VLA Up-Grade Science Discussion November 19 1998
Studying Star Forming Galaxies at High Redshift

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The presence of dust at high redshift leads to a bias in optical studies against the dense, dusty stages of star formation in high z galaxies. Current optical estimates of the cosmic star formation rate may under-estimate the total at $z > 1$ by a factor three or more due to this dust bias (Figure 1), based on submm source counts, sub-mJy radio source counts, and ISO source counts (Flores et al. 1998, Hughes et al. 1998, and Cram et al. 1998). Much of this star formation may take place in massive starbursts, with star formation rates ≥ 100 $M_\odot$ year^{-1} (Eales et al. 1998). The situation is analogous to studies of Galactic star forming regions, in which the early stages of the star formation process can be studied only by the radio through far IR observations.

Studying dusty, star forming galaxies at high redshift is one of the main science drivers for NGST, SIRTF, SKA, and the MMA. The VLA upgrade will provide critical, complimentary information on high redshift star forming galaxies out to $z \approx 6$, such as:

- study of the non-thermal radio continuum associated with star formation
- identification of a possible AGN component in some cases
- sub-arcsecond astrometry, thereby facilitating source identification
- sub-arcsecond resolution imaging for studying the distribution of star formation in early galaxies

Moreover, the VLA upgrade could play a unique role in identifying star forming galaxies at $z > 10$, and in deriving a dust-unbiased measure of the cosmic star formation rate to redshifts beyond the reach of optical telescopes due to the Ly break, but within the reach of the planned NGST.

Continuum Observations: Synchrotron emission and the radio-to-far IR correlation – the Condon relations (1 GHz to 10 GHz in the source frame).

The VLA upgrade will allow for study of the non-thermal synchrotron radio continuum emission from 'normal' galaxies (10 $M_\odot$ year^{-1}) to $z = 3$, and ULIRGs (≥ 100 $M_\odot$ year^{-1}) to $z = 5$ (Figure 2). This is complimentary to the optical telescopes, which study the star light from such galaxies, and to the MMA, which will delineate the thermal continuum emission from warm dust and the molecular line emission. The synchrotron continuum emission provides an empirical estimate of massive star formation rate, through the radio-to-far IR correlation (Condon 1992). Polarized radio continuum observations also allow for the study the morphology and strength of interstellar magnetic fields in these galaxies. The sub-arcsecond resolution provided by the VLA provides accurate positions, facilitating follow-up optical and IR identification of faint sources, and the unique capability to image the spatial distribution of star formation in early galaxies on sub-kpc scales.

Radio continuum observations could also help to determine the evolution of the AGN contribution to the energy budget in galaxies as a function of redshift.

A radio loud AGN can be identified both by departures from the radio-to-far IR correlation, and by high resolution imaging of the radio continuum emission.

Another important tool for studying high z galaxies with the VLA upgrade and the MMA will be to obtain redshift estimates from the cm-to-mm spectral indices of faint sources (figures 3 and 4) . The sharp rise in the the Raleigh-Jeans portion of the thermal dust spectrum shifting into the submm bands with increasing redshift implies that the observed spectral index between radio and submm frequencies should evolve strongly with redshift (Carilli and Yun 1998, Hughes et al. 1998), giving rise to the possibility of using the radio-to-submm spectral index as a redshift indicator for star forming galaxies. The upgraded VLA, working in concert with the MMA, will provide samples of high redshift galaxy candidates, which can then be studied with the NGST.

Continuum Observations: Thermal free-free emission (50 GHz to 150 GHz in the source frame):

Detecting thermal (free-free) emission from star forming galaxies at high redshift provides a direct estimate of the massive star formation rate, plus estimates of physical conditions in the star forming regions. One problem with such an observation is separating the non-thermal, thermal free-free, and thermal dust emission in these sources. Below 30 GHz non-thermal synchrotron emission is thought to dominate the emission from star forming galaxies, while above 130 GHz thermal dust emission dominates. Between 30 GHz and 180 GHz, the free-free emission should be the dominant emission component. The strength of the free-free emission could be estimated by multifrequency radio continuum observations from 10 GHz up to 43 GHz. The sensitivity of the upgraded VLA is 0.3 μJy at 33 GHz in 200 hrs. The expected free-free emission from galaxies with star formation rates of 100 $M_\odot$ year^{-1} at z = 2 is about 5 μJy at an observing frequency of 33 GHz.

Continuum Observations: Thermal dust emission ($\geq$ 350 GHz in the source frame).

The next generation optical/IR space and ground based telescopes have set a goal of study galaxies in the universe out to, and perhaps beyond, z = 10. The up-graded VLA could play a fundamental role in such studies by imaging the thermal dust emission emission from z $\geq$ 10 galaxies. This would provide a direct estimate of the massive star formation rates in high z galaxies. The sensitivity of the upgraded VLA in 200 hrs is about 0.5 μJy at 43 GHz. The expected flux density of sources at z $\geq$ 10 with massive star formation rates of 100 $M_\odot$ year^{-1} is $\geq$ 3 μJy in 200 hrs (Figure 5). Note that the 'negative K-correction' for the dust emissivity spectrum more than off-sets the distance losses in this redshift range for an observing frequency of 43 GHz, such that sources at z $\geq$ 10 are significantly brighter than sources at z = 4.

Carilli and Yun 1998, Ap.J. (letters), submitted
Condon, J.J. 1992, ARAA, 30, 575
Cram et al. 1998, Ap.J., 508, 155
Flores et al. 1998, Ap.J., in press
Hughes et al 1998, Nature, 394, 241
Eales et al. 1998, Ap.J., in press

Figure 15 ; Flores et al. 1998

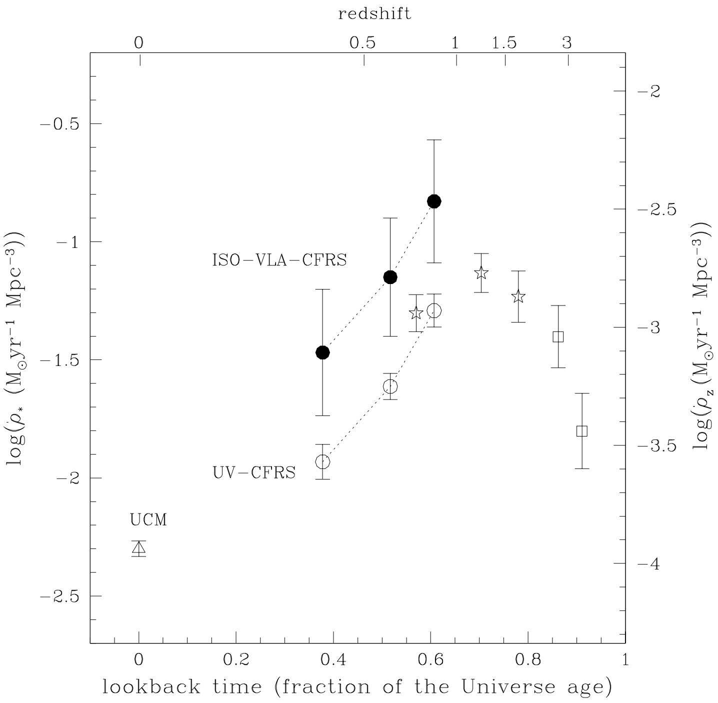

Fig. 15.— Metal production and star formation history for $z \leq 1$ (see text). Our points (filled circles, labeled ISO-VLA-CFRS) are 2.9 times higher in SFR density or in metal production than those (open circles) previously derived from the UV flux density at 2800Å. Other points are from Gallego *et al.* (1995, open triangle), Connolly*et al* (1997) (open stars), Madau *et al.* (1998, HDF) (open squares), and have not been corrected for extinction.

Figure 1. from Flores et al. 1998

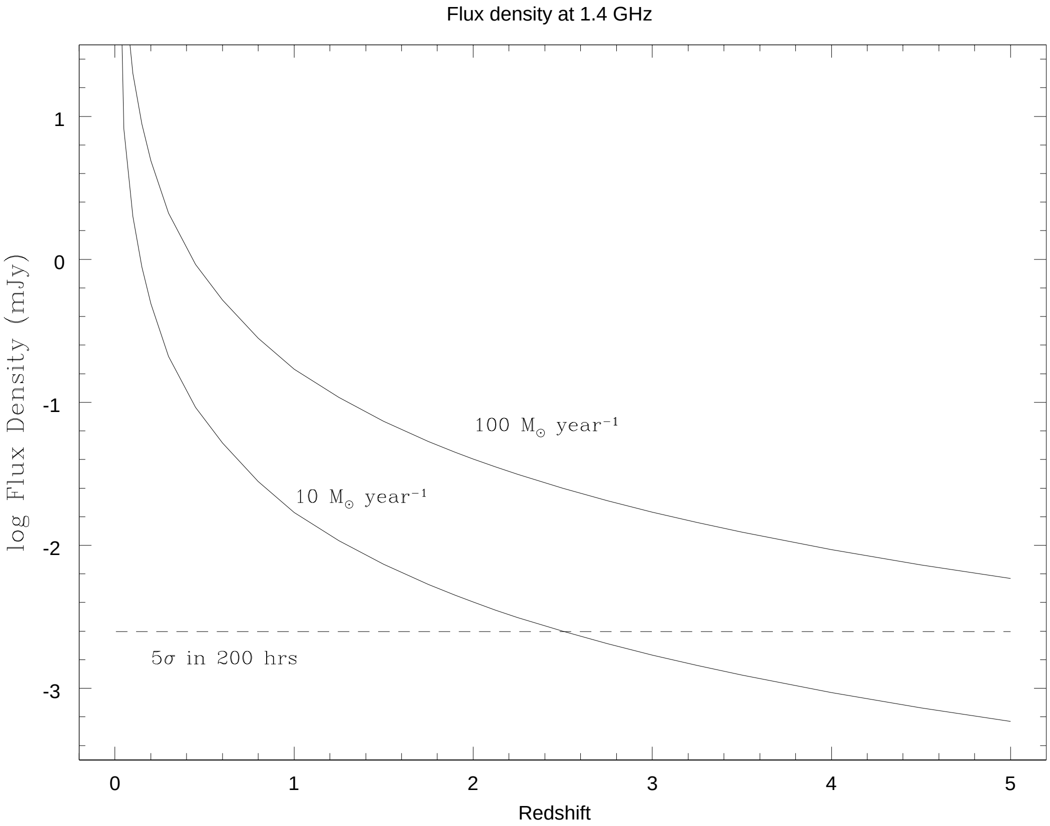

Figure 2. The solid lines show the expected flux density at an observing frequency of 1.4 GHz of star forming galaxies as a function of redshift. The dash line is the expected 5σ limit of the VLA at 1.4 GHz in 200 hrs. Note that in-beam source confusion in the A and B arrays is more than an order of magnitude below this limit.

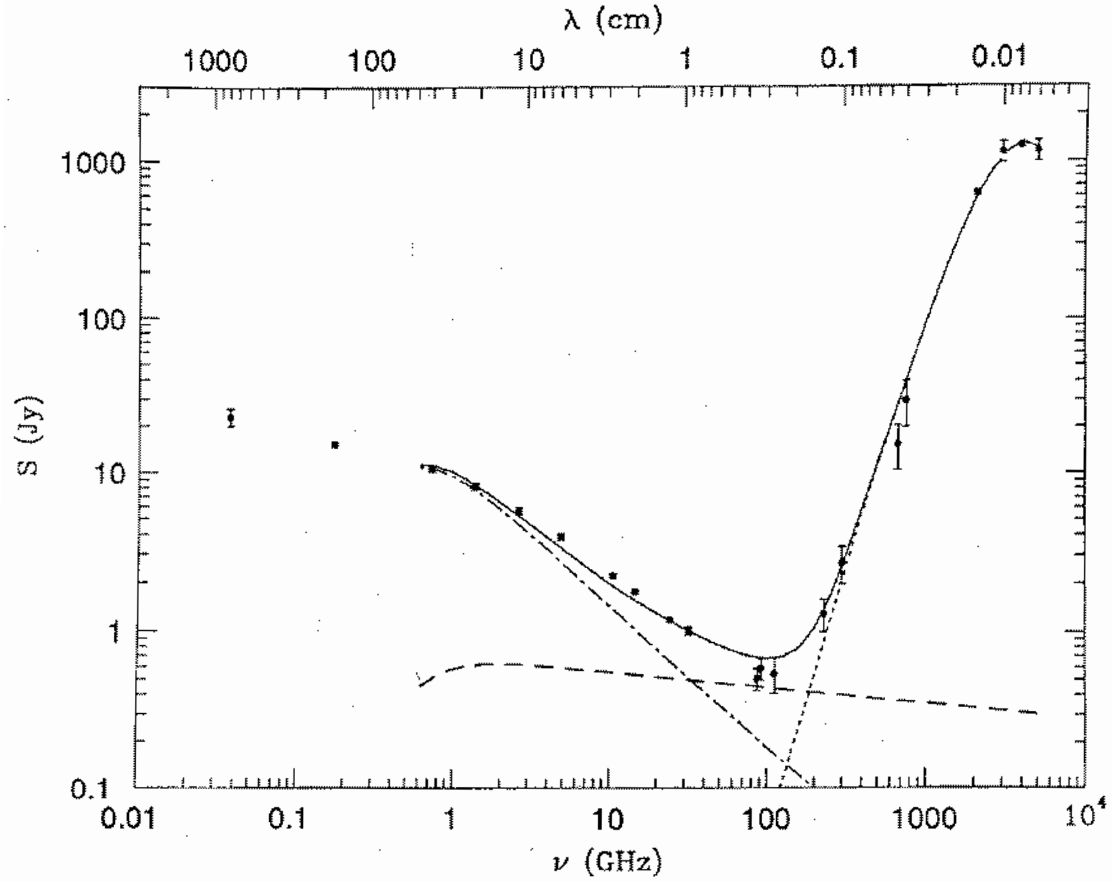

Figure 3. The spectrum of the star forming galaxy M82 at a distance of 3 Mpc, with a star formation rate of about 10 $M_\odot$ yera^{-1} (from Condon 1992). The long dash line is the free-free emission, the dash-dot line is the synchrotron emission, and the short dash line is the thermal dust emission.

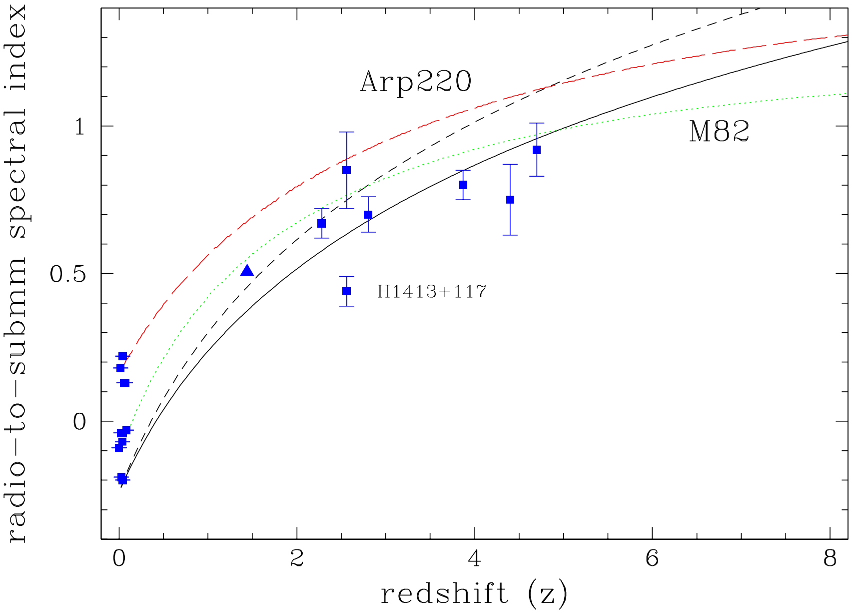

Figure 4. Two power-law models (Carilli and Yun 1998) for the 1.4 GHz to 350 GHz spectral index, $\alpha_{1.4}^{350}$, for star forming galaxies as a function of redshift are shown with a solid curve ($\alpha_{\rm submm} = +3.0$) and a short dashed curve ($\alpha_{\rm submm} = +3.5$). These models are based on semi-analytic expressions for star forming galaxies derived using the radio-to-far IR correlation as quantified by Condon (1992). The assumed radio spectral index is -0.8. The dotted and long-dashed curves show the expected values of $\alpha_{1.4}^{350}$ versus redshift based on the observed spectra of the star forming galaxies M82 and Arp 220, respectively. Also plotted in filled squares are the submm data for the low redshift galaxies from a survey of nearby active star forming galaxies using the JCMT (Hughes et al. 1990, Rigopoulou et al. 1996) and the submm data for the $z > 1$ sources are from Rowan-Robinson et al. (1993), Isaak et al. (1994), Barvainis et al. (1995), Omont et al. (1996b), Ivison et al. (1998ab), Lewis et al. (1998), and Kawabe et al. (1998). The filled triangle marks the 3σ lower limit for the z=1.44 galaxy HR10 (Dey et al. 1998). All the radio data are from the Very Large Array. Overall, the models appear to define (within the errors) the range in observed values of $\alpha_{1.4}^{350}$ as a function of redshift. In particular, the galaxies at $z > 1.5$ have $\alpha_{1.4}^{350}$ values $\geq +0.5$, while the low redshift galaxies have $\alpha_{1.4}^{350}$ values $\leq +0.2$.

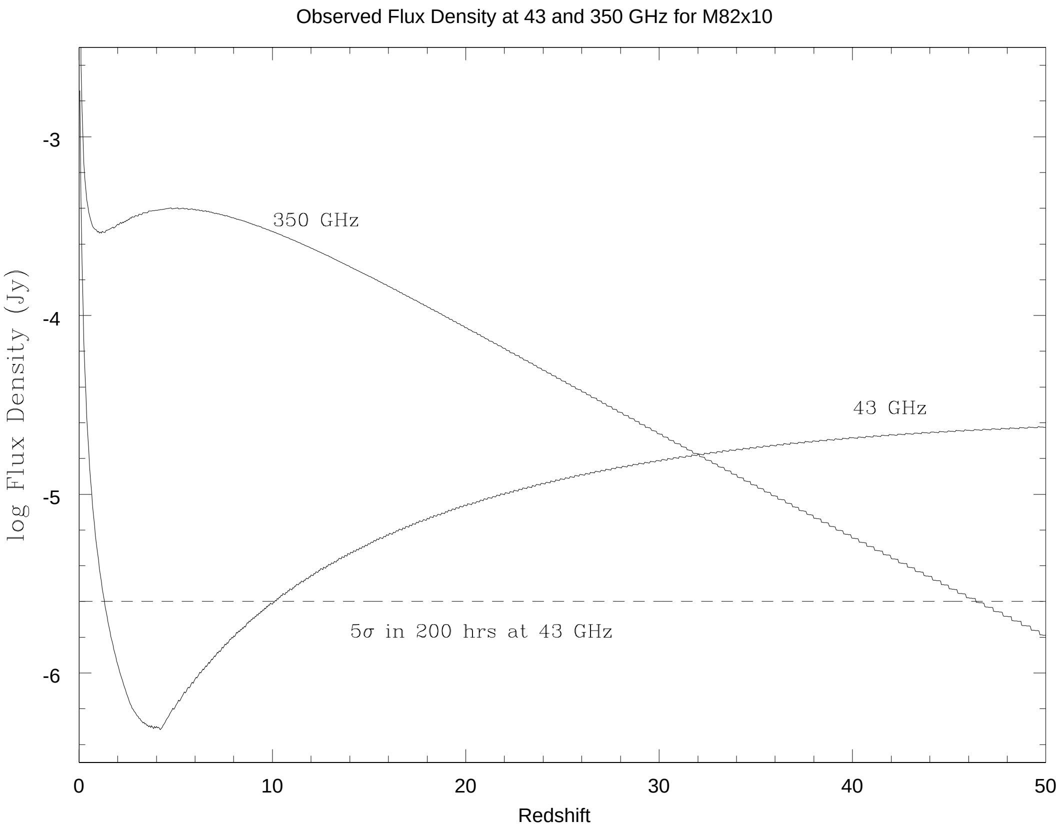

Figure 5. The solid lines show the expected flux density of a galaxy with a star formation rate 10 times that of M82 (ie. comparable to Arp 220) as a function of redshift, at observing frequencies of 43 GHz and 350 GHz. The rise in the flux density with distance (‘inverse