ALMA Capabilities for Observing Other □Planetary Systems

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ALMA Observes Other Planetary Systems

- Emphasis has been on optical and infrared wavelengths, as at these wavelengths the Spectral Energy Distributions (SED) of stars and extrasolar planetary systems peak.
- ALMA, reaching long FIR wavelengths with great sensitivity and spatial resolution, will image dust and gas in these systems.
- We consider the ability of ALMA to observe stars and extrasolar planetary systems in various stages of evolution.

A High Level Science Goal for ALMA

- The observation of extrasolar planetary systems is defined to be one of the most important science drivers for ALMA, the second of the highest level science goals defined by the bilateral agreement.

Highest Level Science Goals

Bilateral Agreement Annex B:

"ALMA has three level-1 science requirements:

- The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- The ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.
- The ability to provide precise images at an angular resolution of 0.1". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees. These requirements drive the technical specifications of ALMA. "

A detailed discussion of them may be found in the new ESA publication *Dusty and Molecular Universe* on ALMA and Herschel.

ALMA Provides a New View of Exoplanets at Many Developmental Stages

- Owing to its sensitivity, ALMA will be able to detect, monitor, and even image (for the largest) a very large number of ‘regular’ stars at wavelengths longer than the mid-IR.
  - About 8000 stars from Hipparcos or Gliese catalogs detectable in ten minutes.
- We consider extraplanetary systems in each of four evolutionary stages, from birth to maturity.

ALMA

- International project to build & operate a large (66-antenna) millimeter/submm (λ ~0.35-10mm) array at high altitude site (5000m) in northern Chile.

- Project began in 2002; Japan joined in 2004; project redefined/rebaselined 2005; construction, hardware production lines underway, software in development;

First Fringes 2007 March 2 at 7:13pm MST

early science ~2010, full science operations 2012.

- Considerable infrastructure is on site now leading to the arrival of the first antenna structures next month.

ALMA – Major Elements

Photo H. Heyer (ESO).

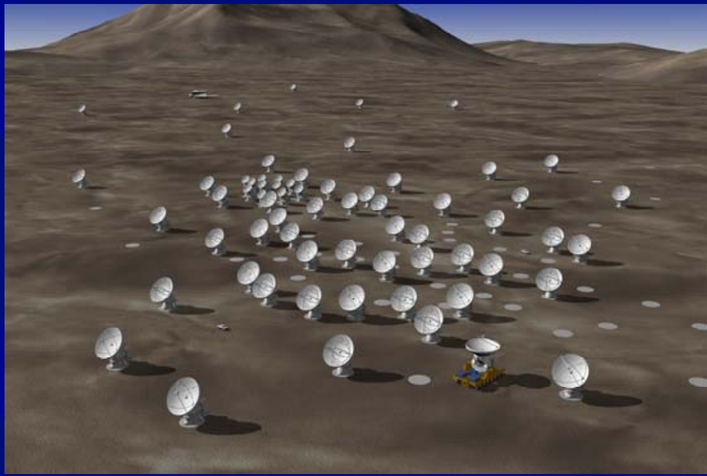
- Partners: ESO – US (NSF)+Canada (NRC) – Chile – Japan ...*Taiwan*

- **Array Operations Site – AOS**
- **Operations Support Facility – OSF**
- **Santiago Central Offices – SCO**
- **ALMA Regional Centers – ARCs + ARClets**

- During full operation, the estimated flow into archive ~ 100 Tbytes per year
- Dataset: proposal, u-v data, a reference image with pipeline processing history, calibration data… modern radioastronomy

ALMA Science Requirements

- High Fidelity Imaging.
- Precise Imaging at 0.1” Resolution.
- Routine Sub-mJy Continuum Sensitivity.
- Routine mK Spectral Sensitivity.
- Wideband Frequency Coverage.
- Wide Field Imaging Mosaicking.
- Submillimeter Receiver System.
- Full Polarization Capability.
- System Flexibility.

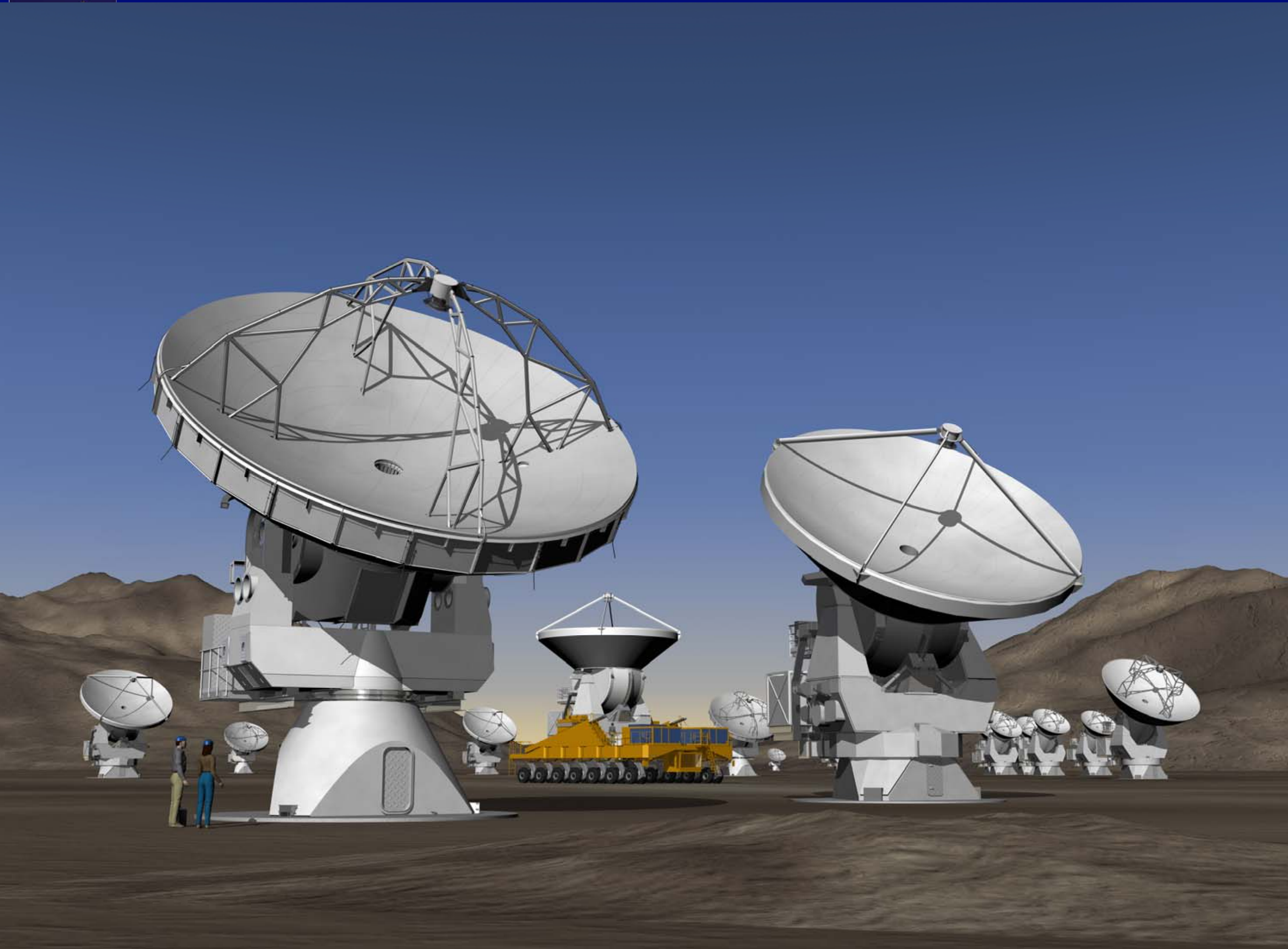


Technical Specifications

- 54 12-m antennas, 12 7-m antennas, at 5000 m altitude site.
- Surface accuracy ±25 μm, 0.6” reference pointing in 9m/s wind, 2” absolute pointing all-sky.
- Array configurations between 150m to ~15 -18km.
- 10 bands in 31-950 GHz + 183 GHz WVR. Initially:
- 84-116 GHz “3”
- 125-169 GHz “4”
- 211-275 GHz “6”
- 275-373 GHz “7”
- 385-500 GHz “8”
- 602-720 GHz “9”
- 8 GHz BW, dual polarization.
- Flux sensitivity 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60 MB/s.
- All data archived (raw + images), pipeline processing.

ALMA: Summary of detailed requirements

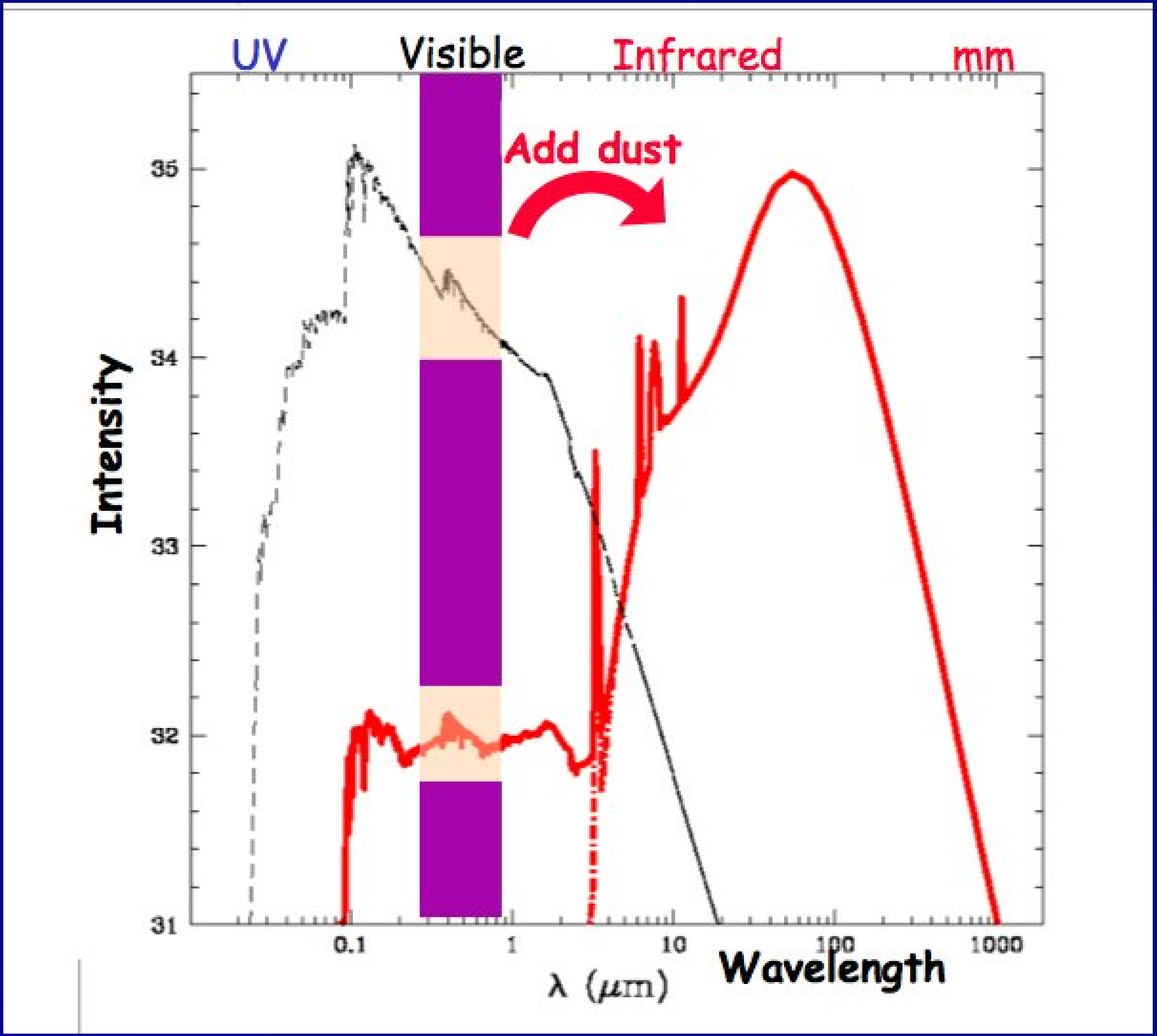
Frequency	30 to 950 GHz (initially only 84-720 GHz fully instrumented)
Bandwidth	8 GHz, fully tunable
Spectral resolution	31.5 kHz (0.01 km/s) at 100 GHz
Angular resolution	30 to 0.015” at 300 GHz
Dynamic range	10000:1 (spectral); 50000:1 (imaging)
Flux sensitivity	0.2 mJy in 1 min at 345 GHz (median conditions)
Antenna complement	50 antennas of 12m diameter, plus compact array of 4 x 12m and 12 x 7m antennas (Japan)
Polarization	All cross products simultaneously



Infrared Emission: An Example

Although ALMA will observe stellar photospheres in the Rayleigh-Jeans part of their Spectral Energy Distibutions, it excels at detecting cool dusty objects

- Emit directly in IR
- Can reprocess shorter wavelength radiation



Best Frequency for ALMA Continuum?

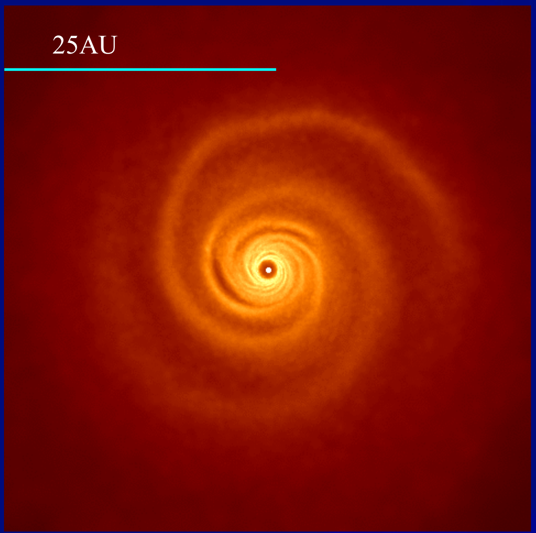
- Define a Figure of Merit
- For observations of any thermal blackbody (with emission which goes like λ^{-2}), the figure of merit that one wants to maximize is $X_\nu=\nu^2/\Delta S$, where ΔS is the noise at frequency ν. We want to maximize X_ν because it is proportional to the SNR obtainable. For ν>350 GHz, need better weather so use pwv=1.5mm below and 0.5mm above this ν.

Frequency	ΔS (mJy)	X_ν
230	0.07	76
345	0.12	99
675	0.85	54

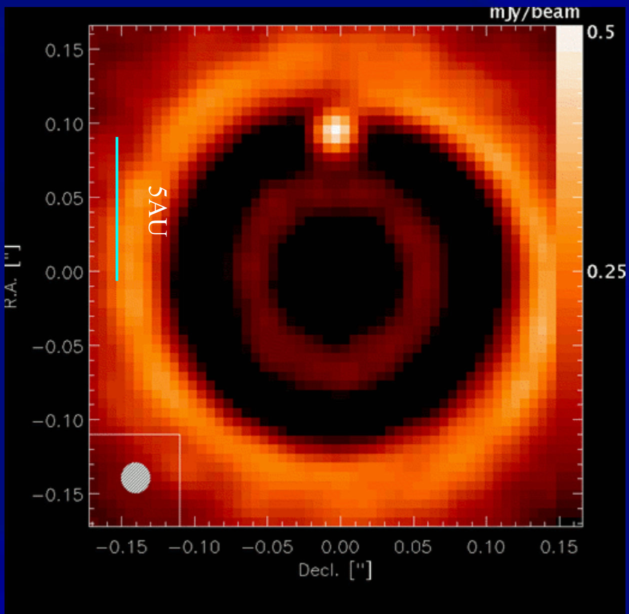
Birth of Stars and Planets

Evolutionary Sequence—
Molecular Cloud Core to Protostar (10^4 yrs) to
Protoplanetary Disk (to ~10^6 yrs) to
Debris Disk (to 10^9 yrs)

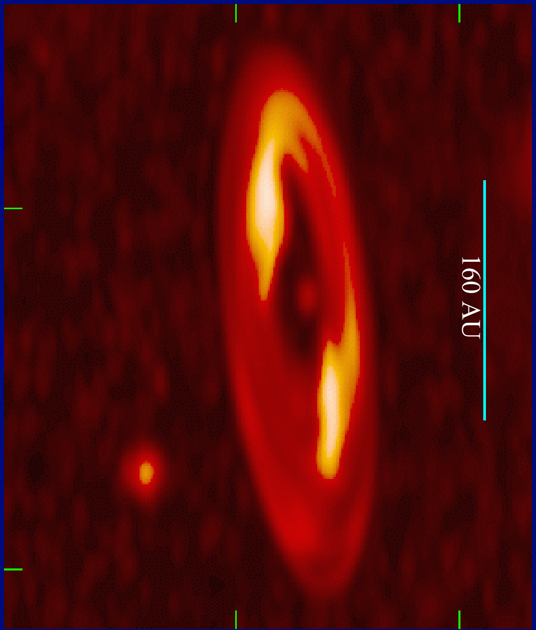
Lodato and Rice 2005



Wolf and D'Angelo 2005



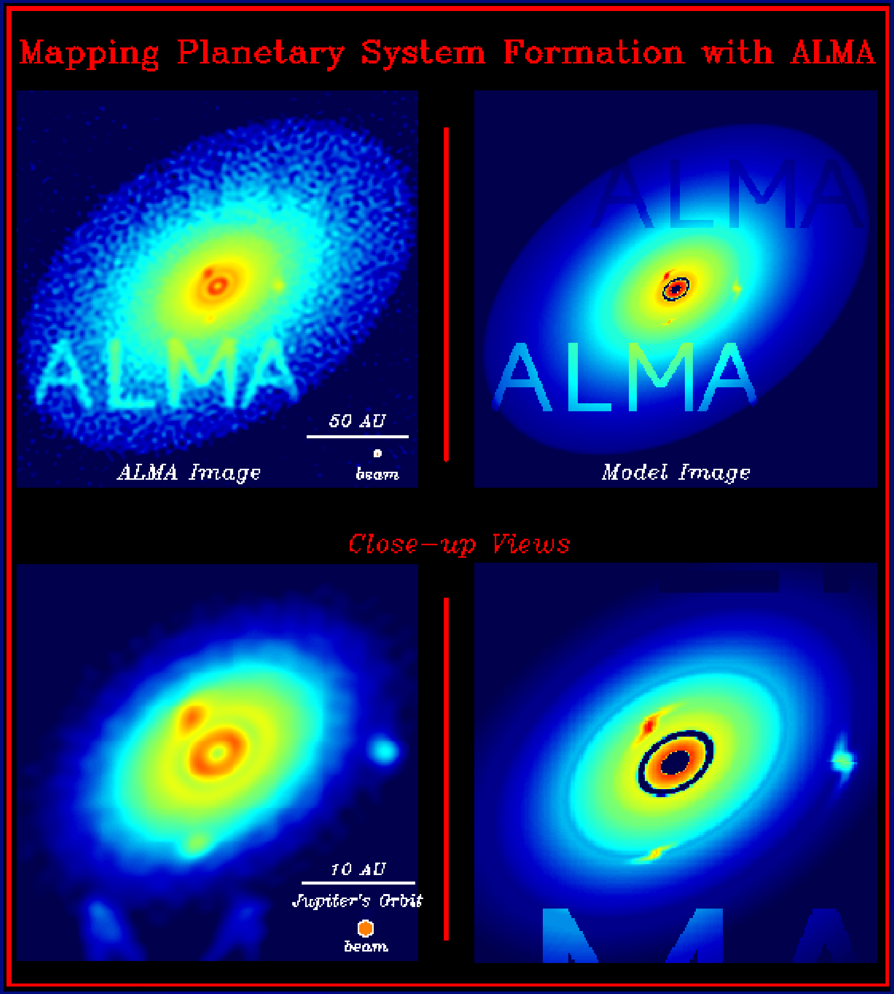
Wilner et al. 2002



Birth of Stars and Planets

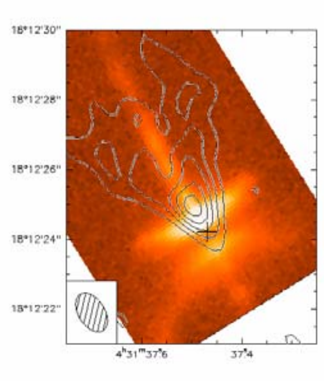
- The nearest Star Formation regions: ~100 pc from the Sun
  - ALMA Beam at 300 GHz (100 pc): 1.5 AU
  - L1457 was once reported to lie at ~80 pc but now seems to be beyond 300 pc.
  - B68 lies at 95 pc (Langer et al.)
  - Rho Oph has parts as close as 120 pc out to 160 pc
  - Taurus has parts as close as 125 pc out to 140 pc
  - Coal Sack and Chameleon and Lupus are about the same.
- The nearest protoplanetary regions lie at ~20 pc from the Sun
  - ALMA Beam at 300 GHz (20 pc): 0.3 AU
  - TW Hya at 56 pc, TW Hya assn is 10 Myr old, not likely to be forming many planets.
  - AU Microscopium, about 14 Myr old, lies only 10 pc from the Sun.
  - Beta Pictoris, 20 Myr old, lies at 17 pc
- The nearest debris disks are even closer—around ~10% of nearby stars.
  - ALMA Beam at 300 GHz (3 pc): 0.05 AU
  - Epsilon Eridani lies a little over 3 pc from the Sun
  - Fomalhaut: 7.7 pc

Protoplanets in formation



- Disks are observed about young stars, but with poor resolution
- ALMA will provide the resolution and the sensitivity to detect condensations, the cores of future giant planets
- As the planets grow, they clear gaps and inner holes in the disks
- On the right are models of this process, and on the left simulations of ALMA’s view showing that condensations, gaps and holes are readily distinguished

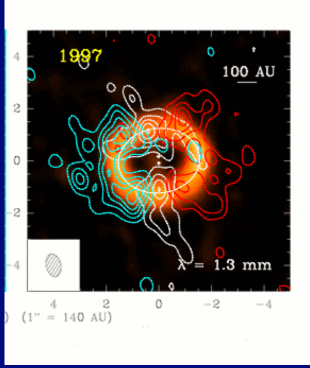
Forming Other Planetary Systems



(1) Infancy. Image the luminous forming stars and planets directly, in emission from stellar photospheres, the gas and dust disk from which the stars formed, and the subsequent assembly of planets from the disk gas and dust.

- Disks are small, <900 AU, requiring high angular resolution (1”~140 AU in nearest star-forming regions)
- Except for the innermost regions, disks are cold (10-30K at R>100 AU) requiring high sensitivity
- Solar-mass stars will have rotation velocities around 2 km/s, turbulence around .2 km/s, requiring high spectral resolution.
- The only way to provide high spectral resolution AND high sensitivity is with large collecting area. ALMA.

Disk Structures



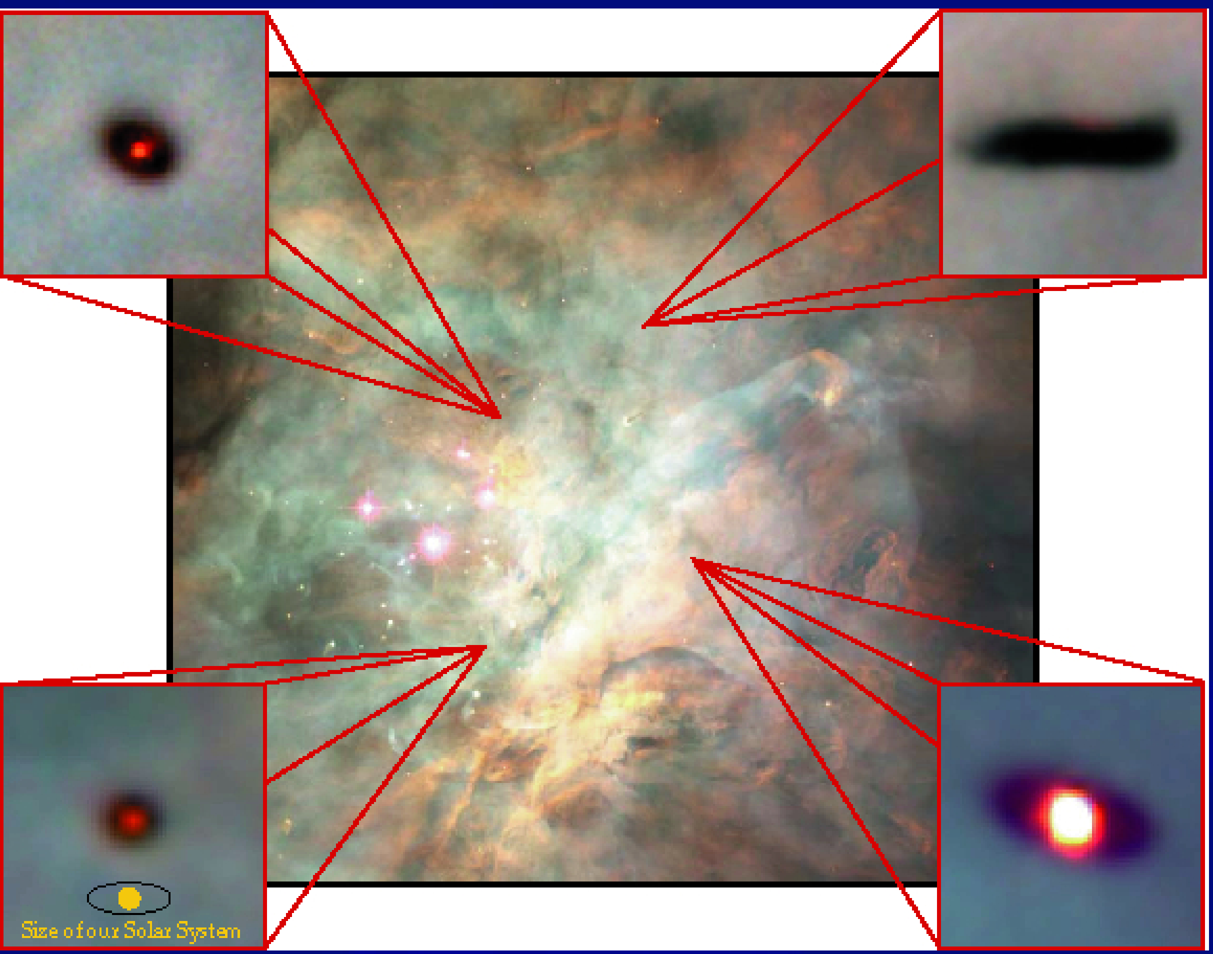
- The partially resolved dust emission probes now the disk at the scale of our solar system, but is not detectable further out with current millimeter array sensitivity.ALMA is sensitive enough to detect the dust emission in the outer optically thin dust disk.
- The CO emission from the outer and from the ~200 AU disk is now detectable. ALMA allows to map optically thick CO lines at the scale of our Solar System (~ 3 −10 AU), providing information about the gas content and its kinematics; current interferometers do not probe closer in than ~40AU.
- Hence one can compare both dust and gas in the same regions.
- The observations of optically thin lines are still difficult but possible. Long integration times should be used to detect and map molecules rarer than CO in order to investigate the chemistry of protoplanetary disks.

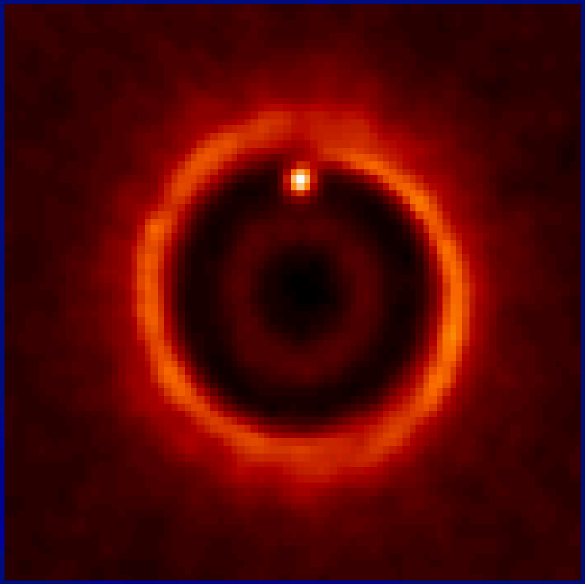
Forming Planets

- (2) Toddler. ALMA will be able to directly detect forming giant planets (‘condensations’) in protoplanetary disks, and the gaps created in these disks as the condensations grow.
- ‘Theoretical investigations show that the planet-disk interaction causes **structures** in circumstellar disks, which are usually **much larger in size than the planet** itself and thus more easily detectable.’ S. Wolf

Formation of Planetary Systems

Wolf and D'Angelo 2005





HST view (left) sees opaque dust projected upon a bright background (if persent). In the ALMA view (above, the dust and the protoplanet appear bright.

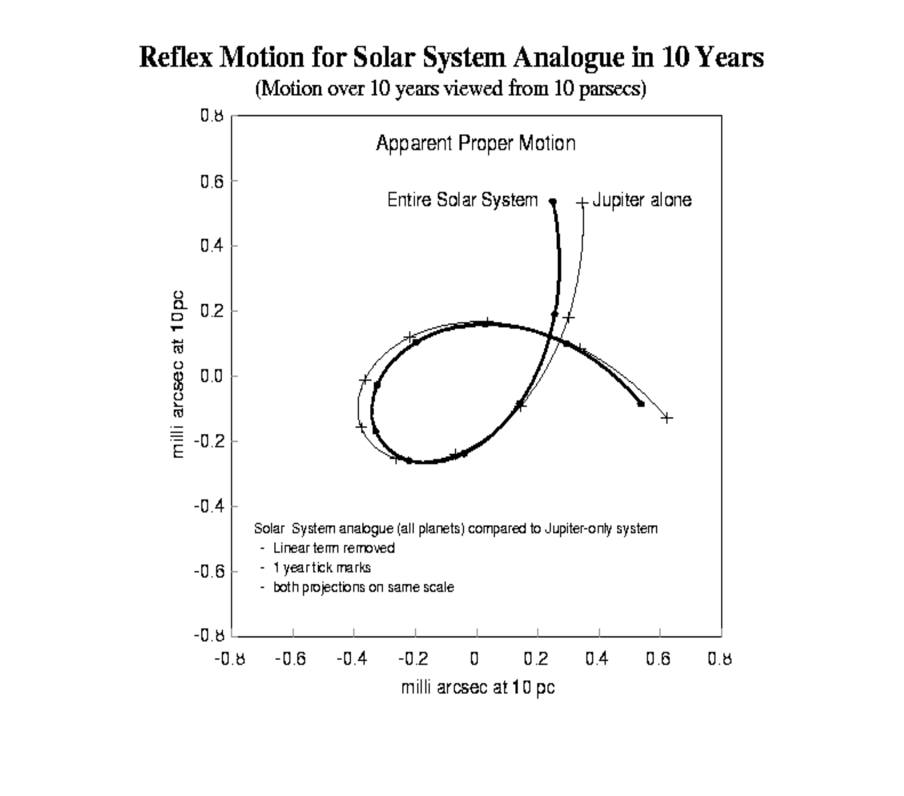
Nearby Planets

- (3) Adolescence. ALMA will be able to directly detect very young giant planets in the nearest star forming regions. Eris, for example, in our own system will be detected in seconds. Integrations times in days for several cases:

Distance (pc)	Jupiter	Gl229B	Proto-Jupiter
1	1.5	0.01	<1hr
5.7	>1yr	12.5	<1hr
10	>1yr	120	<1hr
120	>1yr	>1yr	12.5

Indirect Detection of Mature Planetary Systems

- (4) Adult - ALMA will be able to indirectly detect the presence of giant planets around nearby stars through the use of astrometry. ALMA will also be able to detect and image dust/debris disks around nearby stars (zodiacal analogs).
  - A planet orbiting its central star causes the star to undergo reflexive motion about the barycenter
  - ALMA would measure this motion accurately in its long configuration at submm wavelengths.
  - ALMA could detect photospheres of e.g. 1000 stars well enough to detect a 5Jovian mass planet at 5AU. (10 minute integration).
  - Inclination ambiguities for companions now known could be resolved.



Numerology

- Assume: 5AU orbit
- Three mass ranges: 5 Jovian, Jovian, Neptunian
- 10 minute integrations, 345 GHz, 1.5mm H_2O

Then:

- 800, 180, 0 Hipparcos stars about which a companion might be detected, virtually none solar type.
- 200, 120, 30 Gliese stars about which a companion might be detected.
  - 100, 30, 0 of these are solar type stars.

European ALMA News (www.eso.org),
ALMA/NA Biweekly Calendar (www.cv.nrao.edu/~awootten/mmaimcal/ALMACalendars.html)

ALMA
ATACAMA LARGE MILLIMETER ARRAY

www.alma.info

The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.