TÄHT7039: Radio astronomy and interferometry

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Some of the figures are from Wilson, Rohlfs, Hüttemeister: 'Tools of Radio astronomy'

Outline

Recap from lecture 1

Opacity

Black body radiation and the brightness temperature

Nyqvist theorem, power and noise temperature

Emission mechanisms and radio sources

Recap from lecture 1

The ionospheric plasma attenuates radio radiation below the *plasma frequency*

$$\frac{\nu_{\mathrm{p}}}{\mathrm{kHz}} = 8.97\sqrt{\frac{N_{\mathrm{e}}}{\mathrm{cm}^{-3}}}. \tag{1}$$

Total flux density S_ν:

$$S_\nu = \int_{\Omega_{\mathrm{s}}} I_\nu(\theta, \phi)\,\cos\theta\;\mathrm{d}\Omega \tag{2}$$

The unit of S_ν is $\mathrm{W\,m^{-2}\,Hz^{-1}}$.

$$1\,\mathrm{Jy} = 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}} \tag{3}$$

$$1\,\mathrm{SFU} = 10^{-22}\,\mathrm{W\,m^{-2}\,Hz^{-1}} \tag{4}$$

Optical depth or opacity τ

When *optical depth* τ_ν is defined as

$$\tau_\nu(s) = \int_{s_0}^{s} \kappa_\nu(s)\,\mathrm{d}s, \qquad (5)$$

and it is further assumed that the medium is isothermal, we get

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T)\left(1 - e^{-\tau_\nu(s)}\right), \qquad (6)$$

κ_ν is the absorption measure of the medium. So the medium decreases the observed intensity but also radiates black body radiation proportionally. If optical depth is very large, the observed intensity is totally black body radiation:

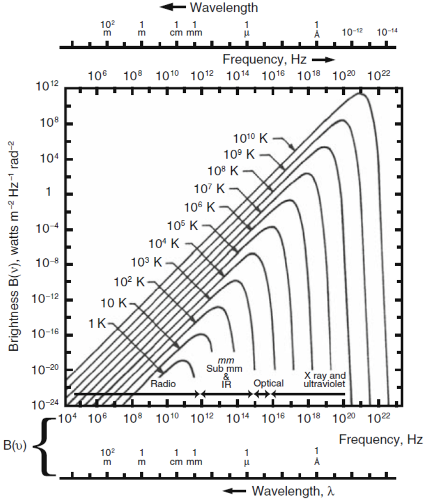
$$I_\nu = B_\nu(t). \qquad (7)$$

Black body radiation and the brightness temperature

The spectrum of the radiation of a black body in thermodynamic equilibrium is given by the Planck law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}, \quad (8)$$

which gives the power per unit bandwidth ($\frac{\mathrm{W}}{\mathrm{Hz}}$).



The Stefan-Boltzmann radiation law

When the Planck law is integrated over frequency, we get the *total brightness of black body* or *Stefan-Boltzmann radiation law*:

$$B(T) = \sigma T^4, \tag{9}$$

where

$$\sigma = \frac{2\pi^4 k^4}{15 c^2 h^3}. \tag{10}$$

The **radiation maximum** of Stefan-Boltzmann radiation law is at the wavelength of

$$\lambda_{\mathrm{max}}[\mathrm{mm}]\, T[\mathrm{K}] = 2.8978. \tag{11}$$

This is called as the *Wien's displacement law*.

Planck law approximations, Rayleigh-Jeans law

The Planck law can be approximated by simpler expressions at the frequency extremes.

Rayleigh-Jeans law, $h\nu \ll kT$:

$$B_{\mathrm{RJ}}(\nu, T) = \frac{2\nu^2}{c^2} kT = \frac{2kT}{\lambda^2} \tag{12}$$

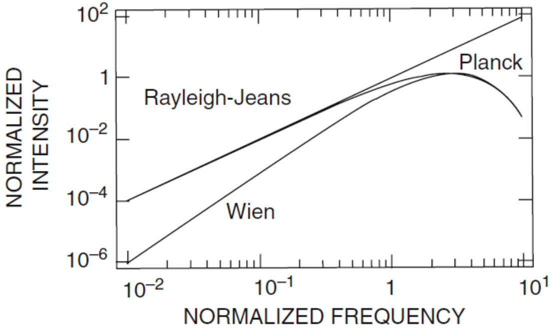
Widely used in radio astronomy. Holds when $\nu \ll 20.84\,T$ where ν is in gigahertz and T in Kelvins.

Planck law approximations, Wien's law

Wien's law, $h\nu \gg kT$:

$$B_{\mathrm{W}}(\nu, T) = \frac{2h\nu^3}{c^2} e^{-h\nu/kT} \tag{13}$$

Holds in visible and ultraviolet, not in radio.



Brightness temperature

Rayleigh-Jeans law implies that the brightness and the temperature of the black body that emits this radiation are strictly proportional. Because of this, the brightness of an extended radio source is measured using its *brightness temperature* T_b.

$$T_b = \frac{\lambda^2}{2k} I_\nu \tag{14}$$

Because

$$S_\nu = I_\nu \Delta\Omega, \tag{15}$$

the total flux density radiated by a black body is

$$S_\nu = \frac{2k}{\lambda^2} T_b \Delta\Omega \tag{16}$$

The concept of brightness temperature is used for convenience also in cases where the radiation is not caused by a black body. Then it is the *equivalent* brightness temperature that corresponds to a black body in the given temperature.

Total flux density and brightness temperature

For a Gaussian source with a brightness temperature T_b the total flux density is

$$S_\nu = \frac{2.65\, T_b\, \theta^2}{\lambda^2}, \qquad (17)$$

where S_ν is in Jansky, θ in arcminutes, and λ in cm.

Brightness temperature and opacity

When a source is observed through an absorbing medium, e.g. the atmosphere, the observed brightness temperature is changed from the original $T_b(0)$ as a function of the attenuation and the temperature of the physical medium. The medium absorbs the radiation but also radiates and increases the observed brightness temperature.

If the medium is isothermal, the observed brightness temperature $T_b(s)$ with medium thickness s is

$$T_b(s) = T_b(0)e^{-\tau_\nu(s)} + T(1 - e^{-\tau_\nu(s)}). \tag{18}$$

If opacity is very small, the absorbation and radiation of the medium has no effet. However, if it is very large, the observed brightness temperature is the *physical temperature of the medium*.

Nyqvist theorem and noise temperature

Radio astronomy receivers and detectors measure a (very small) electric power. The relation between electric power and temperature makes a connection between the received electic power and source noise temperature and finally to total flux density.

A resistor, at a temperature of T, produces an electric power of P (electrons are moving due to the temperature i.e Johnson noise). This phenomenon is reciprocal, i.e. if electric power is dissipated by the resistor, its temperature is rising by T:

$$P_\nu = kT, \tag{19}$$

i.e. the total power in unit bandwidth, or the total power

$$P = kTB, \tag{20}$$

where k is the Boltzmann constant and B is bandwidth.

What optical & radio astronomers observe?

Optical (X & γ) astronomers

- Count photons
- Photon noise is Poisson noise (shot noise, few photons)

Radio (& IR) astronomers

- Measure noise power i.e. noise temperature
- Gaussian noise statistics

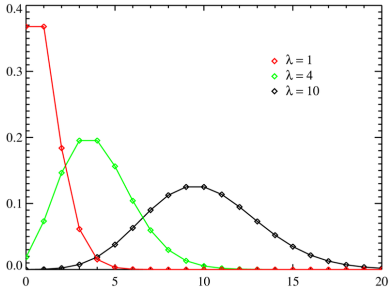
Probability to observe n photons in time t:

$$p(n,t) = \frac{(\mathcal{N}t)^n e^{-\mathcal{N}t}}{n!},$$

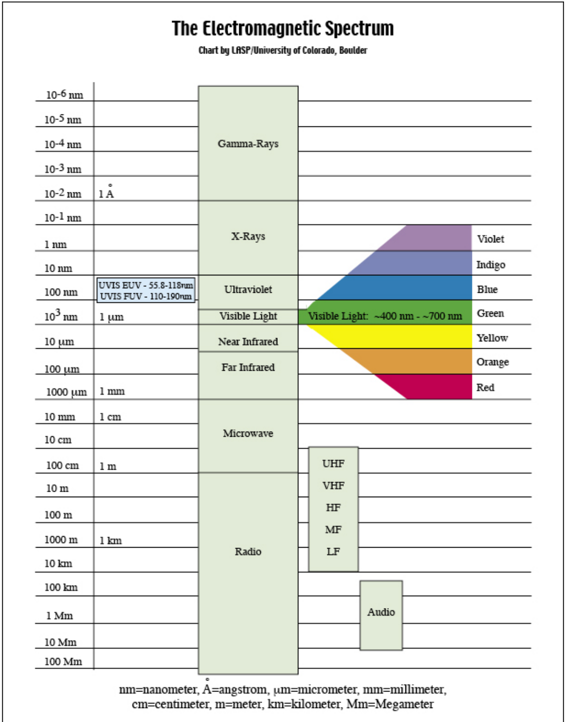
$$\mathcal{N}t = \lambda$$

$\mathcal{N}$ = mean photon flux

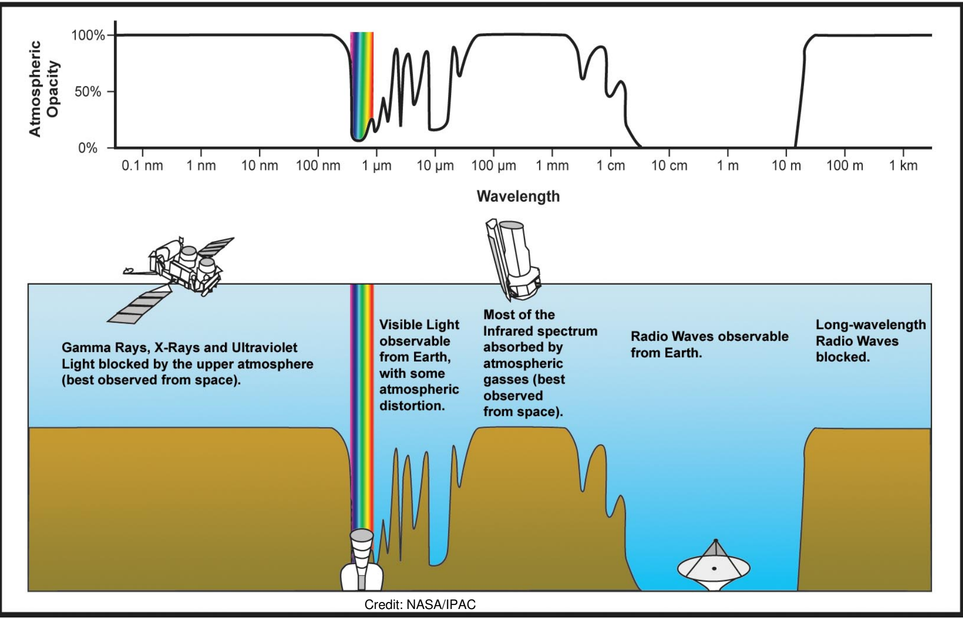
$$\sigma_{RMS}(N) = \sqrt{N}$$



With large $\mathcal{N}t \Rightarrow$ Gaussian (CLT).



- Radio regime: $0 \sim 300$ GHz or $\infty \sim 1$ mm
- Infrared ~ 1 mm – 700 nm
- Visible 700 nm – 400 nm
- $\nu = c/\lambda$

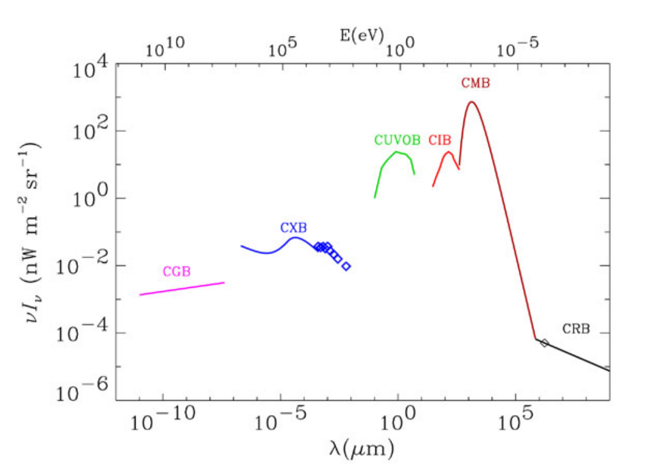


Credit: NASA/IPAC

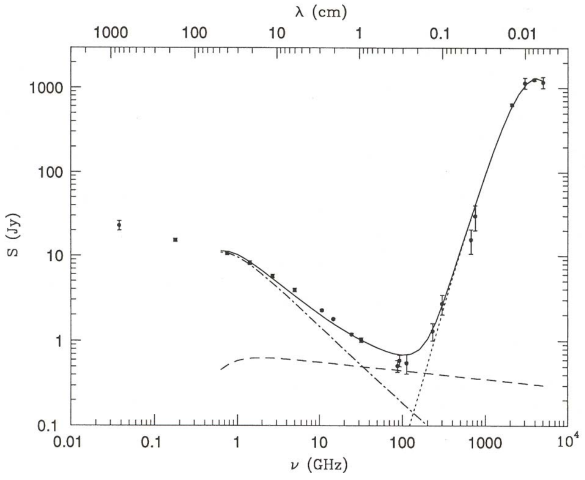
How does the sky look like at radio?

Many of the following images are from J.J. Condon's lecture held at NAIC/NRAO School on Single-dish Radio Astronomy 2003.

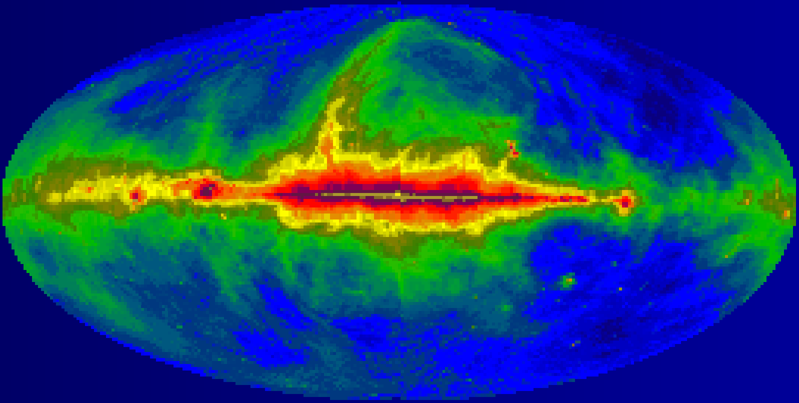
Electromagnetic energy spectrum of the universe



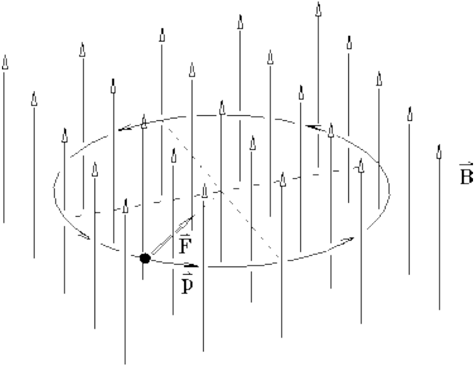
Synchrotron (dash-dot curve), free-free (dashes), and dust (dots) spectra typical of most spiral galaxies



408 MHz continuum emission, galactic coordinates

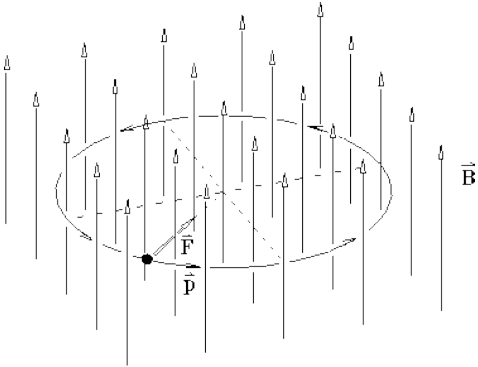


Synchrotron radiation I



- Produced by gyrating electron in magnetic field
- Emission directed into a narrow beam in the direction of the electron

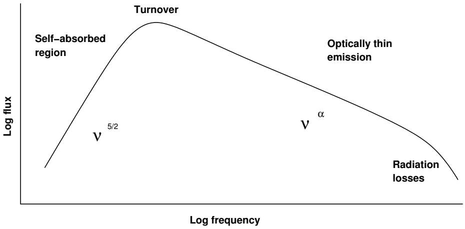
Synchrotron radiation II



Subclassified by the energy of the electron

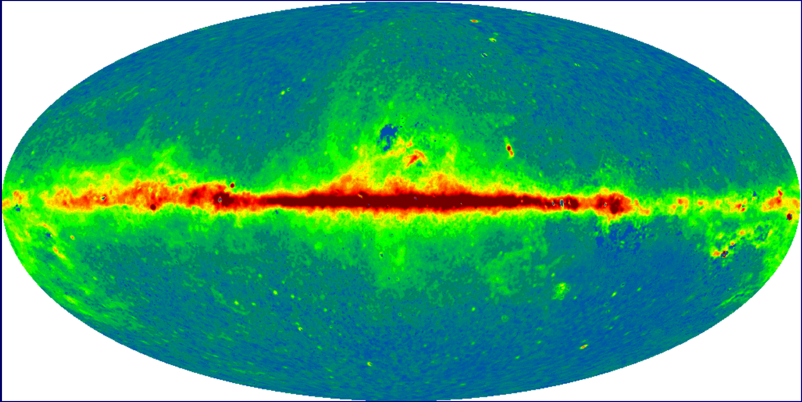
- Gyroresonance (cyclotron) (non relativistic)
- Gyrosynchrotron (mildly relativistic)
- Synchrotron (relativistic)

Synchrotron radiation spectrum (AGN)

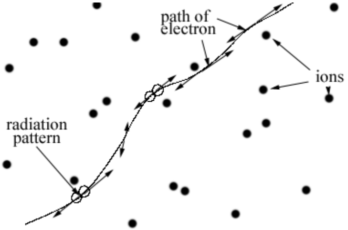


- $\nu < \nu_{\rm Smax}$: source optically thick $\Rightarrow$ electron absorbs a photon emitted by another electron $\Rightarrow$ self absorption, $\alpha = 2.5$.
- Turnover: given size, S and ν_{max} we get e.g. magnetic field density, number density and energy density of the relativistic electrons.
- $\nu > \nu_{\rm Smax}$: optically thin region, α depends on the energy distribution of emitting electrons.

Galactic synchrotron emission (WMAP)



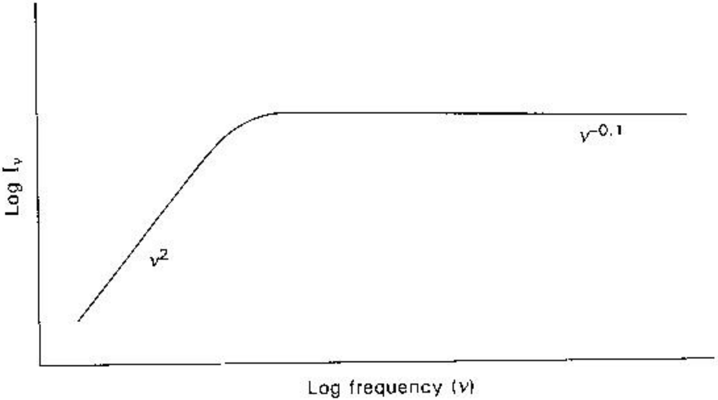
Free-free radiation



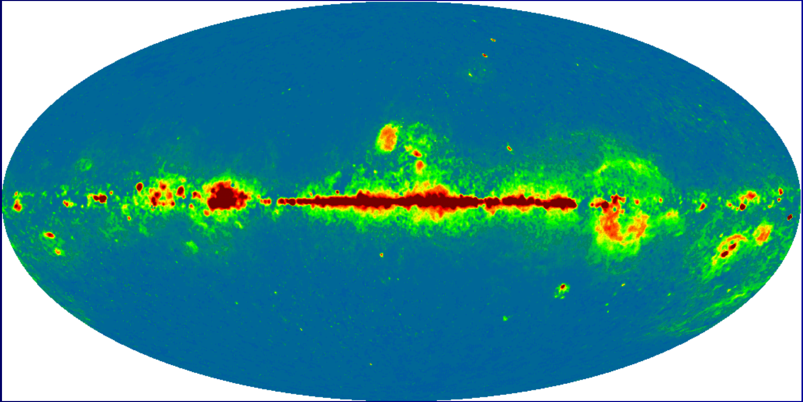
Credit Prof. Dale E. Gary NJIT

- Also called as bremssthralung
- Due to accelerations caused by collisions between electrons and ions (Coulomb collisions)

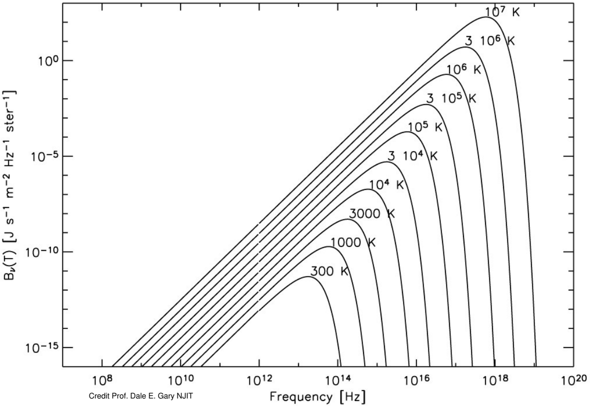
Free-free radiation spectrum



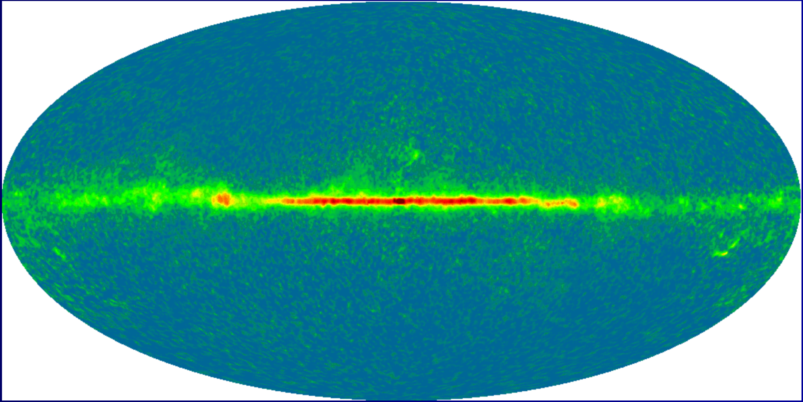
Galactic free-free emission (WMAP)



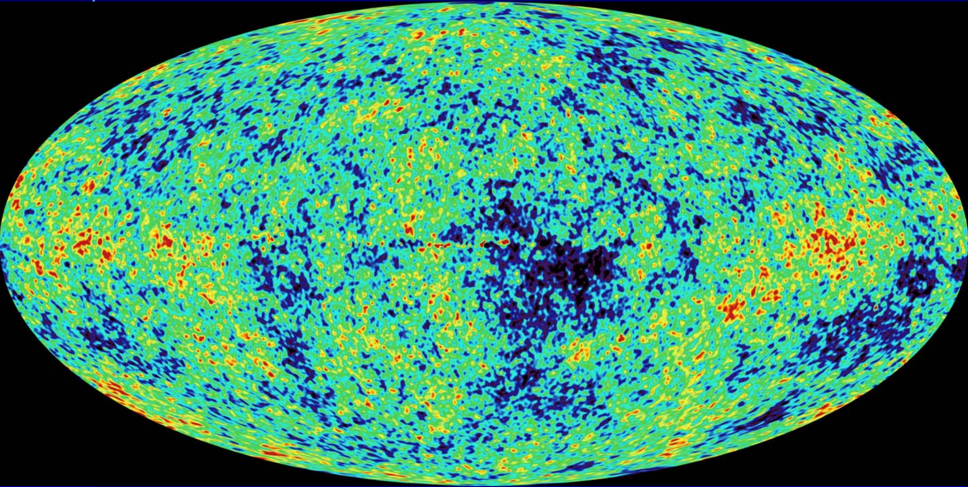
Thermal (black body) radiation



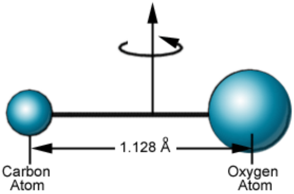
Galactic thermal dust emission (WMAP)



3K microwave background



Spectral line radiation I

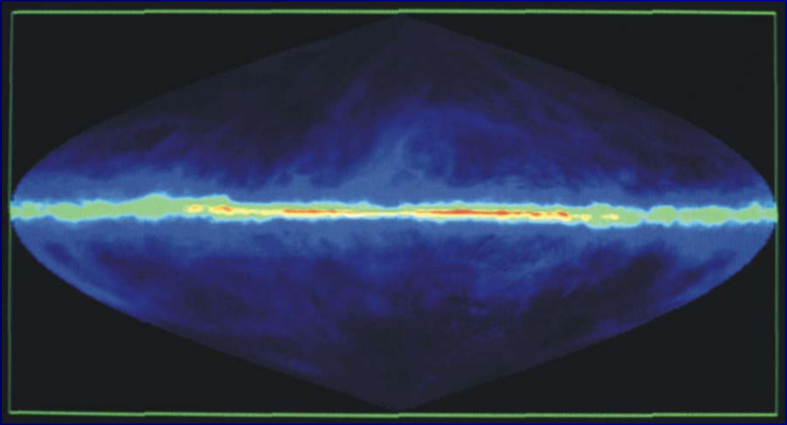


Credit Prof. Dale E. Gary NJIT

Molecular vibrational lines:

- Molecules spin and vibrate in quantized modes
- Transitions between modes emit or absorb radiation
- E.g. diatomic molecule CO
    - $J = 0$ to 1 transition at 115 GHz
    - $J = 1$ to 2 transition at 230 GHz

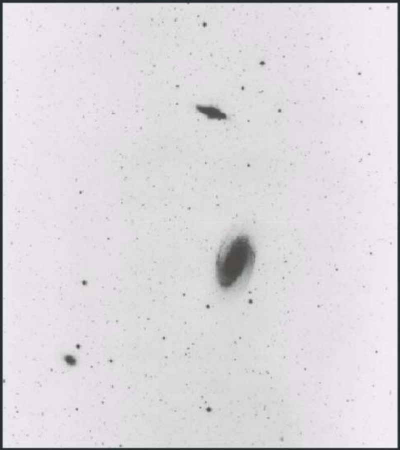
1420 MHz HI line emission, galactic coordinates



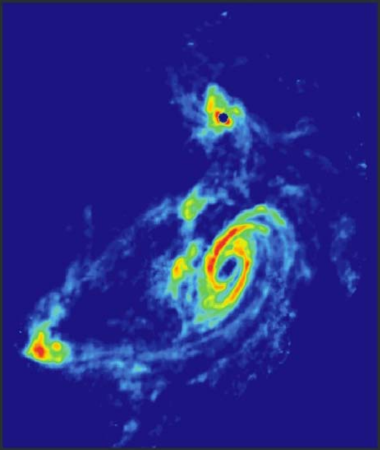
115 GHz CO emission and optical dust absorption, first quadrant of the Galaxy

Extended HI emission tracing the interaction history of the M81 group

Stellar Light Distribution



21 cm HI Distribution



Spectral line radiation II

MASER radiation:

- Microwave radiation from an optically pumped hot molecular cloud
- Usually very intense and narrowband
- H_2O: 22.23508 GHz
- SiO: 43.12203 and 86.24335 GHz
- CH3OH: 6.6685192, 12.178597, 19.9673961, 23.1210242, 25.12487, 44.06943, and 97.98097 GHz

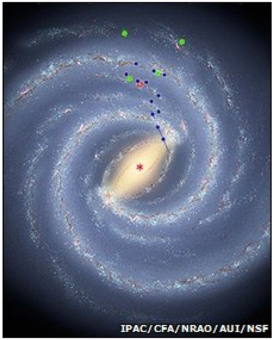
Milky Way 'bigger than thought'

Our galaxy is much bigger than once thought, according to research presented at a major astronomy meeting this week.

The results suggest the Milky Way is roughly the same size as Andromeda, the largest galaxy in our local group.

What is more, it is moving 15% faster than earlier predictions.

The greater mass means that future collisions with nearby galaxies could happen sooner than thought, according to the researchers.



Andromeda was previously thought to be larger than the Milky Way

Mark Reid of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, US, and his colleagues made use of the Very Long Baseline Array (VLBA) to deduce the Milky Way's size and speed.

Dr Reid was speaking at the 213th American Astronomical Society (AAS) meeting in Long Beach, California.

The VLBA is a system of 10 radio telescopes scattered across and around North America that together allow unprecedented resolution in astronomy measurements.

SEE ALSO

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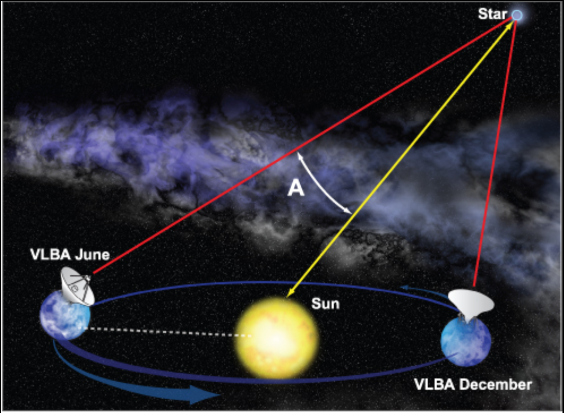
Dr. Mark Reid

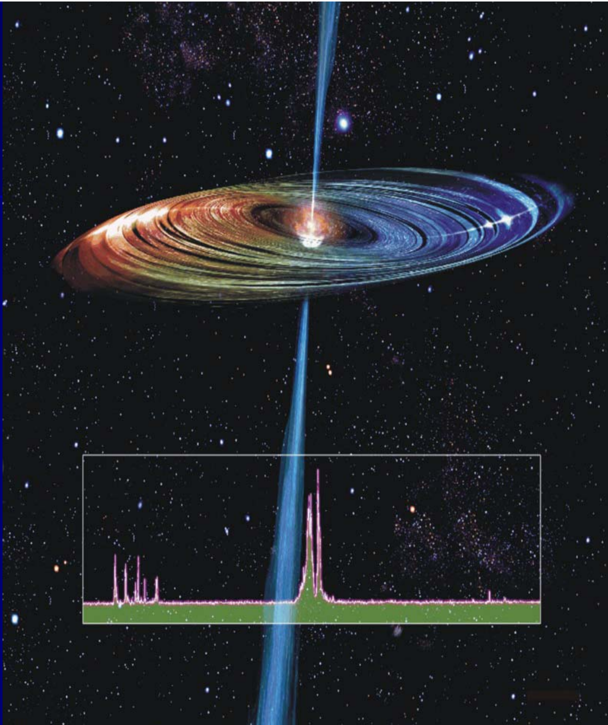
Credit: CfA



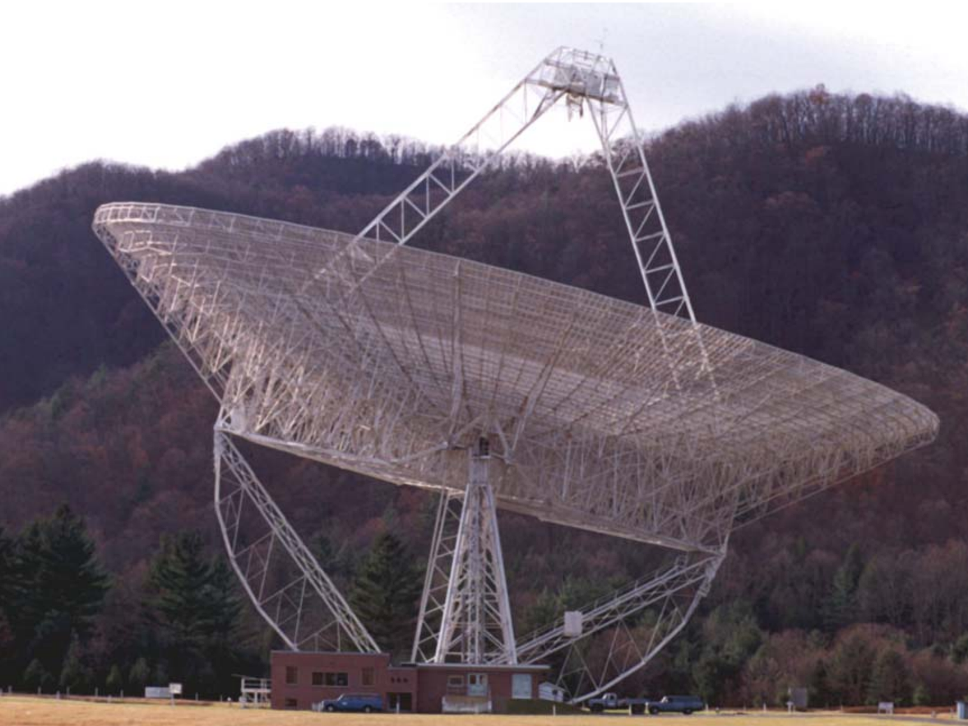
Very Long Baseline Interferometry provides extremely high precision that can extend use of the parallax technique to many more celestial objects. Parallax is a direct means of measuring cosmic distances by detecting the slight shift in an object's apparent position in the sky caused by Earth's orbital motion.

Credit: Bill Saxton, NRAO/AUI/NSF

Spectrum of the water maser around the massive black hole in NGC 4258

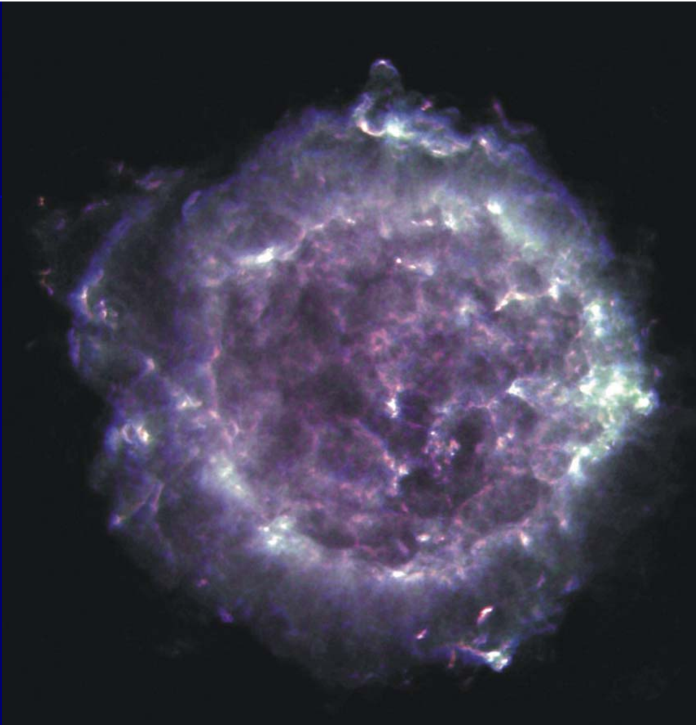


4.85 GHz sky over Green Bank

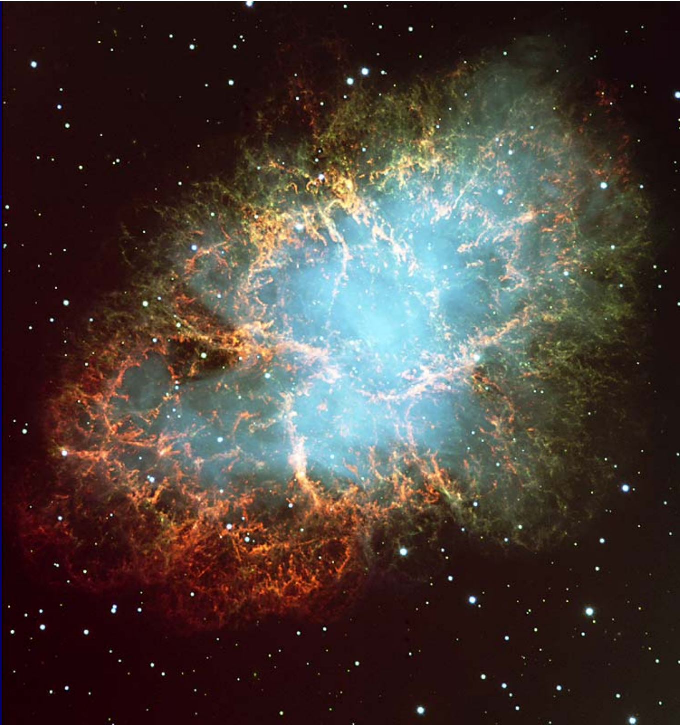


VLA (1 km D-configuration)

Cas A:
supernova
remnant
at 1.4, 5, and
8 GHz

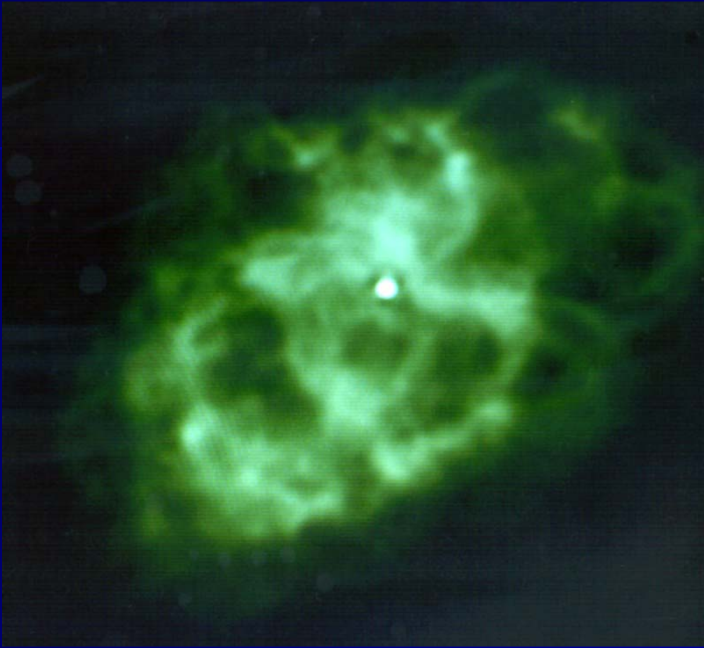


Crab Nebula remnant of 1054 AD supernova

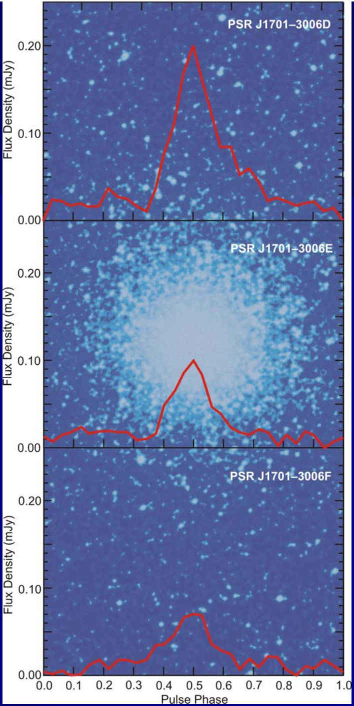


Crab nebula 5 GHz image

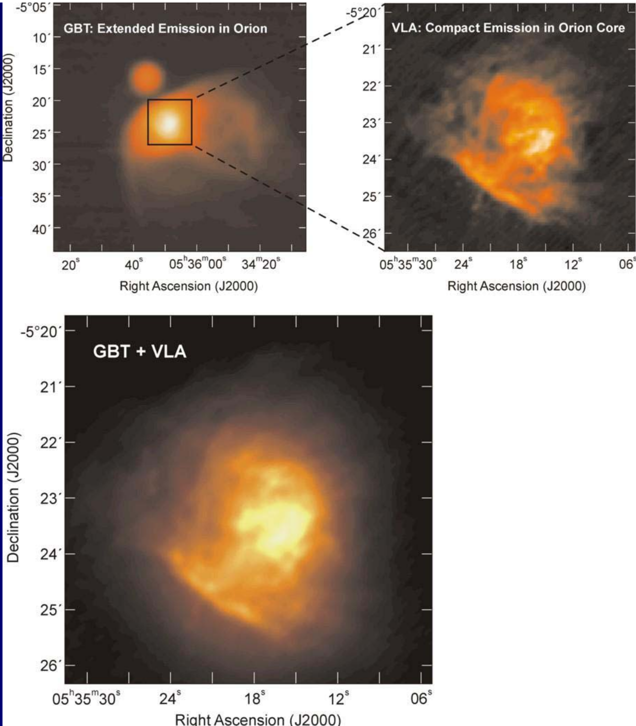
Crab nebula and pulsar at 327 MHz



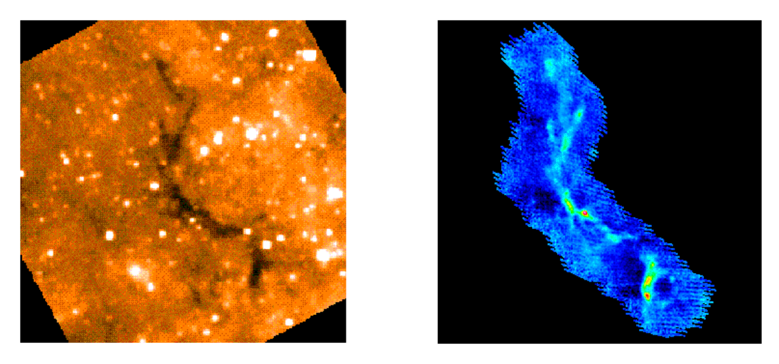
M62 pulsars

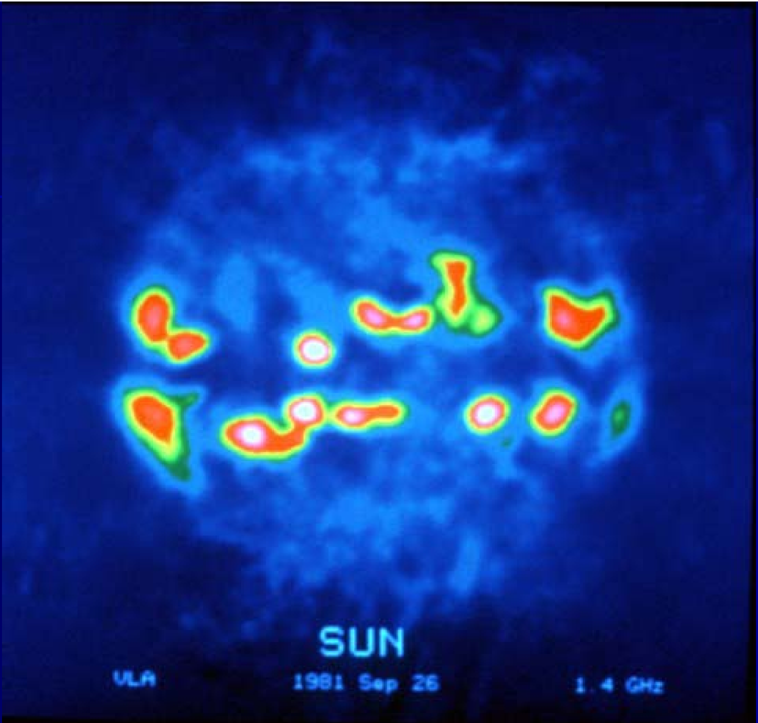

PSR J1701–3006D
PSR J1701–3006E
PSR J1701–3006F
Flux Density (mJy)
0.00
0.10
0.20
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Pulse Phase

Orion
Nebula
HII region
8.4 GHz

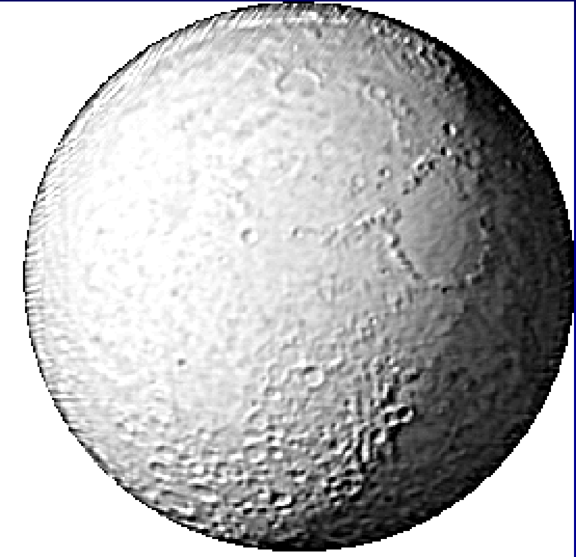


The Galactic dark cloud G11.11-0.12 in absorption at 8 microns (left) and emission at 850 microns (right)

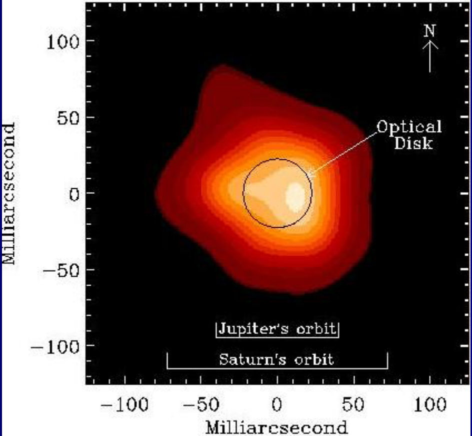



SUN
VLA
1981 Sep 26
1.4 GHz

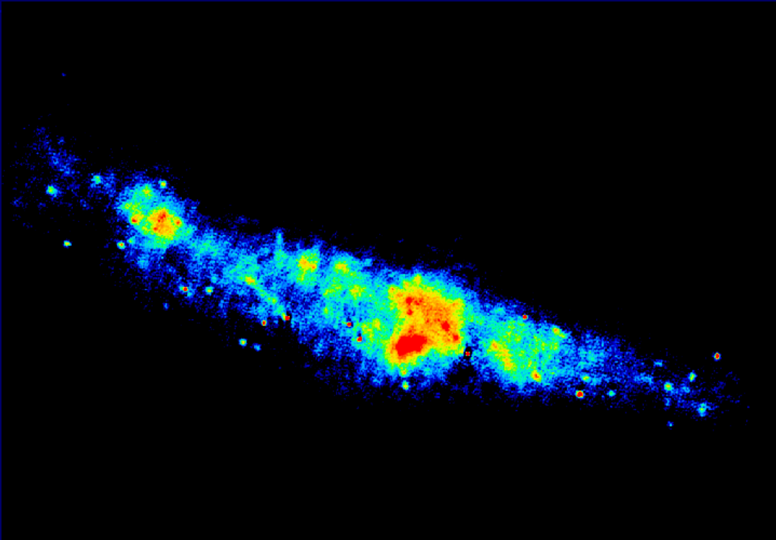
850 micron thermal emission from the Moon, observed with SCUBA on the JCMT

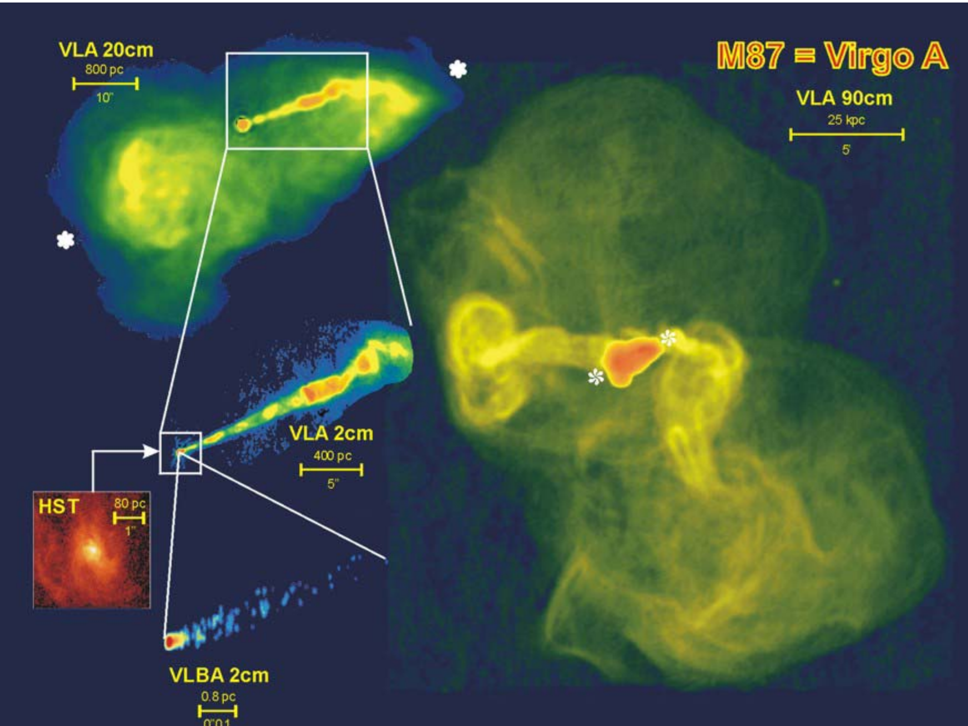


Betelgeuse: 45 GHz thermal emission from the stellar wind of a red supergiant star



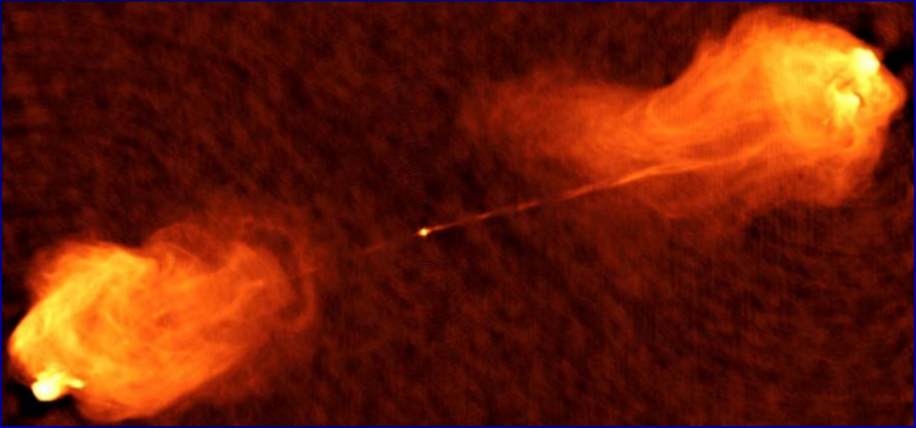
Starburst galaxy M82 continuum emission





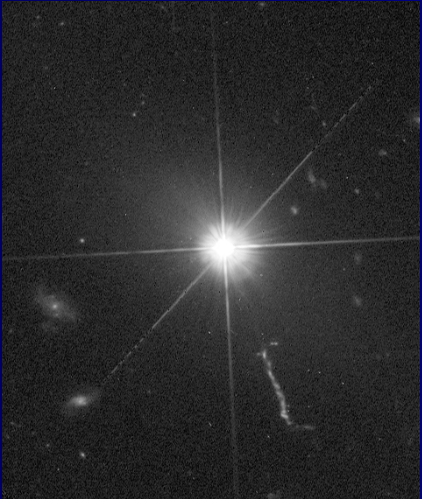
M87 ≡ Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc

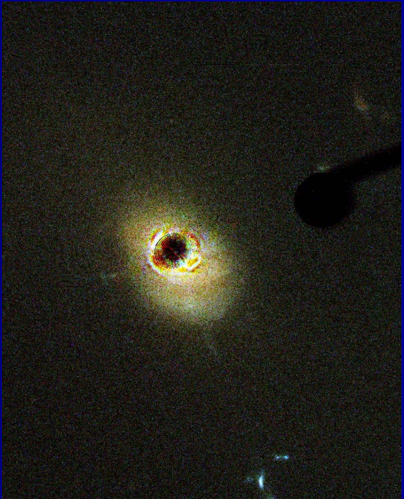
Cygnus A



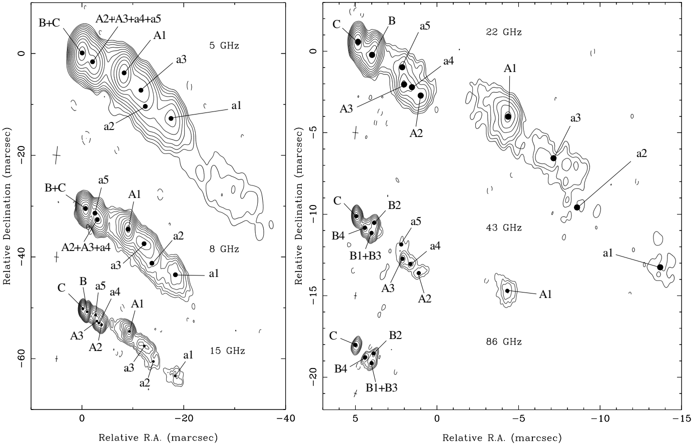
Cen A, peculiar galaxy with radio lobes (from HST web site)

Quasar (3C 273) and host galaxy with quasar subtracted

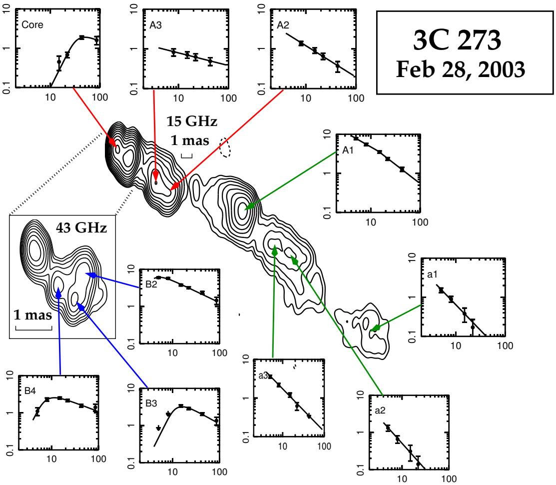




Our view of 3C 273: Maps from 6 frequencies



Our view of 3C 273: Component spectra



Isotropy of radio sources