this variety. A rather bright $I = 18.3$ mag disk galaxy with an unusually steep radio spectrum of $\alpha > 1.6$. There is no known star-forming, or spiral galaxy in the local Universe with such a steep non-thermal spectrum. About 10% of the radio sources fit into this ultrastEEP class.
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