


Radio Astronomy

Lecture 4

Emission Mechanisms in Radio Astronomy

Lecturer: Jason Hessels (j.w.t.hessels@uva.nl)

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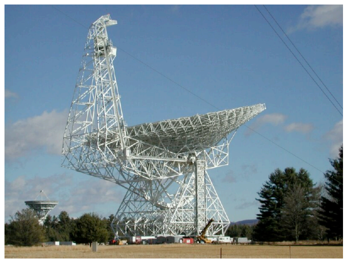


- In this lecture we'll overview the radio emission mechanisms that are relevant to radio astronomy.
- Understanding these mechanisms, their observational characteristics and physical origins is critical for interpreting radio astronomical data and planning useful observational studies.
- Say you measure the spectrum of a radio source: what does it tell you about the physical conditions and processes relevant to that source?
- Say you want to measure some physical property of a radio astronomical source - e.g. its magnetic field - what observables do you need to infer that property?

Emission Mechanisms in Radio Astronomy

Lecture outline

- Thermal emission processes

  Blackbody radiation, free-free emission

- Spectral line emission

  Radio-recombination lines, 21-cm line, molecular lines, MASERs

- Non-thermal emission processes

  Cyclotron emission, synchrotron emission, inverse Compton, synchrotron self-Compton, pulsar emission

- Propagation effects
- Bringing it all together

• The goal of this lecture is not to deeply investigate the theory of radiation emission mechanisms, but rather to remind you of some of the processes that you may have seen before and how they fit into the context of radio astronomy.
• Electromagnetic emission is produced by the acceleration of charged particles (both thermal and non-thermal processes).
• Roughly speaking, emission can be either thermal or non-thermal and either broadband or narrow-band.
• Several of these emission mechanisms are generic to other areas of astronomy, but remember that radio astronomy is largely a study of non-thermal (particle acceleration processes) and spectral lines like the 21-cm line.
• As it travels through the magneto-ionized interstellar medium, radio emission can also experience propagation effects that influence the observed properties and cause them to deviate from the emitted (intrinsic) properties of the emission at the source. This complicates the interpretation of the observed emission, but it also nicely provides a probe of the intervening material (e.g. its magnetic field strength, density and line-of-sight distribution).

“Boson Astronomy”

Understanding the emission/absorption of electromagnetic radiation is key to astronomy... but it’s not our only window on the Universe.

Boson Astronomy: Photon astronomy (Radio-Gamma), Graviton astronomy (GWs)

Pneumatic Astronomy: Acoustic waves, magnetohydrodynamic waves

Particle Astronomy: Cosmic-rays, neutrinos, dark matter, meteorites

Direct Techniques: Space probes, manned exploration

• Just a contextual note: despite the differences between radio astronomy and other types of astronomy like optical astronomy it is still fundamentally a similar approach because we’re using electro-magnetic radiation to give us our information (as opposed to some of the other conceivable ways in which we can probe astronomical sources at a distance).

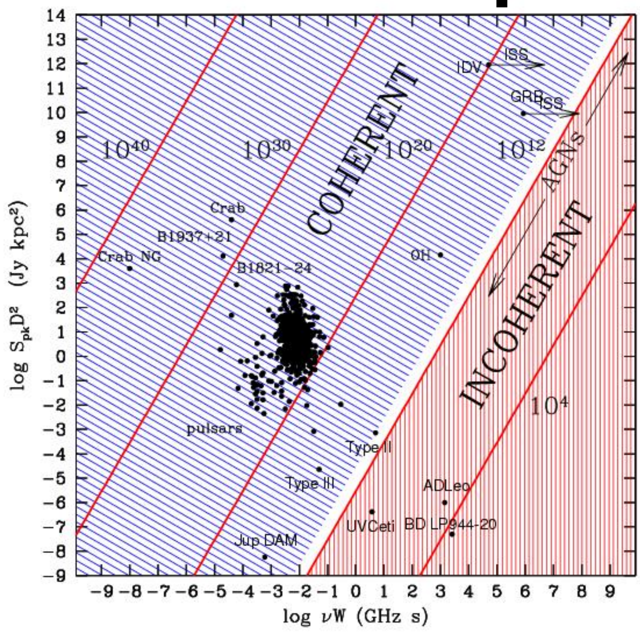
Emission Mechanisms

- EM radiation is emitted by accelerated charged particles.
- Thermal emission depends only on the temperature of the emitting object.
- Non-thermal emission does not depend on temperature.
- Photon frequency proportional to energy.

$$\lambda = \frac{c}{\nu} = \frac{hc}{E}$$

- Wiggle a charged particle and you can get photons. This is basic electrodynamics.
- However, the reason the charged particle is in motion can have radically different origins: e.g., sometimes this has to do with temperature and sometimes with non-thermal particle acceleration.
- The observed frequency of the emission is intimately related to the energies involved.

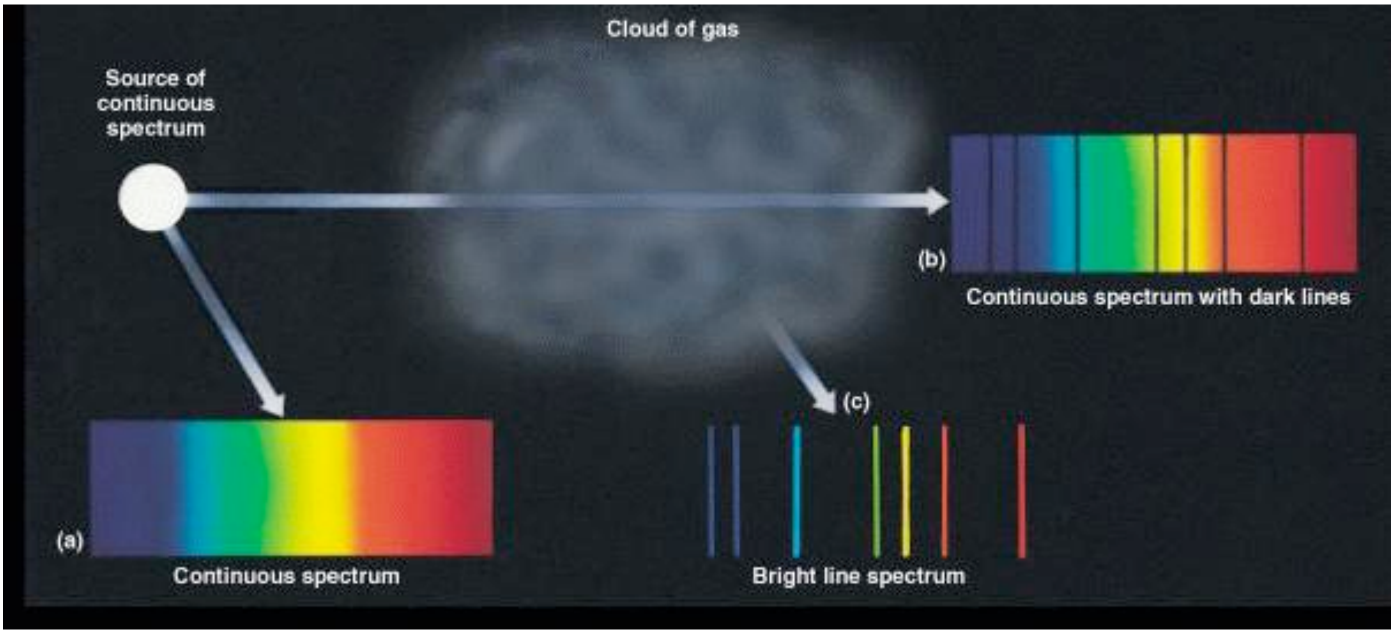
Brightness Temperature



- Brightness temperature: the equivalent temperature of a blackbody emitting the same intensity.

- In radio astronomy we often use the term "brightness temperature", even if the source of the radiation is non-thermal.
- Brightness temperature gives the equivalent temperature of a blackbody emitting at the same observed intensity.
- Above a certain threshold, roughly 10^12 K (see the labelled diagonal lines in this graph), we talk about a transition between incoherent (disordered) and coherent (ordered, in phase) emission.
- The highest observed brightness temperatures in the Universe approach ~10^38 K and can be found in the nanosecond-long giant pulses generated by the young Crab Pulsar. NB: the nanosecond-duration of these pulses also sets a limit on the size of the coherent emission region, based on the light travel time across it. In fact, this implies that the emission region is < 1m across!

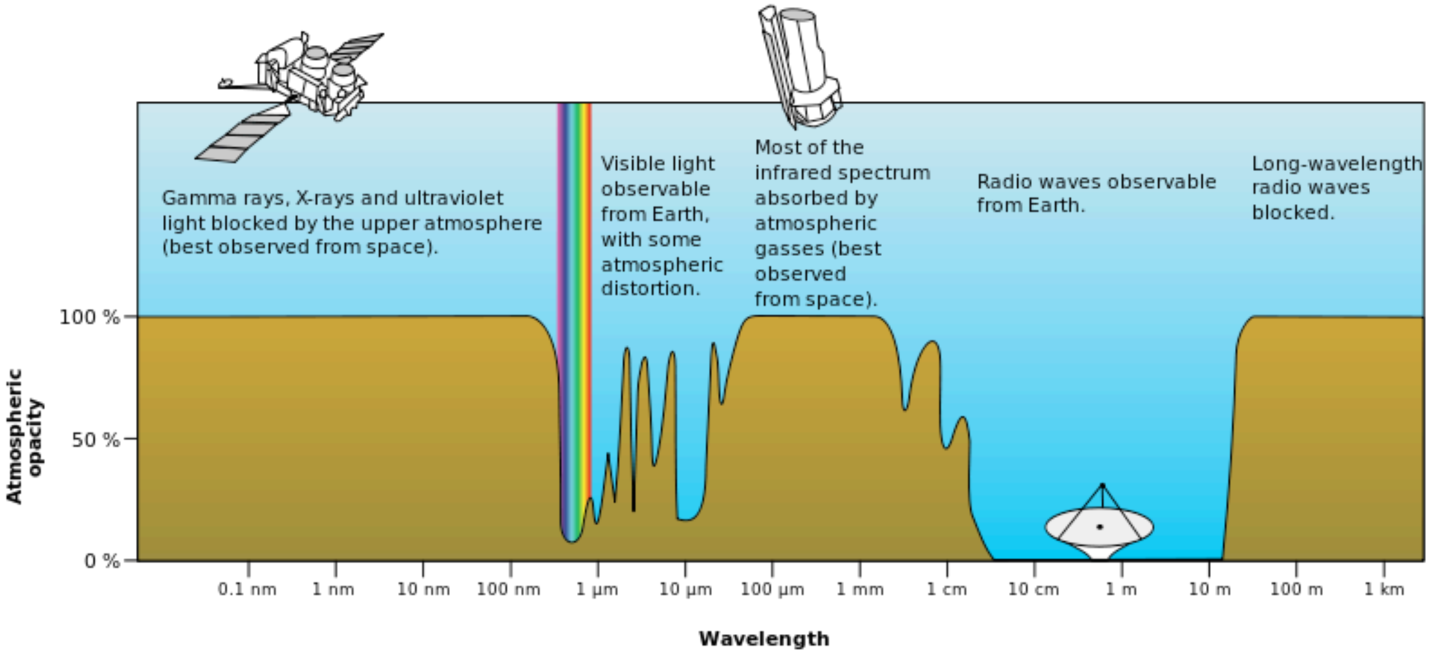
Continuum vs. Line Emission



- Continuum: wide-range of particle energies.
- Line: discrete energies due to transitions in atoms or molecules.

• Both continuum and line emission are important drivers for the science of radio astronomy.
• Continuum emission implies a spectrum of particle energies.
• Line emission is due to discrete transitions in either atoms or molecules. Note that some of these transitions imply energies that are far too small to be observed in the optical (cf. equation on slide 5).
• As in the optical, we can sometimes observe radio spectral lines in emission and sometimes in absorption.

EM Spectrum



- Only optical/IR and radio pass through the atmosphere.
- Radio window: 1cm - 30m / 10MHz - 30 GHz (or more)

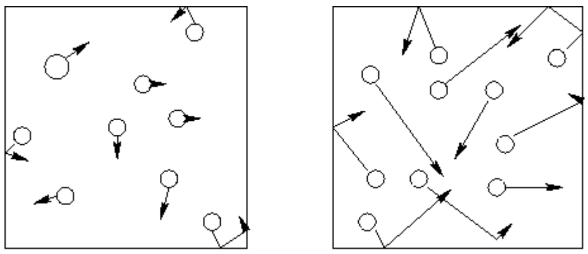
• Just a reminder that here we will be considering emission mechanisms that are relevant in the radio window, i.e. the region of the EM-spectrum that is observable from Earth's surface.
• In principle, radio astronomy could also be conducted from space at frequencies below 10MHz, but this is an almost unexplored domain.
• The highest frequency radio waves observable from Earth are strongly affected by weather and atmospheric absorption. This is why, e.g., the high-frequency ALMA interferometer (which can observe from about 30 - 1000 GHz) is located in a very high-altitude, dry area. Reaching these high frequencies is scientifically very interesting because, e.g., it gives access to a lot of interesting astro-chemistry through the molecular state transitions that are observable through lines at these frequencies.

Thermal Emission Processes

- Thermal emission: emission that depends on the source temperature.

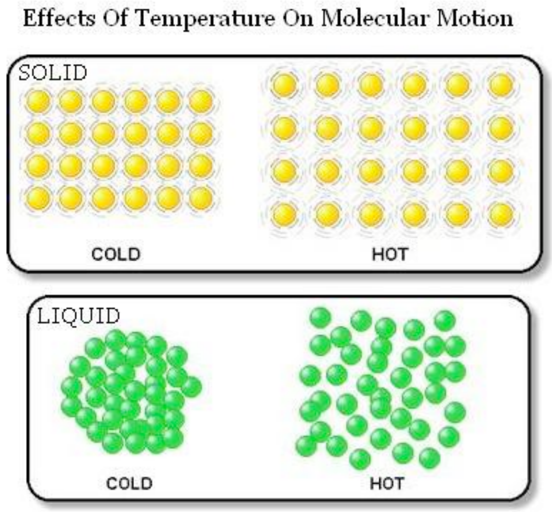
Thermal Emission

- Any object with a temperature above 0K emits thermal radiation.
- Temperature is related to particle motion.



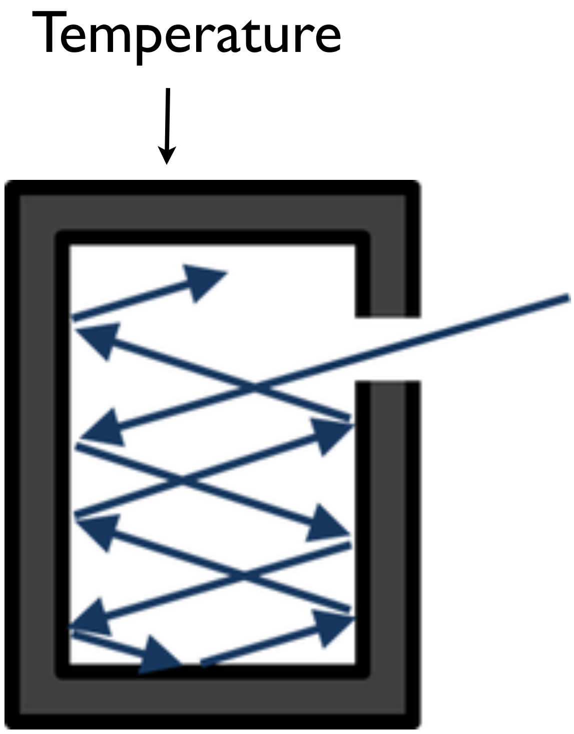
Cool gas, fewer and less energetic collisions

Hot gas, more and more energetic collision



- First we'll consider thermal emission, which (obviously) probes the temperature of an astronomical object or gas.
- The atoms/molecules of all objects with temperatures above 0 Kelvin are constantly in motion - charged particles with a very wide-range of energy are being accelerated.
- Idealized analytically by the isothermal perfect blackbody that is in thermal equilibrium.
- The emission depends only on the temperature of the body (and not its microscopic properties).
- As we've discussed before, the spectral range probed in radio astronomy corresponds to very low temperatures.

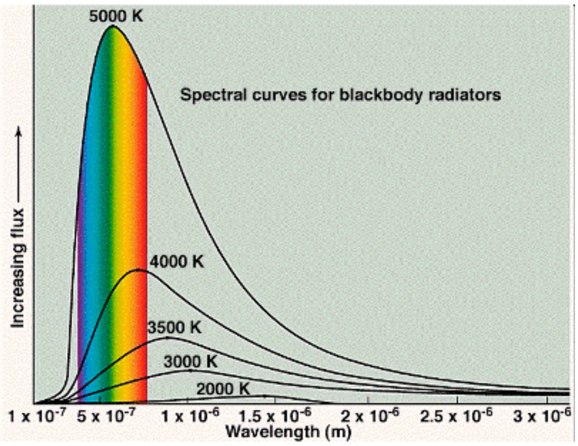
Blackbody



- A true blackbody *only absorbs* radiation and reflects none.
- Blackbody reaches a thermal equilibrium and re-radiates in the characteristic "blackbody spectrum".

• You have very likely seen the concept of an ideal black-body before. This perfect equilibrium state is an approximation, but a useful one for associating observed spectra and temperature.
• Emit some energy at *all* wavelengths.

Blackbody Radiation



- Intensity and spectrum *depends only on temperature*.
- Blackbody spectrum described by Planck's law.
- Even relatively cool objects (e.g. the Earth) peak well above the radio band (in infrared).

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

- This single blackbody equation allows us to relate the observed spectrum and the temperature of the emitter itself.

Blackbody Radiation

Steffan - Boltzmann Law: $E = \sigma T^4$

$\sigma = 5.6705 \times 10^{-5}$ erg - cm^{-2} - K^{-4} - sec^{-1}

(Steffan - Boltzmann Constant)

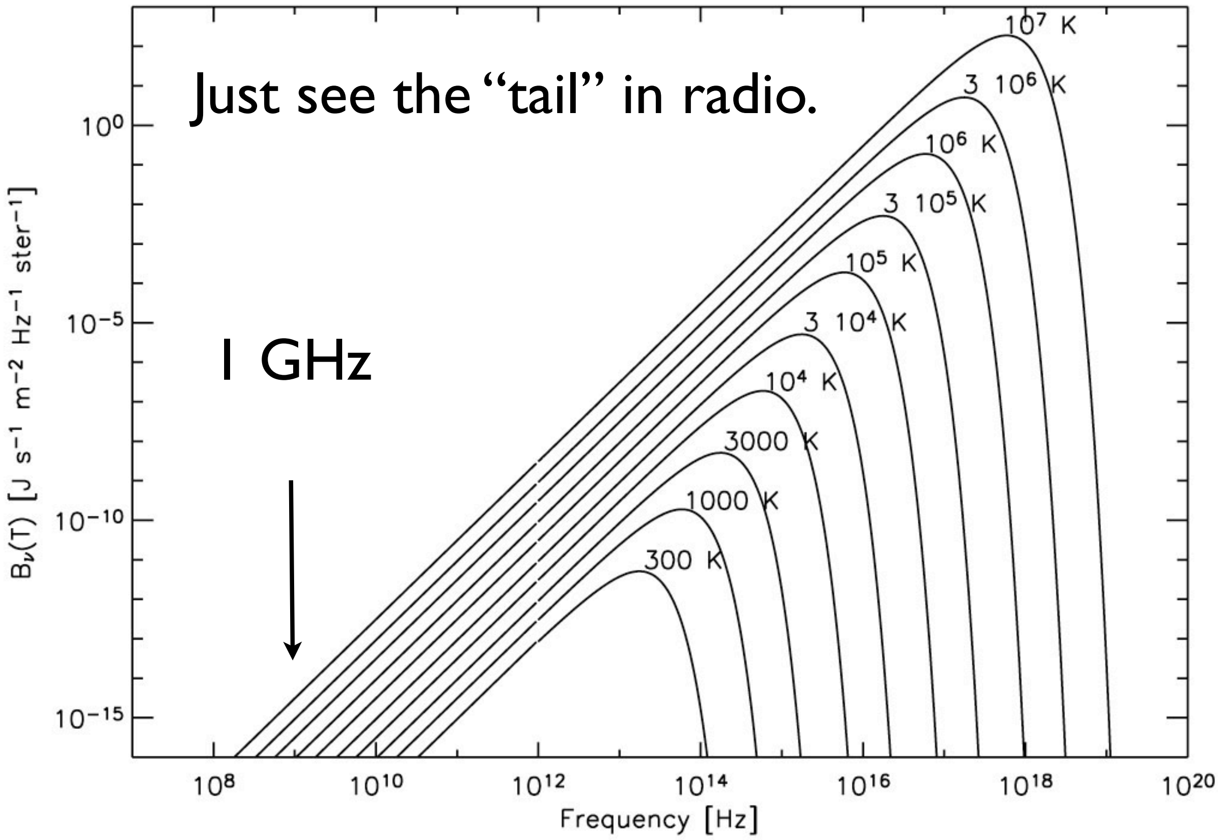
Wien Displacement Law: $\lambda_{Max} = \frac{3 \times 10^7}{T}$

(λ in Angstroms T in Kelvin)

- Stefan-Boltzman Law: total emitted energy increases rapidly with temperature.
- Wien's Law: peak frequency depends on temperature.

• Some very useful relations related to Planck's law. You've very likely seen these before.
• Stefan-Boltzmann Law allows us to relate the temperature of the emitter and the total emitted energy. This is a very steep function of temperature.
• The higher the temperature the more energy emitted - i.e. the area under the BB curve increases.
• Wien's Law: for any given temperature we can easily determine the wavelength at which the blackbody spectrum peaks.
• The higher the temperature the higher the frequency at which the maximum energy is emitted.

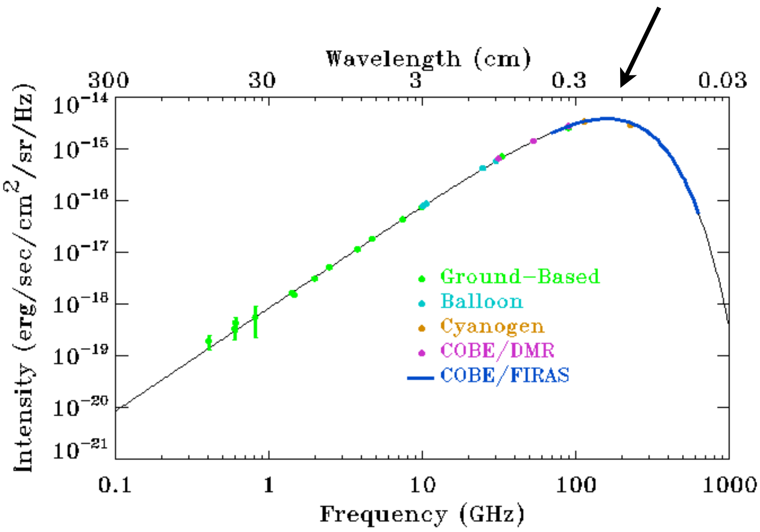
Blackbody Radiation

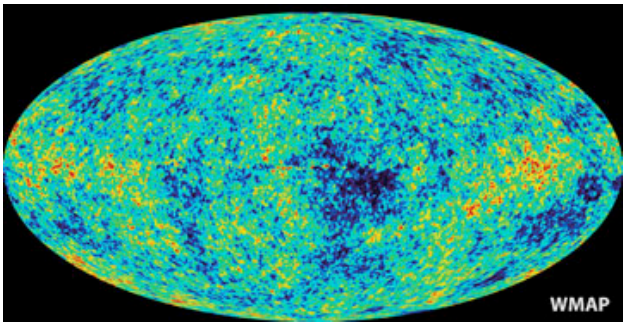


• Often in radio we can only see the tail ("Rayleigh-Jeans tail") of the blackbody radiation (and this is often well below the sensitivity of our radio telescopes anyway).
• Even objects at room temperature peak well above the radio window (even well above the 1000GHz upper frequency of ALMA).
• Thermal emitters that produce radio waves are therefore very cool, i.e. < 10 Kelvin! e.g. dark dust clouds in the Milky Way.

CMB: The Perfect Blackbody

Spectrum peaks around 200GHz

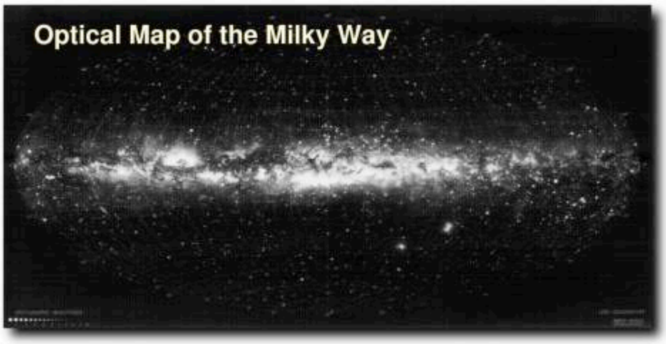


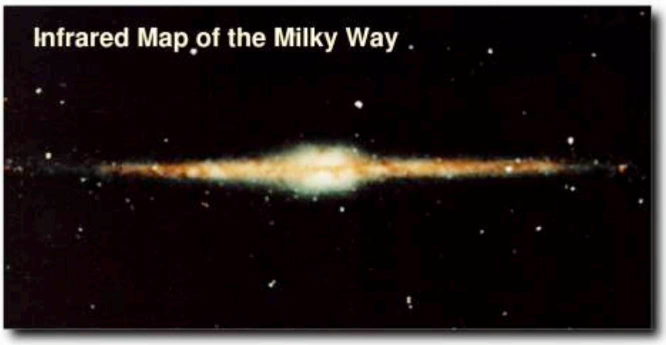


The CMBR has a thermal blackbody spectrum at a temperature of 2.72548±0.00057 K

• A big exception where the blackbody does peak in the radio band is the Cosmic Microwave Background (CMB).
• With a temperature of ~2.7K, the CMB peaks around 200GHz.
• Mapping the peak of the CMB blackbody curve has been done with COBE, WMAP and Planck - all of which were space-based radio telescopes.
• Ground-based and balloon-borne instruments have mapped the tail of the spectrum.
• In order to map the extremely subtle temperature fluctuations (the radiation is isotropic to one part in 100,000!) of the CMB, very careful calibration is needed. Even more careful calibration is needed to make an accurate polarimetric map of the variations.

Thermal Emission from Dust

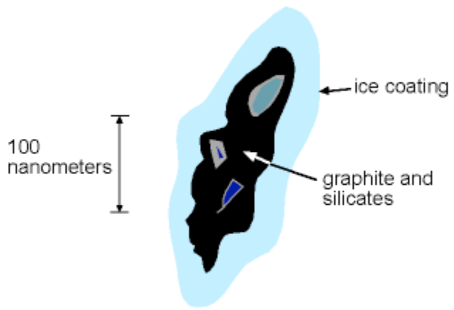




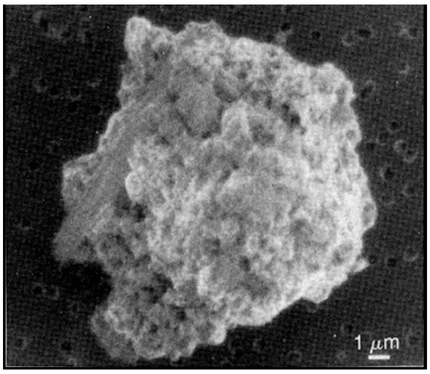
- Blackbody radio emitters are extremely cool, < 10K.
- For example, dark dust clouds in the Milky Way.
- Also dust with T ~ 50K, which is redshifted.

- Optical map of the Milky Way shows dark lanes of dust absorption in the Galactic plane.
- The corresponding infrared map shows a mostly unabsorbed picture.
- Thermal emission from this absorbing dust is detectable a radio wavelengths because it is extremely cool.
- When looking at redshifted (receding) gas, the peak of the spectrum can also be pushed into the radio band.

Thermal Emission from Dust



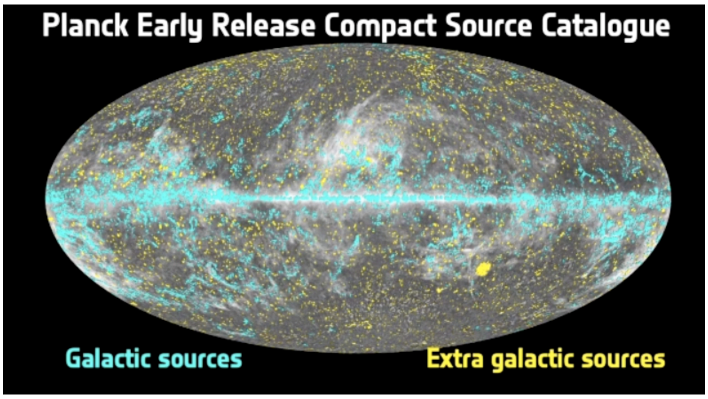
A typical dust grain (note the tiny scale!).

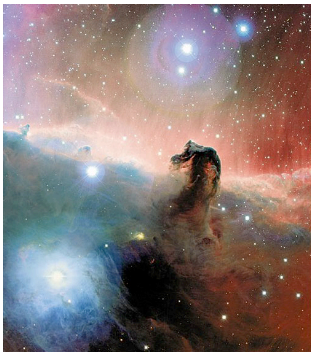


- Silicate or graphite dust grains, sometimes coated with ice.
- Average size ~0.1mm, more smaller grains, less bigger grains.
- In star-forming regions, the nebular dust can be re-heated.
- Dust radiates as a "grey body" (extra emissivity factor).

- Dust grains are made of silicate and graphite material, coated with ices in cold regions. Thermal emission from dust is common in the ISM of the Milky Way and other galaxies.
- There is a grain size distribution (more small grains, fewer large grains), with an average size of ~ 0.1 mm.
- Dust is intermixed with H_2 in molecular clouds, with $M(dust)/M(H_2) \sim 0.01$.
- The majority of dust emission is from nebulae with ongoing star formation, where the dust is heated by nearby stars.
- Such observations can trace the conditions in star-forming regions.
- The radiation is not a perfect blackbody, but rather a "grey body" because these dust grains have a non-zero albedo (i.e. some fraction of the radiation hitting them is reflected and not absorbed).
- For a single dust grain: $F(\nu) = A\ Q_{em}(\nu)\ B(\nu,T) / D^2$, where $F(\nu)$ = flux density, A=geometric cross section ($=\pi r^2$), $Q_{em}(\nu)$ is the emissivity (a modification to the cross-section term), $B(\nu,T)$ is the Planck function, D=distance to grain.
- In the case of thermal equilibrium, Kirchhoff's law states that: $Q_{em}(\nu) = Q_{abs}(\nu)$.
- $Q_{abs}(\nu) = 0$ - perfect dielectric grain - no radiation absorbed.
- $Q_{abs}(\nu) = 1$ - perfect absorber (blackbody).
- In the opt/uv, $Q_{abs}(\nu) \sim 1$ and all the radiation is absorbed and re-radiated in the FIR.

Thermal Emission from Dust

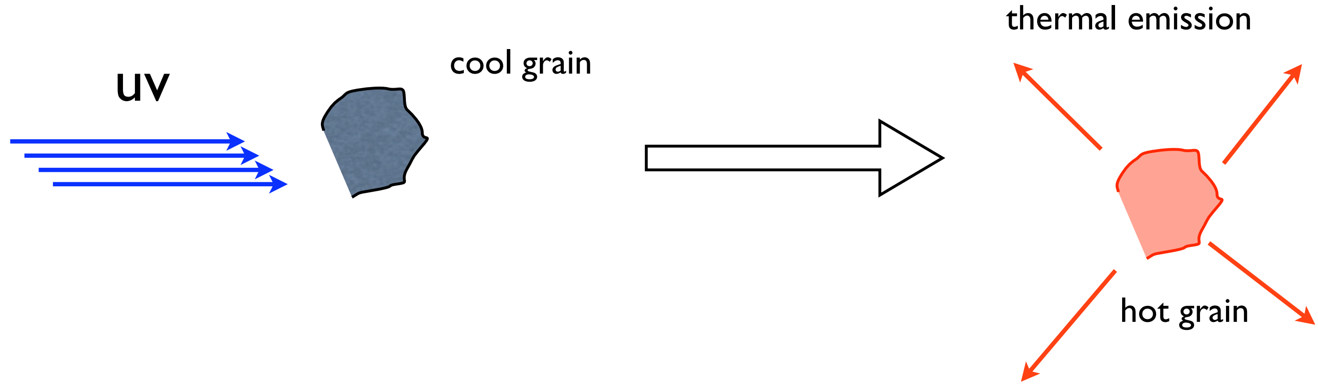




Horsehead nebula

- Can find dust in H_2 (molecular) clouds, where M(dust)/M(H_2) ~ 0.01.
- Dust emission from star-forming regions in which the dust can be heated (emit above radio band).

- Where does one find this dust?
- Can find it in molecular clouds (i.e. where stars form).
- Note that while H_2 (molecular hydrogen) makes up the vast majority of the mass, it is hard to detect directly in radio (and infrared). Instead, one typically uses CO (carbon monoxide) to trace the H_2 (see slide 28).
- Galactic dust structures are an important foreground contaminant for CMB studies (as was recently dramatically shown by the falsified BICEP2 results).
- Horsehead nebula: The dark cloud of dust and gas is a region in the Orion Molecular Cloud Complex where star formation is taking place. This "stellar nursery", as it is known, can contain over 100 known kinds of organic and inorganic gases as well as dust; some of the latter is made up of large and complex organic molecules.



Slide from M. Garrett

Dust absorption (optical) *Dust emission (FIR)*

• Cool dust grains can be heated by the stars in a star-forming region and the hot grains can then re-rediate thermally at wavelengths observable in the radio.

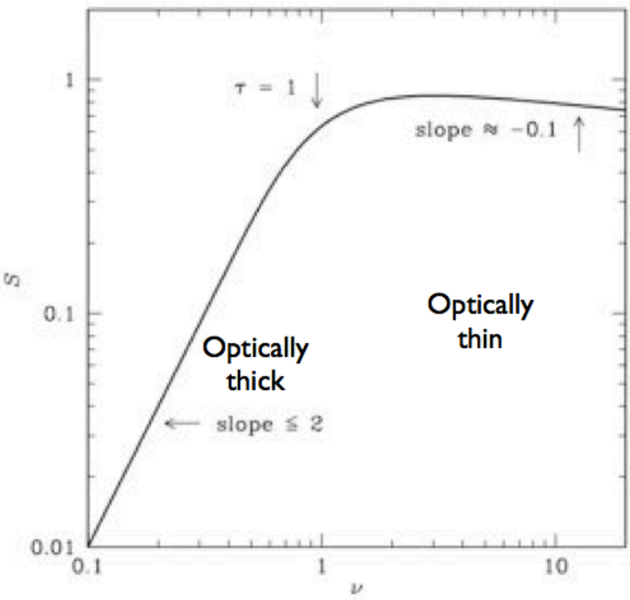
Free-Free Emission
a.k.a. thermal bremsstrahlung

Electron passing by an ion

- Consider an ionized gas (plasma).
- Such a plasma emits radiation continuously.
- Much of visible Universe is a diffuse, hot (10^4K) plasma.
- Not in thermal equilibrium. Too diffuse to absorb/emit photons regularly.

- Much of the visible universe is a diffuse, hot (e.g. 10^4K) ionized plasma - so diffuse that photons are not frequently absorbed and scattered. Such regions cannot be considered to be a blackbody.
- Switching gears, another important process is free-free emission (a.k.a. thermal bremsstrahlung) in which a free electron passes by an ion and remain unbound. This releases a photon.
- The ability of a source to absorb radiation is described by its optical depth, τ, such that the spectral flux density traveling through an absorber is reduced by a factor e^($-\tau$) i.e. $S'_\nu = S_\nu$ e^($-\tau$).
- So if S_ν decreases, T_b will also decrease. The optical depth of a diffuse ionized region varies with the source electron temperature T_e, and the frequency ν of the radiation.
- An unmagnetized diffuse, ionized source produces bremsstrahlung (free-free) emission. It is produced by the deflection (acceleration) of a charged particle (usually an electron in astrophysical situations) in the electric field of another charged particle (usually an atomic nucleus). Also referred to as free-free emission because the electron is free both before and after the deflection.

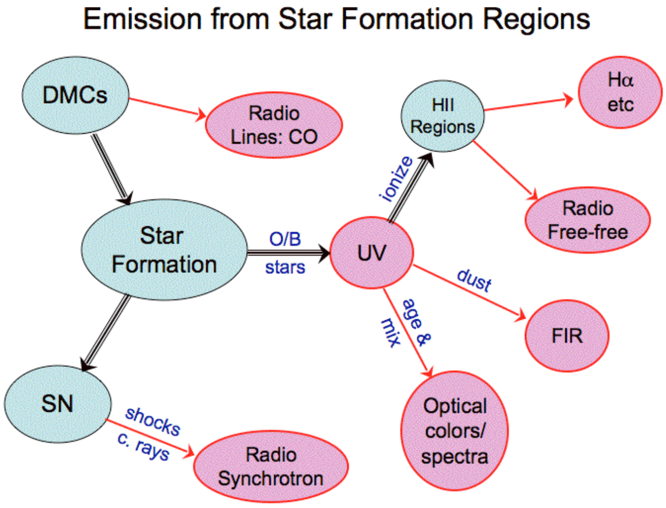
Free-Free Spectrum



- Spectrum almost "flat" (frequency independent) in the optically thin regime.
- Spectrum approaches that of a blackbody as the optical depth increases. At low-frequencies photons cannot escape easily and undergo many absorptions and emissions.

• We will not prove it here (see any standard radiation mechanisms text), but the the spectrum of free-free emission in a lightly absorbing (optically thin), diffuse ionized gas is only weakly dependent on frequency. e.g. the spectrum from a diffuse region of ionized hydrogen gas is almost flat (compared to the "steep" spectra of synchrotron sources).
• If the free-free emission can easily escape the host plasma without scattering, then it is in the optically thin regime and produces a very flat (frequency independent) spectrum.
• If the optical depth becomes large, then the spectrum turns over and approaches that of a blackbody because the photons undergo many absorptions and re-emissions.
• The turn-over frequency of the spectrum is itself a very valuable probe of the plasma conditions (e.g. density).

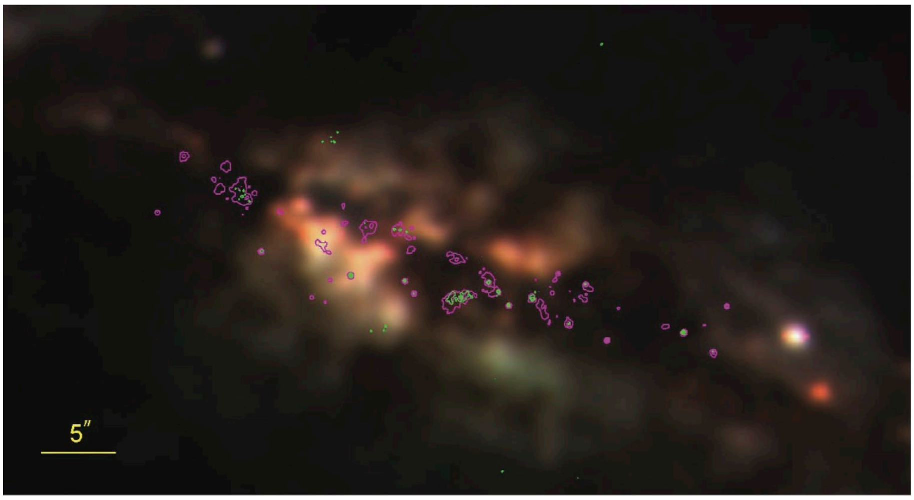
Free-Free Emission
a.k.a. thermal bremsstrahlung



- Ionized gas around star forming region.
- Ionized gas around active galactic nuclei (AGN).

• The emission from gas and plasma in (e.g.) a star-forming region is strongly influenced by the feedback from the stars imbedded in that region. A somewhat similar situation exists in the case of active galactic nuclei.

Free-Free Emission from Star-Formation Regions



M82 in radio continuum at high (~0.2") resolution. Magenta contours are 2cm emission, green contours are 7mm. Nearly all of the radio emission comes from the obscured region, shown by comparing to the false color VRI image from Spitzer SINGS, Tsai et al. 2009.

• M82 is a nearby (~4Mpc), basically edge-on starburst galaxy. It's star-forming regions are obscured in the optical by dust lanes, but can be picked out in the radio.

Spectral Line Emission

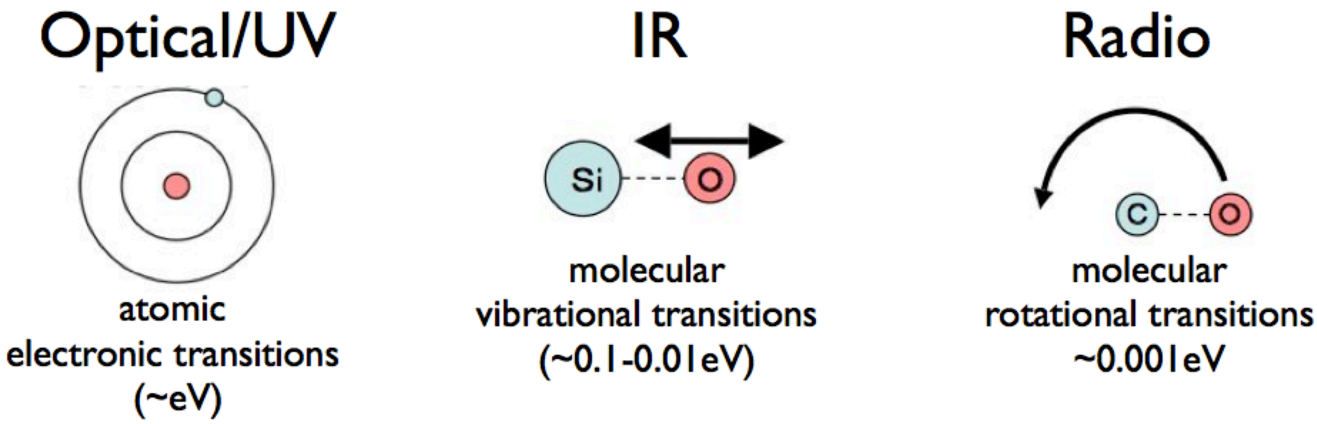
Radio Spectral Lines

Remember why emission/absorption lines are important

- Atoms and molecules have different, *quantized*, energy states.
- Measure frequency, strength, width and profile of line.
- Probe kinematic state of the emitting (or absorbing) material.
- Probe density, temperature, and relative abundance.
- 21-cm line the most famous and most important, but there are many others.

- Radio spectral lines are physical probes just like they are in optical astronomy, but the radio lines provide access to physical conditions not probed by other wavelengths.
- Remember e.g. that the 21-cm line allows us to probe the kinematics of even the far side of the Milky Way.
- Spectral line emission (and absorption) is a useful diagnostic in astrophysics because line strengths, widths, and profiles are powerful tools for determining the physical conditions (density, temperature, rel. abundance etc) and kinematic state of the gas associated with various astrophysical objects.
- Unlike the continuum processes we have considered so far in this lecture, spectral line emission occurs only at specific discrete frequencies. Line emission involves changes in the internal energy of atoms and molecules that have very specific allowed (quantized) values.
- Most spectral line emission studied in radio astronomy arises from different emission line processes that you may be familiar with at higher frequencies i.e. at NIR/Optical/UV wavelengths (e.g. quantized changes in electron energy state levels). Jumping between electron shells produces (or absorbs) photons that have an energy (frequency) that is mostly too high to fall within the radio part of e-m spectrum. Most radio emission by molecules is due to discrete rotational transitions.

Radio Spectral Lines



- Unlike optical, often dealing with molecular rotation transitions.

• In optical we're accustomed to thinking about different quantized energy levels of an electron in an atom. In radio, quantized rotational states of molecules become relevant. Note that we're talking about much smaller energies absorbed/liberated, which again is what puts us into the radio domain.

Molecular Lines

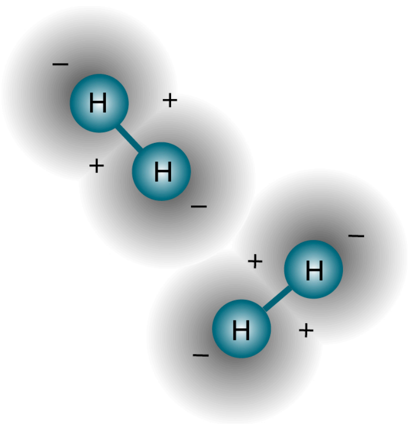
- More "complicated" than for atomic lines.
- Radio line emission results from vibrational and rotational transitions.
- About half the mass of the ISM in molecular hydrogen (H_2).
- About 1% of the cloud mass is dust, which causes extinction.
- Cloud temperatures typically 10-20K, with densities n(H_2) ~ 10^4cm^{-3}.

• As you might imagine, spectral-line emission from molecules is a lot more complicated than single atoms.
• Changes in the rotational or vibrational state, by collisions or interactions, will emit photons. Most vibrational transitions result in emission in the IR. However, rotational transmission emit photons in the mm and sub-mm domain.
• The most common atoms in the Universe are H, He, C, N, O. About half the mass of the ISM is found in molecular hydrogen. H_2 is found in molecular clouds - cool dense regions of the ISM

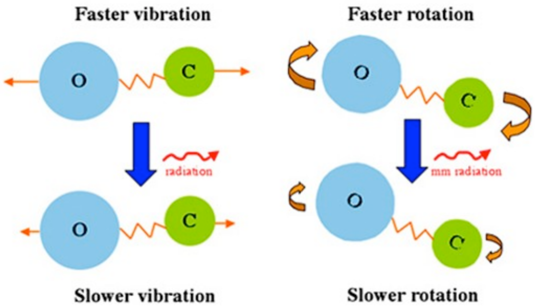
composed with temperatures of 10 to 20 K and densities of the order of n(H2) = 10^4 cm^-3 (c.f.

to a typical laboratory vacuum of n ~ 10^7 cm^-3).
• Dust particles of carbon or silicate material comprise about 1 per cent of a cloud's mass, and are the cause of extinction within the cloud.
• Molecular hydrogen is difficult to detect (it has no dipole moment), so the molecule most commonly used to trace H2 is the next most common, carbon monoxide. The ratio between CO luminosity and H2 mass is roughly constant, with a H2/CO ratio of around 10^5.
• The atoms in molecules are bound together by shared electrons. Again, electronic transitions, which occur when electrons in atoms or ions move from one orbit or energy level to another, produce high frequency photons.
• In addition, there are two other types of transitions possible – vibrational transitions and rotational transitions – which also result in line emission.

Tracing Molecular Hydrogen



- Molecular hydrogen (H_2) is hard to detect because it has no dipole moment.
- CO (carbon monoxide) is the second most abundant molecule and can be used as a tracer for H_2.
- The ratio between CO luminosity and H_2 mass is ~10^5.



The frequency of the emitted photon is:

$$\nu = \Delta E_{rot}/h = (h/4\pi)\, J/I$$

For any reasonable numbers ν lies in the mm and sub-mm domain e.g. J=1 to 0 => ν=115.2712 GHz.

Other CO tranasitions: 115, 230, 346, 461, 576, 691, …GHz

- Even though molecular hydrogen is a very significant mass component of the ISM, it is very hard to detect directly. Luckily, we can indirectly detect it (and quantize it) through emission from other molecular species, notably carbon monoxide.
- "J" quantizes the different rotational states.
- These transitions are at frequencies that are observable with ALMA.
- Most interstellar molecules are found in the dark centers of dense nebula of gas and dust where they are shielded from uv-radiation ==> spectral line emission from interstellar molecules is a good tracer of the dense, cold regions of the interstellar medium.

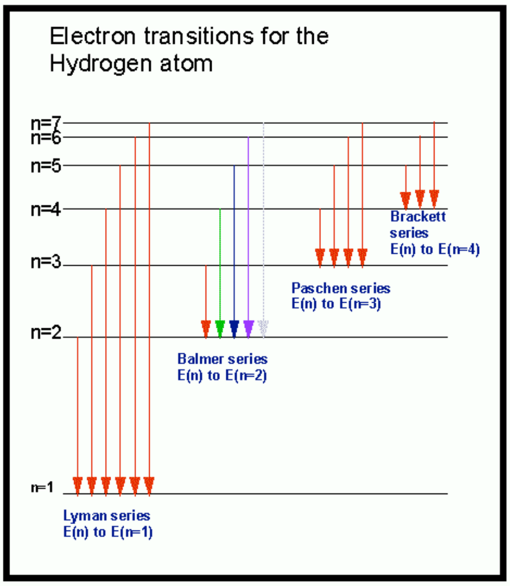
Radio Recombination Lines

$\nu = 3.3E15\ (1/m^2 - 1/n^2)$ (in Hz)

Hydrogen atom

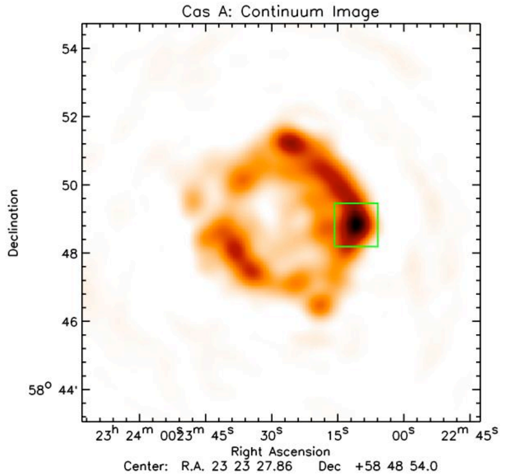
H600α: 30MHz
H109α: 5GHz
H40α: 100GHz

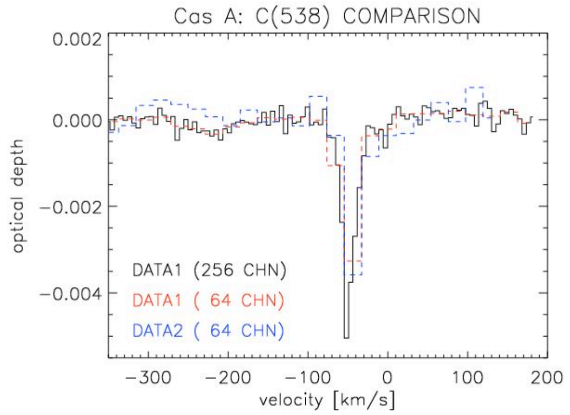
Recall α is Δn = 1
β is Δn = 2



- Radio recombination lines are electronic atomic transitions with very high quantum numbers.
- This is the only radio spectral line emission that is associated with changes in the electronic state of an atom.
- The relevant quantum numbers are so high that the photon energies/frequencies are very low and hence observable in radio.
- You'll notice in the equation above that if n and m are small numbers (the familiar case for Ly-alpha etc) the radiation occurs in the optical/uv.
- However, if m and n are large (e.g. m=176 and n=177!) the radiation will emerge at radio frequencies. This particular transition (Δn=1) would be referred to as: H176α. Transitions with Δn=2 are referred to as β transitions etc.
- This process can occur in HII regions i.e. regions of the ISM in which the Hydrogen is mostly ionized (e.g. due to uv photons produced by young star clusters in star forming regions). In some cases the electrons will recombine, and cascade downwards towards the n=1 ground state. In doing so, they can emit weak radio lines at cm and mm wavelengths.

Radio Recombination Lines

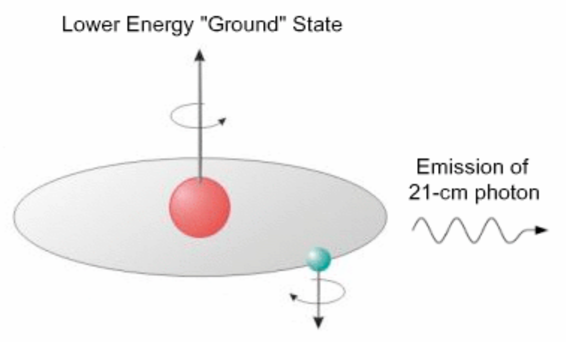




- Only radio lines that *are* due to electronic transitions.
- Quantum numbers need to be very high (> 100).
- HII can show RRLs from electrons cascading down into the ground state.
- *Weak and hard to detect:* only 0.1-1% of the continuum.
- Emerging area for LOFAR.

• While most radio lines are due to molecular vibration/rotation, radio recombination lines are due to electronic transitions.
• HII (ionized hydrogen) can show a host of radio recombination lines as electrons "cascade" down to the ground state.
• Such emission is very weak, however, so often we only see this in absorption, where an extremely bright background continuum radio source "illuminates" the intervening gas.
• Radio recombination lines are difficult to detect. Outside of the Milky Way only a handful of nearby galaxies have been detected. The main problem is that the recombination line: continuum ratio is 0.1 -1%. High spectral resolution is required with good dynamic range.
• Upgraded telescopes like the EVLA (and eventually SKA) will transform this area of research. LOFAR will be able to look for low-frequency recombination lines. Until these instruments come on line, these recombination lines do not play a big role in radio spectral line studies.

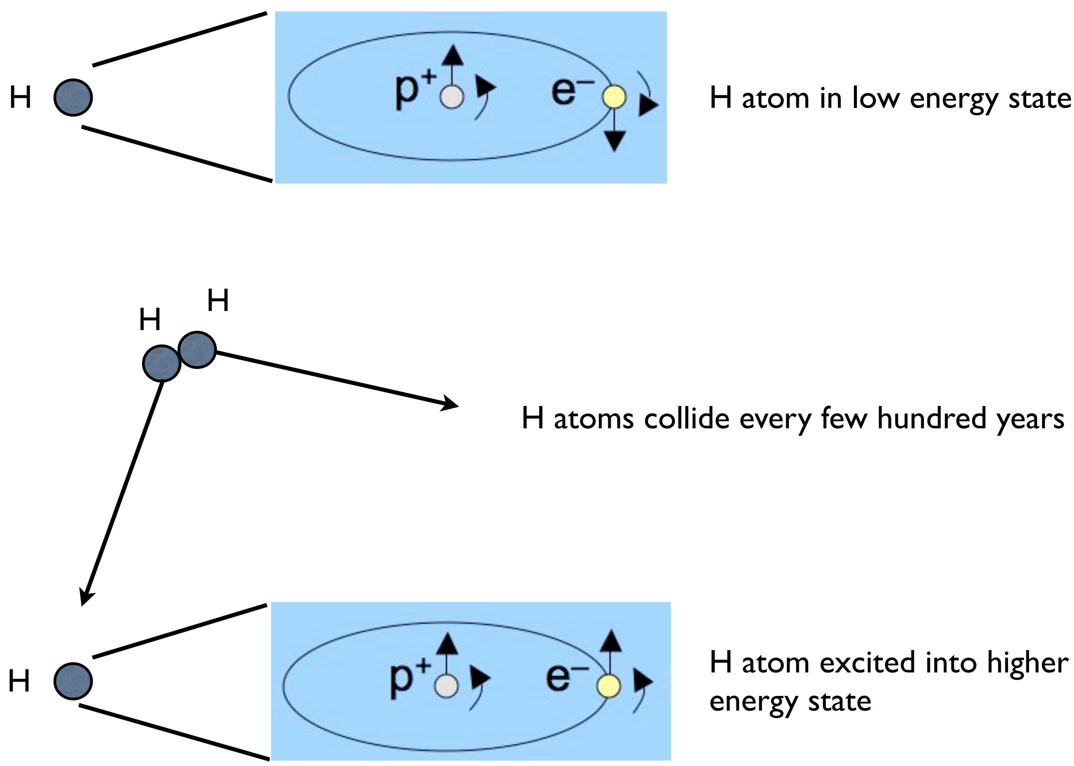
21-cm Line of Hydrogen



- Recall: hyperfine structure in hydrogen.
- Undoubtedly the most important line for radio astronomy.
- Think of protons and electrons as spinning distributions of charge each creating a magnetic field (i.e. "spin").
- Chance of Hydrogen randomly flipping its spin configuration is very low (spontaneous flipping once in ~11 million years).
- HI emission is collisionally induced (in ISM, typical timescale of ~200 years).

- The most important spectral line in the radio domain is undoubtedly the 21cm neutral hydrogen (HI) line.
- Recall that, in a hydrogen atom, the electron spin with respect to the proton spin can release/absorb a 21cm/1420MHz photon.
- Because the proton and electron are spinning distributions of electric charge they create minute magnetic fields which interact, creating a small energy difference between the state in which the poles are aligned versus counter-aligned.
- This effect is referred to as hyperfine splitting of the ground state of the Hydrogen atom.
- The very small energy difference between the 2 states (dE ~ 6 μeV) corresponds to 21cm line (ν =1420.40575 MHz).
- Flipping of the spin configuration does not happen randomly (very unlikely) but rather it is induced by collisions in the gas.

21-cm Line of Hydrogen



• A spontaneous spin-flip from the one state to another is highly forbidden with an extremely small probability (the Einstein A coefficient) A_{10} ~ 2.85E-15 s^-1. This means that the time for a single isolated atom of neutral hydrogen to spontaneously undergo this transition is 1/2.9E-15 s^-1 or around 11 million years!

• In local thermodynamic equilibrium, the population level of any two states is given by the Boltzmann equation: N_n/N_l = (g_n/g_l) e^-(ΔE/kT_s) where N_n is the number of H-atoms in the high energy hyperfine state, N_l is the number of H-atoms in the lower energy hyperfine state, ΔE is the excitation energy, and T is the excitation temperature, in the case of HI this is usually referred to as the "spin temperature", T_s.

• However, when collisions between H atoms occur, an exchange of electrons can take place, and this can lead to a random spin-flip transition with one (or both) atoms being excited to the higher (or lower) energy state. The ISM of Milky Way (and other Galaxies) is filled with a very diffuse distribution of neutral hydrogen gas which has a typical density of about 1 atom/cm3 (10^{-24} g/cm3).

• The collision rate, C_R, is just the inverse of the mean time between collisions: $C_R \sim n_H v \sigma$ (s^-1) where n_H is the H atom number density v is the mean H atom velocity and σ i the collisional cross-section of H.

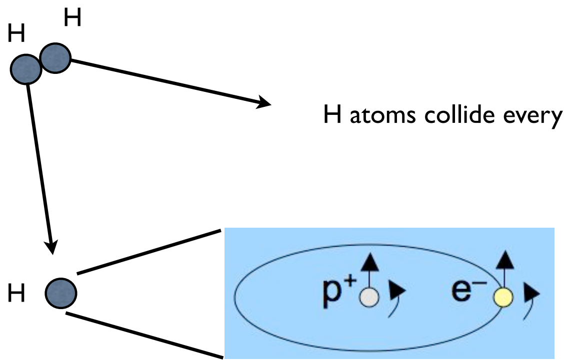
• For a typical discrete HI cloud, n_H = 10 cm^-3, T ~ 100K, σ = 1.4 x 10^-16 cm^-2 and therefore C_R ~ 1.5 x 10^-10 s^-1.

• The mean time between collisions is t_c = 1/C_R ~ 6.7E9 secs = 210 years. i.e. in the ISM Collisions occur about every 200 years (for a given atom).

• Neutral hydrogen 21cm emission is therefore collisionally induced - it depends on collisions with other neutral atoms that have random motions described by the kinetic temperature of the gas, for this transition, $T_{ex}=T_S \sim T$.

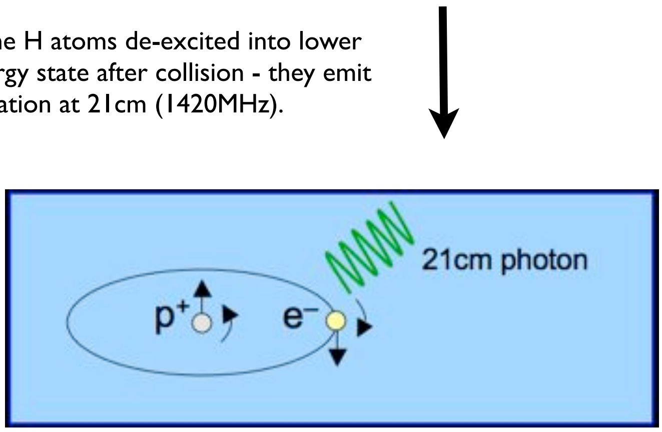
• Since the HI spin temperature is about equal to the kinetic temperature of the gas, HI measurements permit us to measure the temperature of the ISM HI gas clouds.

21-cm Line of Hydrogen



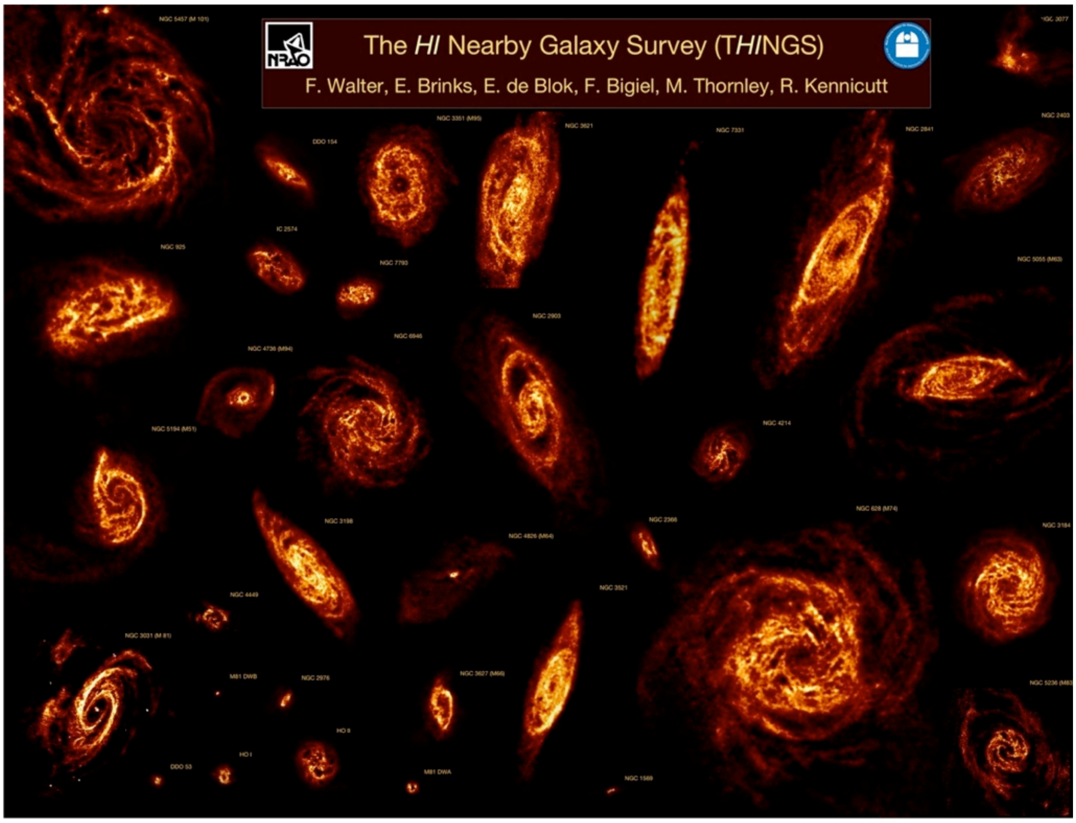
H atoms collide every few hundred years

Some H atoms de-excited into lower energy state after collision - they emit radiation at 21cm (1420MHz).



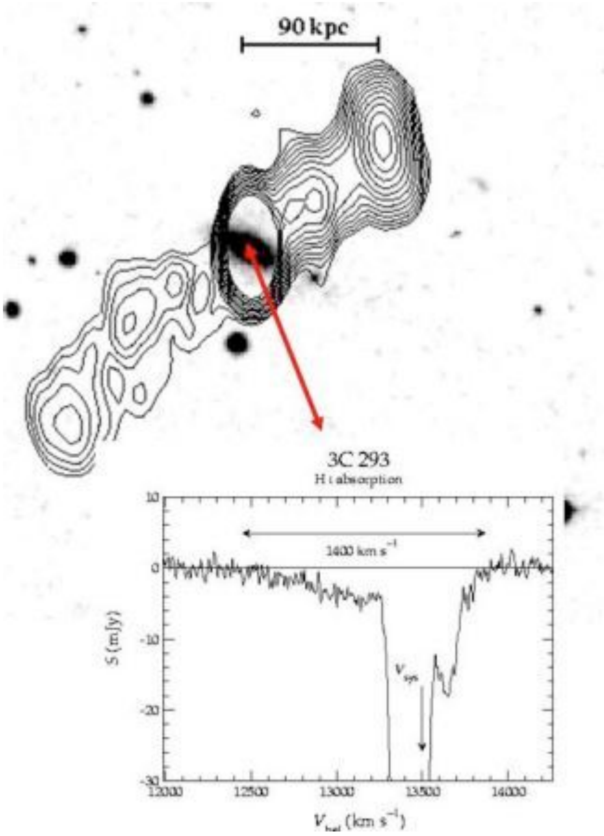
Although this transition is rare, there is just so much Hydrogen in the ISM, that 21cm line emission is ubiquitous in the Milky way and other galaxies. And since the line has an extremely small natural width (because of its long lifetime, $1/A_{10}$), broadening of the line is usually due to doppler shifts caused by the motion of the gas relative to the observer. This is useful in studying the dynamics of regions in our own and other galaxies.

21-cm Line of Hydrogen



- As an example of HI in emission in nearby galaxies: "THINGS", The HI Nearby Galaxy Survey.
- This image shows an HI composite of all galaxies observed as part of The HI Nearby Galaxy Survey (THINGS). All galaxies are shown on the same physical scale and the color indicates HI surface brightness; all galaxies have been observed using the same linear resolution (VLA D, C and B array). Galaxies include small dwarf galaxies with HI masses of 10 Million solar masses up to massive spiral galaxies with HI masses of 10 Billion solar masses. For the first time, these images show the impressive complex structures in the interstellar medium of galaxies in a wide range of galaxy environments.

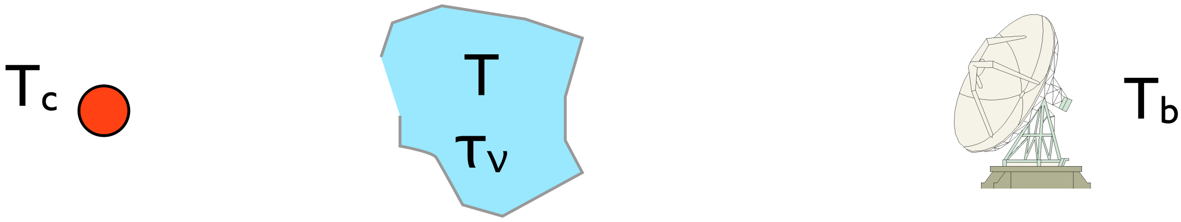
21-cm Line Absorption



• The 21-cm line is often seen in absorption and probes the intervening HI (neutral) cloud.
• Depends on temperature of background continuum source and the intervening H1 cloud.

• The 21-cm line is often seen in absorption and probes the intervening HI (neutral) cloud.

21-cm Line Absorption



$$T_b(\nu) = T_c\, e^{-\tau_\nu} + T(1-e^{-\tau_\nu})$$

The excess brightness temperature from the cloud is:

$$\Delta T_b(\nu) = T_b(\nu) - T_c = e^{-\tau_\nu} + T(1-e^{-\tau_\nu}) = (T-T_c)(1-e^{-\tau_\nu})$$

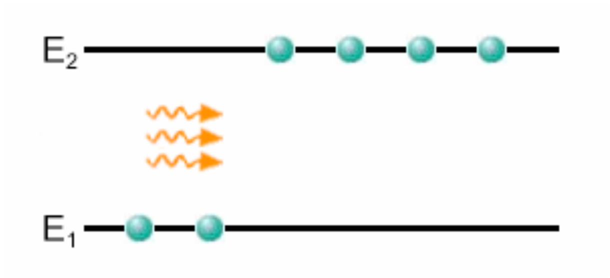
or $\Delta T_b(\nu) = T - T_c \quad (\tau_\nu >> 1)$ and $\Delta T_b(\nu) = (T-T_c)\,\tau_\nu \quad (\tau_\nu << 1)$

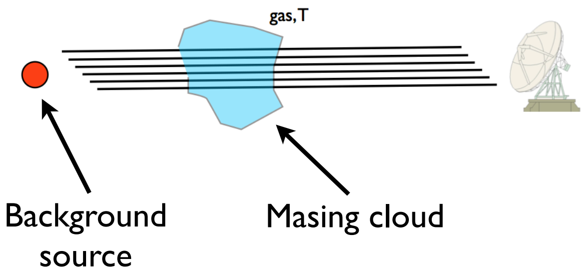
If $T > T_c$ ==> emission line; if $T < T_c$ ==> absorption line

• Consider the case where there is also background continuum emission (Tc) behind the foreground HI cloud with temperature T, optical depth $\tau(\nu)$.
• Whether one sees absorption or emission at 21-cm depends on whether the intervening cloud is hotter or cooler than the background continuum source.

MASER Emission

MASER: "Microwave Amplification by Stimulated Emission of Radiation"





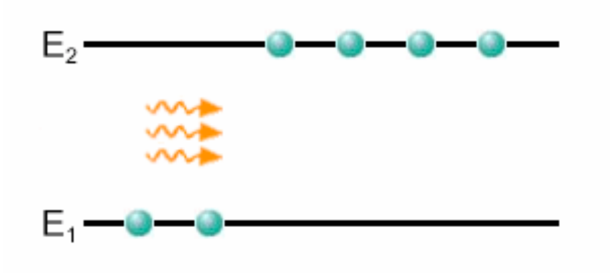
- A "radio LASER".
- Associated with molecules.
- Ensemble of molecules pumped to a higher-energy state (population inversion, E_2 not too different than E_l).
- Requires an energy source to pump the molecules.

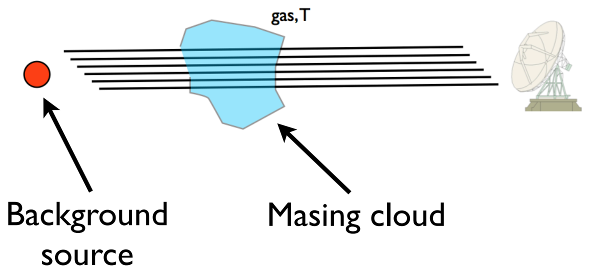
- When we're talking about amplified emission from an ensemble of molecules, then we're talking about MASER emission.
- The difference between energy state E2 and E1 is small, and hence emission will be in radio regime.
- Remember that for a gas in local thermal equilibrium, the population level of any two states is given by the Boltzmann equation: $N_n/N_l = (g_n/g_l)$ e^-(ΔE/kT).
- For any substance in thermal equilibrium at a positive (ordinary) temperature, the Boltzmann distribution requires that N_l be greater than N_n resulting in net absorption of any radiation passing through the gas. If , however, N_n is greater than N_l there are more particles that emit than those that absorb, so that the particles amplify the incoming wave.
- At radio astronomy frequencies the term e^-(ΔE/kT) is small because the energy difference between the states is small. So N_n and N_l are not very different - in other words it does not take much to induce a population inversion: $g_l N_n / g_2 N_l > 1$.
- If this happens stimulated emission > absorption and incident radiation is amplified!

- An energy source is required to create the negative temperature distribution of particles needed for a maser. This source is called the pump. In astrophysical masers the pumping mechanism can be FIR radiation from dust or collisional - many sources of maser emission are associated with star forming regions.

- The background electromagnetic waves in astronomical masers can be any weak source of radio emission that travels through the masing clouds of gas, far enough to amplify the waves enormously even on a single pass through the cloud. In star forming regions there are plenty of seed sources of radio emission.

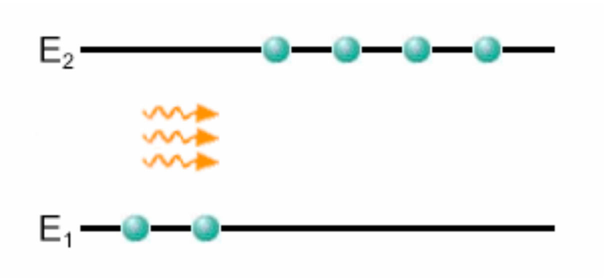
MASER Emission

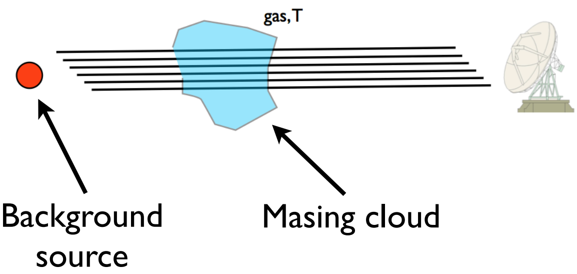




- Naturally occur in molecular clouds and the envelopes of old stars.
- Often associated with star-forming regions.
- Common lines from Hydroxyl (OH), silicon oxide (SiO), water (H_20), methanol (CH_3OH), ammonia (NH_3), and formaldehyde (H_2CO).

MASER Emission





- MASERs show:
- Month-year variability.
- Narrow line widths (< 1km/s).
- High brightness temperatures (10^{10}K).
- Are compact.
- Polarization.

List of important radio spectral lines (< 1 THz)

1. Deuterium (DI) 327.384 MHz
2. Hydrogen (HI) 1420.406 MHz
3. Hydroxyl radical (OH) 1612.231 MHz
4. Hydroxyl radical (OH) 1665.402 MHz
5. Hydroxyl radical (OH) 1667.359 MHz
6. Hydroxyl radical (OH) 1720.530 MHz
7. Methyladyne (CH) 3263.794 MHz
8. Methyladyne (CH) 3335.481 MHz
9. Methyladyne (CH) 3349.193 MH
10. Formaldehyde (H2CO) 4829.660 MHz
11. Methanol (CH2OH) 6668.518 MHz
12. Ionized Helium Isotope (3HeII) 8665.650 MHz
13. Methanol (CH3OH) 12.178 GHz
14. Formaldehyde (H2CO) 14.488 GHz
15. Cyclopropenylidene (C3H2) 18.343 GHz
16. Water Vapour (H2O) 22.235 GHz
17. Ammonia (NH3) 23.694 GHz
18. Ammonia (NH3) 23.723 GHz
19. Ammonia (NH3) 23.870 GHz
20. Silicon monoxide (SiO) 42.519 GHz
21. Silicon monoxide (SiO) 42.821 GHz
22. Silicon monoxide (SiO) 42.880 GHz
23. Silicon monoxide (SiO) 43.122 GHz
24. Silicon monoxide (SiO) 43.424 GHz
25. Carbon monosulphide (CS) 48.991 GHz
26. Deuterated formylium (DCO+) 72.039 GHz
27. Silicon monoxide (SiO) 86.243 GHz
28. Formylium (H13CO+) 86.754 GHz
29. Silicon monoxide (SiO) 86.847 GHz
30. Ethynyl radical (C2H) 87.300 GHz
31. Hydrogen cyanide (HCN) 88.632 GHz
32. Formylium (HCO+) 89.189 GHz
33. Hydrogen isocyanide (HNC) 90.664 GHz
34. Diazenylium (N2H) 93.174 GHz
35. Carbon monosulphide (CS) 97.981 GHz
36. Carbon monoxide (C18O) 109.782 GHz
37. Carbon monoxide (13CO) 110.201 GHz

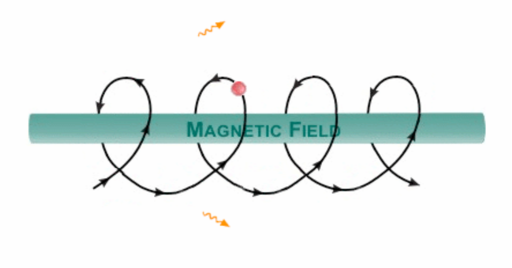
41. Carbon monoxide (C17O) 112.359 GHz
42. Carbon monoxide (CO) 115.271 GHz
43. Formaldehyde (H213CO) 137.450 GHz
44. Formaldehyde (H2CO) 140.840 GHz
45. Carbon monosulphide (CS) 146.969 GHz
46. Water vapour (H2O) 183.310 GHz
47. Carbon monoxide (C18O) 219.560 GHz
48. Carbon monoxide (13CO) 220.399 GHz
49. Carbon monoxide (CO) 230.538 GHz
50. Carbon monosulphide (CS) 244.953 GHz
51. Hydrogen cyanide (HCN) 265.886 GHz
52. Formylium (HCO+) 267.557 GHz
53. Hydrogen isocyanide (HNC) 271.981 GHz
54. Dyazenulium (N2H+) 279.511 GHz
55. Carbon monoxide (C18O) 312.330 GHz
56. Carbon monoxide (13CO) 330.587 GHz
57. Carbon monosulphide (CS) 342.883 GHz
58. Carbon monoxide (CO) 345.796 GHz
59. Hydrogen cyanide (HCN) 354.484 GHz
60. Formylium (HCO+) 356.734 GHz
61. Dyazenulium (N2H+) 372.672 GHz
62. Water vapour (H2O) 380.197 GHz
63. Carbon monoxide (C18O) 439.088 GHz
64. Carbon monoxide (13CO) 440.765 GHz
65. Carbon monoxide (CO) 461.041 GHz
66. Heavy water (HDO) 464.925 GHz
67. Carbon (CI) 492.162 GHz
68. Water vapour (H218O) 547.676 GHz
69. Water vapour (H2O) 556.936 GHz
70. Ammonia (15NH3) 572.113 GHz
71. Ammonia (NH3) 572.498 GHz
72. Carbon monoxide (CO) 691.473 GHz
73. Hydrogen cyanide (HCN) 797.433 GHz
74. Formylium (HCO+) 802.653 GHz
75. Carbon monoxide (CO) 806.652 GHz
76. Carbon (CI) 809.350 GHz

- This huge list isn't even nearly complete. e.g. it doesn't include the radio recombination lines (due to electronic transitions in atoms).
- Spans the whole radio window from 10s of MHz up to 1000 GHz.

Non-thermal Emission Processes

• Non-thermal emission: emission that does not depend on the sources temperature, e.g. synchrotron emission (charged particles being accelerated in a strong magnetic field).

Non-thermal Emission



• Emission increases towards longer wavelengths.
• Synchrotron is the most common mechanism.
• Electrons (typically) accelerated by magnetic field.
• First identified in the 1940s as an interfering signal in particle accelerators.

• Particle acceleration is at the root of non-thermal emission, and this often involves magnetic fields.
• Spectrum is such that the emission becomes stronger towards lower frequencies (opposite to the Rayleigh-Jeans tail from thermal blackbody emission).
• Since the electrons move in a helical path they are being accelerated, and therefore radiate e-m radiation. This mechanism was first observed (as a nuisance) in particle accelerators in the 1940's.

Grote Reber

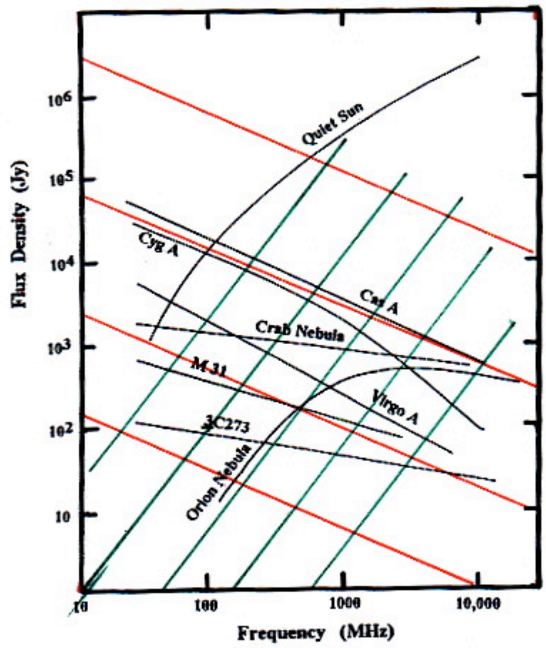
(1911-2002)

- Mystery of low-energy (non-thermal, synchrotron) emission.
- Also the beginning of high-energy astrophysics. (radio astronomy is high-energy astrophysics!)

• Recall from the first lecture that Grote Reber's early work in measuring radio source spectra surprisingly revealed that they were getting brighter towards lower frequencies.
• In fact, he had to switch to receivers at increasingly low frequency before he could make his first detection.

Thermal / non-thermal

Non-thermal $S \propto \nu^{-0.8}$ (synchrotron with $N(E) \propto E^{-2.6}$)



Thermal $S \propto \nu^2$ (blackbody)

• We saw this in Lecture 1 as well. This shows the radically different spectra of some well-known thermal and non-thermal astronomical sources.
• Radio sky is dominated by non-thermal emission at metre and centimetre wavelengths.
• Simply measuring the spectral index of power-law continuum emission can tell you a lot about the physical mechanisms at play.

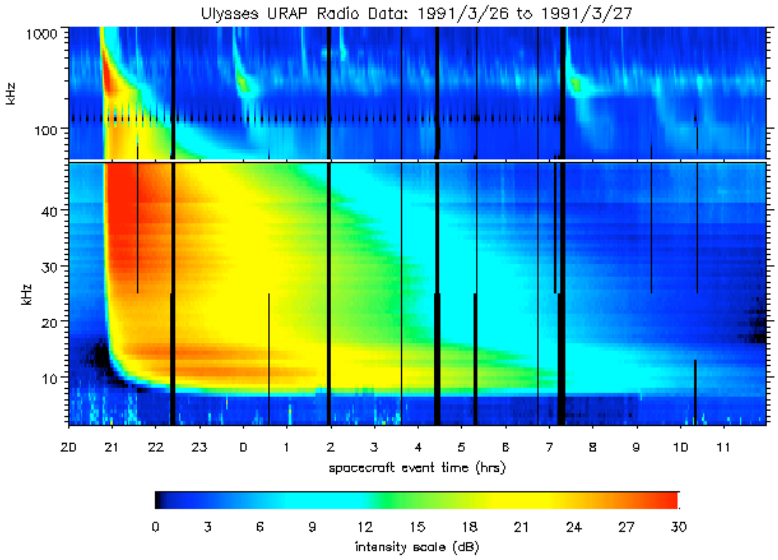
Cyclotron Emission

Derive
Cyclotron frequency

- Non-relativistic case of an electron spiraling along magnetic field lines.
- ISM typically has B = microGauss fields.
- Cyclotron (gyro) frequency of ~3Hz in ISM (not observable radio emission).

- Let's consider first the non-relativistic case of an electron spiraling in a magnetic field. This is known as cyclotron radiation.
- If we equate the magnitude of the Lorentz force (F = q[E + (v x B)]) on the electron with the centripetal force we have: e v B = m_e v^2 / r_L or rearranging r_L = m_e v / (e B) where e=electron charge, B=magnetic field, m_e = mass of the electron, v= electron velocity and r_L is the Larmor radius.
- The period of 1 electron "orbit" (the "gyro-period") is just: T = 2π r_L / v = 2π m_e /(eB).
- Note that this does not depend on the velocity (energy) of the electron.
- And the angular electron gyro-frequency, ω_G, is: 2π/T = eB/ m_e ~ 18E6 rad/sec x B (Gauss)
- Since $\nu_e = \omega_G/2\pi$ the electron cyclotron frequency in MHz is: ν_e ~ 2.8B
- For a magnetic field typical of the Interstellar Medium (ISM) in our own galaxy (B ~ microGauss) ==> ν_e ~ 3 Hz.
- Since the radiation field varies with the same frequency as the gyro-frequency, such cyclotron radiation in the Interstellar Medium (ISM) does not generate observable radio emission.

Cyclotron Emission

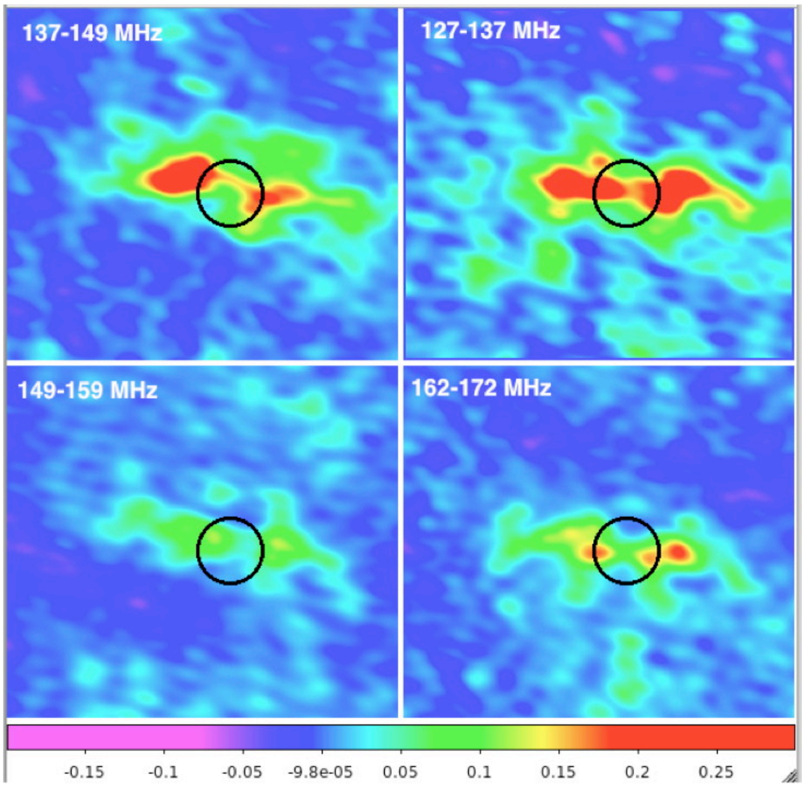


Sun (below 1MHz)

- Higher B-field in Earth (~1G), Sun (~300G), Jupiter and Saturn.
- Magnetic stars.
- *Much* higher B-fields in white dwarfs (10^6G) and neutron stars (10^{8-15}G).

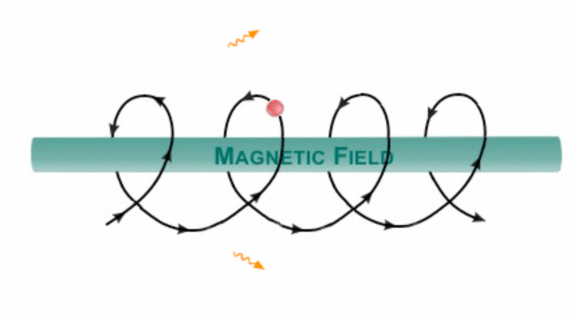
• Places where the magnetic fields are strong enough to produce observable radio emission from the gyro-cyclotron process include compact objects with strong magnetic fields e.g. pulsars (though this does not fully explain the coherent pulsar emission process).
• Strong cyclotron radio emission is also observed at low- frequencies from the Sun (B ~ 300 Gauss), Jupiter and Saturn. Magnetic stars (e.g. AM Herculis stars) also exhibit cyclotron radiation.

Cyclotron Emission



- Jupiter radiation belt with LOFAR.

Synchrotron Emission



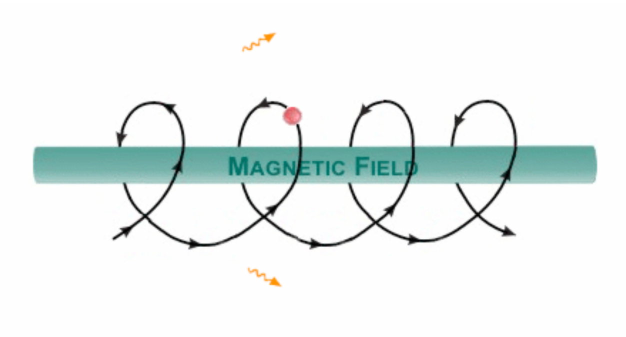
$m = \gamma m_e$

where $\gamma = (1-(v/c)^2)^{-1/2}$

- Acceleration of (ultra-) relativistic charged particles (typically electrons) in a magnetic field.
- Particles spiral along magnetic field lines.
- Emission frequency related to velocity of the particle.
- Electrons need to be traveling relativistically to be detectable astronomically (cyclotron radiation typically not detectable).

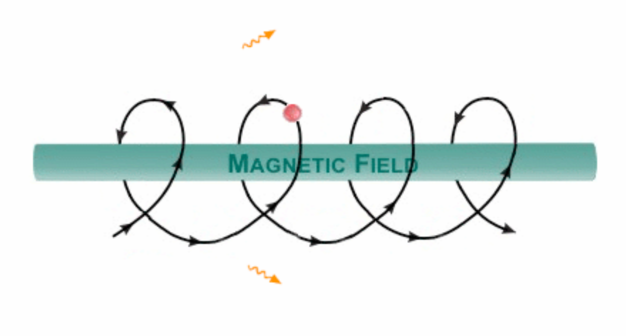
- Synchrotron emission is associated with the acceleration of *relativistic* and *ultra-relativistic* electrons in a weak magnetic field.
- If the electrons are relativistic, then the energy emitted does not depend *only* on the magnetic field (see previous cyclotron equation) but also on the energy of the electrons themselves.
- How does energy enter in the case of synchrotron emission ? The key point is that we no longer deal with the rest-mass of the electron, with electron velocities v ~ c we must consider the relativistic mass (see equations above).
- Note that it's beyond the scope of the course to discuss synchrotron emission in gory detail, but we will now touch on some of the most important points.

Synchrotron Emission



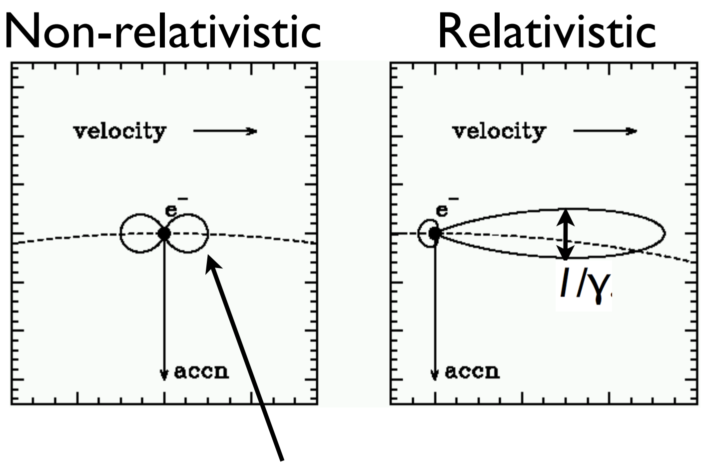
- Relativistic particles mean that the emitted energy does not depend purely on the B-field (see Cyclotron emission) but also on the energy of the particles (electrons) themselves, b.c. relativistic mass.
- Power-law spectrum.
- Spectrum describes the energy distribution of the seed electrons.

Synchrotron Emission



- To maintain synchrotron emission, a continuous supply of relativistic electrons is necessary.
- Typical energy sources include supernova remnants, quasars, or other types of active galactic nuclei.
- Signal is polarized because of magnetic directionality.

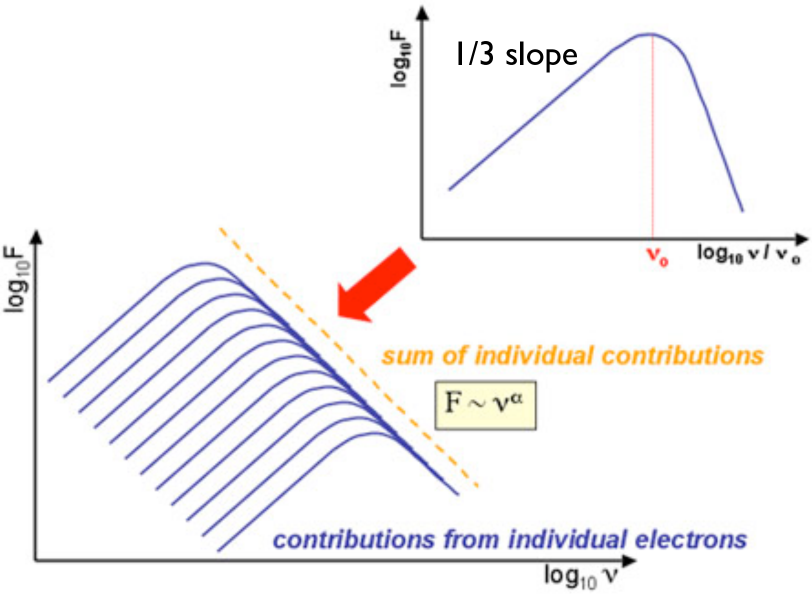
Synchrotron Emission



• Relativistic motion causes beaming (opening angle related to the Lorentz factor).
• Lorentz factor boosts the emission frequency into the observable radio range (even for a weak B-field).

• When the electron is relativistic, the normal dipole power pattern of the electron becomes beamed in the direction of motion.
• The radiation is relativistically beamed (squashed) in the direction of the observer into a narrow cone of angular width $1/(\gamma)$.

Synchrotron Spectrum



- Powerlaw.
- Observed spectrum is a superposition of the individual electron spectra.

• If all electrons had the same velocity (energy distribution) the synchrotron spectrum would look something like the top plot.
• The spectrum of a single electron has a logarithmic slope of 1/3 at low frequencies, a broad peak near the critical frequency ν_{max}, and falls off sharply at higher frequencies.
• In practice, the electrons have a wide range of energies. Like cosmic rays, the energy distribution of

electrons radiating in synchrotron sources also appears to follow a power-law: $N(E) \propto E^{-\beta}$ where $\beta \sim 5/2$.
• $N(E)dE$ = number of particles with energy E to E+dE.
• If a synchrotron source containing any arbitrary distribution of electron energies is optically thin ($\tau \ll 1$), then its low-frequency spectrum is the superposition of the spectra from individual electrons.

• The total power from an ensemble of relativistic electrons $P(\gamma)$ is proportional to: $P(\gamma) \propto P_e(\gamma) N(\gamma) \propto \gamma^2 \gamma^{-\beta} \propto \gamma^{(2-\beta)}$.
• To see how the total power is related to observables (e.g. observing frequency) we note that: $P(\gamma) = P(\gamma)\, d\gamma/d\nu \propto \gamma^{(2-\beta)} \gamma^{(-1)} \propto \gamma^{(1-\beta)} \propto \nu^{(1-\beta)/2}$
• Since the Flux Density S is proportional to P, related to observing frequency we note that: $S(\nu) \propto \nu^{(1-\beta)/2}$. Which for $\beta \sim 5/2$ gives $S(\nu) \propto \nu^{(-0.75)}$.
• This "steep spectrum" is very close to what we observe in many (but not all!) radio sources.

Synchrotron Spectrum

Strong dependence on the Lorentz factor

$$\nu_{max} = \nu_e \gamma^2 \qquad P_e \sim 2\,\gamma^2\, U_{mag}$$

Larger B-field increases the emission frequency and energy loss rate

$$\nu_{max}\ \alpha^{al}\ E^2 B \qquad dE/dt\ \alpha^{al}\ E^2 B^2$$

Power-law distribution of electron energies

$$N(E)\ \ \alpha^{al}\ E^{-\beta} \quad \text{where } \beta \text{ is} \sim 5/2$$

Power-law (photon) spectrum

$$S(\nu)\ = \alpha^{al}\, \nu^{(1-\beta)/2} \qquad S(\nu)\ \ \alpha^{al}\ \nu^{-0.75} \quad \text{For } \beta = 5/2$$

• In addition, the frequency of the radio emission is no longer independent of energy and becomes concentrated into a narrow frequency range at a characteristic frequency ν_{max} where it radiates most of its energy: $\nu_{max} = \nu_e\ \gamma$^2.

• Since (γ >> 1) this boosts the emission frequency of synchrotron emission into the radio domain.

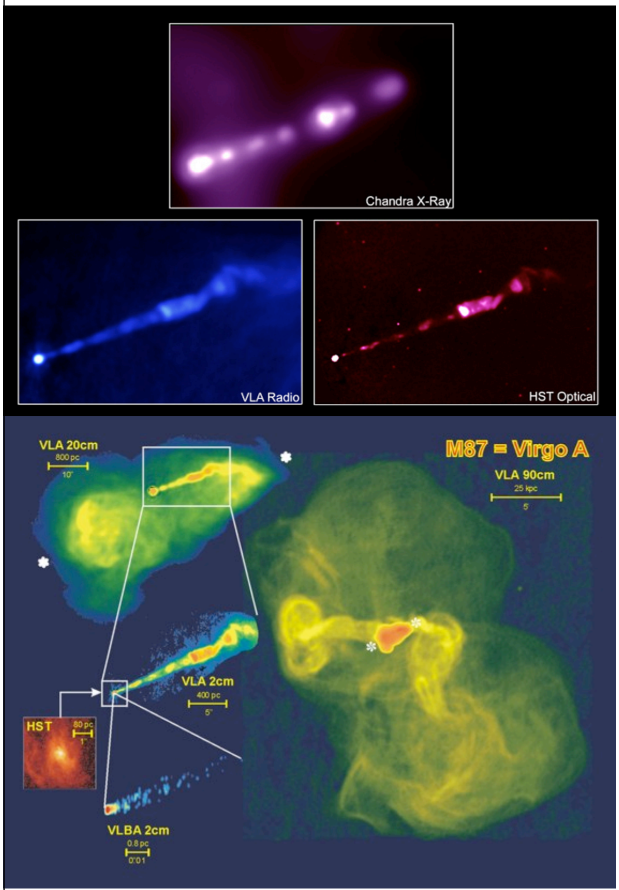
• e.g. an electron with an energy of 10GeV accelerating in the galactic magnetic field (B ~ 3E-6 Gauss) radiates most of its energy at 10 GHz.

• P_e is the radiated power of a single electron. Note also that P = dE/dt.

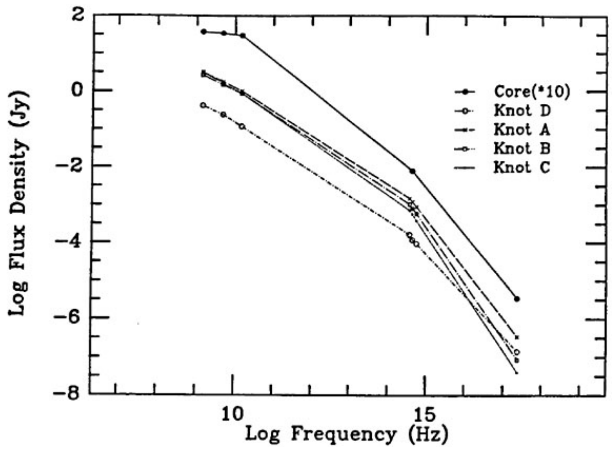
• U_{mag} is the magnetic energy density = B^2/8π.

• Increasing B causes particles to radiate at higher frequencies and to lose energy more quickly.

Synchrotron Emission

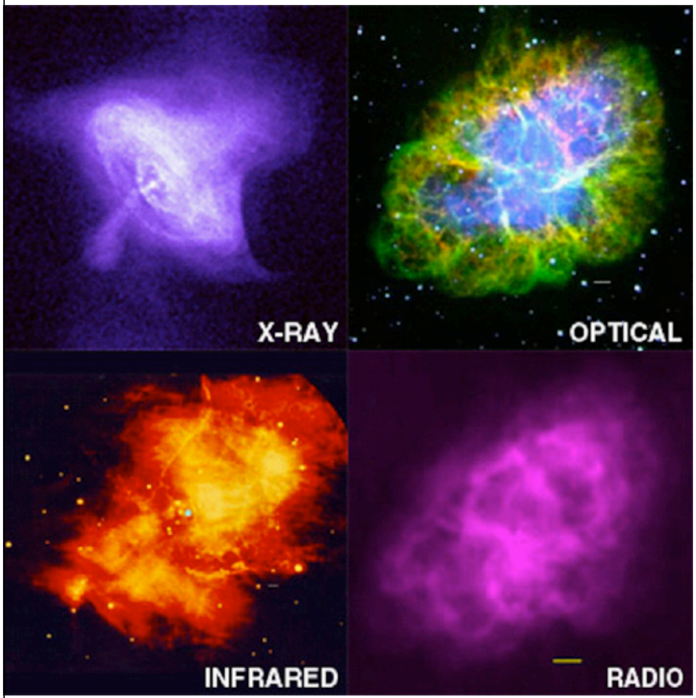


- Multi-wavelength synchrotron emission from an AGN jet.
- Reflects the power-law electron energy distribution.



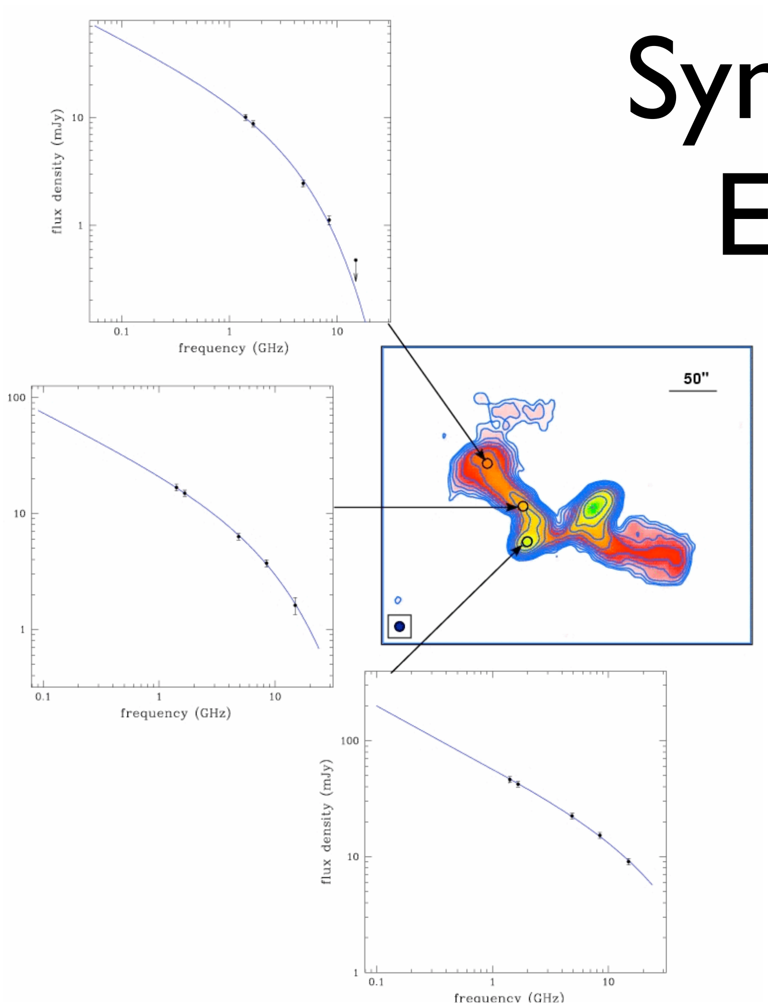
- Synchrotron emission is not only important at radio frequencies but it is observed in (e.g.) AGN at IR, optical, UV and even X-ray wavelengths.
- Synchrotron emission observed in Virgo-A (M87). Note that the morphology of the synchrotron jet is basically the same at each waveband.
- The spectrum of the source across these wavelengths is a steep power- law and reflects the power-law that describes the energy distribution of the electrons.

Synchrotron Emission



- Another example of multi-frequency synchrotron.
- Spectral aging: high-energy electrons, emitting at the highest frequencies, lose energy more quickly (E vs. E^2).
- Causes an extra steepening at the highest frequencies.

• Note that synchrotron radiation is also observed in the optical and X-ray domain, not only in AGN but also in SNR e.g. the crab nebula in our own galaxy.
• The bluish glow from the central region of the Crab Nebula is due to synchrotron radiation. Since optical light has ν ~ 10^8 MHz, that means the Lorentz factor is γ ~ 10^6.



Synchrotron Emission

- Spectral aging in the radio galaxy NGC326.
- The loss of energy is fastest for those electrons that have the highest energies and emit at the highest frequencies. In “old” sources, this leads to an even steeper observed spectrum and is referred to as “spectral aging”.

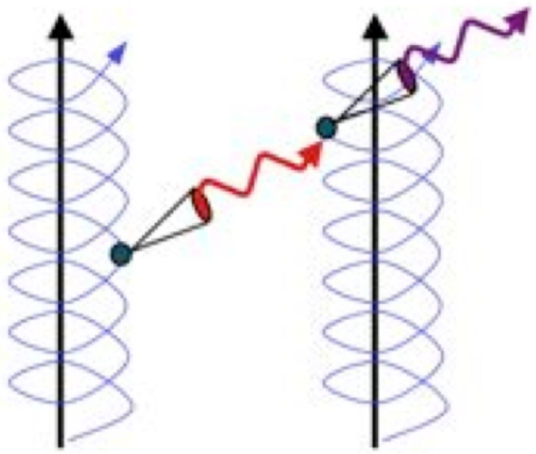
• As we have seen, the loss of energy is fastest for those electrons that have the highest energies and emit at the highest frequencies. In “old” sources, this leads to an even steeper observed spectrum and is referred to as “spectral aging”.

• The energy loss rate is α γ^2 B^2 so the energy loss time scale E/(dE/dt) α 1/(γ B^2).
• In fact, the lifetime of an electron being accelerated in a magnetic field is given by: t ~ 2.5 x 10^13/(γ B^2) years (B in microgauss).

• e.g. for a 100 GeV electron in the ISM of a normal galaxy B ~ 1 microGauss , t ~ 10^8 years.

• For a radio galaxy, (=10^4 and B ~ 200 microG, t ~ 150000 years.
• If we compare this to the physical extent of the radio jets in many AGN this lifetime is much shorter than the dynamical age of the radio source. Therefore there must be a continuous injection of relativistic electrons into the jet that continuously fuels the lobes.
• Radio spectra sometimes curve downward at higher frequencies (i.e., the spectral index α increases - becomes steeper - as ν increases). The basic reason for this is that the electrons radiate at frequencies proportional to their energy E, and the rate at which they lose energy is proportional to E^2. Thus, the highest-energy electrons radiate away their energy the most rapidly, thus depleting the emitted spectrum at the high-frequency end first, if no replenishment of the high-energy electrons occurs.
• Shown above: radio image of the galaxy NGC 326 and radio spectra of selected regions in the source. The total intensity is plotted as blue contours. The color coding refers not to the intensity of the radio emission but to its spectral index (red indicates very steep spectral index, green flatter spectral index). The different curvatures of the spectra can be used to infer the different ages of the various parts of the radio galaxy: stronger curvature indicates older radio emitting material. Note that outer regions are, as expected, older than the inner parts - Courtesy of M. Murgia.

Synchrotron Self-Absorption

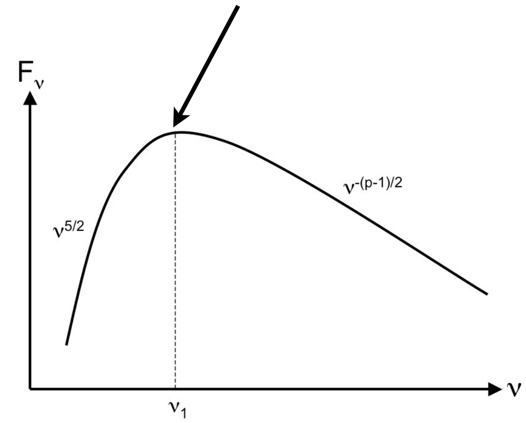


• Principle of "detailed balance": any mechanism that can emit radiation can also absorb it.
• What happens to the steep power-law spectrum of synchrotron radiation at lower and lower frequencies (can't increase forever)?
• Happens in compact sources at low frequencies (i.e. when they become optically thick).

• Following the principle of "detailed balance", any mechanism that can produce radiation can also absorb it. Thus the synchrotron mechanism can also be an absorption mechanism.
• Previous slides might make it appear that at low frequencies the flux density of synchrotron radio sources will increase without limit. However, as the intensity of the synchrotron radiation within a source becomes sufficiently high, the spiraling electrons begin to reabsorb the low-energy photons. In particular, this can occur in radio sources which are compact (e.g. AGN with size << 1 kiloparsec) and have very high synchrotron electron densities i.e. they become optically thick at lower frequencies.
• This re-absorption of radiation is termed as 'synchrotron self absorption' and it can significantly modify the overall spectrum of the source at low frequencies.

Synchrotron Self-Absorption

Turnover frequency



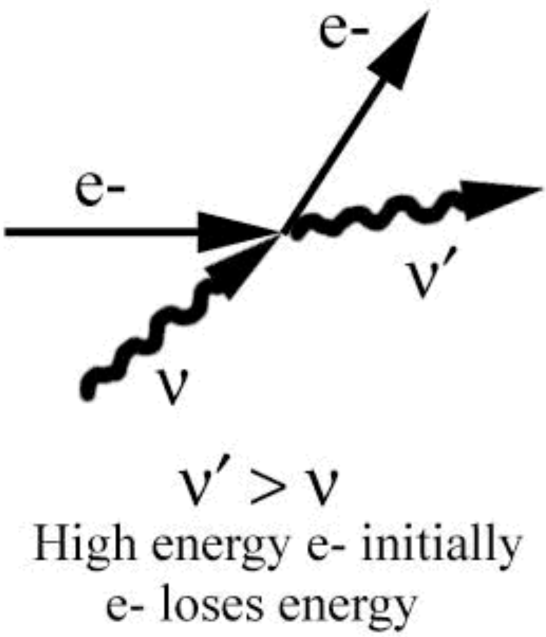
Optically thick

Optically thin

- When the brightness temperature becomes equal to the electron temperature, the source becomes opaque.
- A self-absorbed source has a 5/2 power-law spectrum.
- Turnover frequency related to electron density.

- It turns out that at a sufficiently low radio frequency e.g. ~ 100MHz, the brightness temperature T_b of any synchrotron source will approach the effective electron temperature T_e. At that frequency the source will become opaque.
- The turn-over frequency increases with the density of relativistic electrons in the source, although it depends on other parameters as well.
- For an ultra-relativistic gas, E ~kT_e, and so: T_e α E α γ
- And since ν_{max} ~ ν_e γ^2 : T_e α ν^(1/2).
- Remembering that: I_ν =2kT_bν^2/c^2 and setting T_b ~ T_e we then see that I_ν α ν^(5/2).
- Thus the spectrum of a synchrotron self-absorbed source is a power law of slope 5/2.

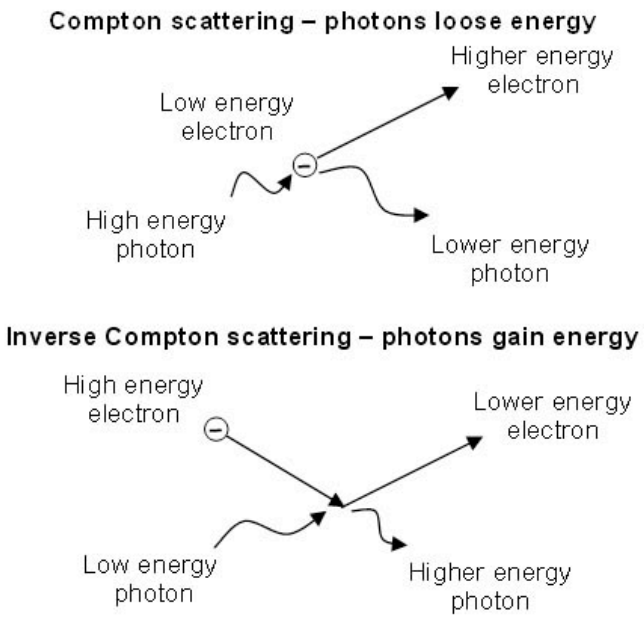
Inverse Compton Scattering



- Low-energy photons scattered to higher energies by relativistic electrons.
- Seed photons from, e.g., the CMB.
- Observed near synchrotron sources (sources of relativistic electrons).

• Inverse Compton emission is also relevant to radio astronomy studies (and also at higher frequencies e.g. X-ray production). It occurs when lower energy (frequency) photons are scattered to higher energies (frequencies) by relativistic electrons. Since synchrotron sources contain relativistic electrons by definition, inverse Compton is expected to be observed in this kind of source environment.

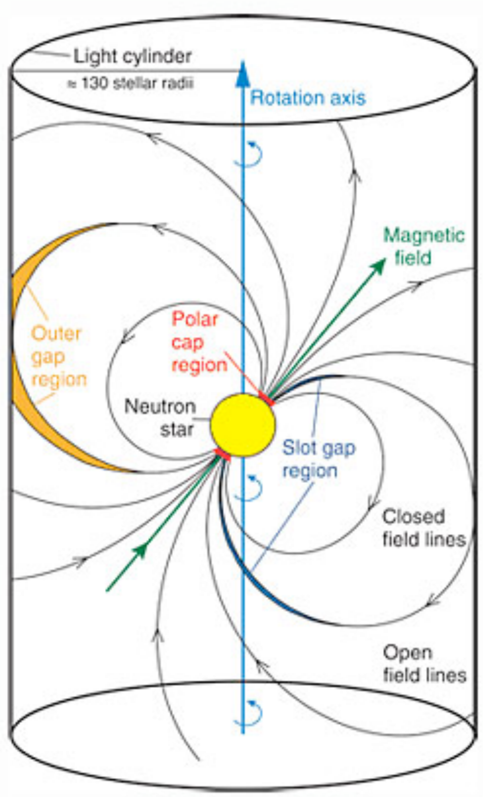
Synchrotron Self-Compton



- Synchrotron emission provides the low-energy photons that can be up-scattered by other relativistic electrons.
- Photon scattered by a relativistic electron increases its energy by the Lorentz factor squared.

- The low-energy photons have a variety of potential sources e.g. they may belong to the cosmic background radiation or alternatively they may found in synchrotron radio sources themselves i.e. the synchrotron photons emitted by the energetic electrons. The latter process is called the synchrotron self-Compton process.
- As the electrons have a wide range of energies (the same power-law distribution as noted before), the radiation emitted covers a wide (continuum) frequency range.
- N.B. A photon scattered by an electron with Lorentz factor γ, increases its energy by γ^2.
- This means that a radio photon in synchrotron source can find itself up-scattered by a factor of ~ 10^8 i.e. into the X-ray region of the EM-spectrum!
- In the case of compact AGN, the self-Compton mechanism is believed to be more important than synchrotron radiation losses as responsible for cooling the relativistic electron population.
- The mechanism limits the brightness temperature of radio sources to Tb ~ 10^12 K.

Pulsar Emission



- Enormous brightness temperatures.
- Exact emission mechanism still eludes us.
- Must be a coherent process.
- Emits pulsations from low-frequency radio up to GeV gamma-rays.
- See lecture 9 for more details.

• The exact emission mechanism for radio pulsars remains elusive, but it is clear that it must be some kind of coherent emission mechanism because the inferred brightness temperatures are well above 10^12 K.

Propagation Effects

Propagation Effects

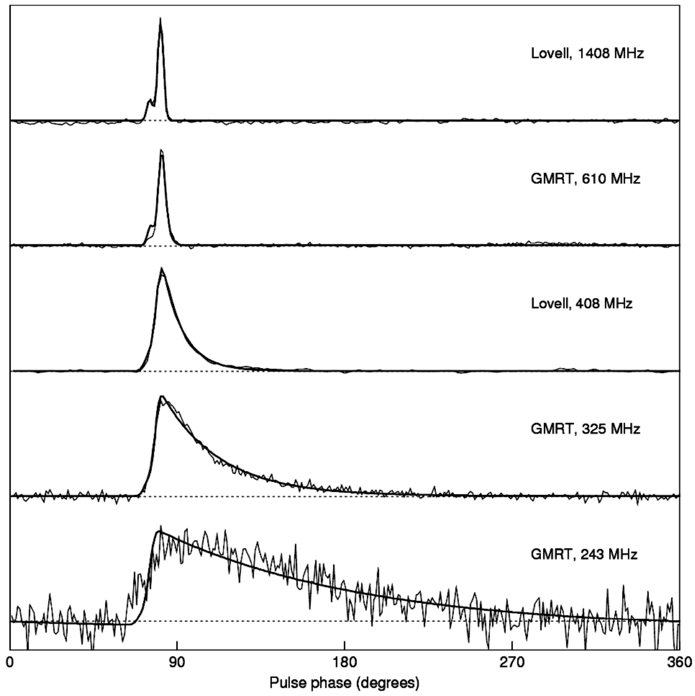
Observed signal — Emitted signal — Dispersion — Faraday rotation

$$I(t) = g_r g_d S(t) * h_{\rm DM}(t) * h_d(t) * h_{\rm Rx}(t) + N(t)$$

Refractive and diffractive scintillation — Scattering — Instrumental noise

• Of course, what we observe is not necessarily what was emitted by the source we're interested in studying.
• The interstellar medium is ionized and magnetized. It is also clumpy on a variety of scales.
• The interstellar medium imparts a number of so-called propagation effects onto the properties of the radio signal. These are summarized in the above relation.
• Though propagation effects can be very limiting for some radio astronomical studies, their effects also serve as a probe of the interstellar medium.
• We'll discuss propagations effects in more detail in the context of pulsars.

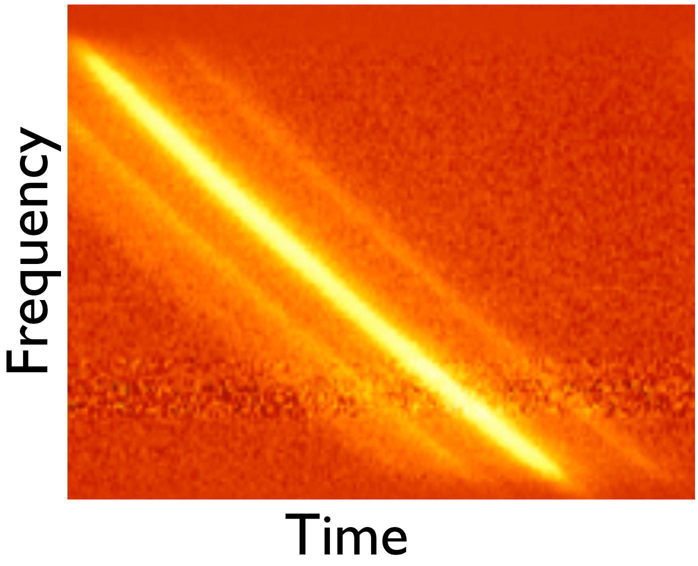
Scattering



- Multi-path propagation.
- Asymmetric scattering tail, roughly follows an exponential decay.

- Scattering time scales as roughly ν^-4.4 for a medium with a Kolmogorov turbulence spectrum.
- Amount of scattering depends on the distribution of the material along the line of sight.

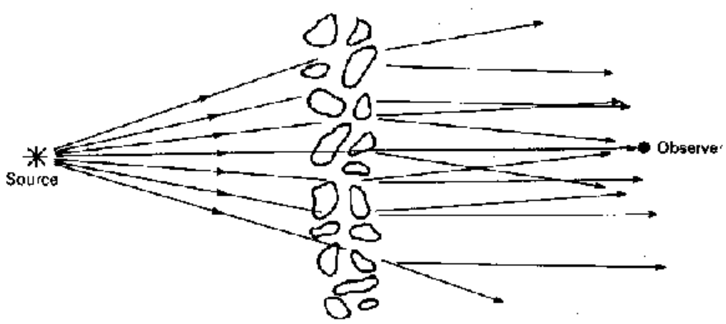
Dispersion



• Frequency dependent travel time.
• Signal arrives quadratically later at low frequencies.
• Delay also linearly proportional to the "dispersion measure" - i.e. the total electron content along the line-of-sight.

• Signal is delayed as ν^-2 (exactly, as far as we can tell).
• The dispersion measure (DM) is the line-of-sight column density of free electrons.

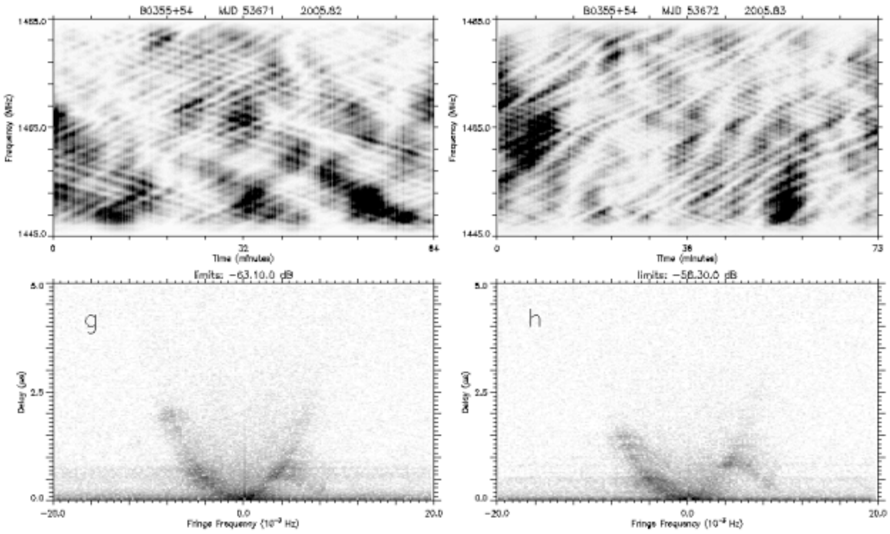
Scintillation



• Constructive/ destructive interference.
• Each line-of-sight gives typical time and frequency scintillation scales.

• Scintillation can occur both because of diffraction and refraction in the interstellar medium. The two types of scintillation have their own characteristic timescales and coherency bandwidths.

Secondary Spectra



• Measure distance to intervening screens.

• One example application: looking at the time/frequency structure of scintillation maxima towards a point source can be used to locate the position of the intervening thin screen.

Bringing it all together

Overview of common radiation processes in the radio spectrum and their environment

λ	Spectral line	Continuum
metre, cm and mm	Neutral Hydrogen (HI) 21cm fine structure line - neutral gas Hydrogen recombination lines -ionised gas; OH, H20, SiO Masers - dense, warm molecular gas; Molecular rotation lines - cold molecular gas	Thermal Bremsstrahlung (free-free emission) – HII regions Synchrotron Radiation – Jets in radio Galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc., acceleration of electrons in stellar and planetraty systems Thermal emission from dust – cold, dense gas.
sub-mm (and FIR)	Molecular Rotation Lines – warm, dense gas. Solid State features (silicates) –dust Hydrogen recombination lines – ionised HII regions.	Thermal emission - warm dust

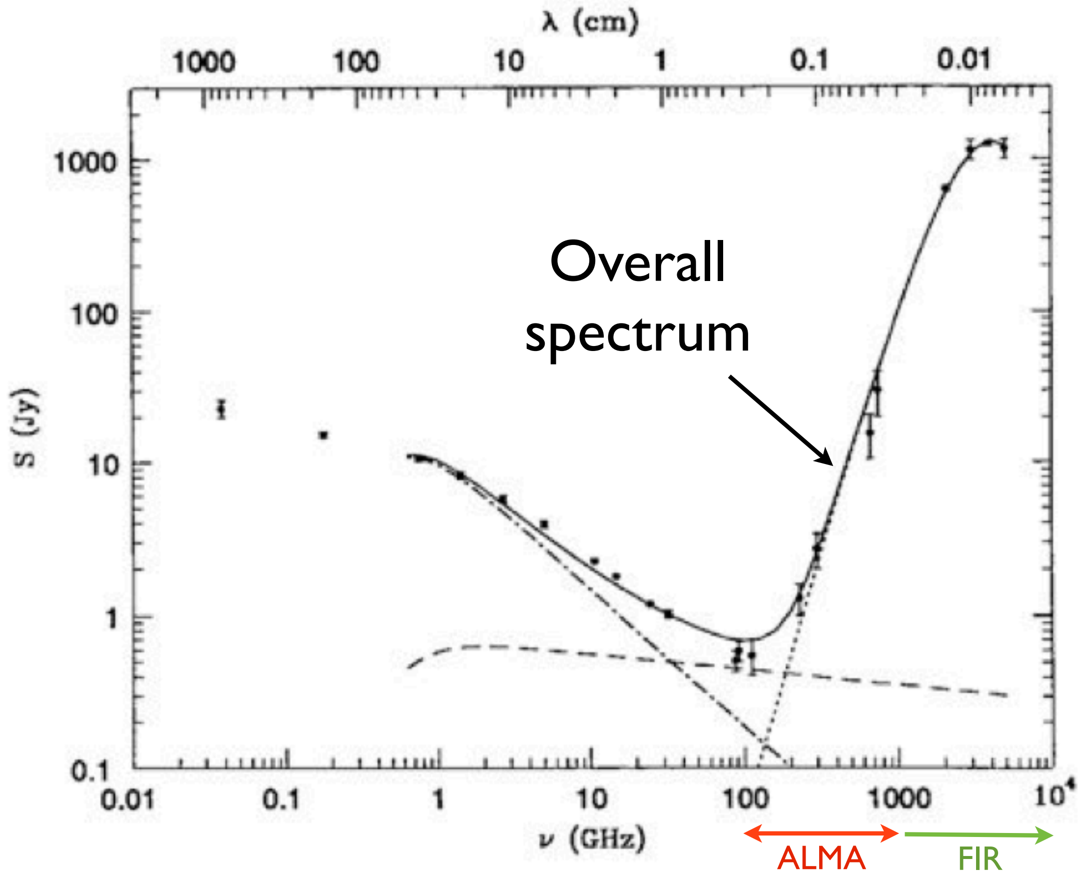
Courtesy M. Garrett

Bringing it all together

- Thermal (blackbody), free-free, and synchrotron emission/absorption can describe the continuum spectrum of many (extra-)galactic sources.

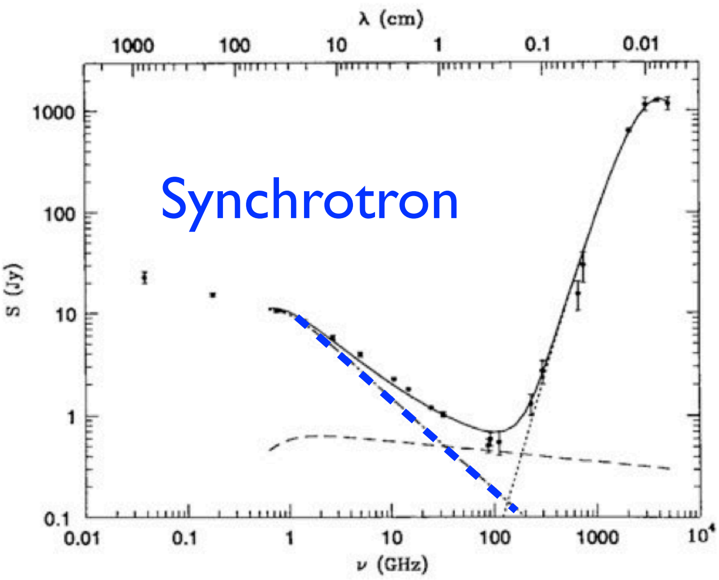
• These basic radiation processes: (i) thermal emission, (ii) synchrotron emission/absorption and (iii) thermal bremstrahlung (free-free) emission provide a basic explanation for the continuum spectra of most galactic and extra-galactic sources observed in the radio domain.A good example to look at is the radio spectrum of a star forming galaxy like M82 (see next slide).

Star-forming galaxy M82



• In most radio sources all of these radiation processes we have studied are present at one level or another: e.g. normal star forming galaxies (like the Milky Way) or Starburst systems like M82.
• Solid black line: represents overall spectrum.

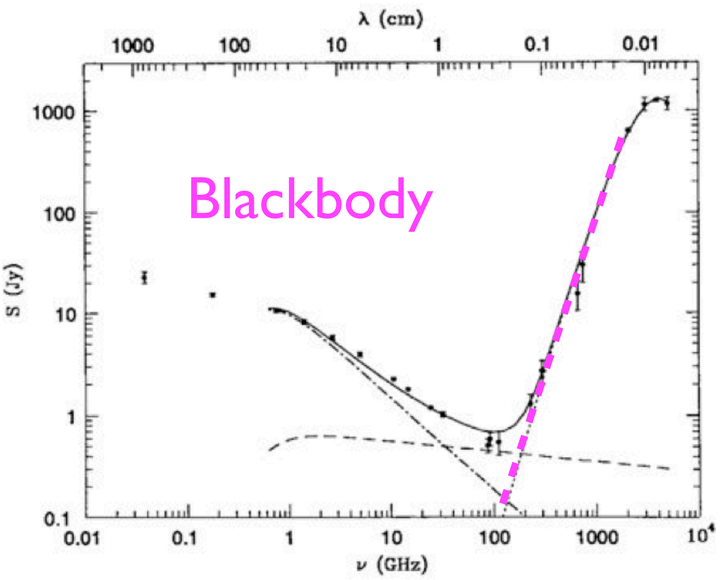
Star-forming galaxy M82



- Cosmic-ray electrons in the galaxy's magnetic field.
- SNe create the seed electrons.
- Note turnover.

• Dashed (blue) line is steep spectrum synchrotron emission - mostly from cosmic-ray electrons accelerating in M82's magnetic field - the source of the relativistic electrons is believed to be shocks from supernovae - massive stars that exploded into the ISM. The supernova events themselves, also produce short- lived synchrotron emission. Note the synchrotron self-absorbed turnover at lower frequencies.

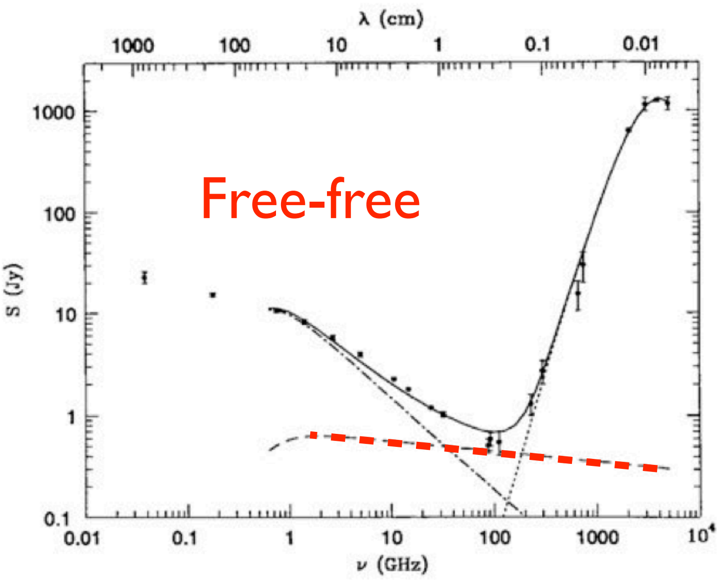
Star-forming galaxy M82



- Dust heated by uv-photons.
- Tail in IR, but can be redshifted into the radio band.

• Dashed (magenta) line is thermal blackbody emission (in the Raleigh-Jeans limit) from dust that has been heated up by uv-photons from the same massive stars that produced the supernovae that fuel the radio emission. The dust absorbs the uv-photons, heats up, and re-emits in the FIR. N.B. for sources at high redshift, the FIR gets redshifted into the radio (sub-mm) domain.

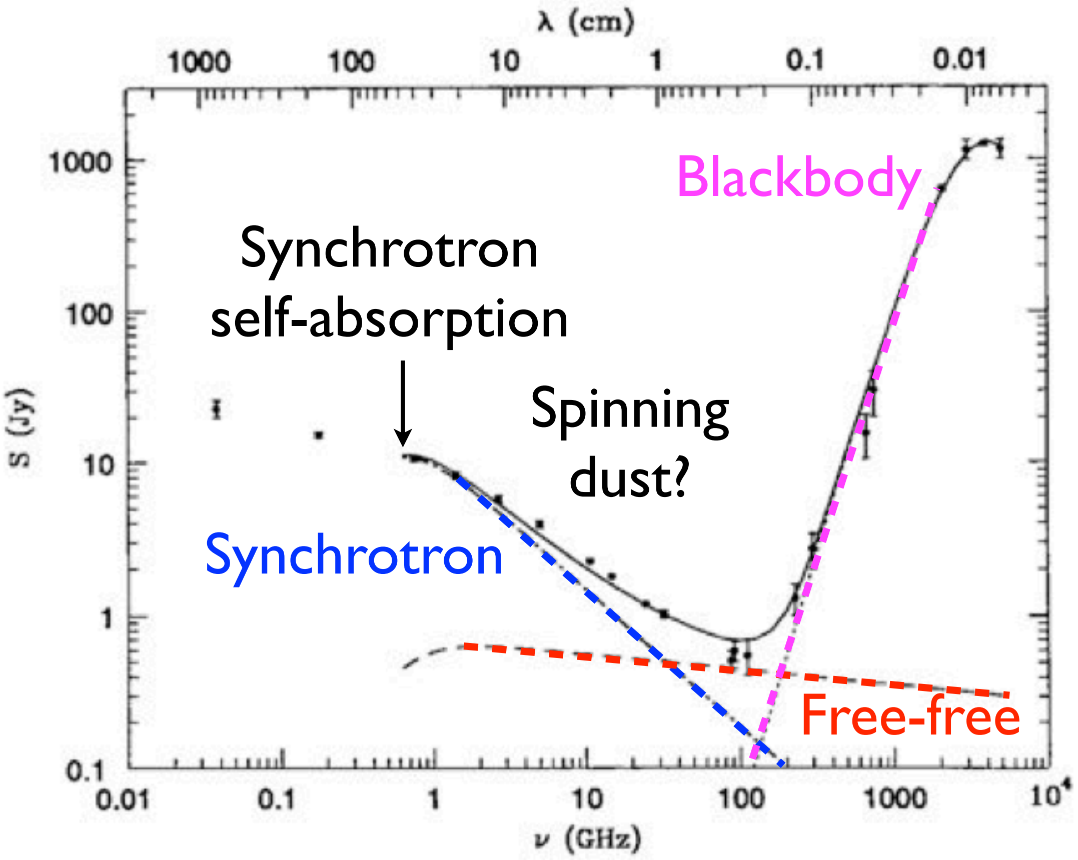
Star-forming galaxy M82



- Tenuous, ionized gas.
- HII regions.

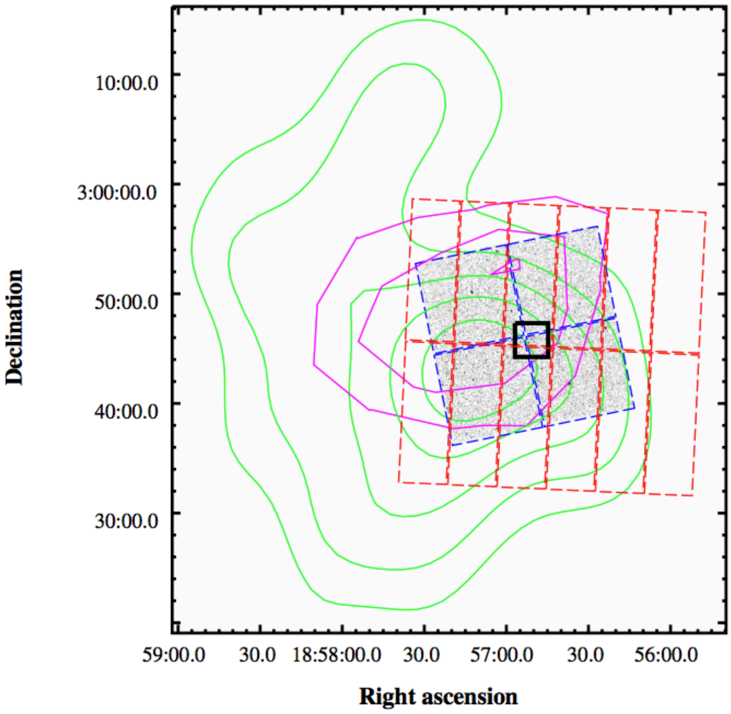
• Dashed (red) line is thermal free-free emission from hot, ionized and tenuous HII regions that are common in star forming regions that contain young massive stars (the same massive stars that produced the supernovae that fuel the radio emission, and that heat the dust to produce thermal emission!).

Star-forming galaxy M82



- Here's the total picture, plus...
- In some galaxies (and regions of our own galaxy) there is recent evidence for so-called "anomalous radio emission" probably from spinning dust.
- Anomalous emission is unexpected and appears as an excess in the radio emission of galaxies and regions of the Milky Way at ~ 20GHz.
- The evidence comes from very detailed CMB background subtraction studies that need to be highly accurate (the CMB is peaking around the same frequencies as spinning dust).
- Draine & Lazarian (1998) proposed that very small grains containing 10 – 100 carbon atoms could be spun up to 10s of GHz frequencies in the ISM. Their likely electric dipole moments implies they are likely to produce radio emission at these frequencies with the detailed spectrum depending upon the conditions in the local ISM.
- So in addition to free-free, thermal and synchrotron emission, spinning dust is a fourth component that is present in radio emission from other external galaxies and our own Milky Way.

TeV Pulsar Wind Nebulae



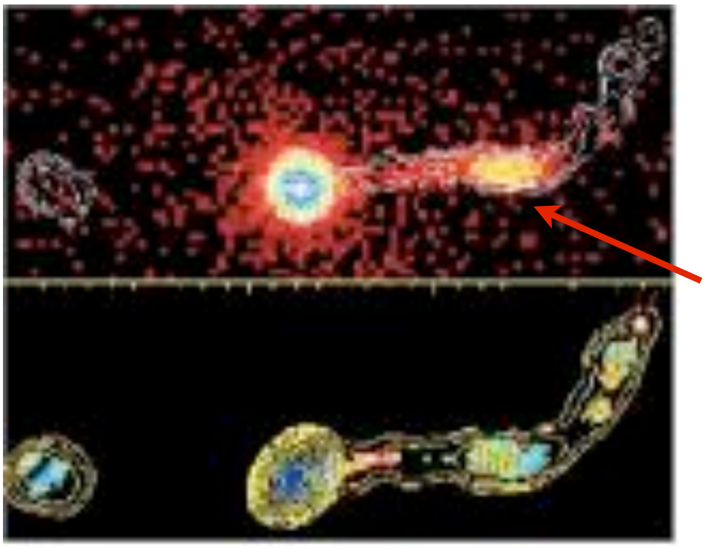
- Inverse Compton?
- Seed photons from the CMB.

Synchrotron Self-Compton

N.B. A photon scattered by an electron with Lorentz factor γ, increases its energy by γ^2.

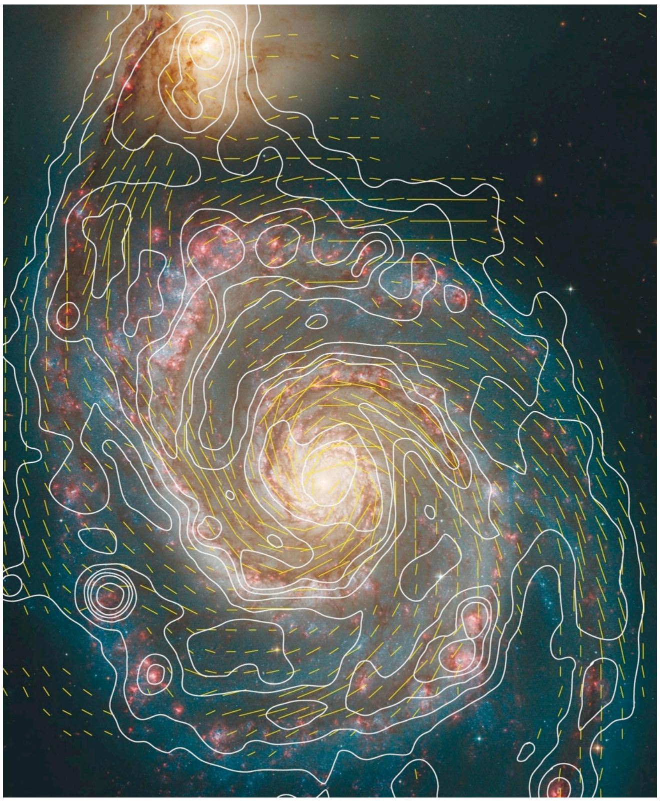
This means that a radio photon in synchrotron source can find itself upscattered by a factor of ~ 10^8 i.e. into the x-ray region of the e-m spectrum!

In the case of compact AGN, the self-Compton mechanism is believed to be more important than synchrotron radiation losses as responsible for cooling the relativistic electron population.
The mechanism limits the brightness temperature of radio sources to $T_b \sim 10^{12}$ K.



Left: X-ray emission (false colours) with radio contours superimposed. The xray hotspot is believed to be due to SSC.

Map Magnetic Fields



- Contours: VLA and Effelsberg radio data at 5GHz.
- Optical image from Hubble.
- Direction of lines indicate magnetic field vector.
- Length of lines indicate B-field strength.
- Derived based on polarization of synchrotron emission.

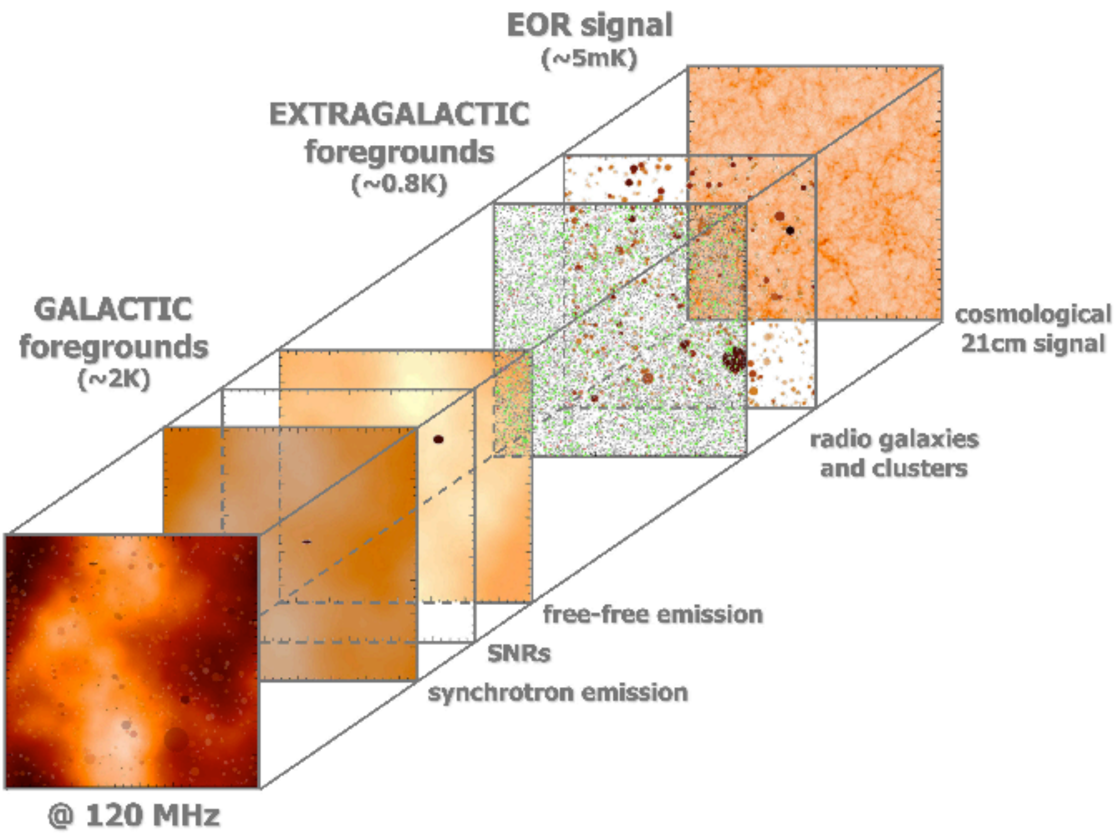
• The theory of synchrotron emission also predicts that when the electrons are contained within a uniformly ordered magnetic field, that the radiation is highly linearly polarized. The theory predicts that degree of linear polarization is given by: $\Pi = (\beta + 1)/(\beta + 7/3)$. Thus for $\beta=5/2$, $\Pi = 72\%$!

• Note however, that this prediction is based on the assumption of an ordered magnetic field. If the field is actually random, then the degree of polarization is zero.

• If observations do measure partial linear polarization, the magnetic fields must be ordered. We see this in many AGN and in parts of our own galaxy. Typical values for AGN are a few percent. The values often depend on the resolution of the observations.

• In any given resolution element then there are regions with different polarization (magnetic field) characteristics. The beam thus smoothes out the polarization of the source, and the measured polarization will be less than the true source polarization. This is called beam de-polarization.

EOR Foregrounds



Sources

Radiative Processes in Astrophysics (Rybicki & Lightman)

NRAO: http://www.nrao.edu/index.php/learn/radioastronomy/radiowaves

Wikipedia: http://en.wikipedia.org/wiki/Radio_astronomy

Other course slides (see links on course wiki page):

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2017

Many figures taken from Garrett.

Questions?