Millimetre Astronomy

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Millimetre Astronomy

- Introduction
- Molecular lines
- Science overview
- Toward the future

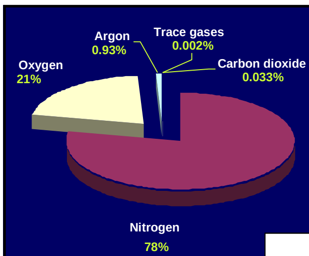
At 100 GHz (λ = 3 mm):

$E = h\upsilon/q = 4 \times 10^{-4}$ eV

$T = h\upsilon/k = 5$ K

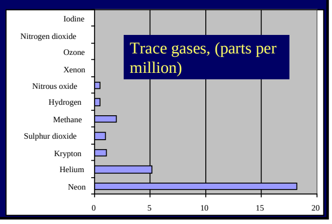
This tells us what kind of phenomena we will be dealing with.

But first, a few words about the earth's atmosphere...

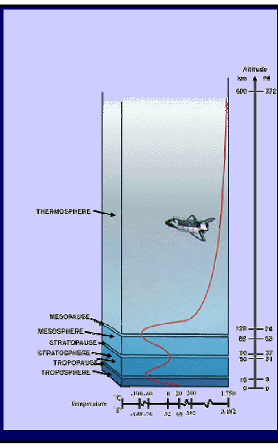


Composition of dry air

NB: "Real" air also contains 0 ~ 5% water vapour.

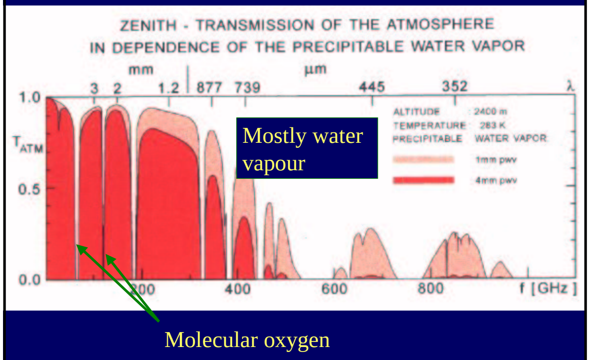


J.W.V. Storey, 2000

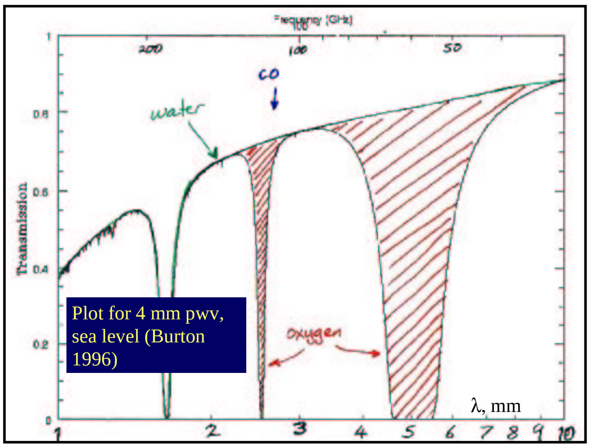


The distance from here to the stratosphere is roughly the same as the distance from Epping to the Sydney Opera House.

http://liftoff.msfc.nasa.gov/



http://maisel.as.arizona.edu

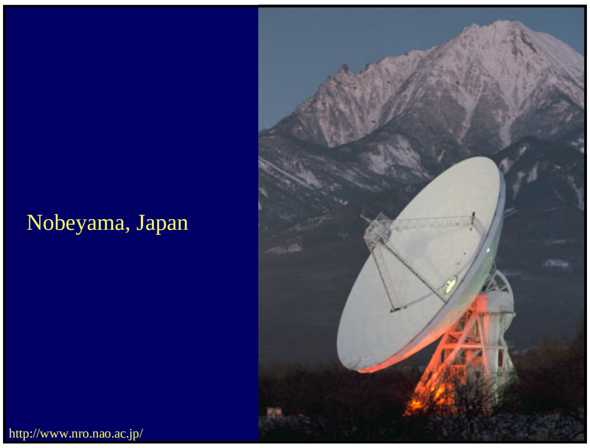


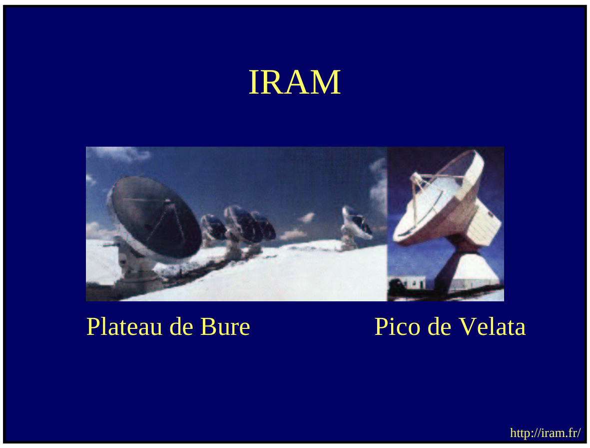
12-metre, Kitt Peak, Arizona

http://kp12m.as.arizona.edu/


High accuracy surface
Small subreflector
SEST
Swedish/European Submillimetre Telescope, Chile
http://www.ls.eso.org/


Picture by Lauri Haikala
http://www.ls.eso.org/


Nobeyama, Japan
http://www.nro.nao.ac.jp/


IRAM
Plateau de Bure
Pico de Velata
http://iram.fr/

IRAM, Pico Veleta,
Spain

http://www.iram.es/

IRAM, Plateau de Bure, France

http://iram.fr/

BIMA—the Berkeley/Illinois/Maryland Array,
Hat Creek, California.

http://bima.astro.umd.edu/

Owens Valley Radio Observatory, California

http://www.ovro.caltech.edu/

Mopra

The mm upgrade and operation of Mopra Observatory is a collaboration between UNSW and ATNF.

http://www.atnf.csiro.au

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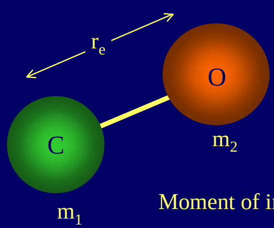
For a linear molecule such as carbon monoxide:

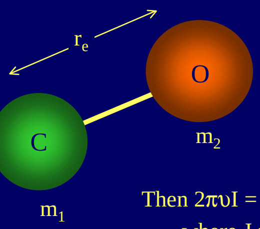


Moment of inertia =

$I = m_1 m_2 . r_e^2/(m_1 + m_2)$

Angular momentum = $I\omega = 2\pi\upsilon I$

Let's say the angular momentum, $2\pi\upsilon I$, is quantised in units of $h/2\pi$.

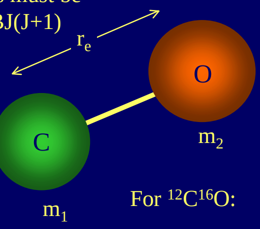


Then $2\pi\upsilon I = Jh/2\pi$,
where J = 0, 1, 2 ...

$\therefore\ \upsilon = Jh/4\pi^2 I$
$= 2BJ$, where $B = h/8\pi^2 I$
and B is the *rotational constant.*

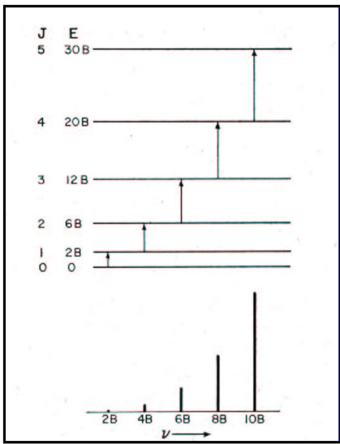
So, we have $\upsilon = 2BJ$.

The energy levels must be given by $E(J) = BJ(J+1)$



For $^{12}C^{16}O$:

B = 57.9 GHz, and we can derive $r_e = 0.1128$ nm.

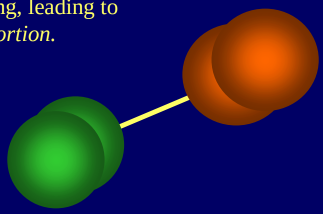


Energy levels and spectrum of a well-behaved linear molecule.

From Gordy and Cook (1970)

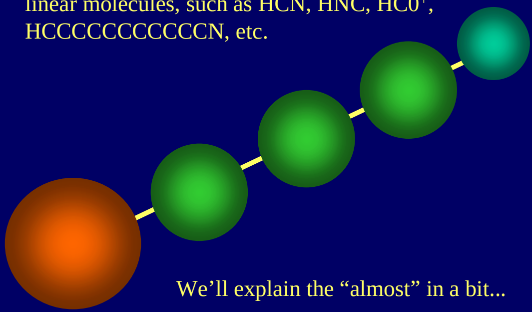
We call this the *rigid rotor* approximation.

In fact, the bond between the atoms is more like a little spring, leading to *centrifugal distortion.*



We let $E_J = BJ(J + 1) - DJ^2(J + 1)^2$,
From which $\upsilon_{J+1 \to J} = 2BJ - 4DJ^3$,
where D is the *centrifugal distortion* constant.

This simple analysis works for (almost) all linear molecules, such as HCN, HNC, $HC0^+$, HCCCCCCCCCCCN, etc.

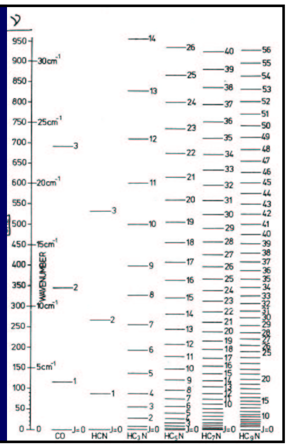


We'll explain the "almost" in a bit...

The bigger the molecule, the larger the *partition function.*

That is to say, at any given temperature the molecules can be distributed over a larger number of available energy levels.

For any given molecule, increasing the temperature will increase the population in higher lying states, while decreasing that in the lower.



Line Intensities (linear molecules)

Only certain transitions are permitted.

For dipole-allowed transitions they are those with $\Delta J = \pm 1$.

We have $A_{ij} \alpha \upsilon^3 |\mu_{ij}|^2$,

Where A_{ij} is the *dipole moment matrix element* connecting the two states i and j, and depends on the molecule's dipole moment, μ.

For CO, μ = 0.10 D. For HCN, μ = 3.00 D.

Line Intensities (linear molecules)

For CO, μ = 0.10 D. For HCN, μ = 3.00 D.

The A coefficient for the J = 1 -> 0 transition of HCN is therefore ~1000 times that of CO.

Molecules such as N_2 and H_2 have no dipole moment and thus have no dipole-allowed transitions.

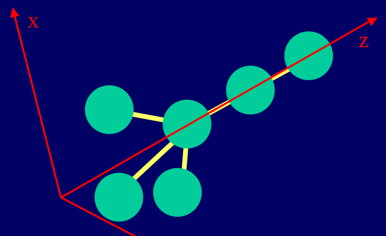
Line Intensities (any molecule)

The observed emission line intensity depends on the A coefficient, A_{ij}, and the column density of molecules in the upper state, which in turn depends on:

- The column density of H_2
- The molecular abundance relative to H_2
- The molecular partition function
- The temperature of the gas
- The density of the gas.

(Assuming, of course, that the line is *optically thin*. If it is *optically thick*, the intensity depends **only** on the gas temperature.)

For 2- and 3- dimensional molecules, such as methyl cyanide (CH_3CN),



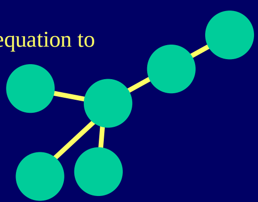
we identify the three principal axes and then define A, B, C as $A = h/8\pi^2 I_A$ etc., with A > B > C.

We then set up a Hamiltonian

$$H = AP_a^2 + BP_b^2 + CP_c^2,$$

where P_a etc is the component of angular momentum along that axis.

We then solve Schrödinger's equation to obtain the energy levels.

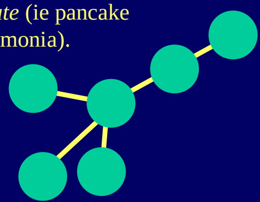


If A = B = C, we have a *spherical top*, which is unlikely to be interesting (eg, methane).

If A > B = C, we have *prolate* (ie, cigar shaped) *symmetric top* (eg methyl cyanide).

If A = B > C, we have an *oblate* (ie pancake shaped) *symmetric top* (eg ammonia).

If A > B > C, we have an *asymmetric top* (eg water) and a very complicated spectrum.



The energy levels of a prolate symmetric top are given by

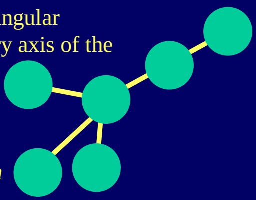
$E_{JK} = BJ(J + 1) + (A - B)K^2$

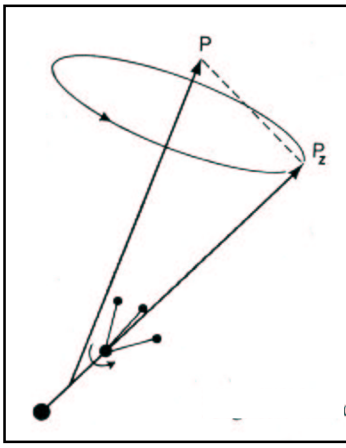
and for an oblate symmetric top by

$E_{JK} = BJ(J + 1) + (C - B)K^2$

where K is the component of angular momentum along the symmetry axis of the molecule.

Note that ΔE does not depend on K to first order; however it does when centrifugal distortion is taken into account.

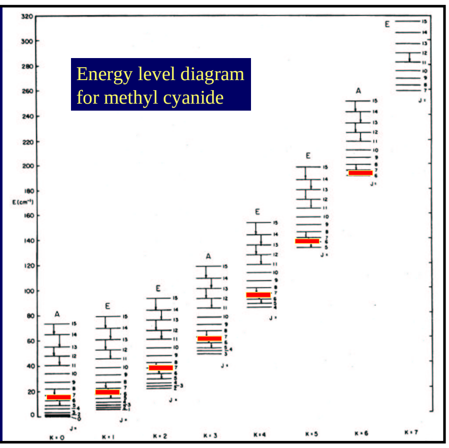




K is the projection of the total angular momentum on the symmetry axis.

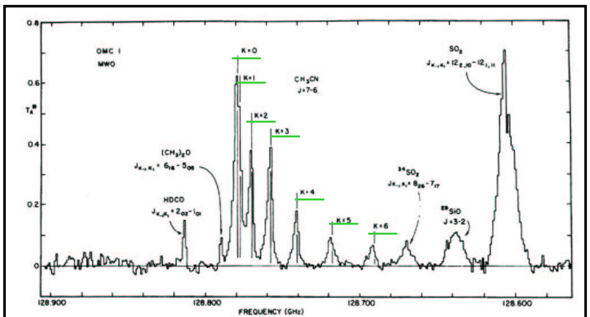
For a symmetric top, the dipole-allowed transitions are those with $\Delta J = 0, \pm 1$ and $\Delta K = 0$.

From Gordy and Cook (1970)



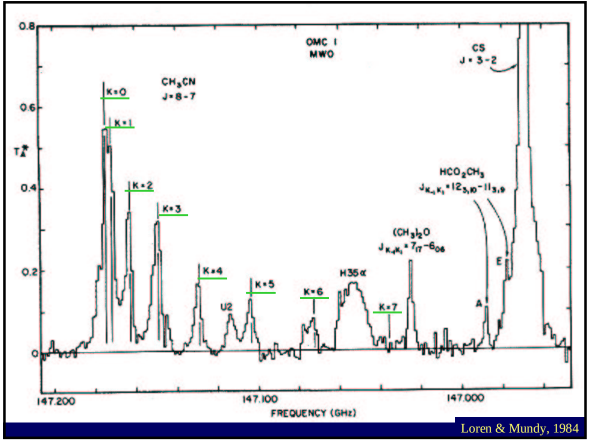
Energy level diagram for methyl cyanide

Loren & Mundy, 1984

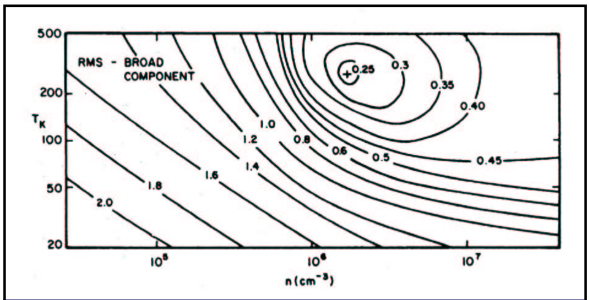


Methyl cyanide is a popular symmetric top

Loren & Mundy, 1984

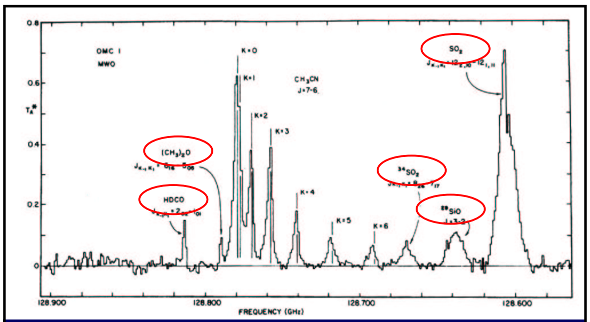


Loren & Mundy, 1984



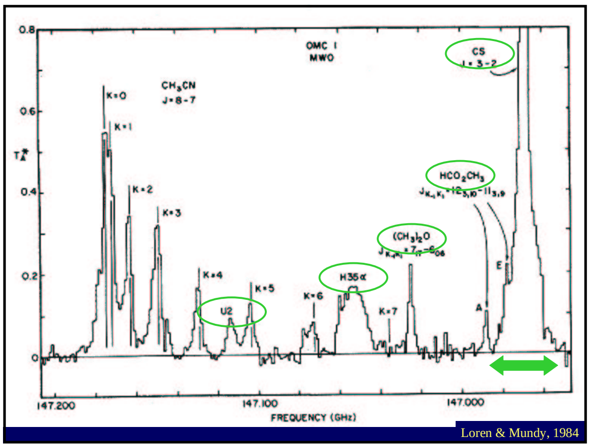
Such molecules are sensitive probes of temperature and/or density throughout a molecular cloud.

Loren & Mundy, 1984



But wait! There's more...

Loren & Mundy, 1984



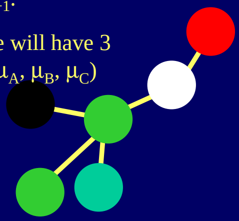
Loren & Mundy, 1984

Asymmetric tops

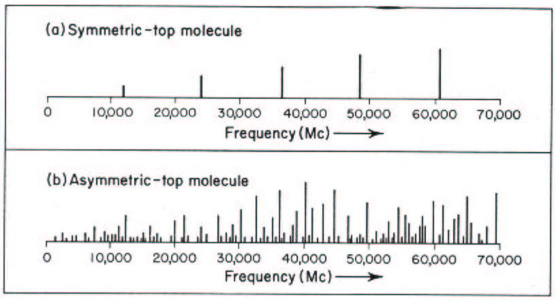
The three rotational constants (A, B & C) are all different.

Each energy level is characterised by three quantum numbers: J, K_{-1}, K_{+1}.

In the worst-case scenario, we will have 3 dipole moment components (μ_A, μ_B, μ_C) and lines all over the place.



While we *could* calculate their frequencies, we will more likely just look them up at:
http://physics.nist.gov/PhysRefData/micro/html/contents.html



Whereas linear molecules and symmetric tops have nice orderly spectra, those of asymmetric tops are a complete mess...

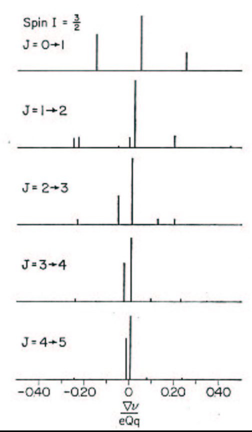
From Gordy and Cook (1970)

Nuclear quadrupole splitting.

If a molecule contains a nucleus with a nuclear spin, I, of 1 or more, the interaction between the nuclear quadrupole moment and the molecular electric field gradient results in splitting of the energy levels.

Single lines become *multiplets.*

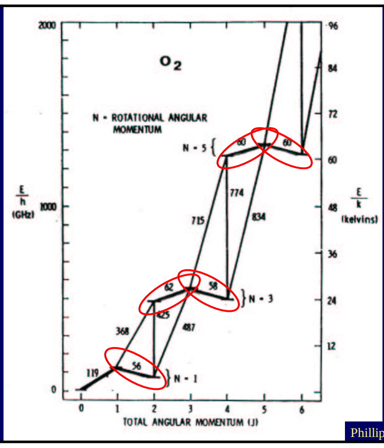
^{14}N has I = 1, and hence N-containing molecules exhibit quadrupole splitting.



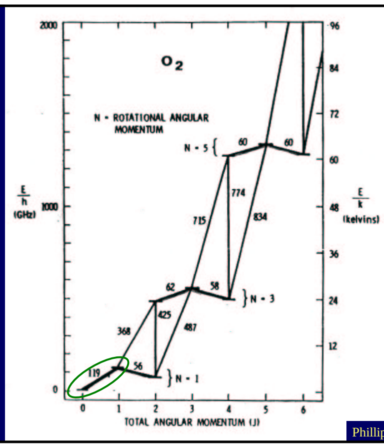
From Gordy and Cook (1970)

Non-comformist molecules.

- OH has an unpaired electron and a $^2\Pi$ ground state, leading to *Λ-doublet* transitions at cm wavelengths.
- O_2 is symmetrical like N_2, but has a $^3\Sigma$ electronic ground state (instead of $^1\Sigma$), leading to *magnetic dipole-allowed* transitions.
- NH_3 can undergo an *inversion* motion, like an umbrella on a windy day, leading to transitions throughout the 12 mm region.



Phillips & Keene, 1992



Phillips & Keene, 1992

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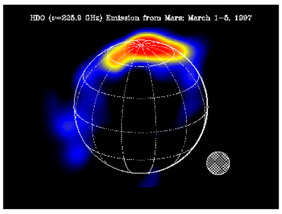
Science

- Atmospheric science
- Planetary science
- Star formation
- Post AGB stars and planetary nebulae
- AGNs, Galaxy evolution and cosmology
- Cosmic microwave background

Mm observations provide data on trace atmospheric gasses important to ozone depletion and global warming studies.

http://seds.lpl.arizona.edu/

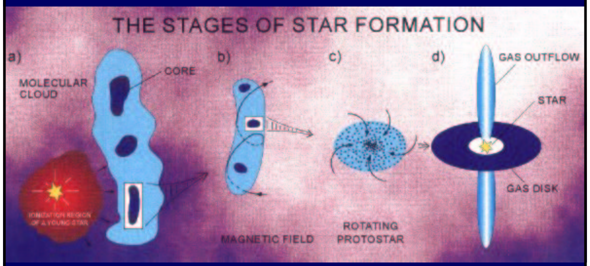
Planetary Sciences



OVRO Interferometer image of integrated HDO (3 1 2 - 2 2 1) line emission from Mars during northern summer solstice. Emission is concentrated over the Northern Polar Cap, indicating vigorous sublimation from water ice.

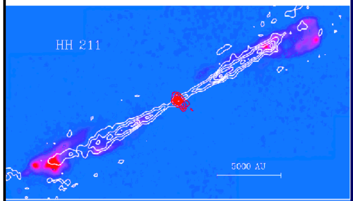
- study abundances of molecular species, probing atmospheric chemistry and transport
- resolve planetary disks to study variation of atmosphere with position and time
- study atmospheric dynamics through direct observation of doppler shifts in line cores

http://cfa-www.harvard.edu/~dwilner/



http://maisel.as.arizona.edu/

Molecular Clouds and Star Formation

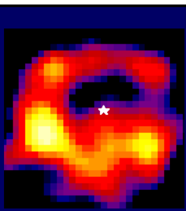


CO J=2-1 map of the protostellar jet in HH211 from the IRAM PdBI overlaid on a near infrared image of excited H_2; red contours delineate a dust concentration around the protostar.

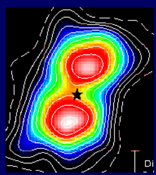
- probe the turbulence, fragmentation and gravitational collapse of star forming clouds
- determine the nature of protostellar outflows and measure mass-loss and accretion rates
- obtain abundances and study the chemistry of low temperatures and dissociative shocks

http://cfa-www.harvard.edu/~dwilner/

Continuum studies (SCUBA sub-mm)



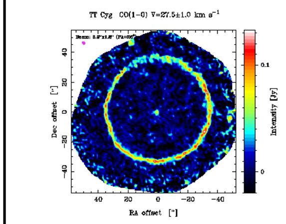
Ring of dust particles around Epsilon Eridani



Disk-like dust structure around Fomalhaut

http://www.jach.hawaii.edu/

AGB Stars and Planetary Nebulae

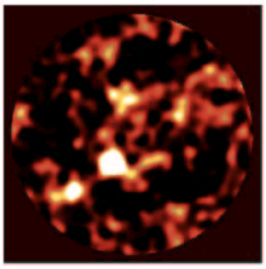


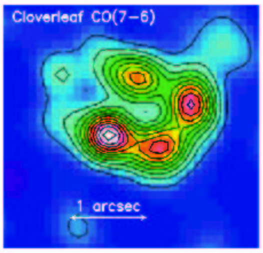
CO J=1-0 image of the carbon star TT Cyg from the IRAM PdBI (Olofsson et al. 1999)

- Image (multi) thin shells to study episodic mass loss rate in the AGB phase (e.g. TT Cyg).
- Map disks and bipolar outflows associated with the transition from AGB to PN
- Detect polarization of molecular emission resulting from IR excitation.

http://cfa-www.harvard.edu/~dwilner/

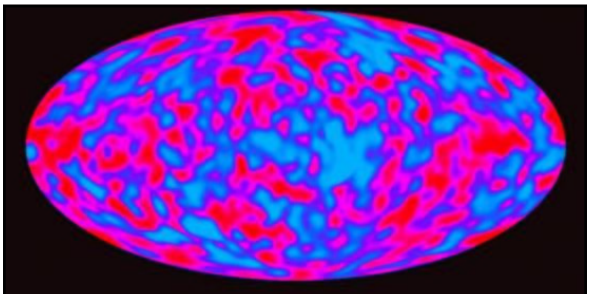
Galaxy Evolution and Cosmology





Left: 850μm SCUBA image of the Hubble Deep Field showing a new population of dusty galaxies. *Right:* Lensed CO J=7-6 emission from the Cloverleaf quasar imaged by the IRAM PdBI.

http://cfa-www.harvard.edu/~dwilner/



CMBR anisotropy, polarisation, S-Z effect, etc.

http://maisel.as.arizona.edu:8080/bitmaps/COBE.jpg

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ALMA

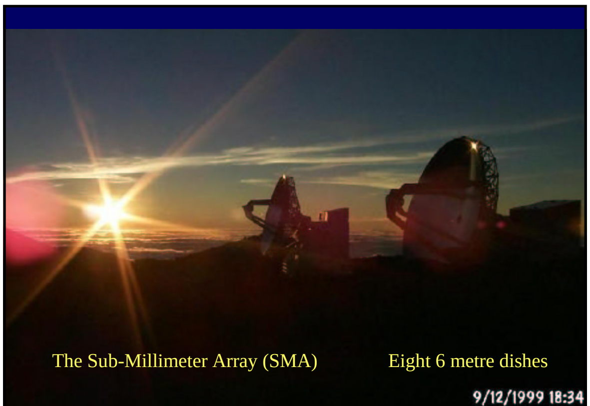
The Atacama Large MM Array

http://www.mma.nrao.edu/

Chanjantor, Chile. 5,000 metre elevation.

Proposed: 64 6-metre dishes; up to 10 km baseline.

http://www.tuc.nrao.edu/



The Sub-Millimeter Array (SMA) Eight 6 metre dishes

http://sma2.harvard.edu/

http://cfa-www.harvard.edu/~adair/

References

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IAU Symposium #197, 2000, *Astrochemistry: from Molecular Clouds to Planetary Systems*, eds. Y.C. Minh & E.F. van Dihoeck

H.W. Kroto 1975, *Molecular Rotation Spectra*, Wiley (London)

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T.G. Phillips & J. Keene 1992, Proc. IEEE, **80,** 1662

C.H. Townes & A.L. Schawlow 1955, *Microwave Spectroscopy* (reprinted by Dover, NY, 1975)