Atacama
Large
Millimeter
Array

Imaging Cosmic Dawns

The Atacama Large Millimeter Array

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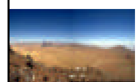
NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Atacama Large Millimeter Array

A project of the National Science Foundation through Associated Universities, Inc. and the National Radio Astronomy Observatory, Caltech, Berkeley, Illinois and Maryland in cooperation with the National Research Council of Canada, and the European Southern Observatory and its partners The Centre National de la Recherche Scientifique(CNRS),France; Max Planck Gesellschaft (MPG), Germany; The Netherlands Foundation for Research in Astronomy, (NFRA); Nederlandse Onderzoekschool Voor Astronomie, (NOVA); The United Kingdom Particle Physics and Astronomy Research Council, (PPARC);The Swedish Natural Science Research Council, (NFR);and the Ministry de Ciencia y Tecnologia and Instituto Geografico Nacional (IGN,)(Spain). The Science Ministry of Japan (MEXT) through the National Astronomical Observatory of Japan participates in an affiliated role. CONICYT Chile participates through holding the concession on the land and its seat on the ALMA Board.

ECC

NFR PPARC

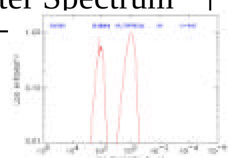


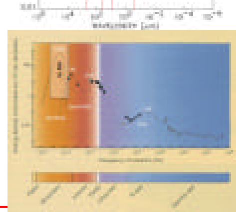
- The Atacama Large Millimeter Array, or ALMA, is an array of precision engineered antennas each 12 meters in diameter which will work together to make detailed images of astronomical objects.
- The scope of the ALMA Project is an array of 64 antennas that can be positioned as needed over an area up to 14 kilometers in diameter so as to give the array a zoom-lens capability, with resolution reaching 10 milliarcseconds.
- The faintest millimeter/submillimeter source yet detected shines at about 1 mJy; ALMA will reach this sensitivity in seconds. ALMA's great sensitivity and resolution make it ideal for medium scale deep investigations of the structure of the submillimeter sky.
- ALMA has been endorsed as the highest priority project for the next decade by the astronomical communities of the United States, Canada, the United Kingdom, France, the Netherlands and Japan (the latter as LMSA).

Al Wootten, ALMA/US Project Scientist

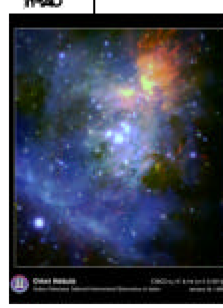
The Millimeter Spectrum

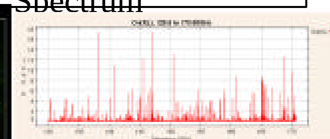
- Millimeter/submillimeter photons are the most abundant photons in the spectrum of the Milky Way and most spiral galaxies, and in the cosmic background.
- After the 3K cosmic background radiation, millimeter/submillimeter photons carry most of the energy in the Universe, and 40% of that in for instance the Milky Way Galaxy.
- ALMA range – wavelengths from 1cm to 0.3 mm.





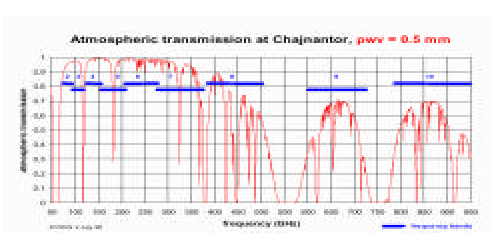
Contributors to the Millimeter Spectrum





- In addition to dominating the spectrum of the distant Universe, millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.
- Most of the observed transitions of the 129 known interstellar molecules lie in the mm/submm spectral region
- However, molecules in the Earth's atmosphere inhibit our study of many of these molecules. Furthermore, the long wavelength requires large aperture for high resolution, unachievable from space.

Complete Frequency Access

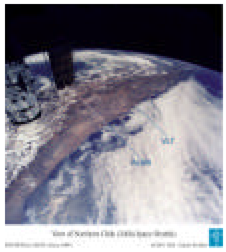


South America

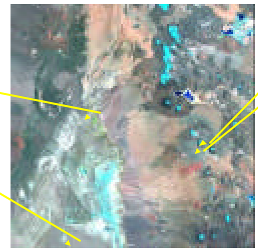
Where can such transparent skies be found??

Northern Chile

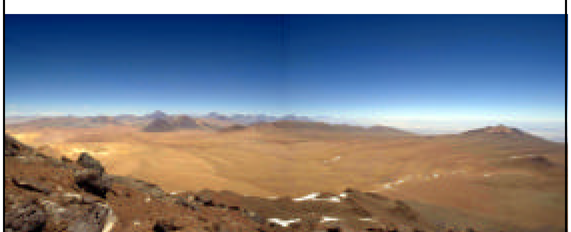
Site must be high to make the best use of the atmospheric windows.
Site should also be accessible, supported by reasonably close support facilities.
Site should be dry for transparency.
Chajnantor lies relatively close to the ancient town of San Pedro de Atacama, inhabited for more than two millennia.
San Pedro is relatively near the Calama airport, and not far from the ESO site at Paranal.
Chajnantor lies astride the paved Pasa de Jama road to Argentina.



Salar de Atacama

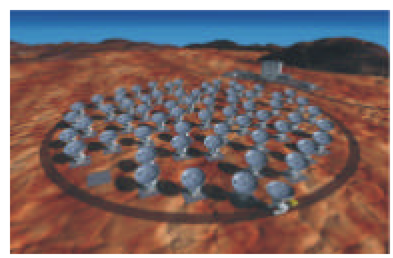


Chajnantor



SW from Cerro Chajnantor, 1994 May

ALMA at Chajnantor



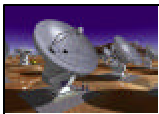
Chajnantor Evaluation

- Clarity of atmosphere: superior to Mauna Kea; at best better than South Pole
- Source accessibility: superior to South Pole
- Site monitoring continues
  - Comparison with first year of Caltech CBI operations
    - Eruption of Lascar caused no discernable problems
  - Evaluation
    - Transparency monitoring extended to supraTHz windows
    - Radiosonde campaign extended to cover all seasons
    - Installation and upgrade of monitoring equipment, communications
  - Array center site chosen

ALMA Specifications

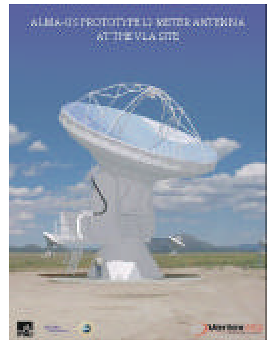
Antennae	64 × 12 m
collecting area	> 7000 m^2
Configurations	150 m – 14 km
resolution (300 GHz)	1.4 – 0.015"
Frequency	30 – 950 GHz
wavelength	10 – 0.3 mm
Receiver sensitivity	close to quantum limit
Correlator	16 GHz / 4096 chan.
Site	excellent

Result: A leap of *over two orders of magnitude in both spatial resolution and sensitivity*



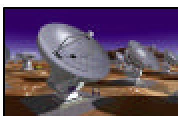
ALMA Technologies Enable the Sensitivity Leap

- Antenna -- Mechanical Engineering, Materials
- Correlator -- Special purpose IC for high speed signal processing
- Computing -- Non-linear imaging algorithms
- Detectors -- Improving the best in the world
- Remote Access – Bringing the telescope from the 16500 Chajnantor site into the observer's control
- Photonics -- Light waves to radio waves



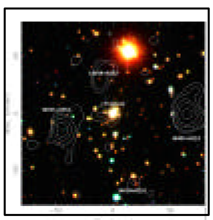
Vertex Antenna Concept

The ALMA prototype antenna makes extensive use of carbon fiber reinforced plastic (CFRP) technology in order for the antenna to maintain a stable parabolic shape in the harsh thermal and wind environment characteristic of the ALMA site at 16,500 feet elevation in the Andes mountains of northern Chile.

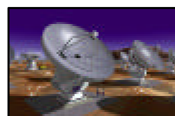


Science with ALMA

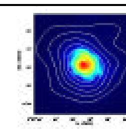
- Formation of Galaxies and Clusters
- Formation of Stars
- Formation of Planets
- Creation of the Elements
  - Old stellar atmospheres
  - Supernova ejecta
- Low temperature thermal science
  - Planetary composition and weather
  - Structure of Interstellar gas and dust
  - Astrochemistry and the origins of life



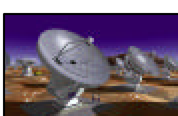
An 850 micron SCUBA image of the core of the cluster A1835 (contours) superimposed on a multi-colour Hale telescope image of the field [Ivison et al. 2000]. Despite the coarser resolution of the SCUBA image it is clear that the red cluster member galaxies are not typically submillimeter sources, while the counterparts to the labeled submillimeter sources are faint optical objects. The two views of this fieldhence provide complementary information. ALMA will providesubmillimeter images with finer resolution than the optical image.



Cosmology



- Sunyaev-Zel'dovich Imaging
  - Independent estimate of H_0 to beyond $z = 1$
  - Estimate of mean gas fraction on cluster scales
  - Greater field of view than VLA
  - Southern hemisphere



Formation of Galaxies

Energy distribution of dusty star-forming galaxies peaks in far-infrared, near 200 microns.

This is also the peak of the energy distribution in the post-reionization Universe; much of the photons and energy in the Universe lie within the ALMA bands

Expansion of the Universe redshifts radiation from distant galaxies into ALMA bands

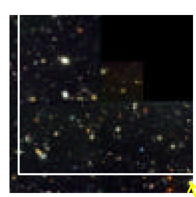
The greater brightness of galaxies at shorter wavelength compensates for the dimming due to greater distance

ALMA's sensitive 850 micron band is optimal for detection of continuum radiation from dust by galaxies at z = 2–4

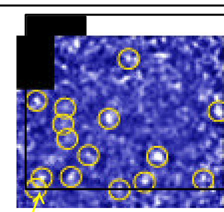
The kinematics of galaxies at this epoch can be probed with their gas content; the most abundant detectable gas will be CO.

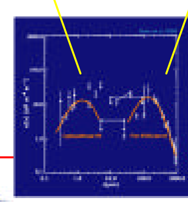
The star-forming epoch of galaxies peaked during this epoch.

ALMA is an ideal instrument for study of the star forming history of the Universe and the creation of galaxies.

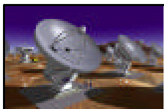


Optical is not the whole story

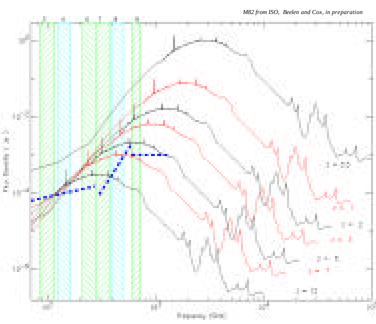




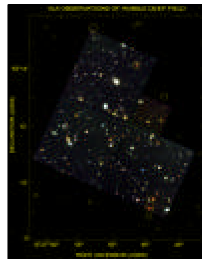
Population of rare but high luminosity sources (10^{12} L_{sun}) matches energy output of UV-selected population at high z

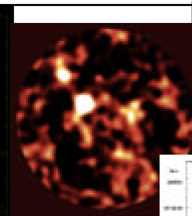


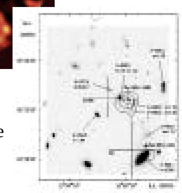
- As galaxies get redshifted into the ALMA bands, dimming due to distance is offset by the brighter part of the spectrum being redshifted in. Hence, galaxies remain at relatively similar brightness out to high distances.



Hubble Deep Field



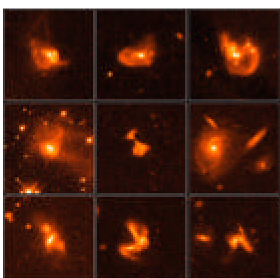




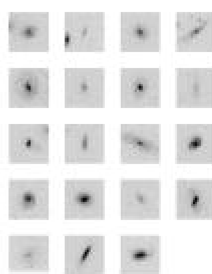
Owing to the redshifts, galaxies which are redshifted *into* ALMA's view *vanish* from view optically. ALMA shows us the distant Universe *preferentially*.

Galaxy Evolution

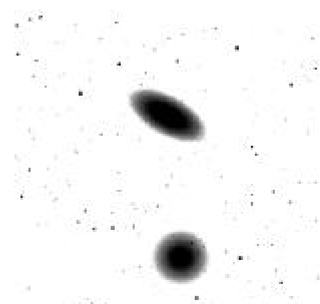
Galaxies at $z > 2$ are multiple with evidence of merging



Assembly of large Galaxies was evidently completed at $z<1$

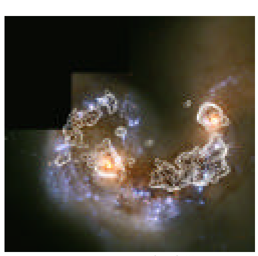


The merging of two Galaxies



Current Observations

- Some of the highest redshift objects known today are very luminous sources at millimeter wavelengths
  - About a dozen objects have been observed in one or more lines of CO
  - The detection in BR1202-0725 (z=4.7) at a look-back time of 92% of the age of the Universe suggests early enrichment of the interstellar medium with CNO.
- Even in the nearby Antennae, the strongest infrared emitting region, and that of most active star formation, is obscured in optical/near infrared light.



Wilson et al. 2000

An ALMA Redshift Survey in a 4'×4' Field

Step 1

A continuum survey at 300 GHz, down to 0.1 mJy (5 s). This requires 140 pointings, each with 30 minutes of observation, for a total of 3 days. Such a survey should find about 100-300 sources, of which 30-100 sources will be brighter than 0.4 mJy. This field is twice the size of the HDF.

Step 2

A continuum and line survey in the 3 mm band down to a sensit ivity of 7.5 mJy (at 5 sigma). This requires 16 pointings, each with 12 hours of observation, so a total of 8 days. The survey is done with 4 tunings covering the 84-116 GHz frequency range.

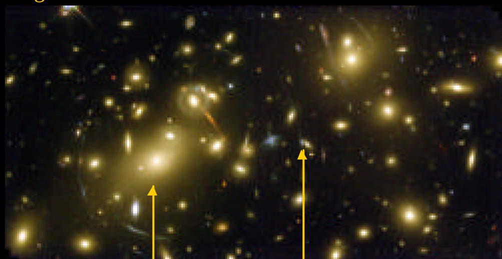
The 300 to 100 GHz flux density ratio gives the photometric redshiftdistribution for redshifts z > 3 -4. For expected line widths of 300 km/s, the line sensitivity of this survey is 0.02 Jy.km/s at 5 s. Using the typical SED presented earlier this should detect CO lines in all sources detected in Step 1.

At least one CO line would be detected for all sources above z = 2, and two for all sources above z = 6. The only ``blind'' redshiftregions are 0.4 -1.0 and 1.7 -2.0.

Step 3

A continuum and line survey in the 210-274 GHzband down to a sensitivity of 50 mJy (at 5 sigma). 8 adjacent frequency tunings would be required. On average, 90 pointings would be required, each with 1.5 hours, giving a total of 6 days. Together with Step 2, this would allow detection of at least one CO line for allredshifts, and two lines for redshifts greater than 2.

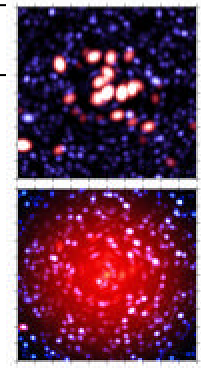
The Distribution of (invisible) Dark Matter can be mapped using the (Gravitational Lens) Distortion of the Images of Background Galaxies



Lensing: A Cluster at z=0.2

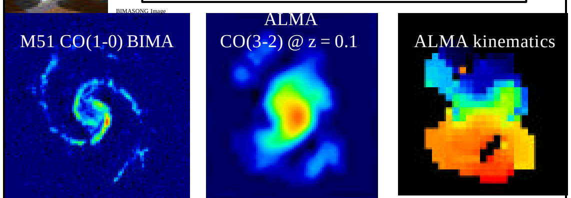
Simulated ALMA image at a frequency of 350 GHz at a relatively low resolution of 3 arcsec (below right). Also shown: a simulation of the same field in the optical R-band (top right). The images are 100" square. **Red:** galaxies that are members of the cluster and the diffuse emission from the Sunyaev-Zel'dovich effect. **Blue:** represents background galaxies magnified by the cluster.

The submillimeter image is *much more sensitive to the high-redshift background galaxies*. A survey of the whole field with ALMA (about 30 ALMA pointings) would reveal the brightest sources, while the faintest sources (with fluxes of 0.01 mJy) in the 350-GHz image could be detected in about 70 hours per field.



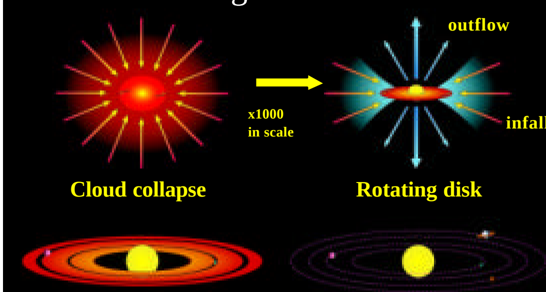
Gas in Normal Galaxies

BIMASONG Image



- CO (1–0) image of M51 from BIMA SONG (*z* = 0.0015)
- simulated ALMA CO (3–2) image of M51 at *z* = 0.1 at 1" resolution
- velocity field of simulated image
- CO will be mapped, providing kinematics, in normal galaxies out to appreciable redshifts
- CO will be detected in nuclear regions at nearly any redshift

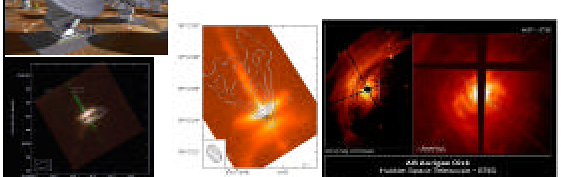
How are single stars created?



Scenario largely from indirect tracers.

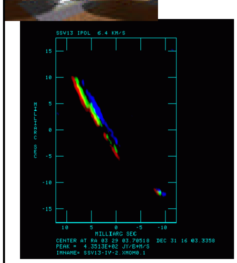
Adapted from McCaughrean

Protoplanetary Disks



- ALMA will be able to trace the chemical evolution of star-forming regions over an unprecedented scale from cloud cores to the inner circumstellar disk. At spatial resolution of 5 AU, it will determine the nature of dust-gas interactions the extent of the resulting molecular complexity, and the major reservoirs of the biogenic elements. Angular resolution will exceed that of the HST

Proper Motion and Structure of Shocks in Dense Clouds



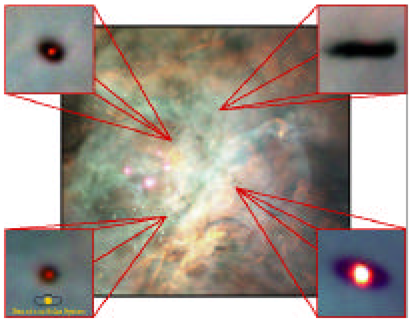
Masers near SVS13; 1mas=0.34AU
Blue Epoch I, Green Epoch III, Blue Epoch IV
Wootten, Marvel, Claussen and Wilking

Water masers observed over four epochs encompassing 50 days. Several of the masers define an arc structure about 5AU in length. This consistently moved at a rate of 0.023 mas/day, or 13.6 km/s.

Including the radial velocity offset, a space velocity of 13.7 km/s is calculated at an inclination of 6 degrees from the plane of the sky.

These structures apparently represent water emission from interstellar shocks driven by the outflow from SVS13.

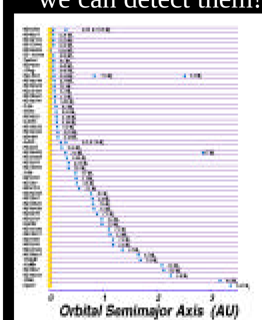
About 2x Sun-Pluto, or 1-2'' on the sky.



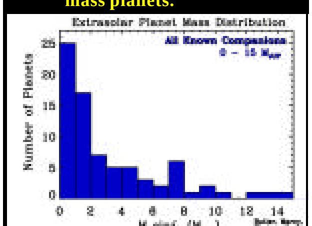
ALMA and Exoplanetary Systems

- After the formation of the star, planets form from the remnant disk. Planets forming from accretion will be directly imaged by ALMA in nearer star-forming regions.
- In later stages, planets mature, becoming cooler and smaller. Currently suspected exoplanets will emit only a few microJy of flux in the submillimeter, requiring weeks of ALMA observing time and are essentially not directly detectable.
- Reflex motions can be easily measured by ALMA. All accessible stellar hosts of exoplanetary systems can be imaged in seconds by ALMA which can measure positions to ~0.1 mas accuracy.
- Debris disks can easily be detected and imaged by ALMA. ALMA's resolution can relieve confusion from background galaxies. ALMA's accurate imaging will reveal debris disk patterns suggesting the presence of planets.

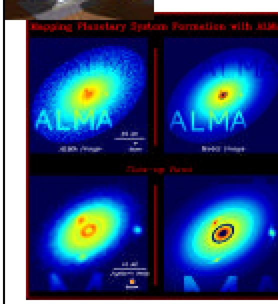
we can detect them!



Radial velocity surveys are sensitive to ~Jupiter/Saturn mass planets.



Protoplanet Formation

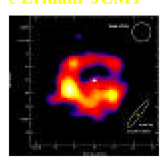


- Disks are observed about young stars, but with poor resolution
- ALMA will provide the resolution and the sensitivity to detect condensations, the cores of future giant planets
- As the planets grow, they clear gaps and inner holes in the disks
- On the right are models of this process, and on the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

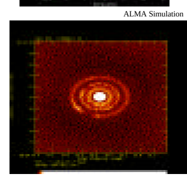
Indirect Detection of Planets

- 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
- Inclination ambiguities for companions now known could be resolved.

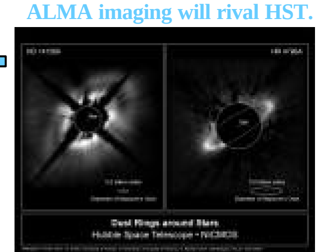
e Eridani JCMT

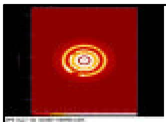


ALMA Simulation

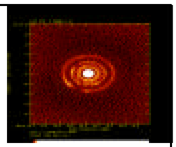


Present mm-wave cameras provide only a few pixels, ALMA imaging will rival HST.



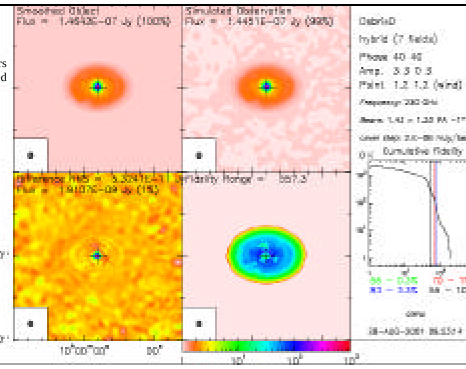


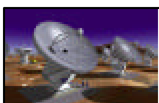
Debris Disks



- These provide a challenge to ALMA imaging because:
  - They are faint about nearby stars – 1mJy is about half a lunar mass at 12 pc
  - They are extended about nearby stars—several fields of view at 12 pc for instance
  - They emit most strongly in the submillimeter, where imaging is the greatest challenge.
- But they can provide best evidence for planetary systems

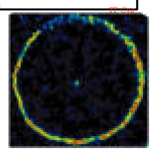
7 field mosaic
Phase errors
Pointing errors
Amplitude errors
TP data included



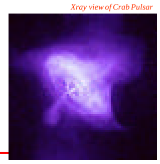


Elemental Enrichment of the ISM

- Evolved stars and supernovae eject newly created elements into the interstellar medium where they are incorporated into molecules as gas cools
- Rotational lines of molecular isotopomers are well-separated in frequency in the millimeter and submillimeter regimes, allowing detailed study of the isotopic distribution of the elements near the site of their creation.
- ALMA will study for the first time dust formation at distances of a few stellar radii around evolved stars and observe the levitation of material from the stellar surface. Together with measurements of abundance profiles of molecules as functions of distance from the star, it will be possible to directly observe the precipitous drop in the abundances of refractory molecules when they condense into dust grains. Resolved images of stellar ejectawill determine the past history of mass loss, as in TT Cyg.



Xray view of Crab Pulsar



ALMA Schedule

1998 – 2001 Design and Development
- 1999 International partnership established
- 2002 Construction begins for US partner, and ESO
- Prototype antennae--an end product of design and development
  - 2000 February contracts awarded (US, Europe)
  - 2002 3Q delivery to VLA site of Vertex Antenna
  - 2003 2Q delivery of EIE, Japanese prototype antennas
- 2004 Prototype interferometer; Japanese entry?
- 2002 – 2010 Construction
- Production antennae
  - 2004 contract award
  - 2005 4Q initial delivery to Chajnantor

4Q 2006 Early Operations
4Q 2011 Completion of construction phase

ALMA on the WWW

http://www.alma.nrao.edu

Instrument description
Project book
Memo series
Workshop reports
Newsletter
Meeting minutes
Links to partners

Science Case: http://iram.fr/guillote (construction proposal to ESO) and PASP Conference Series Vol. No. 235, a conference held at the Carnegie Institution

ALMA Median Sensitivity

(1 minute; AM=1.3; 75%Quartile opacities λ>1mm, 25% λ <1mm)

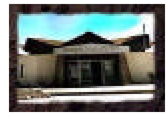
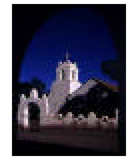
Frequency (GHz)	Continuum (mJy)	Line 1 km s^{-1} (mJy)	Line 25 km s^{-1} (mJy)
35	0.02	5.1	1.03
110*	0.027	4.4	0.89
140	0.039	5.1	1.01
230*	0.071	7.2	1.44
345*	0.12	10.	1.99
490			
675*	0.85	51.	10.2
850	1.26	66.	13.3.

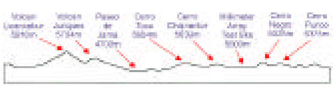
Brightness Temperature Sensitivity

1 min, AM 1.3, 1.5mm, *0.35 PWV, 1 km/s

Frequency (GHz)	B_{max} 0.2km ΔT_{cont} (K)	B_{max} 0.2km ΔT_{line} (K)	B_{max} 10km ΔT_{cont} (K)	B_{max} 10km ΔT_{line} (K)
35	0.002	0.050	0.48	130
110	0.003	0.049	0.84	120
230	0.0005	0.054	1.3	140
345	0.0014	0.12	3.6	300
409	0.0030	0.23	7.6	580
675*	0.0046	0.28	12	690
850*	0.011	0.58	27	1400
1500*	1.4	57	3600	140000

San Pedro de Atacama

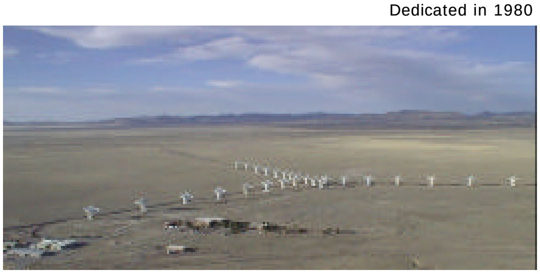
100-meter Green Bank Telescope

GBT

Dedicated in 2000

The Very Large Array - VLA

Dedicated in 1980



Installation at the Very Large Array in New Mexico, USA

Construction of the Vertex antenna’s concrete pad is nearly complete; antenna acceptance scheduled for April 2002. Three prototypes to be tested side-by-side for selection of a final design in 2004.

The ALMA Antenna

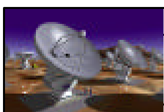
Mechanical Engineering at the Heart of the Array

- Must maintain accuracy at 16,500 foot Llano de Chajnantor
  - Surface accuracy better than 20 microns
  - Pointing accuracy better than 0.6 arcseconds
- Despite
  - high winds (50 percentile 6.5 m/s)
  - no vegetation - windblown grit and dust
  - annual median temperature -2.5 C (range -20 to +20 C)
  - pressure 55% of sea level--UV radiation (170% of sea level)
- Three designs
  - ALMA/NA Vertex, of Santa Clara, CA much carbon fiber of a novel sort
  - ALMA/EU EIE, of Venice, Italy with Castamasagna and Alcatel Space considerable carbon fiber
  - ALMA/JP refinement of ASTE pre-prototype soon to be open bid
- Final design after 1.5yrs of tests in New Mexico

The ALMA Correlator

High Speed Signal Processing

- Analog input at 64 x 8 x 2GHz per second digitized and transmitted at 96 Gigabits per second from each antenna
- Fiber optic transmission to digital filters, then to correlator
- Correlator. Achieving 1.7 x 10^{16} multiply and add operations per second! cross-correlates signals from 32*63=2016 pairs of antennas on 16 msec timescales; autocorrelates signals from 64 antennas on 1 msec timescales, 32 Gbyte/s output
- Design offers flexibility of selection of
  - Bandwidth
  - Spectral window placement
- Power requirement 150 kW.
- Under construction NRAO-CDL Charlottesville for delivery to New Mexico and Chajnantor



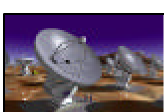
Detectors

Many Laboratories Worldwide

- Radio receivers *amplify* weak signals, usually after *mixing* with a locally generated signal (LO)
- Receivers will cover the entire observable submillimeter spectrum observable from Earth's best site
- Superconducting tunnel junction receivers (4K) mix and HEMT amplifiers at e.g. 4-12 GHz amplify for frequencies above ~90 GHz
- 8 on each of 64 antennas–the most extensive superconducting electronic receiving system in astronomy

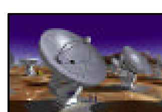
Receiver Research Involves 20 Institutions in 10 Countries

North America	Europe	Japan
NRAO (Charlottesville, Tucson, Socorro USA)	ESO	NAOJ
HIA (Canada)	OSO (Sweden)	NRO
OVRO (Caltech)	RAL, MRAO (UK)	U. of Tokyo
U. Cal. Berkeley	NOVA/SRON (Netherlands)	U. of Osaka
U. Illinois	MPIfR (Germany)	
U. Maryland	IRAM (Germany, France, Spain)	
	DEMIRM (France)	
	Arectri (Italy)	

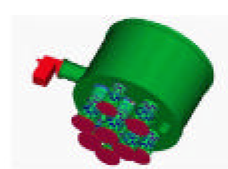


Front End Specifications

- Frequencies from 31 to 950 GHz covered in 10 bands
  - requires RF bandwidth up to 30%
- All bands dual polarization
- 8 bands use SIS mixers at 4K
- Mixers separate sidebands where possible, and balanced
- Highest possible sensitivity and stability
  - receiver noise close to quantum limit
  - wide detection bandwith (IF 4-12 GHz recommended)
- Highest reliability (1280 systems)
- Modular design



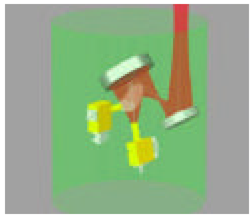
Front End Concept



- Ten bands, one 1 m diameter dewar with 70K, 15K and 4K stages
- Each band a modular 'cartridge' held by flexible thermal links
- All bands share focal plane, cartridges plug in from bottom, optics atop

Preliminary Cartridge Design

- Optics
- Two mixers
- IF amplifiers
- Local oscillator
- Cables
- Mount



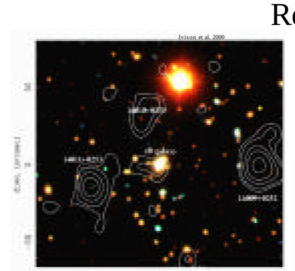
Remote Access

- Astronomers anywhere can interact with the system, and receive interim images in real time
- Requires high speed communication

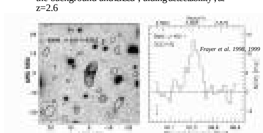
Photonics

- LO - IR lasers beat together produce reference frequency for mixing, distributed to all antennas over fiber optics
- Key technology is high frequency (>100 GHz) photodiodes–developed by NTT Japan to 300 GHz
- After mixing and amplification, signal is digitized and transmitted over fiber optics to correlator

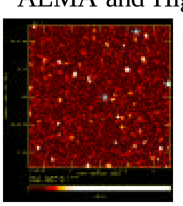
Complementarity to OIR Observations at Similar Resolution

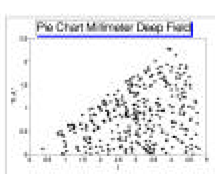


- Multicolor optical image of galaxy cluster Abell 1835 – Hale Telescope image shows bright cD elliptical well
- Submillimeter 850 micron SCUBA image shows spirals strongly which are very weak in the optical image, while the elliptical is weak
- ALMA's spatial resolution will improve on SCUBA by orders of magnitude accompanied by a similar increase in sensitivity – what SCUBA achieves in tens of hours ALMA achieves in tens of minutes.
- OVRO has measured the CO in SMM14011+0253, in the background and lensed, aiding detectability, at z=2.6



ALMA and High Redshift Galaxies





Current estimates suggest a background of about 10000 galaxies per square degree brighter than 1 mJy at submm wavelengths (850 μm).

For a luminosity function based on IRAS counts of nearby galaxies (Saunders et al.), this suggests the distant Universe has about 1000 times more submm-bright galaxies as the local Universe, implying a general evolution.

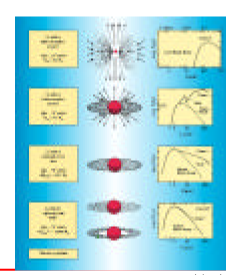
Predictions using a Gaussian evolution model (Blain et al. 1998) suggest ALMA will see a density of *distant* galaxies equal to the density of relatively nearby galaxies found in the Hubble Deep Field

Because ALMA is intrinsically a spectroscopic instrument, it will serendipitously measure CO lines, hence allowing redshift determinations, for about 25% of the distant population.

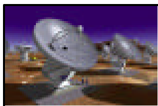
Formation of Stars

Paradigm: material falls through a rotating circumstellar disk onto a forming star from more extensive envelope, fuelling a bipolar flow which allows loss of angular momentum

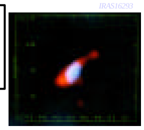
Without sufficient resolution, separation of these motions is difficult



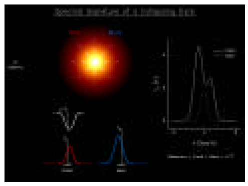
Andre et al.

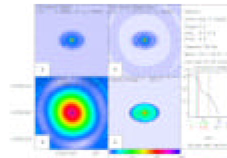


Formation of Stars



- A key observation, not currently achievable, would be to observe the infalling gas in *absorption* against the background protostar
- ALMA will provide adequate sensitivity
- In the bipolar flow, shock waves process envelope molecules, providing a rich chemistry
- ALMA will be able to observe the progress of these shocks *in real time* and study how their composition changes





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