ALMA
Recent Progress
Synergies with VLBI
Outline

- What is ALMA?
- ALMA and VLBI
- ALMA as it will be
- Early Science
- Current status
Atacama Large Millimetre/Sub-Millimetre Array

- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths (1cm - 0.3mm/30 – 950 GHz)
- High, dry site, Chajnantor Plateau, Chile (5000m)
- 50 dishes with 12m diameter (EU/NA).
- Baselines from ~15m to 14.5km.
- ALMA Compact Array (ACA) provided by Japan
  - 12 7m dishes in compact configurations
  - 4 12m dishes primarily for total-power
- Low-noise, wide-band receivers.
- Digital correlator giving wide range of spectral resolutions.
- Software (dynamic scheduling, imaging, pipelines)
Physical processes

- Aside from non-thermal emission, most of what ALMA will see comes from elements heavier than H and He (except recombination lines, LiH). Therefore probe stellar products.

- Temperatures are < stellar surface – the “Cold Universe”

- Continuum: thermal emission from dust (scattered emission polarized)

- Lines: molecular rotational transitions + redshifted atomic

- Line polarization: Zeeman, Goldreich-Kylafis

- Heating via stellar UV, cosmic rays, hard photons from AGN – hence the link to star and galaxy formation

- Non-thermal mechanisms include synchrotron (lower frequencies; linearly polarized) and Compton scattering (Sunyayev-Zeldovich).
ALMA and VLBI (1)

- ALMA probes very similar scales to VLBI arrays
  - 15km at 0.3mm wavelength $\leftrightarrow$ 1500km at 3cm
- Emission mechanisms are different e.g.
  - Thermal emission from cold dust, molecular lines, masers ....
  - Synchrotron emission from ultrarelativistic electrons, masers again, HI absorption ....
- Compare the same physical scales in different emission mechanisms
Formation of planets - dust?

**Birth of planets**

- $\frac{M_{\text{planet}}}{M_{\text{star}}} = 1.0 \, M_{\text{Jup}} / .5 \, M_{\text{sun}}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus

**HST**

**ALMA 850 GHz**

Robert Laing
European ALMA Instrument Scientist

Manchester, Sept 22nd
... or pebbles?

22 GHz observations of the disc around the young star HL Tau (Greaves et al. 2008)
AGB stars

ALMA will probe the chemistry of the molecular photosphere

Robert Laing
European ALMA Instrument Scientist

Manchester, Sept 22nd 2022
Current observations can resolve only the brightest sub-mm galaxies. These seem to be short-lived examples of maximal star formation in ongoing mergers.

Velocity fields disc-like or irregular.
Starbursts are easy with ALMA

Spectral energy distribution of the nearby starburst galaxy M82

The effect of redshift on the SED: dusty galaxies are easily detected at high $z$

Robert Laing
European ALMA Instrument Scientist

Manchester, Sept 29th 2010
M82: from arcmin to mas

Robert Laing
European ALMA Instrument Scientist
Manchester, Sept 24th 2010
The first galaxies

CII – Main coolant in the Milky Way
Line of choice for EoR studies
Quasar, z = 6.4
[CII] in the EoR

ALMA
- Band 10 (787-950 GHz)
- Band 9 (602-720 GHz)
- Band 8 (385-500 GHz)
- Band 7 (275-370 GHz)
- Band 6 (211-275 GHz)
- Band 4 (125-163 GHz)
- Band 3 (84-119 GHz)

EVLA
- Q 0.7cm (40-50 GHz)
- Ka 1.0cm (26-40 GHz)
- K 1.3cm (18-26 GHz)
HDF mJy radio source classification
More ALMA science areas

- Dust emission from star-forming galaxies at $z \sim 10$
- Blind surveys for CO in star-forming galaxies at all epochs
- Detailed studies of cold gas and dust in nearby galaxies; AGN torus structure
- Dynamics of molecular gas around the Galactic Centre
- Star formation: physics and chemistry of collapse, accretion, outflows and disks.
- Complex organic (including prebiotic) molecules
- Molecules and dust around evolved stars
- Planetary atmospheres, cometary nuclei, asteroids
- ...............
ALMA and VLBI (2)

- ALMA as part of a mm/sub-mm VLBI array
  - Galactic Centre (Fish, Doelman)
  - Jet formation
  - Masers
  - ....

- ALMA needs VLBI techniques
AGN jet collimation

Kovalev et al. (2007)
2cm VLBA

Relative Right Ascension (mas)

Relative Declination (mas)

1 pc

M87
AGN jet collimation

M87 VLBI 86GHz
(Krichbaum
Collimation region
<70 x 20 $R_S$
ALMA as it will be
Key performance numbers

- Baseline range 15m – 14.5 km + ACA + single dish
- Field of view / arcsec ≈ 17 (\(\lambda/\text{mm}\)) [12m dish]
  
  29 (\(\lambda/\text{mm}\)) [7m dish]
- Resolution/ arcsec ≈ 0.2(\(\lambda/\text{mm}\))/(max baseline/km)
  
  0.04 arcsec at 100 GHz, 14.5 km baseline
  
  0.005 arcsec at 900 GHz, 14.5 km baseline
- Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … → sub-mJy continuum sensitivity and wide spectral coverage
- Full polarization
Transparent site allows full spectral coverage

Atmospheric transmission at Chajnantor, pwv = 0.5 mm
Basic numbers

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency</th>
<th>Primary Beam (FOV; '')</th>
<th>Largest Scale (')</th>
<th>Continuum Sensitivity (mJy)</th>
<th>Compact Angular Resolution (')</th>
<th>ΔT_{line} (K)</th>
<th>Most Extended Angular Resolution (')</th>
<th>ΔT_{line} (K)</th>
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<tbody>
<tr>
<td>Band 1</td>
<td>31.3 - 45 GHz</td>
<td>56</td>
<td>37</td>
<td>0.05</td>
<td>3.18</td>
<td>0.07</td>
<td>0.038</td>
<td>482</td>
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<tr>
<td>Band 2</td>
<td>67 - 90 GHz</td>
<td>48</td>
<td>32</td>
<td>0.06</td>
<td>2.5</td>
<td>0.071</td>
<td>0.03</td>
<td>495</td>
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<tr>
<td>Band 3</td>
<td>84 - 116 GHz</td>
<td>48</td>
<td>32</td>
<td>0.06</td>
<td>2.5</td>
<td>0.071</td>
<td>0.03</td>
<td>495</td>
</tr>
<tr>
<td>Band 4</td>
<td>125 - 163 GHz</td>
<td>35</td>
<td>23</td>
<td>0.05</td>
<td>3.18</td>
<td>0.07</td>
<td>0.038</td>
<td>482</td>
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<tr>
<td>Band 5</td>
<td>163 - 211 GHz</td>
<td>27</td>
<td>18</td>
<td>0.10</td>
<td>1.52</td>
<td>0.104</td>
<td>0.018</td>
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<tr>
<td>Band 6</td>
<td>211 - 275 GHz</td>
<td>18</td>
<td>12</td>
<td>0.20</td>
<td>1.01</td>
<td>0.167</td>
<td>0.012</td>
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<td>9</td>
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<td>Band 8</td>
<td>385 - 500 GHz</td>
<td>9</td>
<td>6</td>
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<td>0.641</td>
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<td>Band 9</td>
<td>602 - 720 GHz</td>
<td>7</td>
<td>5</td>
<td>1.1</td>
<td>0.38</td>
<td>0.940</td>
<td>0.005</td>
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</tr>
<tr>
<td>Band 10</td>
<td>787 - 950 GHz</td>
<td>7</td>
<td>5</td>
<td>1.1</td>
<td>0.38</td>
<td>0.940</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

Continuum sensitivities for 8 GHz bandwidth, Lines 1 km/s; 2 polarizations, 50 antennas, 60s
Spectral modes

- Channel bandwidth 31.25 MHz – 2 GHz (x4 baseband channels)
- Maximum 4096 x (4/N) x (2/P) spectral points/channel, where N = 1, 2 or 4 is the number of channels and P=2 for full polarization; 1 for parallel hands only.
- Maximum spectral resolution 3.8 kHz.
- Tunable FIR filter bank to subdivide 2 GHz baseband into 32 (possibly overlapping) sub-channels, each 62.5 or 31.25 MHz wide
- Flexible combinations of centre frequency and resolution
Phase calibration

Requirements
- Reduce atmospheric and electronic phase fluctuations to as low a level as possible
- Required by imaging and flux scale (decorrelation)

Techniques
- Fast switching (interleave with observations of a nearby calibrator, perhaps at a lower frequency). 20 – 300s cycle times. Requires calibrator within ~2°.
- Water-vapour radiometry (measure emission from 183 GHz atmospheric line; deduce phase fluctuations on 1s timescales).
- Self-calibration
ALMA Operations

- **Basic concepts**
  - Service mode, scheduled dynamically (weather)
  - All observations executed as scheduling blocks, which contain all of the information required to schedule and run the observations (calibration)
  - Primary data products are image cube; raw, calibrated visibility data also available.
  - Everything is archived.

- **Support**
  - Software for proposal preparation, reduction, pipeline
  - Documentation
  - Face-to-face support
ALMA Projects

Data-cubes will be primary product

uv data also archived
ALMA Regional Centres

- Three ALMA Regional Centres
  - Europe
  - North America
  - East Asia
- Primary interfaces to their respective user communities
  - Assist users in proposal/programme preparation and data reduction
  - Manage the time allocation process
  - Run archive mirrors and deliver data
  - Provide AOD and commissioning personnel
The European ARC

- Central Node at ESO
  - Archive and data delivery
  - Proposals
  - e-mail helpdesk
  - VLT support model
  - Funded by ESO/ALMA
- Regional nodes
  - Face-to-face user support
  - Regional users
  - Specialised expertise
  - Local/EU funds

IRAM (France, Spain, MPG)
Jodrell Bank (UK)
Leiden (Netherlands)
Bonn/Koeln/Bochum (Germany)
Onsala (Nordic countries)
IRA Bologna (Italy)
Czech Republic (Ondrejov)
Current Status
European Antennas assembled
Infrastructure

AOS

OSF
Seven Antennas (close-packed)
Raw Phase Stability

345 GHz 3C454.3 black, Uranus red, Phaseref green, Target blue

Time (from 2010/08/20)

Robert Laing
European ALMA Instrument Scientist

Manchester, Sept 29th 2010
WVR correction in action

WVR phase correction in CASA—Blue raw (2 baselines) Orange Corrected

Robert Laing
European ALMA Instrument Scientist

Manchester, Sept 22
Commissioning images: Starburst Galaxy NGC253
NGC253: CO
NGC253: 690 GHz
What is Early Science?

**Minimum**
- 16 antennas with at least 3 bands out of 3, 6, 7, 9
- Single-field synthesis imaging
- Antenna stations to provide good coverage out to 250m
- Calibration equivalent to current mm arrays (loads + WVR)
- Software
- At least 33% of time available (1 year scheduling period)

**Goals**
- Bands 3, 6, 7 and 9 on all antennas; 4 and 8 on some
- Pointed mosaics
- Baselines out to at least 1 km
- Linear and circular polarization
- Single-dish mapping (including OTF)
- Calibration better than existing arrays
Current Schedule

- First fringes at AOS 2009 April 30
- Three antennas at high site, closure phase, 2009 Nov 26
- Start of Commissioning and Science Verification 2010 Jan 22
- Early Science Decision Point Nov 2010
- Call for Proposals end 2010+
- Proposal deadline early 2011+
- Start of Early Science with 16+ antennas Autumn 2011+
- Full operation early 2013
Outlook

- No show-stoppers
  - All main subsystems basically work
  - Key technical risks (phase correction, local oscillator distribution) addressed
  - Construction budget adequate for completion

- Schedule
  - Still very tight (especially front ends)
  - EU antennas

- Reliability and efficiency
  - Much work needed to make system fully reliable (antenna control; correlator)
  - Software test and optimization
Not without problems
... but ALMA is coming soon

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).