Science Justification for Frequency Bands 1, 4 and 8

and the Future/Enhanced Correlator

I. Introduction

At its meeting in Tokyo in April 2001, the E-ACC requested at its next meeting in June 2001 a presentation of the science cases for several of the enhancements of the baseline 2-way project that are being considered, in particular Frequency Bands 1, 4 and 8 and the Future/Enhanced Correlator. In the following, a brief written summary of the science justification for these components is given, prepared by members of the ASAC and technical groups. More details can be found in the documents at `http://www.cv.nrao.edu/~awootten/mmaimcal/asac/asacmay31agenda.html`. The general scientific background is contained in the recent proposal for ALMA Phase II submitted to ESO in December 2000, and in similar cases submitted to the other agencies. The Atacama Compact Array (ACA), which is a high priority enhancement, is not considered in this document, but continues to be studied intensively through simulations.

The atmospheric windows accessible to ALMA from the Chajnantor site range from 7 mm (31.3 GHz) to 0.35 mm (950 GHz), and can be covered in 10 frequency bands. The ASAC goal is to have ALMA equipped eventually with all 10 frequency bands, and is driven by (i) continuous coverage of the main CO and [C II] lines with redshift; (ii) dust emission over a wide range of frequencies to determine dust properties and - for high redshift galaxies - photometric redshifts; (iii) ability to probe gas with a wide range of physical conditions, with temperatures ranging from less than 10 K up to 2000 K; and (iv) astrochemistry.

In the following, the science cases for Bands 1, 4 and 8 are discussed under the assumption that Bands 3, 6, 7 and 9 are available as the 'first light' receivers and that Band 10 will be added as soon as it is technically ready. Bands 2 and 5, which have the lowest scientific priority, are not discussed here. The science case for the Future/Enhanced Correlator is discussed with reference to the capabilities of the Baseline Correlator as specified in Table 10.3 of the ALMA project book. The bands are discussed in order of increasing frequency without any scientific prioritization.

Overview of ALMA Frequency Bands

Band	Frequency Range (GHz)
1	**31.3–45.0**
2	67.0–90.0
3	84.0–116
4	**125–163**
5	163–211
6	211–275
7	275–370
8	**385–500**
9	602–720
10	767–950

II. ALMA Band 1: 31.3–45.0 GHz

ALMA's lowest frequency Band 1 offers many unique scientific opportunities which no other telescope will be capable of, even by 2010. As well as being a vital adjunct to the main ALMA science programs at higher frequencies, Band 1 would also bring to ALMA an observational community largely distinct from that at (sub)millimeter frequencies. Its observing programs can be carried out even in poor weather. Compared with the upgraded VLA (EVLA), ALMA will be 3.8 times faster at 35 GHz for point-source detection and 17 times faster for wide-field imaging due to its higher aperture efficiency, better site and larger primary beams. Moreover, because ALMA has many short baselines and much better image fidelity, it allows programs not even possible with the EVLA. The key science arguments for Band 1 are as follows.

1. High-resolution SZ imaging of cluster gas at all redshifts

The Sunyaev-Zeldovich (SZ) effect, in which the cosmic background (CMB) photons are scattered by hot gas in clusters, is independent of redshift and an excellent tracer of cluster mass and physics, especially in combination with new X-ray data provided by Chandra and XMM. Dedicated SZ surveys from the ground and space will be done over the next few years at lower spatial resolutions of a few arcmin, but ALMA is unique in its ability to map the small-scale structure in cluster gas on tens of arcsec scales (see Fig. 1). Many hundreds of clusters will be detected by these surveys by the end of the decade, and will be available for ALMA follow-up. The ALMA close-packed array with Band 1 is ideal for this purpose since it contains many short baselines and reaches μK sensitivity in only a few hours.

ALMA will also be important in imaging the very small-scale CMB anisotropies, which occur in the power spectrum at multipoles of $\sim$10,000. At these scales, theoretical models predict strong CMB fluctuations due to local reionization by early bursts of star formation and due to the effects of massive black hole formation (see Fig. 2). ALMA is the only planned instrument capable of probing the CMB power spectrum on these scales and testing these poorly understood physical processes in the early universe.

2. Mapping the cold ISM at intermediate and high redshift

The reservoirs of gas from which galaxies form may be quite cool, even at moderate redshift z. Most high redshift CO searches to date have focussed on the J=4–3, 5–4 or 6–5 lines shifted to millimeter wavelengths. Because the CO levels with $J \geq 3$ require densities and temperatures well in excess of what is normally found in average giant molecular clouds, these data preferentially trace the gas associated with dense, actively star-forming regions. The low-lying CO 1–0 and 2–1 lines are the only way to trace very cool gas and measure the kinematics and redshifts of this gas. The recent detection of the 1–0 line in a $z = 3.91$ quasar at 23.4 GHz indicates the presence of a cold halo which is 10–100 times more massive than the gas traced by the higher excitation lines (Papadopoulos et al., Nature, 2001). Band 1 provides the only means to probe this gas in the CO 1–0 line in the redshift range z=1.6–2.7 and in the 2–1 line at z=4.1–6.3.

3. Other applications

Other science drivers for Band 1 include (i) Observations of optically thin dust emission from circumstellar disks to probe grain size evolution; (ii) Disentangling the contributions of dust, free-free and synchrotron emission in objects ranging from protostars and supernova remnants in our own Galaxy to starburst galaxies and AGN; (iii) Searches for the lowest excitation lines of heavy macro-molecules; and (iv) Zeeman splitting of molecules (in particular CCS and SO) to measure magnetic field strengths.

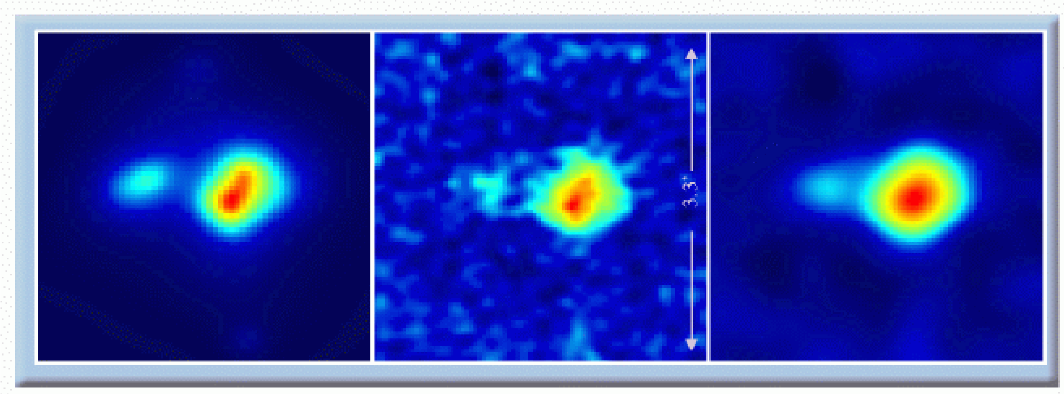

Figure 1. The left panel shows a hydrodynamical model of a 2.5×10^{14} $M_{\odot}$ cluster at $z = 1$. The center panel is a 4-hr ALMA image of the cluster at 35 GHz in compact configuration. The rightmost panel shows the same image, smoothed to 22 arcsec (Figure by J. Carlstrom).

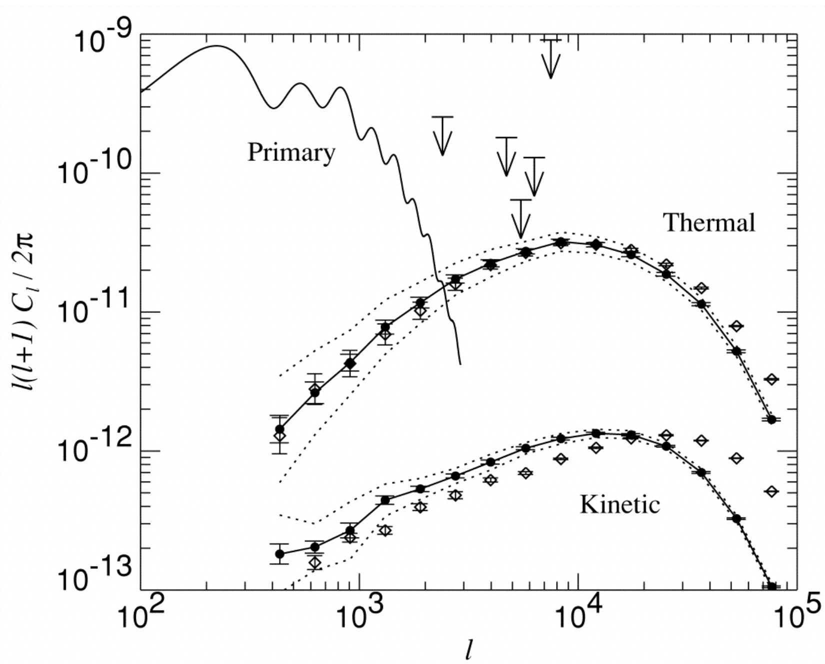

Figure 2. Prediction of the CMB power spectrum on scales of relevance to ALMA by Springel et al. (2001, Astrophys. J.); a few upper limits from previous experiments are shown. ALMA Band 1 in the close-packed configuration gives many baselines between 15 and 100 m, corresponding to multipoles of 10^4 to 10^5, right at the predicted peak of the thermal SZ power spectrum. ALMA has sufficient sensitivity to detect these effects, even the kinetic SZ effect, since its sensitivity corresponds to $10^{-12} - 10^{-13}$ in the units plotted on the vertical axis.

III. ALMA Band 4: 125–163 GHz

ALMA Band 4 covers the range 125–163 GHz (2.4–1.8 mm), where the atmosphere is very transparent even under mediocre conditions. It is situated in between two other 'workhorse' frequency bands, Band 3 —containing the CO J=1–0 line at z=0— and Band 6 —containing the J=2–1 line—, and is a crucial band to measure redshifted CO, [C II] and dust in critical redshift ranges. It also provides important opportunities for astrochemistry.

1. Photometric redshifts and [C II] of the most distant galaxies

In the Band 4 frequency range, the flux densities of high redshift galaxies of a given luminosity do not vary strongly with redshift. With the expected sensitivity, a $4\times10^{12}L_\odot$ galaxy located anywhere between $z = 1-10$ will be detected with $S/N = 10$ in ~ 1 hour in the thermal dust continuum (see Fig. 4). Band 4 is particularly important for the determination of the spectral energy distribution of the highest redshift systems. At $z \sim 10$, the adjacent higher frequency Bands 6 and 7 probe only the peak of the dust spectrum, whereas at the lower frequencies covered by Bands 3 and 1, the emission decreases too steeply to be detectable. To determine the photometric redshift, and eventually also the dust mass and temperature, the turnover frequency of the submillimeter emission needs to be measured, for which ALMA Band 4 is uniquely suited.

Another signitifcant use of Band 4 includes the search for the redshifted [C II] 158 μm emission line in sources with z=10–14, the principal cooling line of neutral atomic gas. As Fig. 4 shows, ALMA has the sensitivity to detect this line even at very high redshifts.

2. Evolution of normal galaxies up to $z \approx 1$

In normal field galaxies like the Milky Way, most of the molecular gas is in cold ($T \approx 10-20$ K) low density gas, in which only the lowest CO J=1–0 and 2–1 lines are significantly excited; observations of local galaxies show that even the J=3–2 line is up to a factor of 10 weaker. Band 3 contains redshifted CO 1–0 and 2–1 lines in the ranges z=0.0–0.4 and z=1.0–1.8, but the crucial range z=0.4–1.0, during which a strong evolution in star formation is known to have occurred from optical observations, is not covered by this band. Band 4 offers the opportunity to probe the mass, distribution, and kinematics of cold gas in disk galaxies in the critical $z = 0.4 - 0.8$ range.

3. Astrochemistry and galactic studies

The Band 4 wavelength range is known to be very rich in spectral lines in star-forming regions and in circumstellar envelopes of AGB stars, and is expected to be a key band for probing the chemistry of circumstellar disks. It contains the $J = 2 - 1$ transition of many simple linear molecules composed of 3 to 4 atoms of cosmically abundant elements, the fundamental transitions of H_2S and NO, important lines of H_2CO, and lines of many linear carbon chain molecules C_nH as well as large organic molecules. In circumstellar envelopes, the conditions are such that the excitation of these heavy molecules peaks in Band 4, so that this will be the prime band to search for rare molecules. Besides carbon-chains, also salts and metal-containing species (AlF, MgNC, NaCN, ...) and their isotopes can be observed in Band 4 (see Fig. 5), which provide unique probes of the nucleosynthetic history of stars.

Deuterated species in cold clouds are important diagnostics of the temperature evolution of the region, but their lowest $J = 1 - 0$ lines occur in the low-priority Band 2 and are thus not covered. Their higher 3–2 transitions occur in Band 6, but those lines probe only a small fraction of the cold gas. Band 4 covers the 2–1 lines and is therefore best suited to measure the orders of magnitude enhancements of deuterated species in cold regions.

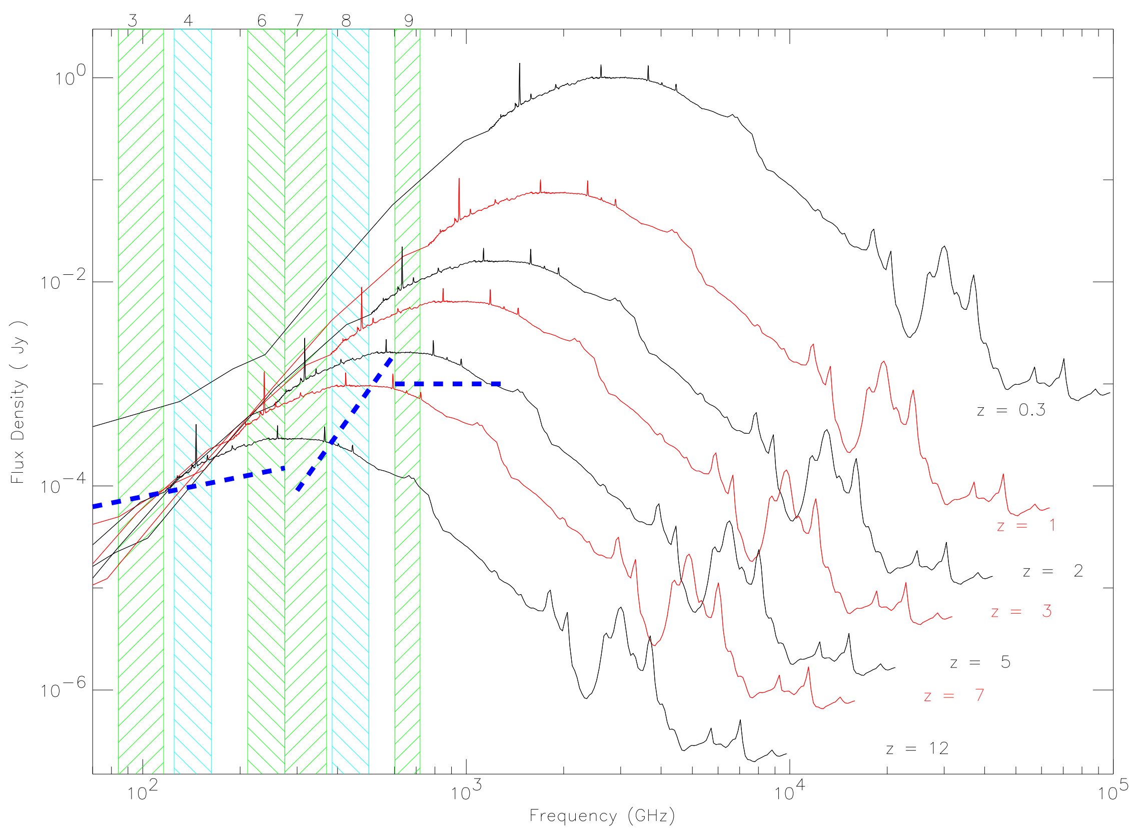

Figure 4. Observer-frame spectrum of a $4 \times 10^{12} L_\odot$ galaxy with increasing redshifts from z=0.3 to 12. The figure is based on the observed spectrum of M82 including the ISO spectral data and all available radio- and submillimeter data, and assumes a cosmology with $H_o = 50$ km s^{-1} Mpc^{-1}, $\Omega_0 = 1$ and $\Omega_\Lambda = 0$ (Beelen & Cox, in preparation). The strongest emission line is the [C II] fine-structure line at 158 μm. The positions of the ALMA Bands are shown by hatched areas. The thick dashed curves are 5 sigma detection limits after 1 hour of integration time.

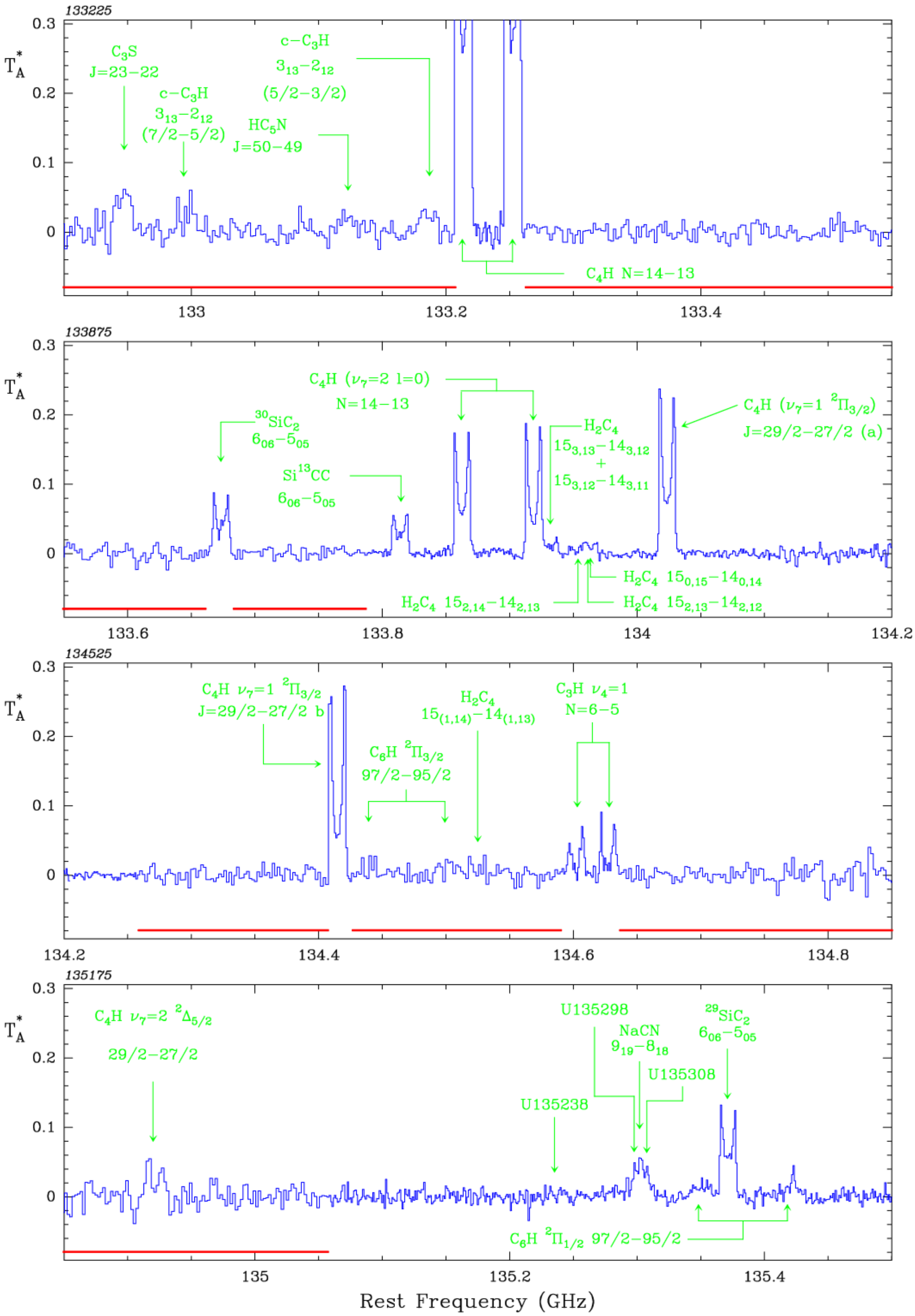

Figure 5. Part of the 2 millimeter spectrum of the carbon-rich AGB star IRC+10216 observed by Cernicharo et al. (2000, A&AS). Note the many lines from carbon-chain and metal-containing species that can be observed in Band 4.

IV. ALMA Band 8: 385–500 GHz

1. [C I] fine-structure line in our own and nearby galaxies

The principal driver for Band 8 is the [C I] $^3P_1$ – $^3P_0$ ground-state fine-structure line at 492 GHz. This line and the excited [C I] $^3P_2$ – $^3P_1$ line at 809 GHz in Band 10 are the *only* fine-structure transitions of an abundant element whose rest frequencies fall in the ALMA range. They probe the transition layer between the atomic medium where most molecules are photodissociated by ultraviolet radiation and the molecular clouds where young stars form. Thus, the [C I] data delineate the surfaces of molecular clouds, and provide vital information on the distribution of the radiation sources as well as the detailed structures of the clouds themselves. Since the star formation rate is likely a sensitive function of the radiation field, ALMA [C I] observations will play a crucial role in improving our understanding in the role of cloud formation and destruction in star formation and galaxy evolution.

Existing single-dish [C I] surveys provide valuable data on the [C I] distribution in Galactic clouds, but high spatial resolution ALMA data are essential for at least three applications: (i) Nearby galaxies up to $z \approx 0.2$, where ALMA provides comparable resolution to that with single dishes for galactic sources. Recent data (see Fig. 6) show that —in contrast with our own Galaxy— the [C I]/^{13}CO ratio is highly variable in different galaxies. ALMA is needed to map the [C I] and ^{13}CO distributions; (ii) Planet-forming disks around young stars in our own Galaxy, which are typically only a few arcsec in extent. Recent studies have shown that the chemistry and thermal balance in the upper layers of disks are controlled by ultraviolet radiation, and [C I] is uniquely suited to trace this; (iii) Physics of Galactic clouds, where only ALMA has the spatial resolution to resolve the <1000 AU ($< 1''$ at 1 kpc) transition layer and test models. Targets will be edge-on clouds, circumstellar shells and planetary nebulae.

Of the two [C I] lines, the ground-state 492 GHz line is the choice for determining the total column of [C I], whereas the 809 GHz line is needed to constrain its excitation. In terms of mapping efficiency, the 492 GHz line will be an order of magnitude better than the 809 GHz line.

2. Redshifted [C II] fine-structure line at $z = 2.7 - 3.8$

Band 8 covers the red-shifted [C II] fine-structure line ($^2P_{3/2}$ – $^2P_{1/2}$; rest frequency 1.9 THz=158 μm) in the important redshift range $z = 2.7 - 3.8$, where much of the star formation and AGN activity is thought to peak. Since [C II] is the dominant cooling line of the neutral atomic gas, it is an important and unique probe of the 'active' universe.

3. HDO fundamental transition in solar system objects

The water molecule plays a key role in the astrophysics of star-forming regions as well as solar system objects such as comets. While ALMA cannot observe thermal emission from H_2O itself due to the atmosphere, a substantial fraction of ALMA observing may be devoted to studies of deuterated water, HDO, through its fundamental transition 464 GHz, tracing the thermal history of the cloud. Moreover, the deuterium fraction in comets is critical for an understanding of their origin and plays a large role in discussions on the origin of water on Earth. The ALMA HDO data will complement observations of H_2O with the Herschel Space Observatory to be launched in 2007; this capability should not be much delayed if the same comets are to be observed.

4. CO $J = 4 - 3$ in our own and local galaxies

In many circumstances, the CO J=4–3 line at 460 GHz is the most intense cooling line for warm, dense molecular gas, such as that associated with supernova remnants and outflows from young stars. The COBE results show that for our Galaxy, the $J = 4 - 3$ line is a good measure of the cooling rate in the vicinity of the nucleus. The high spatial resolution of ALMA is needed to resolve shock structures in our own Galaxy (typically few 100 AU, $< 1''$ at 1 kpc) as well as the nuclei of external galaxies.

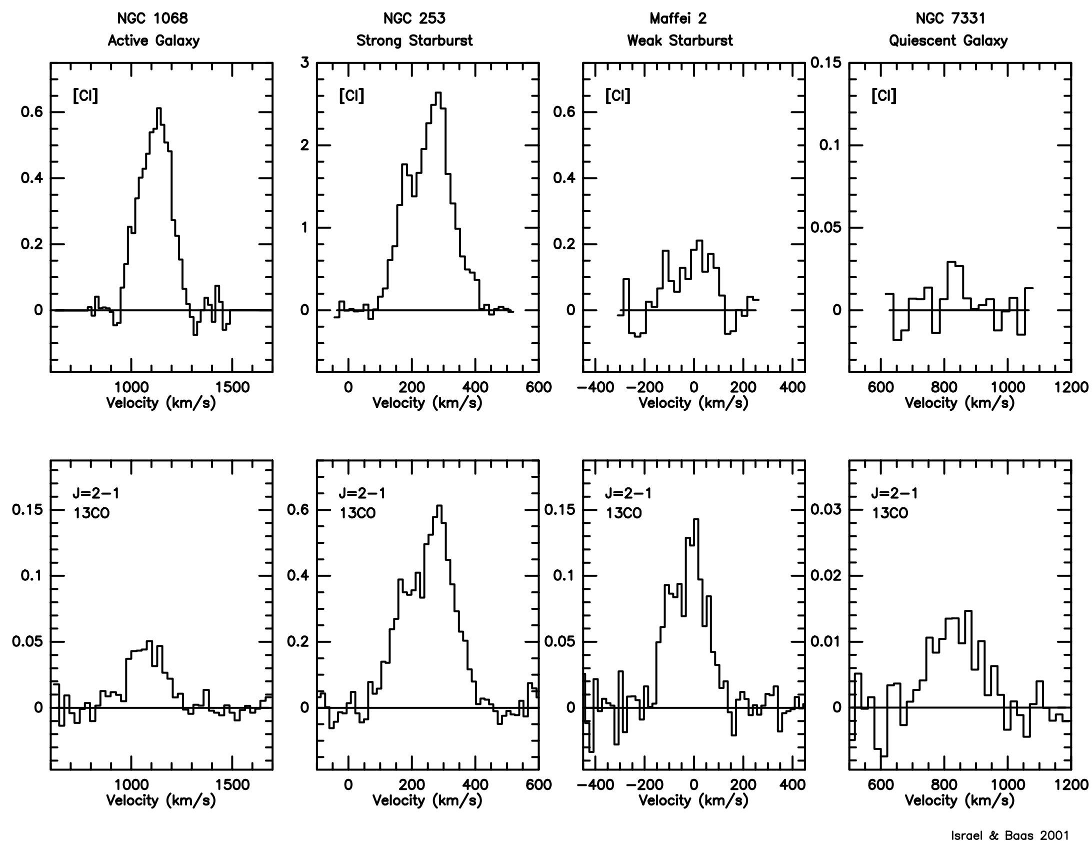

Figure 6. Single-dish [C I] 492 GHz and ^{13}CO 2–1 observations of different types of galaxies. Note the different [C I]/^{13}CO ratios for active, starburst and quiescent galaxies. ALMA is needed to image the distribution of these species and determine the physical cause for the differences (from Israel & Baas. 2001, in preparation).

V. Future/Enhanced Correlator

The Future/Enhanced Correlator will provide two major improvements to ALMA with respect to the baseline correlator: (i) a much higher spectral resolution over the largest bandwidth; and (ii) a highly flexible use of the bandwidth and the 64 telescopes. It can increase the observing speed of some highly ranked programs by a factor of two or more, especially in the areas of high-redshift galaxies and protoplanetary disks around young stars, which require long integration times. At a minimum, the observing efficiency is increased by 9% without any correlator capacity losses. A few science cases are described below; working examples can be found at the WWW site.

1. Distant dusty sources

ALMA will be a major instrument in cosmology, in particular in high-angular resolution studies of dusty distant galaxies which optical telescopes cannot probe. The CO lines are the principal redshift indicators and are separated by 115 GHz in the rest frame, and by 115 GHz $/(1+z)$ at high redshift, or 19 GHz for z=5. Thus, with only a few frequency settings, ALMA will be able to detect at least two lines, as needed to determine z. Such searches will use the maximum bandwidth, primarily in the lower frequency bands, e.g. Band 3. The Baseline Correlator will have a resolution of $\sim$60 km s^{-1} at 80 GHz over the maximum bandwidth, whereas the proposed Future/Enhanced Correlator should have $\sim$2 km s^{-1} under the same conditions. The difference is important because the earliest galaxies are likely to consist of small units with line widths of about 100 km s^{-1} or less, so that such galaxies may only be 'detected' in a single channel at 60 km s^{-1} resolution. Not only would this make the detection unreliable, it would preclude any dynamical studies.

The superb point-source sensitivity of ALMA combined with the Future/Enhanced Correlator also makes it feasible to conduct unbiased spectral surveys of absorption lines toward high-redshift quasars as weak as a few mJy. This capability opens the door to study the missing link between the Lyman-α clouds and galaxies.

2. Line surveys and searches for pre-biotic molecules

A Future/Enhanced Correlator with a large bandwidth and high spectral resolution ($<$ 0.5 km s^{-1}) is also very beneficial for unbiased spectral surveys, which provide a wealth of information ranging from an unbiased census of the principal molecules in the sources, to the use of line ratios to constrain their physical structure. With the Baseline Correlator, the required spectral resolution of $<$0.5 km s^{-1} allows a $\sim$ 1 GHz bandwidth at 230 GHz. With the Future/Enhanced Correlator, this is increased to $\sim$ 8 GHz, improving the observing speed to cover a full atmospheric window by more than a factor of 10. It gives a spectroscopic capability that parallels that of the modern echelle spectrometers that are now standard equipment in leading ground-based optical telescopes.

Unbiased line surveys also offer the opportunity for unexpected discoveries of new species. This includes not only exotic molecules, but also pre-biotic molecules such as sugars and amino acids. For example, the simplest amino acid conformer glycine II has about 60 transitions in a 16 GHz band around 100 GHz, and its detection requires observations of the largest possible number of transitions at 0.1–0.2 km s^{-1} to positively identify this species. In colder regions with less confusion such as protoplanetary disks, the lines are narrow ($<$100 kHz) and often spaced by tens of MHz. Here the flexibility of the Future/Enhanced correlator will allow more than twice the number of lines to be selected at very high spectral resolution ($<$ 0.1 km s^{-1}) and imaged simultaneously. Since the integration times for these projects are very long ($>$ 8 hr per setting), the gain in observing speed is substantial.

3. Probing deep into the centers of active galaxies

The central regions of galaxies contain a mixture of quiescent gas clouds with very narrow lines and gas with extremely wild motions due to rapid rotation and explosive outflows. Such an environment can be probed accurately only with the high spectral resolution and wide bandwidth delivered by the Future/Enhanced Correlator.