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ALMA: GALAXIES AND AGN

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ABSTRACT

With the ability to see into optically obscured regions with more than an order of magnitude better sensitivity and spatial resolution relative to current (sub)mm telescopes, ALMA will provide a unique look into the physics of galaxy formation and active galactic nuclei. In this paper I summarize the ALMA potential for studying star forming galaxies and active galactic nuclei from the nearby universe to the epoch of formation of the first luminous objects.

Key words: galaxies: radio, mm, IR; AGN.

1. INTRODUCTION

Studies of the cosmic 'background' radiation at optical through far infrared wavelengths show two peaks of roughly equal power (Franceschini 2001). This background is not a true (ie. diffuse) background, like the CMB, but arises from the summed light from galaxies throughout the universe. The optical peak corresponds to direct starlight, while the peak in the FIR corresponds to star light that has been reprocessed by dust. While such 'background' calculations compress a tremendous amount of information, the basic fact that the FIR and optical peaks are of similar strength implies that roughly half the star light in the universe is absorbed by dust and re-emitted in the infrared.

Far-IR through radio telescopes have the ability to see through the dust in galaxies, into the regions of most active star formation. An excellent example of the affect of dust on our view of 'galaxy formation' in the nearby universe is the galaxy IC 342 at a distance of 2 Mpc. Figure 1 shows an overlay of the optical, mm continuum, and CO emission from IC 342 (Meier & Turner 2004). The optical emission is dominated by a young star cluster at the galaxy center. However, the mm continuum (corresponding to thermal emission from warm dust) and molecular gas emission both peak at the ends of the inner bar, indicating the sites of most active star formation. These regions are highly obscured by dust in the optical.

Moving to high redshift, perhaps the best example of dust-obscured galaxy formation is the brightest submm galaxy in the Hubble Deep Field – HDF850.1 (Hughes et al. 1998; Downes et al. 1999). Figure 2 shows the overlay of the optical and mm images of this field. Accurate radio interferometry has shown that there is no optical counterpart to HDF 850.1 down to the limit of the HDF. Subsequent imaging in the near-IR has found a faint, red source (K = 23.5; I-K > 5.2) at the radio/mm position, likely corresponding to a $z > 3$ star forming galaxy (Dunlop et al. 2004). If so, the intrinsic IR luminosity is $\sim 7 \times 10^{12}$ $L_\odot$, with a star formation rate of a few thousand $M_\odot$ year^{-1}. Perhaps most impressively, this single source (as opposed to 10^4 optical galaxies) could potentially dominate the cosmic star formation rate density at $z > 2$ in the HDF (Hughes et al. 1998).

A complementary viewpoint of the affect of dust on our understanding of galaxy formation at high redshift is the study by Adelberger (2001) of the UV through IR SEDs of high redshift galaxies. He finds that selection at rest frame uv wavelengths (ie. uv-dropouts or Ly-break galaxies) is a very sensitive means of finding high redshift galaxies, to well below L_*. However, he finds little correlation between uv luminosity and bolometric luminosity. In other words, the higher luminosity galaxies are also more heavily dust-obscured, such that, while uv selection may find most of the star forming galaxies at high redshift, the presence of dust complicates the physical analysis of the cosmic star formation rate from uv selected samples.

2. ENABLING TECHNOLOGIES

Telescopes such as ALMA and Herschel are being designed to study dust obscured galaxy formation throughout the cosmos. What are the principle technological advances for ALMA that will lead to major advances in the study of galaxy formation?

The most important advance for ALMA will be the two orders of magnitude increase in sensitivity over existing mm arrays. Figure 3 shows the continuum spectrum of the active star forming galaxy Arp 220 in

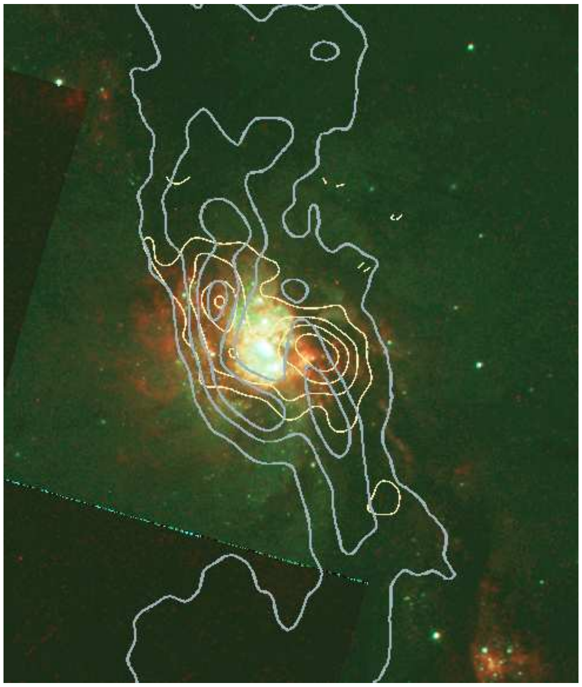

Figure 1. Images of IC342 in the optical (color), CO 1-0 (grey contours), and mm continuum (white contours; from Meiers & Turner 2004). The mm continuum peaks indicate the regions of most active star formation, at the ends of the inner bar, are optically obscured.

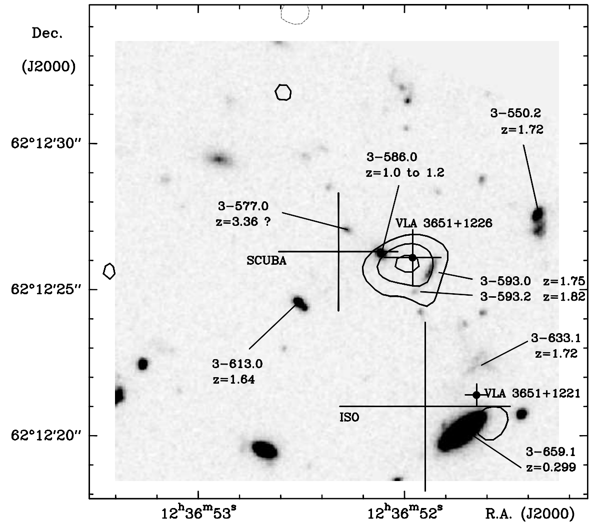

Figure 2. The contours show the PdBI image of the brightest (sub)mm source in the Hubble Deep Field, HDF850.1 (Downes et al. 1999), and the greyscale is the HST image. Accurate astrometry shows that the submm source has no optical counterpart to the depth of the HDF.

the radio through IR range, redshifted to z=2,5, and 8. Also shown are the sensitivities of some current, or near-term, instruments, as well as ALMA. Current mm arrays such as the Plateau de Bure interferometer and CARMA can, and have, detected ultraluminous infrared galaxies (ULIRGs, $L_{IR} > 10^{12}$ or star formation rates > a few hundred $M_\odot$ year^{-1}) to very high redshifts, assisted by the large 'inverse-K' correction on the Rayleigh-Jeans side of the dust spectrum. This large inverse-K correction can be seen in the submm part of the spectrum in Fig. 3, where the flux density of Arp 220 at a fixed observing wavelength is roughly constant for redshifts from 0.5 to 8. Such ULIRGs are rare in the nearby universe, and are certainly not representative of what may be the normal star forming galaxy population at high redshift, such as the Ly-break galaxies, for which star formation rates are typically well below 100 $M_\odot$ year^{-1} (Adelberger 2001). The radical increase in sensitivity afforded by ALMA will enable study of even dwarf starbursts ($\sim$ 10 $M_\odot$ year^{-1}) out to extreme redshifts.

Figure 3 also shows the complementarity of ALMA with planned facilities at other wavebands, such as the Square Kilomter Array and the JWST. Future instruments will provide a pan-chromatic view of star forming galaxies to extreme redshifts, into the epoch of 'first light' in the universe (see section 5). Each of these wavebands provides unique probes of the galaxy formation process, from the non-thermal emission from star forming galaxies and AGN at cm wavelengths, through the dust and molecular gas at mm and submm wavelengths, to the stars, ionized gas, and AGN in the near-IR.

The second enabling technology for studying galaxy formation with ALMA is the nearly two orders of magnitude improvement in spatial resolution over existing connected-element mm arrays. Figure 4 shows the 'Walker diagram' of angular resolution vs. frequency for cm and mm arrays. ALMA will provide a resolution down to 10's of milliarcsecs at 100's GHz, with brightness temperature sensitivity below 1 K. This increase will reveal star formation on scales of Giant Molecular Clouds (GMCs) out to 200 Mpc distances.

3. SOME CURRENT EXAMPLES AND WHERE ALMA WILL TAKE US

3.1. Nearby galaxies

Consider the recent 'state-of-the-art' multi-transition study of molecular gas in the very nearby star forming galaxy IC342 by Meier and Turner (2004). Through detailed studies of both low and high density gas tracers, as well as other physical diagnostics such as photodissociation region tracers, they were able to delinate the complex star formation processes throughout the disk, bar, and nucleus of IC342 down to GMC scales. These processes include dense gas associated with the most active star forming regions at the ends of the inner bar, as traced by eg. HC_3N emission, and PDR regions associated with the central star cluster, as traced by C_2H.

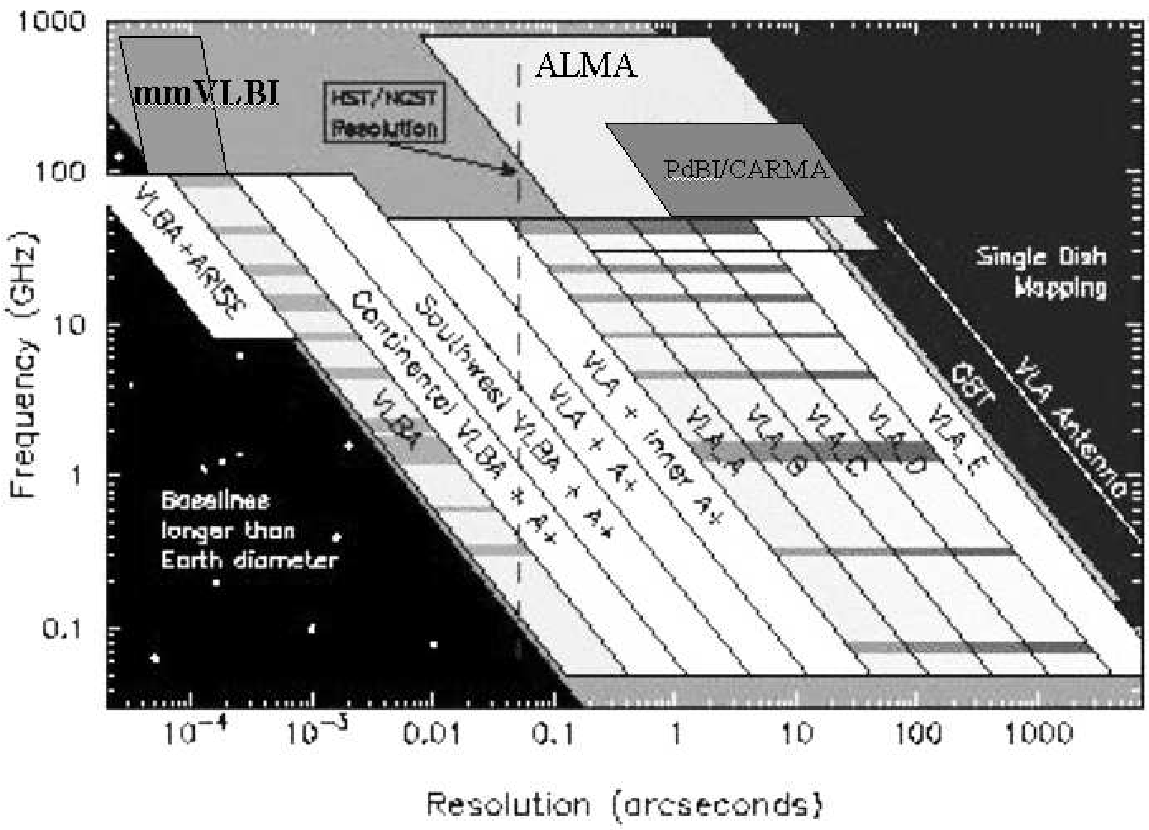

Figure 4. The 'Walker' diagram of resolution vs. frequency for current and future radio and mm telescopes.

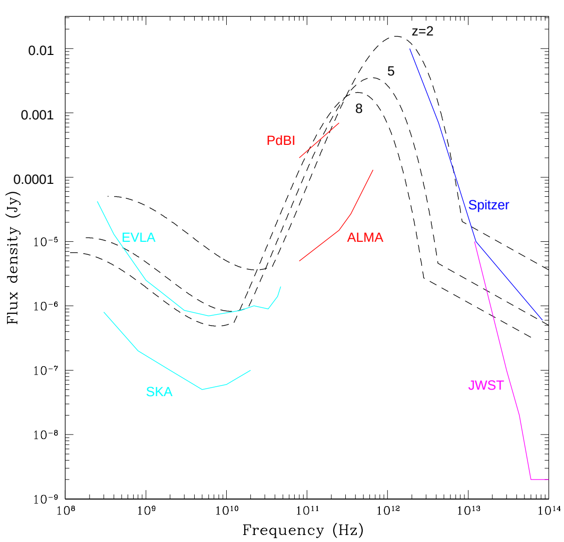

Figure 3. The dash lines show the spectrum of the active star forming galaxy Arp 220 ($L_{FIR} = 1.3 \times 10^{12}$ $L_\odot$) at three redshifts ($z = 2$, 5, 8). The solid lines show the rms sensitivity of current and future instruments (in one transit) at cm through near-IR wavelengths.

Similarly telling probes of gas dynamics on GMC scales in galaxies have been obtained by Schinnerer et al. (2004) in NGC 6946 at 5.5 Mpc distance. These PdBI observations of CO 2-1 emission at 0.5″ resolution show clear signatures of changing gas dynamics, and likely nuclear gas 'feeding', in the inner 10's of parsecs.

The important point is that these studies require physical resolutions on scales of GMCs, and currently we are limited to galaxies not far beyind the local group (< few Mpc). ALMA will provide the resolution and sensitivity to extend these studies out to 200 Mpc distance, encompassing rich clusters such as Virgo and Coma, as well as extreme starburst galaxies, such as Arp 220 and MRK 273, and luminous AGN, such as Cygnus A, M87, and MRK 231.

3.2. High redshift galaxies

Studies of the evolution with redshift of the cosmic star formation rate density (eg. Blain et al. 2002) show a peak in the range $z = 1.5$ to 3. One of the unanswered questions in this regard is the effect of dust on this critical inventory of galaxy formation. Unfortunately, current submm observations are limited to only the most extreme systems at these distances (Fig 3). ALMA will push down to flux densities of 10's of μJy, ie. to normal star forming galaxies at high redshift (star formation rates $\sim$ 10's $M_\odot$

year^{-1}), with sufficient resolution to avoid confusion limits that plague single dish observations (Figure 5). At this level the (sub)mm source counts are comparable to the optical galaxy density observed in the HDF (few$\times 10^6$ deg^2). The key point is that deep ALMA and optical surveys are clearly complementary, with optical surveys dominated by galaxies at lower redshift ($z \leq 1$), and ALMA surveys revealing dusty star forming galaxies at higher redshift ($z > 1$).

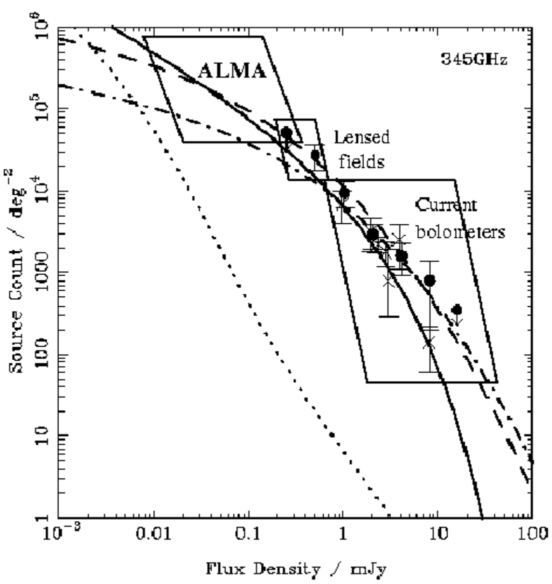

Figure 5. Source counts at 350 GHz (from Blain et al. 2002).

In terms of molecular line studies, Cox (this volume) summarizes the current situation for CO observations of low and high redshift galaxies. He shows the clear correlation between FIR luminosity and CO luminosity for low redshift galaxies, consistent with a powerlaw of index 1.7 (Gao & Solomon 2004; Beelen et al. 2004; Carilli 2004). The high redshift sources, which by necessity are also the highest luminosity, are also shown, and interestingly, the high z sources continue the correlation to higher luminosity. Most of these sources host known AGN, and yet they follow the same correlation of L_{FIR} vs. L'_{CO} as the low z star forming galaxies. This correlation could be used to argue that star formation is still the dominant dust heating mechanism in the high z sources (ie. coeval starburst and AGN).

The second strongest molecular line emission from star forming galaxies is from the HCN molecule (Gao and Solomon 2004), with the HCN emission typically being about 10% that of the CO luminosity, although this fraction increases with increasing IR luminosity. Figure 6 shows the L_{FIR} vs. L'_{HCN} correlation for nearby galaxies, plus some recent measurements of high redshift galaxies using the VLA (Carilli et al. 2004; Solomon et al. 2004). HCN is in important diagnostic, tracing dense gas directly associate with star forming regions (critical density for excitation $\sim 10^5$ cm^{-3}), as opposed to CO which traces all the molecular gas (critical density for excitation $\sim 10^3$ cm^{-3}). Interestingly, the HCN - FIR correlation is linear (power-law index = 1), unlike the non-linear CO-FIR correlation. This suggests that the FIR luminosity is linearly correlated with the dense gas mass associated with active star forming clouds. The high z sources generally fall along the linear correlation defined by the low z galaxies, again suggesting a similar dust heating mechanism (ie. star formation). However, a number of the high z sources have only HCN lower limits, which would allow for some dust heating by the AGN.

ALMA will push the studies of molecular line emission to the normal galaxy population at high redshift, probing to Milky way type molecular gas masses out to $z \sim 3$. Moreover, ALMA will provide sub-arcsec imaging of the gas, to probe dynamics and dark matter on kpc-scales. Modelling by Blain (2001) has shown that blind surveys by ALMA should detect 10's of galaxies per hour via their CO emission in the redshift range 0.5 to 2.5.

However, it should be noted that for dense gas tracers like HCN, ALMA will be forced to study the higher order transitions at high redshift (eg. a 90 GHz observing frequency corresponds to HCN 5-4 at $z = 4$). It is possible (likely?) that these transitions are sub-thermally excited due to the very high critical densities involved. In this case, study of the dense gas tracers at high redshift may be better done using large area cm telescopes working in the 20 to 50 GHz range, such as the EVLA, and eventually the SKA (Carilli & Blain 2003).

One area where ALMA will clearly make fundamental breakthroughs is in the study of the ISM submm cooling lines, such as C+ and CI (van der Werf 1999, Papadopoulos et al. 2004). This area has been dissapointing at high redshift, due to the relative weakness of the strength of the C+ line in galaxies with warm IR spectra (Malhotra this volume). This effect may be due to a decrease in the efficiency of photoelectric heating by charged grains in regions of high radiation fields (Wolfe 2004). By pushing down to normal galaxies, where the C+ line is expected to dominate ISM cooling, ALMA will open an exciting window into ISM physics in early galaxies.

4. COMPLEMENTARITY

ALMA will not work in a vacuum (unfortunately!), and it is important to recognize contributions from other telescopes. Indeed, this conference is meant to highlight the dual roles of ALMA and Hershel in the study of extragalactic astronomy, as can be seen in these proceedings. But in the mm regime itself, there will also be large single dish telescopes providing complentarity to ALMA as well, such as the LMT, GBT, APEX, ASTE...

One area where the single dish telescopes will contribute is through very wideband spectroscopy (up to 32 GHz). Such wide band spectra will have multiple

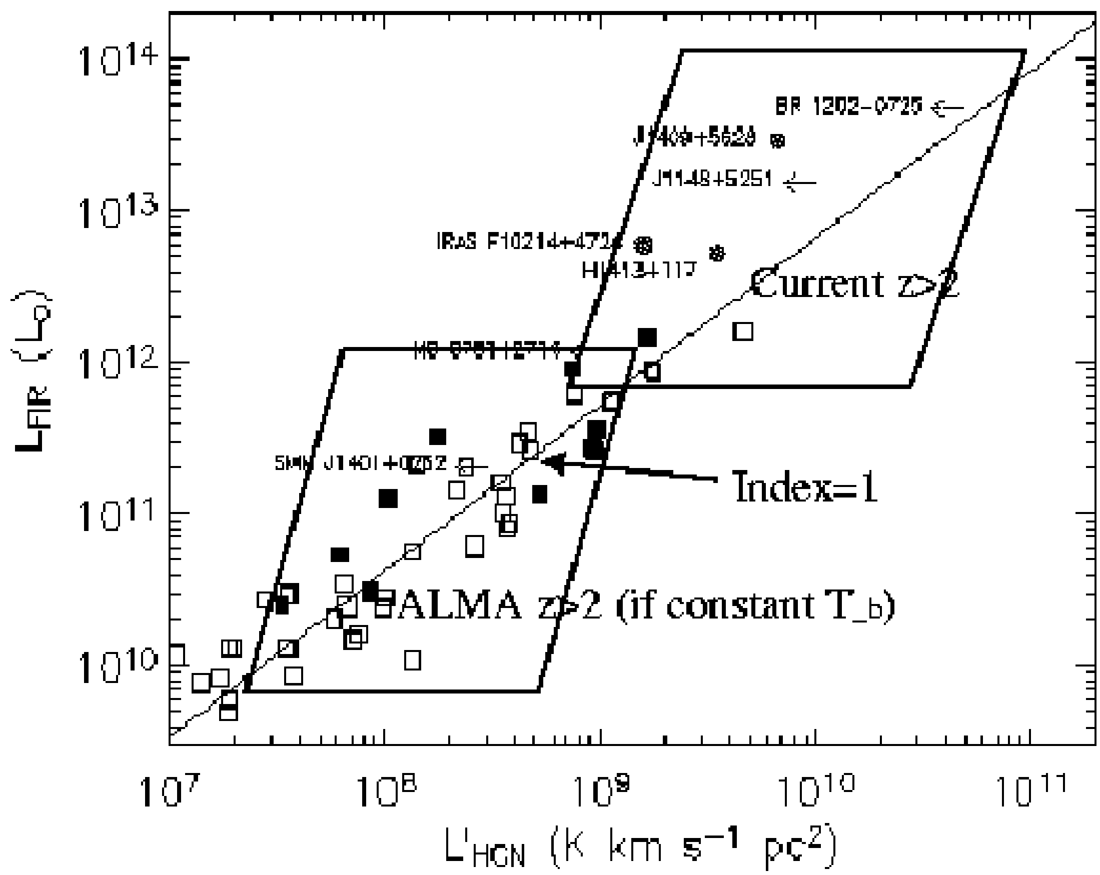

Figure 6. The correlation between FIR and HCN luminosity for low z (squares) and high z (circles) galaxies and AGN (Gao & Solomon 2004; Beelen et al. 2004; Carilli et al. 2004).

transitions of CO, C+, HCN, and other molecules in a single spectrum of a high z source, and hence provide redshifts without having to rely on optical spectroscopy.

A second area where single dish telescopes will contribute is with large format bolometer cameras doing very wide field surveys to sub-mJy sensitivity. The important point is that the small FoV of ALMA makes very wide field surveys difficult. Indeed, future bolometer cameras will be competitive with, or superior to, ALMA, in terms of survey sensitivity for fields larger that $15' \times 15'$. Hence, one can invision very wide field surveys with future sub-mm bolometer cameras, as well as with radio and far-IR telescopes, to define samples of interesting sources which can be followed-up with sensitive, high resolution observations with ALMA to study the detailed physics of the sources. Of course, for ultra-deep (μJy), narrow field studies of the submm source population, ALMA will be incomparable.

5. ALMA STUDIES OF COSMIC REIONIZATION

The discovery of the Gunn–Peterson absorption trough in the spectra of the most distant quasars ($z > 6$), corresponding to Ly α absorption by the neutral IGM, implies that we have finally probed into the epoch of cosmic reionization (EoR; White et al. 2004). The EoR sets a fundamental benchmark in cosmic structure formation, corresponding to the formation of the first luminous objects (star forming galaxies and/or accreting massive black holes). Unfortunately, G-P absorption during the EoR precludes observations of objects at wavelengths longer than 0.9 micron. Hence study of the first galaxies and AGN is the exclusive realm of near-IR to radio astronomy. The last few years has seen a revolution in the number of objects discovered at $z > 6$ using near-IR imaging and spectroscopy, including star forming galaxies (Malhotra & Rhoads 2004; Stanway et al. 2004; Hu & Cowie 2002; Kodaira et al. 2003) and AGN (Fan et al. 2003).

The recent discovery of molecular line emission, ther-

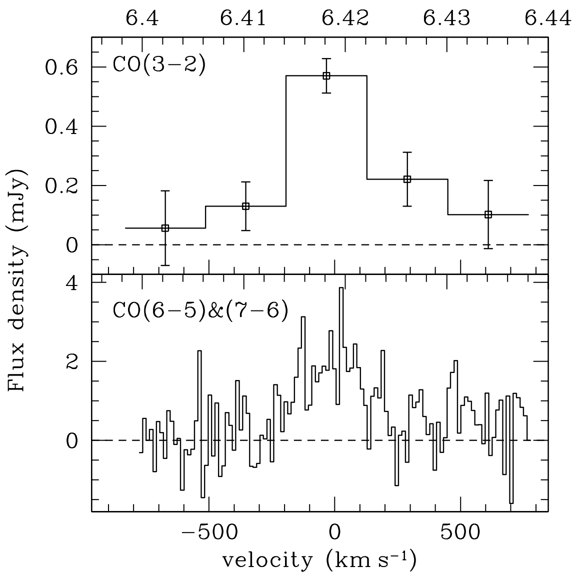

Figure 7. The CO line emission from the most distant QSO, 1148+5251 at $z = 6.42$ (Walter et al. 2003; Bertoldi et al 2003). The 3-2 line was observed with the Very Large Array at 47 GHz, while the higher order transitions were observed with the Plateau de Bure interferometer. The implied molecular gas mass is 2.2×10^{10} $M_\odot$.

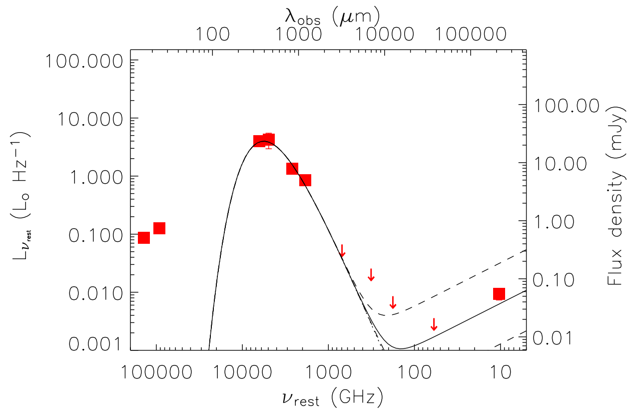

Figure 8. The radio through IR SED for the highest redshift QSO, 1148+5251 at $z = 6.4$ (Beelen et al. 2004). The curve shows the expected SED for a star forming galaxy.

mal emission from warm dust, and radio syncrotron emission, from the most distant QSO 1148+5251 at $z = 6.4$ (Bertoldi et al. 2003a,b; Walter et al. 2003; Carill et al. 2004), implies very early enrichment of heavy elements and dust in galaxies, presumably via star formation, within 0.8 Gyr of the big bang (Figure 7). The presence of a massive starburst in the host galaxy of 1148+5251 is supported by the observed radio-FIR SED (Figure 8), which follows the radio-FIR correlation for star forming galaxies, with an implied star formation rate of order 10^3 $M_\odot$ year^{-1} (Beelen et al. 2004). Likewise, high resolution imaging of the CO emission shows that the gas extends over ≈ 1", with two peaks separated by 0.3", suggesting a merging galaxy system (Figure 9). HST imaging shows that the optical QSO is associate with the southern CO peak (White et al. 2004). And from the gas dynamics, Walter et al. (2004) conclude that the supermassive black hole forms prior to the formation of the stellar bulge in the earliest AGN host galaxies.

These studies of 1148+5251 demonstrate the power of mm line and continuum studies of the earliest galaxies and AGN. Unfortunately, the observations of 1148+5251 stretch current instrumentation to the extreme limit, such that only rare and pathologic objects are detectable, ie. hyperluminous IR galaxies with $L_{FIR} > 10^{13}$ $L_\odot$. The two orders of magnitude increase in sensitivity afforded by ALMA will enable study of the molecular gas and dust in the first 'normal' galaxies within the EoR. Such studies will reveal the physics and chemistry of molecular gas reservoirs required for star formation, and provide a unique probe of gas dynamics and dynamical

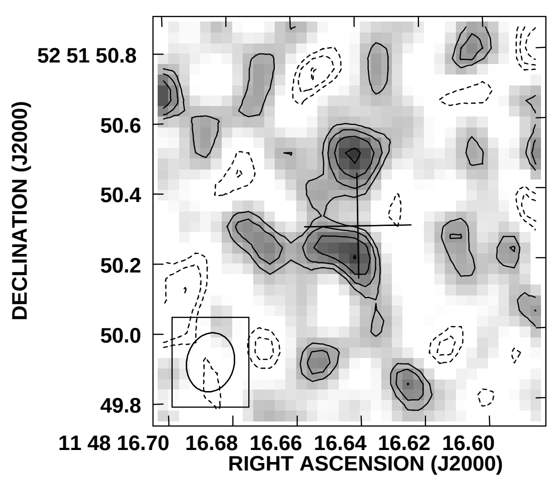

Figure 9. A high resolution (0.15") VLA image of the CO 3-2 emission from the highest redshift QSO, 1148+5251 at $z = 6.4$ (Walter et al. 2004). HST imaging of the optical QSO shows that it is associated with the southern CO component (White et al. 2004).

masses of the first galaxies. In parallel, radio continuum studies with nJy sensitivity in the frequency range 1 to 10 GHz with the EVLA and, eventually, the SKA, will present a dust-unbiased view of star formation in these systems.

As a concrete example of the types of objects that might be studied, consider the galaxies being discovered in Lyα surveys at $z \sim 6$. The typical UV luminosity is a few$\times 10^{10}$ $L_\odot$. Making the standard factor five dust correction for typical high redshift star forming galaxies (ie. Ly-break galaxies) implies an FIR luminosity $\sim 10^{11}$ $L_\odot$. The predicted thermal emission from warm dust at 250 GHz is 25 μJy, which can be detected at 4σ with ALMA in one transit (6hrs). We expect one or two of these objects in every ALMA FoV.

Lastly, an important aspect of the molecular line observations of galaxies within the EoR is that they give the most accurate redshifts (by far) for the host galaxies. Typical high ionization broad metal emission lines from QSOs are notoriously uncertain in terms of the host galaxy redshifts, with offsets typically on the order of 10^3 km s^{-1} (Richards et al. 2002), while Ly α emission lines are affected severely by absorption. Accurate host galaxy redshifts are crucial in the calculation of the size of cosmic Stromgren spheres around objects within the EoR, since these sizes are derived from the redshift difference between the host galaxy and the on-set of GP absorption (Wyithe & Loeb 2004). The sizes of these ionized regions have been used to constrain the IGM neutral fraction (Wyithe et al. 2005), setting a lower limit to the neutral fraction of 0.1 at $z \sim 6.4$, two orders of magnitude more stringent than the lower limit set by the GP effect.

6. MILLIMETER VLBI OBSERVATIONS OF THE GALACTIC CENTER

A final program we consider is (sub)mm VLBI observations of the supermassive black hole at the Galactic center, including (phase array) ALMA as the most sensitive element in the array. Other possible elements include the LMT, CARMA, JCMT (or CSO or SMA), the HHT, PdBI, and the IRAM 30m. These observations will allow for imaging at $\sim 10\mu$as resolution, well matched to the scale of the expected general relativistic shadow of the SMBH in Sgr A* (Falcke et al. 2000).

Figure 10 shows the expected signature of the black hole on the non-thermal brightness distribution at (sub)mm wavelengths. These observations will provide the ultimate evidence for the existence of a SMBH at the Galactic center, provide a fundamental test of strong field GR, and are the most direct method for separating a Kerr (ie. spinning) from a Schwarzschild black hole. At a minimum, the sensitivity per baseline is adequate to perform model fitting on relatively short timescales (minutes), while the VLBI array itself has enough antennas to provide both closure amplitude and phases, and hence should be adequate for hybrid imaging of the GR shadow of Sgr A*. The existence of reasonable mm-VLBI calibrators (eg NRAO 530) in the vicinity of Sgr A* will allow for phase-referenced fringe fitting, although the source itself is strong enough, and the UV coverage dense enough, to allow for hybrid mapping as well.

The source Sgr A* has been detected at 220 GHz on the PdBI − Pico Veleta baseline (resolution = 300 uas) with a flux density of 2.0 Jy, and an upper limit to the size of order 100 uas (Krichbaum et al. 1998). The proposed observations will have more than an order of magnitude better resolution, more than two orders of magnitude better sensitivity, and, again, enough antennas to perform proper imaging of the general relativistic shadow of Sgr A*.

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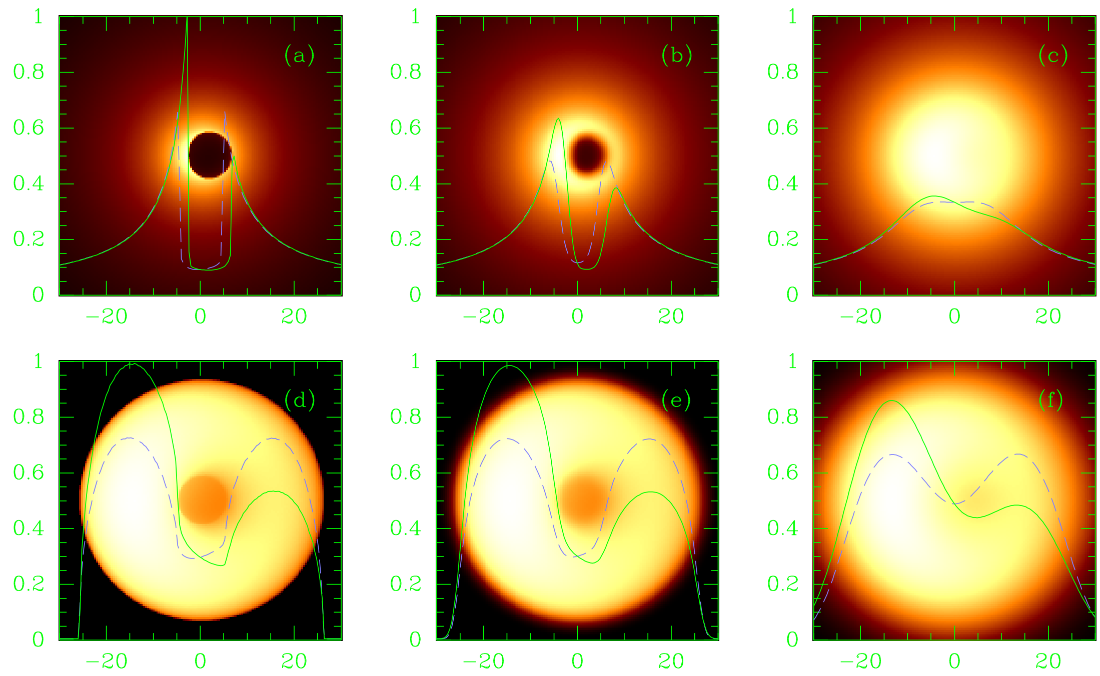

Figure 10. Simulations of the expected general relativistic shadow of the Galactic center supermassive black hole as seen in (sub)mm VLBI images at 10's μas resolution (Falcke et al. 2000). The predicted signature depends strongly on whether the hole is rotating (upper frames) or not (lower frame), ie. Kerr or Schwarzschild, since rotation affects the radius of the last stable orbit. The left frames are the model. The center frames are for observations at 0.6mm, including scattering, and the right frames are at 1.3mm. The tick marks along the X axis are in μas.

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