Prospects For Outflow and Jet Science with ALMA

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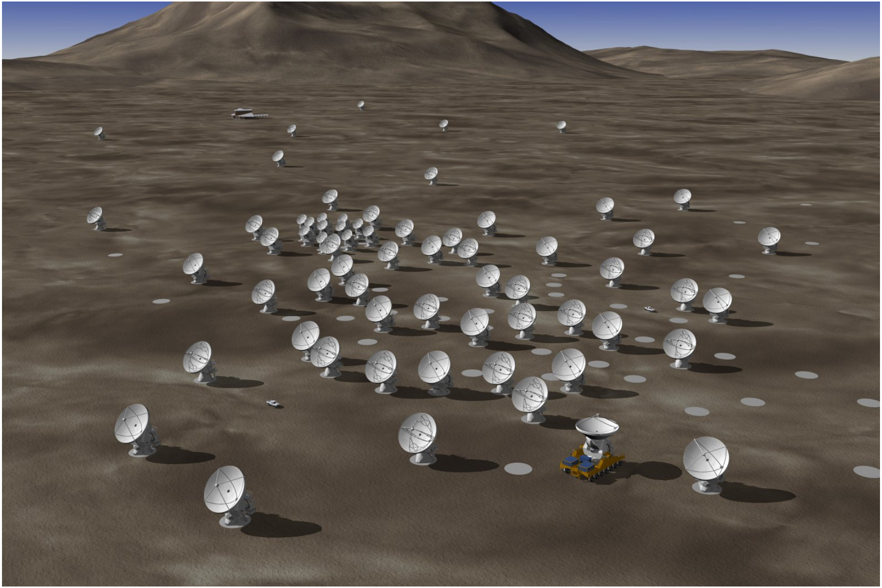
Invited talk given at the conference “Protostellar Jets In Context”, Rhodes, July 2008.

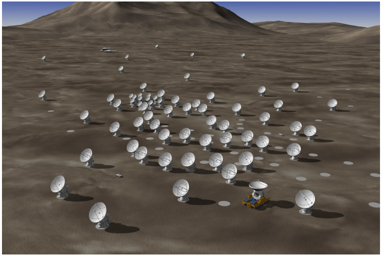
Atacama Large Millimeter/submillimeter Array in 2013



Plan

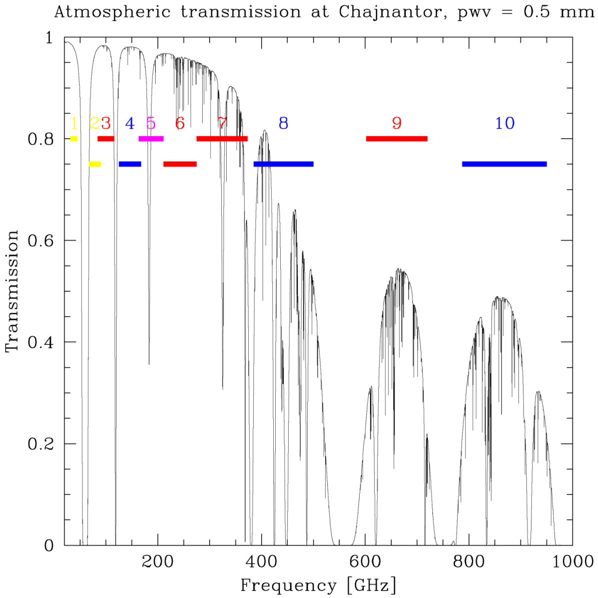
1. ALMA Overview
2. Probing Jets and Outflows with ALMA
3. ALMA Construction Status
4. Conclusions/Challenges

Key Specifications



- 54×12-m plus 12×7-m antennas, at 5000 m site
- Up to 2016 simultaneous cross correlations
- 60 arcsec field of view at 100GHz/3mm
- About 40 configurations, from 150m to 15km in size (3 arcsec to 30 mas at 100GHz)
- 10 receiver bands covering 31-950 GHz
- 84 GHz lowest frequency at first light
- 8 GHz bandwidth, two polarizations, IQUV imaging
- 'Adaptive Optics' to correct atmosphere

Transmission at ALMA site



Why be excited about ALMA?

- Need the submillimetre to study young, embedded systems
  - Class II/III (CTTS and WTTS) are the end-game as far as accretion/ejection is concerned
  - Study earliest phases of disk/jet formation: catch them young! Accretion rates $10^{-4,-5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$
- Angular resolution up to 0.01 arcsec: mapping deep into the potential well
  - Resolve collimation scale, look for rotation and study disk/wind interface
- Measure disk/envelope/jet properties simultaneously
- Exquisite velocity resolution: $< 1\,\mathrm{km\,s^{-1}}$
- No ghastly slits — just data cubes
- thermal brightness sensitivity even on the longest baselines (just!)
- Range of line tracers, probe a wide range of gas conditions
- Full polarisation capability for magnetic field studies

Jet/Disk sources are ideal ALMA targets

- Warm/hot compact gas
- Small scale structure

Limitations:

- Small field of view (18" at 345 GHz): best to target small sources, although mosacing is possible.
- Which molecular tracers exist in regions of interest?

Sensitivity of ALMA after 8 hours integration

ν/GHz	B_{max}	θ_b	$\theta_b(140pc)$	$V_{kep}(1M_\odot)$	ΔT(1km/s)
115	150 m	3.6″	500 AU	1.3 km/s	4.6 mK
	1500 m	0.36″	50 AU	4.2 km/s	0.46 K
	15 km	0.036″	5 AU	13 km/s	46 K
230	150 m	1.8″	250 AU	1.9km/s	6 mK
	1500 m	0.18″	25 AU	6km/s	0.6 K
	15 km	0.018″	2.5 AU	19km/s	60 K
345	150 m	1.2″	170 AU	2.3km/s	9 mK
	1500 m	0.12″	17 AU	7km/s	0.9 K
	15 km	0.012″	1.7 AU	23km/s	90 K
460	150 m	0.9″	130 AU	2.6km/s	32 mK
	1500 m	0.09″	13 AU	8km/s	3 K
	15 km	0.009″	1.3 AU	26km/s	300 K
690	150 m	0.6″	85 AU	3.3km/s	21 mK
	1500 m	0.06″	8.5 AU	10km/s	2.1 K
	15 km	0.006″	0.85 AU	33km/s	200 K

Also (eventually) 900 GHz observations including CO J=8-7

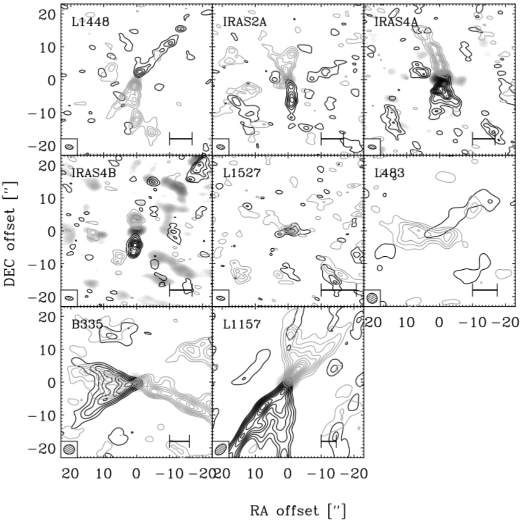
Sensitivity of ALMA after 8 hours integration

- At higher frequencies, resolution increases but observations get harder: atmospheric opacity and phase errors increase
- But bandwidth increases for a given velocity resolution
- Also, a given species' critical density and temperature above ground increases, so expect higher emission strengths (in temperature units)

For example, CO J=6-5

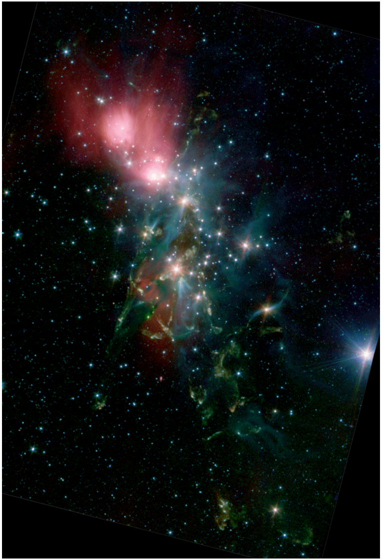
115 K above ground, critical density about $10^5\,\mathrm{cm}^{-3}$

Studying outflow propogation with ALMA



- SMA Outflow Survey $\sim 2''$ beam (Jorgensen et al 2008)
- With ALMA, can be done at e.g. 0.2 arcsec resolution
- $\Delta T = 0.6\,\mathrm{K}$ at CO 2-1
- Need for small mosaics?
- Simultaneous data on disk/infalling material
- Link to star formation

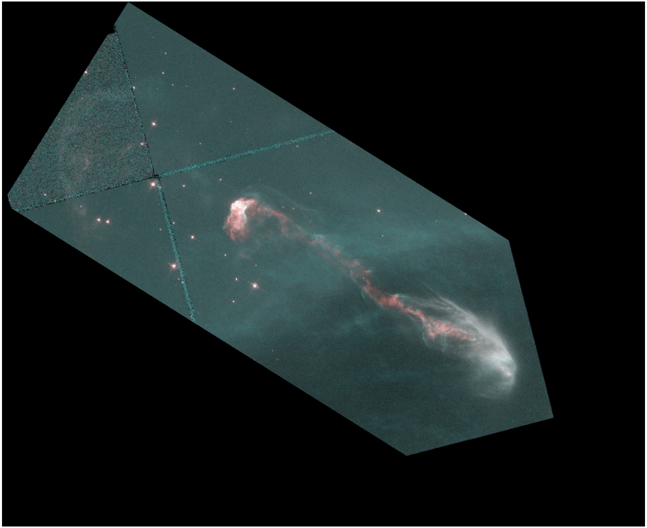
Science made possible with high angular resolution



NGC1333 Hα, [SII], Spitzer (Bally et al)

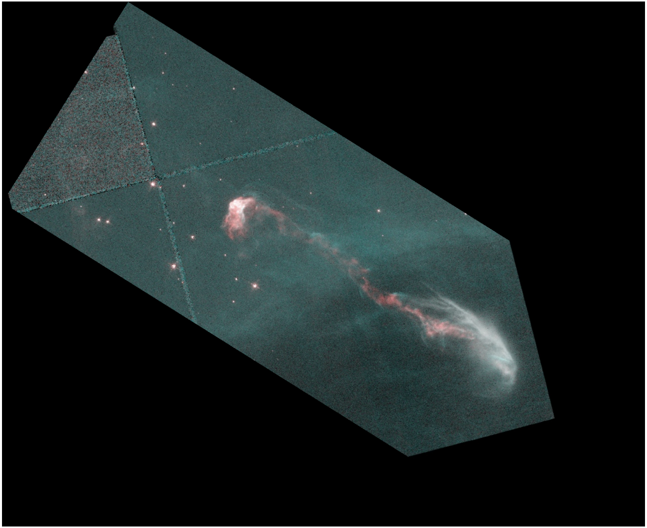
- Multiplicity: resolving confused cluster forming regions
- Resolving distant high-mass outflows
- Studying outflows across the galaxy
- Outflows from low-mass embedded YSOs: testing scaling relations

Proper motions in HH46/7



Hartigan et al 2007

Proper motions in HH46/7



Hartigan et al 2007

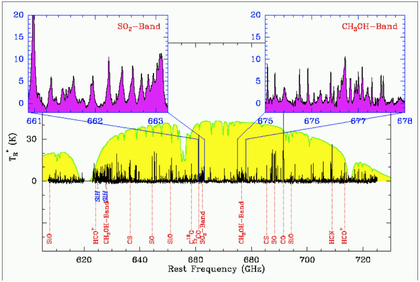
Outflow Proper Motions with ALMA

$$\theta = 0.2'' \left(\frac{D}{100\,\mathrm{pc}}\right)^{-1} \left(\frac{v}{100\,\mathrm{km\,s^{-1}}}\right) \left(\frac{t}{1\,\mathrm{year}}\right)$$

- ALMA will have excellent astrometry
- Typical proper motions detectable after one year/a few years
- Watch the molecular outflows growing, disambiguate models (?)

Don't forget disk proper motion studies as well.

Jet/Outflow Shocks and Chemistry

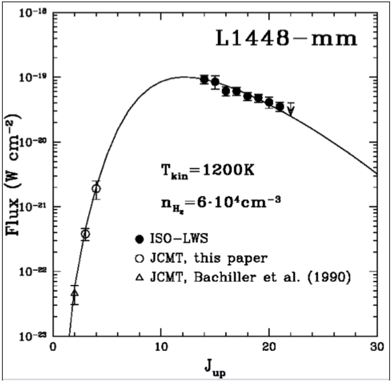


Schilke et al 2007

- Complex chemistry known in outflows
- Detailed shock physics: chemical enhancements in bowshocks, resolving cooling lengths, ion-neutral slippage, link to NIR diagnostics
- 8 GHz bandwidth, high spectral and spatial resolution
- too much detail?

Calorimetry: Measuring the True Power of Outflows

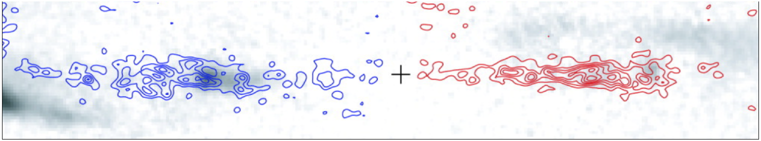
- Good coverage of CO lines: 1-0, 2-1, 3-2, 4-3, 6-5, 8-7
- Accurate excitation, and isotopologues give optical depth.
- Distinguish separate flows with high resolution
- Inclinations from disk geometry (also proper motions?)
- Remaining uncertainty: X(CO)



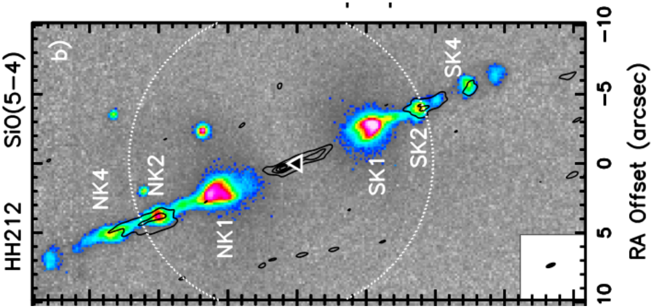
Nisini et al 2000

Towards the central engine

State of the art is about 0.4 arcsec resolution:

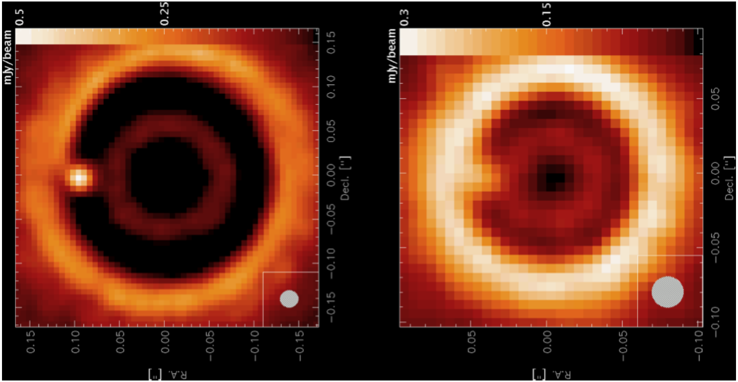


HH211 in SiO 1-0 at 0.5 arcsec resolution (Chandler and Richer 2000), VLA



HH212 SiO 5-4 Codella et al 2007; Plateau de Bure

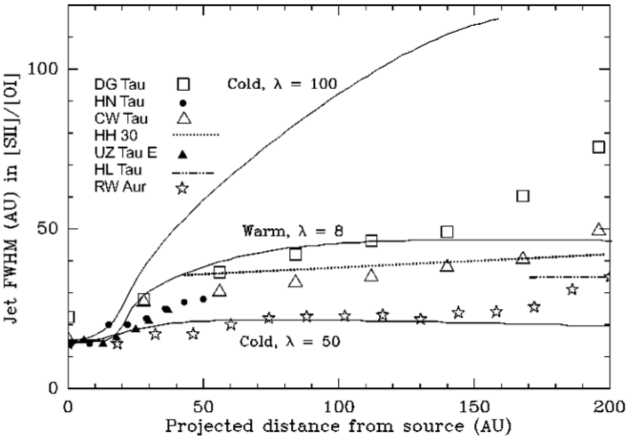
Resolving the Disks (and inner envelopes)



Wolf et al 2005

- Proto-Jupiter at 5AU in a face-on disk at 50/100pc
- 8 hour integration with ALMA at 850 GHz.
- Expect non-axisymmetric disks

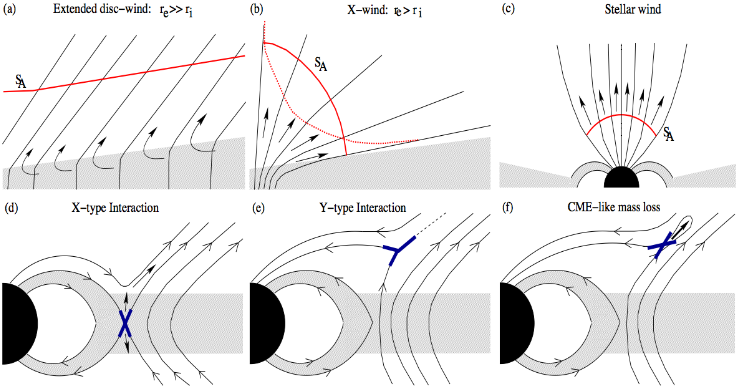
Probing the Launch/Collimation Scale



From Ray et al PPV

- In TTau's at least, collimation scale is below 20 AU

Probing the Launch/Collimation Scale

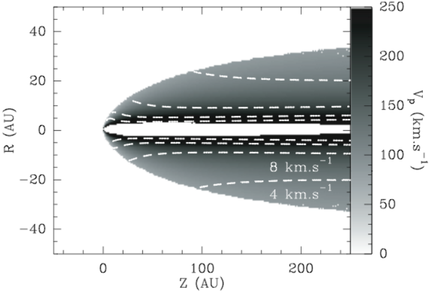


- Lots of models to test!
- Common theme: all the interest is on scales below 20 AU
- Best hope: ALMA long baselines at 650 GHz.

Sensitivity of ALMA after 8 hours integration

ν/GHz	B_{max}	θ_b	$\theta_b(140pc)$	V_k	ΔT(1km/s)
690	150 m	$0.6''$	85 AU	3.3km/s	21 mK
	1500 m	$0.06''$	8.5 AU	10km/s	2.1 K
	15 km	$0.006''$	0.85 AU	33km/s	200 K

Observing Jet Rotation



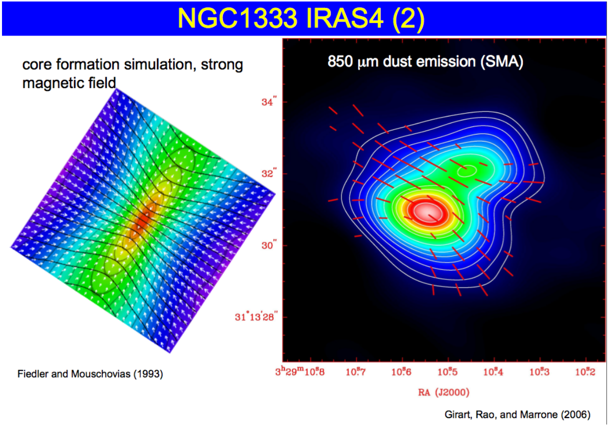
Pesenti et al

- Rotation debate fuelled by marginal angular resolution
- This is easy target for ALMA if molecular tracers in gas phase: CO 6-5? CI? SiO? H_2O?
- Simulations please!
- Note disk rotation also measured straightfowardly

Challenge

- Which tracers exist in the jets?
- CO, SiO, neutral carbon, H_2O? Dust? [See Panoglou, Cabrit poster]
- Or do the molecules just trace entrainment/shocks, and not the atomic D/X/stellar wind?

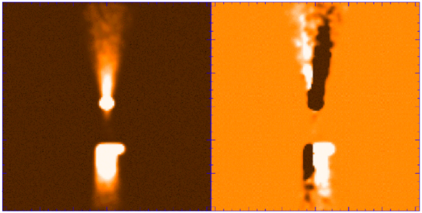
Probing the Magnetic Field: Dust Continuum

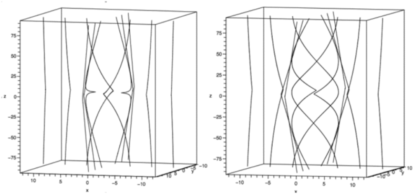


Slide by Dick Crutcher

- ALMA enables such studies down to arcsec scales and below
- Field geometry on 100AU scale (assuming dust aligned)

Probing the Magnetic Field: Dust Continuum





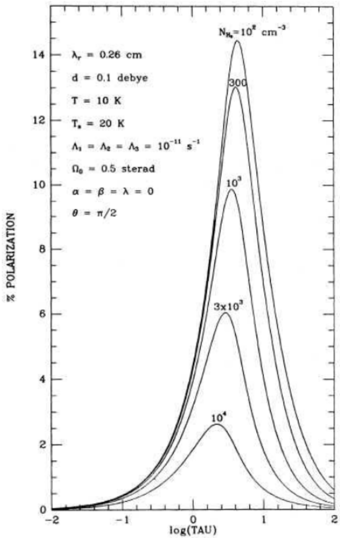
8% NIR circular polarisation modeled as scattering by *aligned grains*. Inferred helical magnetic field (Chrysostomou, Lucas & Hough in Nature, 2008).

Challenge

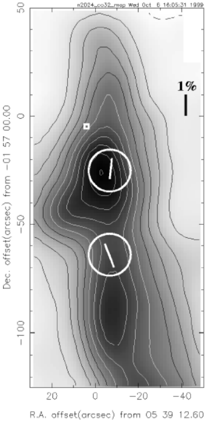
Does the dust stay aligned close to the launch point?

Probing the Magnetic Field: Linearly Polarised Lines

- Goldreich-Kylafis effect: rotational lines linearly polarised by magnetic field
- highly dependent on τ, radiation field, etc.
- hard to interpret



Probing the Magnetic Field: Linearly Polarised Lines



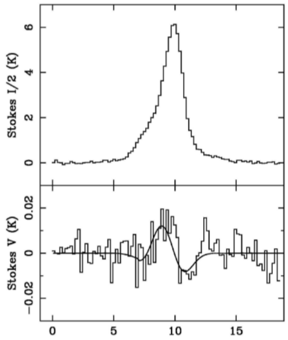
Greaves et al 2005: Polarised CO 2-1 emission in outflow

Challenge

Can we model linear line polarisation and deduce unambiguous field geometries?

Probing the Magnetic Field: Circular Polarisation

CN 1-0 (113 GHz) CN
Zeeman (IRAM 30-m)



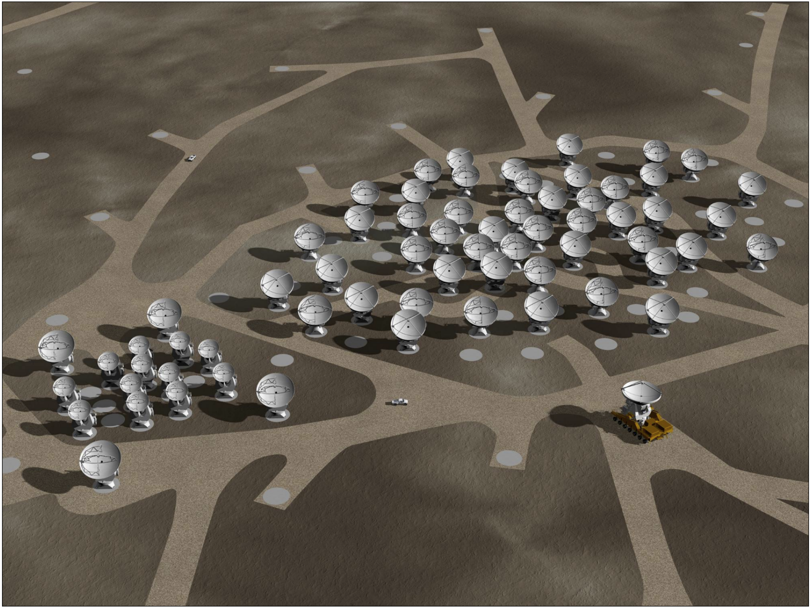
$B_{LOS} = -0.36 \pm 0.08$ mG

Crutcher et al. 1999

- Zeemann signature clean
- But low Zeemann coefficients in the submm
- CN promising at 113 GHz — potentially very high disk/jet fields

ALMA Construction Status

ALMA: Main and Compact Arrays = 66 antennas



Road to ALMA from the salar

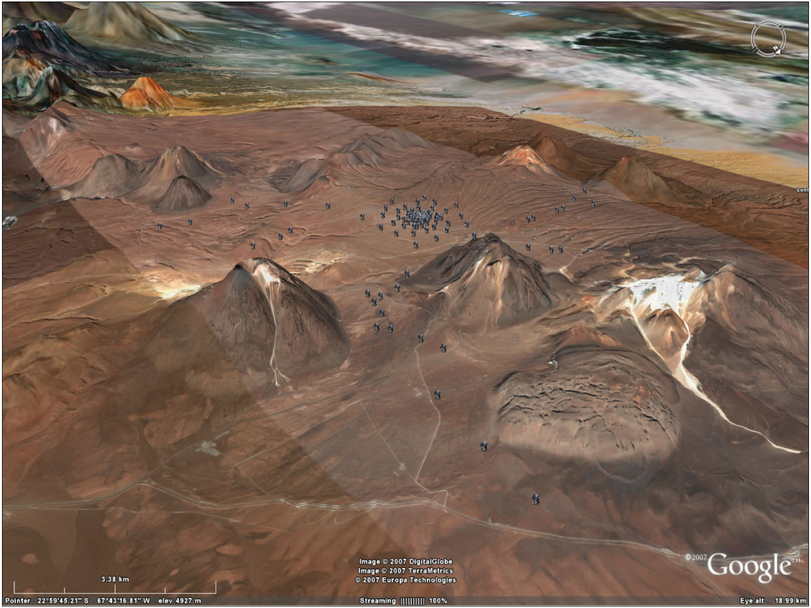
Operations Support Facility at 3,000 m (OSF)

8 Antennas now in Chile

Technical Building at 5,000 m altitude (AOS)

Correlator Room in the AOS Technical Building

Largest configuration of ALMA: 18km baselines



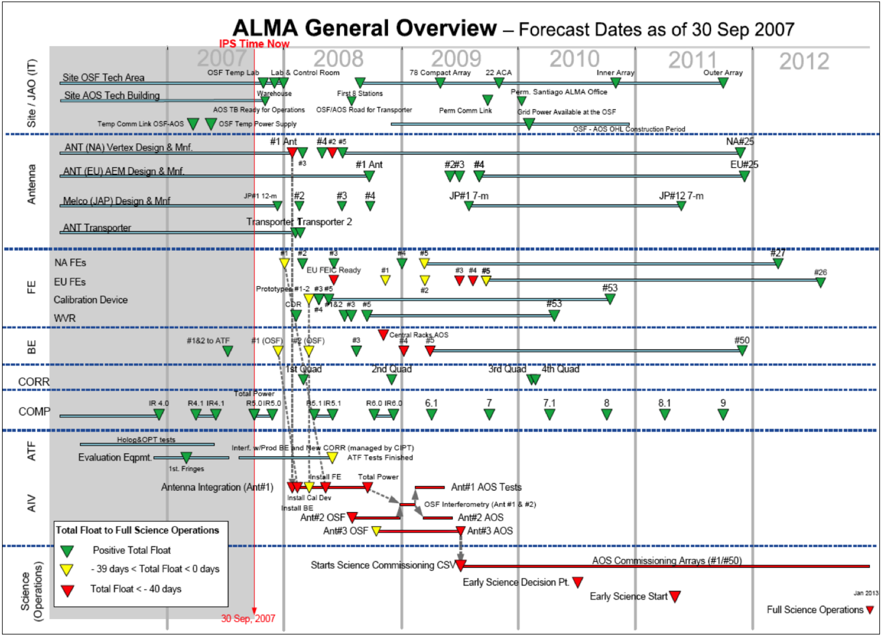
Otto ready for shipping

The ALMA Antenna Transporter

ESO Press Photo 45b/07 (5 October 2007)

First antenna move: July 2008

A recent schedule: completion in 2012 Q4



Conclusions & Challenges

- ALMA is on the move
- Will make many outflow studies easy: jet propogation, bow shocks, jet chemistry etc
- *Just* enough sensitivity to probe down to 2AU — resolve collimation scale, constrain launch scale?
- Interesting opportunities for constraining magnetic field geometry/strength
- 0.1AU is hard: requires optical interferometry on 200 m scales. . . or ALMA++ —with some longer baselines and more antennas
- 10 mas resolution through a turbulent atmosphere
- Accurate polarisation calibration
- What tracers predicted by the various wind models? CO SiO CI?
- Do we expect polarised dust emission on AU scales? Alignment timescale?
- Can we model line polarisation sufficiently well to make this a useful diagnostic tool?
- Zeemann predictions?
- More synthetic observations needed of X + D Wind models!

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership among Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).