Millimeter Astronomy linked to the Far-Infrared

Carsten Kramer
IRAM, Granada
Millimeter Astronomy
linked to the Far Infrared

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I. An example: The nearby spiral galaxy M33

Optical image (B,V,I,H\(\alpha\)) + 21cm line of HI in blue (Rector, Hanna 2005)
I. The nearby spiral galaxy M33

+ Morphological type: SA(s)cd
+ Major & minor diameters: 70.8, 41.7 arcmin
+ PA = 22.5 deg, Incl.: 55.0 deg
+ Distance = 840 kpc (180 kpc from M31)
+ 12 arcsec = 49 pc
+ Brightest HII complex in Local Group (NGC604)
+ Metallicity: subsolar by a factor 2-3 Shallow gradient
I. The nearby spiral galaxy M33

Location of Giant Molecular Clouds (GMCs) overlaid upon an integrated intensity map of the HI 21cm line (Engargiola et al. 2003, Gardan et al. 2007). **GMCs are formed from large structures of atomic gas.**
The HII region NGC603 in M33. (Optical image by HST)
I. The Interstellar Medium in Galaxies

Phases of the Interstellar Medium and their main constituents and tracers:

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<th>Phase</th>
<th>Constituents</th>
<th>Characteristics</th>
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<td>HII Regions</td>
<td>HII, NII, CII</td>
<td>T~10^4K</td>
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<tr>
<td>Warm Ionized Medium (WIM)</td>
<td>HII, NII, CII</td>
<td>n<del>10^{-3}cm^{-3}, T</del>10^5K</td>
</tr>
<tr>
<td>Warm Neutral Medium (WNM)</td>
<td>HI, CII</td>
<td>n<del>0.3cm^{-3}, T</del>8000K</td>
</tr>
<tr>
<td>Cold Neutral Medium (CNM)</td>
<td>HI, CII</td>
<td>n<del>40cm^{-3}, T</del>70K</td>
</tr>
<tr>
<td>Dense Molecular Clouds</td>
<td>H₂, CII, Cl, CO</td>
<td>n<del>10^3-6cm^{-3}, T</del>10-100K</td>
</tr>
</tbody>
</table>

All stars form inside molecular clouds!

McKee & Ostriker 1977, Wolfire et al. 2003, Kramer et al. 2005
I. The Cycle of Matter in Galaxies

Galaxies and the ISM are not stationary, but evolve on different timescales.
+ Molecular clouds are best studied at millimeter and far infrared wavelengths (3mm to 10µm)

+ Observations at visible, UV, or soft X-ray wavelengths are hindered by dust extinction

+ In the continuum, **thermal emission** from dust particles dominates over Bremsstrahlung and synchrotron emission

+ **Spectroscopy of atomic and molecular transitions** allow detailed studies of
  - physical conditions (density, temperature, mass, magnetic field,...)
  - chemical abundances [X/H],
  - structure of the ISM and its dynamics (velocity fields)

+ More than 150 molecules have been detected in the ISM and in circumstellar envelopes to date.

+ Important tool to study planetary atmospheres (see lecture of R.Moreno)
II. Tools of Millimeter and FIR Astronomy

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see the lecture on Polarimetry by C.Thum
II.1 Molecules & Atoms
### II.1 Molecules in the ISM and in shells (5/09)

From the Cologne Data Base for Molecular Spectroscopy (CDMS)

- >150 molecules ongoing research
- +laboratory work
- organic chemistry but also S,P,F,Cl,Fe,Si,...
- kations and also few anions!

Many radicals like CH, C₂H, OH, HCO, CN, ...

Fairly complex molecules like Benzene, ...

**Benzene C₆H₆:**

(Cernicharo et al. 2007 with ISO)

**Ethyl-formate C₂H₅OCHO:**

(Belloche et al. 2009 with the 30m)
II.1 Molecular Transitions

3mm spectrum of the Orion lrc2 massive star forming region taken during commissioning of the new 30m receiver EMIR.
Atmospheric zenith transmission, $T = \exp(-\tau)$, in the frequency range accessible to the IRAM 30m telescope

Atmosphere:
+ Transmission
+ “Windows”
+ $H_2O, O_2, O_3, + ...$
+ Models

ISM lines:
+ CO, HCN, HCO$^+$, ...
+ Transitions
+ Spacing
Atmospheric zenith transmission, $T = \exp(-\tau)$, in the frequency range accessible to the IRAM 30m telescope.

Atmosphere:
- Transmission
- “Windows”
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ISM lines:
- CO, HCN, HCO$^+$, ...
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- Spacing

Planetary Atmospheres (see Lecture of R. Moreno)
II.1 Molecular Transitions

\[ E_{\text{tot}} = E_{\text{el}} + E_{\text{vib}} + E_{\text{rot}} \]

Assumes decoupling of nuclear and electronic motions (Born-Oppenheimer approx.)
\( E_{\text{el}} \sim 10^4 \text{ cm}^{-1} \) is the binding energy at equilibrium separation of 1Angs. of the nuclei.

**Diatomische Moleküle.**

**Vibrational Energy:**
\[ E_{\text{vib}} \sim h(v+1/2) \text{ with } v=0,1,2,... \]
\[ h \sim 10^{-2}-10^{-3} \text{ cm}^{-1} \]
Vibrational bands \( \Delta v = +/-1 \) lie near 3 to 10\( \mu \)m.

**Rotational Energy:**
\[ E_{\text{rot}} \sim B e J(J+1) \text{ with } J=0,1,2,... \text{ and the rotational constant } B_e = h^2/I \text{ with} \]
\[ I = 2 \mu R_e^2 \text{ with the reduced mass } m = m_1 m_2/(m_1+m_2). \]
\[ E_{\text{rot}} \sim 1 \text{ cm}^{-1} \]

If the molecule has a permanent electric dipole moment, electric dipole transitions are allowed, with \( \Delta J = +/-1 \).
\[ E_{\text{tot}} = E_{\text{el}} + E_{\text{vib}} + E_{\text{rot}} \]
Assumes decoupling of nuclear and electronic motions (Born-Oppenheimer approx.)

\[ E_{\text{el}} \sim 10^4 \text{ cm}^{-1} \]
is the binding energy at equilibrium separation of 1 Angs. of the nuclei.

**Diatomic Molecules**

**Vibrational Energy**

\[ E_{\text{vib}} \sim h \nu (v + 1/2) \] with \( v = 0, 1, 2, ... \)

\[ h \nu \sim 10^2 - 10^3 \text{ cm}^{-1} \]

vibrational bands \( \Delta v = \pm 1 \) lie near 3 to 10 \( \mu \)m.

**Rotational Energy**

\[ E_{\text{rot}} \sim B_e J (J+1) \] with \( J = 0, 1, 2, ... \)

the rotational constant \( B_e = \frac{h^2}{I} \)

\[ I = 2 \mu R_e^2 \] with the reduced mass \( m = \frac{m_1 m_2}{m_1 + m_2} \).

\[ E_{\text{rot}} \sim 1 \text{ cm}^{-1} \]

If the molecule has a permanent electric dipole moment, electric dipole transitions are allowed, with \( \Delta J = \pm 1 \).
II.1 Molecular Transitions

Linear Molecules - Rotational Energy (continued):

**CO, HCN, CS** have $\mu \sim 7m_H$ and $J=1-0$ transition at a wavelength of a few mm. **OH, CH, HCl** have $\mu \sim m_H$ and $J=1-0$ transition in the submm/fir range.

**H$_2$** has no electric dipole moment. Only weak quadrupole transitions are allowed. The lowest pure rotational transition of H$_2$ between $J=2-0$ lies at 28$\mu$m.

Higher order effects make spectra more complicated:
+ Anharmonicity of the potential for vibrations,
+ Centrifugal distortion for rotations,
+ Coriolis forces couple rotational and vibrational motion.
II.1 Molecular Transitions

Polyatomic Molecules.
Non-linear, polyatomic molecules have 3 axes of rotation

If the molecule has a three-fold (or greater) symmetry axis, the moments of inertia of two of the three principle axes must be identical. These molecules are called symmetric tops.

Prolate case: $I_a < I_b = I_c$
Oblate case: $I_a = I_b < I_c$

Examples are:

Ammonia NH$_3$, Acetronitrile CH$_3$CN, Methylacetylene CH$_3$CCH.

Because of symmetry, two quantum numbers only: J, K
Selection rules for radiative transitions: $\Delta J = +/-1$, $\Delta K = 0$.
Possible further split-up of transitions:
  - inversion (symmetric/antisymmetric nuclear wave function)
  - quadrupole/magnetic dipole
  - hyperfine structure
II.1 Molecular Transitions

Polyatomic Molecules (continued).

**asymmetric tops:**

Moments of inertia about all 3 axes differ. None of the projections of the total rotational angular momentum onto these axes is a good quantum number. Rotational levels are labeled by $J_{K^-K^+}$ where $K^-$ and $K^+$ are approximate quantum numbers.

Examples are: $\text{H}_2\text{O, SO}_2, \text{H}_2\text{S}$.

Transitions between different K-ladders are allowed.
### II.1 Molecular Excitation

**Molecular excitation**

**Pure rotational transitions**

- Population distribution not in thermodynamic equilibrium but determined by competition radiative and collisional processes

- Critical density $\propto \mu^2 \nu^3$ => higher frequencies probe higher densities and temperatures

E. van Dishoeck
II.1 Tracing the physical conditions

See the Lecture on Astrochemistry by Ewine van Dishoeck on her homepage!
II.1 Continuum, Molecular Lines & Atomic Lines in Infrared Galaxies
II.1 Fine structure lines of atoms and ions

Electrons: orbital angular momentum $I$, spin $s$
Atoms: Total orbital momentum $L = \Sigma I$, Total spin $S = \Sigma s$

Magnetic spin-orbit splitting leads to transitions in the 10-300\(\mu\)m wavelength range.
II.1 Fine structure lines of atoms and ions

electrons: orbital angular momentum $l$, spin $s$

atoms: Total orbital momentum $L=\Sigma l$, Total spin $S=\Sigma s$

Magnetic spin-orbit splitting leads to transitions in the 10-300\(\mu\)m wavelength range.

**Spectroscopic notation:** $^{2S+1}L_J$

with the

- multiplicity $2S+1$
- the total orbital angular momentum $L$ (denoted $S, P, ...$)
- total angular momentum $J=L+S$.

**Fine structure doublet** with $S=1/2, L=1, J=3/2-1/2$:
C$^+$ with a single fine structure transition $^2P_{3/2} - ^2P_{1/2}$ at 158\(\mu\)m (1900GHz)

**Fine structure triplets** with $S=1, L=1$:
O with two transitions at 146 and 63\(\mu\)m: $^3P_0 - ^3P_1 - ^3P_2$
C with two transitions at 370 and 609\(\mu\)m (810 and 492GHz): $^3P_2 - ^3P_1 - ^3P_0$

Transitions are magnetic dipole transitions with $\Delta J=0, +/-1$, $\Delta L=0$, $\Delta S=0$. 
II.1 Fine structure lines of OI, CI, CII
II.1 Far infrared emission

- Peak of the dust continuum emission of the cold dust

- Many of the strongest fs cooling lines lie in the FIR: [CII](158), [OI](63, 145), [NII](122, 205)

- Highly excited rotational transitions of molecules like CO, HCN, HCO+, ... tracing hot star forming gas

- Light Hydrides: NH, NH₂, SH, PH, LiH, H₂O, ...

- Important deuterated species: H₂D⁺, D₂H⁺
II.1 THz transitions

[CII] impossible to observed from the ground! Really?
II.1 Molecular lines at 800-900 GHz

The THz regime is rich in lines

SHARC/CSO 350micron dust emission map of Orion A
(Lis et al. 1998)

Unbiased spectral line survey of Orion KL at 350 micron by Comito et al. (2005) at the CSO:
26 species and 929 transitions
Dominant coolants: $SO_2$, $CH_3OH$, CO, SO, $H_2CO$, HCN,...
(HCN contains 25% of $SO_2$ cooling intensity)
II.1 Far infrared emission

HCN & HCO$^+$
High-lying rotational transitions in the THz regime

- Orion KL line survey in the 350μm window
  (Comito et al. 2005)
  
  HCN 9-8  797GHz  95K Tmb
  HCN 10-9  886GHz  57K
  HCO$^+$ 9-8  802GHz  56K
  HCO$^+$ 10-9  892GHz  30K
  
  $T_{rot}$=150K, $n=10^{7-8}$ cm$^{-3}$
  (if collisionally excited, IR pumping?)

In addition:
  $^{13}$HCN, HC$^{15}$N, HCN-v2, DCN

- IRC+10216: HCN with ISO/LWS
  (Gernicharo et al. 1996)
II.1 Far infrared emission

**CO**

- Very stable: abundance insensitive to physical conditions, $E_{diss} = 11.1$ eV
- CO traces a large range of excitation conditions in molecular clouds:
  
  $E_{up}/K = 2.8 \, J \, (J+1)$  
  
  $n_{cr}/cm^{-3} = 4 \times 10^3 \, J^3$

  e.g.
  
  CO 14-13: 590 K, $1.1 \times 10^7$ cm$^{-3}$  
  CO 7-6: 157 K, $1.4 \times 10^6$ cm$^{-3}$  
  CO 4-3: 56 K, $2.6 \times 10^5$ cm$^{-3}$

**Unresolved observations:**

- High-J CO lines: FIRAS/COBE, KAO, 0.6m ISO

**Velocity resolved observations:**

- CO 7-6: several observations (+galactic nuclei upto z=6.4)
- CO 9-8: very few observations so far:
  
  Marrone et al. 2004 (0.8m RLT), Kawamura et al. 2002 (10m HHT),
  Boreiko & Betz 1991, 1997 (0.9m KAO)

- CO 11-10, 13-12: very few observations so far:
  
  Wiedner et al. 2006 (CONDOR @ 12m APEX),
  Marrone et al. 2005 (0.8m RLT)

- CO 17-16:
  
  Boreiko, Betz, et al. 1989, 1997 (0.9m KAO)
II.1 Gas energy balance

Gas energy balance: CO the main coolant

What heats the gas? FUV photons / Cosmic Rays / X-rays / Shocks?
II.1 Far infrared emission

Ions, Atoms, and Molecules as tracers of temperature and density

- OI 145\,\mu m
- OI 63\,\mu m
- CI 370\,\mu m
- CI 609\,\mu m
- CO 14-13, 590 K, 1.1 \times 10^7 \, \text{cm}^{-3}
- CO 7–6, 157 K, 1.4 \times 10^6 \, \text{cm}^{-3}
- CO 4-3, 56 K, 2.6 \times 10^5 \, \text{cm}^{-3}

Collisions with H for CII, OI, CI
Collisions with H_2 for CO

October 2005
II.1 [NII] 205 and [CII] 158 in the Milky Way

[NII]

Observations so far:

- KAO: Both lines observed in the Galactic HII region G333.6-0.2: Colgan et al. 1993

- FIRAS/OBE (Fixsen et al. 1999): [NII] lines are strongest after [CII] for λ>100µm

- ISO/LWS: 122µm line strong also in disks of spiral galaxies: e.g. Contursi et al. 2002, Kramer et al. 2005

- SPIFI/AST/RO: 205µm line detected from ground in Carina I HII region (Oberst et al. 2006)

[Molecular spectroscopy at 1-2 THz]

The Milky Way with FIRAS/Cobe

COBE FIRAS 158 µm C⁺ Line Intensity

COBE FIRAS 205 µm N⁺ Line Intensity

[NII] stems from the diffuse warm ionized medium (WIM), [CII] partly
II.1 [CII] 158μm from space 
with HIFI/Herschel

see Lecture of E.Caux!
II.1 30m observations of the \([\text{CII}]\) line

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

\[ \nu = \nu_0/(1+z) = 1.9 \text{ THz}/(1+6.4) = 256 \text{ GHz} \]

\[ \text{J1148+5251 (z=6.42)} \]
\[ \text{Maiolino, Cox et al. 2005} \]

30-meter
36 hours integr.

Note: six times brighter than brightest CO line!

Though ‘worst case’ still detectable in \([\text{CII}]\)

Follow-up to resolve line: PdB1 (0.3’’)

\[ \text{[CII] also detected in B1202 [Iono et al. 06]} \]

Earlier limits on high-z sources: Bolatto et al. 04, Marsden et al. 05, van der Werf 98, ...

IRAM Interferometry School 2008
II.1 30m: Redshifted $[\text{NII}]$ 205$\mu$m?

Walter, Weiss et al. 2009

\[ \nu = \frac{\nu_0}{1+z} = 1.9 \text{THz}/(1+6.4) = 256 \text{GHz} \text{ for } [\text{CII}] \]

\[ \nu = \frac{\nu_0}{1+z} = 1.46 \text{THz}/(1+6.4) = 197 \text{GHz} \text{ for } [\text{NII}] \]

7.6Jy/K at 1mm
0.17mK at 197GHz after 8h on-source time
II.1 Redshifted Fine Structure Lines

CO 6-5: $v = v_0/(1+z) = 691\text{GHz}/(1+2.56) = 194\text{ GHz}$

CO 7-6: $v = v_0/(1+z) = 805\text{GHz}/(1+3.56) = 226\text{ GHz}$

Walter, Weiss et al. 2009

see lecture by S. Garcia-Burillo

Walter, Weiss et al. 2009

e.g.

Cloverleaf at $z=2.56$

Figure 4. Frequency coverage of redshifted fine structure lines for some current (and future) key telescopes as a function of redshift. The following lines are plotted (in order of increasing frequency, given in GHz): $\text{C}IV\nu492.2$, CO(6–5)$\nu691.5$, $\text{C}IV\nu809.3$, [N ii]$\nu1461.1$ (= [N ii]$\lambda205\mu\text{m}$), [C ii]$\nu1900.5$, [O i]$\nu2060$, [N ii]$\nu2460$, [O iii]$\nu3393$, [O i]$\nu4745$, [O iii]$\nu5786$). The left panel shows the coverage for the PdBI and CARMA, the middle panel the respective coverages for the EVLA and the IRAM 30 m telescope and the right panel for ALMA (bands 2–9; band 5 is not fully funded and thus appears in lighter color). The three black points in the left and middle panels highlight the positions of the transitions in J1148+5251 discussed in this Letter (CO(6–5), [N ii]$\lambda205\mu\text{m}$ and [C ii]).
II.2 Dust emission
II.2 Thermal Dust emission

Powerful probe of « cold » objects in the Universe

- Debris disks & protoplanetary disks
  - ε Eridani
    - JCMT, Greaves et al.
- Protostars and prestellar cores
  - MC11-MM (Prestellar)
    - IRAM 1.2mm
  - Elias 1 (Class II)
- Nearby Galaxies
  - NGC1569
    - SCUBA 850 μm, Galliano et al. 2005
- High-z Galaxies
  - COSMOS
    - Bertoldi et al. 2007, MAMBO 1.2 mm

+ e.g. Trans-Neptunian Objects in the solar system (see R.Moreno)
II.2 Thermal Dust emission

Thermal Emission from Cold Dust \((T_d \sim 5\text{-}50 \text{ K})\)

- Optically thin emission at (sub)mm wavelengths
  \(\rightarrow\) Direct mass/column density estimates:
  \[ M = \frac{S_v \, d^2}{B_v(T_d) \, \kappa_d} \]

- \(\lambda \sim 100\text{-}500 \mu\text{m}\) : good diagnostic of the dust temperature \((T_d)\)
- \(\lambda \sim 0.8\text{-}2 \text{ mm}\) : good tracer of the mass & opacity \((\kappa_d \sim \lambda^{-\beta})\)
II.2 Thermal Dust emission

\[
\frac{S_{1.3}}{\Omega_b} = \tau_{1.3} B_\nu(T_d)
\]

\[
S_{1.3} \left[ \frac{\text{mJy}/(11\text{as beam})}{\text{[cm}^{-2}]\right] = \frac{(2N(H_2)+N(H))}{0.510^{-22} \frac{11.1/T_d}{\exp(11.1/T_d)}-1}
\]

A cloud with \(N(H_2)=10^{22}\text{cm}^{-2}\) (\(A_v=10\text{mag}\)), \(T_d=10\text{K}\):

\(S_{1.3}=20\text{ mJy/beam (~3mK at 30m telescope, 7 Jy/K at 240GHz)}\)

Sensitivity of MAMBO2/channel: ~30mJy in 1 sec

Multi-wavelength observations allow to derive \(T_d\):

\[
\frac{S_{450}}{S_{850}} = \left(\frac{850}{450}\right)^{3+\beta} \frac{\exp(17/T_d)-1}{\exp(32/T_d)-1}
\]
II.2 Thermal Dust emission

+ ISM dust grains have diameters of $a \sim 0.01$ to $1 \mu m$
+ Efficient absorbers of short-wavelength radiation ($\lambda < a$)
+ In equilibrium of heating and cooling, they emit a continuous spectrum closely resembling a thermal spectrum ($T_d$) and smoothly varying absorption/emission efficiency $Q(\nu) = Q_0 (\nu/\nu_0)^\beta$.

Hacar et al. 2009 in prep.

see lecture by A. Weiss
II.2 Thermal Dust emission

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

**Dust emission** peaks at \( \lambda = \frac{hc}{((3+\beta)kT)} = \frac{2.9}{T} \, \text{mm} \)

Example: Spectral Energy Distribution (SED) of a star forming galaxy. With \( T=50\,\text{K} \), dust emission peaks near 60\( \mu \text{m} \) in the far-infrared
II.2 Mapping the cold dust in M51

Herschel/PACS Images of M51 ("Whirlpool Galaxy")

© ESA & The PACS Consortium

160 μm  100 μm  70 μm

see also lecture by A.Leroy
III. The Telescopes
III. Millimeter wave Radio Telescopes

+ Sensitivity: Large collecting surface area and good surface accuracy
+ Angular resolution: Large diameter of primary mirror
+ High altitude to reduce atmospheric amount of precipitable water vapor (pwv)
+ Heterodyne receivers for high spectral resolution >10^-6
+ Bolometer arrays for sensitive continuum mapping

**IRAM 30m telescope**
03:23:33.7 W
37:03:58.3 N

707m² surface
420 Al panels on honeycomb backstructure
50 μm surface accuracy
30m diameter
2850m altitude Pico Veleta/Sierra Nevada

230GHz/10kHz = 2.3 10^-6
Frontends: EMIR, HERA, MAMBO2
III. Radio telescopes: basic parameters

Some basic parameters of a Radio Telescope

Notation: Reflectors diameter \( D \)
Wavelength \( \lambda \)
Beamwidth/resolution \( \Theta_A \)
Reflector surface error \( \varepsilon \)
Aperture efficiency \( \eta_A \)

Beamwidth
\[ \Theta_A \text{ (arcsec)} = 1.2 \frac{\lambda}{D} = 250 \frac{\lambda(\text{mm})}{D(\text{m})} \]

Effective aperture area
\[ A_{\text{eff}} = \pi A \eta_A \theta_D^{2/4} \]

Aperture efficiency
\[ \eta_A = \eta_{\text{ill}} \exp[-(4\pi^2 / \lambda)^2] \] “Ruze” formula

Illumination efficiency
\[ \eta_{\text{ill}} \approx 0.7 \] - feed pattern, blocking, etc.

“Good” telescope performance, if

Pointing accuracy better than 0.1 \( \times \Theta_A \)
Surface accuracy better than \( \lambda/16 \)

For ALMA this means, at 320 \( \mu \)m wavelength:

Pointing 0.6 arc seconds; Reflector error 20 \( \mu \)m

J. Baars-RadioTelescopes-ESO, 2001

IRAM 30m telescope

Beamsize (Resolution, Half power beam widths HPBW):

30" at 80GHz (Full moon has 30′=1800")
10" at 230GHz
7" at 330GHz
III. IRAM 30m telescope: signal path

Mapping the cosmic signals

The antenna's reflector panels collect the cosmic signals and relay them to the sub-reflector, which transfers them to the receivers located inside the antenna. Due to the great cosmic distances, the incoming signals are very weak.

To amplify the signals, the receiver starts by converting them to a lower frequency.

The cosmic signal is then mixed (inside the mixer-block, part of the receiver) with a locally produced signal at a frequency close to that of the original signal.

The superconducting junction, the active element of the mixer, sends out the difference between the two incoming signals, the so-called intermediate frequency, which is low enough to be amplified.
## III. Radio telescopes: basic parameters

### Some basic parameters of a Radio Telescope

<table>
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<th>Notation</th>
<th>Description</th>
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<tr>
<td>Reflector diameter</td>
<td>( D )</td>
</tr>
<tr>
<td>Wavelength</td>
<td>( \lambda )</td>
</tr>
<tr>
<td>Beamwidth/resolution</td>
<td>( \Theta_A )</td>
</tr>
<tr>
<td>Reflector surface error</td>
<td>( \epsilon )</td>
</tr>
<tr>
<td>Aperture efficiency</td>
<td>( \eta_A )</td>
</tr>
</tbody>
</table>

- **Beamwidth**: \( \Theta_A \) (arcsec) = \( 1.2 \frac{\lambda}{D} \) = 250 \( \frac{\lambda (mm)}{D (m)} \)
- **Effective aperture area**: \( A_{\text{eff}} = \eta_A^{1/2} \lambda D^{3/4} \)
- **Aperture efficiency**: \( \eta_A = \eta_{\text{ill}} \exp\left[-\left(\frac{4\pi \epsilon}{\lambda}\right)^2\right] \) “Ruze” formula
- **Illumination efficiency**: \( \eta_{\text{ill}} = 0.7 \) (good pattern, blocking, etc.)

“Good” telescope performance, if:
- **Pointing accuracy** better than \( 0.1 \times \Theta_A \)
- **Surface accuracy** better than \( \lambda/16 \)

For ALMA this means, at 320 \( \mu \text{m} \) wavelength:
- **Pointing**: 0.6 arc seconds; **Reflector error**: 20 \( \mu \text{m} \)

\( J.\text{Baars-RadioTelescopes-ESO, 2001} \)

### IRAM 30m telescope

- **Aperture efficiency at 230GHz**: 45%
- **Pointing accuracy**: \( \sim 2^{\prime\prime} \), i.e. \( 0.1 \times \text{HPBW(115GHz)} \) or \( 0.3 \times \text{HPBW(345GHz)} \)
- **Surface accuracy**: \( \sim 50\mu m \), i.e. \( \lambda/16 \) at 345GHz
III. Herschel Space Observatory

- launched on 14.5.09
- FIR/Submm Observatory: 55-672 μm
- 3.5m Telescope
- 12” beam at 158 μm (1.9THz, [CII])
- ηA ~ 70% at 158μm

see lecture by E.Caux