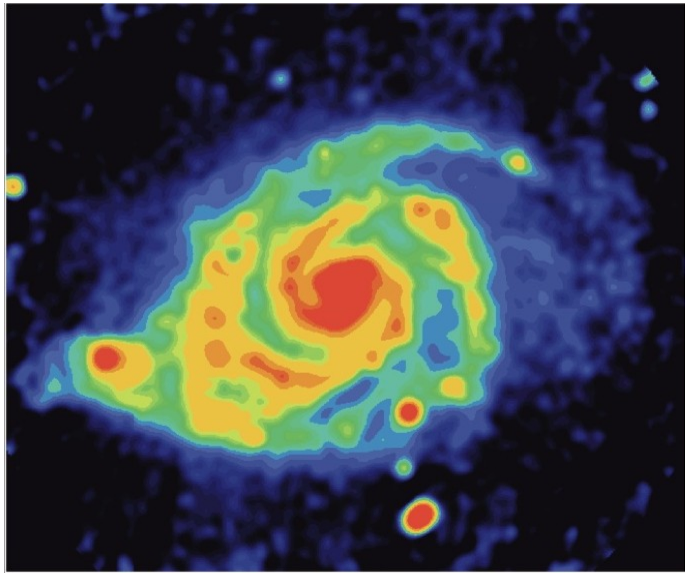
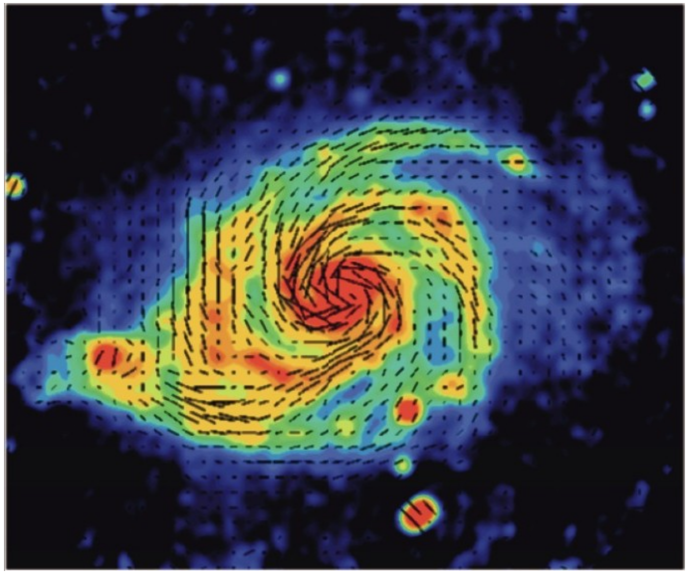
ASTRONOMICKÝ ÚSTAV
Akademie věd České republiky, v. v. i.

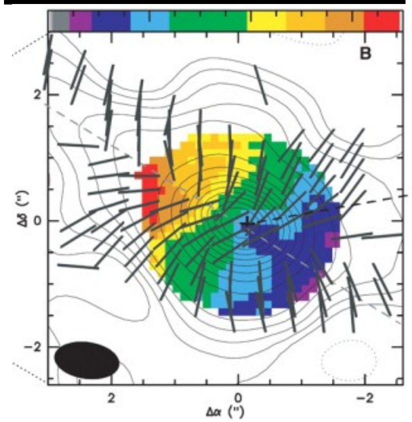
Astrophysical polarimetry

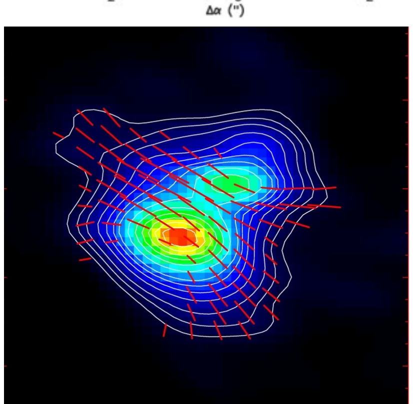
Dr. Frédéric Marin





Total radio continuum emission from the "Whirlpool" galaxy M51 (NRAO/AUI)





Overview

I General introduction

II Polarization : what is it and where can we observe it ?

III Theory

IV Polarization mechanisms

V Observational techniques

VI Modeling polarization

VII Project about radio-loud quasars and polarization

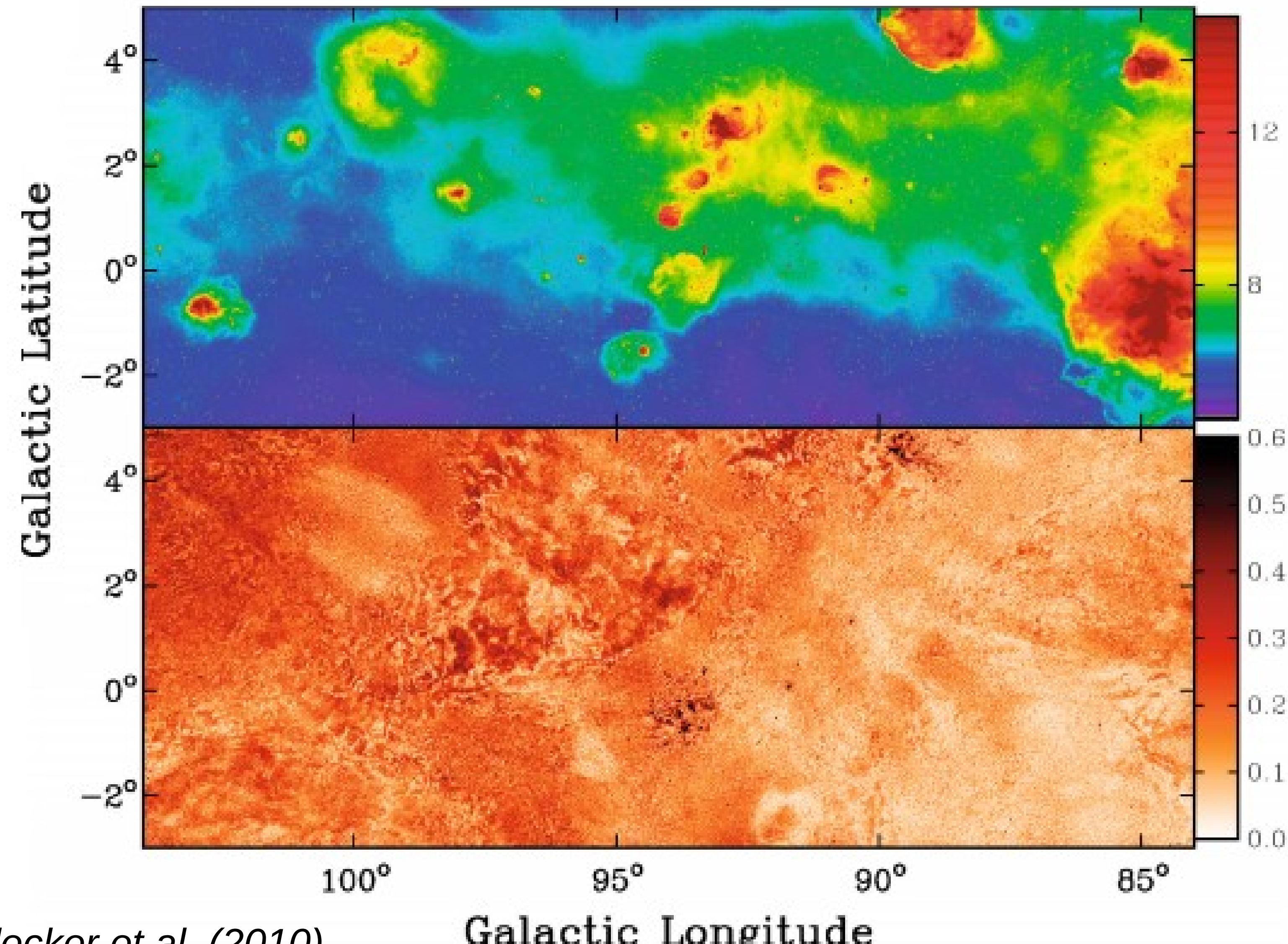
Polarization mechanisms

A variety of physical phenomena may alter the polarization state of an (un)polarized photon

- (Re)Emission mechanisms
- Scattering along the observer's line-of-sight
- Absorption / dilution
- Influence of magnetic fields
- General relativity

Analyzing the resulting polarization of observed light will ultimately bring informations about the location, composition, magnetic fields or physics of the astronomical object of interest

Polarization mechanisms



Landecker et al. (2010)

1420 MHz maps of total intensity (multi-colour) and polarized intensity (orange) in the Galactic Center region

Polarization mechanisms

Emission mechanisms

2 fundamental types of electromagnetic emissions: thermal and non-thermal mechanisms

Thermal radiation

- Continuous spectrum emissions related to temperature
- Specific frequency emissions from atoms and molecules
- ...

Non-thermal radiation

- Emissions due to synchrotron radiation
- Amplified emissions due to astrophysical masers
- ...

Polarization mechanisms

Thermal mechanisms: Black-Body

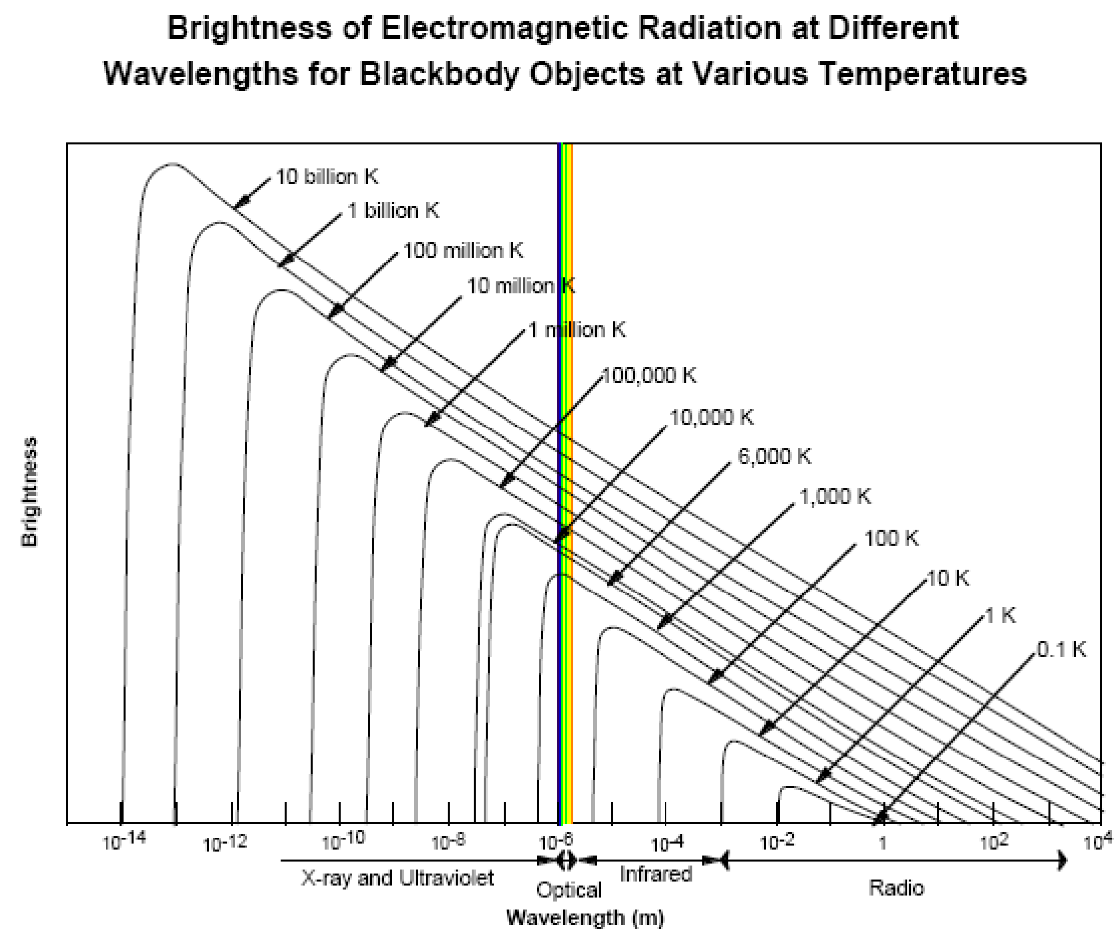
Electromagnetic radiation is produced whenever electric charges accelerate (i.e. speed or direction change)

In T > 0°K molecular regions
- vibration (solid)
- bumping (liquid,gas)

→ molecules send each other off in different directions and at different speeds

→ Each of these collisions produces isotropically emitted radiation

→ T-dependence



Polarization mechanisms

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Type of Radiation	Wavelength Range (nanometers [10^{-9} m])	Radiated by Objects at this Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Few astronomical sources this hot; some gamma rays produced in nuclear reactions
X-rays	0.01 - 20	10^6 - 10^8 K	Gas in clusters of galaxies; supernova remnants, solar corona
Ultraviolet	20 - 400	10^5 - 10^6 K	Supernova remnants, very hot stars
Visible	400 - 700	10^3 - 10^5 K	Exterior of stars
Infrared	10^3 - 10^6	10 - 10^3 K	Cool clouds of dust and gas; planets, satellites
Radio	More than 10^6	Less than 10 K	Dark dust clouds

Polarization mechanisms

Thermal mechanisms: Spectral line emission

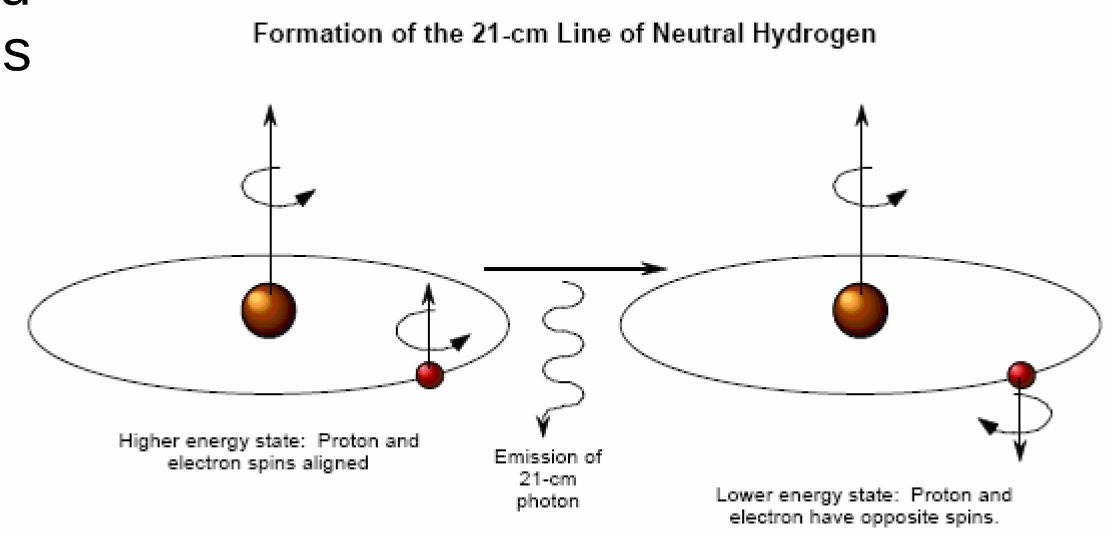
Line emissions from neutral hydrogen (H I) and other atoms and molecules involves the electrons changing energy states within the atom

→ emission a photon of energy at a wavelength characteristic of that atom

Example: H I (key element of the Universe)
In the ground state, the proton and electron spin in opposite directions

If the H I atom acquires a slight amount of energy (by collision) the spins can align (excited state)

Return to ground state: 21.11 cm (1428 MHz) isotropic emission



Polarization mechanisms

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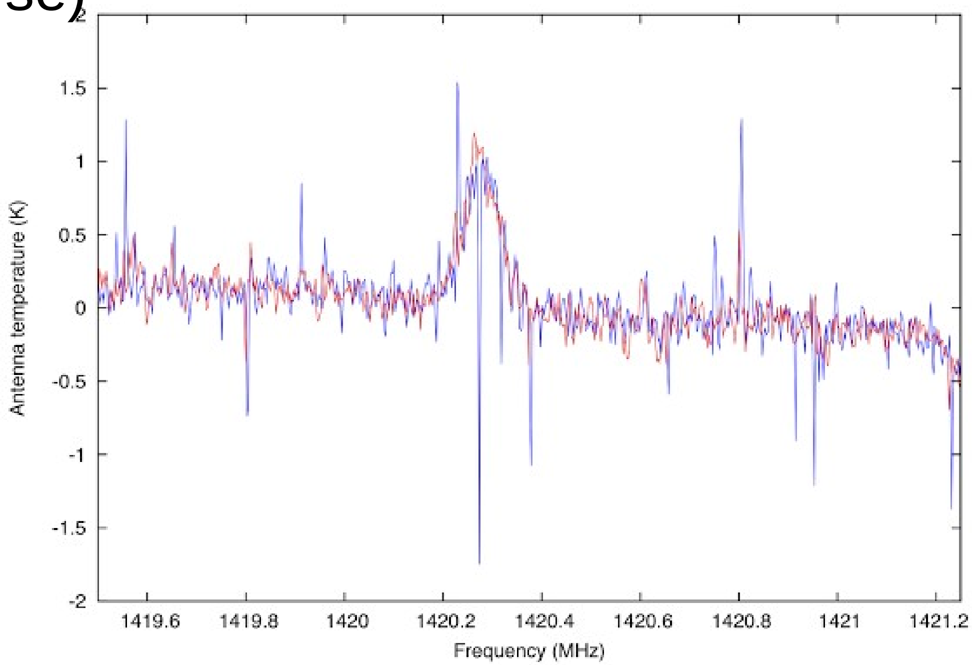


Polarization mechanisms

Emission mechanisms

2 fundamental types of electromagnetic emissions: thermal and non-thermal mechanisms

Thermal radiation

Unpolarized

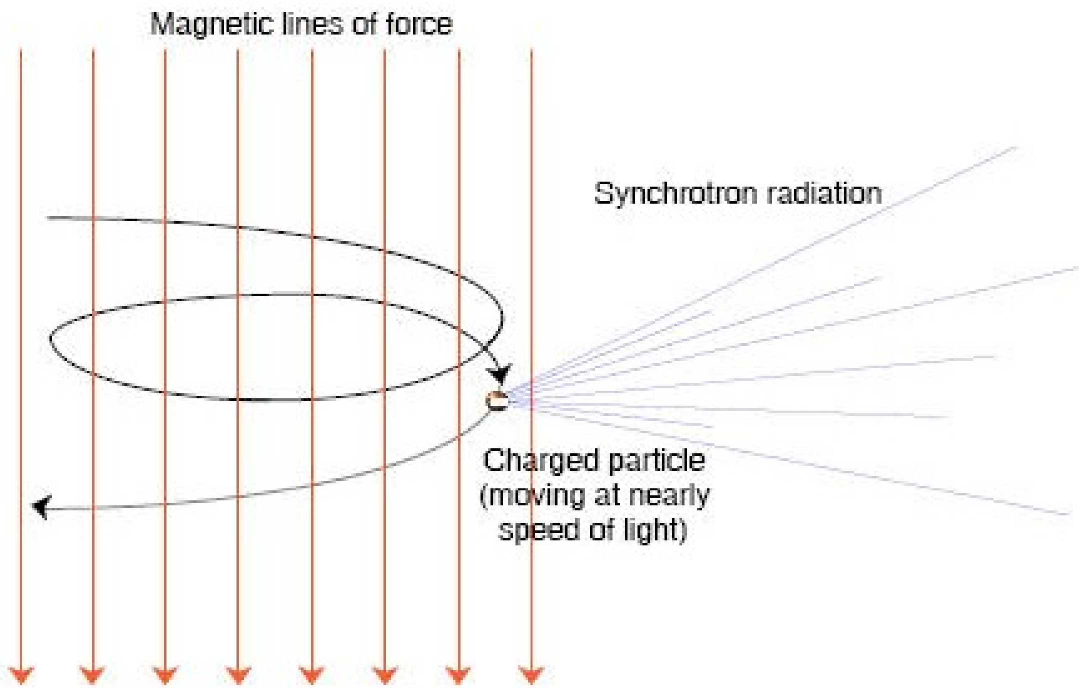
- **Continuous spect[illegible] related to temperature**
- **Specific frequency [illegible]s from atoms and molecules**

Non-thermal radiation

- **Emissions due to synchrotron radiation**
- **Amplified emissions due to astrophysical masers**
- **...**

Polarization mechanisms

Non-thermal mechanisms: Synchrotron radiation



Assume a charge (electron) in a region that has a magnetic field but no electric field

→ acceleration due to the magnetic field (perpendicular to the motion)

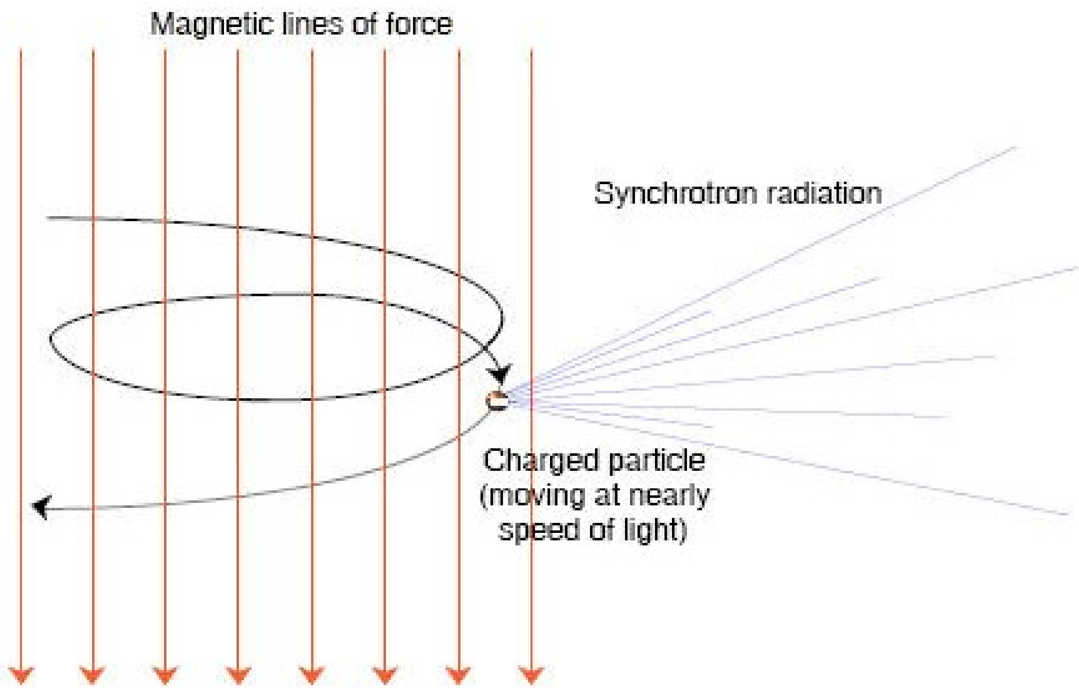
→ a particle of Lorentz factor γ will evolve in momentum and energy

$$\frac{d}{dt}(\gamma m\mathbf{v}) = \frac{q}{c}\mathbf{v} \times \mathbf{B}$$
$$\frac{d}{dt}(\gamma mc^2) = q\mathbf{v} \cdot \mathbf{E} = 0$$

Total speed: constant
Speed along the magnetic field: constant
→ circular motion around the field (with, possibly, a uniform drift)

Polarization mechanisms

Non-thermal mechanisms: Synchrotron radiation



The charge moves in a helix

Perpendicular component of the equation of motion:

$$\frac{d\mathbf{v}_\perp}{dt} = \frac{q}{\gamma mc}\mathbf{v}_\perp \times \mathbf{B}$$

Since $v\perp$ is perpendicular to B,
→ the rate of change of the direction (i.e., the frequency of rotation or gyration) is:

$$\omega_B = qB/(\gamma mc)$$

Cyclotron frequency of a slowly moving particle

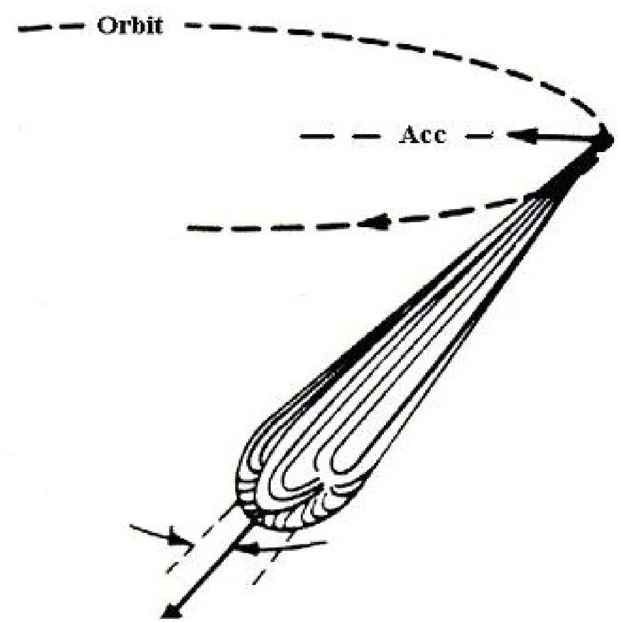
For a fixed Lorentz factor, it is independent of the angle the charge makes to the magnetic field

Polarization mechanisms

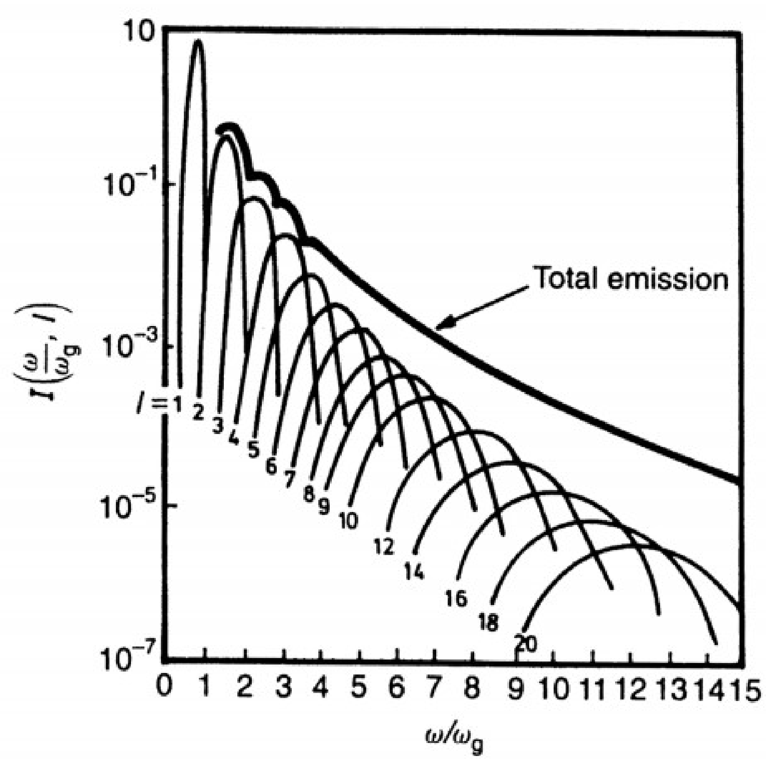
Non-thermal mechanisms: Synchrotron radiation

For relativistic particles, acceleration radiation is beamed in the direction of motion of the charge

→ electric field variation* has sharp peaks



Fourier transform: harmonic decomposition



Power-law synchrotron continuum spectrum

**For very slow particle, the charge is moving in a circle, so the electric field variation is sinusoidal.*

Polarization mechanisms

Non-thermal mechanisms: Synchrotron radiation

The calculation of the polarization of synchrotron radiation can be achieved looking at its perpendicular and parallel component:

$$P_\perp(\omega) = \frac{\sqrt{3}q^3 B\sin(\alpha)}{4\pi mc^2}\left[F(\frac{\omega}{\omega_c}) + G(\frac{\omega}{\omega_c})\right]$$

$$P_{||}(\omega) = \frac{\sqrt{3}q^3 B\sin(\alpha)}{4\pi mc^2}\left[F(\frac{\omega}{\omega_c}) - G(\frac{\omega}{\omega_c})\right]$$

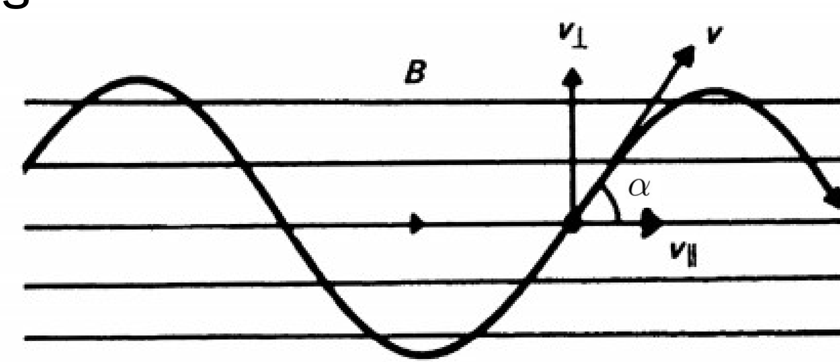
With:

$$F(x) = \frac{\omega}{\omega_c}\int_{\frac{\omega}{\omega_c}}^{\infty} d\epsilon K_{5/3}(\epsilon)$$

$$G(x) = \frac{\omega}{\omega_c}K_{2/3}(\frac{\omega}{\omega_c})$$

$$\omega_c = \frac{3}{2}\gamma^3\omega_S\sin(\alpha)$$

And α the pitch angle of the particle's path is, given by tan $\alpha = v\perp/v_k$
(that is α is the angle between the vectors v and B)



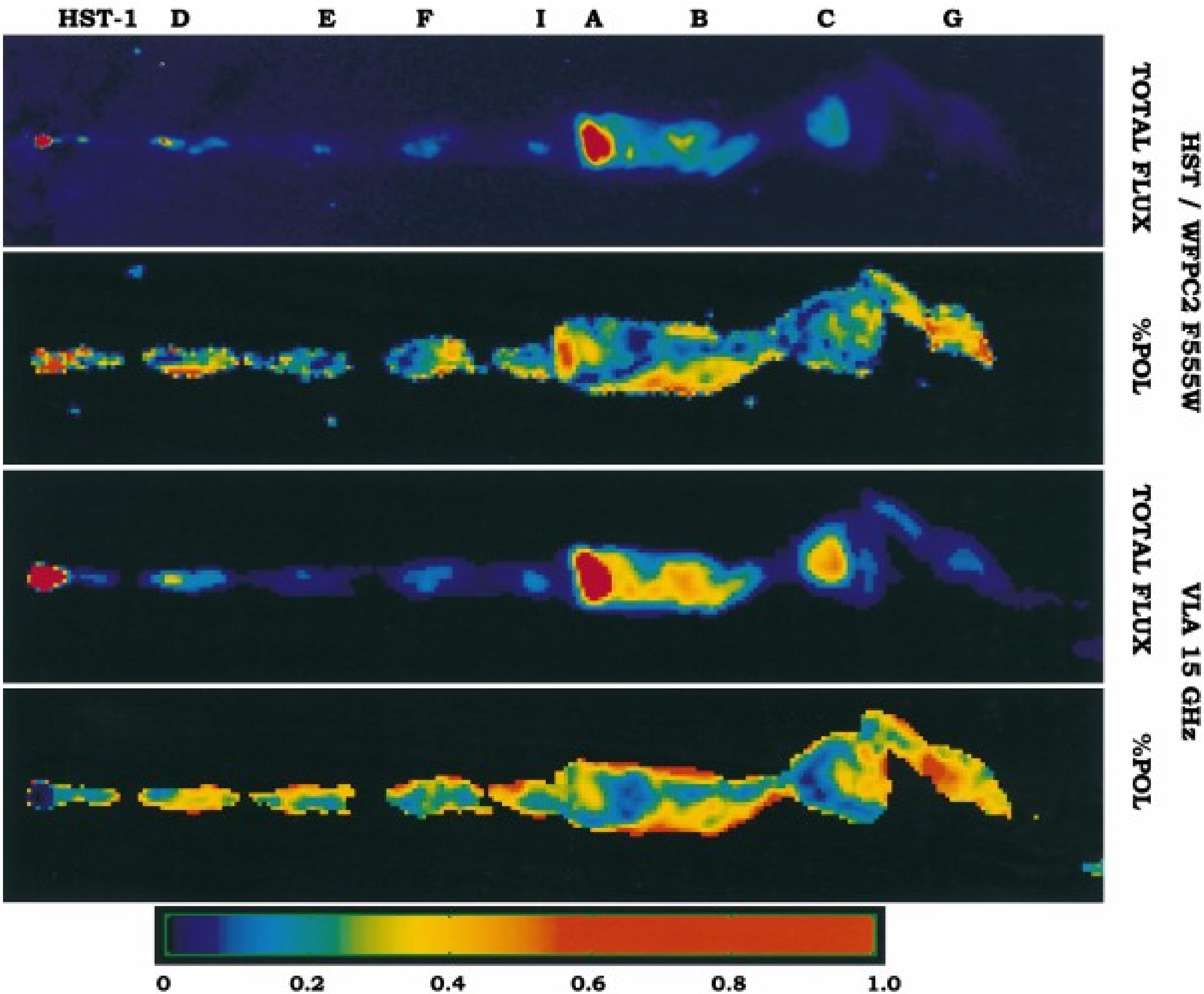
Polarization mechanisms

Non-thermal mechanisms: Synchrotron radiation

If we have a distribution of pitch angles, the right and left circular components cancel out, so we end up with linear polarization

Synchrotron radiation is intrinsically highly polarized, with linear polarization degrees as high as 75 % and an emission polarized parallelly to the projected plane-of-the-sky (perpendicular to the line-of-sight)

Quasars are one of the most powerful sources of synchrotron radiation, from radio to the visible and X-ray bands



M87 HST & VLA observations
Perlman et al (1999)

Polarization mechanisms

Non-thermal mechanisms: Masers

MASER: Microwave-Amplified Stimulated Emission of Radiation

Very compact sites within molecular clouds where emission from certain molecular lines (H2O, OH, SiO, CH3OH) can be enormously amplified

Population inversion (excited state) happens when the clouds are submitted to an intense radiation field (nearby luminous star), or when they collide with H2 molecules

As the radiation causing the pumping travels through the cloud, the original ray is amplified exponentially, emerging at the same frequency and phase as the original ray, but greatly amplified

Intrinsic polarization ? Maybe … but Zeeman effect overwhelms

Polarization mechanisms

<u>Emission mechanisms</u>

2 fundamental types of electromagnetic emissions: thermal and non-thermal mechanisms

Thermal radiation

- Continuous spect[illegible] related to temperature
- Specific frequency [illegible]s from atoms and molecules

Unpolarized

Non-thermal radiation

- Emissions due to syn[illegible]tion
- Amplified emission[illegible]physical masers
- ...

Polarized

Polarization mechanisms

Light – matter interaction

Scattering of light by particles (electrons, atoms, molecules, dust grains …) is one of the most efficient way to create/alter the photon's polarization state

A plethora of scattering mechanisms

- **Thomson scattering**
- **Compton / Inverse-Compton scattering**
- **Rayleigh scattering**
- **Mie scattering**
- **Dichroic extinction**
- **Resonant scattering**

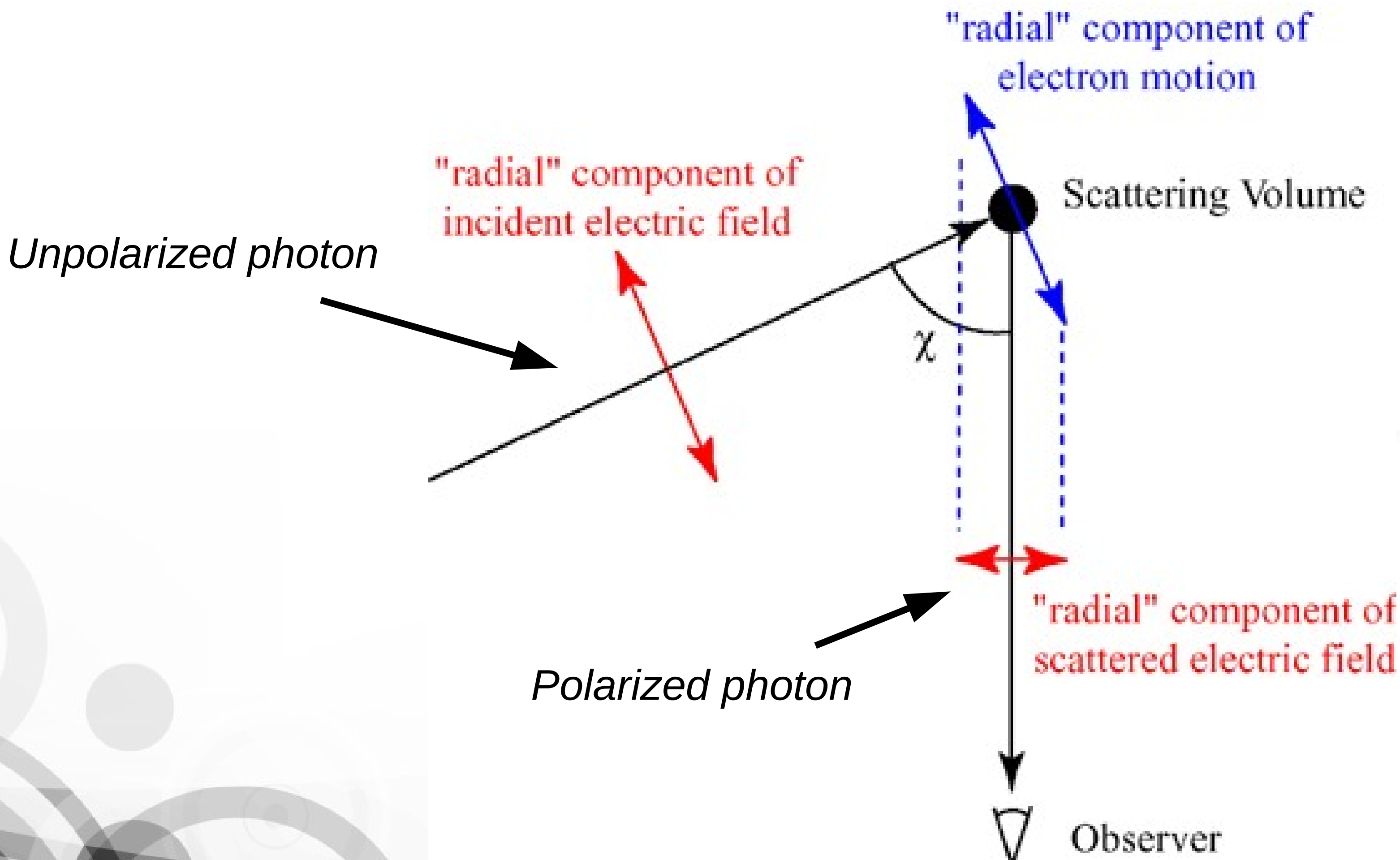
...

Let's focus on several examples

Polarization mechanisms

<u>Electron scattering</u>

Scattering-induced polarization



Polarization mechanisms

<u>Electron scattering</u>

3 regimes

- Scattering of photon by a free, non-relativistic, charged particle ($h\nu << m_e c^2$): Thomson scattering

- Scattering of photon by a free, non-relativistic, charged particle ($h\nu >> m_e c^2$): Compton scattering

- Scattering of photon by a free, relativistic, charged particle ($h\nu >> m_e c^2$): Inverse Compton scattering

Polarization mechanisms

<u>Electron scattering</u>

Scattering of photon by a free, non-relativistic, charged particle ($h\nu \ll m_e c^2$): Thomson scattering

Elastic scattering (kinetic energy is conserved in the center-of-mass frame)

Integrated cross-section (effective area that governs the probability of some scattering or absorption event):

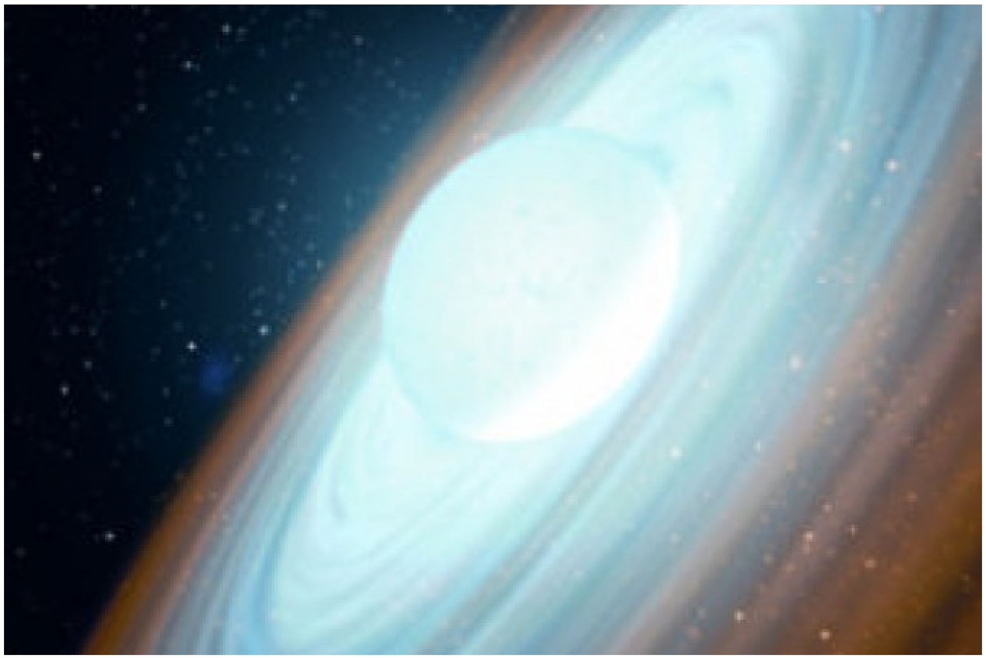
$$\sigma \simeq \frac{8\pi}{3} r_0^2 \simeq 0.665 \times 10^{-24} \text{ cm}^2$$

The scattering matrix describing the transformation of the incoming Stokes vector is given by:

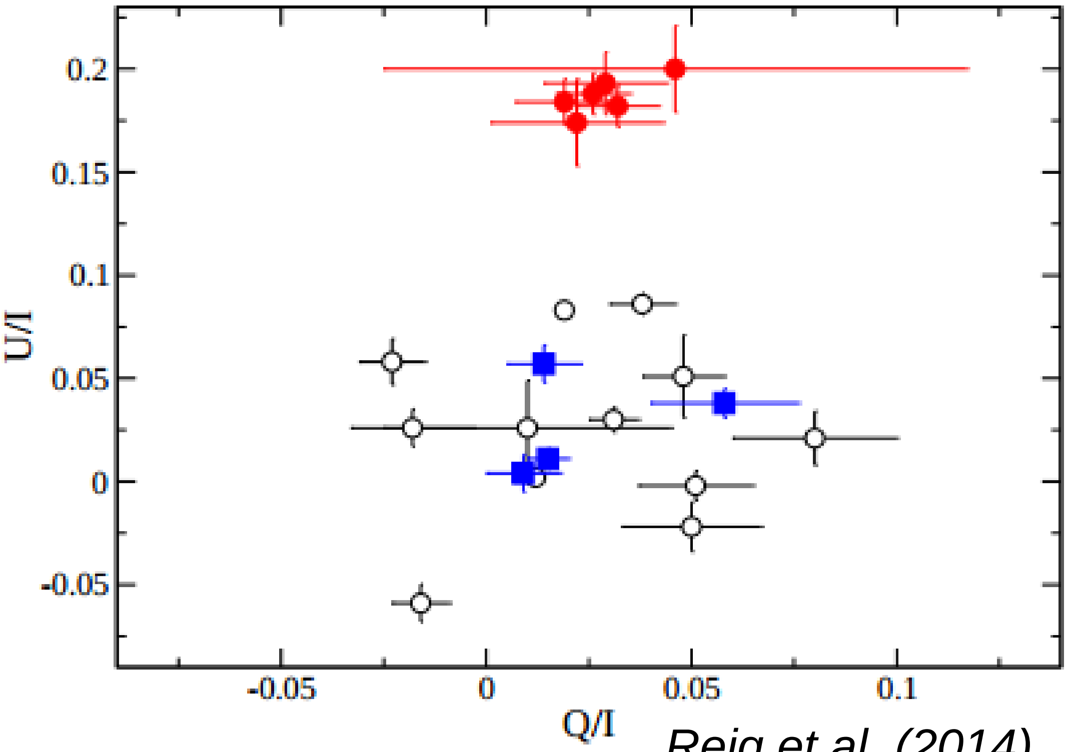
$$\widehat{R}(\mu) = \frac{3}{4} \begin{pmatrix} 1+\mu^2 & \mu^2-1 & 0 & 0 \\ \mu^2-1 & 1+\mu^2 & 0 & 0 \\ 0 & 0 & 2\mu & 0 \\ 0 & 0 & 0 & 2\mu \end{pmatrix}$$

Polarization mechanisms

Electron scattering



Be star



Reig et al. (2014)

Polarization in classical Be stars results from Thomson scattering of the unpolarized light from the Be star in the circumstellar disc

Polarization mechanisms

Electron scattering

Scattering of photon by a free, non-relativistic, charged particle ($h\nu >> m_e c^2$): Compton scattering

Inelastic scattering

Energy shift of the photon (towards longer wavelengths)

Integrated cross-section

$$\sigma = 2\pi r_0^2 \left\{ \frac{1+\delta}{\delta^3} \left(\frac{2\delta(1+\delta)}{1+2\delta} - \ln(1+2\delta) \right) + \frac{\ln(1+2\delta)}{\delta} - \frac{1+3\delta}{(1+2\delta)^2} \right\}$$

Thomson scattering matrix as a bad approximation of Compton scattering matrix

Polarization mechanisms

Electron scattering

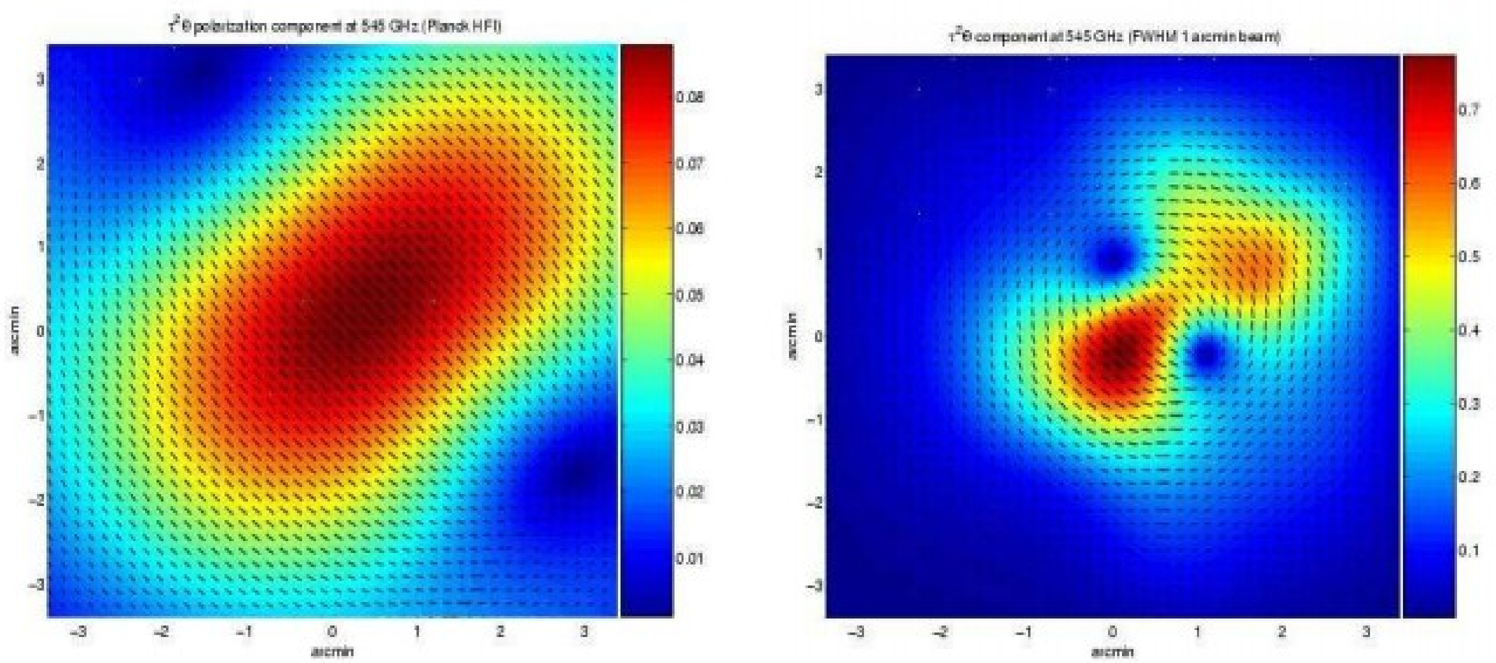


Fig. 9. The $\tau^2\Theta$ polarization component convolved with the Planck HFI 4.5' FWHM beam (left) and with a FWHM 1' beam (right). Color scale is in μK.

Rephaeli et al. (2006)

Compton scattering of the CMB in galaxy clusters

Polarization mechanisms

<u>Electron scattering</u>

Scattering of photon by a free, relativistic, charged particle ($h\nu >> m_e c^2$): Inverse Compton scattering

Inelastic scattering

Energy shift of the photon (towards smaller wavelengths)

Integrated cross-section

$$\sigma(x) = \begin{cases} \frac{1}{3} + 0.141x - 0.12x^2 + (1+0.5x)(1+x)^{-2} & \text{if} \quad x \leq 0.5 \\ (\ln(1+x) + 0.06)x^{-1} & \text{if} \quad x \leq 0.5 \leq 3.5 \\ (\ln(1+x) + 0.5 - (2+0.076x)^{-1})x^{-1}) & \text{if} \quad 0.5 \leq x \end{cases}$$

With:

$$x = \frac{2h\nu}{m_e c^2}\gamma\left(1 - \beta\cos(\theta')\right)$$

Polarization mechanisms

<u>Electron scattering</u>

Scattering of photon by a free, relativistic, charged particle ($h\nu >> m_e c^2$): Inverse Compton scattering

If *x* is the initial photon beam energy with $x = h\nu/m_e c^2$, *x′* the scattered photon beam and an isotropic electron gas with a fixed energy χ, then the Compton scattering matrix is:

$$\widehat{R}(x, x_1, \mu, \chi) = \begin{pmatrix} R & R_I & 0 & 0 \\ R_I & R_Q & 0 & 0 \\ 0 & 0 & R_U & 0 \\ 0 & 0 & 0 & R_V \end{pmatrix}$$

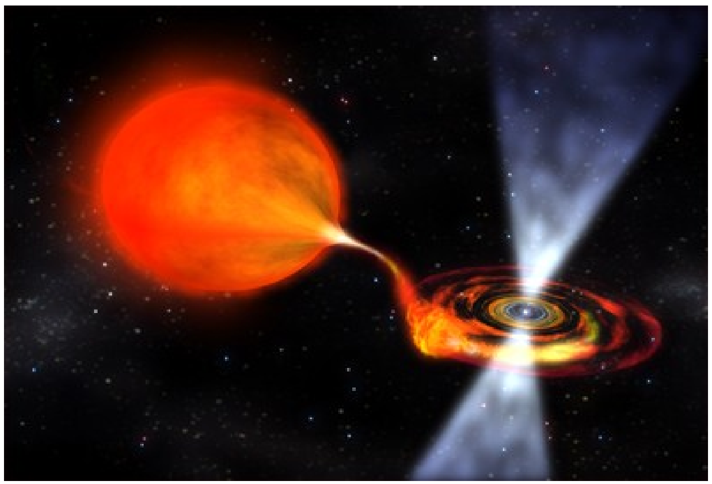
$$\begin{aligned} R &= R_a + R_b \\ R_I &= R_a + R_c \\ R_Q &= \frac{2}{Q} + 2\frac{u-Q}{rq}\left[\frac{u-Q}{rq}(2Q+u) - 4\right] + \frac{2u}{vq} + 2R_c \\ R_U &= R_U + R_a \\ R_V &= R_b - qR_a \end{aligned}$$

$$\begin{aligned} R_a &= u\frac{(u^2-Q^2)(u^2+5v)}{2q^2v^3} + u\frac{Q^2}{q^2v^2} \\ R_b &= \frac{2}{Q} + \frac{u}{v}\left(1 - 2\frac{2}{q}\right) \\ R_c &= \frac{u}{vq}\left(\frac{u^2-Q^2}{rq} - 2\right) \end{aligned}$$

$$\begin{aligned} q &= xx_1(1-\mu) \\ Q^2 &= x^2 + x_1^2 - 2xx_1\mu \\ u &= a_1 - a \\ v &= aa_1 \\ r &= \frac{1+\mu}{1-\mu} \\ a^2 &= (\chi - x)^2 + r \\ a_1^2 &= (\chi + x_1)^2 + r \end{aligned}$$

Polarization mechanisms

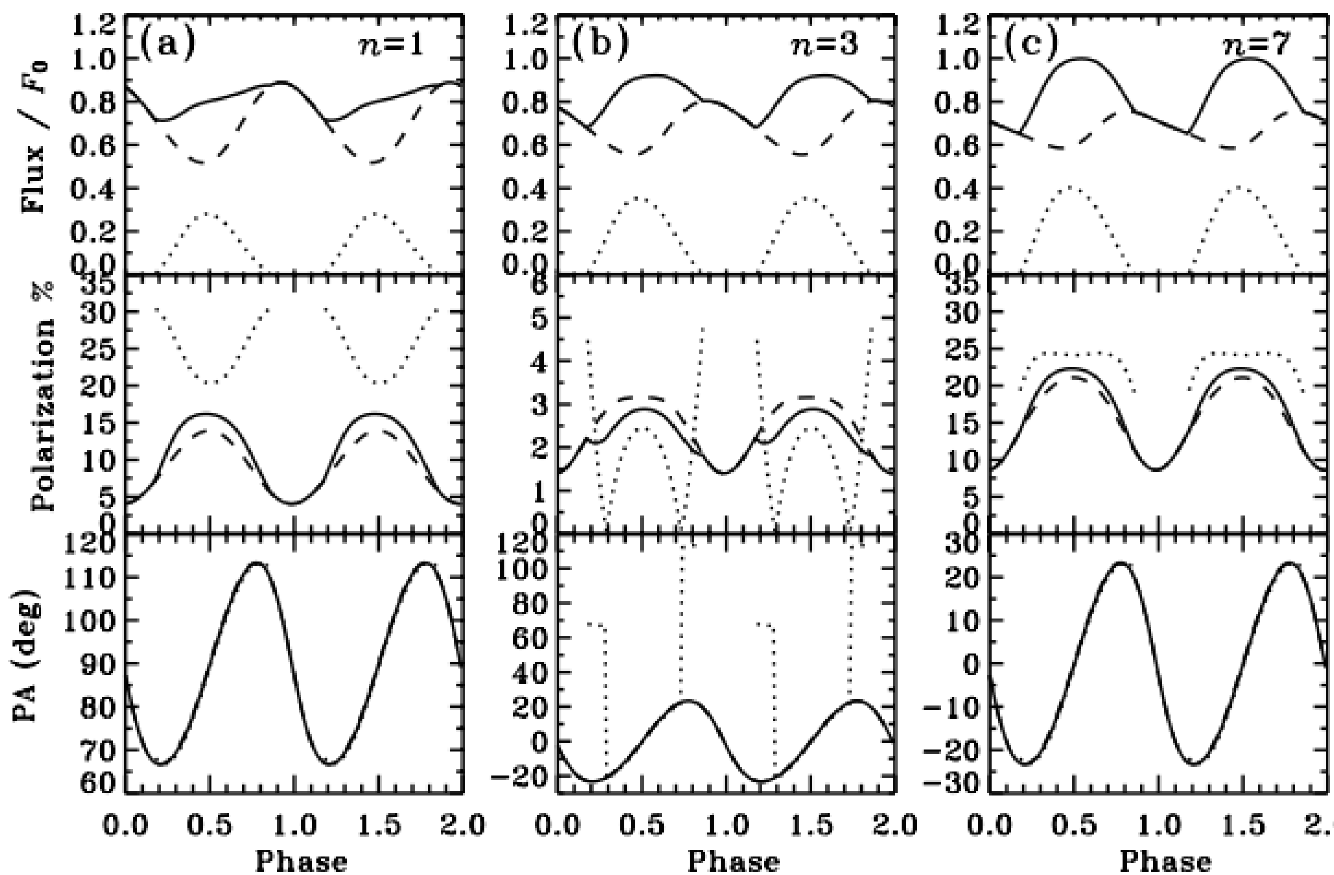
Electron scattering



Accreting milli-second pulsar

The spectra of accreting millisecond pulsars can be represented as a sum of a BB-like emission and a Comptonized tail

Viironen & Poutanen (2004)



Polarization mechanisms

<u>Atom scattering</u>

Collision event between radiation and an atom
→ Rayleigh scattering mechanism

The theory is similar to Thomson scattering but in the case of Rayleigh scattering, the electron is bound to the atom ($\omega << \omega 0$), so the scattering cross section becomes:

$$\sigma_\omega \simeq \frac{8\pi}{3} r_0^2 \left(\frac{\omega}{\omega_0}\right)^4$$

The scattering cross section is now wavelength-dependent. It increases with the frequency of the incident radiation (approximatively increasing with λ^{-4})
→ similar scattering matrix

The Thomson/Rayleigh scattering matrix holds for non-relativistic electrons and atoms with sizes inferior to 0.2 λ

Polarization mechanisms

<u>Atom scattering</u>

Buenzli & Schmid (2009)

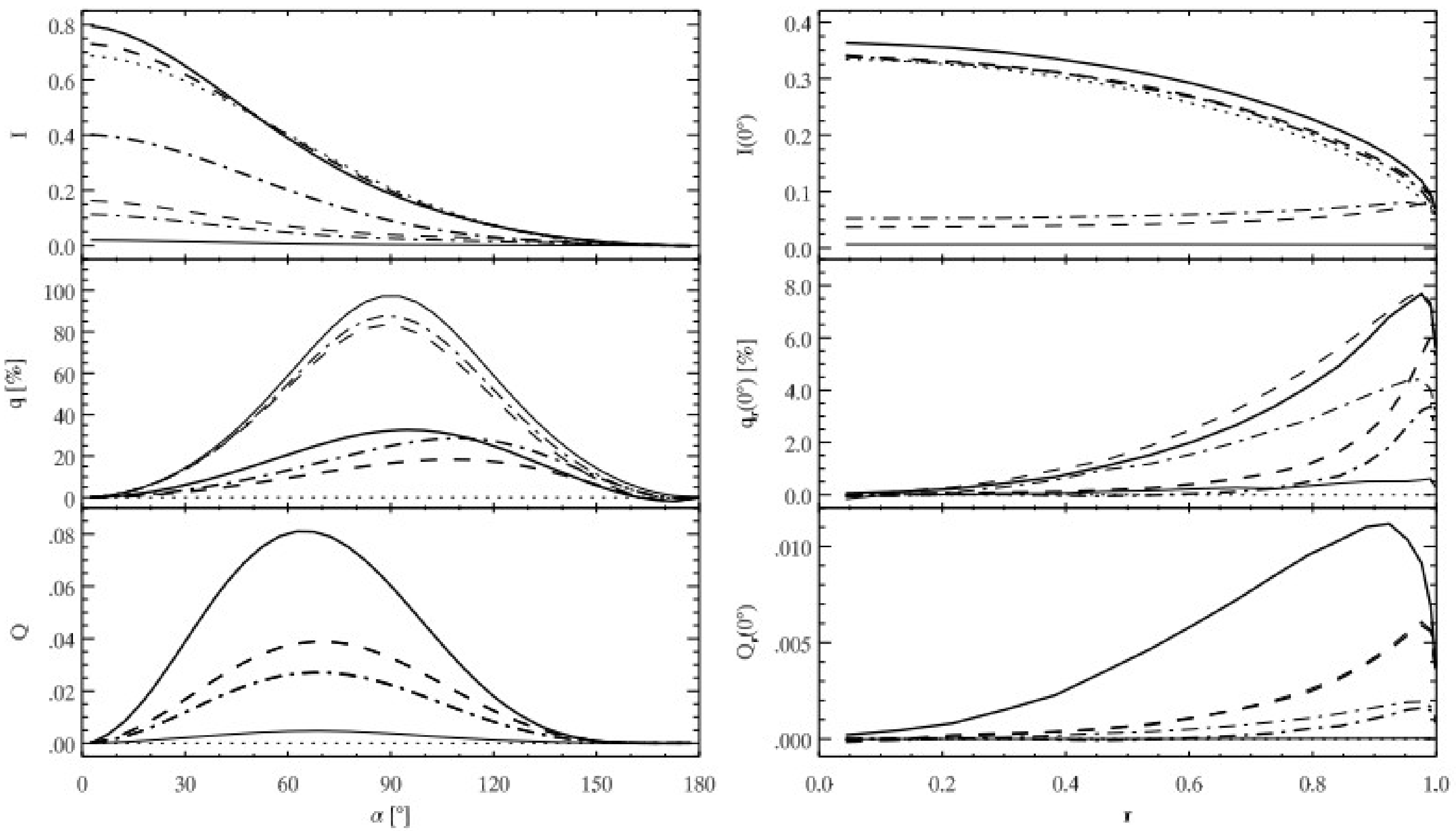


Fig. 2. *Left*: phase dependence of the intensity I, fractional polarization q and polarized intensity Q for Rayleigh scattering atmospheres. *Right*: radial dependence of the intensity I, radial polarization q_r and radial polarized intensity Q_r at opposition. Line styles denote: semi-infinite case $\tau_{sc} = \infty$ (solid) for single scattering albedos $\omega = 1$ (thick), 0.1 (thin) and finite atmosphere ($\tau_{sc} = 0.3$) with $\omega = 1$ (dashed) and 0.6 (dash-dot) for surface albedos $A_S = 1$ (thick) and 0 (thin). Also shown is the intensity curve for conservative semi-infinite isotropic scattering (dotted).

Rayleigh scattering on planetary atmospheres

Polarization mechanisms

Dust grains scattering

Scattering events by small particles with dimensions smaller than the incident photon wavelength are called Rayleigh scattering

In the case of spherical particles of the same or larger size than the wavelength, Rayleigh scattering does not hold anymore and one must take into account another scattering mechanism

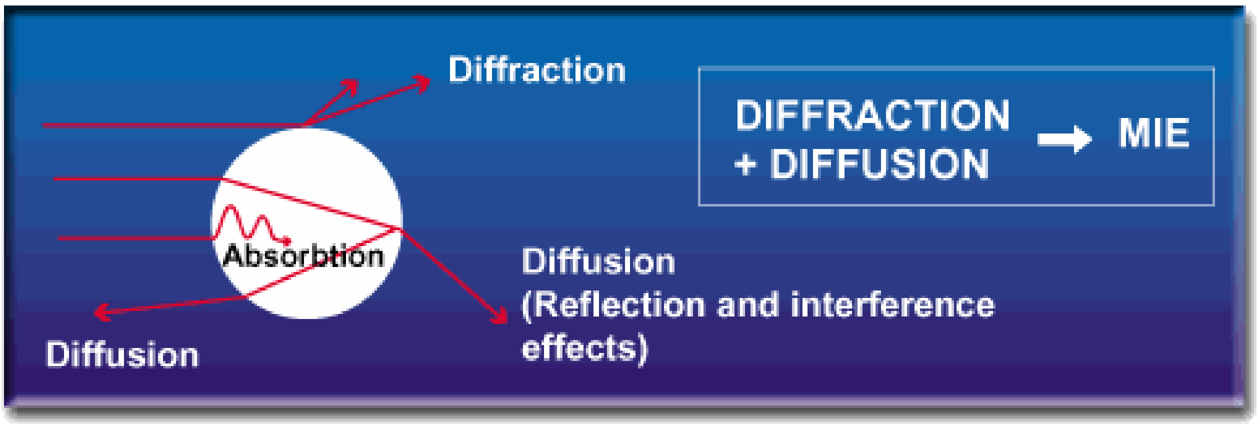
→ Mie theory

Based on Maxwell's equations

Scattering mechanism for reprocessing off spheres immersed in an isotropic medium, having a homogeneous refractive index and dimensions in the range of the incoming wavelength

Polarization mechanisms

Dust grains scattering



The Mie model takes into account both diffraction and diffusion of the light around the particle in its medium.

To use the Mie model, it is necessary to know the complex refractive index of both the sample and the medium

This complex index has a real part, which is the standard refractive index, and an imaginary part, which represents absorption

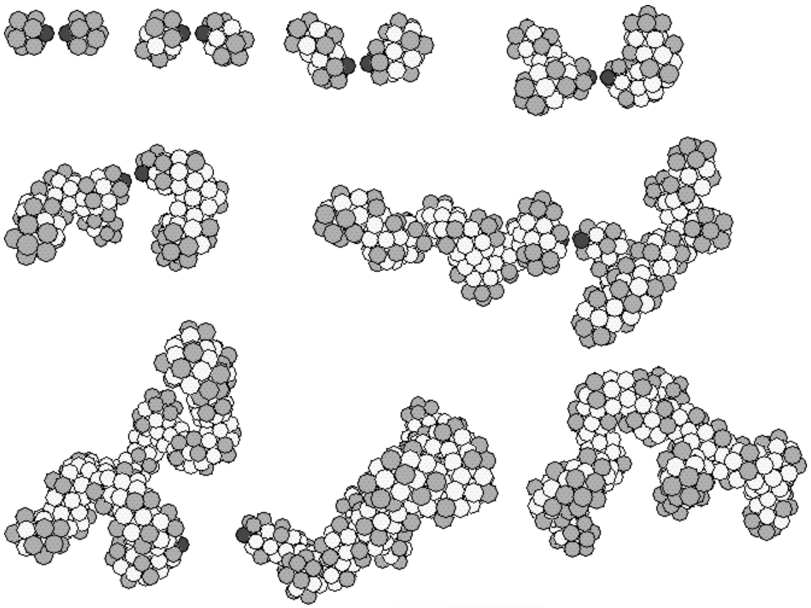
Polarization mechanisms

<u>Dust grains scattering</u>

In the case of an ideal, homogeneous, isotropic medium filled with dust grains, if there system is symmetric with respect to any central point, the grains have no rotational capabilities and the scattering matrix is simple

However, if the dust model includes dust grains with different sizes and composition (such as graphite and silicate), the scattering and extinction properties must be integrated:

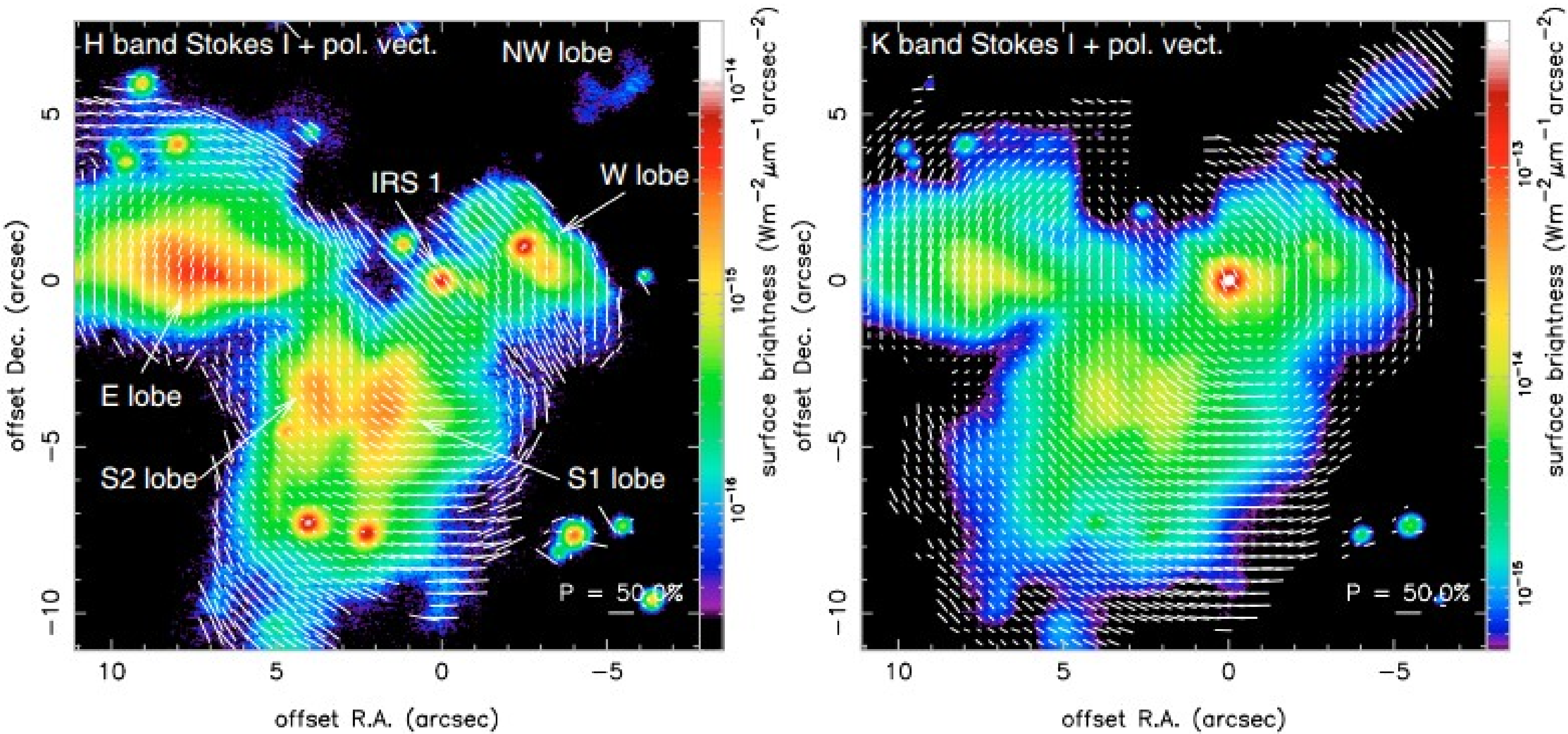
$$\widehat{R}(\theta) = \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{21} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & S_{43} & S_{44} \end{pmatrix}$$



Polarization mechanisms

Dust grains scattering

Murakawa et al. (2008)



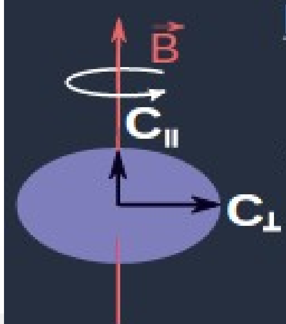
Dust environment of the massive proto-stellar object CRL 2136 (infrared)

Polarization mechanisms

Dust grains scattering

Ideal models of spherical dust grains; reality is much more unsymmetrical

Ovoidal grains can be characterized by their parallel and perpendicular symmetry axis: two distinct absorption cross sections can be attributed along the particle vertical and horizontal planes



Radiative transfer:

$$\frac{d}{ds}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = -n(s)\begin{pmatrix} C_{ext} & \Delta C_{ext} & 0 & 0 \\ \Delta C_{ext} & C_{ext} & 0 & 0 \\ 0 & 0 & C_{ext} & -\Delta C_{pha} \\ 0 & 0 & \Delta C_{pha} & C_{ext} \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Cross sections :

$$C_{ext} = C_{ext\perp} + C_{ext//}$$
$$\Delta C_{ext} = C_{ext\perp} - C_{ext//}$$
$$\Delta C_{pha} = C_{pha\perp} - C_{pha//}$$

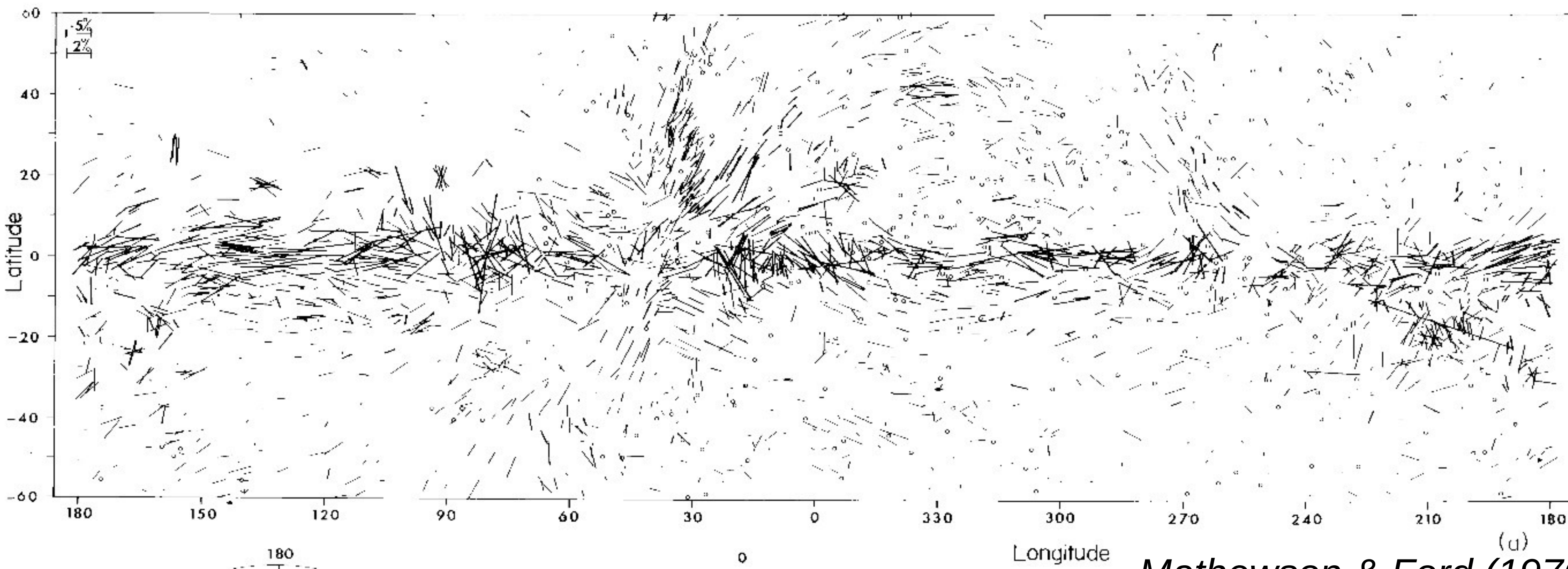
And if the dust grains are immersed in a magnetic environment, they statistically align along the magnetic fields

Aligned non-spherical grains produce scattered polarization signatures in optical wavelengths and polarized emission in far-IR wavelengths

→ dichroic extinction

Polarization mechanisms

<u>Dust grains scattering</u>



Mathewson & Ford (1970)

Interstellar polarization map of the Galaxy

Polarization mechanisms

Molecule scattering (Raman effect)

1928: discovery of the fact that the wavelength of a small fraction (approximately 1 in 10 millions) of the radiation scattered by certain molecules differs from that of the incident beam
Raman (1928), Raman & Krishnan (1928b,a)

Furthermore, the shifts in wavelength depend upon the chemical structure of the molecules responsible for the scattering

In fact, there is an energetic exchange between the molecule and the radiation that can produce either an emission line at the same frequency or emission lines at shifted frequencies

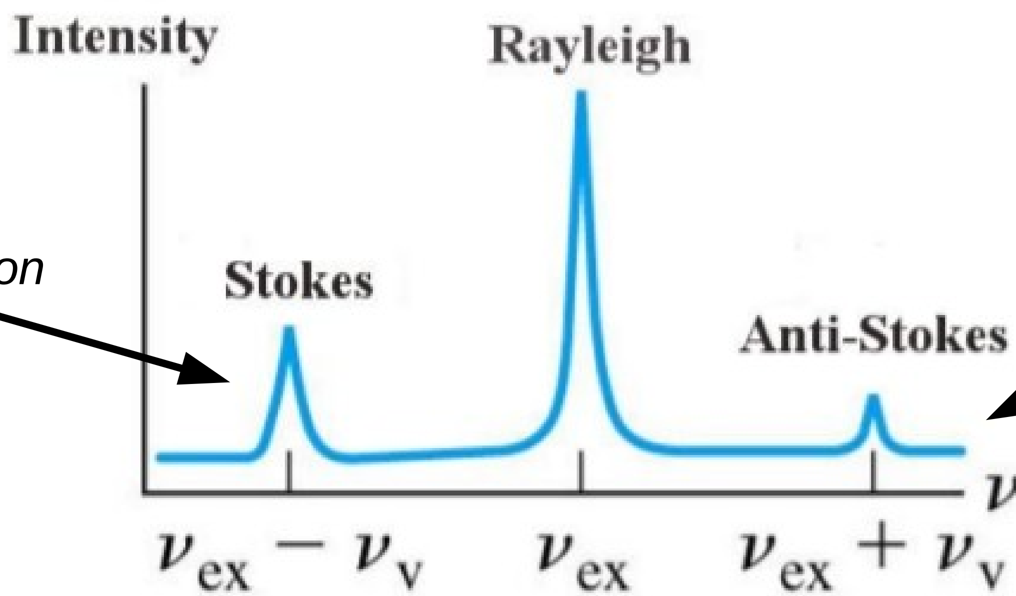
This is the Raman effect

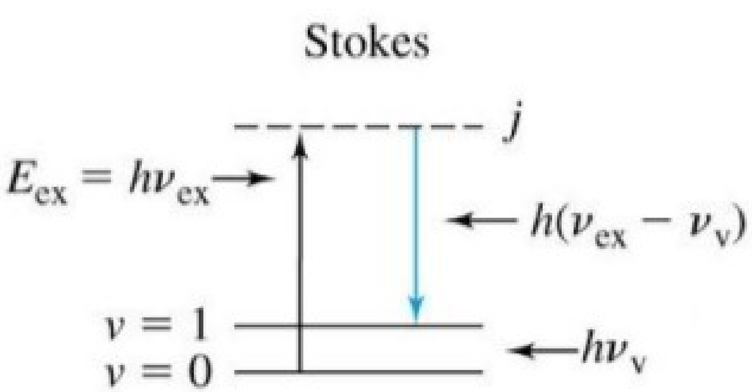
Polarization mechanisms

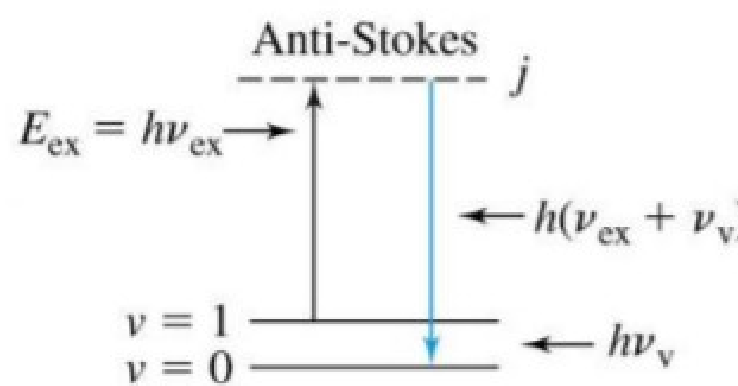
<u>Molecule scattering (Raman effect)</u>

Small depolarization

Small depolarization



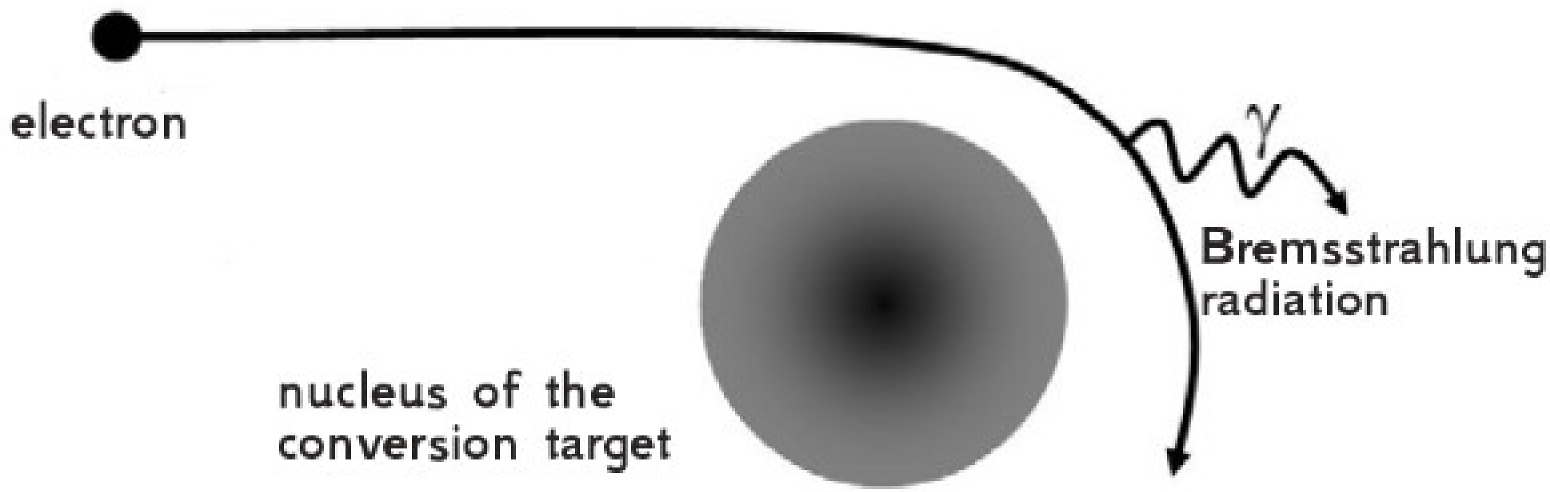




Polarization mechanisms

<u>Bremsstrahlung</u>

The classical theory of electromagnetism predicts that if a particle of mass *m* and charge *z* passes in the vicinity of the electric field of a nucleus of charge *Z*, it is deflected from its original path and slowed down



The energy given away by the particle results in the emission of electromagnetic radiation with a continuous, bremsstrahlung spectrum

Polarization mechanisms

Bremsstrahlung

The energy carried by the escaping radiation is defined by the energy loss ΔE_{br} such as:

$$\Delta E_{br} = \frac{z^2 \ Z^2 \ e^4}{m^2 \ r^4}$$

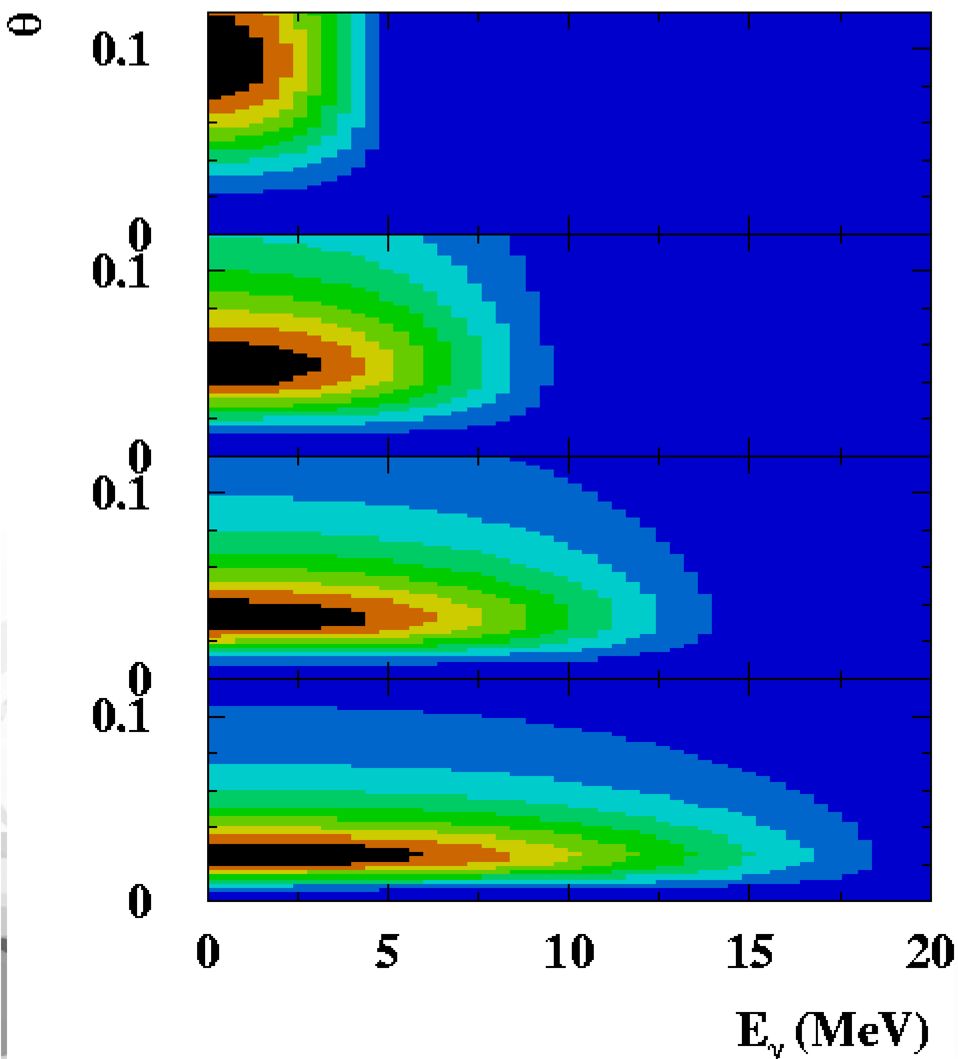
with *r* the distance between the electron and the charged particle and *e* the elemental electron charge

Bremsstrahlung radiation is generally polarized regardless of the polarization state of the incident electron (McMaster 1961):

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I \\ D \\ 0 \\ -S_1 L - S_2 T \end{pmatrix}$$

Polarization mechanisms

Bremsstrahlung



Degree of polarization for four different electron beam energies in dependence of the photon energy (x-axis) and the emission angle θ (y-axis)

Bremsstrahlung polarization is more relevant for laboratory experiment (particles accelerators) than in astronomy where no net polarization is usually detected

May & Wick (1951)
Helmholtz-Zentrum Dresden-Rossendorf

Polarization mechanisms

Reemission mechanisms

As seen from the previous section, when photons scatter on atoms or molecules, they are deviated from their original path and their polarization properties change

However, it may happen that the photon is converted by matter to emit another, different electromagnetic wave with new properties

- Atomic recombination
- Fluorescent emission

Polarization mechanisms

Atomic recombination

When electrons and ions are confined in a hot plasma, with electron temperatures exceeding 10^6 °K, various collisional processes occur (primarily through electron-ion interactions)

Collisional processes (major contribution):

- Excitation
- Ionization

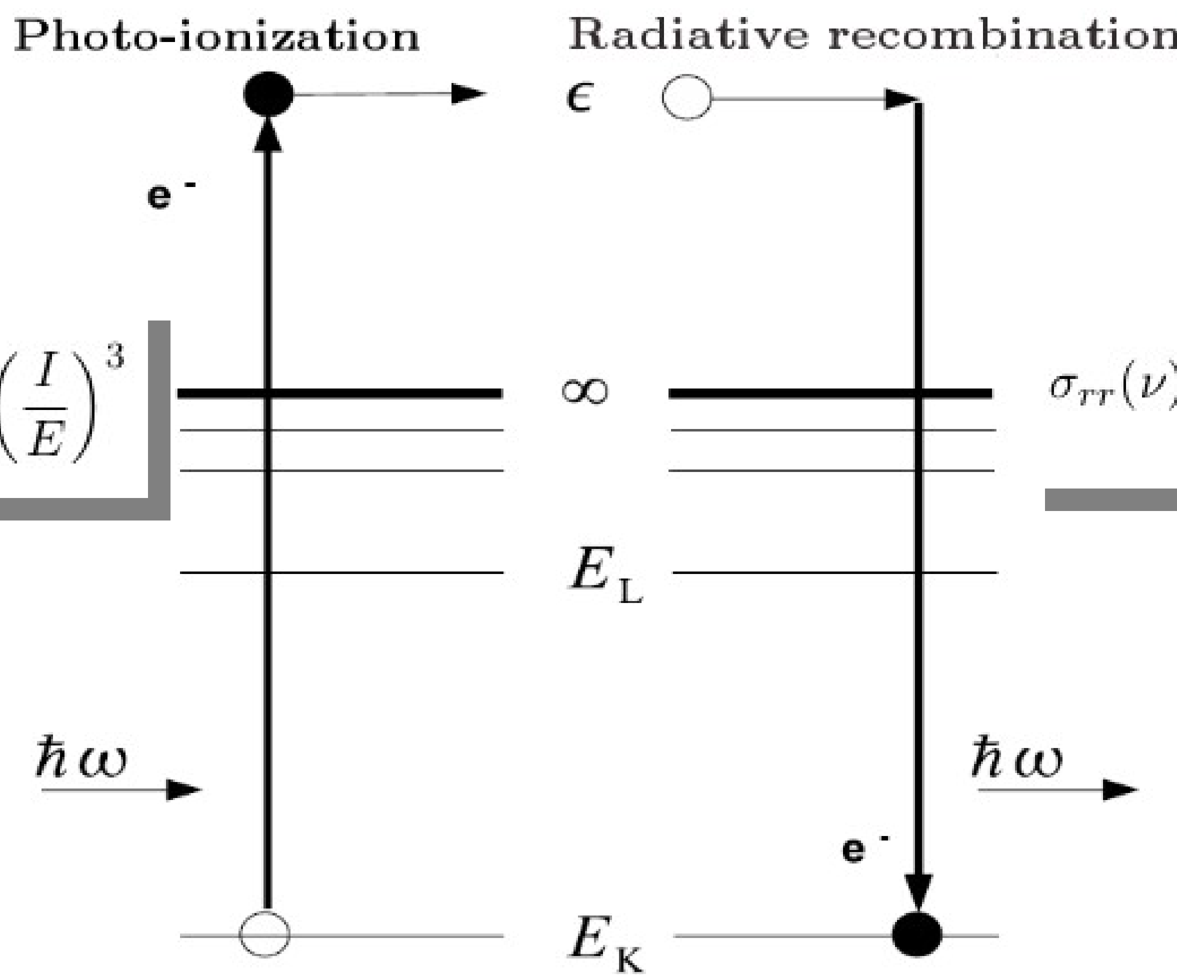
Recombination processes (minor contribution)

Recombination processes are important in determining the ionization equilibrium and the population of excited states in non-equilibrium plasmas.

Polarization mechanisms

Atomic recombination

$$\sigma_{ph} = \frac{64\pi}{3\sqrt{3}} \frac{n\xi b_0 g(E,n)}{Z^2} \left(\frac{I}{E}\right)^3$$



$$\sigma_{rr}(\nu) = \frac{E^2 g_n \sigma_{ph}}{m_e^2 c^2 \nu^2}$$

Hahn & Rule (1977)

An incident free electron is captured by an ion of charge Z, considered at rest, giving a final ion of charge Z – 1 with the simultaneous emission of a recombination photon. Radiative recombination is the inverse process of photo-ionization

Polarization mechanisms

<u>Atomic recombination</u>

If the radiative recombination cross section is averaged over a Maxwell distribution of electrons, the recombination coefficient R_n to level n can be obtained:

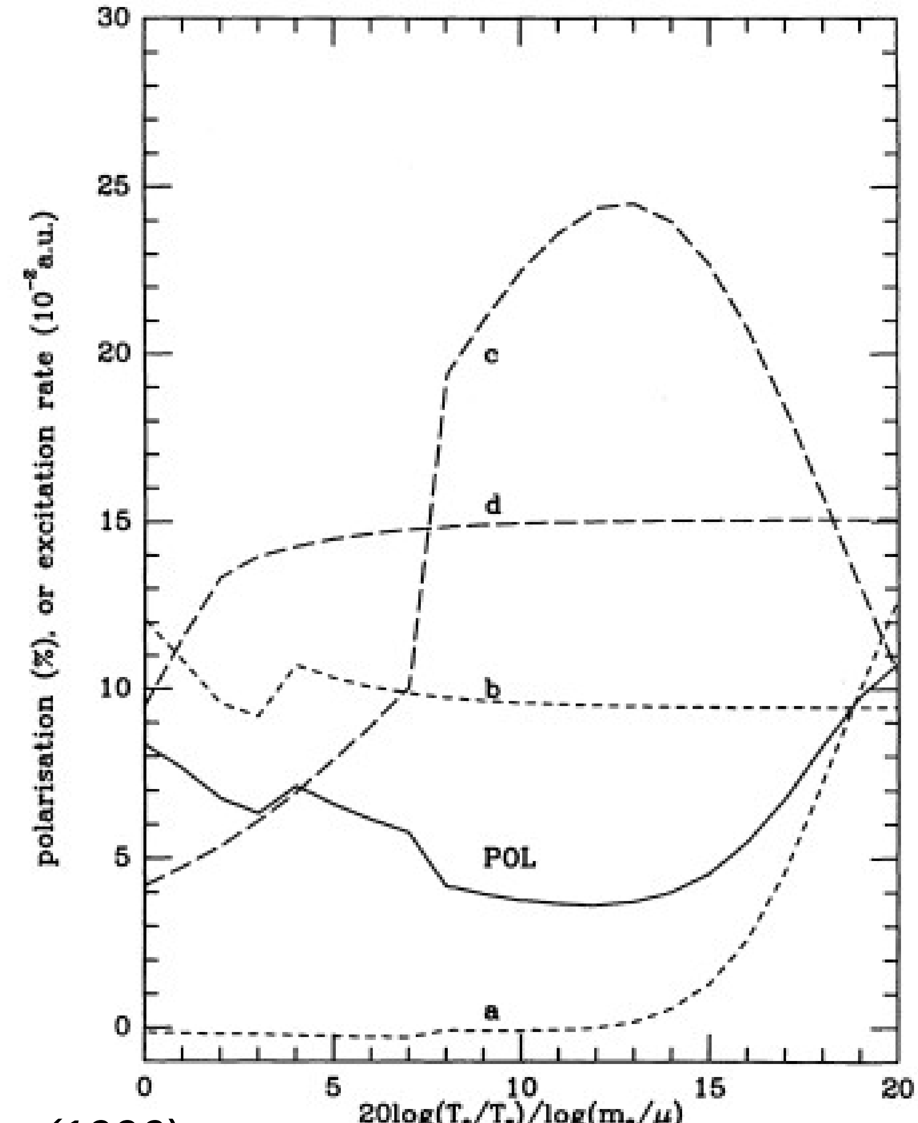
$$R_n = n_i n_e \int_0^\infty \nu f(\nu) \sigma_{rr}(\nu) \mathrm{d}\nu$$

Ion density

Electron density

Maxwellian distribution

(non)radiative shocks in supernovae remnants



Laming (1990)

Polarization mechanisms

<u>Atomic recombination</u>

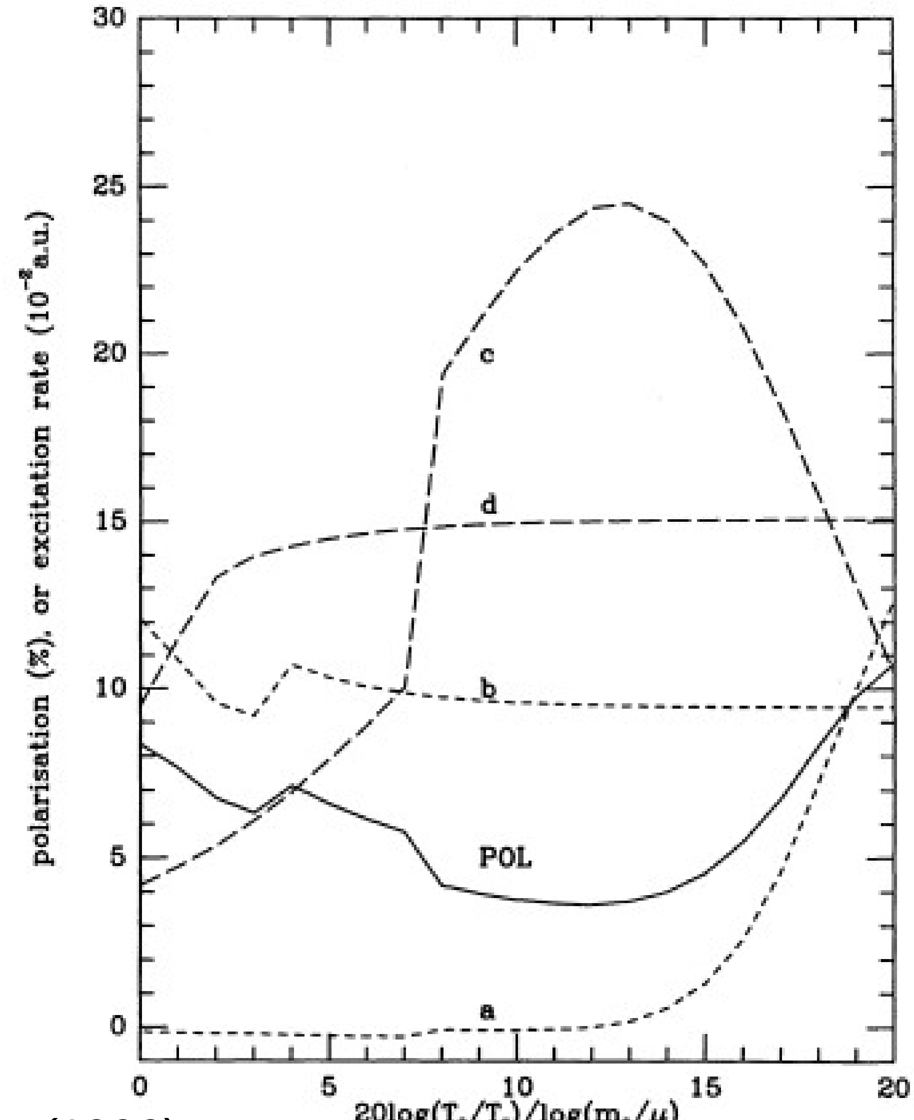
For directive incident electron beam, the polarization degree of radiative recombination can be obtained by the formula:

$$P(\theta) = \frac{\sum_{L_2=2}^{\infty} B_{L_2}(1,-1) D_{20}^{L_2}(\theta)}{\sum_{L_2=0}^{\infty} B_{L_2}(1,1) D_{00}^{L_2}(\theta)}$$

Complex quantum function

Rotational function

(non)radiative shocks in supernovae remnants



Laming (1990)

Polarization mechanisms

Fluorescent emission

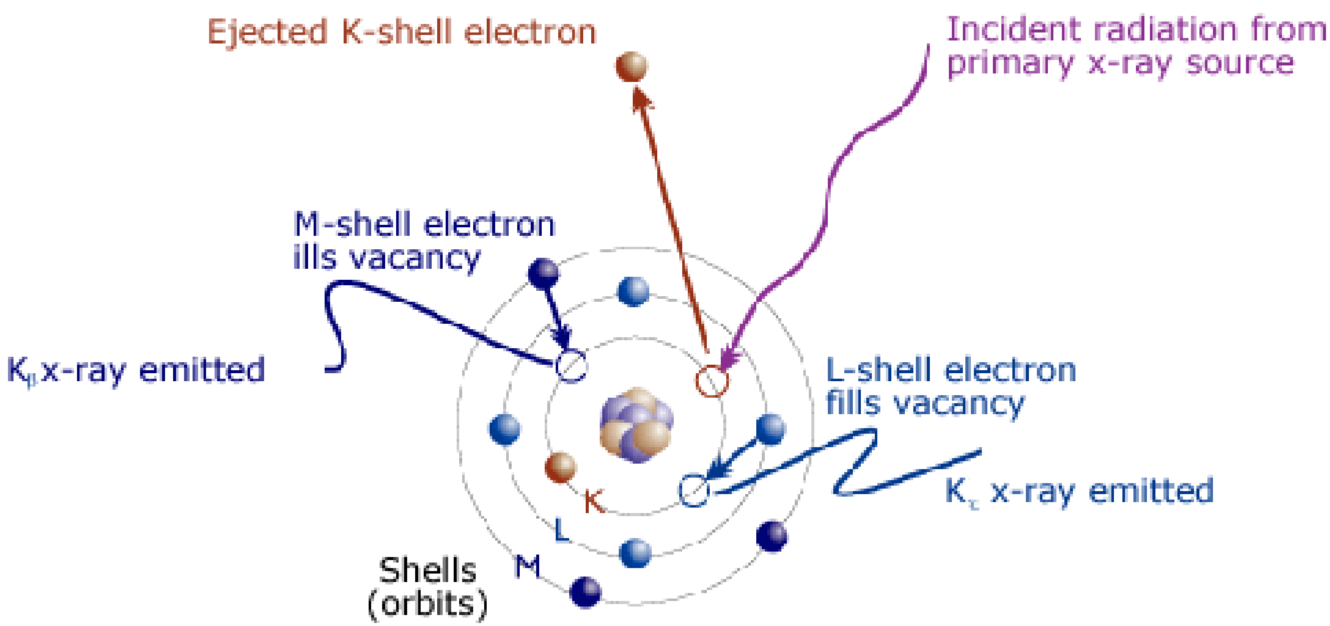
As seen from the previous sections, when photons scatter on atoms or molecules, they are absorbed and (lately) re-emitted in form of scattered radiations

However, when a highly energetic photon (such as X-ray radiation) scatters on an atom, its energy might be large enough to expel an electron from the inner electron shells, leaving a vacant electron position (photo-ionization)

The atom is ionized and excited. As it is in an unstable state, the atom's electrons rearrange themselves to fill the gap with electronic transitions from the outer shells to the inner shells. As the physical process is exo-energetic, the atom releases the exceeding energy in terms of a UV photon if the energy transition is moderated or a X-ray photon for deeper, more energetic transitions → fluorescence emission

Polarization mechanisms

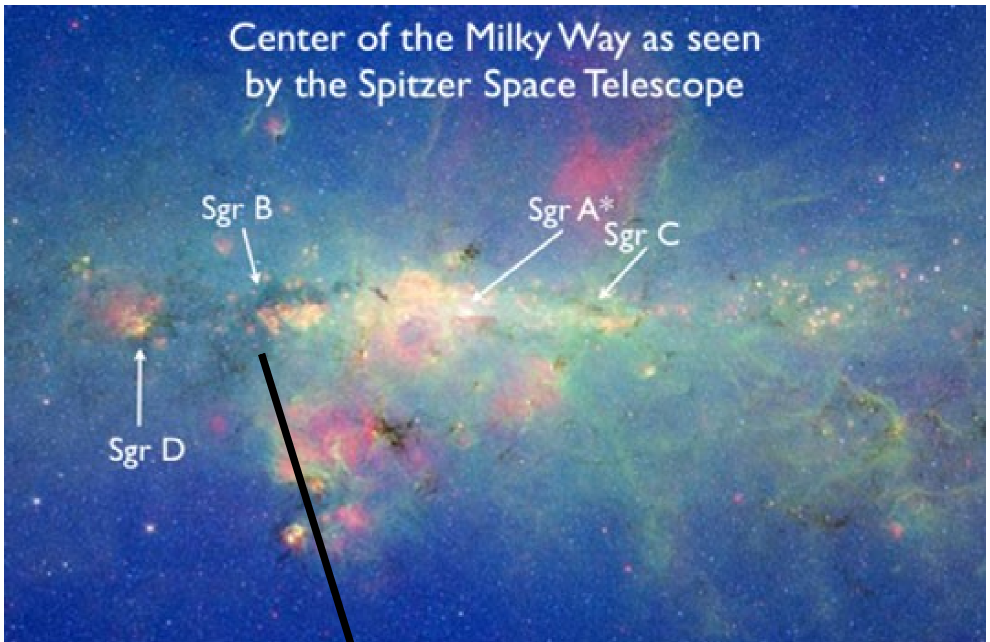
Fluorescent emission



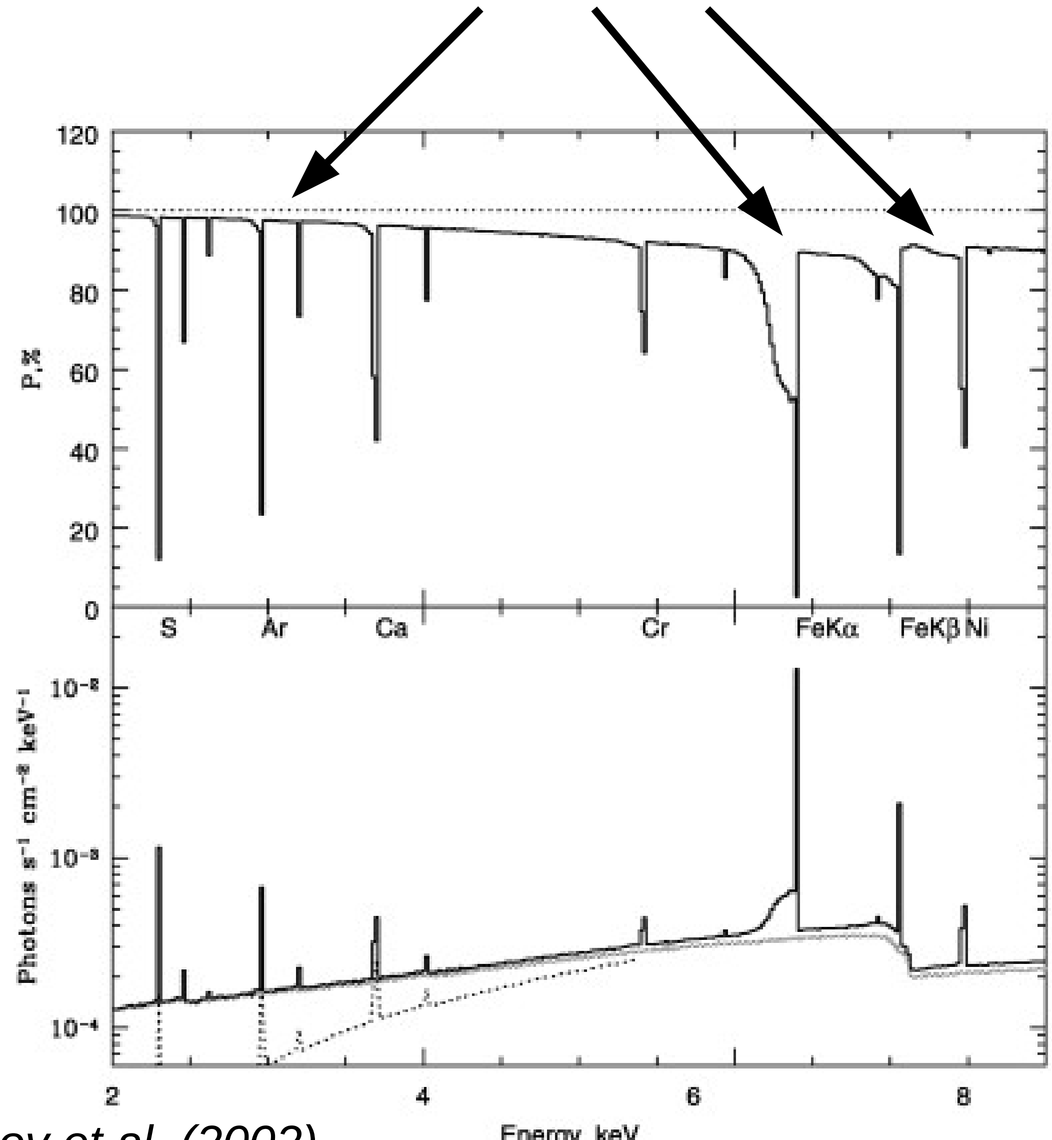
It might also happen that the electronic rearrangement expels one, or more (electron cascades), electron lately called an Auger electron

Polarization mechanisms

Fluorescent emission



Unpolarized



Churazov et al. (2002)

Polarization mechanisms

Magnetic fields

Magnetic fields don't directly affect light; they affect the polarization currents in the material the light is passing through

With a magnetic field parallel to the direction of travel of the light, the charges will be displaced perpendicular to the plane of polarization, and will add a component of the other polarization

If the magnetic field is perpendicular to the polarization and propagation directions, the displacement due to the magnetic field is in the direction of travel, so this won't affect the polarization

- **Faraday rotation**
- **Zeeman effect**
- **Hanle effect**

Polarization mechanisms

Faraday rotation

When passing through a magnetized plasma, an electromagnetic wave will see its polarization plane rotated by an effect called Faraday rotation

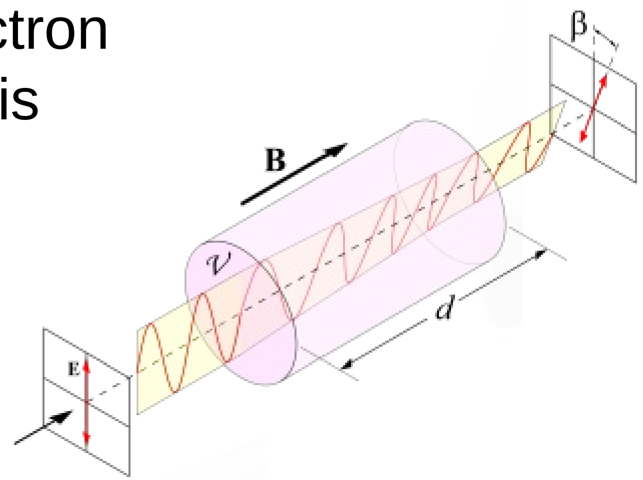
The rotation is linearly proportional to the component of the magnetic field in the direction of propagation

The rotation angle β can be expressed in terms of:
with λ being the photon wavelength

$$\beta = \alpha\lambda$$

And the Faraday rotation measure α, where the electron density n_e multiplied by the projected magnetic field is integrated along the observer's line-of-sight *d*:

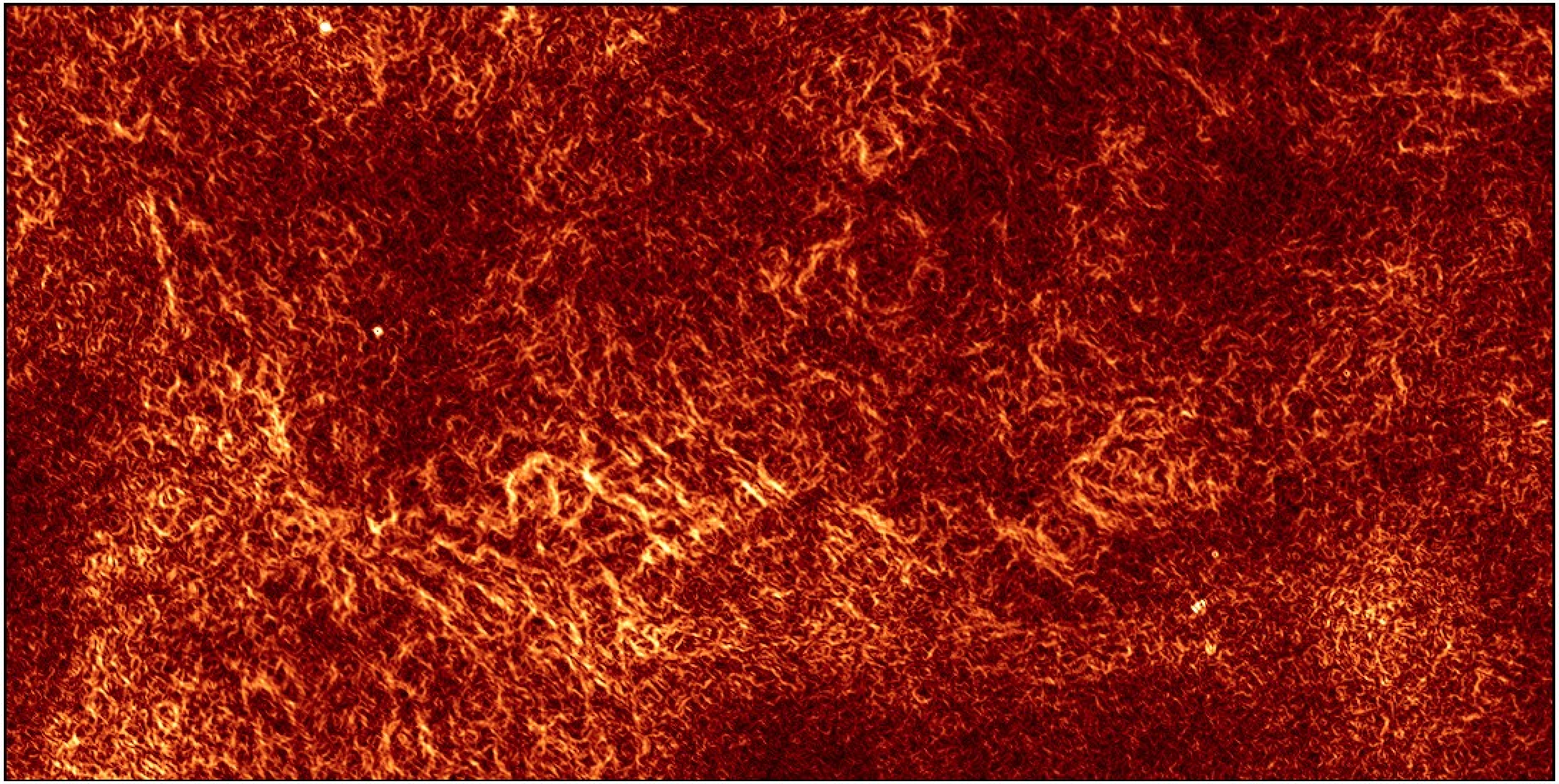
$$\alpha = \frac{q^3}{2\pi m_e^2 c^4} \int_0^d n_e B \, \mathrm{d}s$$



Polarization mechanisms

Faraday rotation

Widely used tool for the measurement of magnetic fields, which can be estimated from rotation measurements at a given electron number density



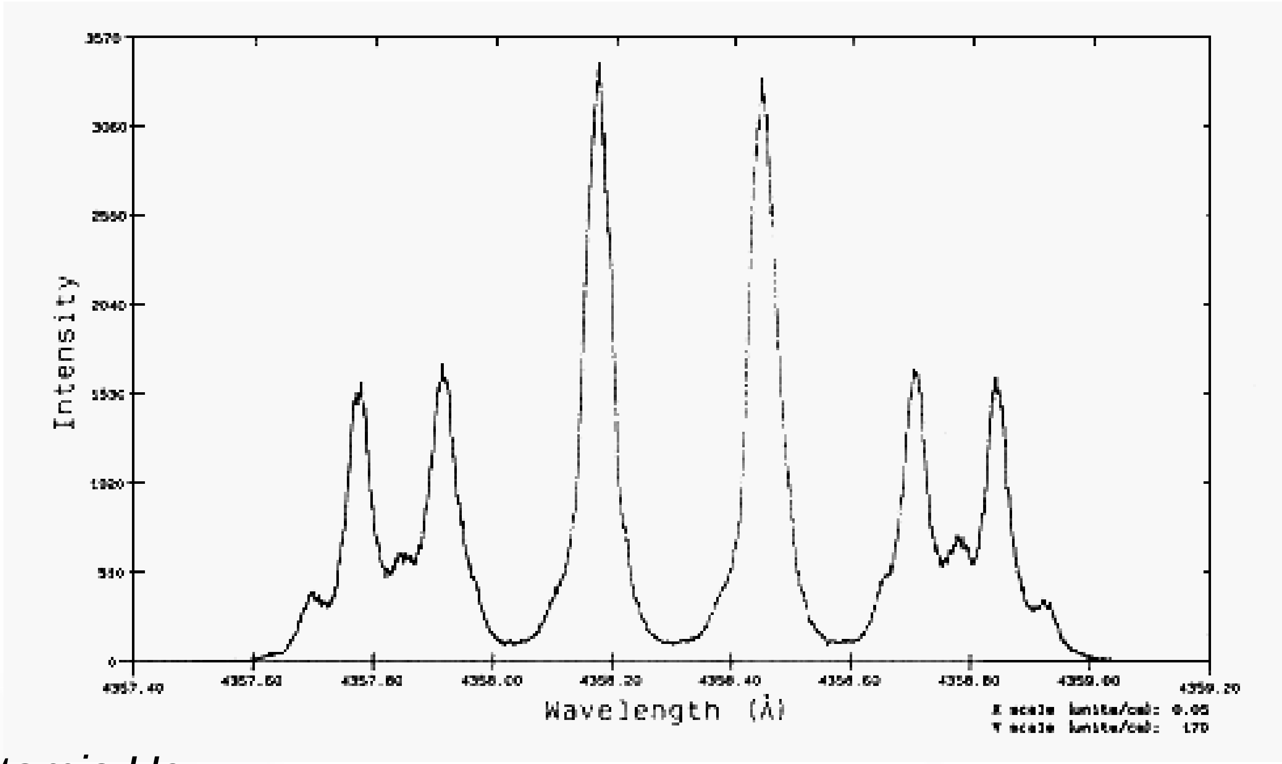
Turbulence-driven gradients of linear polarisation over an 18 deg² region of the Southern Galactic Plane due to rapidly changing density and magnetic field (Gaensler et al. 2011)

Polarization mechanisms

Zeeman effect

When an atom is surrounded by a magnetic field, each of its emitted lines will be split in a variable amount of equidistant lines, separated by an interval proportional to the magnetic field strength

→ Zeeman effect



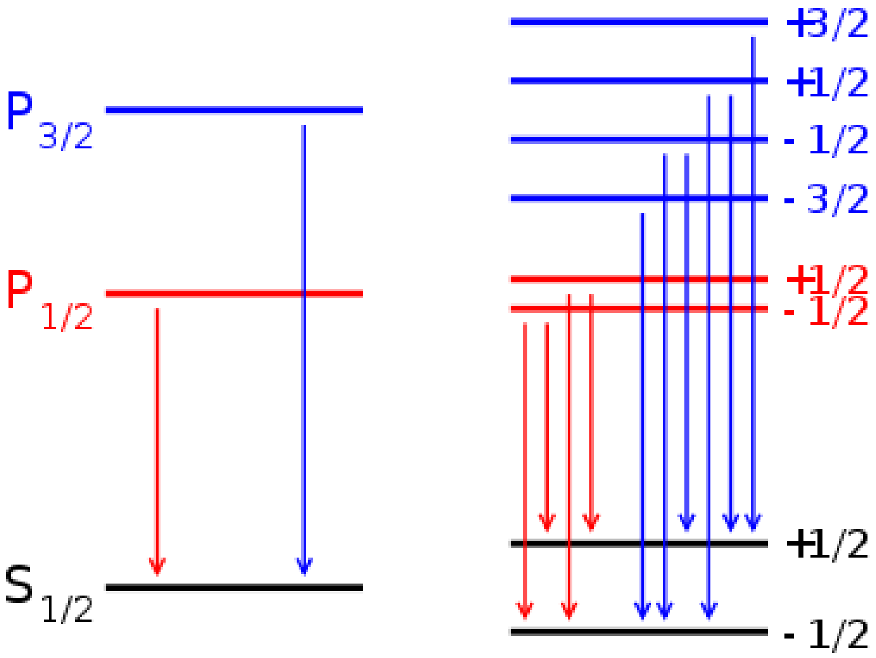
Zeeman effect spectra for the 4358.4 Å, 73S1 --> 63P1 line in atomic Hg

Polarization mechanisms

Zeemen effect

It is due to the fact that the Zeeman effect splits the level degeneracy
→ each values of the magnetic quantum number split into two possible values (±1/2)

The different lines are expected to have different polarizations



Left : fine structure splitting (non-magnetic but due to spin (L)-orbit (S) coupling)
Right: additional Zeeman splitting

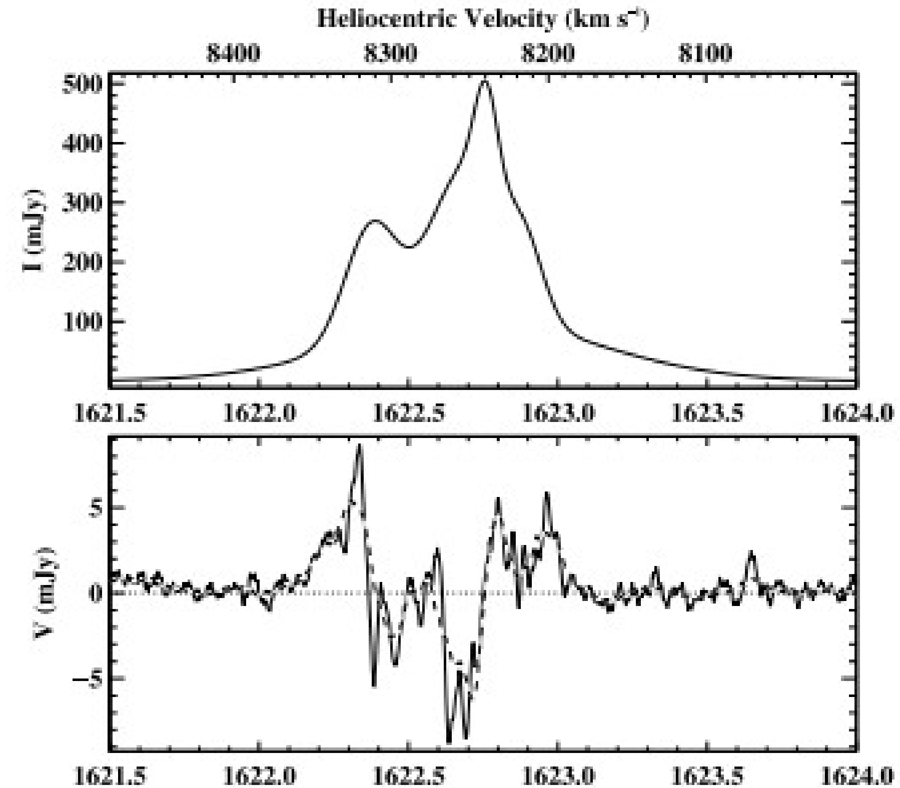
Polarization mechanisms

Zeeman effect

It is due to the fact that the Zeeman effect splits the level degeneracy
→ each values of the magnetic quantum number split into two possible values (±1/2)

The different lines are expected to have different polarizations

Particularly important around OH (mega)masers



Total intensity and circular polarization results for IRAS F01417+1651 (Robishaw et al. 2008)

Polarization mechanisms

Hanle effect

In non-magnetic regimes, some spectral lines might be linearly polarized by an anisotropic irradiation exciting the emitting atoms and molecules (→ resonant scattering)

But, in the case of a magnetized environment, a depolarization effect appears, coupled to a rotation of the polarization plane

→ Hanle effect

Any relevant study effect must undergo a rigorous quantum mechanical explanation for the existence of this zero-field level-crossing spectroscopy (the Hanle effect)

Polarization mechanisms

Hanle effect

As for polarization:

$$R(f,g) = C \sum_{\mu\mu',mm'} \frac{f_{\mu m} f_{m\mu'} g_{\mu' m'} g_{m'\mu}}{1 - i(E_\mu - E_{\mu'})\tau/\hbar}$$

represents the rate at which light of polarization **f** is absorbed and light of polarization **g** is re-emitted by a free atom

With:

$$f_{\mu m} = \langle \mu | \vec{f} \cdot \vec{r} | m \rangle$$
$$g_{\mu m} = \langle \mu | \vec{g} \cdot \vec{r} | m \rangle$$

Polarization mechanisms

Hanle effect

The Hanle effect is very subtle and not yet largely know

Studies of the Sun and Its atmosphere (Leroy et al. 1977, Sahal-Brechot et al. 1977 and Bommier & Sahal-Brechot 1982)

Remains poorly used for the analyzes of extra-solar bodies

Bommier & Sahal-Brechot (1982)

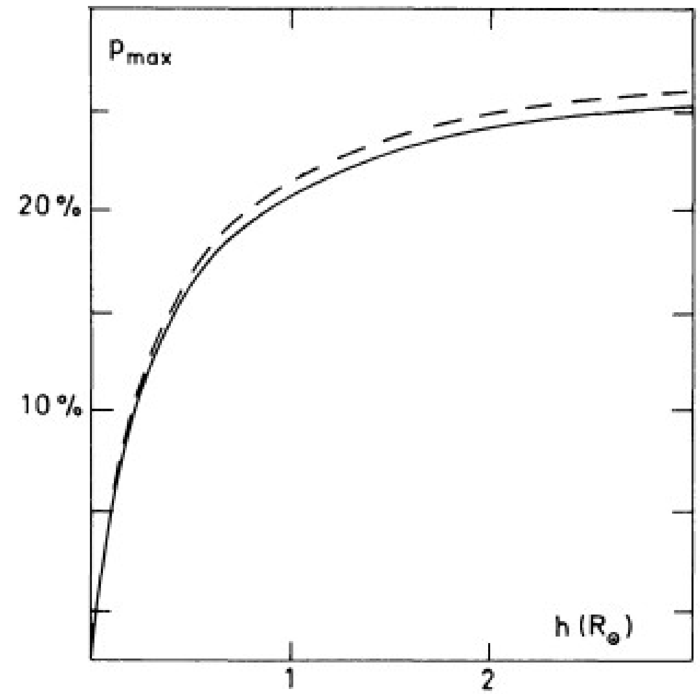


Fig. 3. Zero-field polarization degree p_{max} as a function of the height above the Sun's surface. *Full line*: The hyperfine structure of Lα has been taken into account. *Dotted line*: The hyperfine structure has been neglected. The limit value (infinite height) is 26.7% in the first case, 27.3% in the second case. The scattering point has been assumed to be located in the plane of the sky.

Polarization mechanisms

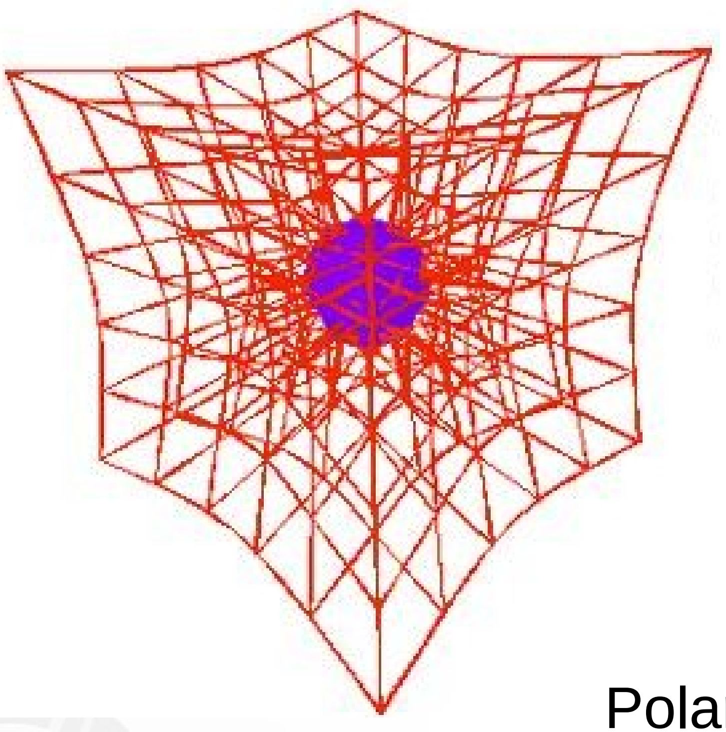
General relativity

One last physical process that can alter polarization

- General relativity

Polarization mechanisms

General relativity



According to Einstein's theory of gravity, the space-time around compact objects is expected to be non-Euclidean (curved)

Photons propagating close to the gravitational well are thus bent and move along geodesics

Polarization features are also affected by general relativistic effects. But GR effects do not create polarization, they just alter it !

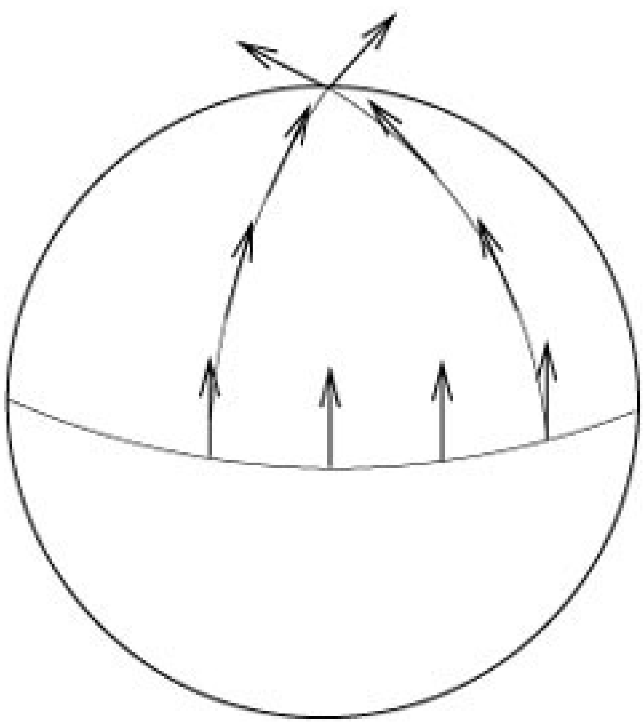
Polarization mechanisms

General relativity

The polarization vector of light is parallely transported along the photons null geodesic while the degree of polarization is a scalar invariant

$$\nabla_k f = 0 \quad \text{and} \quad k \cdot f = 0$$

Where “nabla_k” is the covariant derivative along the null ray

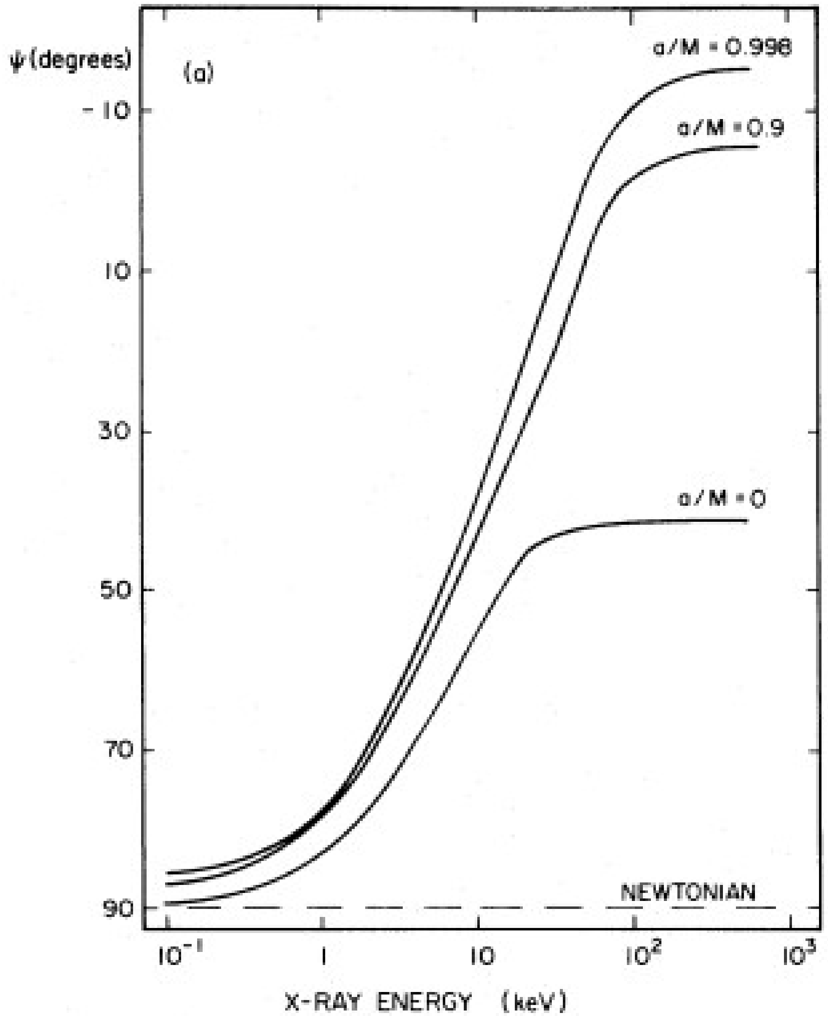


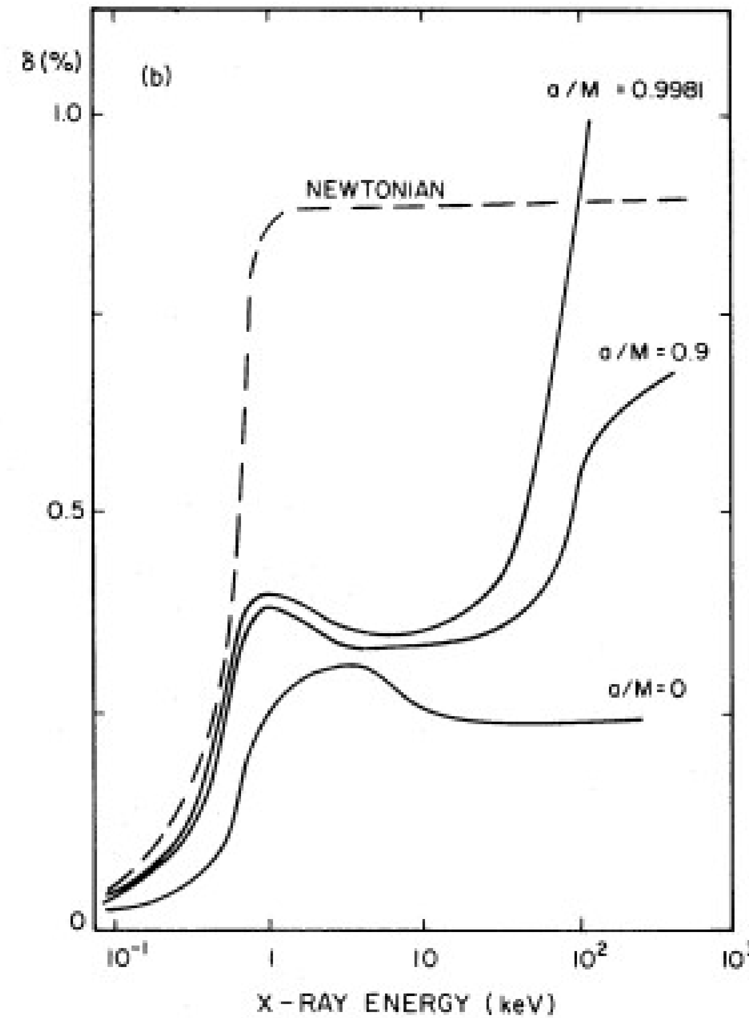
Consider an original vector.
Parallel transport it along the equator by an angle θ, and then move it up to the north pole as before.

It is clear that the vector, parallel transported along two paths, arrived at the same destination with two different values (rotated by θ)

Polarization mechanisms

General relativity





Connors et al. (1980)