Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz
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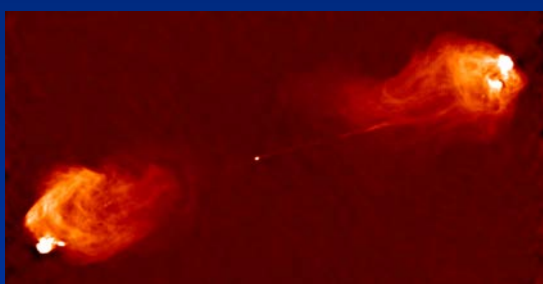
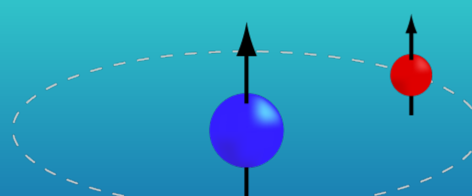
An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg





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Tentative Schedule:

16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Line radiation (HB)
11.12. Radiation transfer (HL)
18.12. Buffer ...
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

Radio Astronomy

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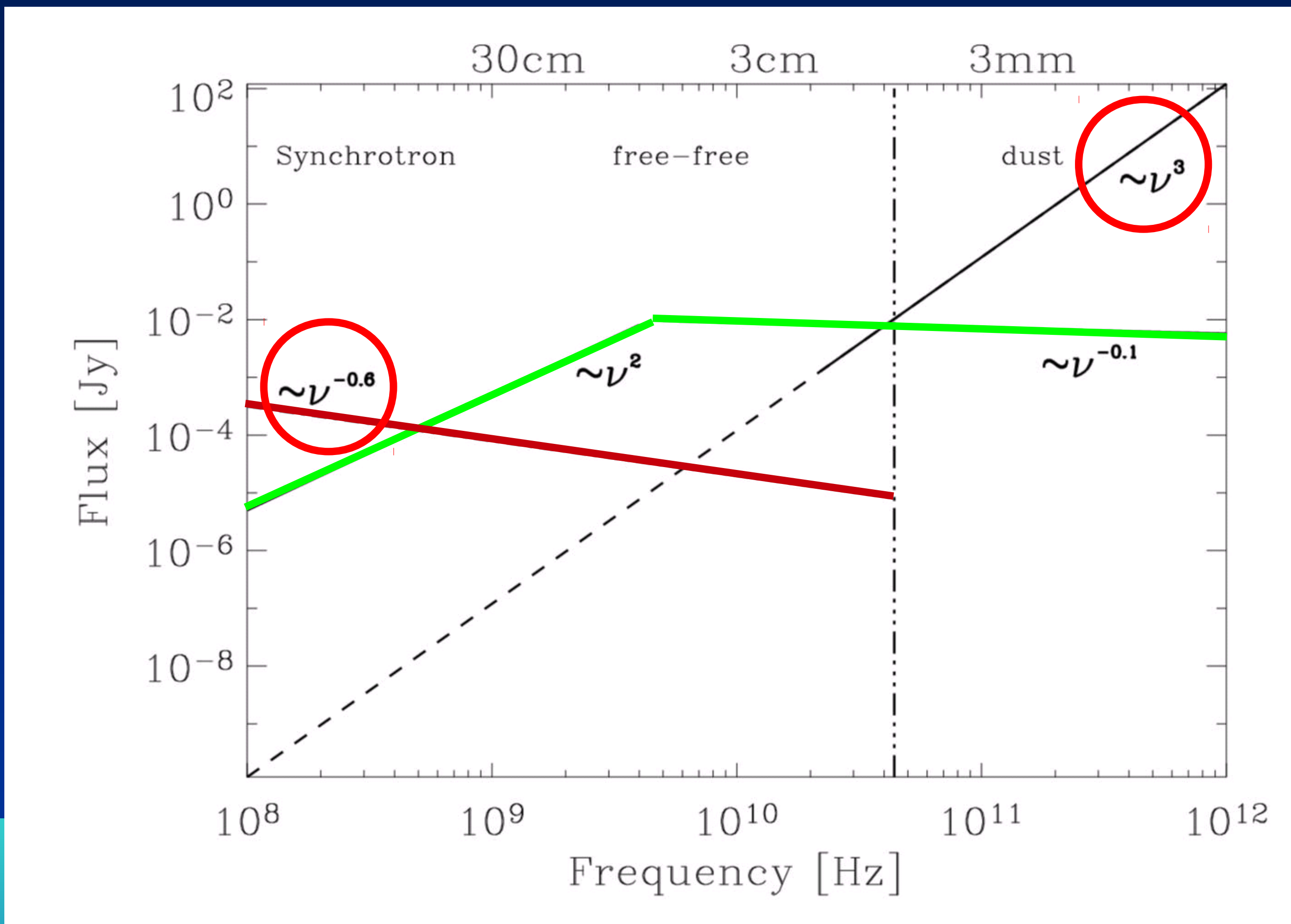
<u>Topics for today:</u>

- dust emission at long wavelengths

- free-free emission

- Synchrotron emission

Basic overview for continuous radiation in the radio range



Thermal dust emission:
Micrometer- to millimeter-sized dust grains with temperatures 10 … 100 K

Synchrotron radiation:
Fast charged particles in a magnetic field

Free-Free emission:
In a plasma: free electrons have close encounters with ions

Basic overview for continuous radiation in the radio range

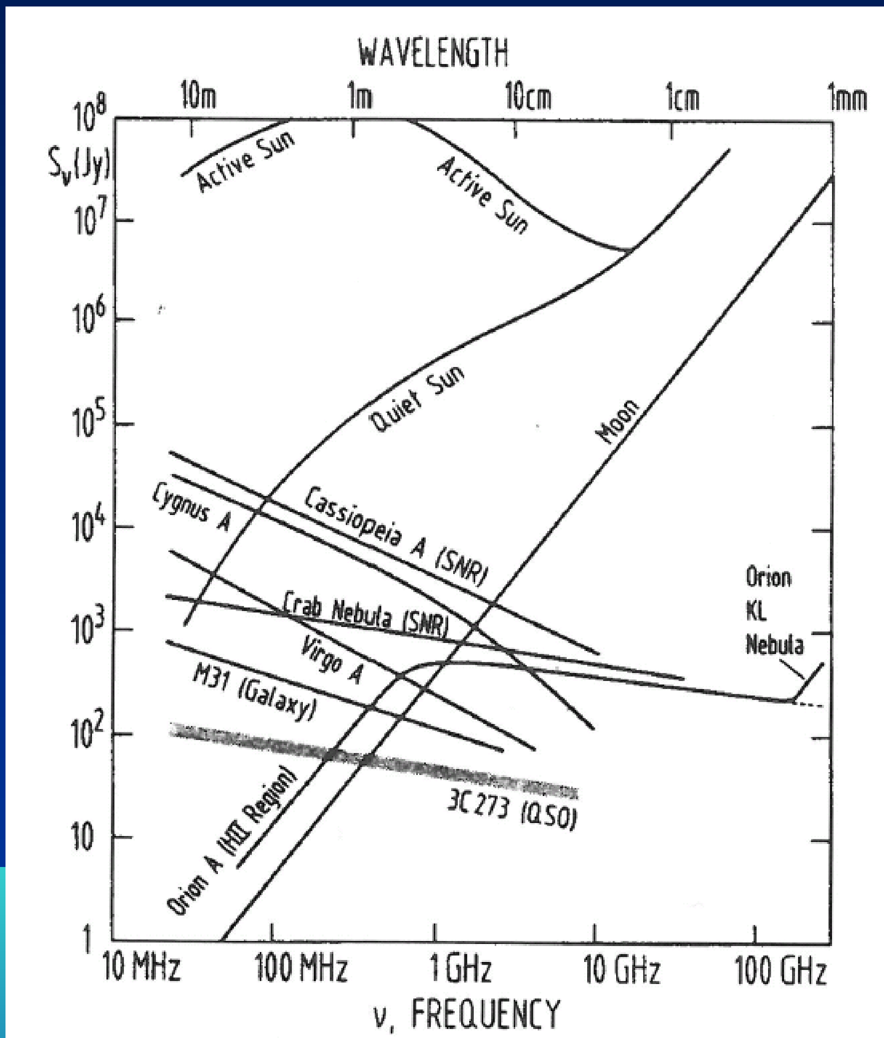


Figure from Rohlfs & Wilson book

Real-life examples for spectral energy distributions of astronomical sources.

Shown are some of the strongest radio sources.

The Moon, the quiet Sun, and the HII region Orion A (at low frequencies) are examples for Black Bodies. (Orion takes off for another black body contribution coming from dust emission in Orion BN/KL beyond 200 GHz.)

The active Sun, supernova remnants like the Crab nebula and Cassiopeia A, and radio galaxies like Cygnus A and 3C273 show non-thermal emission.

Basic overview for continuous radiation in the radio range

Thermal dust emission:
Effects in (amorphous) solid-state particles (“dust”) produce continuum emission

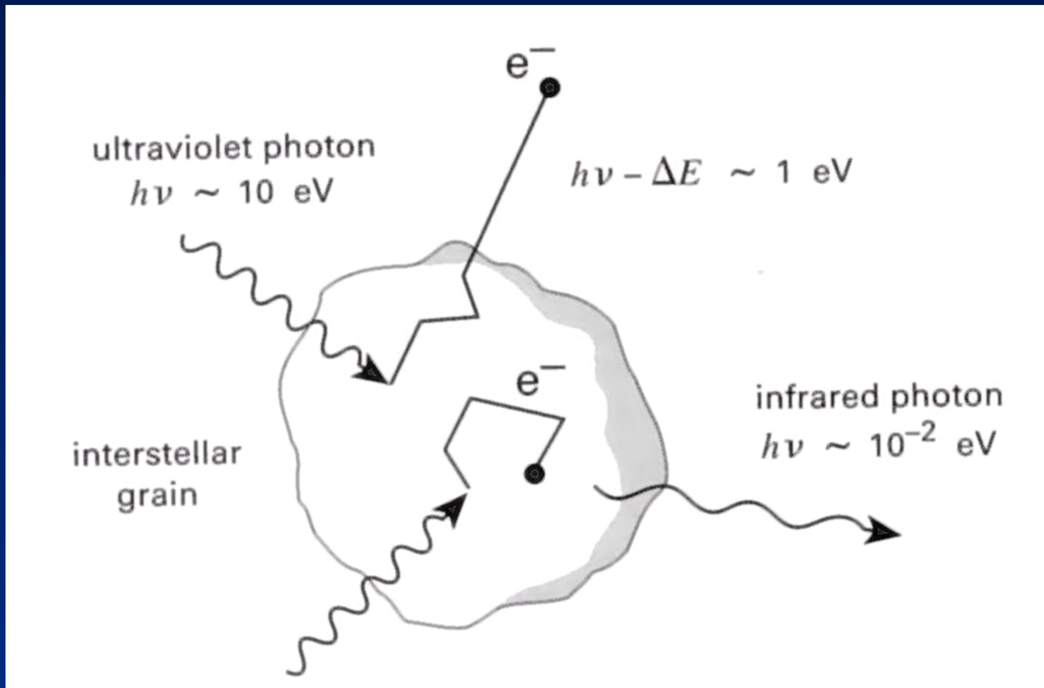
Synchrotron radiation and Free-Free emission:
Basic underlying principle is that accelerated charges emit electromagnetic radiation.

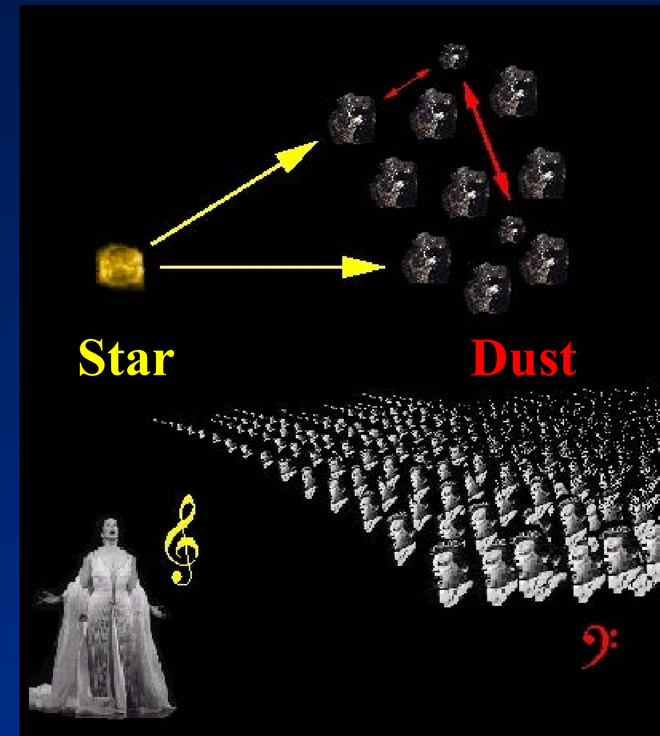
Free-free emission: free electrons are influenced by the electrostatic fields of neighbouring ions

Synchrotron emission: motions of free charges are influenced by magnetic fields

Interestingly, both the dust emission and the optically thick free-free emission can display black-body radiation behaviour despite the different emission mechanisms on a micro-level. → blackboard ...

Dust re-emission: reprocessed light transformed to long wavelengths

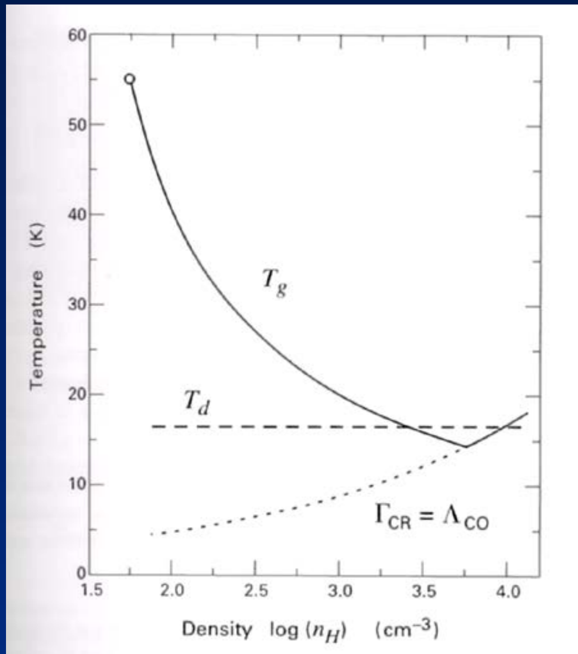


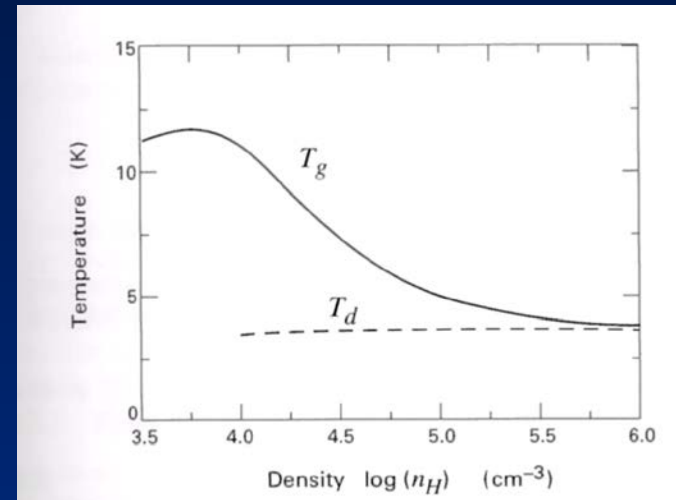


A dust grain is hit by a UV photon. Sometimes, the energy is transformed within a photoelectrical event into kinetic energy of an electron that can leave the grain and eventually hits and heats a gas molecule.

In most cases, the electron remains inside the dust grain and excites lattice vibrations that are eventually transformed into IR photons that are being emitted.

IR and (sub-)mm dust emission in extremely shielded environments





Γ – heating rate Λ – Cooling rate

Comparison of dust and gas temperatures for different density regimes: Thinner (left) and denser (right). Towards higher densities, the coupling of gas and dust gets closer. In the absence of UV photons, the cosmic rays (CR) are the main external dust heating source. Collisions of warmer gas particles with colder dust grains transfer heat to the dust: kinetic energy from the gas is transferred to low-energy lattice vibrations that are re-emitted by the dust in the far-infrared and (sub-)millimetre wavelengths (30 – 3000 µm). The dust temperature does not rise by more than 1 – 2 K due to these collisions.
(The lowest dust temperatures "derived" from real observations are at least 6 – 10 K, not only 4 K as insinuated in this model !)

Flux density of a source with thermal emission from dust, at temperature T_d, and solid angle Ω_S:

$$S_\nu = B_\nu(T_\mathrm{d})\,(1 - e^{-\tau_\nu})\,\Omega_\mathrm{S},$$

For dust thermal emission, we use the absorption coefficient per unit mass density (gas + dust) and unit length, κ_ν (with units of $cm^2\ g^{-1}$). The optical depth τ_ν is given by:

$$\tau_\nu = \kappa_\nu \int_\mathrm{visual} \rho\, dl,$$

The dust absorption coefficient is approximated by a power law of frequency, with exponent β. Usually β is between 1 and 2, depending on the dust properties.

$$\left[\frac{\kappa_\nu}{\mathrm{cm}^2\ \mathrm{g}^{-1}}\right] = 0.1 \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^\beta,$$

We can assume optically thin emission at mm and submm wavelengths.
In the Rayleigh-Jeans aproximation, flux density can be expressed in terms of the mass of the source.

$$S_\nu = \frac{2k\nu^2}{c^2} T_\mathrm{d} \tau_\nu \Omega_\mathrm{S} = \frac{2k\nu^2}{c^2} T_\mathrm{d} \kappa_\nu \frac{A}{D^2} \int \rho\, dl = \frac{2k\nu^2}{c^2} T_\mathrm{d} \kappa_\nu \frac{M}{D^2},$$

In practical units:

$$\left[\frac{M}{M_\odot}\right] = 1.6 \times 10^{-6} \left[\frac{\nu}{1000\ \mathrm{GHz}}\right]^{-(2+\beta)} \left[\frac{S_\nu}{\mathrm{Jy}}\right] \left[\frac{T_\mathrm{d}}{\mathrm{K}}\right]^{-1} \left[\frac{D}{\mathrm{pc}}\right]^2.$$

Slide adopted from a presentation by Robert Estalella (Uni Barcelona)

Many other aspects could be added. I give here just two:

1.) The choice of the (sub-)millimeter dust opacities κ_ν is a matter of debate.

The frequency slope and the absolute gauge depends on the dust material involved (silicates + graphite or silicates + amorphous carbon, thick, thin, or no ice mantles on the grain surfaces), and on the grain size distribution.

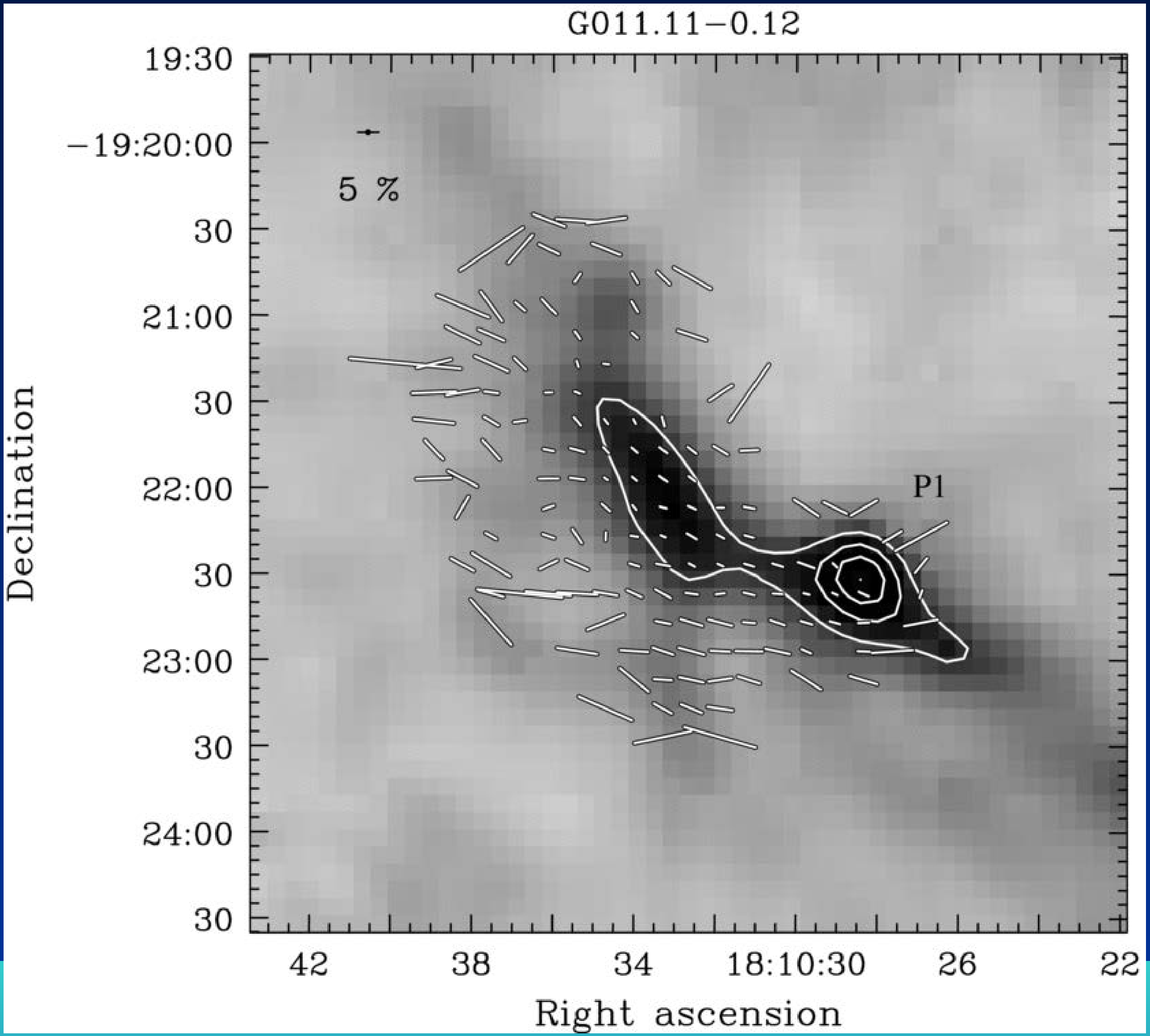
Beware: at very cold temperatures (~10 K), the Rayleigh-Jeans approximation will not be valid even for wavelengths as long as 2 mm!

2.) Dust grains are probably not simple spheres but complicated... as a first approximation, they are elongated.

Several mechanisms are proposed to align (at least a fraction of) the dust grains in a local magnetic field of an astronomical object/region.

→ Aligned grains have one preferred axis where slightly more emission will be released than along the other axis → net emission from the aligned ensemble of dust grains is linearly polarised along this major axis of the grains.

→ Polarimetry in the (sub-)millimeter range to infer information about the magnetic field structure in these dusty regions



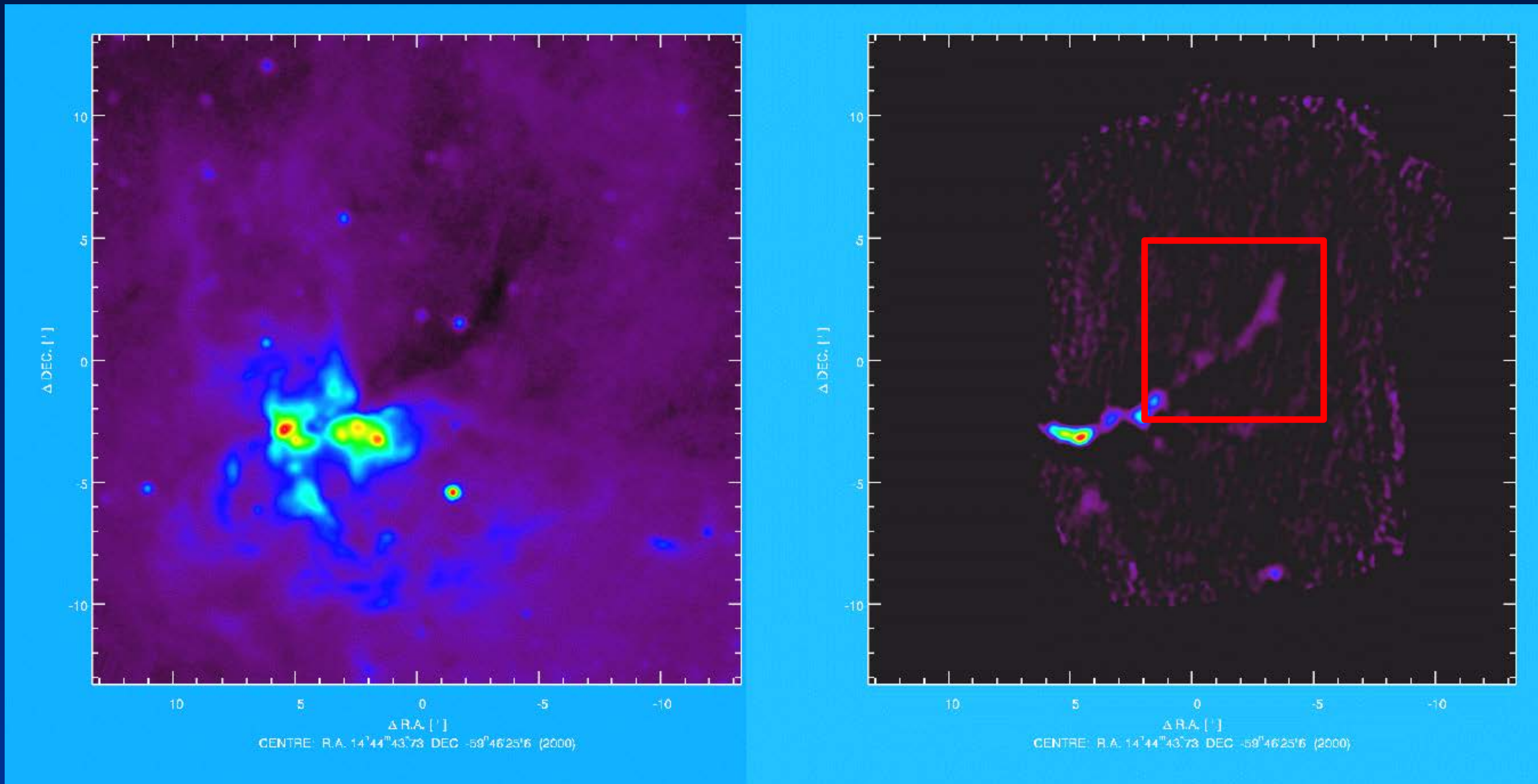
Map at 850 μm of the dust emission in a very young High-mass star-forming filament, the InfraRed Dark Cloud G11.11-0.12 ("Snake").

Inverse grey scale gives the total 850 μm intensity.

The vectors mark the strength and direction of the linear polarisation of this 850 μm emission. A reference in the upper left shows a 5% polarisation vector.

From Matthews, B. et al. 2009, ApJS 182, 143

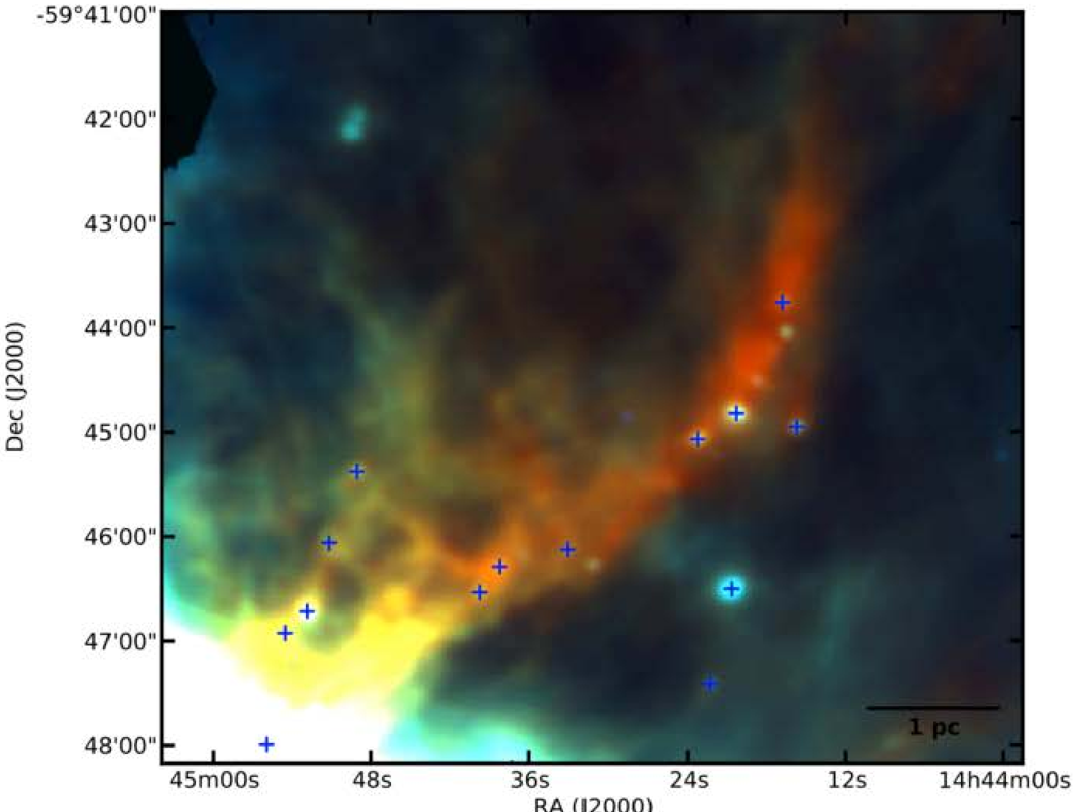
Dust emission: reprocessed light, IR and mm radiation

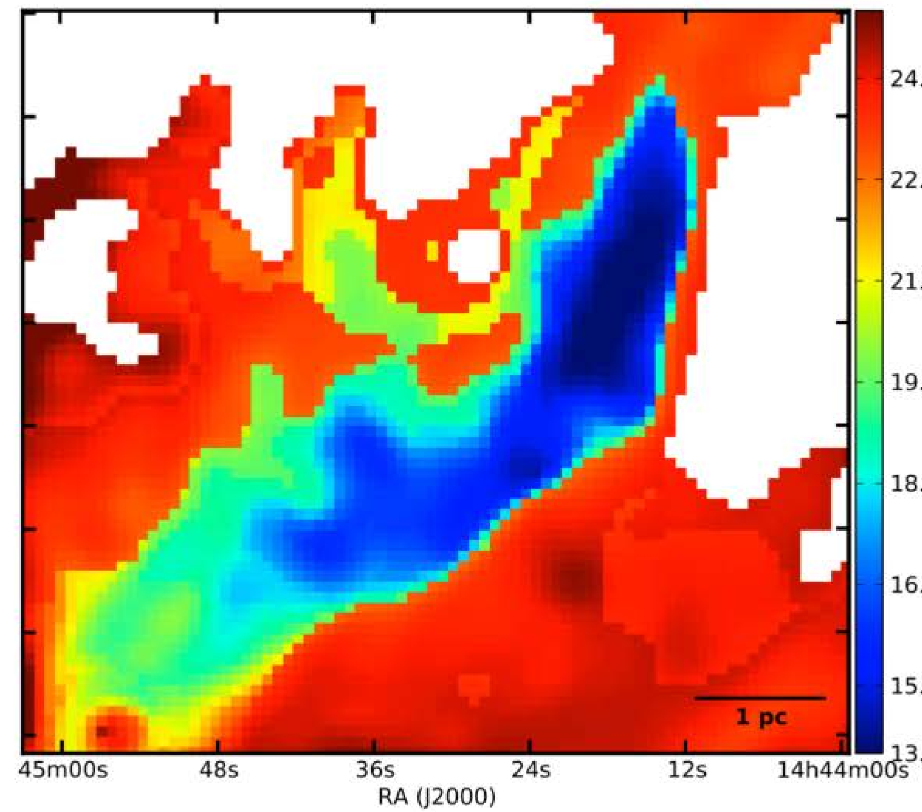


An InfraRed Dark Cloud (IRDC) and its neighbourhood at two different wavelengths.
Left: at λ=8.3 µm (with MSX satellite)   Right: at λ=1.2 mm (with SIMBA at the SEST)

For this class of objects, the material is sufficiently dense to efficiently absorb light still at 8 micron (left). At millimetre wavelengths, this dust can be found in emission.

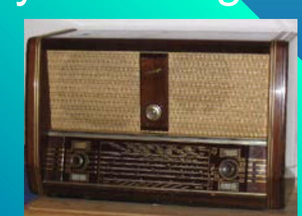
The same IRDC has eventually been observed in 2010 in the far-infrared at several wavelengths covering the peak of the (modified) black-body emission → dust temperature maps can be created



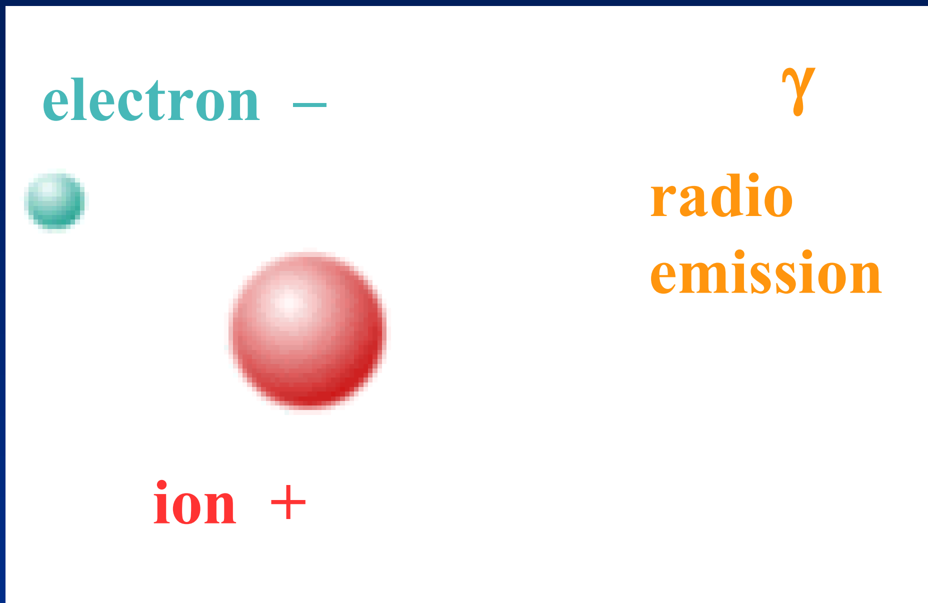


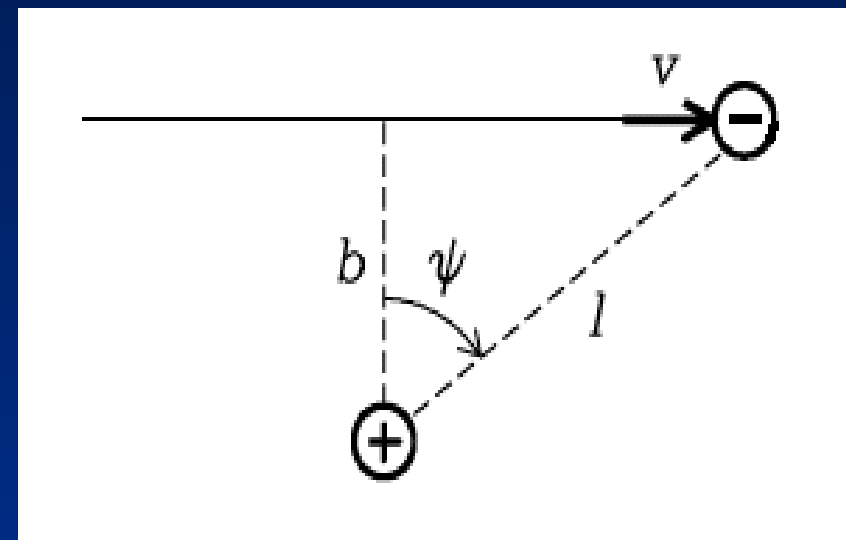
Three-colour composite showing Herschel/PACS Bolometer observations at 70 μm, 100 μm and 160 μm in blue, green, and red, respectively.

The derived dust temperature map (colour bar scaled in Kelvin) has been obtained by analysing all 6 available Herschel intensity maps from 70 – 500 μm, and by choosing a certain dust opacity model.



Free-Free interaction: A basic scattering of free electrons on ions



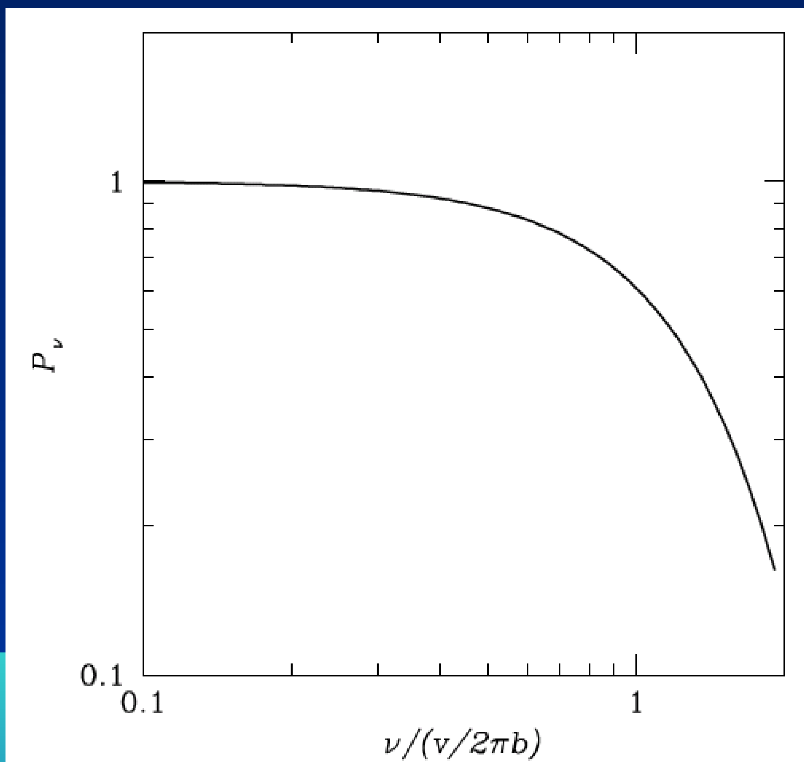


A light, fast electron passing by a slow, heavy ion. Low-energy radio photons are produced by weak scattering in which the velocity vector v of the electron changes little. The distance of closest approach is called the **impact parameter b** and the interval $\tau = b / v$ is called the **collision time**.

Electrons in a $T = 10^4$ K ionised gas have ~ 1 eV of energy, but the radio photons have typical energies < 10^{-4} eV ↔ actual change in direction is tiny (above animation is grossly exaggerated)

An individual electron-ion interaction leads to a single pulse of radiation with a typical pulse time of $\tau = b / v$. A Fourier relation between τ and ν exists: the pulse power spectrum is roughly flat in the $[\, 0 , v / 2\pi b \,]$ interval.

Important for the creation of radiation in the radio range is the acceleration component perpendicular to the original velocity vector.



Power spectrum of a single pulse (frequency in multiples of velocity over (2π b)

Instantaneous power in the pulse can be computed using the Larmor formula:

$$P = \frac{2}{3}\frac{e^2 \dot{v}_\perp^2}{c^3} = \frac{2e^2}{3c^3}\frac{Z^2 e^4}{m_e^2}\left(\frac{\cos^3\psi}{b^2}\right)^2$$

Total energy W is then P integrated over time:

$$W = \frac{\pi Z^2 e^6}{4c^3 m_e^2}\left(\frac{1}{b^3 v}\right)$$

But: knowledge about single pulses is not enough to predict the spectral energy distribution of the free-free emission from a large ensemble of particles ...

What are the distributions of velocities and impact parameters?

Distribution of velocities v is a function of the (electron) temperature T_e

Distribution of impact parameters b is a function of the electron densities N_e and the ion densities N_i.

Free-free emissivity ε_ν (the energy emitted by unit frequency and unit volume):

$$4\pi\epsilon_\nu = \frac{\pi^3 Z^2 e^6 N_e N_i}{c^3 m_e^2} \int_{v=0}^{\infty} \frac{f(v)}{v}\, dv \int_{b_{min}}^{b_{max}} \frac{db}{b}$$

In practice: ion charge Z ~ 1, particle densities $N_{ion} \sim N_{elec}$.

In Local Thermal Equilibrium (LTE) the velocity distribution is given by the (non-relativistic) Maxwellian distribution function:

$$f(v) = \frac{4v^2}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right)$$

In a classical HII region, not involving any dynamically fast shocks, the electrons usually obey the Maxwell distribution.

Therefore, the emerging free-free radiation is often said to be “thermal”.

Another term often used is: “thermal Bremsstrahlung”

(from the German words for “brake” (bremsen) and “radiation” (Strahlung))

Furthermore, estimates for b_{min} and b_{max} are necessary (otherwise, an integral from b = 0 → ∞ would diverge)

b_{min}: The maximum possible momentum transfer during the interaction is twice the initial momentum (m v) of the electron, so:

$$b_{\rm min} \approx \frac{Ze^2}{m_{\rm e} v^2}$$

b_{max}: estimate which impact parameters still generate a significant amount of power at a given radio frequency ν:

$$b_{\rm max} \approx \frac{v}{\omega} = \frac{v}{2\pi\nu},$$

More exact computations lead to a more complex expression for the term related to this impact parameter b: the so-called **Gaunt factor g_{ff}**

Because b_{max} slightly varies with frequency, the Gaunt factor introduces a slight additional frequency dependence of $g_{ff} \sim \nu^{-0.1}$.

Realistically, there will be emission as well as absorption of this free-free radiation Along the line of sight. The absorption coefficient can be obtained from the Planck-function and the emissivity: $\kappa_\nu = \varepsilon_\nu / B_\nu$

Integrating along the sight line s, we get from the absorption coefficient to the optical depth τ :

$$\tau_\nu = \int \kappa_\nu \, ds$$

Collecting terms, one can write the optical depth in a compact manner:

$$\tau_\nu \approx 3.014 \times 10^{-2} \left(\frac{T_e}{\mathrm{K}}\right)^{-3/2} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{EM}{\mathrm{pc\ cm}^{-6}}\right) \langle g_{\mathrm{ff}} \rangle$$

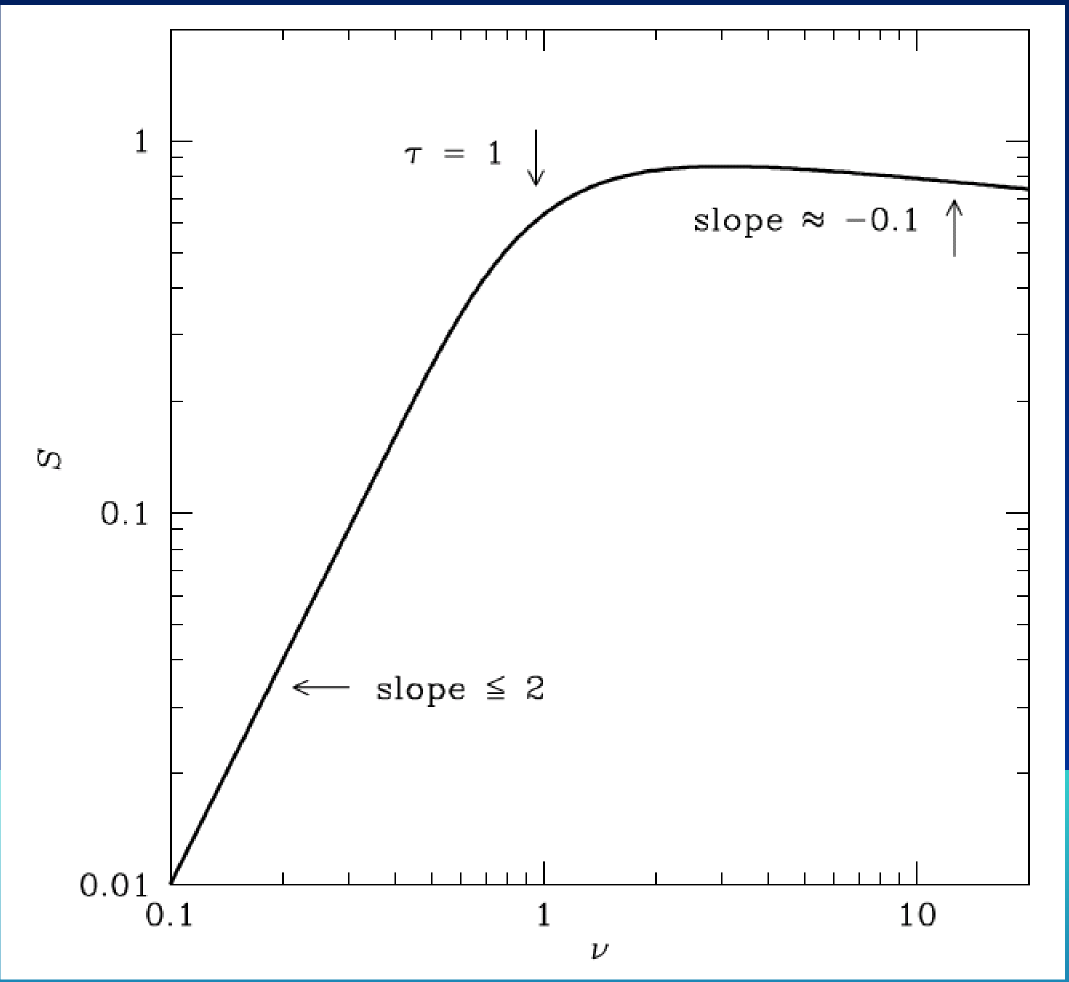
Here, a new quantity has been used, the so-called emission measure EM:

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

Here, N_e^2 appears, since we have used, that $N_i \sim N_e$, hence $N_i N_e \sim N_e^2$!

Finally, when further evaluating terms, we eventually obtain the classic expression:

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



The radio spectrum of our idealized HII region. It is a black body $B_\nu(T_e)$ at low frequencies, with slope 2 (if assuming a uniform cylinder) and < 2 otherwise. At some frequency the optical depth τ_ν ~1 , and at much higher frequencies the spectral slope becomes ~ -0.1,because the opacity coefficient $\kappa_\nu \sim \nu^{-2.1}$.

The brightness at low frequencies depends only on the electron temperature. The brightness at high frequencies depends also on the emission measure of the HII region.

Consider galactic regions with (high-mass) star formation:

The young high-mass stars, after begin of central H-fusion, have large outputs of energetic photons that can ionise hydrogen gas in their surroundings (h ν > 13.6 eV) → HII regions form

Beside the Classical HII regions (Strömgren spheres), more qualitatively different classes can be distinguished:

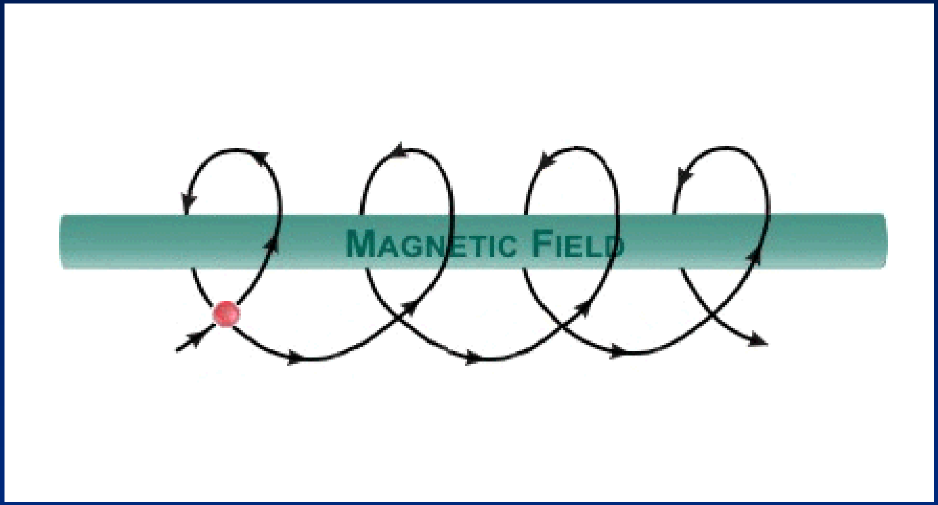
Table 3. Physical Parameters of HII Regions

Class of Region	Size (pc)	Density (cm^{-3})	Emis. Meas. (pc cm^{-6})	Ionized Mass ($M_\odot$)
Hypercompact	$\lesssim 0.03$	$\gtrsim 10^6$	$\gtrsim 10^{10}$	$\sim 10^{-3}$
Ultracompact	$\lesssim 0.1$	$\gtrsim 10^4$	$\gtrsim 10^7$	$\sim 10^{-2}$
Compact	$\lesssim 0.5$	$\gtrsim 5\times 10^3$	$\gtrsim 10^7$	~ 1
Classical	~ 10	~ 100	$\sim 10^2$	$\sim 10^5$
Giant	~ 100	~ 30	$\sim 5 \times 10^5$	10^3–10^6
Supergiant	>100	~ 10	$\sim 10^5$	10^6–10^8

From: Kurtz, S. 2005, IAU Symp. 227, 111

<u>Keep in mind:</u> the higher the EM → the higher the turnover frequency from optically thick to thin

Synchrotron emission: fast charged particles in a magnetic field



Emission mechanism of some peculiar radio sources remained unclear in the Pioneering days of the technique. Finally, good suggestions came in 1950 from two papers by Alfven & Herlofson and Kiepenheuer, and 1951 from Ginzburg et al.

Principle idea: relativistic cosmic ray electrons move in a general interstellar magnetic field. B-fields of 10^{-6} Gauss and electron energies of 10^{9} eV Might explain what was seen back then …

Such radiation had been known to occur in particle accelerators (Synchrotrons), which coined the name … however, earlier (1907, 1912) Schott had mentioned This effect already and called it “Magnetic Bremsstrahlung”.

Synchrotron emission: fast charged particles in a magnetic field

The electrons are (highly) relativistic! Lorentz factors come into play:
The emission will be highly beamed!

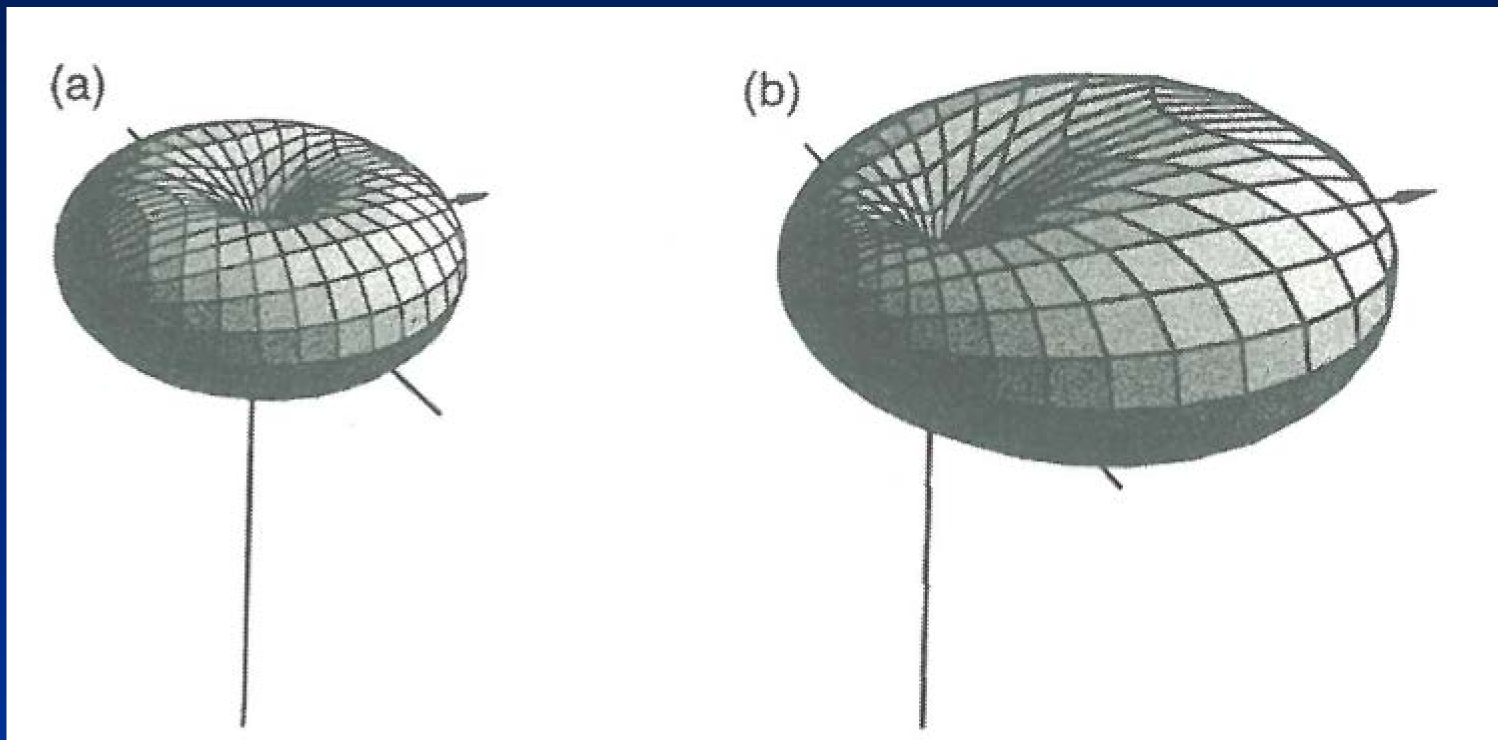


Figure from Rohlfs & Wilson book

Instantaneous emission cones for an electron gyrating in a homogeneous B-field. The electron moves to the right (in the plane of the slide), and the acceleration is directed towards the bottom.

(a) : with $v/c \ll 1$ (b) : with $v/c \sim 0.2$

For $v \sim c$, the emission cone eventually degenerates into a pencil beam subtending
The angle $\tan \Theta = c / (\gamma v)$ with γ as the Lorentz factor

Synchrotron emission: fast charged particles in a magnetic field

Already for a single electron, the assessment of the emission reveals some unpleasant mathematics (taken from Rohlfs & Wilson, chapter 9.7):

The total emissivity of an electron of energy E with $\gamma \gg 1$ which has a pitch angle α with respect to the magnetic field is

$$P(\nu) = \sqrt{3}\,\frac{e^3 B \sin\alpha}{m\,c^2}\,\frac{\nu}{\nu_c}\int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\,\mathrm{d}\eta \qquad (9.69)$$

and the critical frequency ν_c is defined by

$$\nu_c = \tfrac{3}{2}\gamma^2 \nu_G \sin\alpha = \tfrac{3}{2}\gamma^3 \nu_B \sin\alpha\,, \qquad (9.70)$$

where $\nu_G = \omega_G/2\pi$ is the non relativistic gyro-frequency according to (9.57), and $K_{5/3}$ is the modified Bessel function of 5/3 order.

with γ again as the Lorentz factor $1/\mathrm{sqrt}(1 - (v/c)^2)$, and $\varpi_G = e\,B\,/\,m_e$

The spectral radiation density, averaged over all directions for linear polarisations parallel and perpendicular to the (projected) B-field is given by:

$$P_{\perp} = \frac{\sqrt{3}}{2} \frac{e^3 B \sin\alpha}{m\,c^2} \left[F(x) + G(x)\right], \tag{9.71}$$

$$P_{\|} = \frac{\sqrt{3}}{2} \frac{e^3 B \sin\alpha}{m\,c^2} \left[F(x) - G(x)\right], \tag{9.72}$$

where

$$\boxed{F(x) = x \int_x^\infty K_{5/3}(t)\,\mathrm{d}t} \quad , \tag{9.73}$$

$$\boxed{G(x) = x K_{2/3}(x)} \quad , \tag{9.74}$$

and

$$\boxed{x = \nu/\nu_{\mathrm{c}}} \quad , \tag{9.75}$$

$$\boxed{\nu_{\mathrm{c}} = \frac{3}{2}\gamma^2 \frac{eB}{mc} \sin\alpha} \quad . \tag{9.76}$$

$K_{5/3}$ and $K_{2/3}$ are modified Bessel functions of (fractional) order (see Abramowitz and Stegun 1964, Chaps. 9 and 10), $P_{\|}$ and $P_{\perp}$ is the radiative spectral power density for linear polarization.

One interesting aspect that can be taken from this: the linear polarisation of the radiation averaged over all directions is remarkably high!

Polarisation degree $p = (P_{\perp} - P_{||}) / (P_{\perp} + P_{||}) = G(x) / F(x)$

Remember that the dummy variable $x = \nu / \nu_c$ can go from 0 to Infinity

$\rightarrow$ p can vary between 0.5 for $x = 0$ and 1.0 (all radiation completely linearly polarised) for $x \rightarrow \infty$

A more realistic case: an ensemble of particles with a distribution of energies

The volume emissivity (i.e., the power per unit frequency interval per unit volume and Per unit solid angle) of the relativistic electrons is given by:

$$\varepsilon(\nu) = \int P(\nu, E)\ N(E)\ \mathrm{d}E$$

with $P(\nu, E)$: total power that one electron with Energy E emits (see previous slides)

$N(E)\ \mathrm{d}E$: number of electrons per unit volume and per unit solid angle moving in the direction of the observer whose energies lie in $[\ E\ ,\ E + \mathrm{d}E\ ]$

Empirical evidence: cosmic rays have an energy distribution function in form of a power law:

$$N(E)\ \mathrm{d}E = K\, E^{-\delta}\ \mathrm{d}E \quad \textit{for } E_1 < E < E_2$$

with K as proportionality constant

A more realistic case: an ensemble of particles with a distribution of energies

Particle energy power law: $N(E)\ \mathrm{d}E = K E^{-\delta}\ \mathrm{d}E$ *for* $E_1 < E < E_2$

One can use this, and in addition introduce **$n = ½ (\delta - 1)$.**

This formula connects the energy distribution index of the relativistic particles with the spectral index of the resulting Synchrotron emission.

Because: evaluating the emissivity equation from the previous slide shows:

$\varepsilon(\nu) \sim \nu^{-n}$ Hence, also for $\varepsilon(\nu)$ a power law emerges!

For different energy ranges, different power law exponents might be valid, but n is typically around 0.6 … 0.8

In a homogeneous B-field : $p = (n + 1) / (n + 5/3)$ as polarisation degree
(p = Intensity of polarised emission / total intensity)

p is independent of frequency in this case
p achieves 72 % for n = 0.75 (remarkably high)

A more realistic case: an ensemble of particles with a distribution of energies

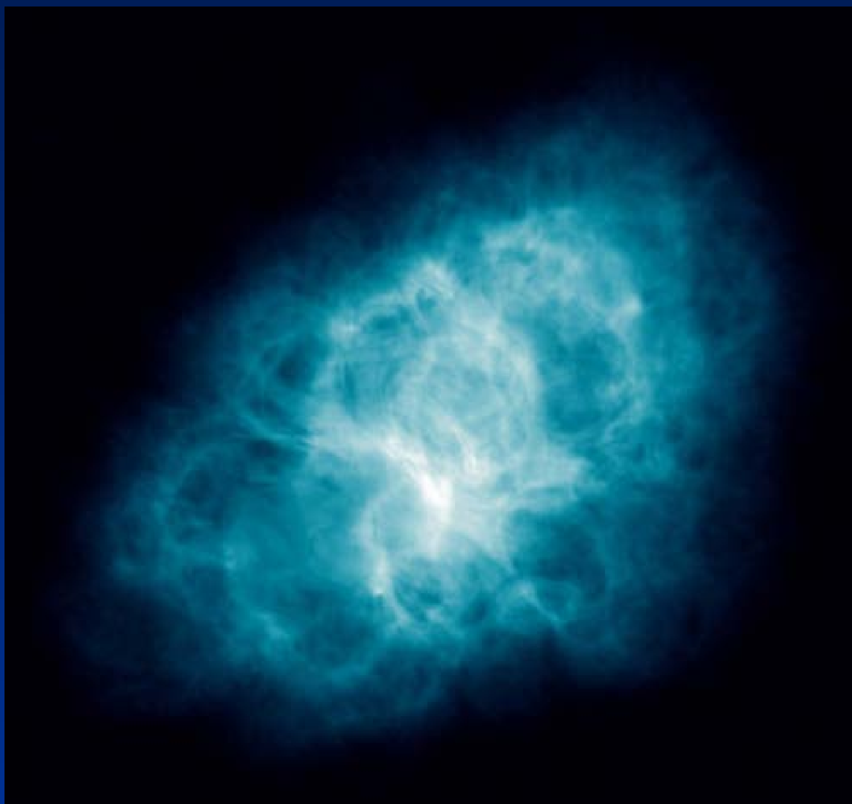
Let us assume a region in which the magnetic field *B* is uniform in strength and orientation, and which extends for the depth *L* along the line of sight. Then the total intensity of the emission is:

$$I(\nu) = 0.933\ a(n)\ K\ L\ B_{\perp}^{n+1}\ \left(6.26 \times 10^{9} / \nu[\mathrm{GHz}] \right)^{n}\ \mathrm{Jy\ sterad}^{-1}$$

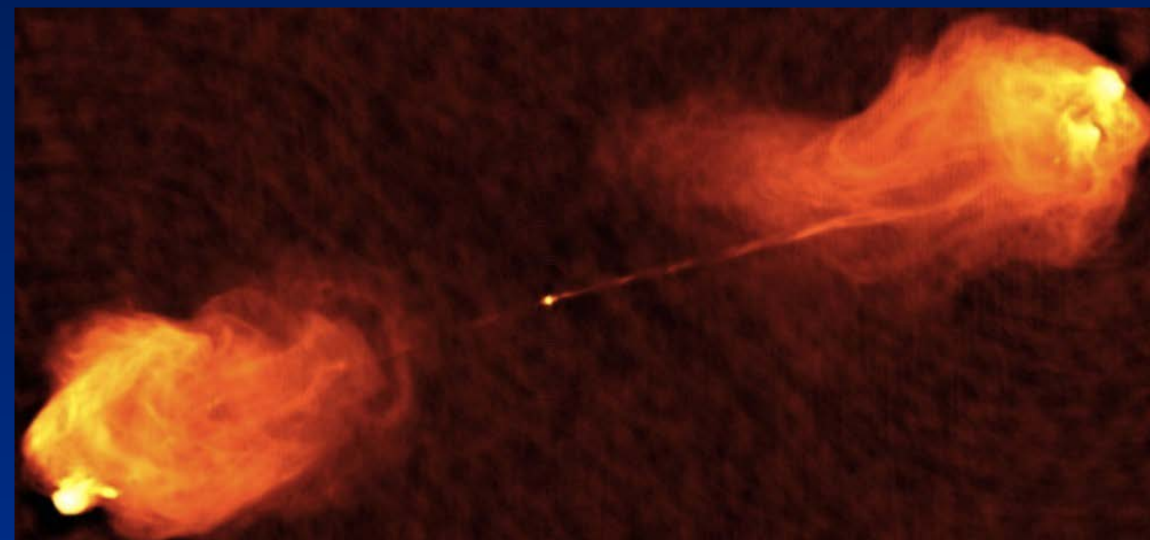
With n = ½ (δ – 1) as seen before,
K as the proportionality constant from the cosmic ray energy power law,
a(n) as a numerical factor that is around 1.5 – 2.5 for the most common n (0.3 – 1.0)

Hence, also the final intensity is ~ ν^{-n} then, and proportional to the strength of the perpendicular component of the B-field to the power of (n+1).

Synchrotron emission in a variety of astrophysical contexts



VLA 5-GHz map of the Crab Nebula, a Supernova remnant



VLA 5-GHz map of Cygnus A, a bright radio galaxy with a prominent jet and lobes

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

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15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week