ALMA: Imaging the cold Universe

C. Carilli (NRAO)
(sub)mm astronomy: unveiling the cold, obscured universe

Wilson et al.

HST / OVRO CO

Shirley et al.
B335 DSS
Giant Steps I: Frequency and resolution

The diagram illustrates the relationship between frequency (GHz) and resolution (arcseconds) for various astronomical instruments and configurations. Key elements include:

- **HST/NGST Resolution**: High angular resolution for high-frequency observations.
- **SMA**: Submillimeter Array, offering high resolution at millimeter wavelengths.
- **CARMA/PdBI**: Combined Array for Research in Millimeter-wave Astronomy and Polarimetric and Diffractive Beam Imaging, providing moderate resolution.
- **ALMA**: Atacama Large Millimeter/submillimeter Array, offering extremely high resolution at submillimeter wavelengths.
- **VLA**: Very Large Array, showing a range of resolutions from low to high depending on the phase configuration.
- **VLBA + New Mexico Array**: Very Long Baseline Array combined with a New Mexico Array, offering intermediate resolution.
- **Space VLBI**: Very Long Baseline Interferometry, providing the highest resolution possible through interferometry.
- **Interstellar Scattering Limit**: The theoretical limit of angular resolution due to interstellar scattering.
- **Baselines longer than Earth diameter**: Indicating the largest possible baselines for interferometric observations.

The diagram also includes a mapping of other single dish and interferometric configurations, such as GBT (Green Bank Telescope) and E-Config (E-configuration).
Giant Steps I: Frequency and resolution

20mas at 0.9THz (300um)
Giant Steps II: Sensitivity

Index = 1.7
Giant Steps II: Sensitivity

Current

$z > 2$

$5 \times 10^{10}$

$M_{\text{sun}}$

Index $= 1.7$
Giant Steps II: Sensitivity

Index = 1.7

Line: 0.1 mJy in 1 hr at 230 GHz

ALMA
z > 2

Current
z > 2

5e10 M\(_{\text{sun}}\)

1e9 M\(_{\text{sun}}\)
<table>
<thead>
<tr>
<th>Optical/ ESO</th>
<th>IR/ ISO</th>
<th>CO 3 - 2/ CSO</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Optical Image" /></td>
<td><img src="image2.png" alt="IR Image" /></td>
<td><img src="image3.png" alt="CO Image" /></td>
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</tbody>
</table>

\[
T_{\text{line}} = \text{sub-K at 0.25 arcsec res.}
\]

\[
T_{\text{cont}} = \text{mK at 0.25 arcsec res.}
\]
Giant Steps IV: Site quality

0.5 at 0.9 THz
Birth of stars: physics/chemistry of star formation in 3D

Line confusion limited => new mode of operation: targeted line studies

Select lines as probes of: density, temperature, excitation, evolutionary state, or dynamics

Puts pressure on laboratory astrophysics, and data analysis/visualization S/W
Birth of planets

- \( \frac{M_{\text{planet}}}{M_{\text{star}}} = 1.0 \, M_{\text{Jup}} / 0.5 \, M_{\text{Sun}} \)
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus
Submm surveys: Probing the epoch of “galaxy formation” \((z = 1.5 - 3)\)

- **SCUBA**
  - 20 mJy

- **SMA/Spitzer**
  - 20 mJy at 350 GHz

Comparable SFR at \(z > 2\) in dusty starbursts (“submm gal”) as optically selected galaxies = formation of large elliptical galaxies?
ALMA Deep field: ‘normal’ galaxies at high $z$

Detect current submm gal in seconds!

ALMA deep survey: 3 days, $0.1\text{ mJy (5}$σ$)$, $4'$

HST: few 1000 Gal, most at $z<1.5$

ALMA: few 100 Gal, most at $z>1.5$

Parallel spectroscopic surveys, 100 and 200 GHz: CO/other lines in majority of sources

Redshifts, dust, gas masses, plus high res. images of gas dynamics, star formation
SDSS J1148+5251: Dust and molecular gas into cosmic reionization

1e9 $M_{\odot}$ in dust, 1e10 $M_{\odot}$ in mol. gas

=>

Hyper luminous IR galaxy ($FIR = 1e13 L_{\odot}$)

: SFR = 1e3 $M_{\odot}$/yr

Coeval formation of SMBH/Galaxy?

Dust formation by massive stars?

Break-down of $M - \sigma$ relation at high $z$?

Early enrichment of heavy elements ($z_{sf} > 8$)

Integration times: hours to days on HLIRGs

IRAM
ALMA into the EoR

Spectral simulation of J1148+5251

Detect dust emission in 1sec (5σ) at 250 GHz

Detect multiple lines, molecules per band => detailed astrochemistry

Image dust and gas at sub-kpc resolution – gas dynamics!

Studying 1st galaxies

Detect ‘normal’ (eg. Ly α), star forming galaxies, like M51, at z > 6, in few hours

Determine redshifts directly from mm spectroscopy
ALMA – panchromatic view of galaxy formation

em: Star formation, AGN

(sub)mm Dust, molecular gas

Near-IR: Stars, ionized gas, AGN
Science with ALMA: a new era for Astrophysics

International Conference, 2006

13 - 16 November 2006

Madrid, Spain
END SHOW
Very wide field surveys: role of bolometer cameras

Bolometers (+ EVLA, Spitzer): survey large areas to sub-mJy sensitivity

ALMA: detailed SED and CO follow-up

ALMA: uJy, narrow field surveys
## Summary of detailed requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>30 to 950 GHz (initially only 84-720 GHz)</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>8 GHz, fully tunable</td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td>31.5 kHz (0.01 km/s) at 100 GHz</td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>1.4 to 0.015” at 300 GHz</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>10000:1 (spectral); 50000:1 (imaging)</td>
</tr>
<tr>
<td><strong>Flux sensitivity</strong></td>
<td>0.2 mJy in 1 min at 345 GHz (median conditions)</td>
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<tr>
<td><strong>Antenna complement</strong></td>
<td>64 antennas of 12m diameter</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>All cross products simultaneously</td>
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UV selected galaxies – large range in bolometric luminosity, but little correlation of $L_{\text{uv}}$ and $L_{\text{bol}}$.
Millimeter VLBI – Imaging the Galactic center black hole (Falcke 2000)

Model: opt. thin synch

0.6 mm VLBI
16uas res

1.3 mm VLBI
33 uas res

Kerr

Schwarzschild

$R_g = 3uas$
Birth of Galaxies: Magic of (sub)mm

\[ L_{\text{FIR}} = 1.5 \times 10^{12} \text{ L}_\odot \]

1 mJy

\[ \Omega = 0.7, \quad \Omega_m = 0.3, \quad H_0 = 70 \]
1e9 M\_sun in Dust, 1e10 M\_sun in mol. Gas =>

Hyper luminous IR galaxy (FIR= 1e13L\_sun)

Early enrichment of heavy elements (z\_sf > 10?)

Dust formation by massive stars?

M\_dyn (r=2.5kpc) = 2.5e10 M\_sun

coeval formation of SMBH/Galaxy?

Break-down of M-\sigma relation at high z?

Integration times: hours to days

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Franceschini

Franceschini

Optical

Infrared

Optical Irradiated

Franceschini

Optical

Infrared

Franceschini

Cosmic Background Radiation

IC 342