ALMA in the Coming Decade: A Development Program

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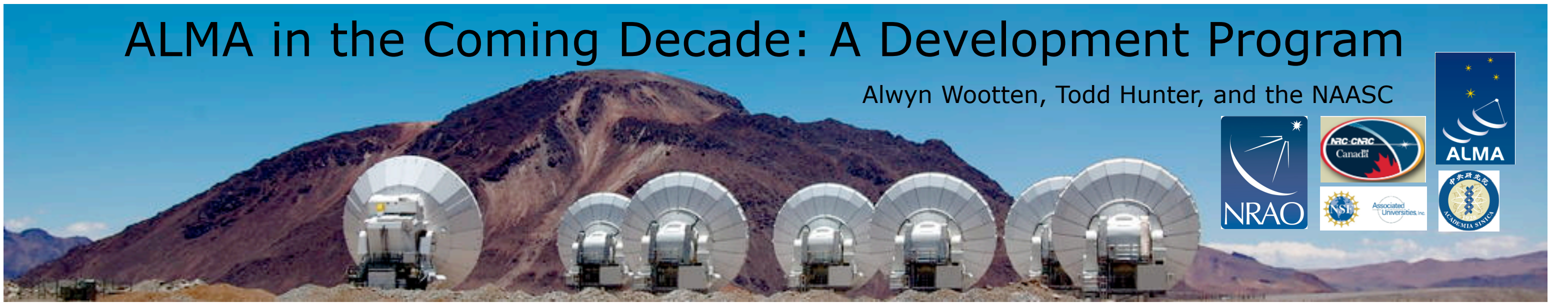


Motivation

ALMA will transform astronomy beginning with Early Science results later this year. It will reach full operation by 2013 and will eclipse any current millimeter or submillimeter array in sensitivity and resolution by nearly two orders of magnitude. ALMA will operate from 3mm to 0.3mm across a decade of nearly complete frequency access as enabled by its broad bandwidth receivers, powerful correlators and spectacular site. As we have invested $1.3 billion to realize the biggest historical advance in ground-based astronomy, it is vital to maintain and expand its capabilities. Toward this end, the ALMA Operations Plan envisages an ongoing program of development and upgrades which may include hardware, software or data analysis tools. With a modest investment of about 1% of capital cost per year (reaching about $15 million in 2015) divided among the three funding regions (North America, Europe, East Asia), ALMA will continue to lead astronomical research through the 2011-2020 decade and beyond. We present the science case for several developments along one possible path.

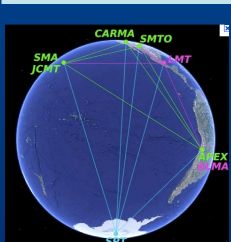
Enable Very Long Baseline Interferometry

Advantages for Science:

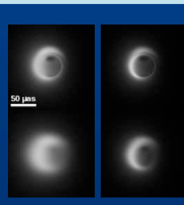
- Extends native resolution from 0".015 to ALMA-VLB's 0".00002 at 345 GHz.
- Very large collecting area enables fast fringe-fitting, excision of atmospheric effects.
- Excellent site for weather & location relative to black holes Sgr A* (δ=-29°), M87 (δ =+12°)
- Superb submillimeter performance less susceptible to interstellar scattering

Prospects for Development:

ALMA's correlator is VLBI-ready, but additional hardware and software is needed to combine the signals from the entire array into a powerful element of a global VLB array.



Location of ALMA with respect to the other millimeter observatory locations—the 'Event Horizon Telescope'.



Models and simulated images of Sgr A* from Doeleman *et al.* (2008)—(left 345 GHz; right 230 GHz; upper images are model and lower images have simulated interstellar scattering.

Excerpts from the Astro 2010 Decadal Survey Report:

"…ALMA is expected to unveil the birthing of new worlds."

"ALMA will revolutionize the imaging of protoplanetary disks…"

"ALMA…will detect the cold gas and the tiny grains of dust associated with the first large bursts of star formation…"

Panel on Radio, Millimeter and Submillimeter Astronomy:

"…fully supports the development plan" ($90 million during the current decade, about 1/3 of which comes from North America)

Milestones for ALMA Development:

- **July 2010**: ESO issues Call for Advanced Study for Upgrades of ALMA (11 proposals received, 4 selected as high priority to continue: Band 9 upgrade from DSB to 2SB, VLBI, Band 5 full production, Implications and cost of doubling the backend bandwidth)
- **Feb 2011**: NSB approves the 2012-2015 NAASC budget, including the ability to fund development projects (once they are accepted and authorized by JAO)
- **March 21-22, 2011: ALMA NA Development Workshop to be held in Charlottesville, VA**
- **Later in 2011**: NA Call for ALMA Development Studies (to help prepare the NA community for future Development Call from JAO)

One Possible Path for Development

1. Immediate-term: VLBI capability

The science case for the Event Horizon Telescope (for which ALMA would be the key member) is well-recognized around the globe and the technology to achieve it is available today (see Left Panels). This project also received high priority in the 2010 ESO Call for ALMA Development Studies.

2. Intermediate-term: Band 1, hardware research, and software tools

Building Band 1 (31-50 GHz) would expand ALMA's science capabilities in the fields of high-redshift molecular gas, Sunyaev-Zeldovich clusters, protoplanetary disks and interstellar chemistry (see Right panels). Support for new technology and software development in the university community is also crucial during this phase:

- Low noise mixer and amplifier development
- New spectral analysis tools for ALMA data
- Continued mm/subm laboratory spectroscopy

3. Long-term: wider bandwidth, more sensitivity

As ALMA matures, a factor of 5 increase in instantaneous bandwidth can be envisioned with future broadband mixers, amplifiers, digitizers and correlators. Combined with a possible factor of ~2 improvement in receiver performance, a 20-fold increase in observing speed is conceivable, particularly in Band 6 and above. Focal plane arrays can also increase speed for mapping projects.

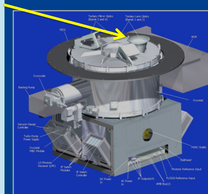
Build Band One (31-50 GHz)

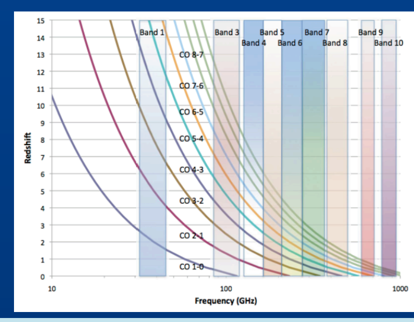
Advantages for Science:

- Allows high angular resolution imaging of the Sunyaev-Zel'dovich effect to study clusters of galaxies.
- Reveals warm molecular gas in high-redshift galaxies, including CO(3-2) at z=6-10 and CO (4-3) at z=9-13.
- Probes protoplanetary disks: long wavelength emission distinguishes between models of large dust grains
- Contains strong emission lines from light abundant molecules with widespread emission (CS, H_2CO)
- Contains strongest emission from heavy organic species such as glycine and prebiotic molecules

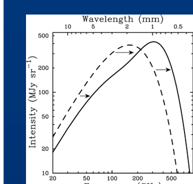
Prospects for Development:

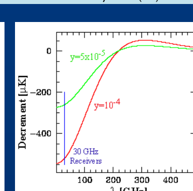
- Can populate existing empty space in cryostat with state-of-the-art HEMT amplifier receivers

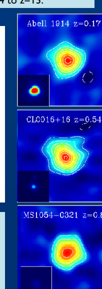




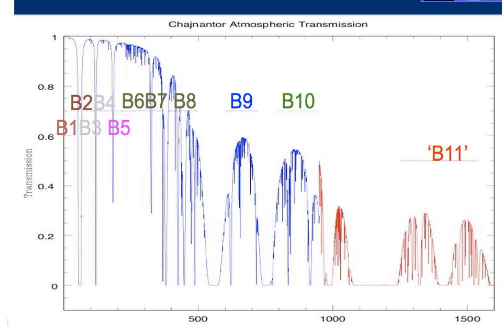
Observed frequency of ^{12}CO transitions as a function of redshift. The frequency range of the ALMA bands is also shown. Band 1 would extend the detectability of CO(4-3) from z=4 to z=13.







Left) The Sunyaev-Zel'dovich Effect is a decrement in the Cosmic Microwave Background at long wavelengths and an increment at short wavelengths. **Center)** For ALMA, Band 1 is optimal as this is the ALMA band with the lowest possible system temperature, and the largest field of view (3 arcmin) which is well-matched to the angular size of clusters. **Right)** SZE images of three clusters at ~30 GHz with corresponding X-ray images inset (Carlstrom et al. / Univ. of Chicago).



Atmospheric transmission from the ALMA site. Blue curve: below 950 GHz is shown with typical weather conditions of 0.5 mm precipitable water vapor (PWV); **Red curve:** above 950 GHz is shown with excellent weather (0.2 mm PWV) demonstrating the possibility of a future Band 11 in the terahertz regime.

Long-term goals: Wider bandwidths, lower noise receivers

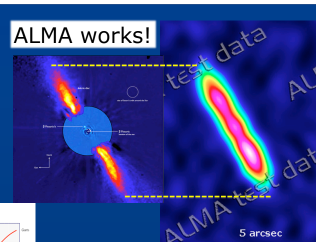
Advantages for Science:

- Improves imaging speed and ultimate sensitivity for all science (up to 20x improvement in speed)
- Vastly increases the number of detectable nearby stars and extra-solar planets

Prospects for Development:

- Upgrade Band 3 with LNA covering 67-116 GHz (the original Band 2+3), frees up space for 'Band 11'
- Develop SIS mixers with wider IF bandwidth (~20 GHz) in Band 6, and eventually higher Bands
- Install faster digitizers in antennas to handle the larger bandwidths
- Construct new correlator, initially for coarse channel continuum studies, later for spectral lines

ALMA works!



Top Left) Beta Pictoris in near infrared light. This very faint environment is revealed after a very careful subtraction of the much brighter stellar halo. The outer part of the image shows the reflected light on the dust disc, as observed in 1996 with ADONIS on ESO's 3.6m; the inner part is the innermost part of the system, as seen at 3.6 microns with NACO on the VLT. The newly detected source is more than 1000 times fainter than Beta Pictoris, aligned with the disc, at a projected distance of 8 times the Earth-Sun distance. **Right)** 870 micron continuum image from ALMA obtained in late 2010 with 8 antennas.

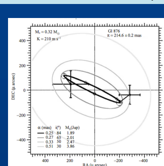
Detecting Extrasolar Planets

Astrometric wobble

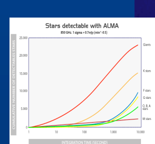
- Unlike transits and radial velocity methods, the magnitude of the signal is independent of the orbital inclination! In fact, the wobble can deliver a measurement of the inclination.
- Radio astrometric accuracy is much finer than the beamsize. With a S/N of 100, one can reach 75 microarcsec at 345GHz.
- ALMA with 50 antennas at 345 GHz can detect the photosphere of a main sequence G star at 10pc (within which there are 20) at 30-sigma in 6 hours (0.25 milliarcsec).
- A factor of 20 increase in speed from a better receiver and bandwidth would enable a 100 sigma detection in 3 hours.

Absorption line studies of transits?

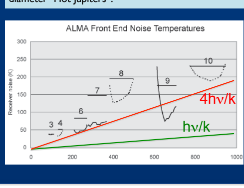
- With the improved sensitivity, it may be possible to detect absorption lines during the (known) transit times of large diameter "Hot Jupiters".



Astrometric deviations on the plane of the sky of Gliese 876 (4.7pc) measured with the HST FGS in fringe-tracking mode (Benedict *et al.* 2002). The wobble amplitude is 250 microarcsec, and the inferred planet mass is 1.9 Jupiter mass.

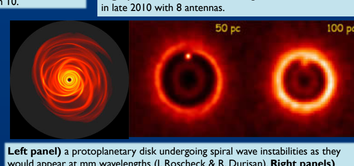


ALMA can detect the thermal photospheres of thousands of stars in Bands 3 through 10.



Receiver development

- ALMA receiver performance is excellent, and approaches 4X quantum limit in most bands (Note: bands 9 & 10 are DSB).
- A factor of ~two improvement is conceivable with further technology development
- Adding a terahertz band to ALMA may become practical as new materials for SIS junctions are explored and good performance is achieved in the lab. It would be prudent to first demonstrate good operational efficiency of ALMA's antennas and calibration at Band 10.



Left panel) a protoplanetary disk undergoing spiral wave instabilities as they would appear at mm wavelengths (J. Roscheck & R. Durisan). **Right panels)** Simulation of 950 GHz ALMA observations of a face-on disk with a gap cleared by a Jupiter-mass protoplanet orbiting at 5 AU radius (Wolf & D'Angelo 2005).

Simple Upgrades for Increased Observing Efficiency

Development: Double the number of frequency subarrays from 2 to 4 in the main array
Science Advantages: Enable simultaneous multiband observations of short duration events in comets, gamma ray bursters; provides synergy with LSST.

Development: Increase data rate from current maximum of 60 MB/s (correlator can produce up to 1 GB/s)
Science Advantages: More of incoming signal collected, higher resolution on more spectral lines.