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OBSERVATIONAL METHODS IN RADIO ASTRONOMY I : SINGLE-DISH

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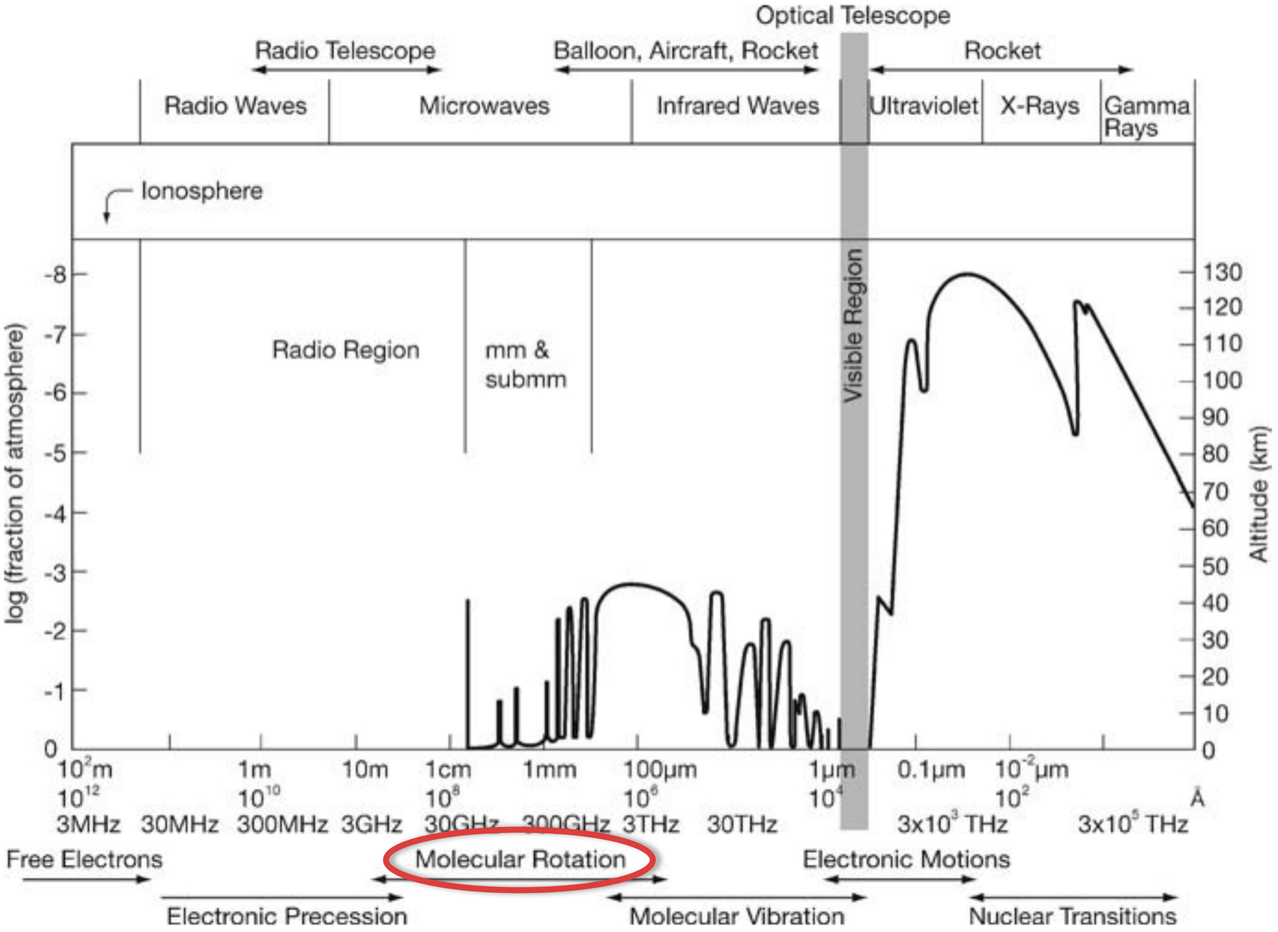
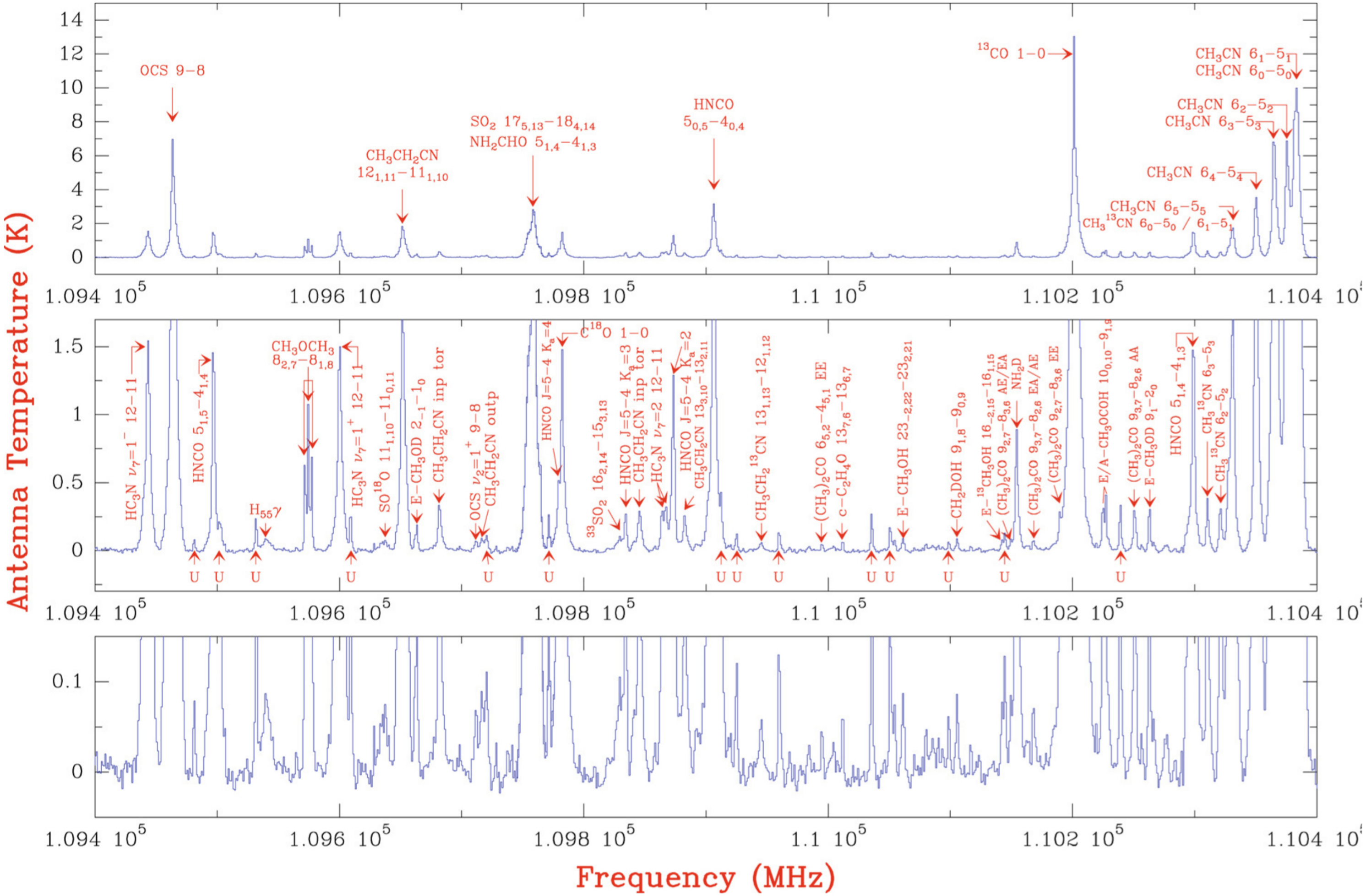
INTRODUCTION

THE MM-SUBMM WINDOW

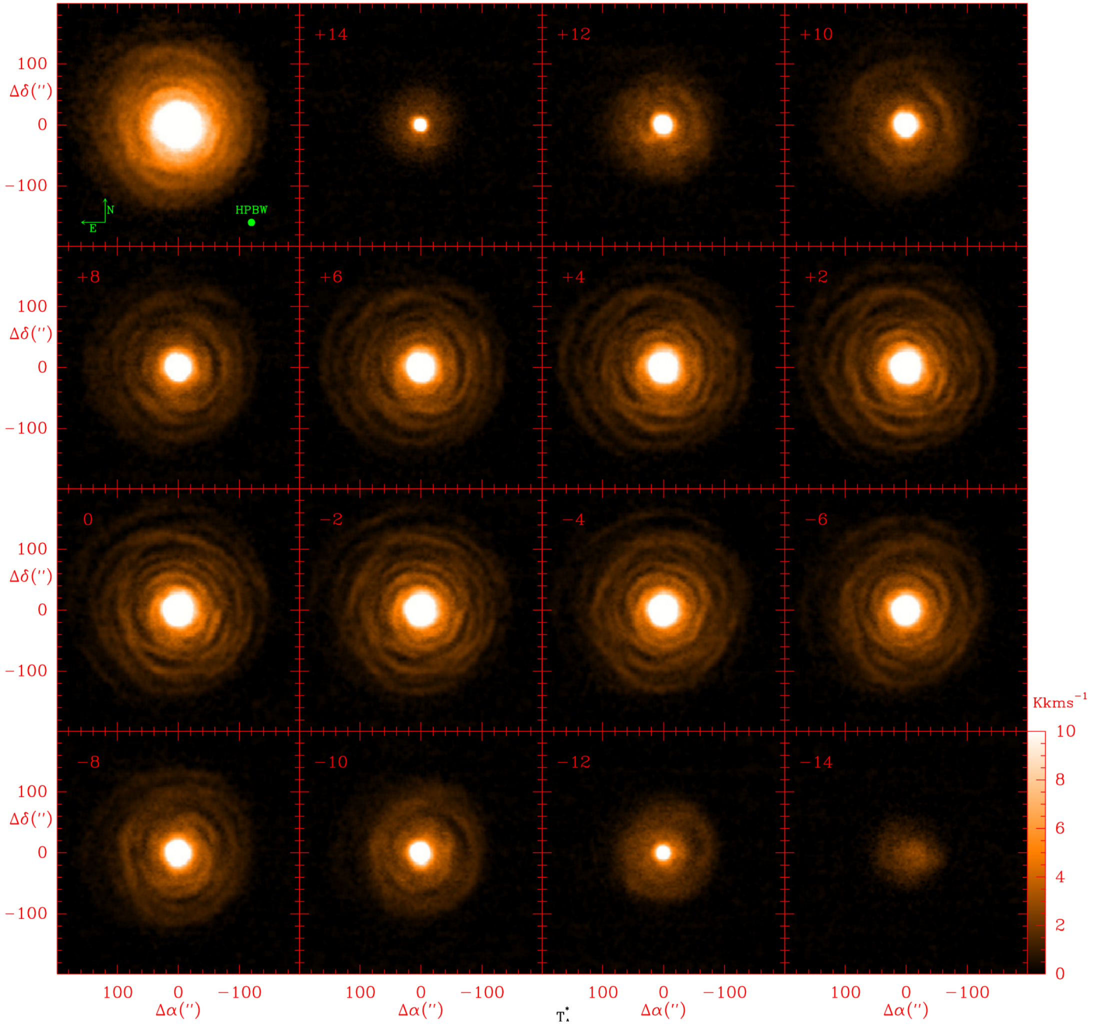


THE MM-SUBMM WINDOW: spectral line surveys



Orion KL
Tercero et al. 2010

THE MM-SUBMM WINDOW: velocity channel maps



IRC+10216; CO J=2-1
Cernicharo et al. 2015

GOALS / QUESTIONS

Goals

- Measure the signal emitted from a particular region in the sky
- Obtain spectral or spatial information of the source
- Determine chemical and/or physical properties

Questions

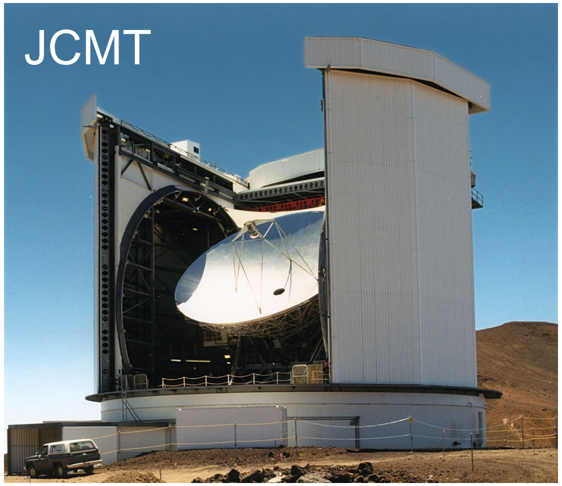
- Measurement fidelity
- Calibration

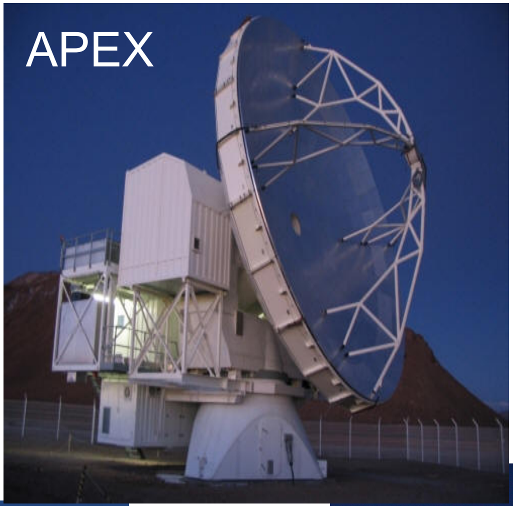
Not covered in this talk

- Receivers and backends

ANTENNAS

RADIOTELESCOPES





RADIOTELES

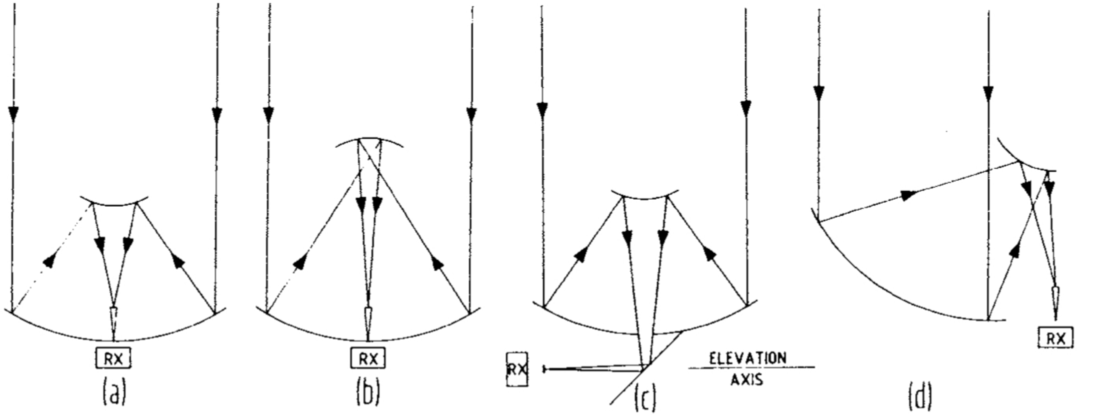


Fig. 7.6 The geometry of (**a**) Cassegrain, (**b**) Gregory, (**c**) Nasmyth and (**d**) offset Cassegrain systems

Parabolic primary dish, but different positions of the receivers:

- Cassegrain: hyperbolic, convex subreflector
- Gregory: elliptical, concave subreflector behind the prime focus (e.g. Effelsberg)
- Nasmyth: hyperbolic subreflector and flat tertiary mirror (e.g. IRAM 30m, APEX)
- Offset Cassegrain: “half” parabolic and hyperbolic subreflector (e.g. GBT)

Advantages of the different optical configurations:

- Secondary focus: 5-10 times larger f/D ratios, less sensitive to lateral focus offsets, increase effective area, decrease spillover
- Nasmyth system: receivers are not tilted with elevation, more space in rx cabin
- Offset Cassegrain: less blockage by subreflector and support structure, less standing waves

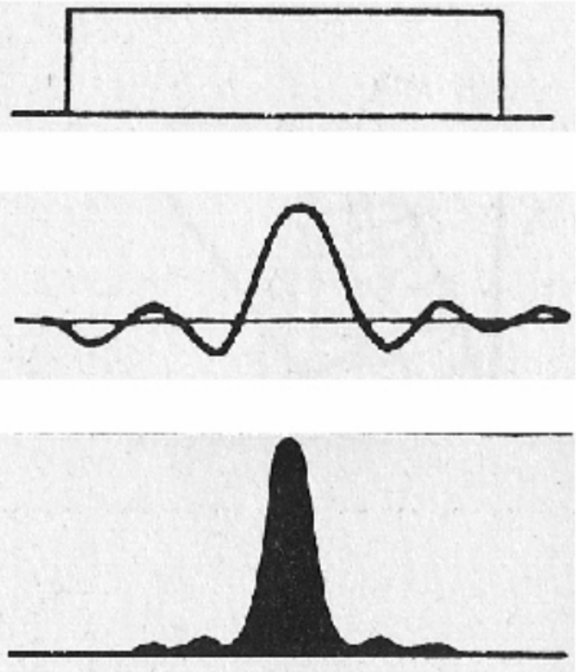
RADIOTELESCOPES

Obs.	D (m)	ν (GHz)	λ (mm)	HPBW (”)	Latitude (deg)
IRAM	30	70 − 345	4 − 0.7	35 − 7	+37
GTM	50 (32)	(73 − 116, 230)	4 − 0.85	20 − 6	+19
APEX	12	230 − 1200	1.3 − 0.3	30 − 6	−22
JCMT	15	210 − 710	2 − 0.2	20 − 8	+20
Herschel	3.5	500 − 2000	0.6 − 0.1	43 − 11	space

collecting area

angular resolution $\sim \lambda/D$

ANTENNA THEORY: POWER PATTERN



- Reciprocity theorem: antenna in emission
- Distribution of electric field on the dish: $E_{ant}(x,y)$
- Far field radiated by the dish: $E_{ff}(l,m) \propto \mathcal{F}\left[E_{ant}(x,y)\right]$
- Power emitted $\propto \left|E_{ff}(l,m)\right|^2$
- Power pattern: $P(l,m) \propto \left|E_{ff}(l,m)\right|^2$
- Beam solid angle: $\Omega_A = \int_{4\pi} P(\Omega)\, d\Omega$
- Effective area: $A_e = \eta_A \cdot A_{geom}$ → η_A : *aperture efficiency*
- Fundamental relation: $A_e \cdot \Omega_A = \lambda^2$

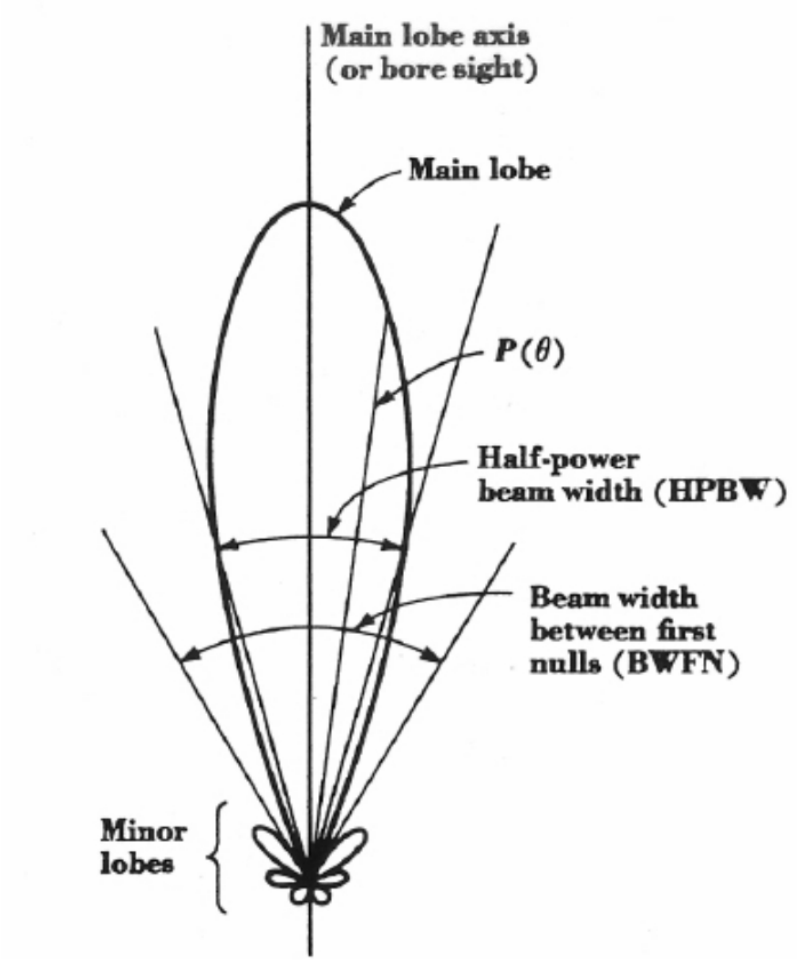
ANTENNA THEORY: POWER PATTERN

Main beam solid angle:

$$\Omega_{MB} = \int_{\substack{main\\lobe}} P(\Omega)\, d\Omega$$

Main beam efficiency:

$$\eta_B = \frac{\Omega_{MB}}{\Omega_A}$$



POWER COLLECTED BY AN ANTENNA

- Power from a monochromatic point source, collected by an area A_e : $$p_\nu = \frac{1}{2} A_e \cdot S_\nu \qquad [\mathrm{W\ Hz^{-1}}]$$

Flux density S_ν measured in Jy: 1Jy = 10^{-26} J s^{-1} m^{-2} Hz^{-1}

- If source is extended: $$\delta p_\nu = \frac{1}{2} A_e \cdot I_\nu \cdot \delta\Omega \qquad [\mathrm{W\ Hz^{-1}}]$$

Brightness I_ν measured in Jy sr-1: 1Jy sr^{-1} = 10^{-26} J s^{-1} m^{-2} Hz^{-1} sr^{-1}

Source flux density is:

$$\boxed{S_\nu = \int_{\Omega s} I_\nu(\Omega)\, d\Omega}$$

BUT observed flux density is:

$$\boxed{S_{obs} = \int_{\Omega s} P(\Omega) I_\nu(\Omega)\, d\Omega < S_\nu}$$

TEMPERATURE SCALES

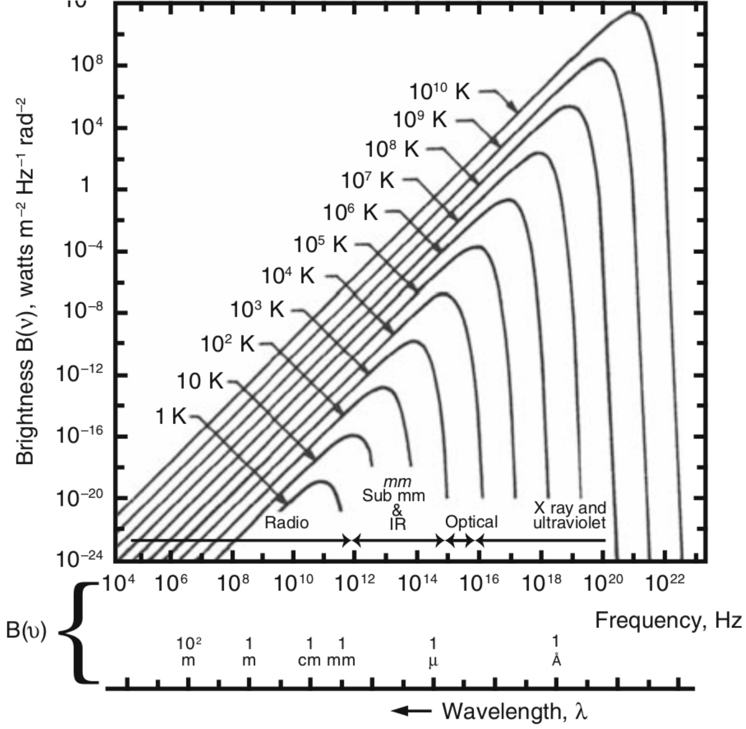
BLACK BODY RADIATION

Planck Law :

$$\boxed{B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}}$$

Rayleigh-Jeans approximation:

$$h\nu << kT \rightarrow B_\nu(T) = \frac{2\nu^2}{c^2}kT$$



Brightness temperature: temperature a black body would have to match the observed intensity of an extended source at frequency ν:

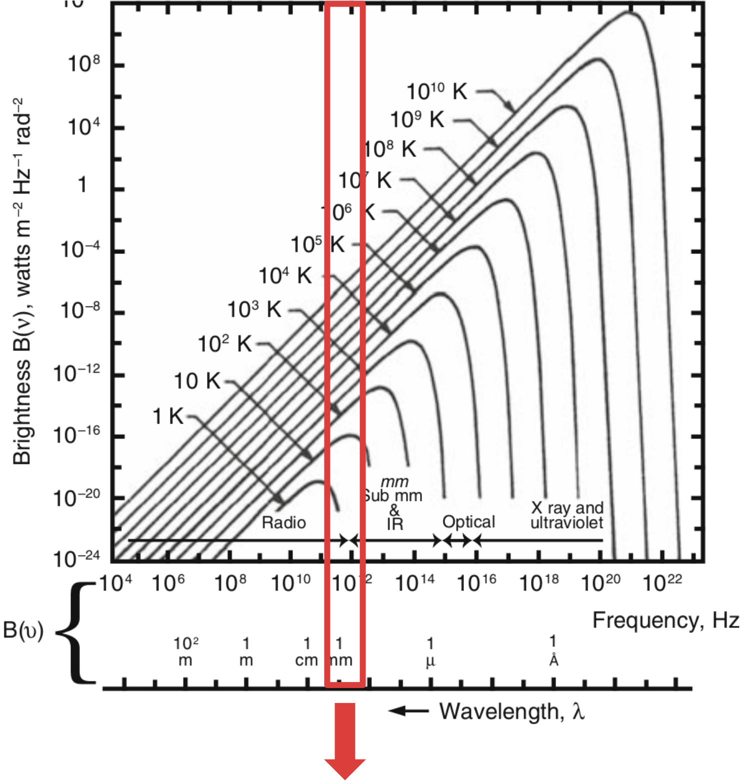
$$I_\nu(\Omega) = B_\nu(T_b) \rightarrow T_b = \frac{c^2}{2k\nu^2}I_\nu(\Omega) = \frac{\lambda^2}{2k}I_\nu(\Omega)$$

$$\boxed{S_\nu = \int_{\Omega s} I_\nu(\Omega)\,d\Omega = \frac{2k}{\lambda^2}T_b\Delta\Omega}$$

BLACK BODY RADIATION

Planck Law :

$$\boxed{B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}}$$



Rayleigh-Jeans approximation:

$$h\nu << kT \;\rightarrow\; B_\nu(T) = \frac{2\nu^2}{c^2}kT$$

Brightness temperature: temperature a bla
match the observed intensity of an extended

$$I_\nu(\Omega) = B_\nu(T_b) \quad \rightarrow \quad T_b = \frac{c^2}{2k\nu^2} I_\nu($$

NOTE this is not valid in the mm and low T:

$$\frac{\nu}{GHz} << 20.84\frac{T}{K}$$

At T=10K: 230 GHz~208.4K
(cold dark clouds)

$$\boxed{S_\nu = \int_{\Omega s} I_\nu(\Omega)\,d\Omega = \frac{2k}{\lambda^2}T_b\Delta\Omega}$$

ANTENNA TEMPERATURE: T_A

- Johnson noise: in thermal equilibrium, the power produced by a resistor is determined by its physical temperature:

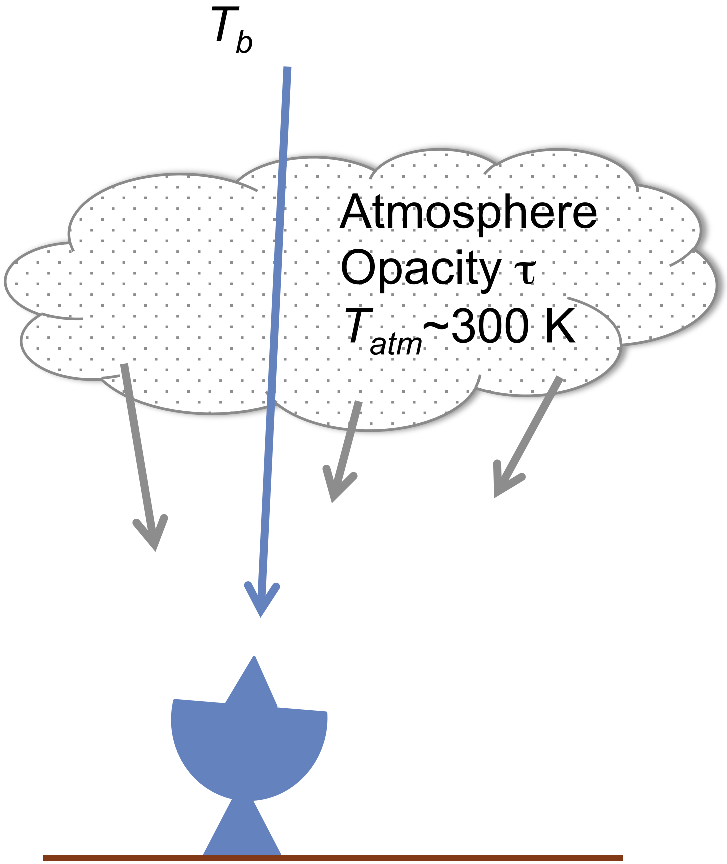
$$p_\nu = kT \qquad \text{(Nyquist theorem)}$$

- We can define an equivalent *antenna temperature:* $\boxed{p_\nu = kT_A}$
- As seen before: $p_\nu = \frac{Ae}{2} \int_{\Omega s} P(\Omega) I_\nu(\Omega) \, d\Omega$

$$\rightarrow \; T_A(\Omega) = \frac{Ae}{2k} \int_{\Omega s} I_\nu(\Omega) P(\Omega) \, d\Omega \quad \text{; using } \; A_e \cdot \Omega_A = \lambda^2$$

$$\rightarrow \; T_A(\Omega) = \frac{1}{\Omega_A} \int_{\Omega s} \boxed{\frac{\lambda^2}{2k} I_\nu(\Omega)} P(\Omega) \, d\Omega = \frac{1}{\Omega_A} \int_{\Omega s} T_b P(\Omega) \, d\Omega$$

ANTENNA TEMPERATURE: T'_A



- Atmosphere effects, at a given ν:

$$T_A = T_b e^{-\tau_\nu} + T_{atm}(1 - e^{-\tau_\nu})$$

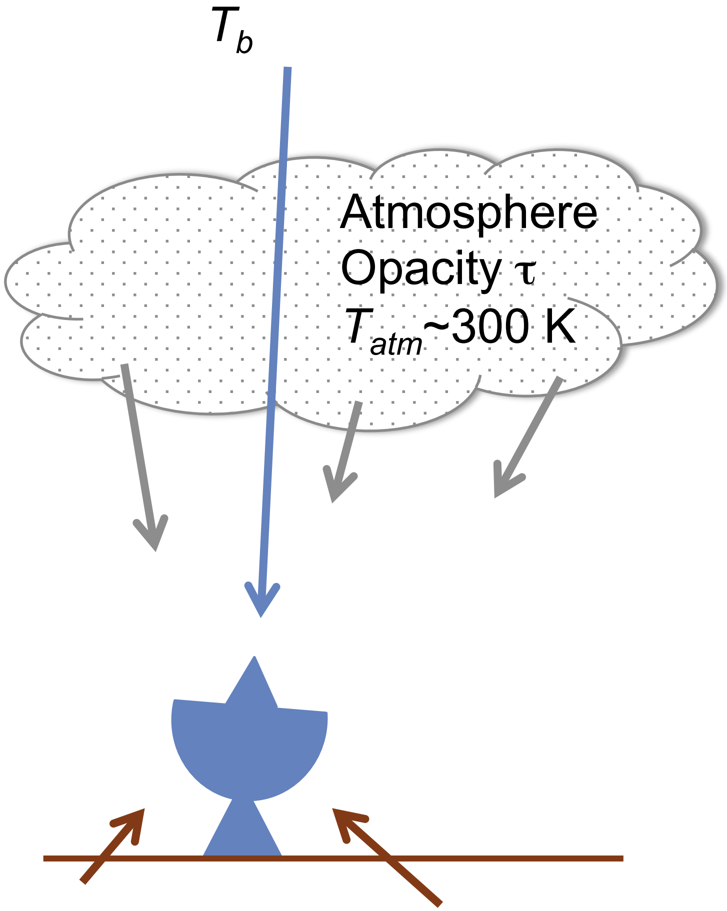
absorption ↓ (for $T_b e^{-\tau_\nu}$) — emission ↓ (for $T_{atm}(1 - e^{-\tau_\nu})$)

- Antenna temperature corrected by atmospheric absorption:

$$\boxed{T'_A = T_A e^{-\tau_\nu}}$$

- Note that for space telescopes, e.g. Herschel: $T'_A = T_A$

ANTENNA TEMPERATURE: T^*_A



- Correct for rear-sidelobes: measure the power received only from the forward 2π sr:

$$T_A^* = \frac{1}{P_{2\pi}} \int_{\Omega s} T_b P(\Omega) \, d\Omega$$

$$T_A^* = \frac{P_{4\pi}}{P_{2\pi}} T'_A = \frac{T'_A}{F_{eff}}$$

- Forward efficiency: $\boxed{F_{eff} = \frac{P_{2\pi}}{P_{4\pi}}}$

MAIN BEAM TEMPERATURE: T_{MB}

- Take into account main-beam and error-lobes
- Same as T^*_A but within the main beam instead of 2π:

$$T_{MB} = \frac{1}{P_{MB}} \int_{\Omega s} T_b P(\Omega)\, d\Omega = \frac{P_{4\pi}}{P_{MB}} T'_A$$

- Beam efficiency: $\boxed{B_{eff} = \frac{P_{MB}}{P_{4\pi}}}$

→ $T_{MB} = \frac{T'_A}{B_{eff}} = \frac{F_{eff}}{B_{eff}} T_A^*$

what we measure is T^*_A or T_{MB} which are NOT T_b

- **Small sources:** $\Omega_s << \Omega_{MB}$: $T_{MB} \approx T_b\, \Omega s / P_{MB} < T_b$

  → **beam dilution**

- **Large sources:** $\Omega_s >> \Omega_{MB}$: $T_A^* \approx T_b \int_{2\pi} P(\Omega)\, d\Omega \Big/ P_{2\pi} \approx T_b$

- **Special case:** $\Omega_s = \Omega_{MB}$: $T_{MB} = T_b \int_{\Omega s} P(\Omega)\, d\Omega \Big/ P_{MB} = T_b$

- **General case:** $\Omega_s \sim \Omega_{MB}$: $T_A^* = T_b \int_{\Omega s} P(\Omega)\, d\Omega \Big/ P_{2\pi}$

- Usually, T_{MB} is used assuming “the source fills the beam”, but…

$\Omega_s < \Omega_{MB}$ → $T_b > T_{MB}$
$\Omega_{MB} < \Omega_s < 2\pi$ → $T_{MB} > T_b > T^*_A$
$2\pi < \Omega_s$ → $T^*_A > T_b$

FROM KELVIN TO JANSKY

- Flux density: $S_\nu = \int_{\Omega s} I_\nu(\Omega)\, d\Omega = \frac{2k}{\lambda^2} \int_{\Omega s} T_b\, d\Omega$
- Power received by the antenna: $kT'_A = k\frac{T_A^*}{F_{eff}} = \frac{1}{2} A_e \cdot S_\nu$

$$\rightarrow \quad \frac{S_\nu}{T_A^*} = \frac{2k}{A} \frac{F_{eff}}{\eta_A} \qquad [\mathrm{Jy\ K^{-1}}]$$

- Depends on the antenna
- Values are tabulated, e.g. for IRAM 30m:

  range from ~ 6 @ 90 GHz, to ~ 11 @ 340 GHz

CALIBRATION

CALIBRATION

Calibration needs to account for:

- Atmosphere:
  - Emission/absorption at frequency ν
  - Turbulence producing phase drifts
- Full detection system:
  - Antenna characteristics and looses
  - Receivers: gain, noise, stability
  - Cables, backends, etc.

Questions:

- How to convert counts at the backend level, to power in physical units
- How to correct for the atmospheric contribution

CALIBRATION

- What we measure… $C_{sou} = \chi\left[T_{rec} + F_{eff}\,\mathrm{e}^{-\tau_\nu}\,T_{sou} + T_{sky}\right]$

where $T_{sky} = F_{eff}(1-\mathrm{e}^{-\tau_\nu})T_{atm} + (1-F_{eff})T_{amb}$

T_{rec}: noise contribution from the receiver

T_{sky}: noise contribution from the atmosphere (T_{atm}),
and the receiver cabin and ground (T_{amb})

→ Details in Lecture by Luis Velilla on friday

- Correct for atmospheric emission and stability (atmospheric and instrumental) → switching bw ON and OFF positions (observing modes)

CALIBRATION: T_{sys} and noise

System temperature: gives a measure of the noise including all sources, from the sky to backends

$$\boxed{\sigma = \frac{T_{sys}}{\sqrt{d\nu \cdot t}}}$$

→ Statistical noise in our spectra (radiometer formula):

$$\sigma = \sqrt{\sigma_{on}^2 + \sigma_{off}^2} = \frac{T_{sys}}{\sqrt{d\nu \cdot \Delta t}} \text{ ; with } \Delta t = \frac{t_{on} \cdot t_{off}}{t_{on} + t_{off}}$$

- dν: spectral resolution
- t_{on}/t_{off}: ON/OFF integration time
- Δt: depends on the observing mode

OBSERVING MODES: position switching

- The telescope cyclically moves between two positions, ON (Source+Atmosphere) and OFF (Atmosphere)

  → Subtracting both positions gives the source signal

- Cons:
  - OFF position without any signal → need to go far away sometimes (and spend time moving the antenna)
  - If OFF position is far, atmosphere varies → bad baselines

- $t_{on} = t_{off} = t_{tot}/2$ → $\Delta t = t_{tot}/4$ → $\boxed{\sigma_{psw} = \frac{2 \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}}$

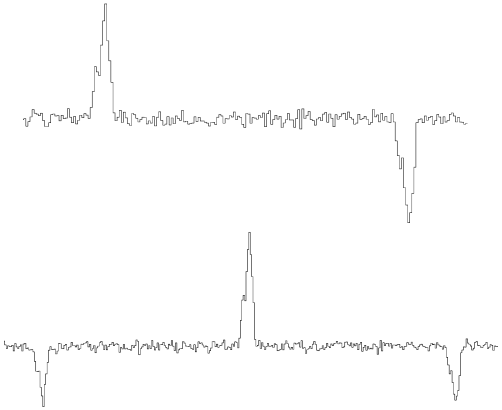
OBSERVING MODES: wobbler switching

- The secondary cyclically and quickly moves between the ON and OFF (usually symmetric OFF – ON – ON – OFF)
- Pros: very good baselines
- Cons:
  - Limited wobbling throw
  - Always in one antenna direction → rotates in the sky

  → Source must be compact
- $t_{on} = t_{off} = t_{tot}/2 \rightarrow \Delta t = t_{tot}/4 \rightarrow$ $\boxed{\sigma_{wsw} = \frac{2 \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}}$

OBSERVING MODES: frequency switching

- The tuning frequency cyclically and quickly changes between two phases: $f_{rest} - f_{throw}$ and $f_{rest} + f_{throw}$
- Pros: The telescope is <u>always</u> ON source
  - No need for OFF positions
  - Lower loise

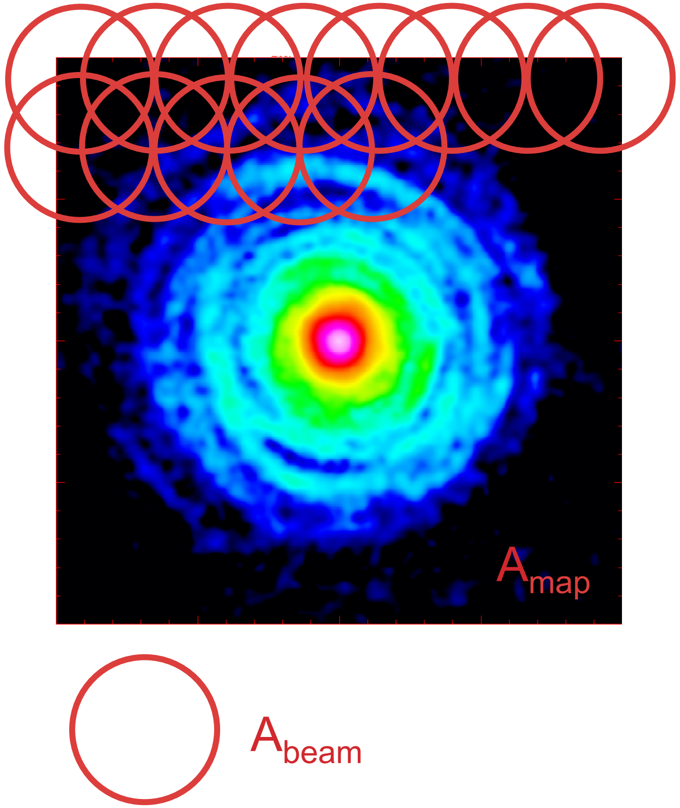


- Cons:
  - Limited frequency throw → narrow lines
  - Presence of negative ghosts → low line density
  - Presence of atmospheric lines
  - Strong ripples in the baselines (standing waves)
- $t_{on} = t_{off} = t_{tot}$ → $\Delta t = t_{tot}/2$ →

$$\boxed{\sigma_{fsw} = \frac{\sqrt{2} \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}}$$

OBSERVING MODES:
on-the-fly mapping

- The telescope continuously slew through the source with time to map it. The result is a cube of spectra



- Nr of independent measurements: $n_{beam} = A_{map} / A_{beam}$
- t_{on}^{beam}, t_{off}^{beam} : $\Delta t = \dfrac{t_{on}^{beam} \cdot t_{off}^{beam}}{t_{on}^{beam} + t_{off}^{beam}}$
- Linear scanning speed and area speed: $v_{area} = v_{linear} \Delta\theta$
- Nyquist sampling: $\Delta\theta = \theta/2$

OBSERVING MODES: on-the-fly mapping

- The telescope continuously slew through the source with time to map it. The result is a cube of spectra
- Frequency switching:

$$t_{on}^{beam} = t_{off}^{beam} = t_{tot}/n_{beam} \rightarrow \Delta t = t_{tot}/2n_{beam} \rightarrow \boxed{\sigma_{fsw} = \frac{\sqrt{2n_{beam}} \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}}$$

- Position switching: share same OFF for multiple ONs

ON-ON-ON-OFF-ON-ON-ON-OFF-…
submap

$$\boxed{\sigma_{psw} = \frac{\left(\sqrt{n_{beam}} + \sqrt{n_{submap}}\right) \cdot T_{sys}}{\sqrt{d\nu \cdot t_{tot}}}}$$

$$\rightarrow \quad \frac{\sigma_{psw}}{\sigma_{fsw}} = \frac{1}{\sqrt{2}}\left(1 + \sqrt{\frac{n_{submap}}{n_{beam}}}\right) \geq 1$$

GOALS / QUESTIONS

Goals

- Measure the signal emitted from a particular region in the sky
- Obtain spectral or spatial information of the source
- Determine chemical and/or physical properties

Questions

- Measurement fidelity : η_A, η_B, F_{eff}, B_{eff}
- Calibration
  - Gain calibration: $C_{sou} \rightarrow T^*_A, T_{MB} \rightarrow S\nu$
  - Observing switching modes: remove noise contribution from the atmosphere and whole detection system

BUT THERE'S MORE…

- Real antenna:
  - Real beam pattern
  - Error beams
  - Antenna deformations: astigmatism, coma, etc.

- Other calibration measurements needed during observations:
  - Pointing: optimize with direction Az, El (gravity)
  - Focus: optimize secondary position in *z* (temperature)

- Receivers: e.g. *image band rejection* (SSB, DSB,..)
- Backends: bandwidth and spectral resolution

FURTHER READING

- “Tools of Radio Astronomy”, T.L. Wilson, K. Rohlfs, S. Hüttemesiter A&A Library, Springer 5th Ed. 2009

- IRAM 30m and interferometry schools: http://www.iram-institute.org/EN/content-page-67-7-67-0-0-0.html

- NRAO Radio Astronomy essentials web course: https://science.nrao.edu/opportunities/courses/era

- IRAM technical reports http://www.iram-institute.org/EN/content-page-161-7-66-161-0-0.html