Issues for the 30–45.5 GHz band on ALMA

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Abstract

The MMA receiver suite included provisions for covering the Ka and Q bands from 30 – 45.5 GHz. It is not clear whether ALMA should retain this band or focus on the higher-frequency bands only. This memo presents some of the scientific drivers for this capability, in particular observations of the Cosmic Microwave Background Radiation anisotropy and scattering of the CMBR from hot gas in massive clusters of galaxies, the Sunyaev-Zeldovich effect. In addition to its unique capabilities at millimeter and submillimeter wavelengths, ALMA will also be a superb instrument at the smallest centimeter wavelengths. ALMA will complement the VLA with its greater effective collecting area at high frequency and a full view of the Southern Sky. We use examples from current CMB, SZE, gravitational lensing, and other extragalactic observations along with theoretical models of large scale structure evolution and galaxy formation to extrapolate the capabilities of ALMA for these programs. Finally, some of the operational advantages and drawbacks of having this low frequency capability for ALMA are summarized.

1 Executive Summary

The question has arisen whether a 30–46 GHz band is needed on ALMA, or whether the costs entailed by a low frequency receiver are justified given the likely budget pressures to be experienced during construction. In this document, we list a number of science issues that the proposed low-frequency receiver suite would address (often uniquely), and also discuss the drawbacks that such a system would have.

ALMA at 30–46 GHz will make significant contributions to the following research areas:

- Observations of anisotropy in the Cosmic Microwave Background Radiation (CMBR) for multipoles greater than $\ell \sim 7500$.
- Imaging of the Sunyaev-Zeldovich Effect (SZE) on angular scales from 0.3 to 3 arcminutes.
- Spectral observations of redshifted molecular lines from the 3mm and 1mm (or possibly higher frequency) bands.
- Important North-South baselines (in conjunction with the VLBA) for VLBI at 30 and 43 GHz.
- High-fidelity imaging of low-surface brightness continuum emission in our galaxy (eg. "spinning dust grains" of Draine et al., supernova remnants, H II regions) and in and around other galaxies (eg. relic radio halos of galaxy clusters, the cosmic ray emission in nearby galaxies). This is particularly powerful in conjunction with the upgraded VLA in an ultracompact E configuration at 15–22 GHz. Note that these galactic phenomena are nuisance foregrounds for arcminute-scale CMBR anisotropies and the SZE!

A more detailed discussion of the science drivers is presented in the next section.

Note that due to the large number of highly efficient antennas and the ability to move them into an ultracompact configuration, the sensitivity of this is sufficient that most, if not all, of the scientific programs considered above can be carried out in single tracks, and will not unduly impact the use of ALMA for the core millimeter and submillimeter observations. The broadening of its wavelength coverage to include the 30–46 GHz window, clearly, should be looked upon as complementing the higher frequencies.

In conjunction with the scientific benefits of having these bands on ALMA, there are a number of logistical considerations that must be taken into account. The most critical is that of actually fitting a second dewar (assuming that the receiver cannot be fit into the proposed single high frequency dewar) into the budget and the telescope.

- Issue: Due to the feedhorn size, the receiver would almost certainly have to be in a separate 15K cryogenic package from the 4K dewar for the millimeter and submillimeter receivers. Thus, additional ambient-temperature optics will be required to allow redirection of the beam to this receiver, at a cost of at least \$50K per antenna (\$3.2M total minimum, probably \$6M all told).

- *Possible mitigation: operation of the 15K cryo system should be much more robust than the 4K system, so maintenance and repair of the 4K dewar can be carried out while low-frequency observations continue. It may also be desirable to use pickup optics for the 185 GHz WVR monitor, which would be designed in conjunction with this. Also, it may be that the 75–90 GHz band is best covered by a HEMT or MMIC based system which could also reside in the 15K dewar.*

There are also a number of other outstanding issues that need consideration in order to make an informed judgment on this issue:

- How much will this actually cost, and is there a reasonable design for the necessary optics?
- Are there significant operational drawbacks or benefits to having a second dewar (at 15K instead of 4K)? For example, can the cryogenics be made sufficiently more robust than the 4K dewar so that the additional maintenance required is minimal? *Note: this is almost certainly true, as the VLA is currently running significantly more than 64 independent 15K receivers with high efficiency. Some allowance will have to be made for the altitude, but otherwise this should be routine.*
- Will the low-frequency observational programs be able to make use of poor weather that is unsuitable or marginal for millimeter-wave observations?
- Can the superior sensitivity and stability of the 30–46 GHz system be exploited for improving calibration of the array, such as faster initial baseline determinations?
- Might some of the cost of this system be borne by outside funds or in-kind contributions from Universities or institutes?
- If the low frequency receivers are in separate dewars, with the provision for installation the pick-up optics in the beam path, then could these be added at a later date? Need all antennas be outfitted? Given

the uncertainties in the "competing" (or "complementing") telescopes (see below) could the provision for a separate package (regardless of frequency!) be kept in the design, with a decision deferred until after the first-light receivers have been built?

- In principle, these receivers are much simpler to design and construct than the millimeter and submillimeter receivers. Is there an advantage to have a small number of the 30–46 GHz (possibly with 75–90 GHz also) receivers in 15K dewars ready for commissioning in 2004-2006?

A final issue is the relationship between the low-frequency bands on ALMA and similar bands on the proposed VLA upgrade and the GBT. For example, ALMA with 64 12-meter antennas will have an effective collecting area greater than the VLA at 30 GHz and 43 GHz above (4640 m^2 for $27 \times$ 25-m at $\epsilon_a = 0.35$, versus 5720 m^2 assuming $64 \times$ 12-m at $\epsilon_a = 0.79$), although unless the ultracompact E-configuration were completed the VLA would be at a significant disadvantage in terms of surface brightness sensitivity and imaging capability. Naturally, there are also a number of scientific programs that suffer from the lack of a sensitive high-frequency array in the Southern hemisphere, which the VLA is unable to observe or for which it is difficult to obtain good uv-coverage. However, the VLA will be superior for high-resolution work (even un-upgraded) as it will have longer baselines. The factor of 2 difference in antenna diameter between the VLA and ALMA could also be looked upon as an advantage for complementary operation, with the VLA at 15–22 GHz and ALMA at 30–46 GHz matched in primary beam size. In extended sources, ALMA would have superior brightness sensitivity and larger field-of-view.

The GBT, on the other hand, is more directly competitive. The resolution of the 100-m antenna will be comparable to 100-m baselines in the compact array of ALMA, and thus a 64-element array receiver on the GBT would produce roughly comparable images to ALMA. Furthermore, the 100-m GBT has similar collecting area to ALMA with 64 12-m antennas. The Green Bank site, on the other hand, is likely to be significantly poorer for 30–46 GHz observing with a single dish (without any of the atmospheric canceling properties of interferometry) for most of the available time. Thus, though it may be possible to build a large-format Q-band array receiver for the GBT that will do most of what ALMA (or the VLA E-configuration) can do down to its limiting resolution of $14''$, there is no question that ALMA would be superior, or at least highly complementary in its ability to add in higher resolution information. (In fact, the GBT would be superb at adding in lower resolution information to ALMA.) It is unclear at this point (before GBT has started regular operation) whether it will be a true competitor against ALMA at 30–46 GHz, but the possibility is there.

In summary, there are a number of scientific benefits to be gained by the addition of a low-frequency system to the ALMA receiver suite. As well, there are real costs and logistical issues that must be balanced against these gains. My own opinion is that it is indeed likely that the 30–46 GHz capability can be added to (or more correctly retained in) the ALMA design without undue hardship and will provide an excellent scientific return for the investment. At the very least, provision for the later installment of a second receiver package that could accommodate the 30–46 GHz band (or any other desired upgrades) should be seriously considered in the design of ALMA.

2 Science Issues

Some of these science issues were also presented in the contribution to the ALMA Science 1999 meeting proceedings (Myers & Carlstrom 1999). See that document, which can be found at

http://www.aoc.nrao.edu/~smyers/alma/

for more details on the CMB and SZE applications in particular.

The use of the 30–46 GHz bands on ALMA is *not expected to be a significant drain on the array schedule which should be directed toward observations in the core millimeter and submillimeter bands.* In particular, the aim would be to mostly use this capability for 7mm observations during non-photometric weather at the higher frequencies, as has been successfully done at OVRO and BIMA by Carlstrom et al. The science highlights presented below are largely in support of key observations at other wavelengths (or angular scales), and due to the high sensitivity of ALMA will only require short observations in this band.

2.1 The Cosmic Microwave Background

There are a number of upcoming and proposed CMBR anisotropy experiments, which cover the parameter space of frequency and angular scale. However, the focus has been largely on the angular scales above 0.25 degrees, where the primary cosmological signatures appear in the fluctuation power spectrum. These larger scales are being extensively mapped by a number of ambitious orbital (COBE, and the upcoming MAP and PLANCK missions), ballon-borne (most recently BOOMERanG: Mauskopf et al. 1999), and even a few intrepid ground-based experiments (see below). However, there are few telescopes that are able to target the fine scale anisotropies beyond $\ell > 1000$ with high sensitivity. ALMA will do this.

The current state-of-the-art ground-based experiments are using fast-switching single-beam telescopes to scan over several degrees on the sky at good sites. The Mobile Anisotropy Telescope (MAT), with its 1-meter primary mirror, was built by Mark Devlin (UPenn) and Lyman Page (Princeton) and run at Cerro-Toco on the Atacama site in Chile. MAT has measured the so-called Doppler Peak at the 1 degree angular scale in the CMBR anisotropy power spectrum (Miller et al. 1999). Similar experiments are also being run at the South Pole. In addition to single dish scanning experiments such as MAT, small special-purpose interferometers such as the Cosmic Background Imager (CBI: Readhead et al.) and the Degree Angular Scale Interferometer (DASI: Carlstrom et al.) are soon to be operating at the Atacama and South Pole sites respectively. DASI will probe the degree scales similarly to MAT, and the CBI will image the CMBR on scales down to 4 arcminutes.

For smaller angular scales, below several arcminutes, larger telescopes or arrays will be needed, with much greater sensitivitity than the current suite of instruments can provide. In fact, some of the earliest important limits on CMB anisotropy were obtained using large single-dish telescopes at 20 GHz (Uson & Wilkinson 1984, Readhead et al. 1989) giving upper limits of 53 microKelvin for rms fluctuations on the 2–7 arcminute scales. In most cosmological models, the expected rms is less than 10 microKelvin below 1 arcminute!

Even if these sensitivity levels are reached, there are other roadblocks. A significant problem affecting intermediate and small-scale CMBR anisotropy observations is the identification and removal of galactic and extragalactic foreground emission. For example, the OVRO 5-meter telescope has measured the CMBR anisotropy on angular scales of $10'$ (Leitch et al. 1999) but confusing foreground emission attributed to an anomalous component of the galactic ISM was found and subtracted (Leitch et al. 1996). ALMA, along with the northern CARMA (the combined OVRO and BIMA) are two instruments with the sensitivity, frequency coverage, and angular resolution required to perform accurate foreground assessment. In addition, an upgraded VLA in an ultracompact "E" configuration could provide complementary information at even lower frequencies (15–22 GHz). Of course, the nature of these anomalous foregrounds is of astrophysical interest in their own right!

The location and amplitude of the first "Doppler" peaks are controlled by the overall matter and energy density, baryon density and curvature of the Universe. On the other hand, the structure in the CMBR anisotropy power spectrum for multipoles beyond $\ell > 1000$ and angular scales less than $20'$ are sensitive to the "microphysics" that controls the formation of large-scale structures in the Universe we see today. Roughly, 1 arc-minute corresponds to 1 comoving megaparsec. By measuring the anisotropies on these small scales, we can get a snapshot of galaxy cluster-sized density perturbations when their amplitudes were less than 10^{-5} of the mean!

With its precision 12-meter diameter primary and its fast and accurate switching capabilities, ALMA will be a powerful instrument with which to image the CMBR anisotropy on small angular scales with unprecedented sensitivity.

2.2 The Sunyaev-Zeldovich Effect

While the primary anisotropies allow us to peer directly at the linear matter density fluctuations at $z \sim 1100$, the Sunyaev Zeldovich effect shows us these same fluctuations in the nonlinear stage as they evolve and collapse to form massive clusters of galaxies.

The space density of the most massive clusters of galaxies is extremely sensitive to cosmological parameters such as the matter density Ω_0, cosmological constant Λ_0, baryon density Ω_B, and "shape parameter" Γ or the Large-Scale Structure related σ_8, the current rms density fluctuation amplitude in spheres of radius $8\,\mathrm{h}^{-1}$Mpc (eg. Bond & Myers 1992b, Bond & Myers 1996, Mohr et al. 1999, Holder & Carlstrom 1999). Because clusters can be detected at any redshift using the SZE, without the cosmological dimming that attenuates the X-ray and optical emission, the SZE "sky" looks very different for differing cosmologies.

The SZE in nearby clusters (Myers et al. 1997) and intermediate redshift clusters (Carlstrom et al. 1996) has been clearly measured by single dishes and imaged by interferometers respectively. In the near future, the CBI will provide SZE images of nearby clusters with $4'$ resolution at 32 GHz. ALMA, and CARMA in the north, will provide even higher resolution with much greater sensitivity, which will allow detailed modeling of a given cluster. This will allow use to use infer other details of the cluster astrophysics as well, such as the importance of magnetic fields and turbulence in the pressure balance of the IGM, and the nature of the dark matter by restricting the possible models which will fit a given cluster given measurements of X-ray emission and weak lensing along with the SZE.

ALMA will also provide high-sensitivity images of the SZE in the most distant clusters as well as survey regions of the sky for the "ambient" SZE to test cosmological models. In particular, ALMA will be able to extend these studies to clusters at higher redshifts, while the addition of the total-power scans to the interferometer data will improve the image fidelity, especially for probing the low level SZE profile in the outskirts of the clusters.

The exquisite sensitivity of ALMA at these frequencies will allow a number of novel measurements to be made. Another example of the potential of SZE as an astrophysical probe is the possibility of detecting the decrement in the region surrounding an FRII radio source (McKinnon et al. 1981, Yamada et al. 1999). The presumably extremely hot gas inside the outer bow shock should have a pressure proportional to the Mach number squared. Thus, if this gas is still in the thermal regime and the SZ decrement were detectable, it should be possible to constrain the Mach number of the jet from such observations.

Part of the enhanced sensitivity of ALMA for SZE imaging, even over proposed SZ arrays such as those for CARMA, and to some extent the enhanced VLA, is due to the superb angular dynamic range. Both long and short baselines are measured simultaneously with high sensitivity, which allows removal of confusing signals and detection of faint extended SZ decrements in the presence of foregrounds and backgrounds. Naturally, this will allow SZE detections in the less rich groups and clusters, as well as possibly measuring the decrement due to the warm (sub keV) ISM of individual galaxies.

2.3 Extragalactic Radio Astronomy

ALMA as a centimeter-wave telescope will be an important addition to the world radio astrophysical arsenal, especially considering that the SKA and ATCA will not operate with significant efficiency at these short wavelengths. There are a number of scientific programs that suffer from the lack of a sensitive high-frequency array in the Southern hemisphere. ALMA with 64 12-meter antennas will have an effective collecting area greater than the VLA at 30 GHz and 43 GHz above (4640 m^2 for 27 $\times$ 25-m at $\epsilon_a = 0.35$, versus

5720 m^2 assuming 64 $\times$ 12-m at $\epsilon_a = 0.79$). In addition, the larger primary beam of ALMA versus that of the VLA will allow imaging of larger objects, while the better beam will improve mosaicing as a second aid to imaging extended structures. A large number of the well-studied radio galaxies fall into this size class that will benefit from the high-fidelity extended-source imaging that ALMA will provide.

Cosmological applications such as the survey for and monitoring of gravitational lenses (eg. Myers 1999) will greatly benefit from ALMA. Studies of the central engines of radio-loud AGN require high-frequency observations to probe deep within the jet. In particular, ALMA will be an important addition to global (and space) VLBI at 7mm. Finally, although the redshifted FIR thermal dust emission from forming galaxies can be detected in the sub-mm and mm (eg. Bond & Myers 1992a), redshifted molecular line emission will be observable at centimeter wavelengths, as well as nonthermal continuum emission from H II regions and the cosmic ray electrons.

When we consider synchrotron radiation from active galactic nuclei and their radio halos, as well as the general cosmic ray medium of more normal galaxies, the high frequency measurements by ALMA at 30–46 GHz as well (perhaps) at 90 GHz will allow us to probe the highest energy ultra-relativistic electrons, presumably being generated promptly by catastrophic phenomena (eg. supernovae, active jets and shocks). Measurement of the synchrotron spectral energy distributions will help us understand the issues of particle lifetimes and magnetic field coupling in these sources.

It should be stressed that very little has been done in this area in this frequency band due to the poor surface-brightness imaging of the current VLA. This is an area where ALMA can make significant impact.

2.4 Galactic Radio Astronomy

Some of the imaging issue for galactic objects are similar to those presented for the extragalactic sources and the SZE — surface brightness sensitivity due to the ability to place the smaller antennas in a compact configuration, as well as having a large number of antennas to keep the collecting area high and simultaneously cover a large range (a decade or more) in angular scale.

The SEDs and especially the structure of galactic SNR at 30 – 46 GHz is largely unexplored at the present. For example, in 1993, an attempt was made by myself and Kulkarni at Caltech to use the OVRO 5m single dish at 30 GHz to measure the brightness of a number of SNR in this band. However, the confusion introduced by nearby galactic emission as well as our inability to resolve these sources limited the usefulness of these (unpublished) observations. The current VLA over-resolves this emission on the other hand. It will require an array such as ALMA to image these difficult objects (see the current low-frequency maps of Cas-A to realize just how difficult!). Furthermore, the geographic location of ALMA will be ideal for observing the galactic core as well as the Magellanic Clouds.

[I NEED SOME HELP HERE!]

2.5 Planetary and Solar Astronomy

[I NEED EVEN MORE HELP HERE!]

3 Summary

- Anisotropy in the Cosmic Microwave Background on scales below $20'$ probes the linear density field and gravitational potential on cluster and supercluster scales at the time of last scattering ($z \sim 1100$).

- ALMA can efficiently make images of CMB anisotropy temperature and polarization fluctuations at 10mm, 7mm and 3mm.

- On angular scales less than $4'$ ALMA will be able to separate out anisoropies due to the primary CMBR fluctuations and those due to the Sunyaev-Zeldovich effect.

- The total power stability and fast switching capability are critical for the meshing of the ALMA interferometric and single-dish data for imaging of extended astronomical targets such as the CMBR, SZE as well as galactic molecular cloud studies.

- A significant problem facing large-scale CMBR and SZE surveys is the identification and removal of galactic and extragalactic foreground emission. Observations at the wavelength of interest (15mm - 3mm) but at higher angular resolution are required. The VLA and GBT will perform this service in the North, but ALMA will be critical for all-sky surveys such as those done by MAP and Planck.

- Probing the very high-redshift Universe beyond a redshift of 6 out to recombination will be the "final frontier". The capability for observing highly redshifted molecular lines will be critical for shedding light on these "Dark Ages" of cosmology.

- There are a number of other important contributions to extragalactic and galactic astronomy that ALMA at 10mm and 7mm will be critical to, such as VLBI (in conjunction with the VLBA and the Southern Hemisphere VLBI telescopes), surveys for and monitoring of gravitational lenses, disentangling star formation and AGN contributions to the radio spectrum of distant galaxies, and the mapping of the small-scale diffuse anomalous galactic emission seen in CMBR observations.
- Conclusion: *The 10mm and 7mm receiver suite proposed for ALMA will add significant new astronomical capabilities to the array, and moreover these capabilites will be unique in the Southern Hemisphere.*

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