ALMA: a new instrument for science in the submm band

M. Massardi
Italian node of ESO ALMA Regional Center
INAF-Istituto di Radioastronomia (Bologna)
ERIS school, 8th september 2011
ALMA basics and status

ALMA organization and tools

Science topics for ALMA
• The Atacama Large Millimeter Array is a mm-submm reconfigurable interferometer

• **World wide collaboration:**
  Europe: ESO (14 countries),
  North America: NRAO (USA, Canada),
  East Asia: NAOJ (Japan, Taiwan),
  Chile

Contributors share the costs and the observing time

• Currently under construction on the Chajnantor plain (**5000m**, Chile)
ALMA numbers

- **Antennas:** 50x12m main array + (12x7m + 4x12m) ACA
- **Baselines length:** 15m -> 150m-16km + 9m->50m
- **Frequency range:** 10 bands between 30-900 GHz (0.3-10 mm)
- **Heterodine receivers operating on 2x8GHz (or 10 GHz for b6)**
- **Bandwidth:** 2 GHz x 4 basebands for each of 2 polarisations
- **70 correlator modes:** 31MHz-2GHz / 8192 ch / single, dual, full polarisation product
- **Mosaic capability**
Interferometry in a nutshell

An interferometer reconstructs an image of the sky at fixed spatial scales (i.e. measures single points in the Fourier domain) corresponding to the projection of the baselines on the sky.

**Imaging quality depends on the Fourier space coverage,**

i.e. on the number of baselines \(\frac{N(N-1)}{2}\).

Resolution depends on the baseline length.

Sensitivity depends on effective collecting area, integration time, bandwidth.

**Water vapour effects get worse as the frequency increases**

\[
\sigma_{\text{image}} = \frac{k_b T_{\text{sys}}}{A \eta} \sqrt{\frac{2}{t \Delta \nu n_{\text{pol}} N(N-1)}}
\]

\[
\theta = 1.33 \frac{\lambda}{b_{\text{max}}}
\]
ALMA numbers

Dry site, low pwv, low Tsys, high sensitivity also at submm frequencies

>6500sqm of effective area and 1225 baselines for the 12m array
+ Short spacings with ACA
Excellent instantaneous uv coverage & high sensitivity
<0.05mJy @100 GHz in 1 hr

Up to 16km baselines, subarcsec resolution

0.2” x (300/freq_GHz)x(1km/max_baseline)
40 mas @ 100 GHz,
5 mas @ 900 Ghz

FOV 12m array: 20.3”/(300/freq_GHz)

Flexibility in spectral and spatial studies

\[ \sigma_{\text{image}} = \frac{k_b T_{\text{sys}}}{A \eta} \sqrt{\frac{2}{t \Delta \nu n_{\text{pol}} N(N-1)}} \]

\[ \theta = 1.33 \frac{\lambda}{b_{\text{max}}} \]
ALMA reconfiguration

Antenna stations at 5000m

Antenna transporter

Antenna stations at 5000m
ALMA sites: OSF

San Pedro de Atacama

Operations Support Facilities
OSF 2900m

ALMA Operations Site
AOS 5000m

Toconao

OSF - 2900m
ALMA sites: AOS

Currently: 18 antennas at AOS
(http://www.almaobservatory.org/)

First ESO antenna at AOS (July 2011)
ALMA current phases

Science Verification
- On-going tests to observe known sources to validate the output of ALMA
- Data public: not for science
  http://almascience.eso.org/alma-data/science-verification
  (See A. Rossetti's tutorial)

Early Science
- 31 March 2011: first call for proposals
- 30 June: proposal submission deadline
  » 919 proposals received!
- 30 September 2011 - 30 June 2012: ES Phase 0 observations (500-700 h)

http://almascience.eso.org/call-for-proposals
**Full array**

- **Frequency range:** 10 bands 30-900 GHz
- **Antennas:** 50x12m + ACA
- **Sensitivity:** 0.15 mJy in 1 min at 230 GHz
- **Max baseline:** 150m-16km
- **Resolution:** 20 mas @ 230 GHz
- **Mosaic capability**
- **Pipeline reduction in Chile**

<table>
<thead>
<tr>
<th>Band Lower frequency [GHz]</th>
<th>Upper frequency [GHz]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>84</td>
<td>116</td>
</tr>
<tr>
<td>6</td>
<td>211</td>
<td>275</td>
</tr>
<tr>
<td>7</td>
<td>275</td>
<td>373</td>
</tr>
<tr>
<td>9</td>
<td>602</td>
<td>720</td>
</tr>
</tbody>
</table>

**Early Science**

- **Frequency range:** 4 bands (3, 6, 7, 9) min 16x12m (no ACA)
- **Sensitivity:** 0.5 mJy in 1 min at 230 GHz
- **Max baseline:** 2 configs: 18-125m 36-400m
- **Resolution:** 1000 mas @ 230 GHz
- **Limited mosaic capabilities**
- **Reduction @ ARCs**

<table>
<thead>
<tr>
<th>Band Frequency [GHz]</th>
<th>Angular Resolution ['&quot;]</th>
<th>Maximum Scale ['&quot;]</th>
<th>T(_{bc}) [mK]</th>
<th>Flux [mJy]</th>
<th>T(_{bl}) [K]</th>
<th>Field of View ['&quot;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>100</td>
<td>5.3</td>
<td>21</td>
<td>0.65</td>
<td>0.14</td>
<td>0.030</td>
</tr>
<tr>
<td>6</td>
<td>230</td>
<td>2.3</td>
<td>9</td>
<td>1.0</td>
<td>0.20</td>
<td>0.029</td>
</tr>
<tr>
<td>7</td>
<td>345</td>
<td>1.55</td>
<td>6</td>
<td>1.8</td>
<td>0.37</td>
<td>0.043</td>
</tr>
<tr>
<td>9</td>
<td>675</td>
<td>0.80</td>
<td>3</td>
<td>15</td>
<td>3.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Properties of the Compact Configuration (baselines of ~18 m to ~125 m)

Properties of the Extended Configuration (baselines of ~36 m to ~400 m)
ALMA data flow

Incoming Sky Signal

Front End

ALMA (66 antennas)

Up to 15 kms of fiber

Back End

Analog | Digital

Array Operation Site | AOS
Correlator

6.4 - 64 mb/s Link

Operation Support Facility | OSF
Archive - Operations - Science
ALMA organization

• 3 sites in Chile
  – **AOS**: ALMA operations site *(5000 m)*
    • Antennas, correlator
  – **OSF**: Operations support facility *(3000 m)*
    • Labs, antenna assembly and maintenance
    • Operators, astronomers
  – **SCO**: Santiago central office
    • JAO (Joint ALMA observatory)
      » Calls for proposals
      » Running ALMA
      » Data reduction pipeline
      » Quality assessment
  • Archive
• **ALMA Regional Centers**
The ALMA Regional Centers (ARC)

- **Interface between JAO and users**
  - 1 ARC per Partner:
    - NRAO for North America
    - NAOJ for East Asia
    - ESO for Europe
- **Operation support**
  - Archive replication
  - Astronomer on duty
  - Software tools
- **User support**
  - Community formation and outreach (schools, workshops, tutorials, ...)
  - Phase 1 (proposal preparation)
  - Phase 2 (scheduling block preparation)
  - Data analysis
  - Archive mining
The European ARC

- ESO European ARC distributed over a 7-nodes network
- ARC center at ESO: core tasks
  - Proposal handling
  - Archive
  - Data product support (ALMA data and software)
  - Helpdesk
- ARC nodes:
  - Face to face support
  - User formation
  - Advanced tools
The Italian ARC node

- Hosted by the IRA in Bologna
  - ARC Manager: Jan Brand
  - 1 tenured position (Massardi)
  - 4 Post-Docs (Casasola, Mignano, Paladino, Rossetti)
  - 1 system manager (Bedosti)
  - 1 ESO ALMA co-funded fellow (Boissier)
  - contributions from 6 members of IRA permanent staff

- **User support**
  - Face to face (ALMA software, CASA)
  - Polarimetry, mosaicing, GRIDDING computations

- Community formation
  - In 2010: community day and CASA tutorials
  - In 2011:
    - About 10 seminars on CASA and ALMA ES in Italian institutes
    - Astrochemistry with ALMA school in June
    - ERIS school
Fundamentals of ALMA observations

ALMA will be dynamically scheduled in service mode

Some tools: the Science Portal and the Helpdesk (SP)  
the Observing Tool (OT)  
the Splatalogue  
the Common Astronomy Software Application (CASA)  
the Observation Support Tool (OST)

Thought to be suited both for experienced and non experienced observers.

For the ALMA full array a pipeline will be operating  
PIs will receive fully reduced images+raw data+scripts  
CASA scripting helps in calibration & reduction.

Care for the huge amount of data (THz)!!!

Care about the limitations in resolution  
and sensitivity before the full array will be available!
ALMA project checklist

Have a good idea!
Estimate required configuration
Write the proposal idea in pdf docs (max 5 page)
Register to the Science Portal
PHASE I – Proposal submission
TAC evaluation
PHASE II – Observing program (Scheduling Blocks) submission for accepted proposals
Observations
Data reduction and analysis

(Maximum 5 pages)

(CASA, Splatalogue, OST, OT)

(SP)

(OT, SP, Helpdesk)

(OT, SP, Helpdesk)

(CASA)
ALMA simulations (CASA sim data)

Simulation of NGC3627 @ z=0.1

Early Science
Baseline 250m

Early Science
Baseline 450m

Full array
The OT interface

- Proposal panel
- Template panel
- Editors Panel
- Feedback Panel

Project Overview Panel

Contextual Help
1. Please ensure you and your co-Is are registered with the ALMA user portal.
2. Create a new proposal by either:
   - Selecting File > New Proposal
   - Clicking on the icon in the toolbar
   - Or clicking on this link
3. Click on the proposal tree node and complete the relevant fields.

View Phase 2 Steps

Phase 1: Science Proposal
- New Science Proposal
- Create Science Goals
- Validate Science Proposal
- Submit Science Proposal

Click on the overview steps to view the contextual help

Importing And Exporting
Template Library
Need More Help?
Proposals will be reviewed by an international proposal review committee. There will at least one Review Panel for each of the main themes:

- Cosmology and the High Redshift Universe
- Galaxies and Galactic Nuclei
- ISM, Star Formation/protoplanetary Disks and their Astrochemistry, Exoplanets
- Stellar Evolution, the Sun and the Solar System

The ranked proposals from the different panels and sub-panels will be merged into a single ranked list in the ALMA Proposal Review Committee (APRC) and assigned a letter grade A through D:

- A: the proposal will be carried over to the following cycle if it is not finished
- B: the proposal should be finished during the current cycle but will not be carried over to the next cycle.
- C: are 'filler' programs observed when no A or B can be scheduled
- D: proposals will not be observed.
Investigators will be notified of the result of the ALMA Proposal Review process via email and successful investigators will be invited to submit a detailed observing plan. The ALMA Observing Tool (OT) is used to prepare individual Scheduling Blocks (SBs, about 30min for weather reasons). The best SBs at any moment will be observed (science, weather, project status).

These will be used by the ALMA Scheduling Software to ensure that the observations are carried out under the required weather conditions. The ALMA Regional Centers (ARC) will provide support to investigators in the Phase II process.

Once the Phase II preparation is finished the Scheduling Blocks will be submitted to the ALMA site and scheduled according to rank and requested observing conditions. Investigators will be able to track the status of their project with the ALMA Project Tracker.
...and then?

For the ALMA full array a pipeline will be operating
PIs will receive fully reduced images + raw data + scripts

For Early Science the pipeline is being assessed
“...ALMA staff will conduct quality assurance on ALMA data...”
PIs will receive raw data + quality assessment scripts

Proposer experience in radio-mm interferometry is required to reduce Early Science data.
Support can be requested to the ARCs.

CASA scripting helps in calibration & reduction.

Care for the huge amount of data!!!
ALMA science in the submm band
The submm band

Mostly observed from space or with SD bolometers because of atmospheric opacity. Region of thermal emission from dust grains & cold gas.

- Good for observing dusty-obscured environments like those surroundings forming structures.

Thanks to the steep rising with freqs of the dust continuum spectrum inverse k-correction compensate for the decrease of brightness as the redshift increases.

- Good for high redshift studies.
The submm band

Mostly observed from space because of atmospheric opacity.
- Region of thermal emission from dust grains.
  - Good for observing dusty-obscured environments like those surroundings forming structures.

Thanks to the steep rising with freqs of the dust continuum spectrum inverse k-correction compensate for the decrease of brightness as the redshift increases.
- Good for high redshift studies.

About 50% of emitted radiation in Universe is in the submm.

Region of emissions from chemical components in dust grains.
- Good for characterize the chemical enrichment in dusty envelopes (stars, planets...).
3 main science/constructive goals

1. Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation
   - frequency bands, large collecting area
   - study of star formation in galaxies up to high redshift, galaxy formation, strong lensing, ...

2. Map dust emission and gas kinematics in protoplanetary disks up to 500 ly far away
   - high baseline number, ACA, high spectral resolution and flexibility
   - study of processes of star and planet formation, stellar evolution and structure, astrochemistry, ...

3. Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution
   - long baselines
   - galaxy merging, AGN core mechanisms, imaging of exoplanets, comets, asteroids, ...
CO and CII in galaxies

CO is a tracer of neutral H2 and hence its abundance measures the interstellar gas mass.

Fine transitions lines redshifted in submm are the major responsible for radiative cooling in galaxies.
AGN and galaxies

Thanks to its high resolution and spectral flexibility ALMA will allow to:

- image the star forming regions in SMG to resolution comparable to HST (Schmidt & Kennicutt law)
- identify AGN (XDR vs PDR)
- study the inner regions of AGN that enclose the mechanisms of interaction and feedback of the BH (verify torus models, fuelling...)
- study the dust distribution and its dynamic with no confusion

SFR given by LIR due to cold gas

Gas mass given by H$_2$ observed through CO

Photo Dissociation Regions

X-ray Dominated Regions

X-rays penetrate deep into the molecular cloud and keep the temperature high that favour HCN

Daddi et al. 2010

Kohno et al. 2008
AGN and galaxies

PdBI NUGA: 0.5-2'' (10-300 pc) @ 5-30 Mpc
NUGA: 12 galaxies in 200 hr

ALMA 0.05-0.1'' (1-10 pc) @ 5-30 Mpc
>100 galaxies in 200 hr

outer ring/spiral arms r~20''~4 kpc
inner ring r~10''~2 kpc
Casasola et al. 2008
Different regions emit different CO transition Reconstructing the CO SED it is possible to classify the emitter. ALMA multifrequency observations allow to reconstruct redshift and classification for the galaxies/AGN.

**ALMA bands**

- Single gas component
- QSO turnover: $J > 6-5$
- SMG turnover: $J \sim 5-4$

---

**AGN and galaxies**

Weiss et al. 2005-2006

- DENSE
- DIFFUSE
- CENTER
- TOTAL

$^{12}$CO flux density in M82 center

$^{13}$CO flux density in M82

- M82 center
- NGC253 center
- Antennae
- MW disk

MW

QSO

SMG

Weiss et al. 2005-2006
By investigating close galaxies ALMA will allow to unveil merging mechanism, chemical structure, density distribution to an unprecedented level of details.

As a test of ALMA’s ability to observe broad spectral lines, we observed the quasar BRI 0952-0115, which is at a redshift of $z = 4.43$. The object is again unresolved on short baselines, but the 158 micron line from ionized carbon is clearly detected in the spectrum, which is impressive given that this observation took only one hour in total.
The source counts for SMGs show a high flux density tail that is due to faint high redshift objects amplified by strong lensing. Submm observations can extract the info from this targets with no absorption or obscuration due to the lens (as in optical bands happens). ALMA will allow to reconstruct the source counts, identify galaxy structure at high-z (exploiting the amplification due to lensing) and constrain the models of galaxy formation.
The SZ effect is the variation of CMB spectrum in the direction of a hot e-cloud. The variation does not depend on z and is positive in the ALMA bands with a well-defined profile depending on the properties of the cloud. With high resolution/sensitivity observation it has to be observable in galaxy clusters and AGN jets.

Recent observations have pointed out that high z clusters are more morphologically complex and less virialized than closer ones and merging events can affect the comparison between SZ and X-ray and hence the cosmological outcome of SZ analysis. ALMA will allow to map the ICM, study merging events, AGN shocks, rotation of ICM, kinetic SZE from various electron components, subclumps...

**Figure 2.** *XMM-Newton* contours (Maughan et al. 2006) superimposed on the 18 GHz ATCA image for Cl J0152−1357. The cross indicates the position of the SZ peak. Flags indicate the peaks of the subclumps mentioned in the text. The contours are taken from an X-ray image, adaptively smoothed to 3σ significance. The lowest contour is set to three times the background level, and subsequent contours are logarithmically spaced.
Prestellar disks & evolved stars

With angular resolution down to 0.01" ~1 AU at 150 pc, 30 AU at 3 kpc and spectral resolution as high as 0.01 km/s ALMA will allow to

- observe SF up to the LMC
- detect circumstellar disk in high-mass (proto)stars;
- study the interaction of disks and outflows;
- derive the mass of the central (proto)star from studies of kinematics
- determine the role of turbulence, gravitation and dissipation in the various stages of stellar evolution
- image the structure of proto stellar disk that will allow to identify the origin of the IMF
Evolved stars

With angular resolution down to 0.01” ~1 AU at 150 pc, 30 AU at 3 kpc and spectral resolution as high as 0.01 km/s ALMA will allow to

- study the mechanism of emission of stellar winds in evolved stars
- verify the structure of shocks in post-AGB stars obscured in other bands

Habing and Olofsson, 2004
Planets & Solar System Science

- Planetary atmospheres
  - Thermal, chemical, and dynamical sounding
  - Benefits from spectral and time resolution
- Small bodies (minor planets, asteroids, Kuiper Belt objects)
  - Thermal emission: size and surface properties
  - CO (+??) in atmosphere (?)
- Comets
  - Atmosphere composition (minor species and isotopes) and dynamics (jets to probe the nucleus structure)
  - Thermal emission: size and surface properties
Protoplanetary disks: SV data

Figure 27: ALMA Test Data (Nov 2010). Emission from the debris disk surrounding the star Beta Pictoris. On the left is a 70μm image from Herschel, (Olofsson et al., SDP Presentations, Madrid, Dec 2009) and on the right is the ALMA test data at 870 μm (Band 7) showing the denser material in the central region. © ALMA (ESO/NAOJ/NRAO)

ALMA HCO+(4-3) moment maps from TW Hya, with white continuum contours at 3 and 100 sigma. From left to right: integrated intensity, intensity weighted velocity field, intensity weighted velocity dispersion are shown.
Interstellar molecules, observed in comets, solar system, galaxies at high $z$, are excellent probes of the physical structure and dynamics of such regions. Molecules play an active role in the energy balance of clouds. Interstellar space is a unique laboratory for chemical processes not normally found on Earth.
...and a lot more!
(just to remember: 919 proposal examined means a lot of science ideas...
and this is only the first call for ES)
Summary

- **ALMA is a unique instrument in the (sub-)mm (0.3 to 10 mm) range**
  - Unequaled sensitivity
    - Large collecting area (7200 m²), excellent dry site (5000 m altitude)
    - e.g. 6 uJy in 6h @ 230 GHz
  - Great imaging capabilities
    - 50 antennas +ACA, variable configuration
    - High resolution (15km = 40 mas @ 100 GHz, 5 mas @ 900GHz)
  - Flexible spectral configuration
  - Pipeline reduced data
- **Early Science is on-going**
  - min16 antennas, baselines up to 450m, reduced capabilities wrt full array
- **Tools are designed to help the experienced AND non experienced user to use ALMA.**
  - Access to the ALMA world through the Science Portal @ www.almascience.org
Summary

- **ALMA is a unique instrument in the (sub-)mm (0.3 to 10 mm) range**
  - **Submm band ALMA properties are good to investigate**
    - dusty-obscured environments like those surroundings forming structures
    - high redshift galaxies and galaxy formation mechanisms
    - galaxy clusters structure via SZ effect up to very high-z
    - AGN inner regions
    - Local galaxies structure, interaction, chemical abundances and profiles
    - Molecular star forming clouds structure
    - IMF in early stellar phases
    - Stellar evolution
    - AGB to PN transition phases
    - Protoplanetary disk formation
    - Chemical enrichments in many astrophysical environments (in the out-of-the-Earth lab!)
    - ...
Welcome to the ALMA era !!!!!!

Contact the Helpdesk and your ARC node for support

Italian ARC node web: http://www.alma.inaf.it
Email: help-desk@ira.inaf.it
Helpdesk: https://alma-help.nrao.edu/

Useful links:
ALMA SP: http://almascience.org/
ALMA PRIMER FOR ES: http://almatelescope.ca/ALMAPrimer.pdf
ALMA CfP: http://almascience.eso.org/call-for-proposals

Credits:
Some material for this lecture has been taken from lectures by
P. Andreani, J. Boissier, V. Casasola, R. Maiolino, L. Testi, G. Umana