Plasma effects on electromagnetic wave propagation

Free electrons and magnetic field (magnetized plasma) may alter the properties of radiation crossing the volume occupied by the plasma.

Such modification is **frequency dependent** and can be measured, providing Indirect measurements of both n_e and H_{II}.

References:

- Fanti & Fanti, cap. 7
- Longair, 12.3.3 & 12.3.4
- Rybicky & Lightman, cap. 8
- https://www.youtube.com/watch?v=Q0qrU4nprB0 (Linear, circular polarization – geometry- [short])
- https://www.youtube.com/watch?v=HH58VmUbOKM (Linear, circular polarization – with explanation)

Let's consider an astrophysical plasma, composed by ionized gas which is, however, neutral as a whole. Maxwell equations are defined for vacuum, but can be adapted to a plasma if we consider charge and current densities ρ_e, $\vec{j}$

Let's consider the dielectric constant of an e-m wave with pulsation ω crossing a medium:

$$\epsilon_r = 1 - \frac{4\pi e^2}{m_e}\left(\frac{n_e}{\omega^2 - \omega_o^2} + \sum_i \frac{N_i}{\omega^2 - \omega_i^2} \right)$$

ω = pulsation incoming radiation

n_e = free electrons number density

ω_o = free electrons pulsation (=0)

N_i = bound electrons number density

ω_i = bound electron pulsation

(in the radio domain, and, in general, when $\omega \ll \omega_i$ then $\sum$ can be neglected)

Plasma frequency

We define the refraction index: n_r (Note that it is frequency dependent!)

$$n_r(\nu) \equiv \sqrt{\varepsilon_r} \simeq \sqrt{1 - \frac{4\pi e^2}{m_e}\frac{n_e}{\omega^2}} = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}$$

where the plasma frequency ν_p has been defined as

$$\nu_p = \sqrt{\frac{e^2 n_e}{\pi m_e}} = 9.0 \cdot 10^3 \sqrt{\frac{n_e}{cm^{-3}}} \quad [Hz]$$

only waves with $\nu > \nu_p$ can travel across the region

those with $\nu < \nu_p$ are reflected (n_r becomes imaginary)

→ Below the plasma cutoff frequency there is no propagation of e-m waves

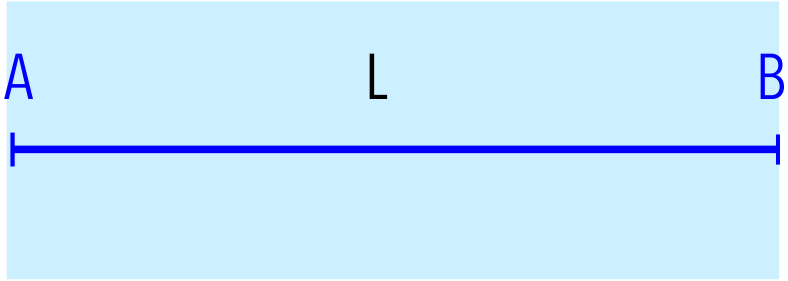
In the ionosphere: $n_e \sim 10^6 cm^{-3}$ implies $\nu_p \sim 10^7 Hz$

In the interstellar medium: $n_e \sim 10^{-3} \Leftrightarrow 10^{-1} cm^{-3}$

implies $\nu_p \sim 3 \cdot 10^2 \Leftrightarrow 3 \cdot 10^3 Hz$

at $\nu > \nu_p$ → the e-m wave travels with group velocity

$$v_g \simeq \frac{\partial \omega}{\partial k} = c \cdot n_r = c\sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}$$



In the ISM, ν_p is generally low, then, even in the radio waves $\nu \gg \nu_p$

consequently (Taylor expansion) $$v_g \approx c\left[1 - \frac{1}{2}\left(\frac{\nu_p}{\nu}\right)^2\right]$$

The time necessary to travel from A to B at a given frequency is

$$T_{A,B}(\nu) = \int_0^L \frac{dl}{v_g} \approx \frac{1}{c}\int_0^L \left[1 - \frac{1}{2}\left(\frac{\nu_p}{\nu}\right)^2\right]^{-1} dl = \frac{1}{c}\int_0^L \left[1 + \frac{1}{2}\left(\frac{\nu_p}{\nu}\right)^2\right] dl =$$

$$= \frac{1}{c}\int_0^L dl + \frac{1}{2c}\int_0^L \left(\frac{\nu_p}{\nu}\right)^2 dl = \frac{L}{c} + \frac{1}{2c}\left[\frac{e^2}{\pi m_e \nu^2}\right]\int_0^L n_e\, dl =$$

$$= \frac{L}{c} + \frac{1}{2c}\left[\frac{e^2}{\pi m_e \nu^2}\right] \mathrm{DM} \quad \rightarrow \quad \mathrm{DM} = \int_0^L n_e\, dl$$

Dispersion Measure

Dispersion Measure

Observing at two different frequencies, the arrival time will be different! A delay is present

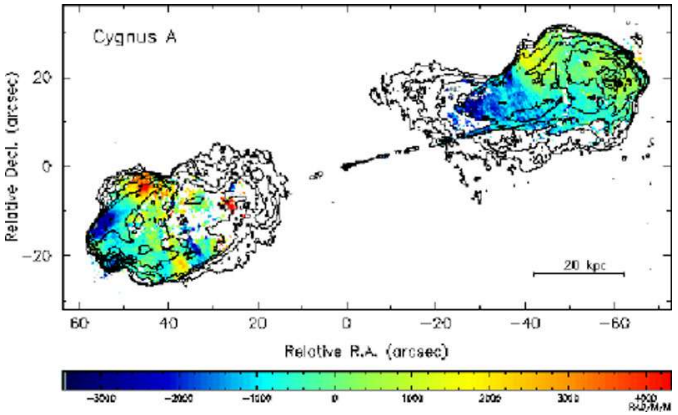
$$\Delta T_{\nu_1-\nu_2} = T_{A,B}(\nu_1) - T_{A,B}(\nu_2) = \left[\frac{L}{c} + \frac{DM}{2c}\left(\frac{e^2}{\pi m_e \nu_1^2}\right)\right] - \left[\frac{L}{c} + \frac{DM}{2c}\left(\frac{e^2}{\pi m_e \nu_2^2}\right)\right]$$

$$\Delta T_{\nu_1-\nu_2} = \frac{DM}{2c}\frac{e^2}{\pi m_e}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)$$

In case it is possible to detect this effect, namely measure $\Delta T_{\nu_1-\nu_2}$ in a given particular case, then it becomes feasible to directly determine n_e along a given LOS (to the object).

QUESTION:

Is a syncrhotron emitting radiogalaxy suitable to measure DM?

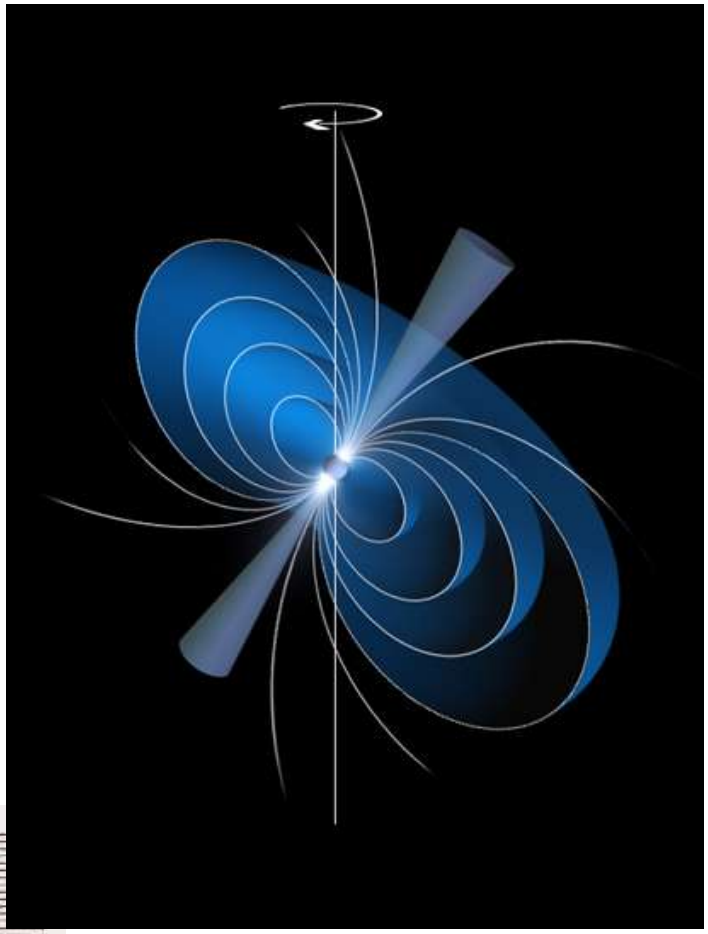


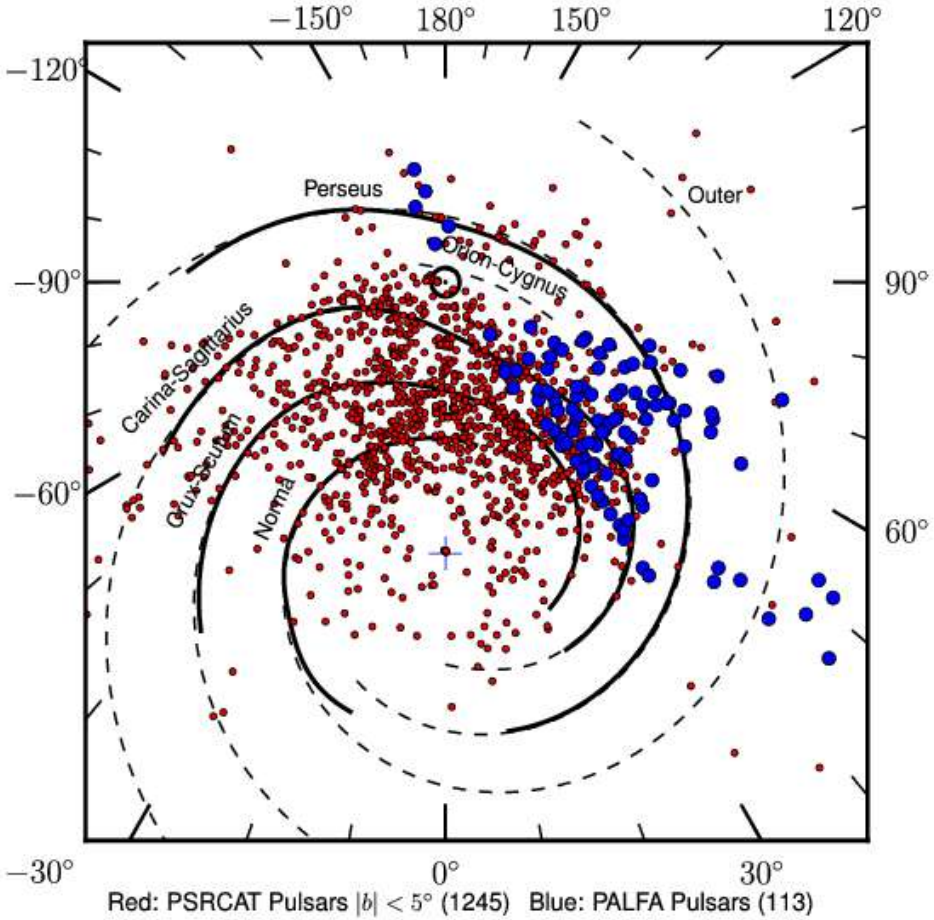
A digression: What is a pulsar?

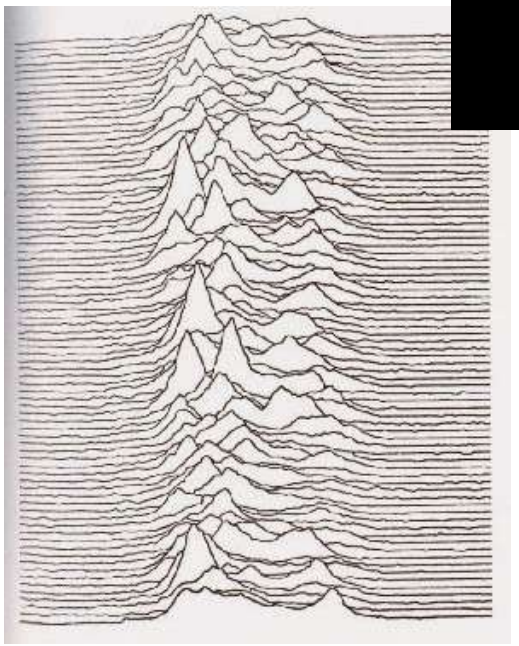
Rapidly spinning netron star (many turns per second)

Stong Magnetic field (misaligned wrt the rotation axis)

Narrow radiation cone (intercepting the LoS to the Earth)





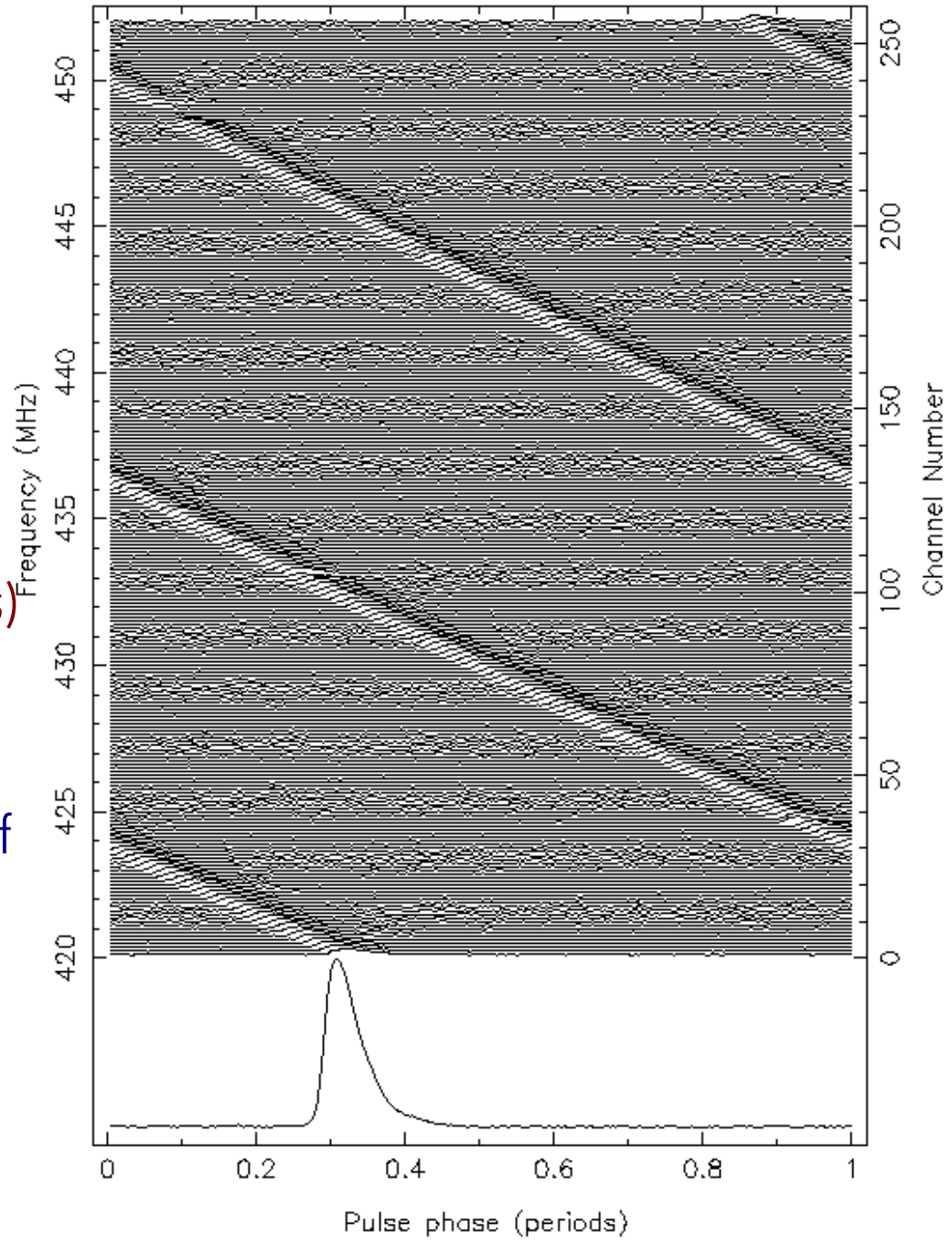


The slope of the pulse arrival time .vs. frequency provides a measure of

$$D.M. = \int_0^L n_e \, dl$$

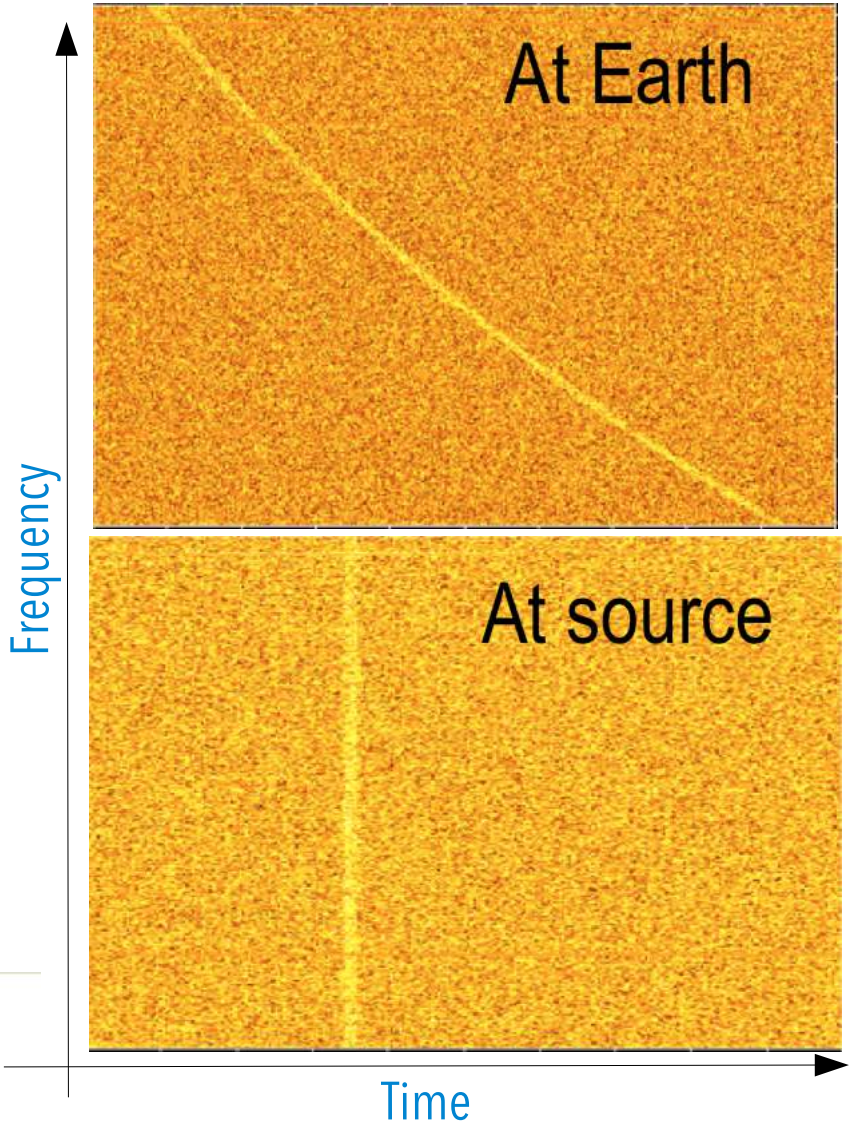
Distances, however, are difficult to determine, except in a few lucky cases (e.g. globular clusters)

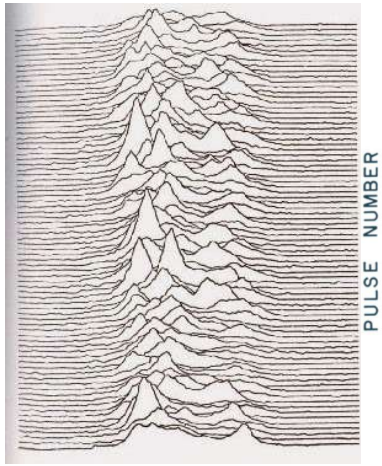
DM can measure the total n_e in a given direction, but not its localization. From models of n_e distribution, distance can be estimated

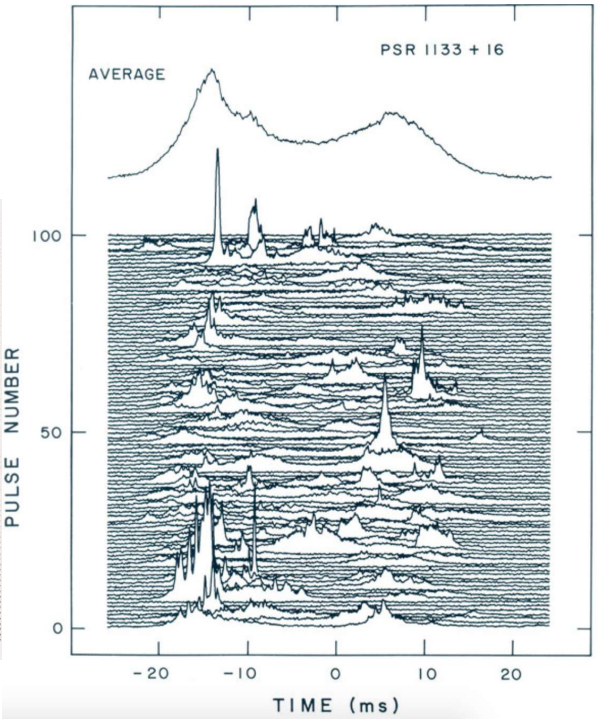


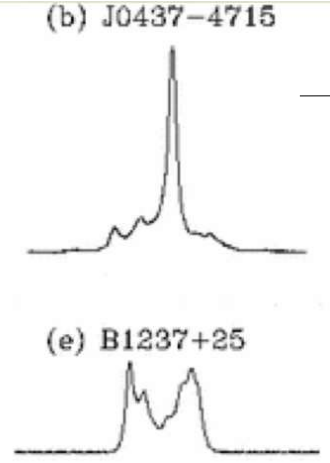
Some info on pulsar detection

- The signal of a pulsar is generally weak
- The removal of the DM (top figure) re-alignes the pulse allowing the Integration in frequency (better S/N)
- Individual pulses in tha same pulsar have different profiles
- The average pulse is characteristic of each pulsar

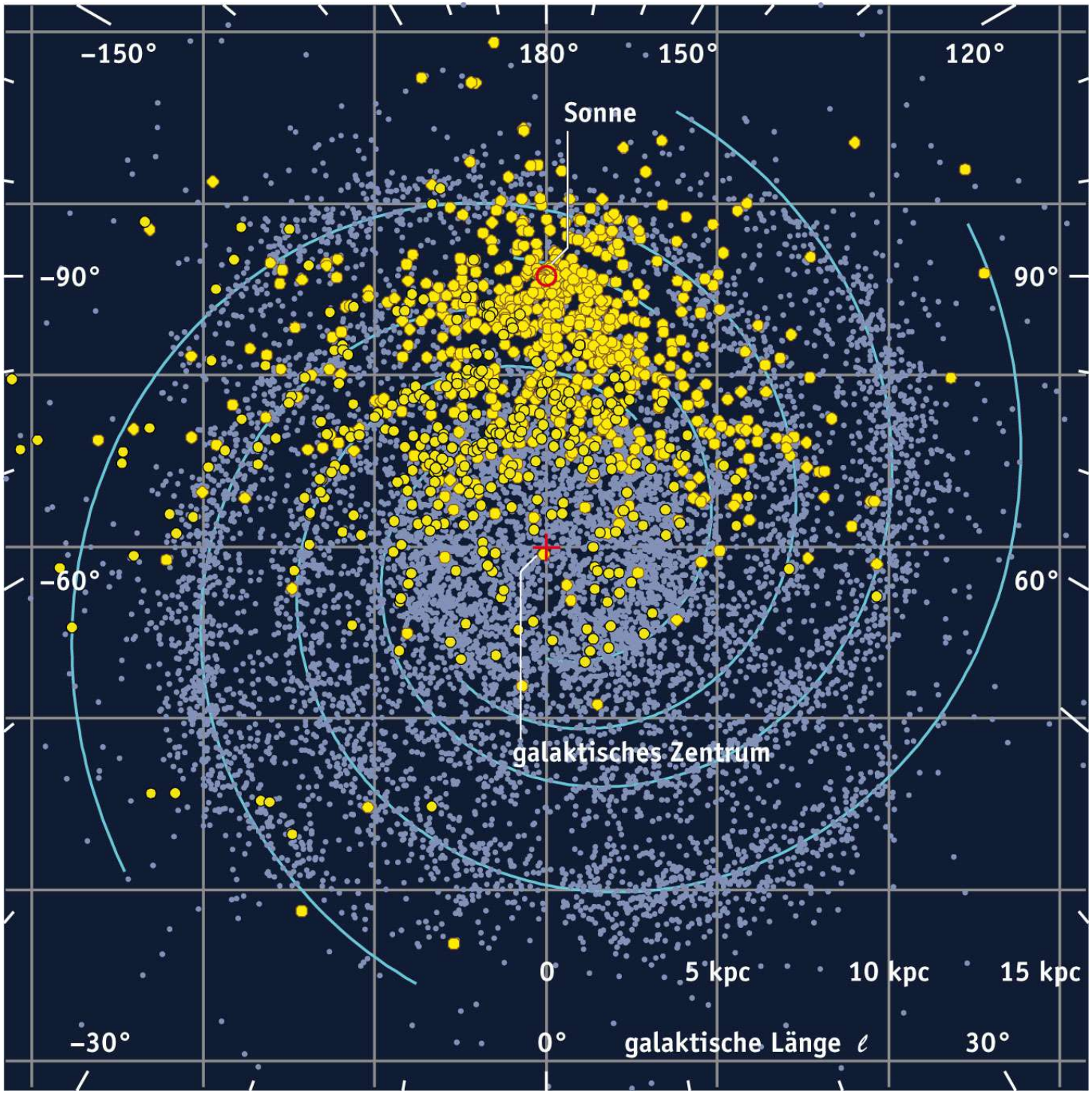






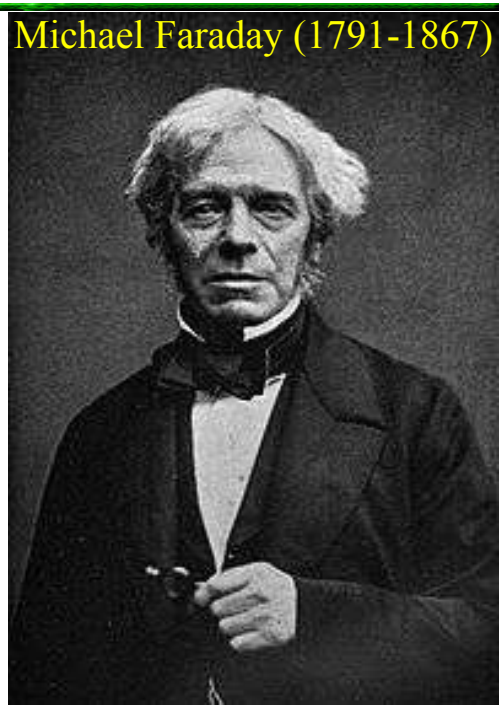


Distribution of known pulsars in our galaxy



Faraday Rotation

Watch: https://www.youtube.com/watch?v=Q0qrU4nprB0
https://www.youtube.com/watchv=HH58VmUbOKM&ebc=ANyPxKph9jGXj29G6qK2lZVL5ZFKPqrjKD_1Wtc5tOwtHYHhkdMw9UJHKHcwuRUYDxBYCcT18waK



Propagation effect arising from an "external" magnetic field H which causes an anisotropic transmission. Let's consider what happens along the field direction:

$$m \frac{d\vec{v}}{dt} = -e\left(\vec{E} + \frac{\vec{v}}{c} x \vec{H}\right) \qquad (**)$$

$$\omega_L = \frac{eH}{m_e c}$$

Let's us assume that the propagating e-m wave is polarized and sinusoidal as a superposition between a LCP and a RCP components.

$$\vec{E}(t) = E_0 e^{-i\omega t}(\vec{\epsilon}_1 \pm \vec{\epsilon}_2)$$

Where + is for RCP and – is for LCP. The dielectric constant is no longer a scalar and becomes a tensor: the "two" modes have different refraction indices

$$(n_r)_{R,L} = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2 \frac{1}{1 \pm (\nu_L/\nu)\cos\theta}}$$

where θ is the angle between the direction of e-m wave propagation and the local direction of $\vec{H}$

Along the field direction

$$\vec{B}_o = B_o \vec{\epsilon}_3$$

and then in equation (**) we get as a solution

$$\vec{v}(t) = -\frac{ie}{m_e(\omega \pm \omega_L)} \vec{E}(t)$$

which provides a dielectric constant

$$\varepsilon_{R,L} = 1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_L)}$$

and therefore the propagation speeds of the two orthogonal modes are different, originating a shift in their relative phase, which implies a rotation of the polarization vector

The difference between the refraction indices is $\Delta n = \frac{\nu_p^2 \nu_L}{\nu^3} \cos\theta$

After a length dl there is a phase difference between the two waves

$$d\phi = \left(\frac{2\pi dl}{\lambda} \Delta n \right) = \frac{2\pi \nu \Delta n}{c} dl$$

which must be integrated!

In case the "Faraday screen" is spatially resolved, the net effect is just a rotation of the linear polarization vector in a given direction

Over a distance L, there is a phase difference ϕ_{RL} based on the wavenumber(s)

$$\phi_{RL} = \int_0^L k_{R,L}\,dl = \int_0^L (k_R - k_L)\,dl = \int_0^L \frac{\omega}{c}\left[\sqrt{1-\frac{\omega_P}{2\omega^2}\left(1+\frac{\omega_L}{\omega}\right)} - \sqrt{1-\frac{\omega_P}{2\omega^2}\left(1-\frac{\omega_L}{\omega}\right)}\right] dl$$

$$\Delta\theta = \frac{1}{2}\,\phi_{RL} = \frac{2\pi e^3}{m_e^2 c^2 \omega^2}\int_0^L n_e H_{\parallel}\,dl \approx \lambda^2 \int_0^L n_e H_{\parallel}\,dl \qquad [\text{radians}]$$

$$RM = \frac{e^3}{2\pi m_e^2 c^4}\int_0^L n_e H_{\parallel}\,dl \quad [\text{rad m}^{-2}] \rightarrow \text{"Rotation Measure"} \quad \Rightarrow \quad \Delta\theta = \lambda^2 RM$$

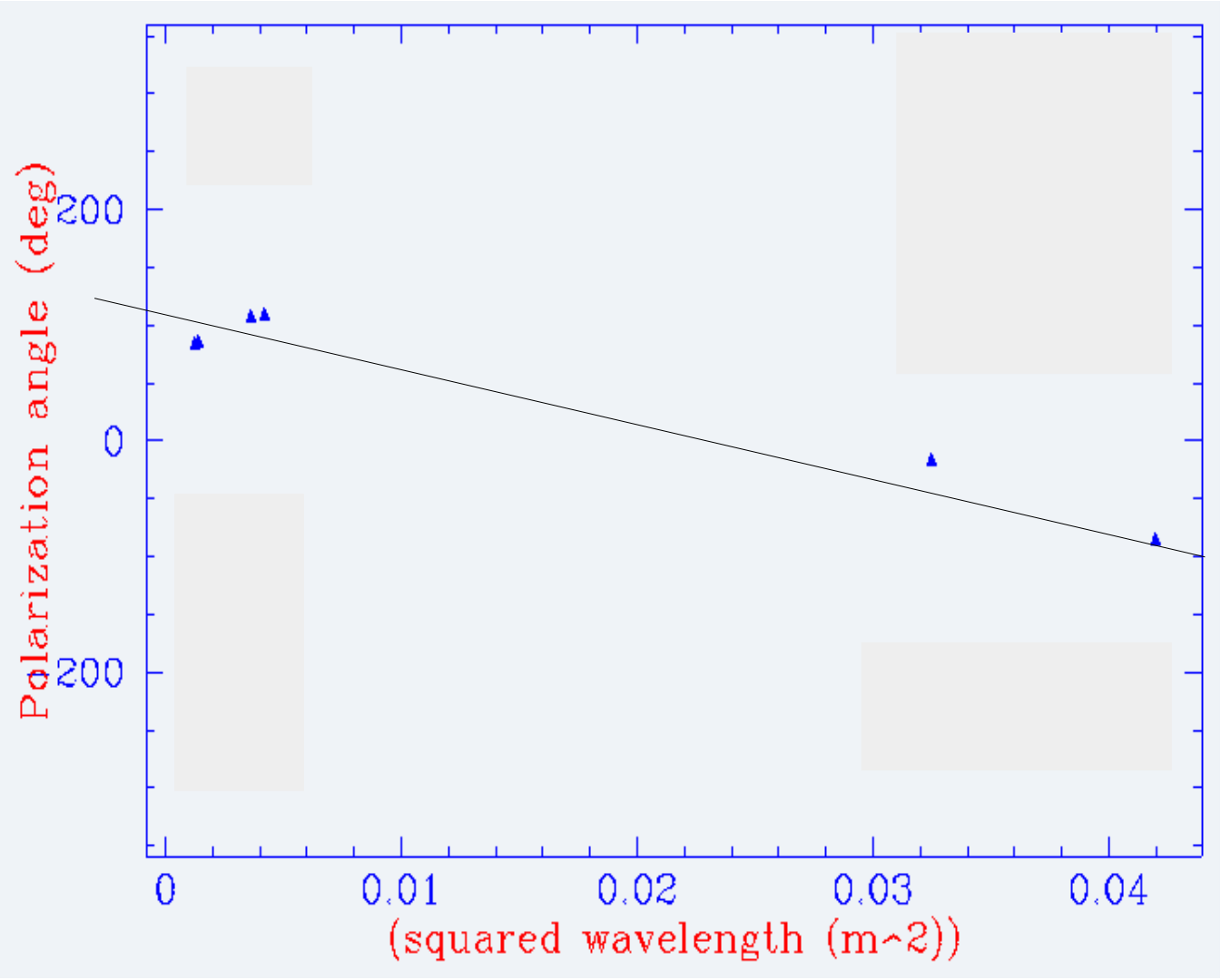
The R.M. determines the magnetic field along the LOS weighted on the electron density n_e.

If the D.M. is available as well, then $\langle H_{\parallel} \rangle \propto \frac{R.M.}{D.M.} \propto \frac{\int n_e H_{\parallel}\,dl}{\int n_e\,dl}$

How to measure RM

Polarization sensitive observations provide the measurement of m and χ at various discrete frequencies (wavelengths) using the Stokes' parameters U &Q for the LINEAR polarization vector

Plot λ^2 and χ
get the slope of the best fit line



How to measure RM (2)

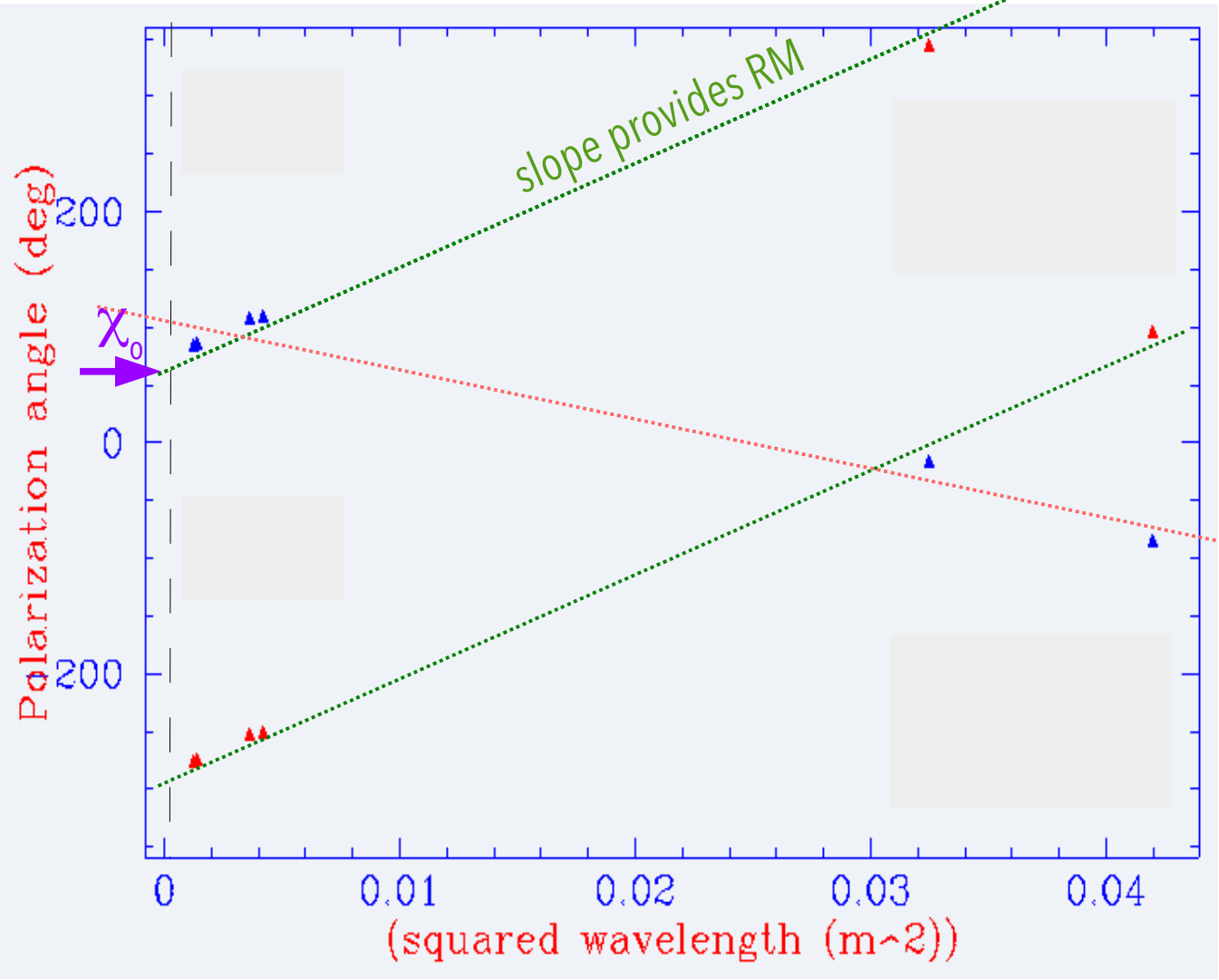
N.B. The slope of the best fit line may be either positive or negative

Plot λ^2 and $\chi \quad (\pm 2n\pi)$

get the slope of the best fit line

obtain RM in $\mathrm{rad\,m^{-2}}$

& the absolute orientation of χ



blue points represents the observations

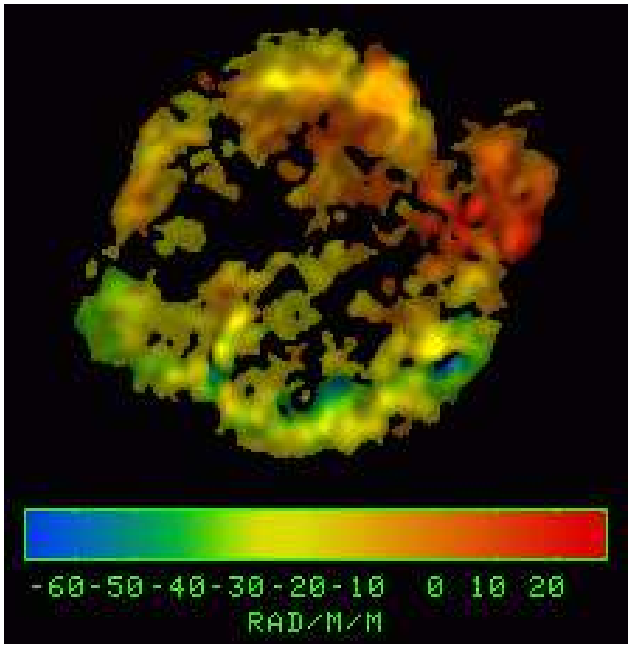
red points are for the $\pm 2n\pi$ ambiguities

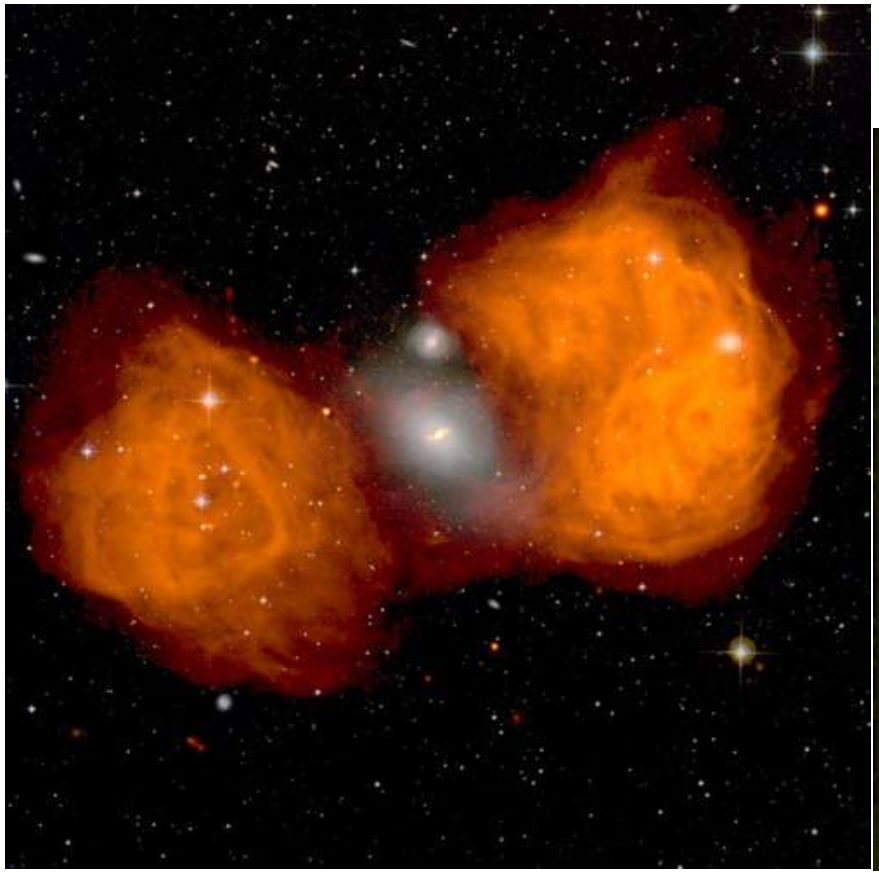
Examples of RM and FR

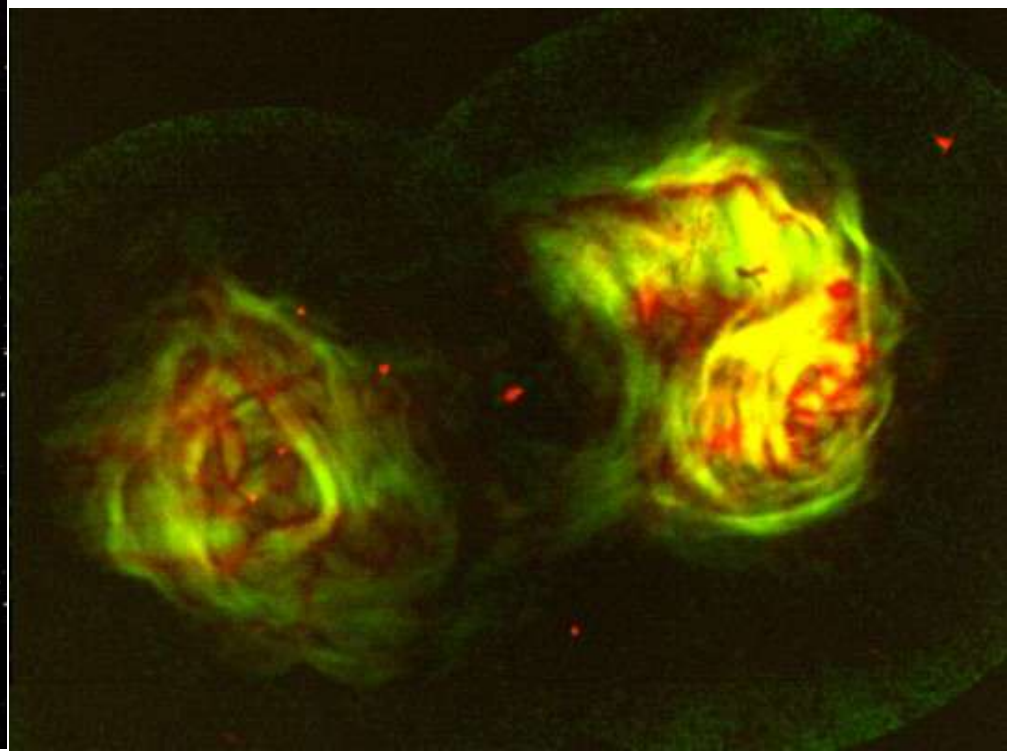
RM needs various frequencies to be measured

Depolarization may take place

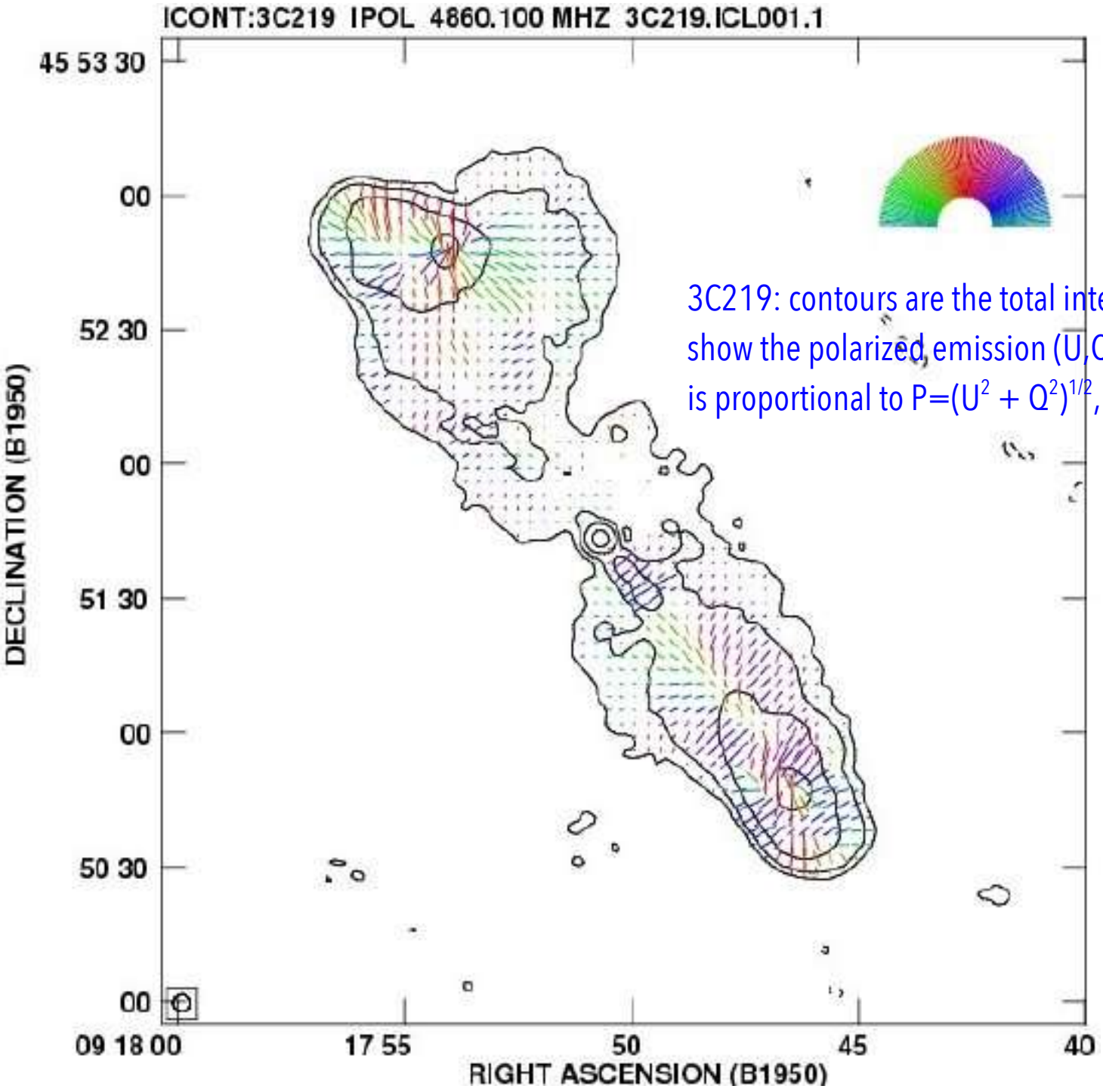
RM may be very different in various locations of the same radio source -> local to the r-source





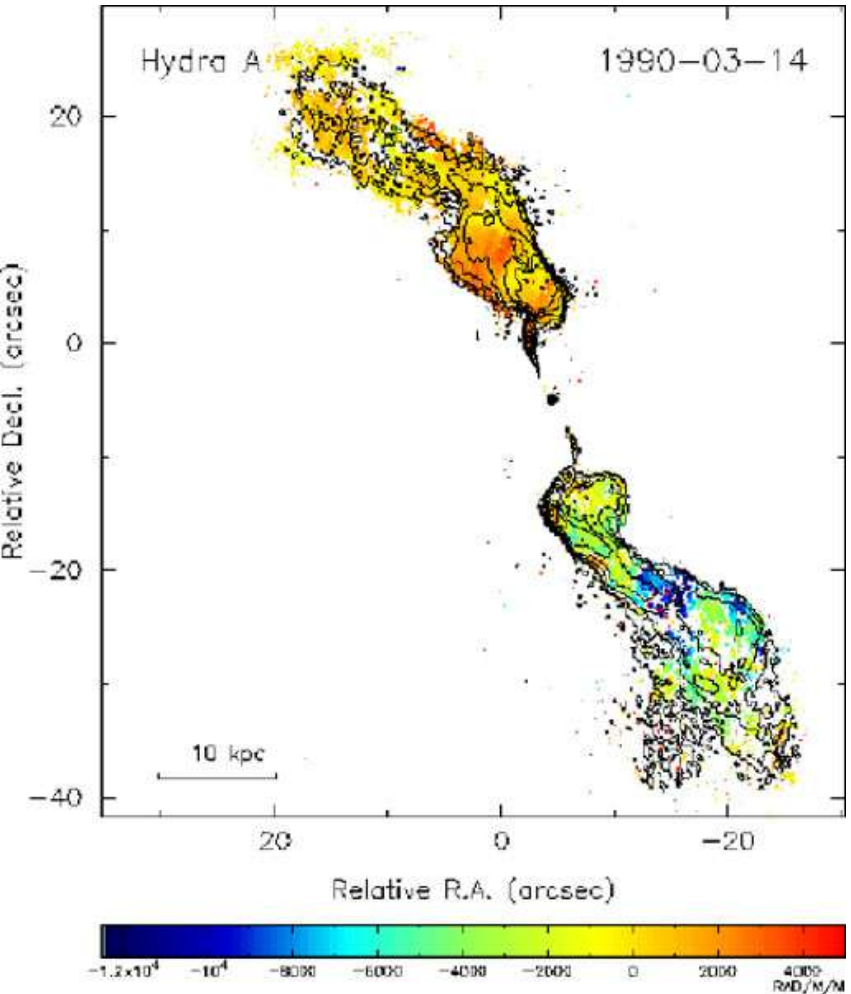


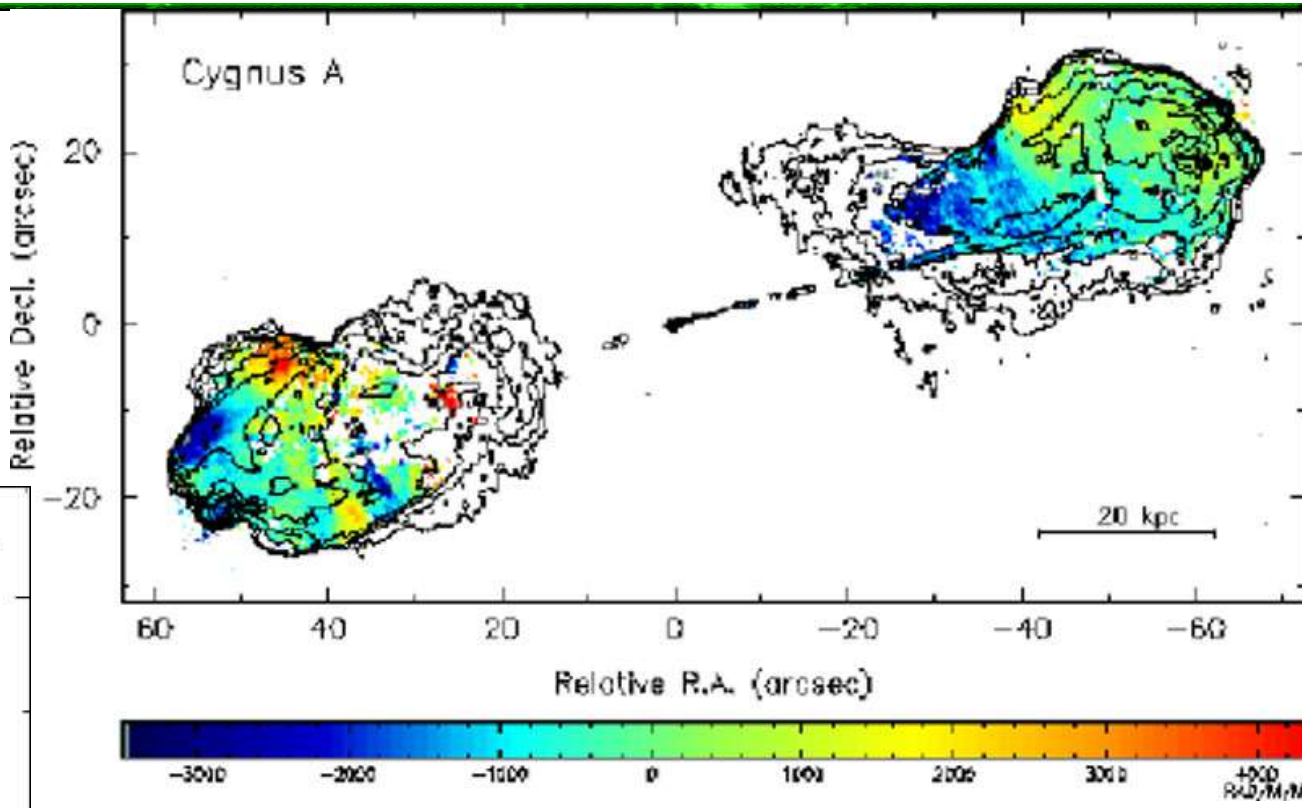
Examples of RM and FR (2)



3C219: contours are the total intensity emission at 4.86 GHz. Vectors show the polarized emission (U,Q of the electric vector), whose length is proportional to $P=(U^2 + Q^2)^{1/2}$, and orientation is $\chi = \frac{1}{2}\,\mathrm{atan2}(U,Q)$

Examples of RM and FR (2)

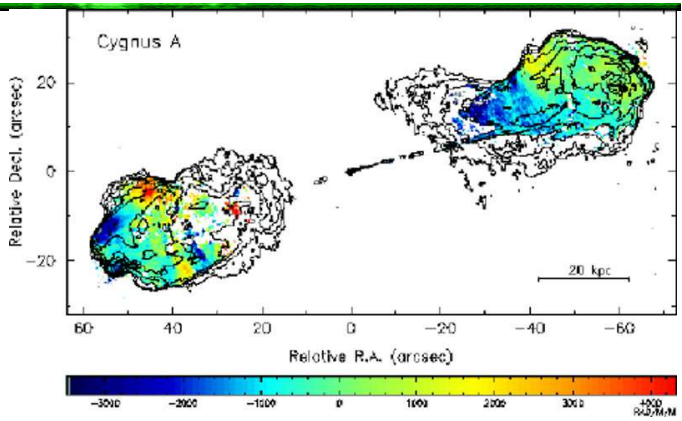


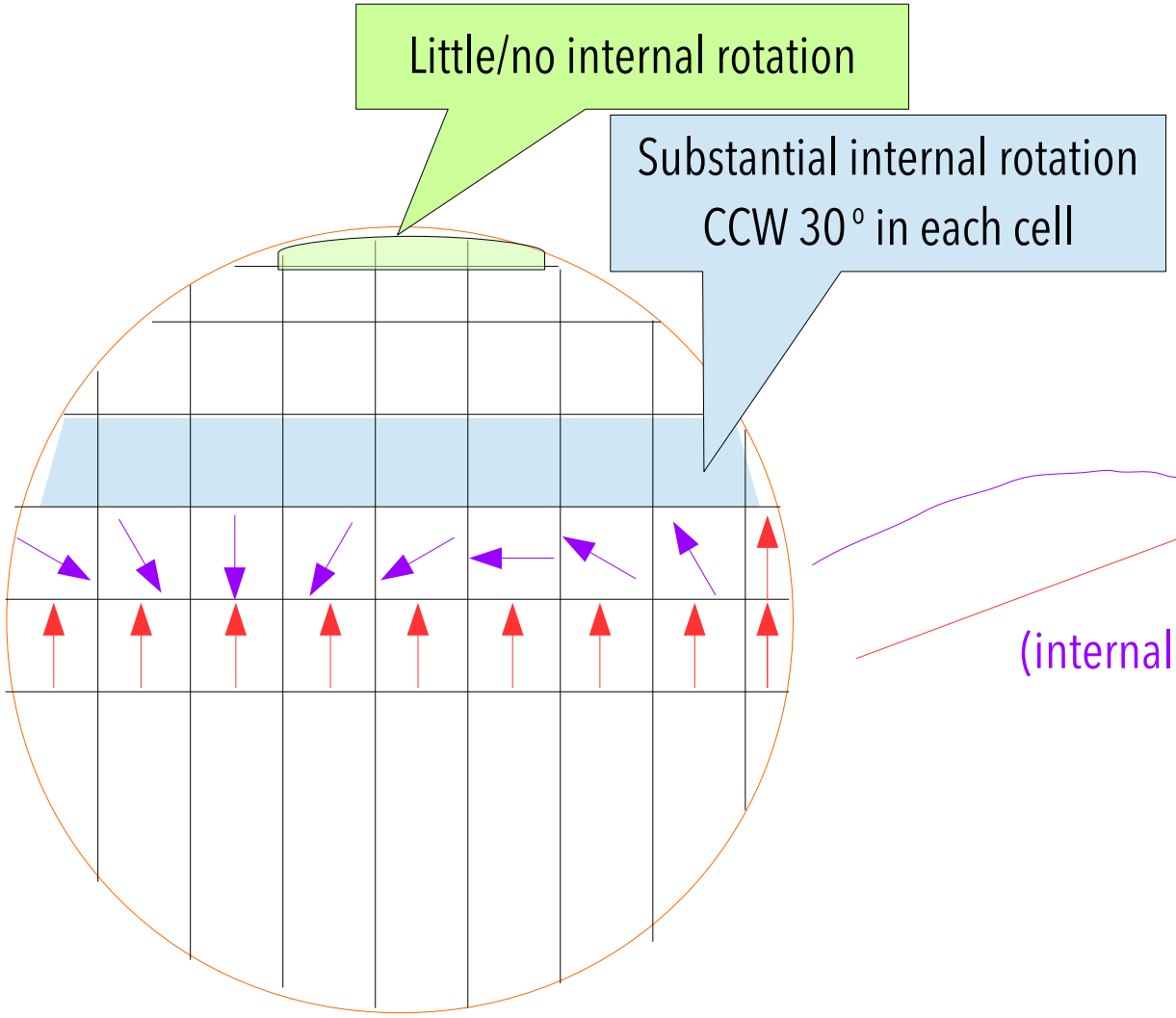


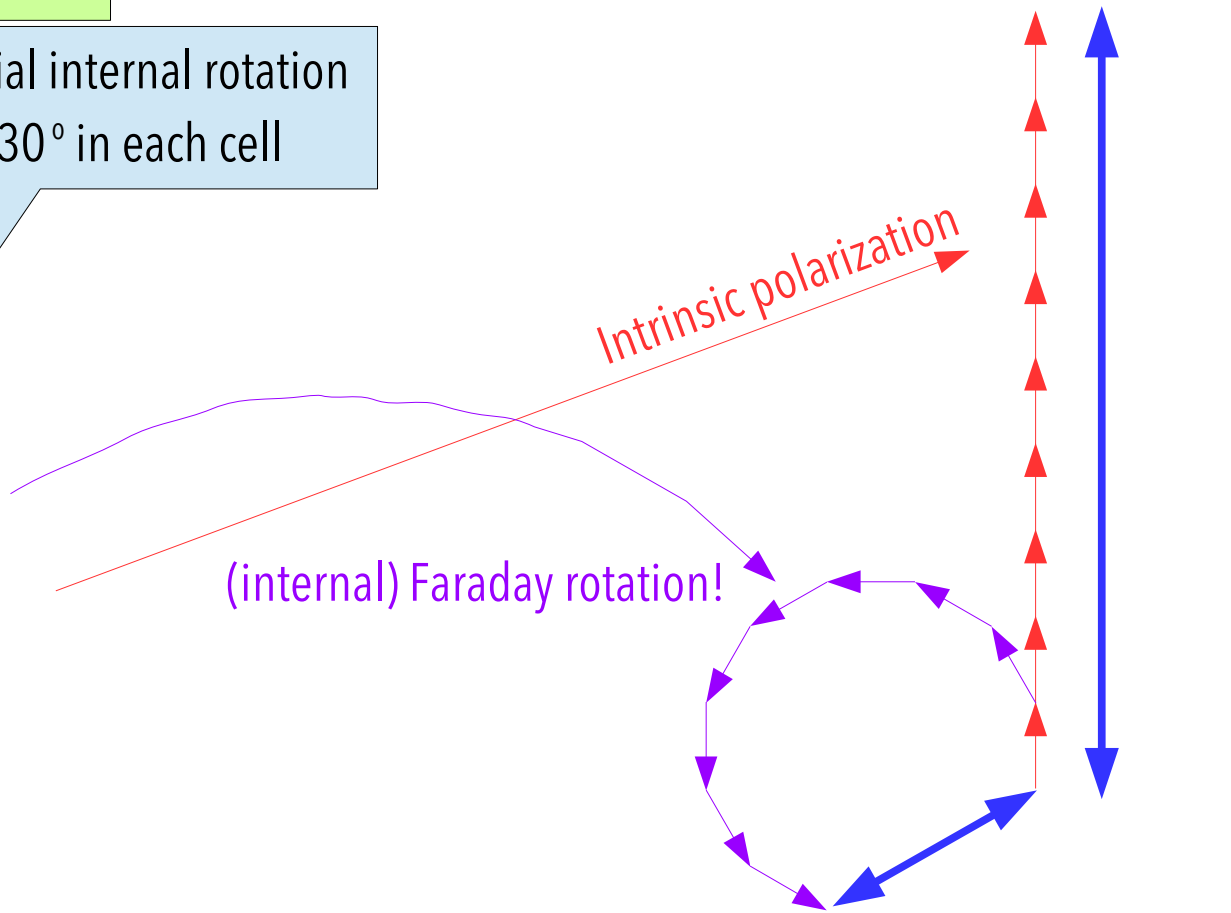
Internal RM: a simplified toy model

Homogeneous plasma (in terms of n_e and H)

Each cell contributes with the same linear polarization







Summary

Plasma are media that

0. Have a characteristic frequency ν_p
   (determined by n_e)

1. Below that frequency, radiation is reflected

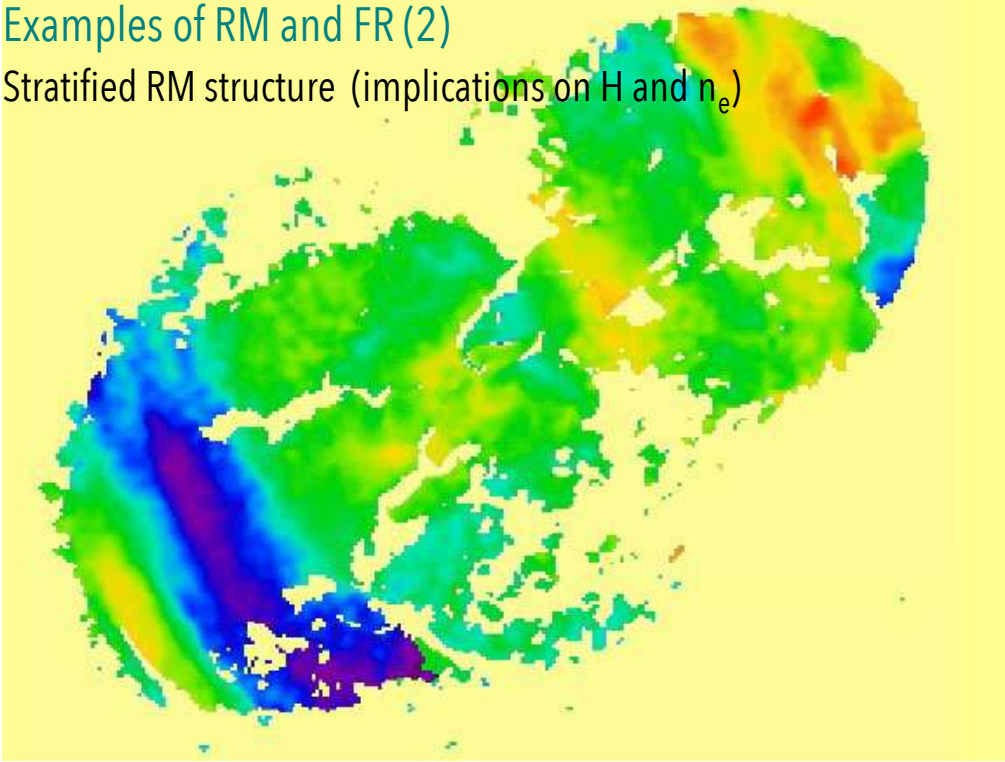
2. Above the plasma frequency, radiation travels
   at different velocities (higher at high ν) and then is dispersed. DM is a measure of such effect.

3. Linearly polarized emission have the orientation of the (electric) vector rotated by
   an amount proportional to λ^2 RM where RM is dependent on n_e , $H_{||}$

3bis. The amount of linear polarization may be reduced → DEPOLARIZATION,
   in case "all the vectors do not line up"

Examples of RM and FR (2)

Stratified RM structure (implications on H and n_e)



Acceleration mechanisms

Motivation: We know/see relativistic particles (nowadays, but also when the Universe was young...)

Stochastic: - collisions among particles/clouds (second order Fermi process)

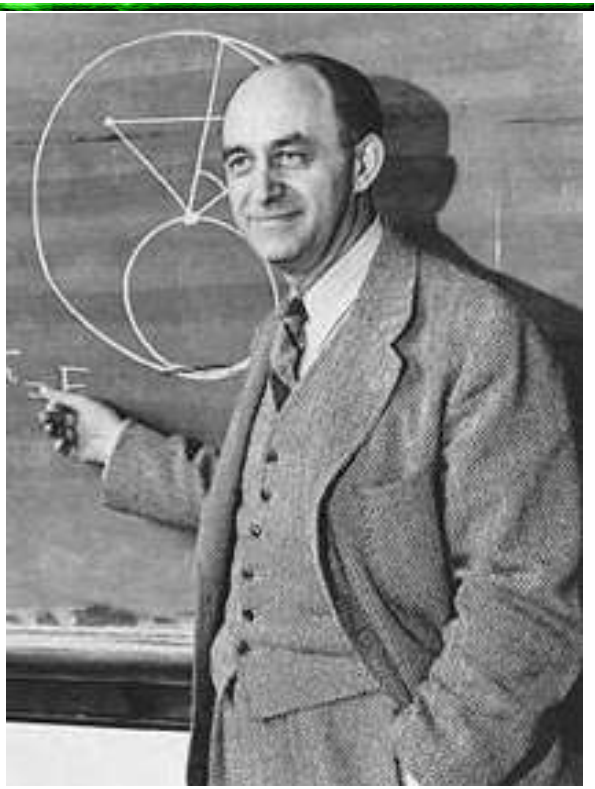
Systematic: - H field compression + scattering/diffusion

- shocks (first order Fermi process)

- e-m processes (e.g. Low frequency-large amplitude waves in pulsar magnetosphere)

⇨ Requires collisionless plasma (otherwise energy gain would be redistributed)

References:
Fanti & Fanti, cap. 9
Longair, 17.1 & 17.3 & 17.4



Proposed by E. Fermi in 1949 and refined in 1954

Ingredients → a charged particle moving at $\vec{v}$

→ a magnetized cloud moving at $\vec{u}$

$\vec{E}$ fields cannot survive given the enormous conducibility

$\vec{H}$ field *only* in the cloud

⇒ Rationale

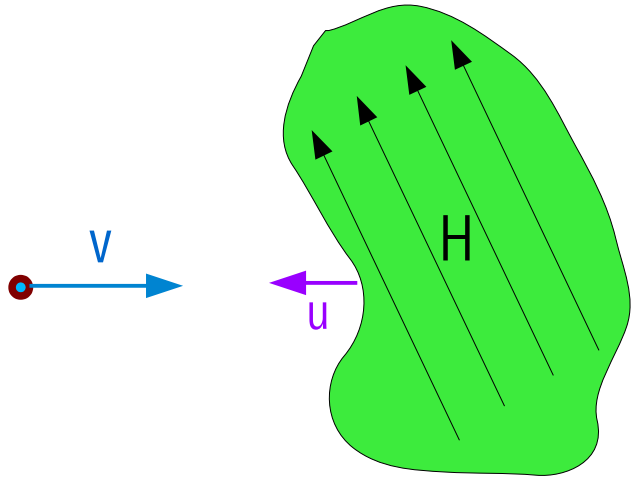
A charge moves in a low density space spiralling around its weak magnetic field

It enters into a moving cloud where both density (irrelevant) and magnetic field are higher

If the field in the cloud is high enough, the charge adiabatic invariant ($\sin\theta / H$) reflects it back

For simplicity, let's consider 1 — D interaction (e.g. along x)

(1 — D interaction, e.g. along x, for simplicity) $[M \gg m_e]$ $(v \gg u)$



When the charge enters in region of progressively higher H field, it ''feels'' an electric field as well

$$\vec{E} \approx -\frac{\vec{u}}{c} \times \vec{H}$$

The total force that the charge ''feels'' is

$$\vec{F}'_e = e\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{H}\right) = e\left(-\frac{\vec{u}}{c} \times \vec{H} + \frac{\vec{v}}{c} \times \vec{H}\right) = m_e \frac{dv}{dt}$$

Let's elaborate on the highlighted formula

Let's we consider a scalar product with $\vec{v}$ it becomes

$$\frac{d}{dt}\left(\frac{1}{2} m_e v^2\right) \approx (-)\frac{e}{c}\,\vec{v} \cdot (\vec{u} \times \vec{H}) = -e\,\vec{\beta} \cdot (\vec{u} \times \vec{H})$$

$$\frac{d}{dt}\left(\frac{1}{2} m_e v^2\right) \approx (-)\frac{e}{c}\,\vec{v}\cdot(\vec{u}\times\vec{H}) = -e\,\vec{\beta}\cdot(\vec{u}\times\vec{H})$$

$(\vec{u}\times\vec{H})$ → Field orientation and direction of cloud motion are very *important*

$\vec{\beta}\cdot$ → Direction of the relative motions of charge and clouds are very *important*

It is necessary that the magnetized cloud is in motion

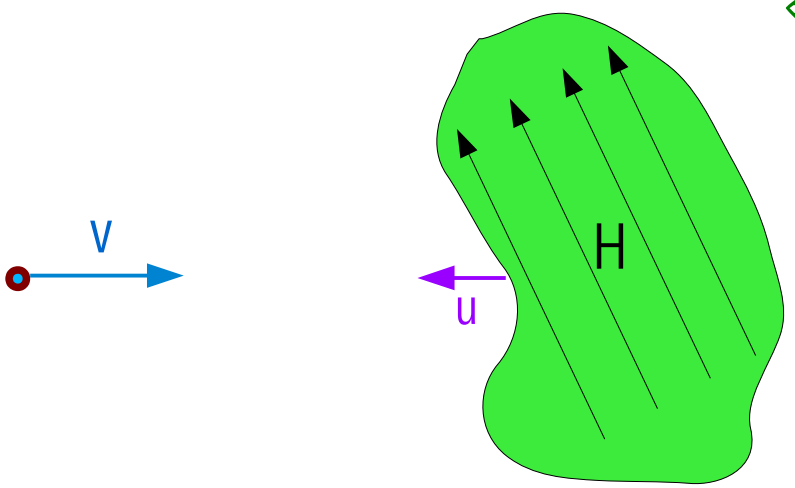
However, the value of $\vec{u}$ may depend on the reference frame.....and could be 0, as well

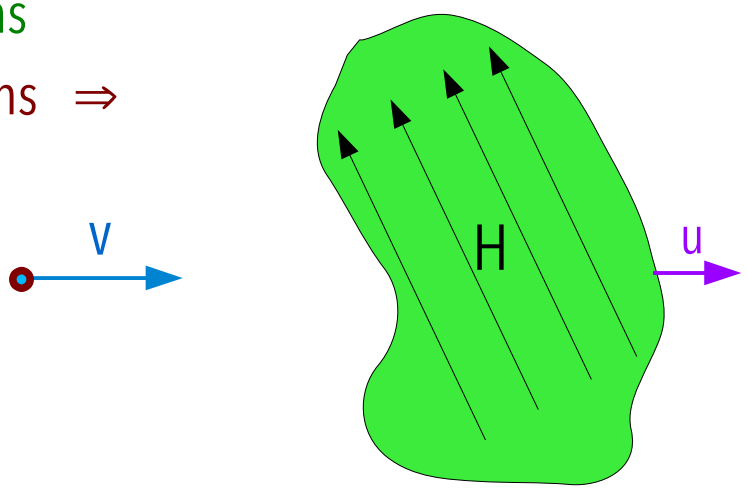
An external observer, however, MUST see both $u \neq 0$ and $v \neq 0$

There are two options:

⇐ Type – I interactions

Type – II interactions ⇒





Elastic collision (energy and momentum conservation): cloud $\leftarrow\rightarrow$ particle

$$v' = \frac{(m-M)v \pm 2Mu}{m+M} \approx -v \pm 2u \qquad \text{given that } m \ll M$$

$$u' \approx u$$

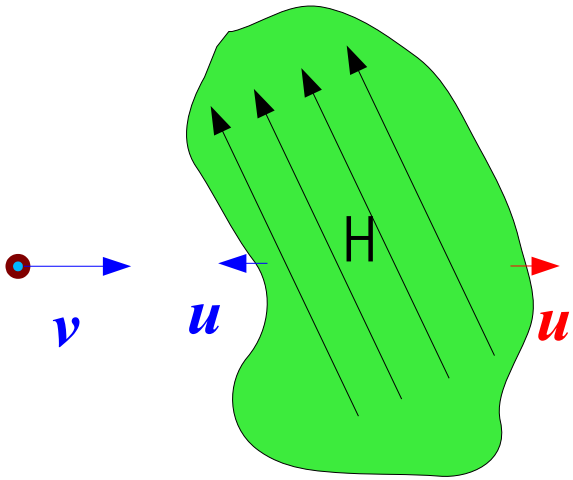
– (Type I)

+ (Type II)

In terms of particle energy before and after the interaction $(\varepsilon, \varepsilon')$

$$\varepsilon' = \frac{1}{2} m_e (v')^2 = \frac{1}{2} m_e (-v \pm 2u)^2 =$$

$$= \frac{1}{2} m_e \left(v^2 \pm 4uv + 4u^2 \right) = \varepsilon \left(1 \pm 4\frac{u}{v} + 4\frac{u^2}{v^2} \right)$$



Energy variation

$$\Delta\varepsilon_I \approx 4\frac{u}{v}\varepsilon \qquad \text{type I collision}$$

$$\Delta\varepsilon_{II} \approx -4\frac{u}{v}\varepsilon \qquad \text{type II collision} \qquad (\approx -\Delta\varepsilon_I)$$

Initial energy

$u^2/v^2 \ll u/v$ since cloud velocity much less than charge velocity $\rightarrow$ neglected!

Type I interactions happen more often than Type II

$$f_I = \frac{v+u}{l_{mfp}} \qquad f_{II} = \frac{v-u}{l_{mfp}} \qquad \text{therefore}$$

$$\left\langle \frac{\Delta\varepsilon}{\Delta t} \right\rangle_F = f_I \Delta\varepsilon_I + f_{II}\Delta\varepsilon_{II} = 4\,\frac{u}{v}\,\varepsilon\,\frac{2u}{l_{mfp}} = \frac{8}{l_{mfp}}\frac{u^2}{v}\varepsilon = \frac{\varepsilon}{\tau_F}$$

A factor 2 more appropriate than 8 (8 valid for head on collisions *only*!) $\left\langle \frac{\Delta\varepsilon}{\Delta t} \right\rangle_F = \frac{2}{l_{mfp}}\frac{u^2}{v}\varepsilon = \frac{\varepsilon}{\tau_F}$

If we integrate $\frac{\Delta\varepsilon}{\varepsilon} = \frac{\Delta t}{\tau_F}$ we obtain:

$$\varepsilon(t) = \varepsilon_o\, e^{\frac{t}{\tau_F}}$$

where $\tau_F \approx \frac{l_{mfp}\, v}{2u^2}$

N.B. Once the particle is accelerated at the required velocity, then should be able to leave the region where acceleration takes place.

Namely, the confining time τ_c should be of the order of (or slightly larger than) the acceleration time τ_F

The initial electron velocity can be estimated if we consider a thermal plasma

$$\frac{1}{2} m_e \langle v^2 \rangle = \frac{3}{2} kT \quad \rightarrow \quad v = \sqrt{\frac{3kT}{m_e}} = \sqrt{\frac{3 \cdot 1.38 \cdot 10^{-23}\, kg\, m^2\, s^{-2}\, ^oK^{-1}\, T}{9.1 \cdot 10^{-31}\, kg}} = 0.67 \cdot 10^4 \sqrt{T} \quad [m\, s^{-1}]$$

Fermi time is based on the cloud parameters $\tau_F \approx \frac{l_{mfp}\, v}{2u^2}$

For cloud velocities u ~ 10 km/s and given the typical cloud size and number density in the ISM (distance = l_{mfp} ~10 - 100 pc) relativistic velocities are achieved after $\rightarrow \quad \tau_F \approx 10^{10-11}$ yr

Wait a while... to remove this rectangle...

ALL IN ALL, despite being interesting, such mechanism is largely inefficient

β = statistical energy increase per collision i.e. after a collision $\varepsilon_1 = \beta \varepsilon_o$

k = # of collisions

p = probability to remain within the acceleration region

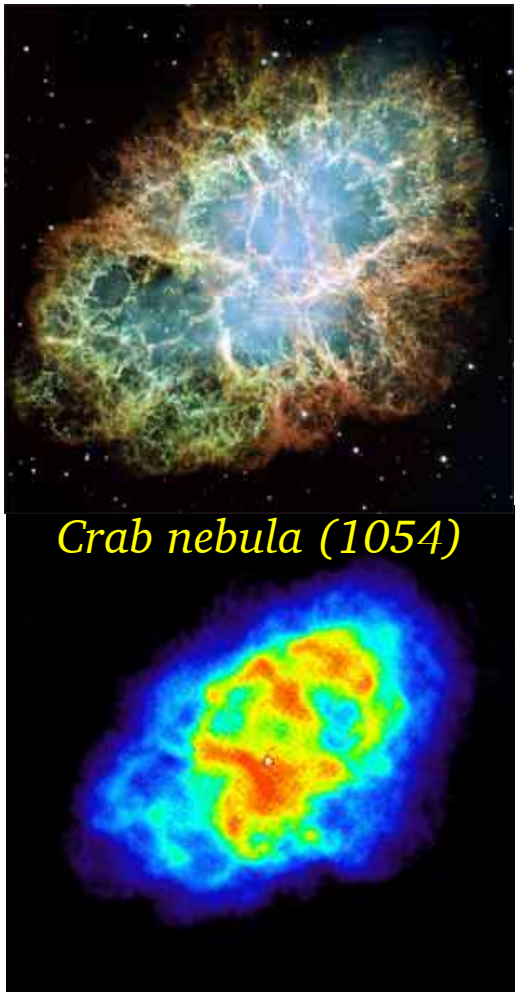
Then, in a given time, after k collisions $\varepsilon_k = \varepsilon_o \beta^k$

and the # of particles with k collisions is $N_k = N_o p^k$

$$\frac{\ln(N_k/N_o)}{\ln(\varepsilon_k/\varepsilon_o)} = \frac{\ln(p)}{\ln(\beta)} = m$$

$$N_k = N_o \left(\frac{\varepsilon_k}{\varepsilon_o} \right)^m \quad \rightarrow \quad N(\varepsilon)d\varepsilon = \text{cost}\ \varepsilon^{-1+m} d\varepsilon$$

i.e. power – law energy distribution



Crab nebula (1054)

Shock waves and Fermi's collisions (1)

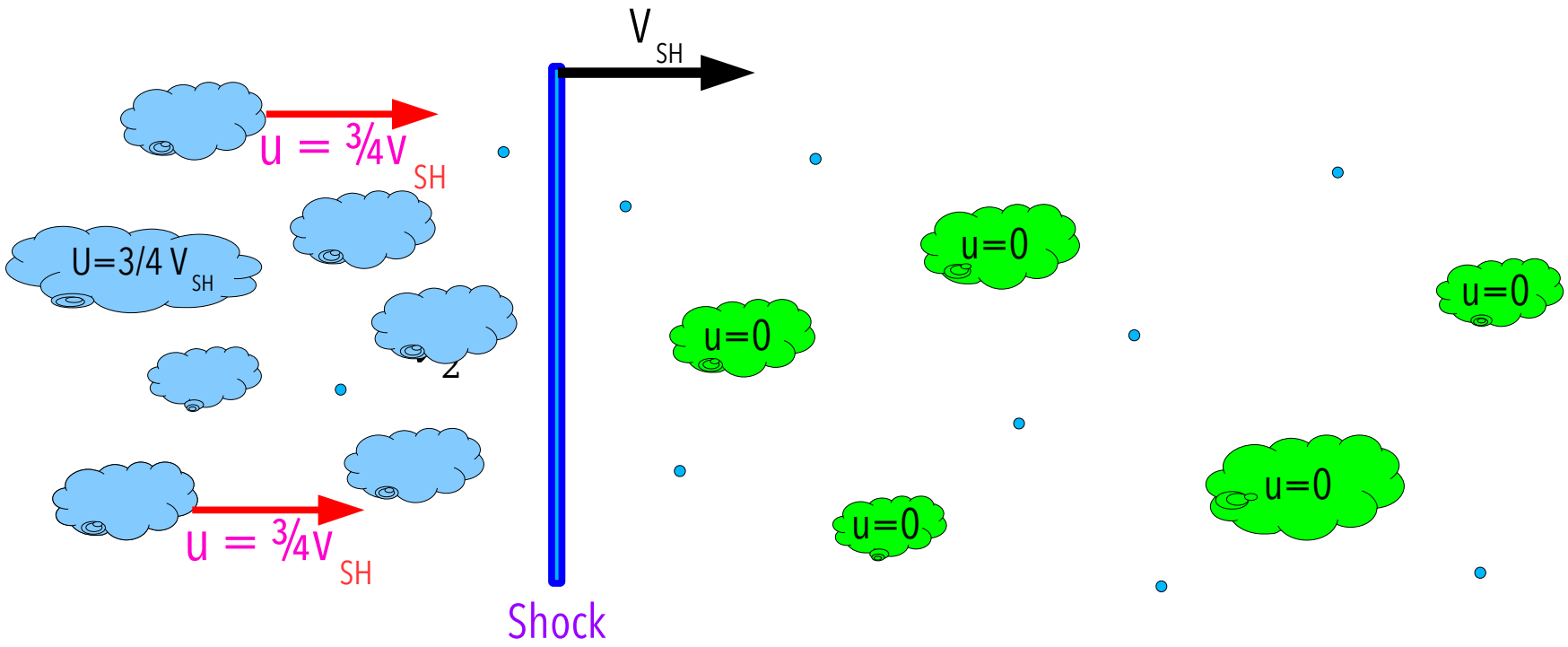
All motions with velocities exceeding $c_s = \sqrt{\frac{\Gamma k T}{\mu m_H}}$ [sound speed for an ideal gas (no H field)] are supersonic

If a perturbation moves at a speed v_{sh} exceeding c_s, a discontinuity is created.

Unperturbed (green) clouds assumed to be ~ at rest ($u_{UN} = 0$).

After going through the shock, their velocity is $u_{SH} = 3/4\, v_{SH}$

Charged particles have a negligible cross section to the shock and are unperturbed by its passage



Shock waves and Fermi's collisions (2)

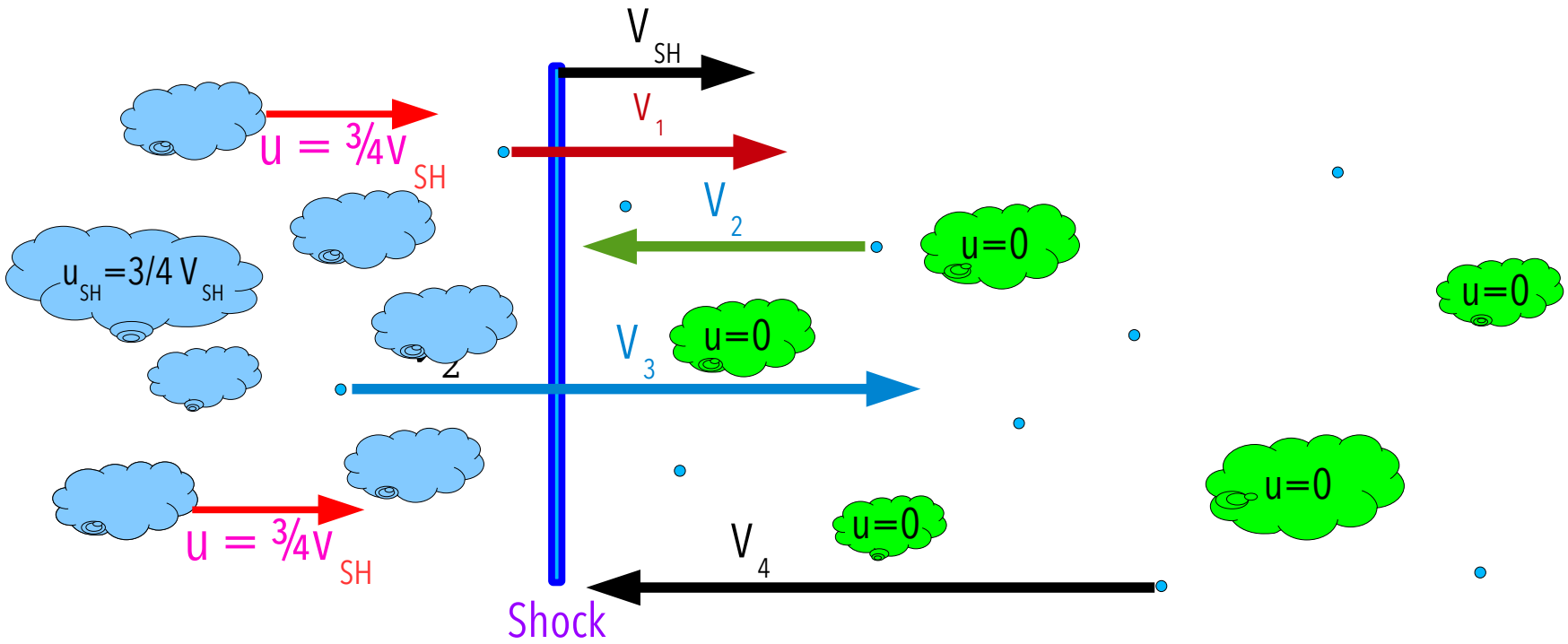
1. A charge interacts with a shocked cloud and rebounds with $v_1 = \mp v - 2u_{SH} = \mp v + 3/2\, v_{SH} \approx +3/2\, v_{SH}$

2. The charge overtakes the shock and goes into the unperturbed region where it interacts with a green cloud being reflected with $v_2 = -v_1 = -3/2\, v_{SH}$

3. The charge goes through the shock and interacts with another shocked cloud gaining $v_3 = -v_2 - 2(3/4\, v_{SH}) = 3/2\, v_{SH} + 3/2\, v_{SH} = 3\, v_{SH}$

4. After overtaking again the shock, there is reflection after inteaction with another green cloud, $v_4 = -3v_{SH}$ and so on...

Each time the charge interacts with a shocked (blue) cloud can gain $3/2\, v_{SH}$ then it is followed by an interaction with a green cloud causing a reflection, with no significant change in the charge velocity



The mechanism allows a particle to have Fermi – I type collisions with shocked clouds and rebounds (with no significant change in velocity) with unperturbed clouds at rest.

the occurrence between collisions is $f \approx \frac{v}{2l}$

and the energy gain in time is $\frac{d\varepsilon}{dt} \approx \frac{3}{2}\frac{v_1}{v}\varepsilon\frac{v}{2l} \approx \left(\frac{3}{4}\frac{v_1}{l}\right)\varepsilon = \frac{\varepsilon}{\tau_F}$

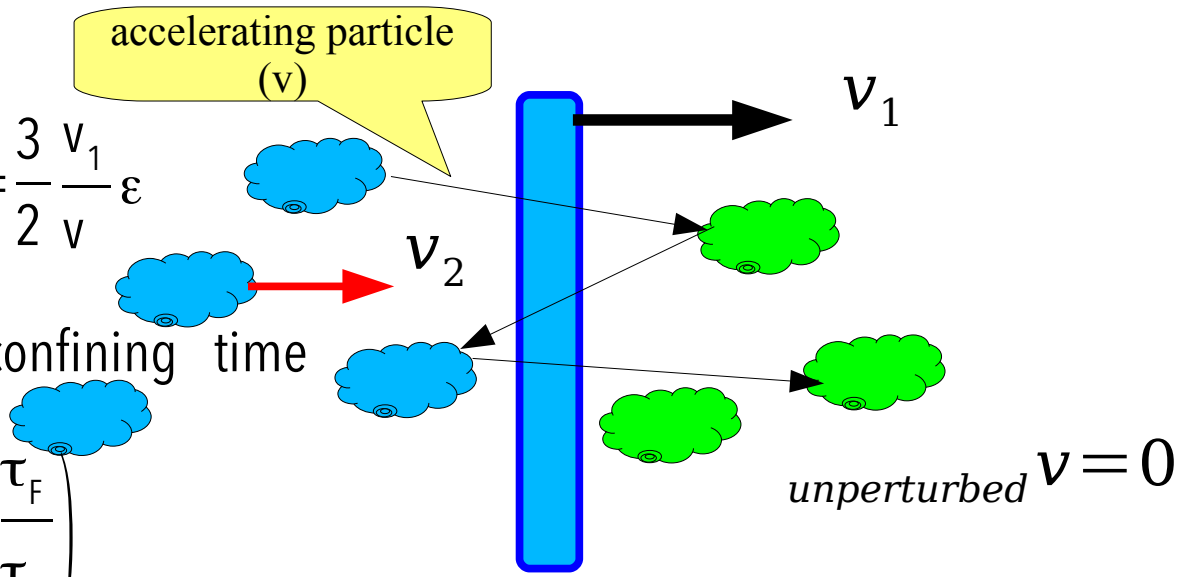
$v_2 = (3/4)\, v_1$

$\Delta\varepsilon_1 = 0$

$\Delta\varepsilon_2 \approx 2\, v_2 \frac{\varepsilon}{v} = \frac{3}{2}\frac{v_1}{v}\varepsilon$

$\tau_c \approx \frac{l}{v_1}$ confining time

$\delta = \left(1 + \frac{\tau_F}{\tau_c}\right)$



The initial electron velocity can be estimated if we consider a thermal plasma

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In SNR the process may be more efficient:

``clouds'' may have higher velocities $(10^3\, km/s)$

``l'' is small (0.1 pc) and then $\tau_F \approx 10^5$ yr

rectangle removed!

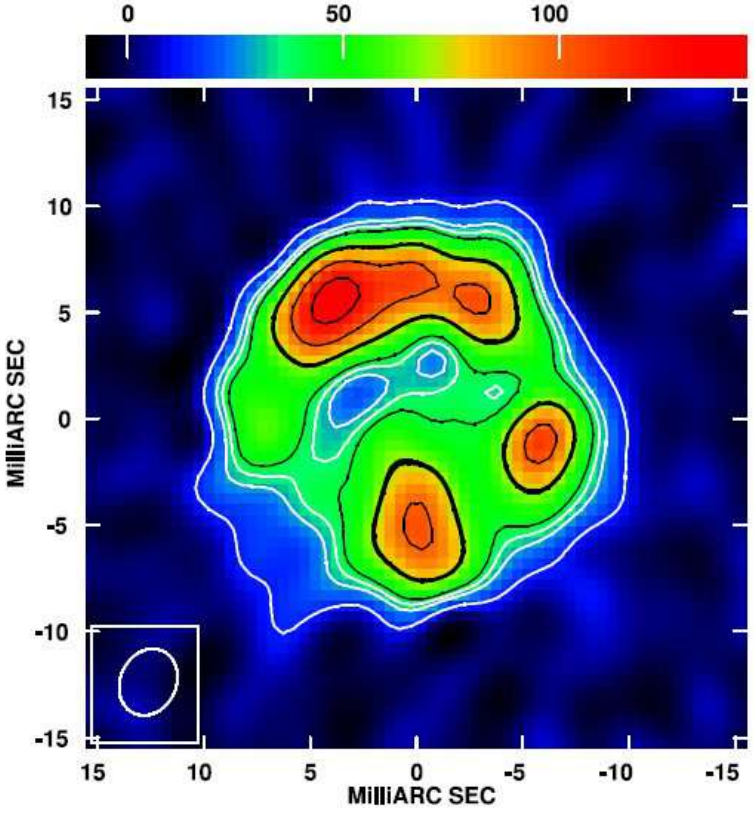
Observations of radio supernovae

Images (on the same scale!) shown aside require that efficient particle acceleration takes place on time scales as short as a few weeks !

Constraints from radio supernovae:

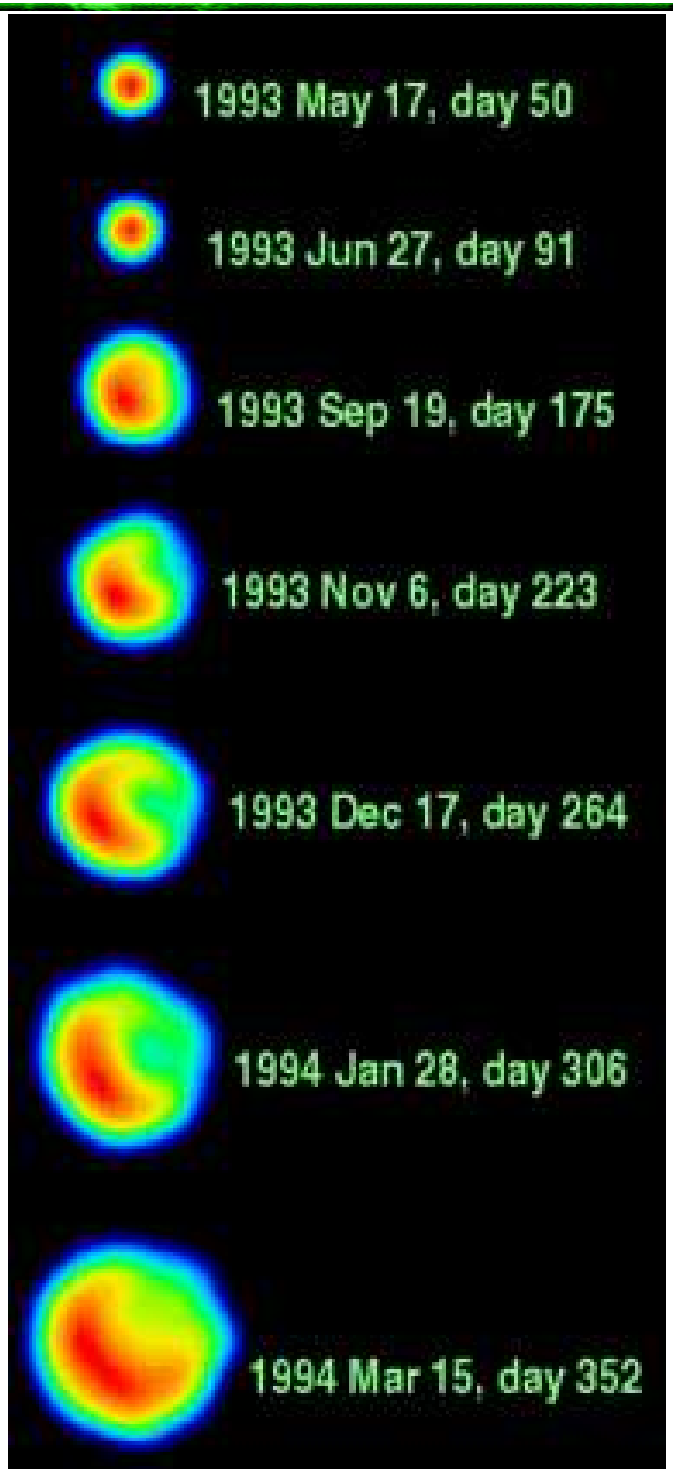
SN1993J in M81: Messier 81: spiral galaxy at a distance of ~3.7 Mpc
Apparent size of the galaxy : ~ 27 ' x 14 ' (from NED)

Try to determine the average expansion speed from the picture below
Pay attention to the units!



Bietenholz + al. 2010

Figure 1: VLBI image of SN 1993J at 1.7 GHz, taken on 2010 March 5-6, or at $t = 16.9$ yr after the explosion. Contours are at 10, 20, 30, 40, 50, 70 and 90% of the peak brightness of 117 μJy bm^{-1}, and the rms background brightness was 3.7 μJy bm^{-1}. The FWHM of the convolving beam is indicated at lower left. North is up and east is to the left.



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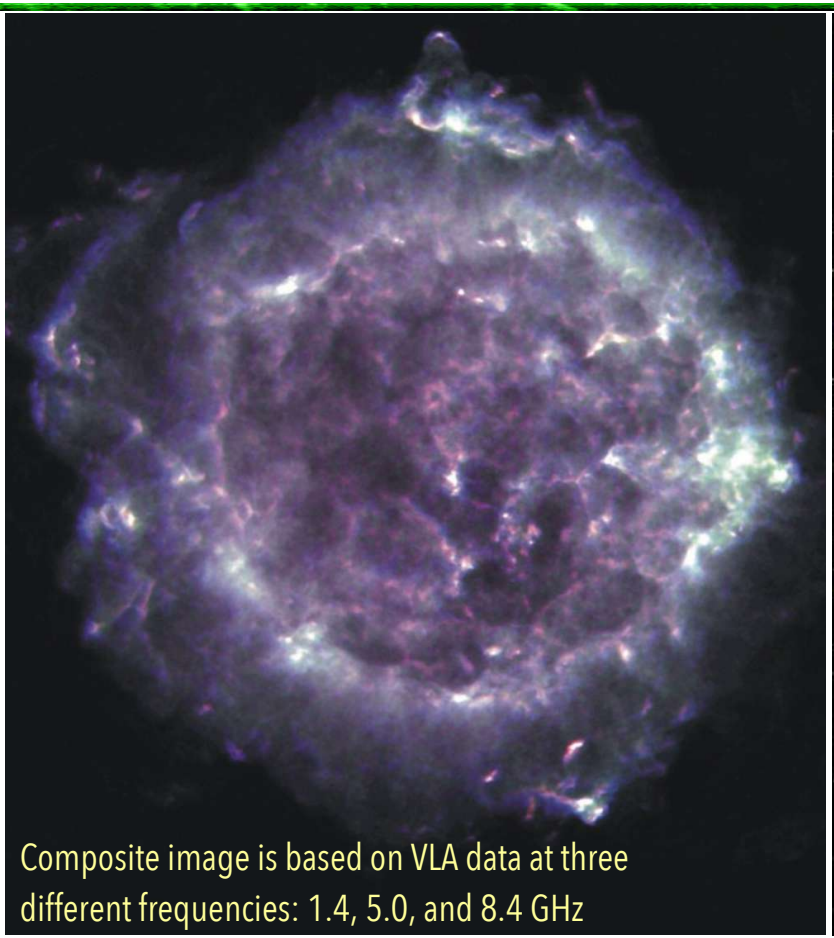
In SNR the process may be more efficient: ``clouds'' may have higher velocities $(10^3 km/s)$ and l_{mfp} is small (0.1 pc) and $\rightarrow \quad \tau_F \approx 10^5$ yr However, this would take too long!

→ **The injection problem:**

In the environment of a shock, only particles with energies that exceed the thermal energy by much (a factor of a few at least) can cross the shock and 'enter the game' of acceleration.

It is presently unclear what mechanism causes the particles to initially have energies sufficiently high.

Shock waves and Fermi's collisions (4): an example. Cas A



Composite image is based on VLA data at three different frequencies: 1.4, 5.0, and 8.4 GHz

False color image from 3 satellites. Red: IR from the Spitzer Space Telescope. Orange: visible from the Hubble Space Telescope. Blue+green: from the Chandra X-ray Observatory `

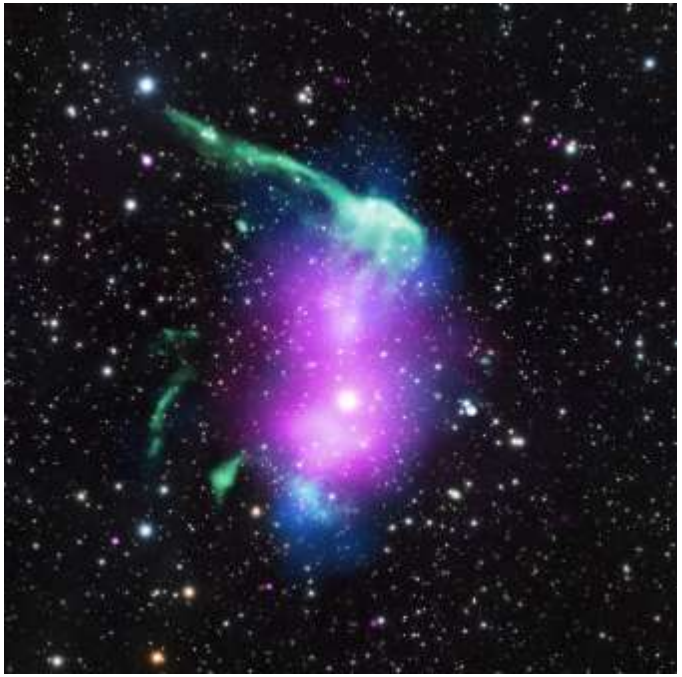
Flux density: 2720 Jy at 1 GHz.

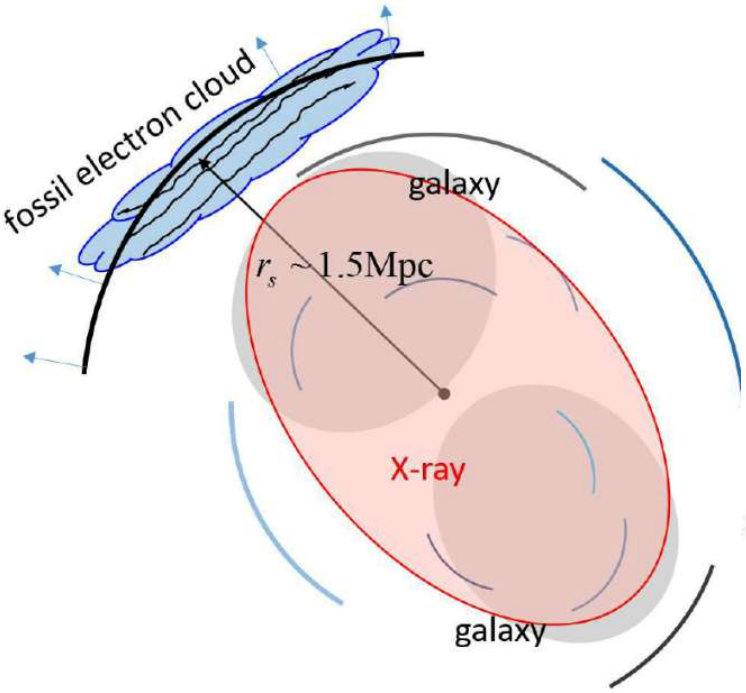
The SN occurred at a distance of approximately 11,000 ly away. The expanding cloud of material left over from the supernova is now approximately 10 ly across. Despite its radio brilliance, however, it is extremely faint optically, and is only visible on long-exposure photographs.

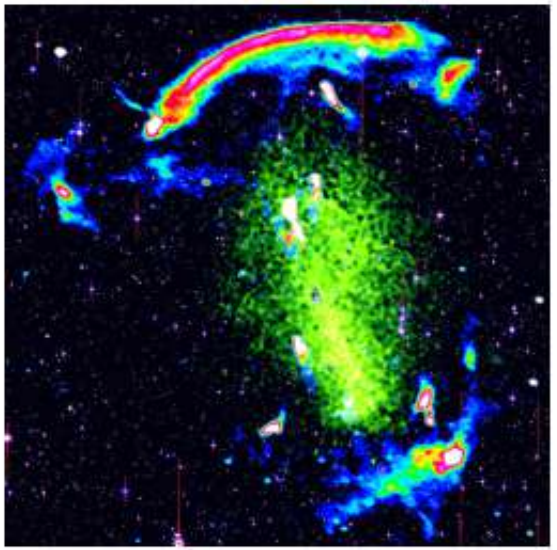
It is believed that first light from the stellar explosion reached Earth approximately 300 years ago but there are no historical records of any sightings of the progenitor supernova, probably due to interstellar dust absorbing optical wavelength radiation before it reached Earth (although it is possible that it was recorded as a 6 mag star by John Flamsteed on August 16, 1680

It is known that the expansion shell has a temperature of around 30 million Kelvin degrees, and is travelling at more than 10^7 miles per hour (4 Mm/s).

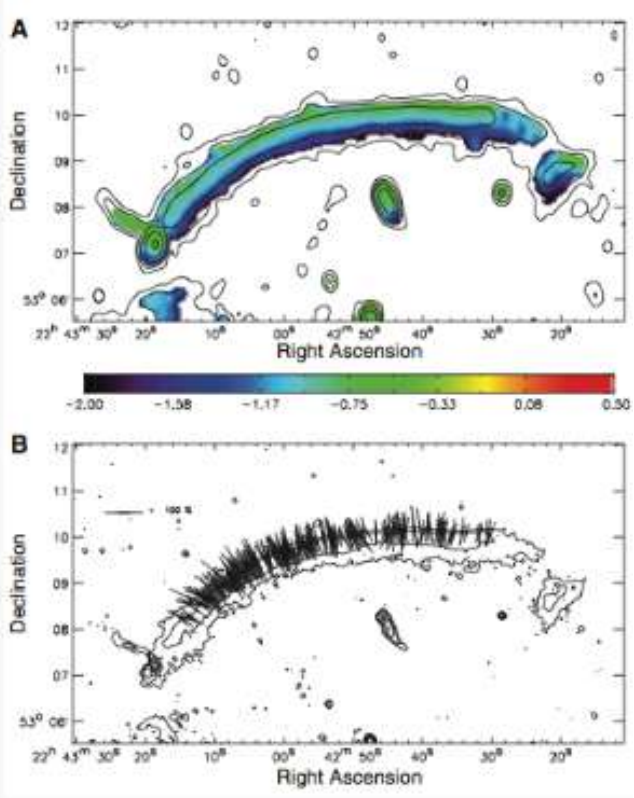
Shock waves and Fermi's collisions (5): an example.







LOFAR (rainbow), Chandra X-ray (green, Orgean+13) and optical (Stroe+15, Jee+15) image



Toothbrush relic (left) and Sausage relic (right).

Shock waves generated into the ICM by accretion processes can accelerate populations of "fossil, relativistic charged particles". This process is more efficient/visible at the cluster periphery where these bubbles are pushed up by buoyancy. The spectral index distribution is fundamental to determine the origin and development of these structures of revived non-thermal plasma. Also polarization (right hand side picture) is consistent with this picture.