ATNF Radio Astronomy School

Radio Astronomy Fundamentals

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Outline

- Astronomy frequency bands
- Radiation intensity, brightness and flux density
- Antenna beams and temperatures
- Thermal and non-thermal emission
- Spectral lines
- Polarisation
- Time variable sources

Basic References

Books:

- Kraus, J. D. “Radio Astronomy” (2nd Edition 1986)
- Burke, B. F., & Graham-Smith, F. “An Introduction to Radio Astronomy” (2nd Edition 2002)
- Rohlfs, K., & Wilson, T. L. “Tools of Radio Astronomy” (2006)

On-Line Course:

- Condon, J. J. and Ransom, S. “Essential Radio Astronomy” (2007)
  http://www.cv.nrao.edu/course/astr534/ERA.shtml

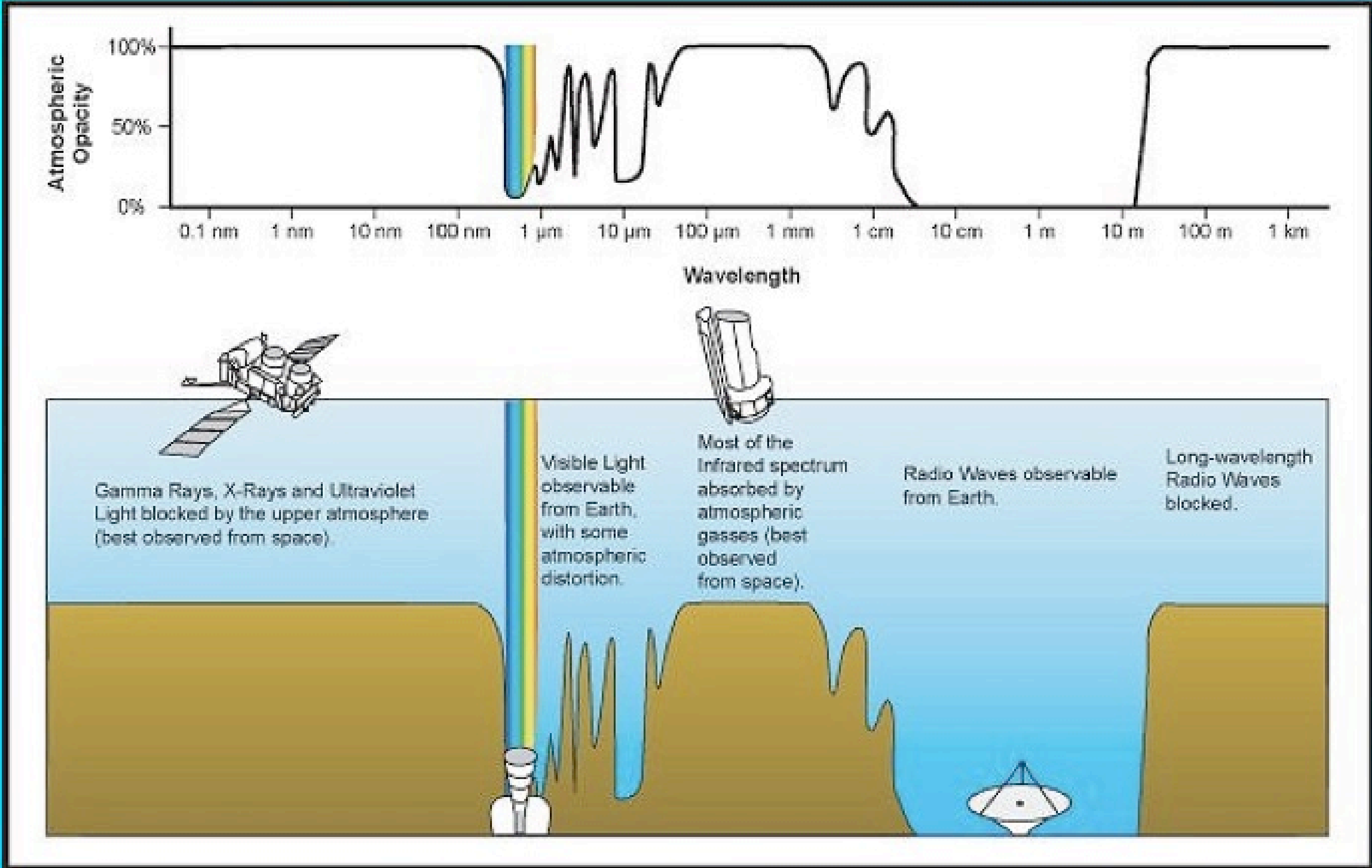
Frequencies and Wavelengths

$$c = \nu\lambda$$

($c = 3 \times 10^8$ m s^{-1})

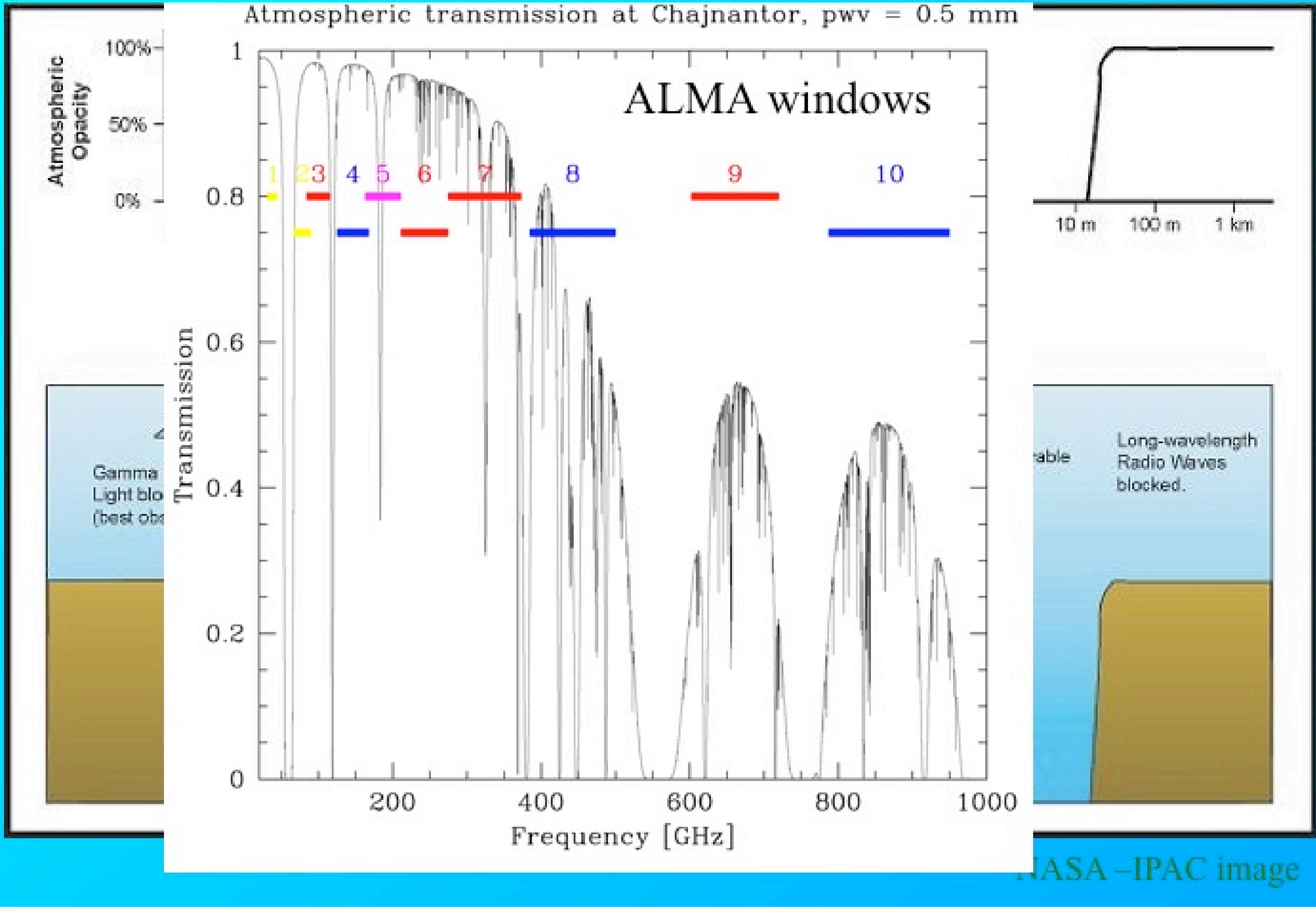
Radio:	10 MHz – 1 THz (10^{12} Hz)	30 m – 0.3 mm
Infrared:	10^{12} Hz – 3×10^{14} Hz	300 μm – 1 μm
Optical:	3×10^{14} Hz – 10^{15} Hz	1 μm – 300 nm
Ultraviolet:	10^{15} Hz – 6×10^{15} Hz	300 nm – 50 nm
X-ray:	6×10^{15} Hz – 10^{20} Hz	50 nm – 3 pm
Gamma-ray:	10^{20} Hz – 10^{26} Hz (1 MeV – 1 TeV)	3 pm – 3 am

Atmospheric Transmission Windows

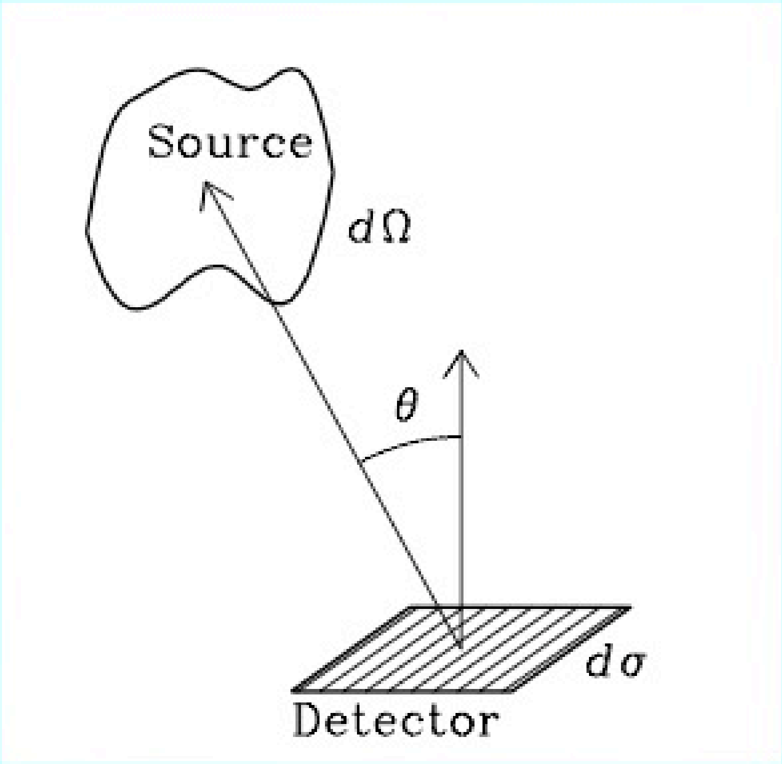


NASA –IPAC image

Atmospheric Transmission Windows



Specific Intensity and Brightness



Power from a source element:

$$dP = I_\nu \cos\theta d\sigma d\Omega d\nu$$

(Watts) $(m^2 \text{ sr Hz})$

Definition of Specific Intensity

$$I_\nu \equiv \frac{dP}{\cos\theta d\sigma\, d\nu\, d\Omega}$$

- Specific intensity is conserved along any ray in empty space
  - Specific intensity I_ν is equivalent to source (spectral) brightness B_ν
  - Source brightness is independent of source distance
  - Brightness is the same at the source and at the detector

Total Intensity, Flux Density and Luminosity

Total intensity: $I \equiv \int_0^{\infty} I_\nu d\nu$

Since the properties of specific intensity apply to all frequency elements within the total band, they apply to the total intensity too.

For a (small) discrete source, we can define a flux density:

$$S_\nu \approx \int_{\text{source}} I_\nu(\theta, \phi) d\Omega$$

(cos θ factor ignored)

The natural unit of flux density is W m^{-2} Hz^{-1}, but this is huge, so a special unit, the Jansky, is defined: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

Flux density is *not* independent of distance since $\Omega_s \sim d^{-2}$
– the inverse-square law.

The (spectral) luminosity of an isotropic source is:

$$L_\nu = 4\pi d^2 S_\nu$$

Thermal Radiation

Light is photons! Planck Radiation Law:

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

Planck's constant: $h = 6.63 \times 10^{-34}$ joule s

Photon energy $E_\nu = h\nu$

Boltzmann's constant: $k = 1.38 \times 10^{-23}$ joule K^{-1}

Stefan-Boltzmann Law:

$$B(T) \equiv \int_0^\infty B_\nu(T) d\nu = \frac{\sigma T^4}{\pi}$$

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} sr^{-1}

Radiant Flux $j = \pi B$ (W m^{-2})

For $h\nu << kT$

$$B_\nu = \frac{2kT\nu^2}{c^2}$$

Rayleigh-Jeans Law

Almost always applicable for radio astronomy

Light is

Planck

$$\frac{1}{\left(\frac{h\nu}{kT}\right) - 1}$$

Boltzm

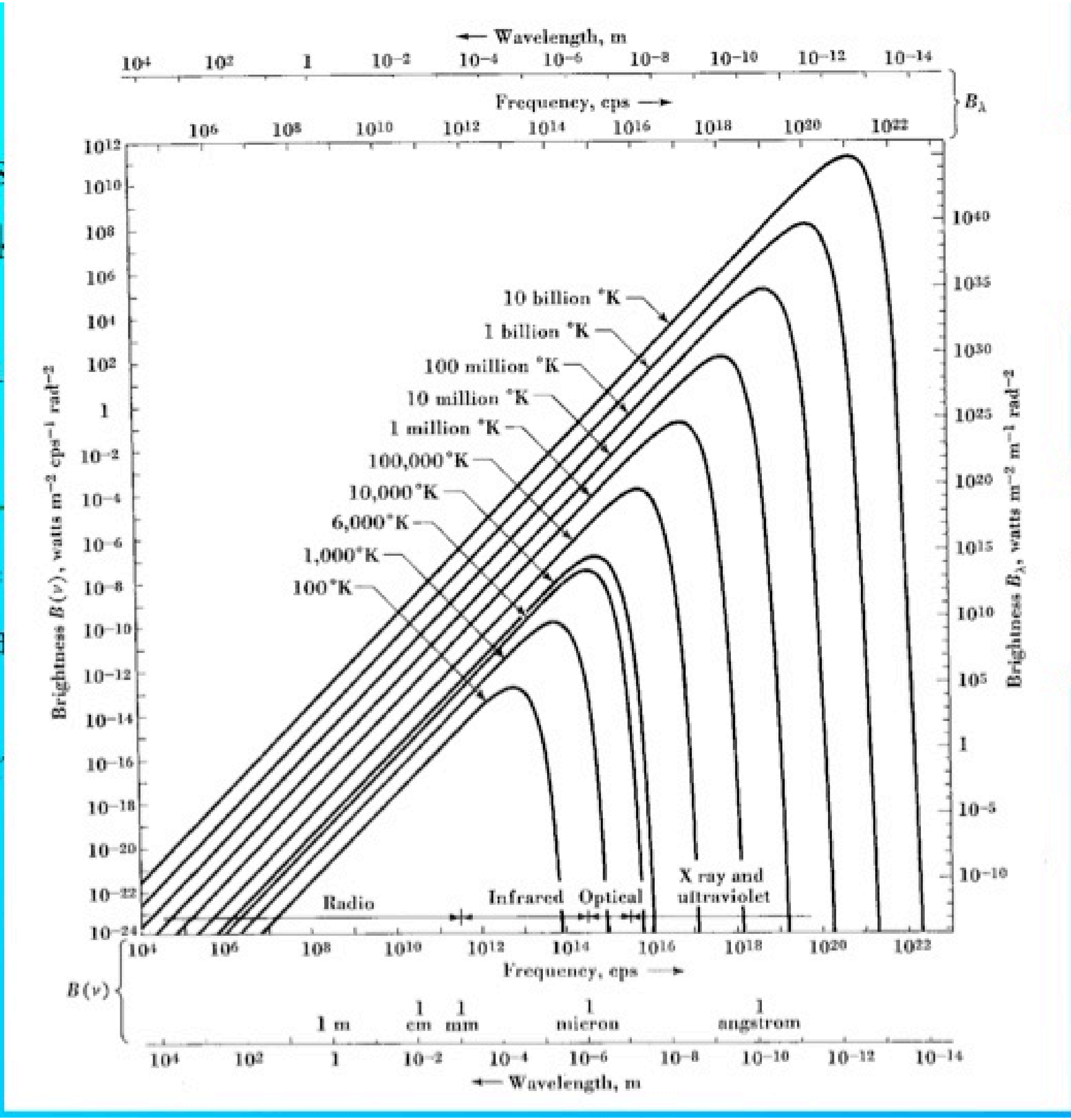
Stefan-

$\sigma =$

Radia

$$= \frac{\sigma T^4}{\pi}$$

For h



Emission and Absorption

Specific intensity is not conserved along a ray when it passes through an absorbing cloud: $dI_\nu/I_\nu = -\kappa\ ds$

Integrating through the cloud:

$$I_\nu(s_{\rm out}) = I_\nu(s_{\rm in}) \times \exp\left[-\int_{s_{\rm in}}^{s_{\rm out}} \kappa_\nu(s')ds'\right]$$

$$I_\nu(s_{\rm out}) = I_\nu(s_{\rm in}) \times \exp(-\tau_\nu)$$

τ_ν is the optical depth of the cloud

For a cloud that both emits and absorbs:

The Equation of radiative transfer

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \epsilon_\nu$$

By integrating the radiative transfer equation through the cloud:

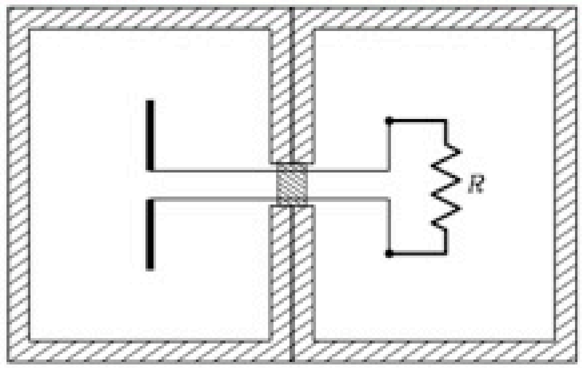
$$B_\nu(\text{obs}) = B_\nu(\text{cloud})(1 - e^{-\tau})$$

Or in the radio case, from the Raleigh-Jeans Law:

$$T_b(\text{obs}) = T(\text{cloud})(1 - e^{-\tau})$$

For $\tau \ll 1$, $T_b \sim T_c\,\tau$

Antenna Effective Area and Temperature



Consider two cavities, one containing an antenna and the other a resistor, both at temperature T, connected by a band-pass filter

In the Raleigh-Jeans limit, the noise power generated by resistor is (the Nyquist formula)

$$P_\nu = kT$$

For antenna, can define effective area:

$$P_\nu = A_e S_{(\text{matched})} = \frac{A_e S}{2}$$

Then

$$P_\nu = \int_{4\pi} A_e(\theta, \phi) \frac{B_\nu}{2} d\Omega$$

In R-J limit,

$$B_\nu = \frac{2kT}{\lambda^2}$$

Therefore

$$\int_{4\pi} A_e d\Omega = \lambda^2$$

or

$$\langle A_e \rangle = \frac{\lambda^2}{4\pi}$$

The average effective area is independent of antenna size!

and $S = 2kT_A/A_e$ T_A is the antenna temperature

$$T_A \equiv \frac{P_\nu}{k}$$

Beam Angles and Efficiencies

The beam solid angle is defined by

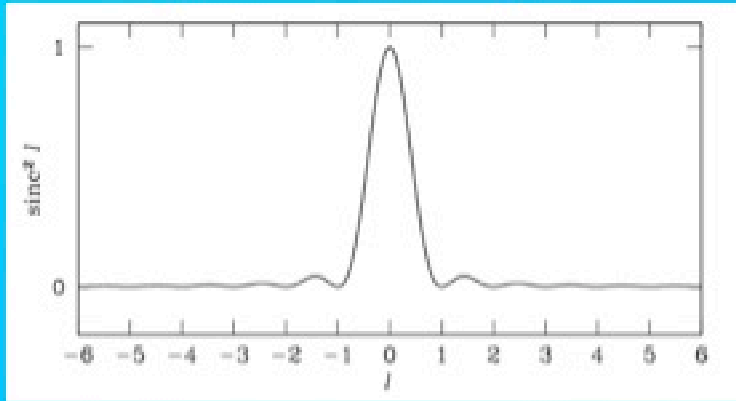
$$\Omega_A \equiv \int_{4\pi} P_n(\theta, \phi) d\Omega$$

where P_n is the normalised antenna power pattern, $P_n(0,0) = 1.0$

For a source of size Ω_s and brightness temp T_b:

$$T_A \approx T_B \frac{\Omega_s}{\Omega_A}$$

For a uniformly illuminated aperture, the beam power pattern is ~ $\text{sinc}^2\,\theta$



Nulls are at $\theta = +/- n\lambda/D$

The main beam is contained within the first nulls and has a solid angle Ω_{MB}

The beam efficiency is:

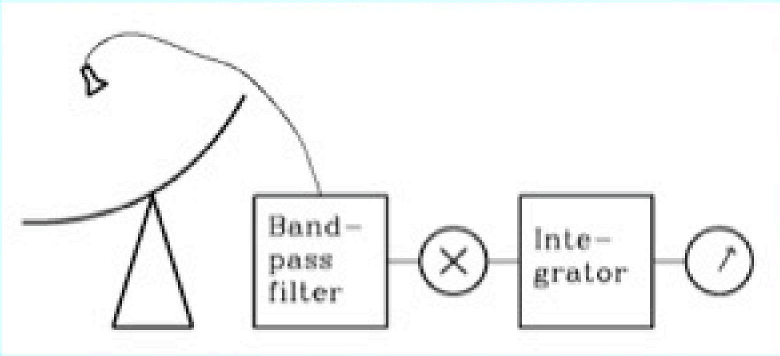
$$\eta_B \equiv \frac{\Omega_{MB}}{\Omega_A}$$

The aperture efficiency is:

$$\eta_A \equiv \frac{\max(A_e)}{A_{geom}}$$

Noise Temperature and System Temperature

A simple receiving system consists of the antenna, feed, a bandpass filter, a detector and an integrator



The concept of antenna temperature can be generalised to represent any source of noise:

$$T_N \equiv \frac{P_\nu}{k}$$

The total system temperature is then the sum of all noise contributions to the recorded power:

$$T_{sys} = T_{cmb} + \Delta T_{source} + T_{atm} + T_{spillover} + T_{rcvr} + \ \ldots$$

In each integration interval τ, there are $2\Delta\nu\tau$ independent (Nyquist) samples, each with noise power $2^{1/2}T_{sys}$. Therefore the rms fluctuation in the output is:

$$\sigma_T \approx \frac{T_{sys}}{\sqrt{\Delta\nu_{RF}\tau}}$$

The Radiometer Equation

Thermal Emission and HII Regions

Gas is ionised by UV radiation from bright massive stars – forms "HII region"

Keyhole Nebula (Carina) (HST)

Radio emission from "bremsstrahlung" or "free-free emission" from electron-ion interactions – accelerated charges radiate

Optical depth: $\tau \sim N_e^2\ \nu^{-2.1}\ T^{-3/2}$

At low frequencies:

$\tau >> 1$, $T_b = T$ and $S \sim \nu^2$

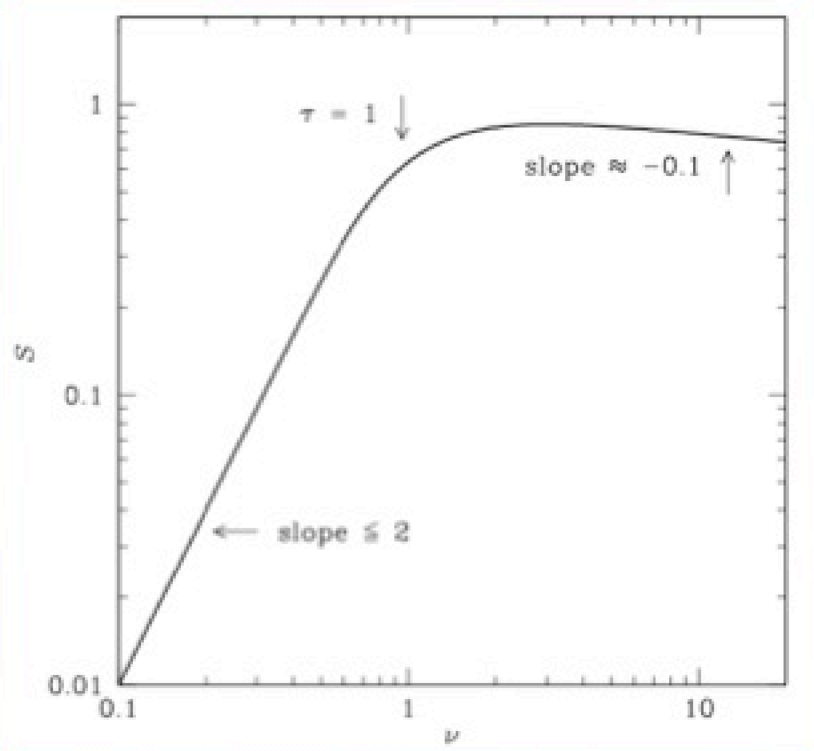
At high frequencies:

$\tau << 1$, $T_b = T\,\tau$ and $S \sim \nu^{-0.1}$

Emission measure:

$$\frac{EM}{\mathrm{pc\ cm^{-6}}} \equiv \int_{\mathrm{los}} \left(\frac{N_e}{\mathrm{cm^{-3}}}\right)^2 d\left(\frac{s}{\mathrm{pc}}\right)$$

$$\tau_\nu \approx 3.28 \times 10^{-7} \left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{-1.35} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1} \left(\frac{EM}{\mathrm{pc\ cm^{-6}}}\right)$$



Non-thermal (synchrotron) Emission

Ultra-relativistic electrons gyrating in a magnetic field radiate synchrotron radiation

Electrons accelerated by interactions near black holes & neutron stars, often in shocks associated with supersonic flow

Crab Nebula

Blue: X-ray (Chandra)

Green: Optical (HST)

Red: Radio (VLA)

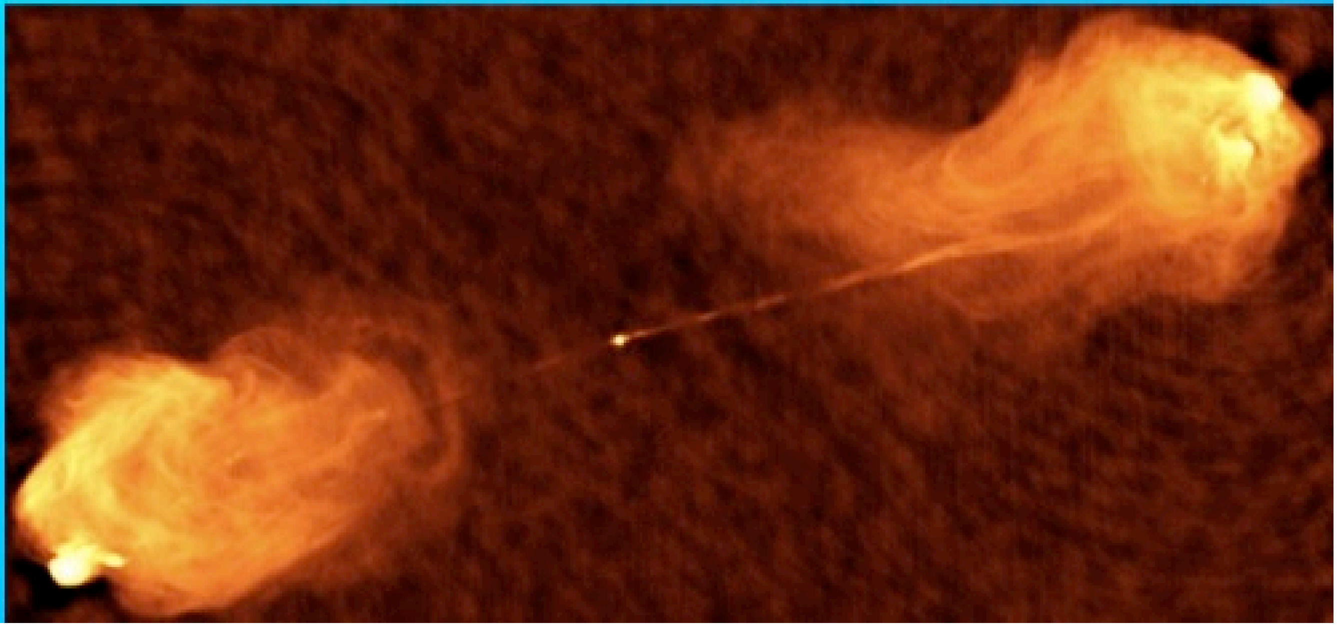
Cygnus A at 5 GHz (VLA)

Image size ~ 2 arcmin

Distance ~ 230 Mpc

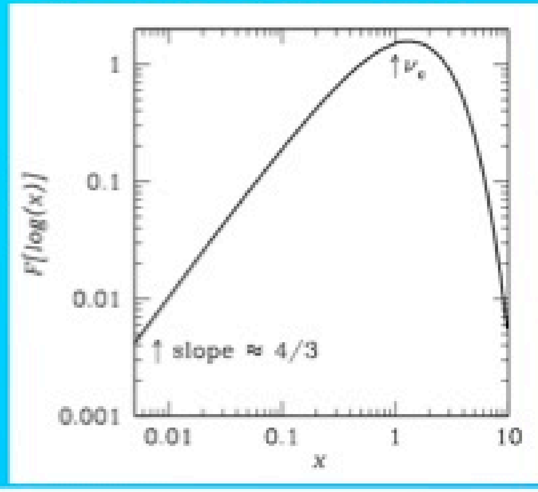
Size ~ 60 kpc

S(1.4 GHz) ~ 2000 Jy



Synchrotron Radiation

For ultra-relativistic energies, gyro-radiation is highly beamed in the forward direction



Radiation from a single electron covers a broad spectrum with a peak at

$$\nu_c = \frac{3}{2}\gamma^2 \nu_G \sin\alpha$$

($\beta = v/c$; $\gamma = (1 - \beta^2)^{-1/2}$; $\nu_G = eB/(2\pi m)$; α = pitch angle)

For many electrons with an energy distribution

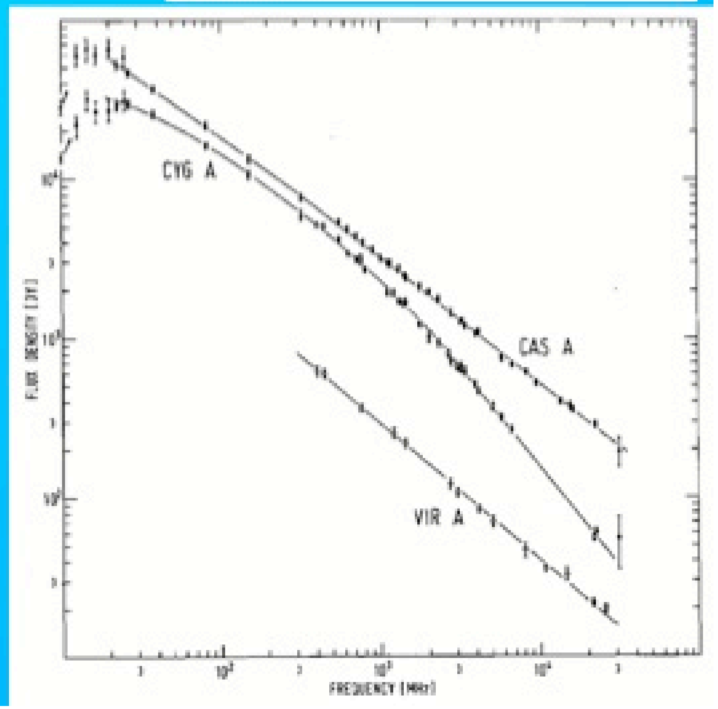
$$N(E)dE \approx KE^{-\delta}dE$$

the emissivity

$$\epsilon_\nu \propto B^{(\delta+1)/2}\nu^{(1-\delta)/2}$$

For an optically thin source: $\alpha = (1-\delta)/2$ where $S = \nu^\alpha$, α = spectral index

For most non-thermal sources: $\delta \sim 2.4$, $\alpha \sim -0.7$



Spectral Line Sources

The ISM contains hundreds of atomic and molecular species

Transitions can occur between spin, electronic, vibrational and rotational states

Can measure radial velocities through Doppler effect

The excitation temperature is defined by

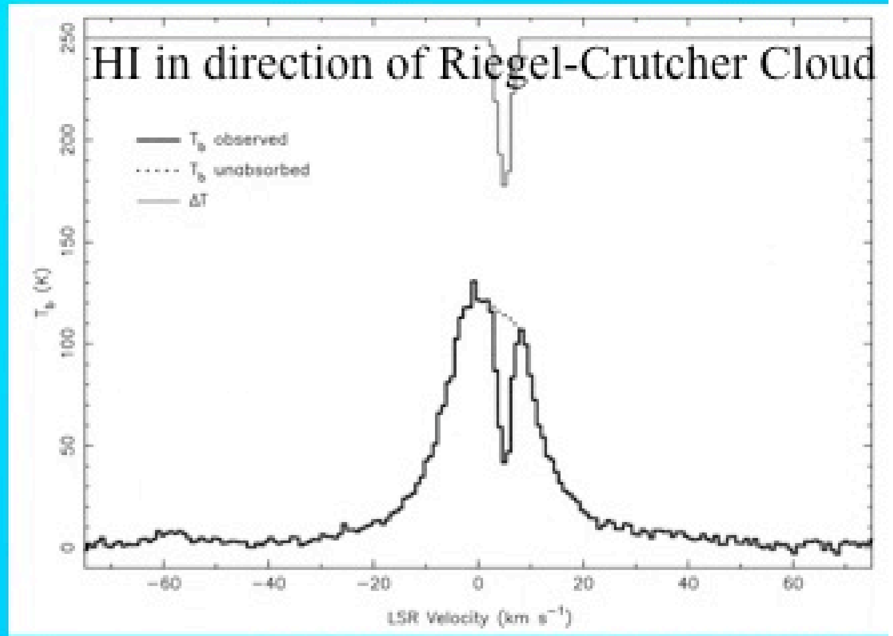
$$\frac{N_U}{N_L} \equiv \frac{g_U}{g_L} \exp\left(-\frac{h\nu_0}{kT_x}\right)$$

If $T_x < T_{bkgnd}$, then line seen in absorption

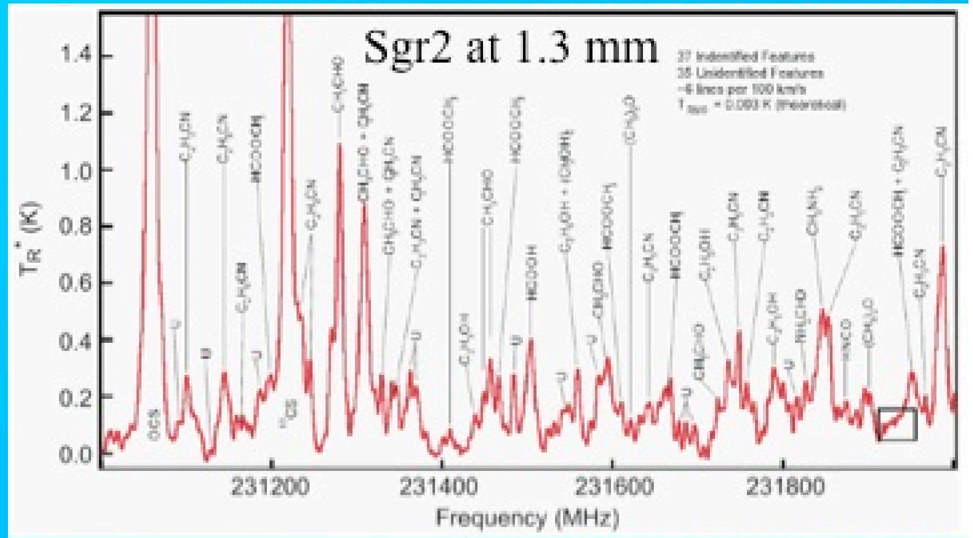
If $T_x > T_{bkgnd}$, then line seen in emission

If $T_x < 0$, then can have maser emission

If system in LTE, then $T_x = T$



(McClure-Griffiths et al. 2005)



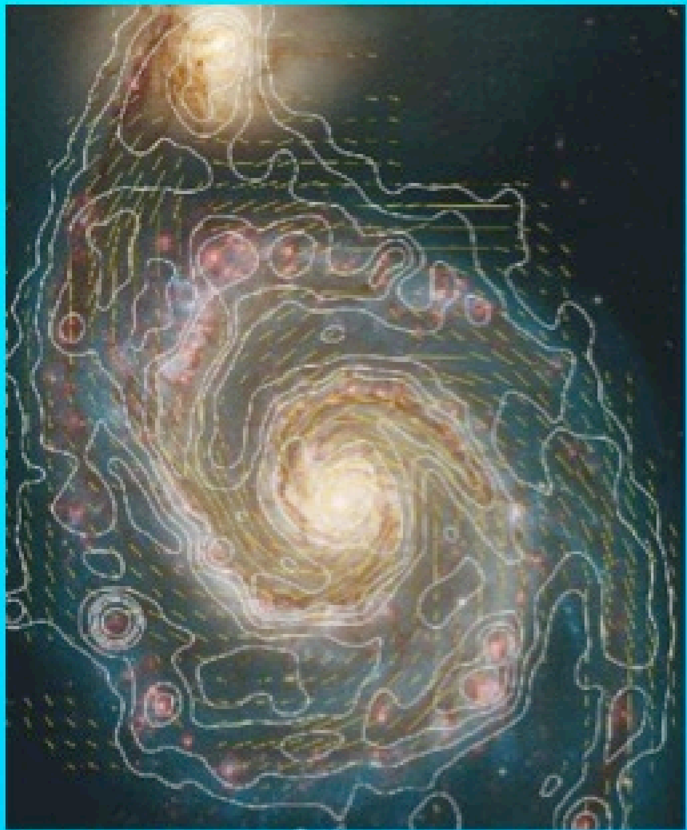
(Ziurys et al. 2006)

Polarisation

Most non-thermal radio emission is polarised

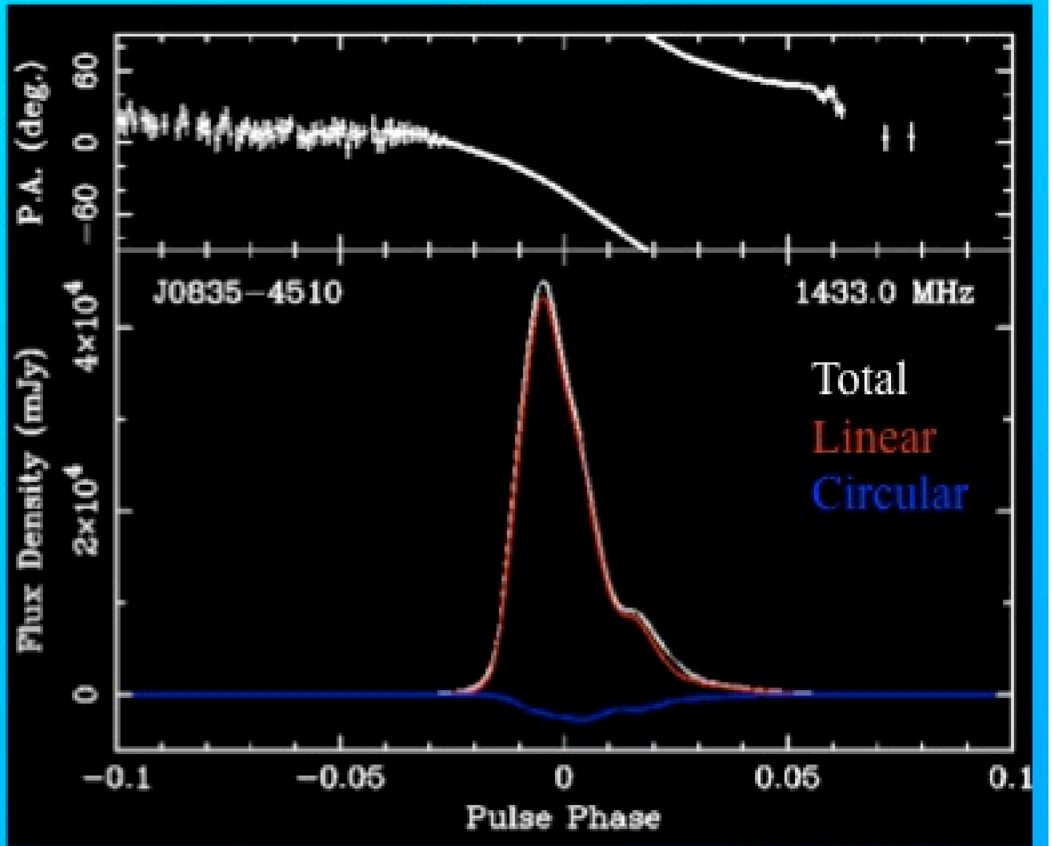
Two types of polarisation: linear and circular – depends on relative amplitude and phase of orthogonal components of wave electric field

M51 Polarisation at 5 GHz



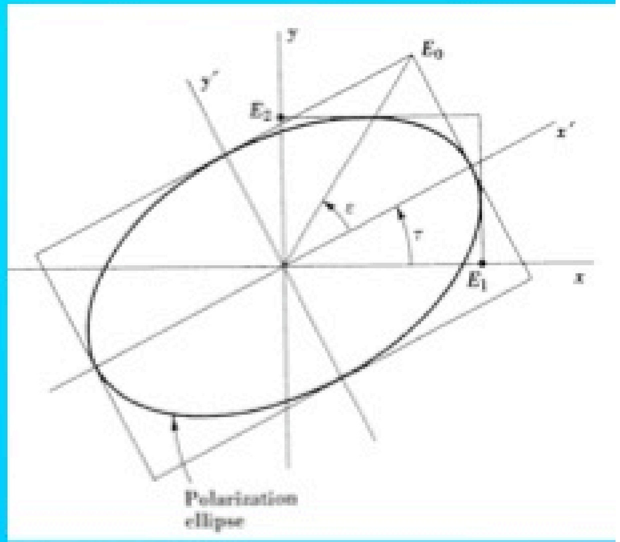
(Beck 2009) (MPIfR, VLA & HST)

Vela pulsar



(Parkes DFB)

Polarisation and Stokes Parameters



$E_x = E_1 \sin(\omega t - \delta)$; $E_y = E_2 \sin(\omega t)$

$E_{x'} = E_0 \cos \varepsilon \sin(\omega t)$; $E_{y'} = E_0 \sin \varepsilon \cos(\omega t)$

Can define Stokes parameters:

$I = S = S_x + S_y = (E_1{}^2 + E_2{}^2)/Z$

$Q = S_x - S_y = S \cos(2\varepsilon) \cos(2\tau) = (E_1{}^2 - E_2{}^2)/Z$

$U = (S_x - S_y) \tan(2\tau) = 2\, E_1 E_2 / Z \cos \delta$

$V = (S_x - S_y) \tan(2\varepsilon) \sec(2\tau) = S \sin(2\varepsilon) = 2\, E_1 E_2 / Z \sin \delta$

For $\delta = 90^o$ and $E_1 = E_2$, $\varepsilon = 45^o$ and $V = S = S_{LH}$ (100% circular)

For $\delta = -90^o$ and $E_1 = E_2$, $V = -S = S_{RH}$ (100% circular)

For $\delta = 0$, $V = 0$ and $U/Q = \tan(2\tau)$ (100% linear) τ = Position Angle

For $\tau = 0$, $Q = S$;   for $\tau = 45^o$, $U = S$

For a partially (or fully) polarised wave:

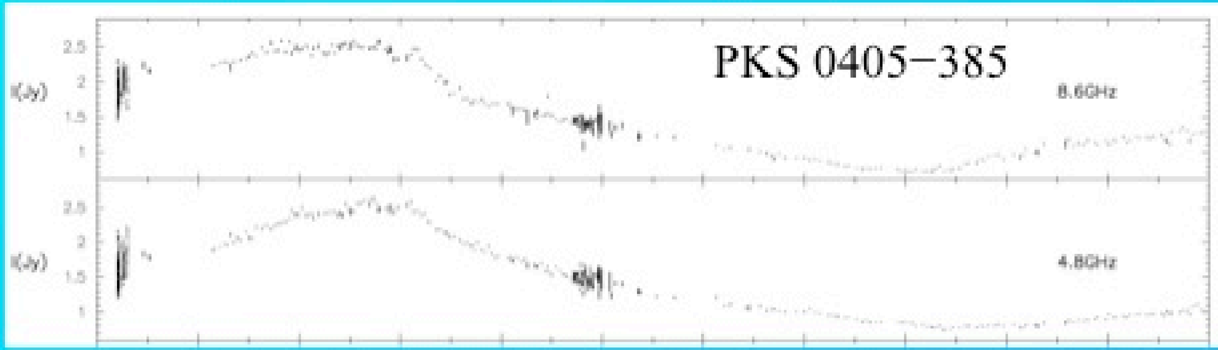
$I = S_0 + S_{90}$; $Q = S_0 - S_{90}$; $U = S_{45} - S_{135}$

$\tau = ½ \tan^{-1}(U/Q)$; $L = (Q^2 + U^2)^{1/2}$; $V = S_{LH} - S_{RH}$

N.B.: Must integrate to get partial polarisation – a Nyquist sample is always 100% polarised!

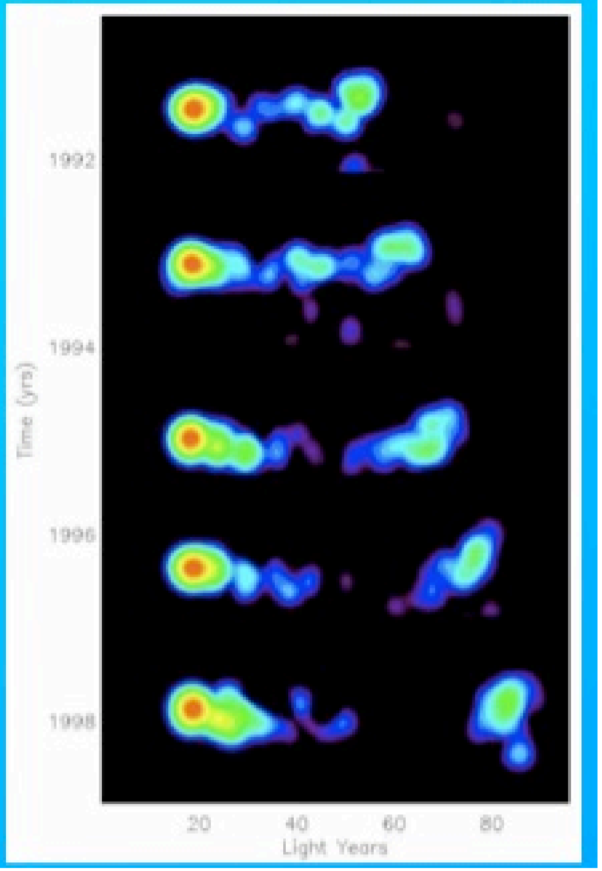
The Time-Variable Universe

- Quasars and AGN vary on timescales of weeks – years
- Due to variations in accretion rate on to central black hole



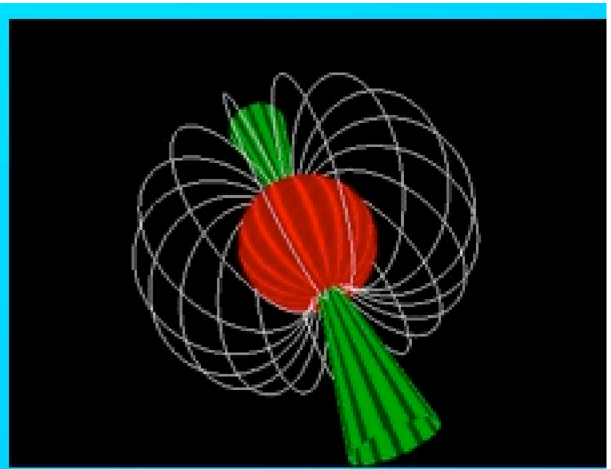
(Kedziora-Chudczer 2006)

3C279
(VLBA)



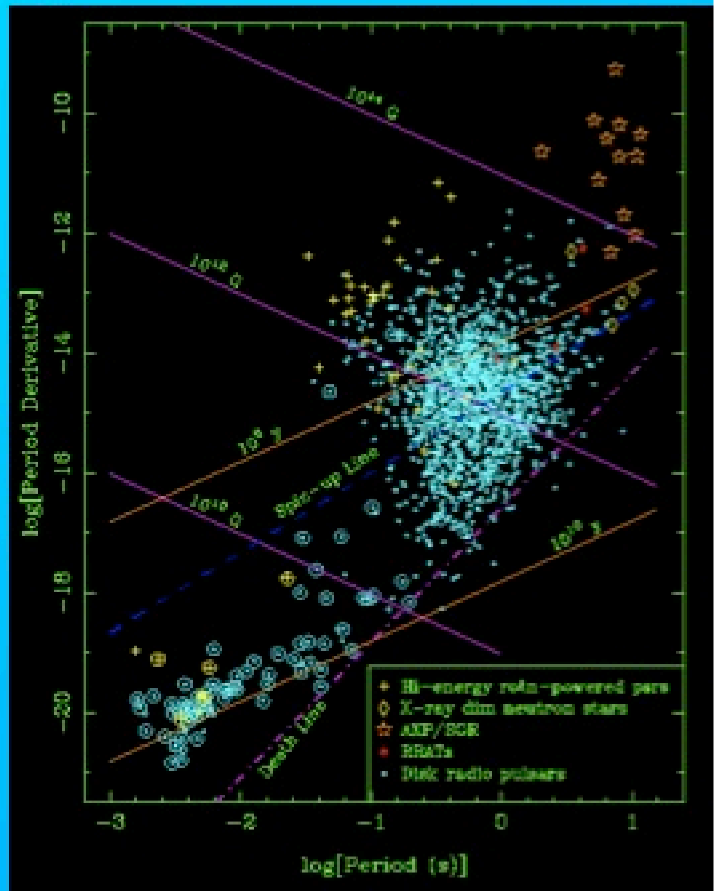
- VLBI observations show (apparently super-luminal) expansion of emission "blobs"
- Short-term (intra-day) variations also observed – due to interstellar scintillation
- Scaled-down versions also observed in Galactic sources – micro-quasars – with accretion on to stellar-mass black hole

Pulsars



- Pulsars are rotating neutron stars – celestial light-houses
- Pulse periodicity is incredibly stable – measured pulse period of PSR J0437-4715 is:

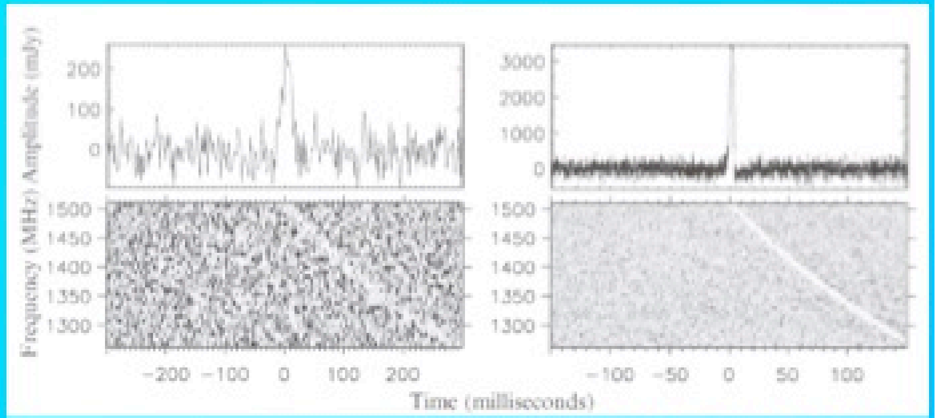
5.757451831072007 ± 0.000000000000008 ms



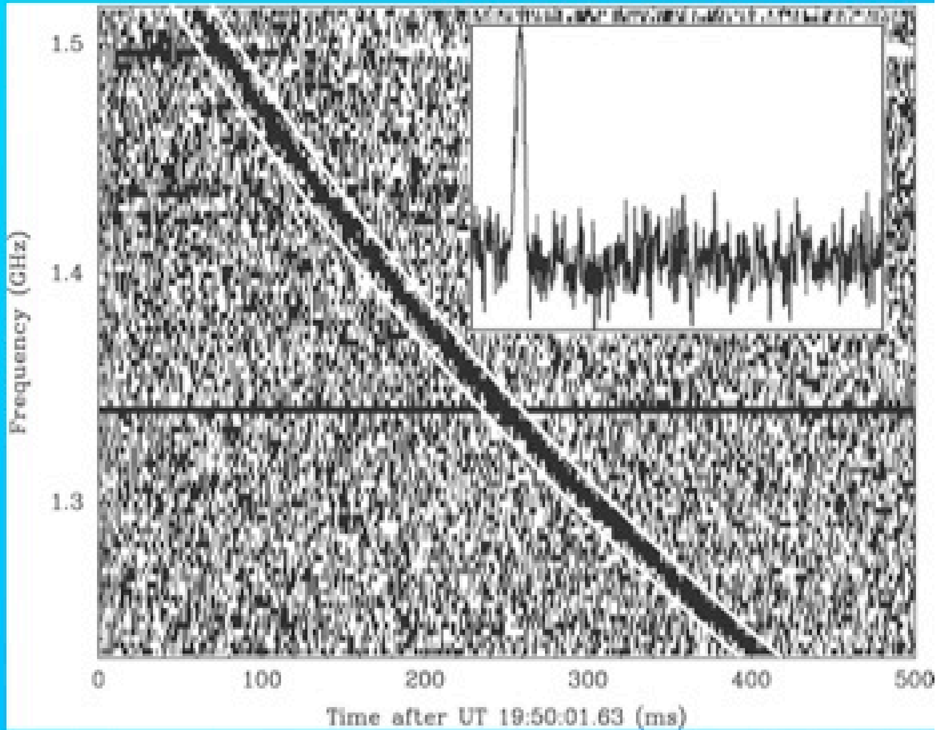
- About 1800 pulsars known, nearly two-thirds discovered at Parkes!
- Pulse periods between 1.396 ms and 12 s
- Most MSPs are in binary systems
- Pulsars slow down due to loss of energy to magnetic-dipole radiation and particle acceleration
- Young pulsars often have pulsed emission at high energies and are associated with supernova remnants

RRATs and Bursts

- RRATs are isolated bursts of radio emission observed in pulsar surveys
- Identified through "dispersion" – propagation delays in the ISM
- Multiple bursts observed in same direction and with same dispersion – typical intervals minutes to hours
- Analysis showed periodicity, typically 5 – 10 s – and slow-down
- RRATs are intermittent pulsars!
- Lorimer burst detected in LMC survey data – just one!
- High DM – extra-galactic origin?



(McLaughlin et al. 2006)



(Lorimer et al. 2007)

The End!

(of the beginning)