A Radio Perspective on Star-Formation in Distant Galaxies

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Abstract.
Determination of the epoch dependent star-formation rate of field galaxies is one of the principal goals of modern observational cosmology. Deep radio surveys, sensitive to starbursts out to $z \sim 1-2$, may hold the key to understanding the evolution of the starburst phenomenon unhindered by the effects of dust. Using deep, high resolution radio observations of the Hubble Deep Field, we show that the $\mu$Jy radio emission from field galaxies at $z \sim 0.4 - 1$ is primarily starburst in origin. In addition, we have discovered a population of optically faint, possibly obscured systems that are candidate high-$z$ protogalaxies. At least one of these radio sources is identified with a sub-mm detection.

RADIO EMISSION AS A STAR FORMATION TRACER

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 wavelengths.

Comparison of the local radio luminosity function (LF) of star-forming galaxies [1] with those derived independently at FIR [2], H$\alpha$ [3], and UV wavelengths [4] shows surprising agreement. Figure 1 shows the four LFs in units of SFRs. This plot suggests that the bulk of local star formation is occurring in modest starbursts with SFR $\sim 10$ $M_\odot$ yr$^{-1}$. However, past the peak in the LF, the H$\alpha$ and UV estimates begin to drop below the radio/FIR rates, and beyond 50 $M_\odot$ yr$^{-1}$ has entirely vanished. This is direct evidence that optically selected surveys are incapable of detecting the most extreme and dust obscured starbursts.
FIGURE 1. Shown is the contribution to the local star-formation luminosity density ($u$) per luminosity interval of star-forming galaxy. The radio, IRAS, Hα, and far-ultraviolet (FUV) luminosities have been converted to SFRs assuming a Salpeter IMF over 0.1-100 $M_\odot$. Notice that the four measures of SFRs all peak at $\sim 10$ $M_\odot$ yr$^{-1}$ (see Cramm, ApJL, 506, 85 for a fuller discussion). The radio and IRAS points are in particularly good agreement, reflecting the tight FIR/radio correlation in star-forming galaxies. The shaded region represents what may be a dust curtain beyond which optical surveys are blind to star formation. If the SFR luminosity function evolves as $L \propto (1 + z)^{3.5}$, then by $z = 1$, it will appear as the solid line. This analysis suggests that the bulk of global star-formation at high $-z$ is hidden from optical surveys.

RADIO EMISSION FROM DISTANT GALAXIES

Our 1.4/8.5 GHz study of the Hubble Deep Field using the VLA and MERLIN has demonstrated that 70% of $\mu$Jy sources are identified with morphologically peculiar, merging and/or interacting disk galaxies, many with independent evidence of star-formation (blue colors, infra-red excess, HII optical spectra) [5] [6]. Radio morphologies from the high resolution VLA/MERLIN observations of the HDF [7] indicate that 95% of $\mu$Jy radio sources are resolved at 0.2″ resolution and suggests a median size of 2″, comparable to the optical extent of these $z \sim 0.4 - 1$ systems. These data exclude AGN as the dominant contributor to the radio luminosity in the majority of these systems. 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$^{-1}$.

We have detected over 100 radio sources in complete samples within 4.5′ of the HDF where deep optical imaging is available. Ninety percent of these radio sources are identified with galaxies of mean magnitude $I_{AB} \sim 22$. However, approximately 10% remain unidentified to $I_{AB} = 28$ in the HDF and $I_{AB} = 26$ in the HDF flanking
FIGURE 2. The greyscale shows a $20'' \times 20''$ HDF I-band image containing the SCUBA detection HDF850.1. The contours correspond to 1.4 GHz emission at the -2, 2, 4 and 6 $\sigma$ level ($\sigma = 7.5$ $\mu$Jy). The three sigma position error circle for HDF850.1 is shown after shifting to the VLA coordinate frame. The original position of HDF850.1 taken from Hughes et al. (1998) is denoted by the diamond. The ISO detection is marked with a cross with three sigma position errors (Aussel et al. 1998, A & A in press). The 0.1$''$ radio/optical registration clearly rules out association with the bright spiral. VLA3649+1221 may be the most obscured part of a larger galaxy 3-633.1 at $z = 1.72$ (located directly underneath the SCUBA error circle; Fernandez-Soto et al. 1998, AJ in press).
FIGURE 3. Radio 1.4 GHz contours drawn at the -2, 2, 4 and 6 $\sigma$ level are overlaid on the HDF I-band image centered on the position of HDF850.4 (20$''$ on a side). A 15 $\mu$m detection from the complete catalog of Aussel et al. (1998) has been associated with this radio source and suggests likely starburst activity in the disk galaxy. The symbols are the same as for Figure 2. We estimate a SFR = 150 $M_\odot$ yr$^{-1}$.

formation rate are premature. On the other hand, the $z < 1$ star-formation history may have been underestimated if a significant fraction of the sub-mm population lies at relatively low redshift, in agreement with the large number of $z = 0.4-1$ radio starbursts we are finding in the HDF. Analysis of the evolving radio star-forming luminosity function promises to shed light on the prevalence of dust enshrouded starburst activity at high $- z$ (see Haarsma & Partridge, elsewhere in these proceedings).

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