Introduction to Millimeter Astronomy
**VISIBLE**

*Hot matter*
Stars between 3000 et 100,000 K
Ionised gas: 10,000 K

**MILLIMETER**

*Cold Matter*
Dust & Molecules
3 à 70 K (-270 à -200 deg Celsius)

**STARS ARE BORN IN COLD MATTER**

Oct. 6-10. 2008 6th IRAM Interferometry School 2008
Because molecular ISM is cold and opaque to the visible and UV, the sub/millimeter is key to probe molecular clouds through:

- Molecular rotational transitions, where the photon energy is $\sim kT_k$
- Cold dust (10-20 K) emission
- Observations of high-z galaxies

*Atmospheric windows: 3, 2, 1 and 0.8 mm*

The 3mm window (72-116 GHz) includes practically one rotation of *most* molecules.

Fortunate situation that the mm windows all include transition of CO, which is the most abundant molecule after $H_2$

$[J=1-0 \text{ at } 115.271 \text{ GHz, } J=2-1 \text{ at } 230.538 \text{ GHz and } J=3-2 \text{ at } 345.796 \text{ GHz}]$

*Millimeter studies fully benefit from the advantages of radio astronomy for high velocity resolution with the heterodyne techniques, and the high angular resolution with large dishes or interferometers.*
Interest of the mm/submm domain

\[ h\nu = kT \quad 1.44 \text{ K} \equiv 30 \text{ GHz} \equiv 1 \text{ cm}^{-1} \]

- Black-body emission peaks at \( \lambda_m = \frac{hc}{3kT} = 0.48/T \text{ cm} \)
- Dust emission peaks at \( \lambda_m = \frac{hc}{(3+\beta)kT} = 0.3/T \text{ cm} \)
- Typical energies involved in molecular transitions
- SED of galaxies
- SZ effect, interstellar scintillation (VLBI)
- Atmosphere transparency
Black body emission: Cosmic Background Radiation

CBR peaks at 1.76 mm
Dark Cloud

Diffuse Cloud

\[ n = 10^3 - 10^6 \text{ cm}^{-3} \]
\[ T = 8 - 15 \text{ K} \]
\[ A_v > 1 \]

\[ n = 10^3 - 10^6 \text{ cm}^{-3} \]
\[ T = 20 - 100 \text{ K} \]
\[ A_v < 1 \]

Dust emission peaks at 0.3 mm
SED of the quasar PSS2322 at $z = 4.12$

Maximum at 2 THz = 94µm

$T_{\text{dust}} = 32$ K

Minimum of continuum emission around 1 cm wavelength
Typical energies involved in molecular transitions

- Electronic transitions
- Vibrational transitions
- Rotational transitions
- Electronic/nuclear Spin interactions
energy level separations

low-energy rotational transitions of small molecules lie at mm wavelength
Atmospheric transmission (calculations by J. Pardo)

Oct. 6-10. 2008

Oct. 6-10. 2008
Emission processes at sub/mm wavelengths

- **Atoms**: electronic *(spin, Rydberg states)*
- **Molecules**: electronic, vibrational, *rotational*
- **Free electrons**:  
  - Synchrotron  
  - Thermal free-free
- **Dust particles** *(grey body radiation)*
Millimeter-wave Radio Telescopes

- Large collecting surface for sensitivity
- Large physical dimensions for angular resolution
- High altitude to reduce atmospheric water vapor absorption
- Heterodyne receivers for high spectral resolution \(10^{-7} \text{ – } 10^{-8}\)
IRAM 30-m telescope (Sierra Nevada, Spain)
Alt. 2900 m; surface accuracy 50 µm (night)
APEX 12-m telescope (Atacama, Chile)
Altitude 5100 m; surface accuracy 17µm
Sub/Millimeter Interferometers

Plateau de Bure  2500 m

CSO, JCMT & SMA (Hawaii) 4300m

Nobeyama Millimeter Array

National Astronomical Observatory of Japan, Nobeyama Radio Observatory

CARMA (Ca) 2300 m

Oct. 6-10. 2008  6th IRAM Interferometry School 2008
The Green Bank telescope

No aperture blockage

Surface accuracy: 300 µm

Oct. 6-10. 2008 6th IRAM Interferometry School 2008
Very Large Array (up to 7 mm)
Advantages of Interferometry

† **High angular resolution** (@ $\lambda=1$ mm: $0.25''$ with PdB; $20 \mu$arcsec with VLBI)
† **Large collective area**
† **No need of reference position** (factor 2 in sensitivity replaced by $N(N-1)/N^2$)
† **Flatter baselines** (depends less on receiver/atmosphere stability). Makes possible composite spectra.
† **Field of view with many independent pixels** → good noise statistics makes possible secure detections down to 4 sigma.
† **Well suited for special observations**: polarimetry, SZ
† **Accurate source positions** (by stable atmosphere: HPBW/SNR)
† **Eliminates extended** (foreground/background) **emission**
Disadvantages of Interferometry

- Several receivers to build; more complex correlator, but heterodyne interferometry is easy
- **Short spacings filtered out**: extended source emission lost (partly recovered by mosaicing techniques)
- **Needs a stable atmosphere** (or needs phase corrections or self-calibration)
- Difficult to observe very strong sources, such as planets (unless modelized)
Interstellar molecules

Aspirine

Ibuprofeno

Paracetamol or acetaminophen

Viagra

benzene
## List of Interstellar Molecules (142, January 2006)

### Hydrogen Compounds

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<tr>
<td>$H_2$</td>
<td>$HD$</td>
<td>$H_3^+$</td>
<td>$H_2D^+$</td>
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### Hydrogen and Carbon Compounds

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<td>$CH_2$</td>
<td>$C_2H$</td>
<td>*$C_3$</td>
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<tr>
<td>CH$_3$</td>
<td>C$_2$H$_2$</td>
<td>C$_3$H(lin)</td>
<td>c-C$_3$H</td>
<td>*CH$_4$</td>
<td>C$_4$</td>
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<td>c-C$_3$H$_2$</td>
<td>H$_2$CCC(lin)</td>
<td>C$_4$H</td>
<td>*C$_5$</td>
<td>*C$_2$H$_4$</td>
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<td>H$_2$C$_4$(lin)</td>
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<td>C$_6$H</td>
<td>*HC$_6$H</td>
<td>H$_2$C$_6$</td>
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<tr>
<td>*C$_7$H</td>
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<td>C$_8$H</td>
<td>*C$_6$H$_6$</td>
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### Hydrogen, Carbon (possibly) and Oxygen Compounds

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<td>(CH$_3$)$_2$CO</td>
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Molecular ions are in **red**. Free radicals are in **purple**. Closed-shell highly unstable molecules are in **blue**.
### Hydrogen, Carbon (possibly) and Nitrogen Compounds

<table>
<thead>
<tr>
<th>NH</th>
<th>CN</th>
<th>$N_2$</th>
<th>$NH_2$</th>
<th>HCN</th>
<th>HNC</th>
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<td>HC$_7$N</td>
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**Other Species**

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<td>cF$^+$</td>
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Ref. PCMI/CNRS
Inter- & Circumstellar molecules

- 135 species (+-5 ?)
- 14 ions (and 2 anions)
- 29 free radicals (part of which identified in space prior to be studied in the laboratory)
- 19 isomers or highly unstable closed-shell molecules
- 18 molecules with refractory atoms, amidst which 8 silicon compounds
- 5 cycles, among which benzene (1 line!). No other benzenic ring detected, except perhaps PAHs.
Interstellar Molecules: where?

- Diffuse IS clouds
- Cold dark clouds
- Protostellar cores
- Hot cores (star forming regions)
- Circumstellar disks
- Circumstellar envelopes
- Jets and shocked regions
- External galaxies: up to $z=6.4!$
Same spectrum as previous one, but with **line identifications** (in red). **Unidentified lines in green (noted U)**
Maps of Orion-IRC2 in the lines of 6 different molecules: The molecules arise from different hot cores (or corinos) labelled A, B, C and D.

Guelin et al. (2006)
AGB star envelope IRC+10216

Spectral line survey 80-250 GHz
Cernicharo, Guelin, Kahane (2000)
Recent Detection of new molecules

Interstellar Propylene
\( \text{CH}_2\text{CHCH}_3 \) in TMC-1

Second interstellar anion
\( \text{C}_4\text{H}^- \) in IRC+10216

Average spectrum of the J=9-8, 11-10, 12-11, 14-13, and 15-14 lines of \( \text{C}_4\text{H}^- \) (histogram) compared with the average of the same lines of the neutral counterpart \( \text{C}_4\text{H} \), scaled down by a factor of 100

Also

Amino Acetonitrile
\( \text{NH}_2\text{CH}_2\text{CN} \) in Sgr B2
and
Phosphaethyne HCP in IRC+10216

(Cernicharo et al. 2007)
First unbiased line survey in a galaxy – IRAM: 129.1 - 175.2 GHz @ dv ~ 9 km/s

(Martin et al. 2006)

IRAM 30-meter

NGC 253

IRAM 30-meter

2MASS - Jarrett
**DETECTED EXTRAGALACTIC MOLECULES**

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<td>CH₂NH</td>
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<td>OCS</td>
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<td>LiH</td>
<td>H₃⁺</td>
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</table>

* NGC 253’s chemistry closely resembles that of Sgr B2(M) (Turner 1989)

* 35 (+ 4 tentatively) detected species

* 13 (+ 2 tentatively) detected rare isotopic substitutions

**Italicics = tentative**

(Compiled: Martin et al 2006; updated by Turner 2007)

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6th IRAM Interferometry School 2008
M82: a different kind of chemistry

CH$_3$OH and HNCO undetected in these maps

CN, C$_2$H and HNC bright & more extended than CO \( \Rightarrow \) effect of strong radiation field

BIMA observations (Meier & Turner, in prep)

M82 “giant PDR”: Garcia-Burillo et al. 2002 (HCO)

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HH211 at 1.5” resolution

Molecular outflow driven by a **Class 0 low-mass protostar**
(dynamical age~1000 yr, distance of 300pc)

High velocity CO J=2-1

(Gueth & Guilloteau 1999)
1.5” $\rightarrow$ 0.3” resolution

Gueth et al. (2008)
GG Tau in the continuum at 267 GHz

Beam 0.45”x0.25”

Pietu et al. 2008

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Example of a starburst: M82

Prominent starburst at 3.9 Mpc (1’ ~ 1.1 kpc)
Central regions are site of tremendous star-forming activity: Halpha, FIR, X-rays outflows, SNRs
M_{tot} \sim 2.3 \times 10^8 M_{\odot} in center, dense and warm gas

In interaction with M81:
M81-M82 tidal tail – (Yun et al. 1993)
⇒ Triggered star formation
Labels of the molecular streamers (S1–S4) and the outflow gas (O-N and O-S);

- Detection of molecular streamers – S1 (and S2) similar orientation and velocities as the HI streamer that point toward M81
- The molecular gas in the inner region is severely affected by the interaction with M81 and its redistribution is the likely trigger of the starburst activity
- The distribution is extended, almost in a halo comparable to ionized gas
  ➔ From velocities, the gas is out flowing through cone into the halo
  ➔ Enrichment of the IGM

Walter et al. (2002)
The dynamical center of the molecular gas coincides with the 2.2 microns nucleus

Weiss et al. (2001)
Nuclear Gas Dynamics
The NuGa View
Detection of CO(2-1) emission in the Halphafilaments surrounding the galaxy NGC1275

- Cold molecular clouds that may fall back in the gravitational potential well of the galaxy
- Positive feedback scenario
- Recent detection of CO as far as 50 kpc from the galactic center

Salome et al. 2008
History of the Universe

- Recombination (z~1000)
- Cosmic ‘Dark Ages’ - no stars/quasars
- Epoch of re-ionization (6<z<20)
- Peak of activity QSOs & submm galaxies (z~2.5)
- Galaxies today

Epochs:
- The Big Bang
- The Universe filled with ionized gas
- The Universe becomes neutral and opaque
- The Dark Ages start
- Galaxies and Quasars begin to form
- The Reionization starts
- The Cosmic Renaissance, The Dark Ages end
- Reionization complete, the Universe becomes transparent again
- Galaxies evolve
- The Solar System forms
- Today: Astronomers figure it all out!
Inverse K-correction
The Galaxy Cluster A 1835

SCUBA image at 850 microns superimposed on an optical image.

Complementary information on the cluster:
*The submm sources are weak in the optical and vice versa.*

- ~300 Deep submm field sources known

- Difficult redshift determinations

Ivison et al. (2000)
For $z \sim 10$, need to observe CO transitions $J>8$

Is gas actually excited?
The two next detections of CO at high redshift

BR1202-0725 at $z=4.69$  
Cloverleaf at $z=2.6$

Omont et al. (1996)  
Alloin et al. (1997)

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Distribution in redshift of high-z sources

Despite the large selection effects of the flux-limited sample, the distribution reflects the current understanding of the star formation history in the Universe.
CO Survey of sub/mm Galaxies (SMG)

- **18** radio-detected submm galaxies with known optical/near-IR redshift detected in CO (sep. 2007)
- **1<z<3.5**
- Variety of profiles: 780+-230 km/s
- Mergers/Rotating Disks
- Star Formation Rate: **720 M\(_{\text{sun}}\)/yr**
- **M\(_{\text{H}_2}\) \sim 3 \times 10^{10} M\(_{\text{sun}}\)**
- **M\(_{\text{dyn}}\) \sim 10^{11} M\(_{\text{sun}}\)**
- The submm-population consists of gas rich and massive, composite starbursts/AGN systems, which are going a major burst of star formation (i.e. **10^8 yr**) and evolving in m*-galaxies

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(Greve et al. 2005; Neri et al. 2004)
Resolving z>4 CO Emission
Paving the Road for ALMA

Ultimate goal: resolve CO emission spatially/kinematically

⇒ **Dynamical masses**, host galaxy sizes, disk galaxies vs. mergers

⇒ compare to optical/NIR: evolution (?) of $M_{BH}$-$\sigma$ relation

**Critical scale:** $1 \text{kpc} = 0.15''$ @ $z=4-6$

Only VLA / IRAM can observe CO in z>4 QSOs at 0.15”-0.3”/1-2 kpc resolution (B array, 10 km; A array, 800 m)

⇒ *We don’t need ALMA for (all of) this!*

**Caveat:** needs 50-80 hours per source
(VLA) – only one/two track at PdBI

& the best weather conditions

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Comparison of K-band image (left panel) of the region near the quasar BR 1202–0725 with the HST F814W (“wide I,” right panel) image, showing the extension in continuum light to the northwest in both images.

Evidence for star-forming activity from Ly$\alpha$ line emission ($\sim$1100 km/s)

Super-wind activity expelling material in the halo region

Hu et al. 1996
Two sources in CO & dust emission
Southern source - 65% of total

Amplification or Merger?

Omont et al. 1996
Carilli et al. 2002

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BR1202-0725 at $z=4.69$ - First Mergers

r.m.s 0.3 mJy/beam
Beam 1.7" x 0.6 "

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J1148+5251 - The Most Distant QSO at z=6.42

- **z=6.42; age~870 Myr**
- **one of the first luminous sources**
  - $M_{BH} \sim 1-5 \times 10^{9} \, M_{\odot}$ (Willot et al. 2003)
  - $M_{dust} \sim 10^{8} \, M_{\odot}$ (Bertoldi et al. 2003)

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Dust continuum at 1.2 mm

Fan et al. 2003; White et al. 2003
CO(3-2) 46.6149 GHz

continuum

Walter et al. 2003
Bertoldi et al. 2003

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Resolving the CO emission in J1148+5251

- Two sources separated by 0.3” (1.7 kpc at z=6.4) containing each $5 \times 10^9$ M$_{\text{sun}}$
- Not likely to be amplified
- If gravitationally bound, $M_{\text{Dyn}} = 4.5 \times 10^{10}$ M$_{\text{sun}}$

Walter et al. (2004)
APM 08279+5255 \((z=3.9)\)

Very warm gas - peaks at CO\((10-9)\)
220 K inner \((65-100 \text{ pc})\) disk
65 K outer \((150-300 \text{ pc})\) disk
\(~10^4 \text{ – } 10^5 \text{ cm}^{-3}\)

Weiss et al. 2007
Other lines: Atomic Carbon (CI)

CI lines detected in Cloverleaf, F10214, SMM14011, PSS2322
- typically fainter than CO by a factor of few

[e.g., Weiss 2003, 2004, Pety 2004]

PSSJ2322+1944, z=4.12
1GHz BW @ 2mm

⇒ Important for follow-up, but not line of choice for search

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[CII] detected at z=6.4

J1148+5251 (z=6.42)
Maiolino, Cox et al. 2005

\[ L_{\text{[CII]}} = 4.4 \times 10^9 L_{\odot} \]
\[ L_{\text{FIR}} = 2 \times 10^{13} L_{\odot} \]
\[ \frac{L_{\text{[CII]}}}{L_{\text{FIR}}} = 2 \times 10^{-4} \]

30-meter
36 hours integr.

Note: six times brighter than brightest CO line!

Though ‘worst case’ still detectable in [CII]

Follow-up to resolve line: PdBI (0.3′′)

[CII] also detected in B1202 [Iono et al. 06]

Earlier limits on high-z sources: Bolatto et al. 04, Marsden et al. 05, van der Werf 98, …
C$^+$ at 256.17 GHz in J1148+5251 at $z = 6.42$

using the Plateau de Bure interferometer

Spectrum: 3.5hrs in D-config

A+ Configuration: beam 0.26’’ x 0.21’’

Walter et al. 2007
Other High Density Tracers: HNC, CN and HCO$^+$

Burillo et al. (2006)
Guelin, Salome et al. (2006)
Riechers et al. (2007)

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PKS1830-211 at $z=0.88582$

2 components, covering each A or B

Wiklind & Combes (1998)

Slight temporal variability

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PKS1830-211 - PdB survey
Low $^{14}\text{N}/^{15}\text{N}$, young stars

Low $^{17}\text{O}/^{18}\text{O}$