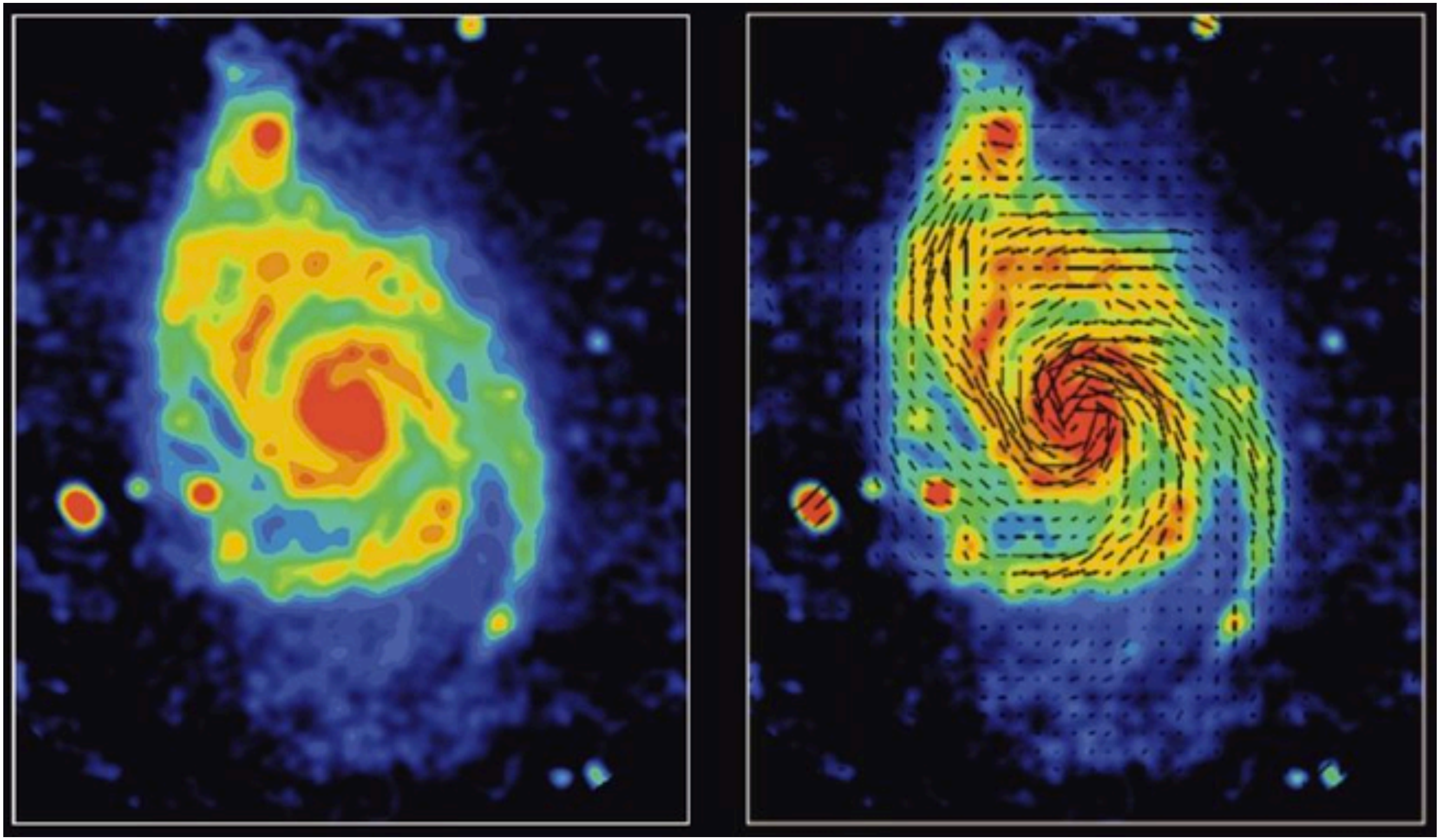
Galactic Magnetic Fields



Galactic Magnetic Fields

- In equipartition with CRs and interstellar radiation field
  - n=1 ev/cm^3
- Align dust grains ->polarized emission from dust
- CRs follow B-field lines
- Support the ISM
- Shklovsky (1953) suggested that synchrotron radiation powers the Crab Nebula; optical polarization was found the next year by Russian astronomers.

Motion of particles in B field

Charged particles undergo helical motion around magnetic field lines A key parameter is the ***cyclotron frequency*** $\boldsymbol{\omega_B}$. The relativistic mechanics of a particle with charge *q* and rest mass m_0 in a uniform field ***B*** can be stated as:

$$\frac{d\vec{v}}{dt} = \vec{\varpi}_B \times \vec{v} \qquad \vec{\varpi}_B = \frac{1}{\gamma}\left(\frac{q\vec{B}}{m_0 c}\right)$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = v/c$$

$$\nu_B(\mathrm{e}) = 2.80\ \mathrm{Hz}\ \frac{1}{\gamma}\left(\frac{B}{\mu\mathrm{G}}\right)$$

Orbital periods and curvature radius

- Values for cyclotron freq. (γ=1) are for a 5 μG field:
  - ω_B = 17.6 MHz B for electrons = 88 Hz
  - ω_B = 9.60 KHz B (Z/A) for ions= 0.048 Hz (for protons)

- Curvature radii are: $v = \omega_B r$, using $v \approx c$:
  - 3.4e8 cm for electrons
  - 6.2e11 cm for protons

- These are small numbers compared by interstellar standards
  - Electrons and protons spiral all the time along magnetic field lines !!

Standard Treatment of Synchrotron Radiation

Basis

- circular orbits, gyrofrequency ω_B
- Lorentz factor γ
- helical pitch angle α
- L-W retarded potentials
- relativistic limit $\gamma >> 1$

Results

1. **Mean Power**

$$\frac{dP(\varpi)}{d\varpi} = \frac{2}{3}\frac{q^2}{c}(\varpi_B \beta \sin\alpha)^2 \gamma^4$$

(relativistic Larmor formula)

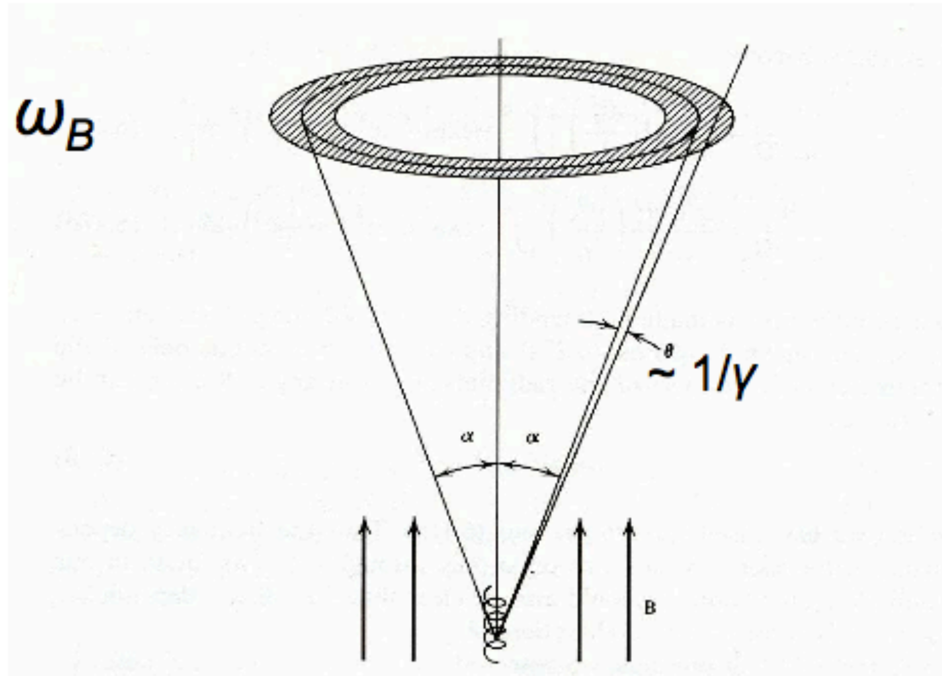
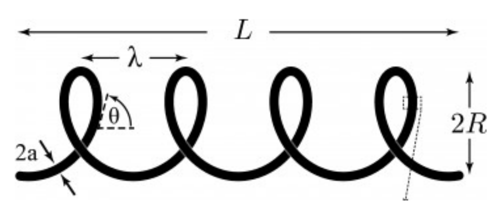


Figure 6.5 Synchrotron emission from a particle with pitch angle α. Radiation is confined to the shaded solid angle.

Rybicki-Lightman Fig. 6.5b



Synchrotron Radiation Results

2. **Angular Distribution** – searchlight in cone of half-angle α about ***B*** and width $1/\gamma$ (previous figure).

3. **Frequency Distribution** -

$$\frac{dP(\omega)}{d\omega} = CF\left(\frac{\omega}{\omega_c}\right)$$

$$\omega_c = \frac{2}{3}\gamma^3\omega_B \sin\alpha$$

$$C = \frac{\sqrt{3}}{2\pi}\left(\frac{q^2}{c^2}\right)\left(\frac{|q|B}{m_0 c}\right)\sin\alpha$$

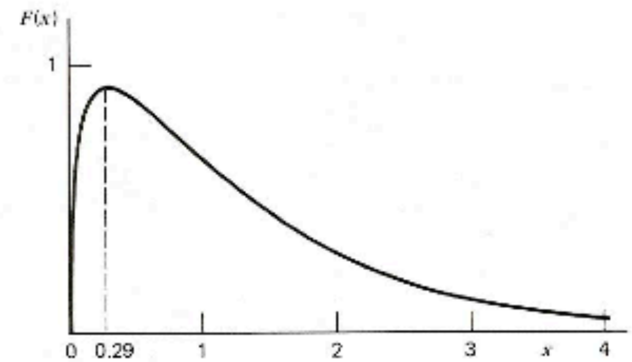


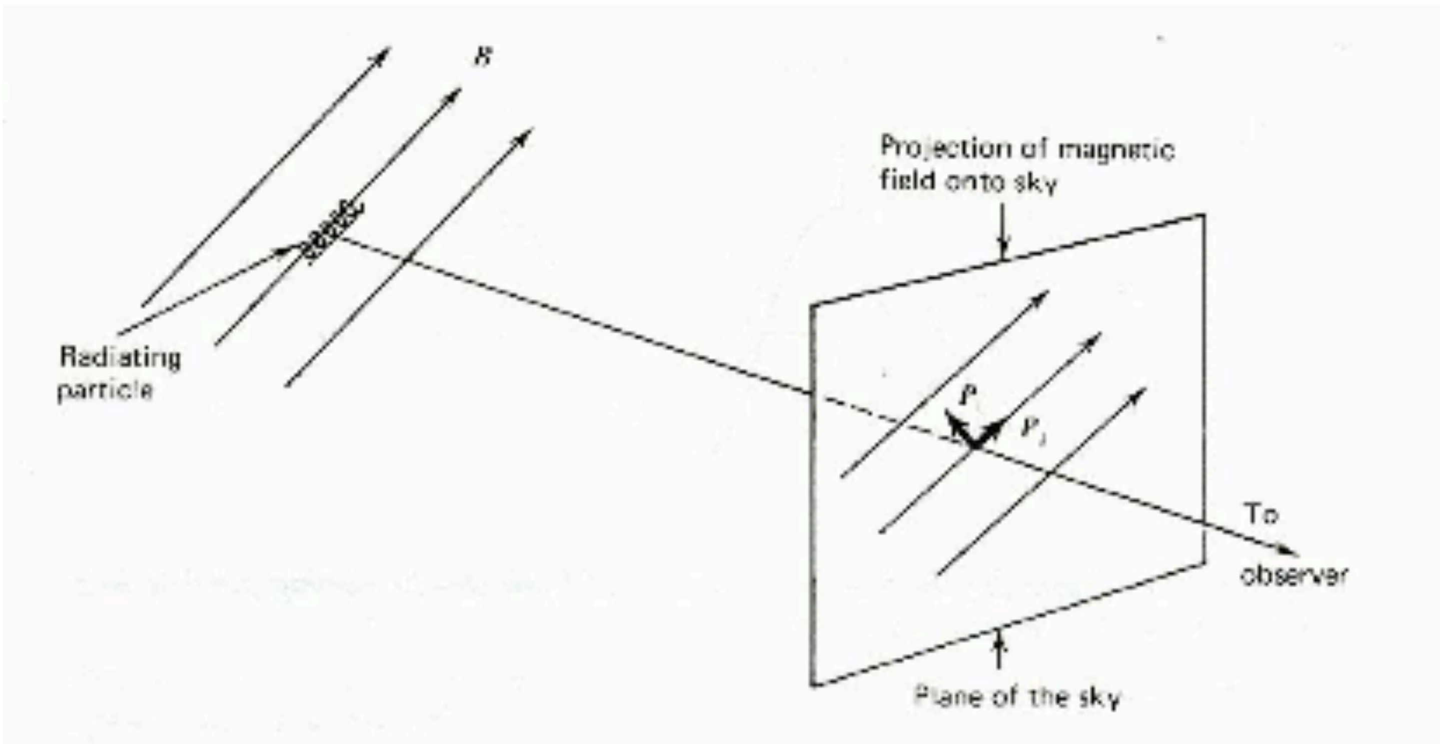
Figure 6.6 Function describing the total power spectrum of synchrotron emission. Here $x = \omega/\omega_c$. (Taken from Ginzburg, V. and Syrovatskii, S. 1965, Ann. Rev. Astron. Astrophys., 3, 297.)

F plotted vs. ω/ω_c
(Rybicki & Lightman Fig. 6.6)

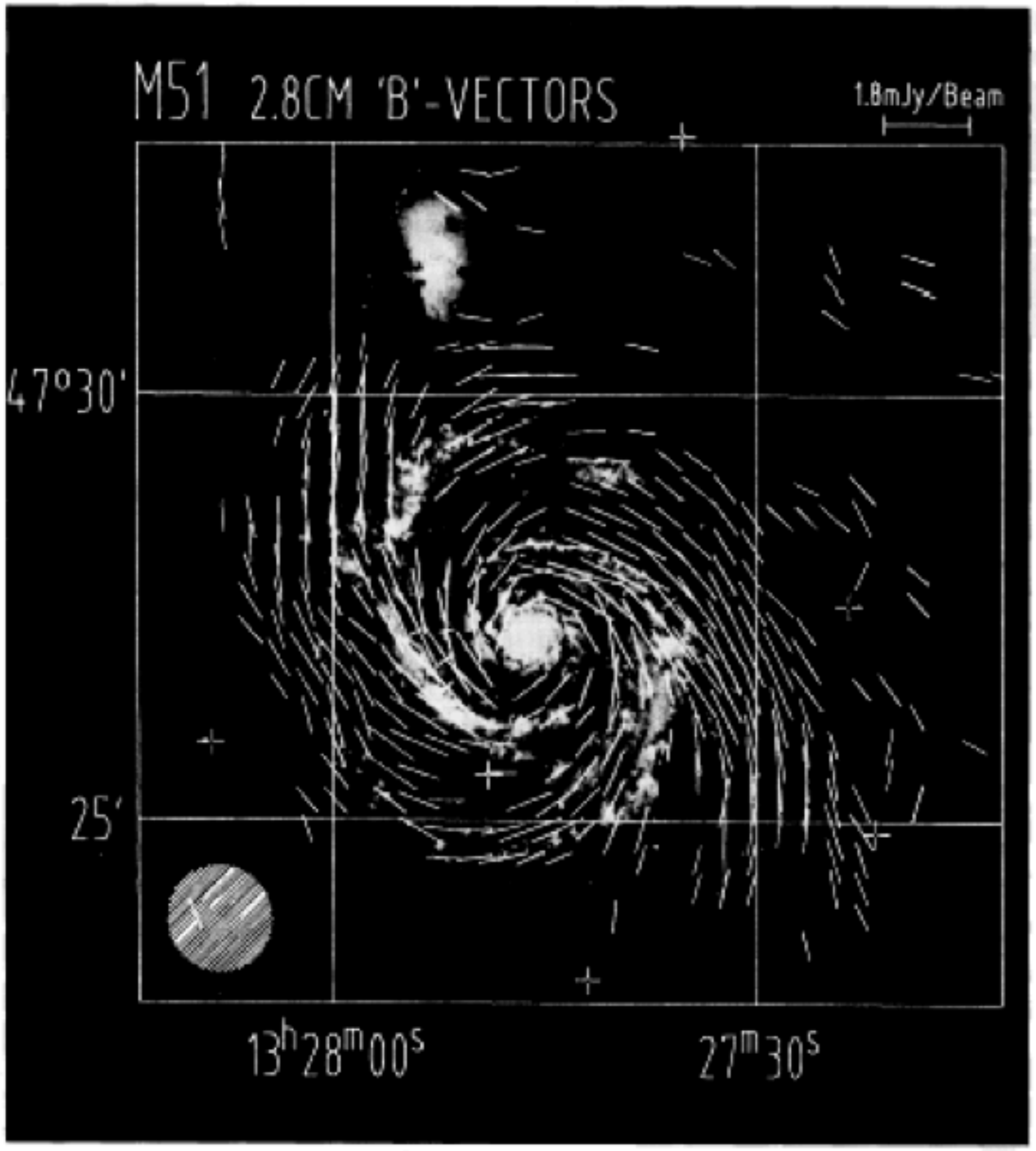
4. **Polarization** ~ 75%, integrated over the spectrum for fixed γ, the emission is ***plane-polarized*** in the plane of the sky (perpendicular to the line of sight), the classic signature of synchrotron emission.

Polarization

- The radiation from an ultra-relativistic particle is mainly polarized in the plane of motion: i.e. perpendicular to B



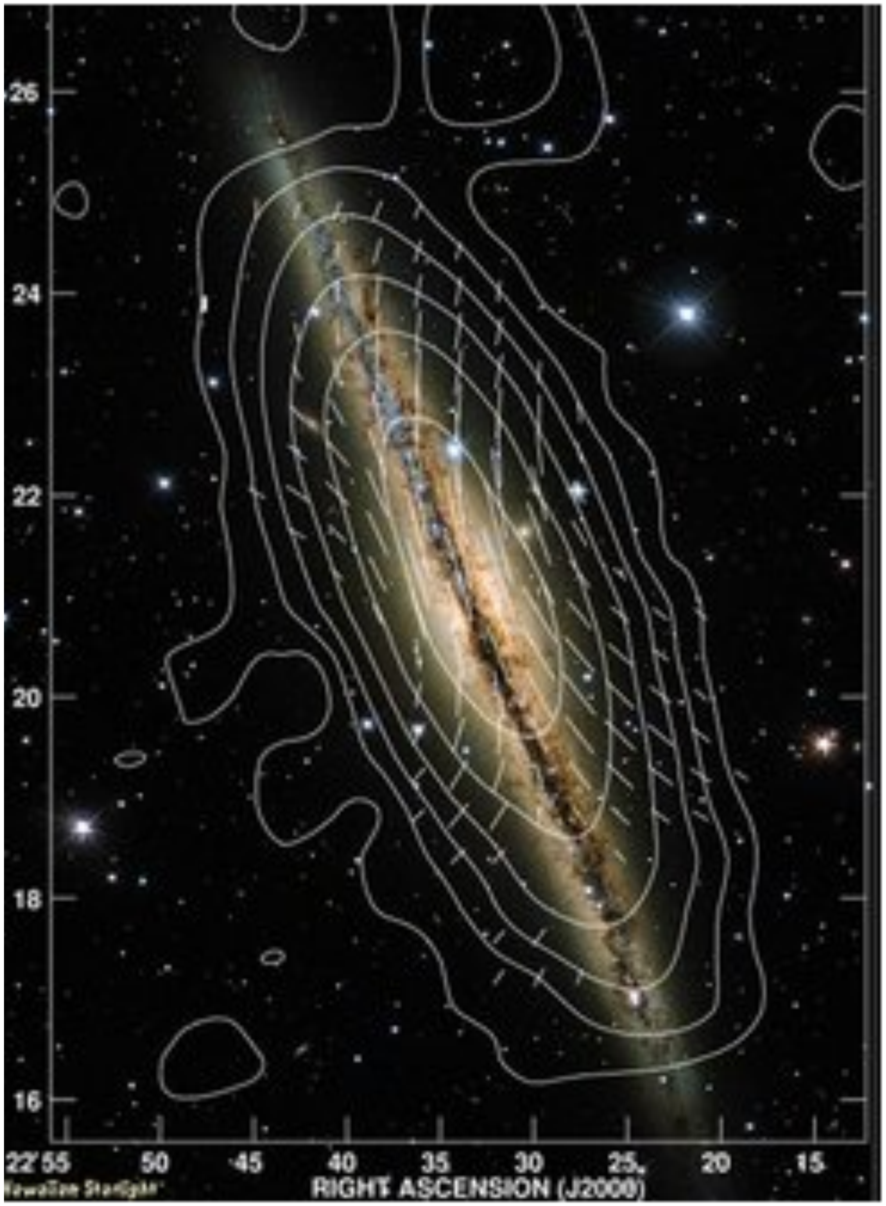
Radiation is almost linearly polarized perpendicular to B, signature of synchrotron radiation



Neininger, A&A 263 30 1993

2.8 cm observations of polarized emission from the face-on galaxy M51. ***The magnetic field directions follow the spiral arms.***

Fig. 3. ***B***-vectors of the intrinsic magnetic field of M51, obtained by rotating the measured ***E***-vectors by 90° superimposed onto the same optical plate as Fig. 2. The length of the vectors is proportional to the polarized intensity



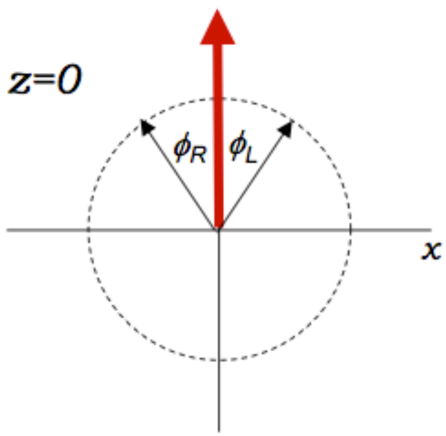
6 cm synchrotron emission from the edge-on galaxy NGC 891 showing ***halo emission***.

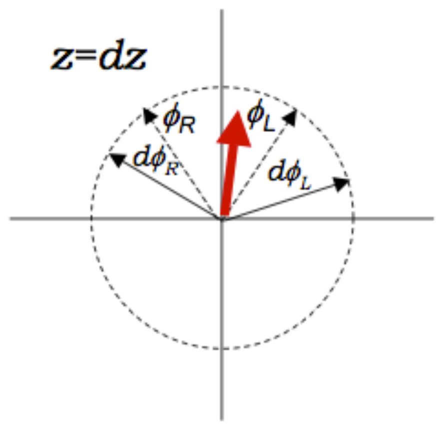
Sukumer & Allen
ApJ 382 100 1991

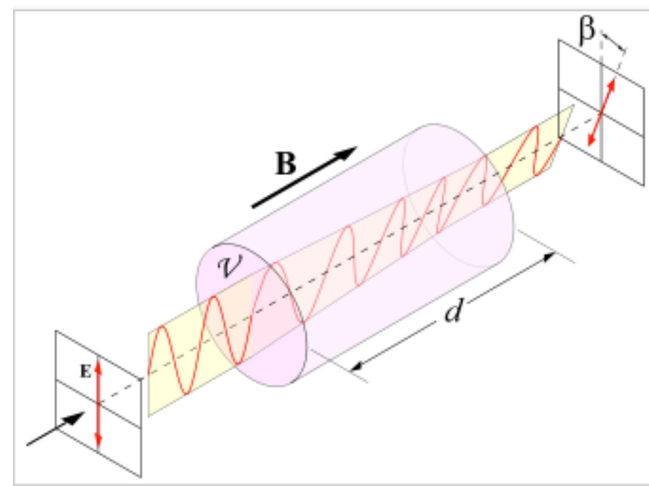
Magnetic fields as well as cosmic rays must extend above the disk of the galaxy.

Rotation Measurement

- Discovered by Faraday, it allows the measurement of the Magnetic field `along' the line of sight
- Linear polarized wave can be decomposed into two circularly polarized counter-rotating waves



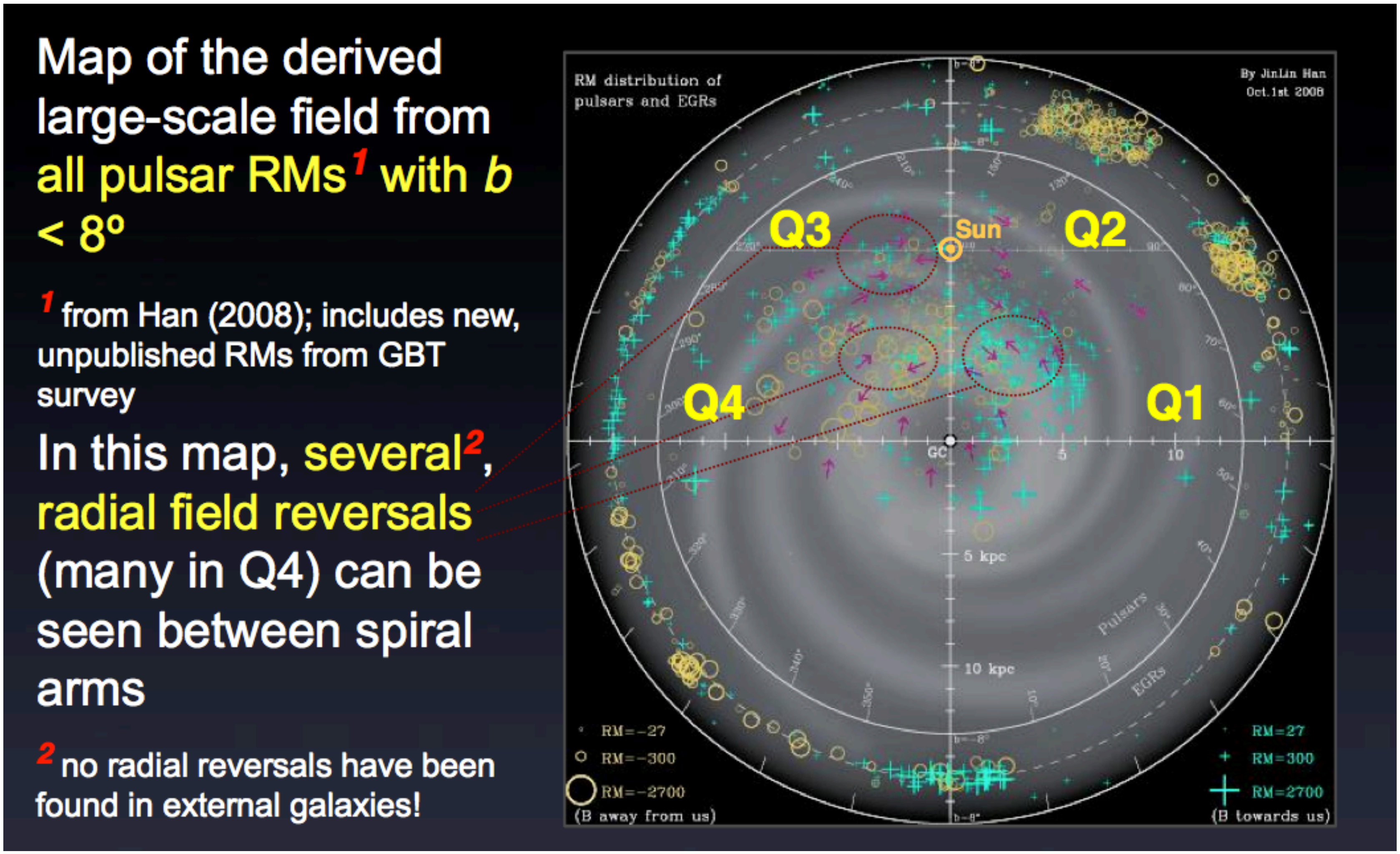




- The left and right rotating waves propagate differently through a magnetized plasma
  - They would experience a different refractive index dependent on whether the created magnetic field is parallel or opposite to the ISM B

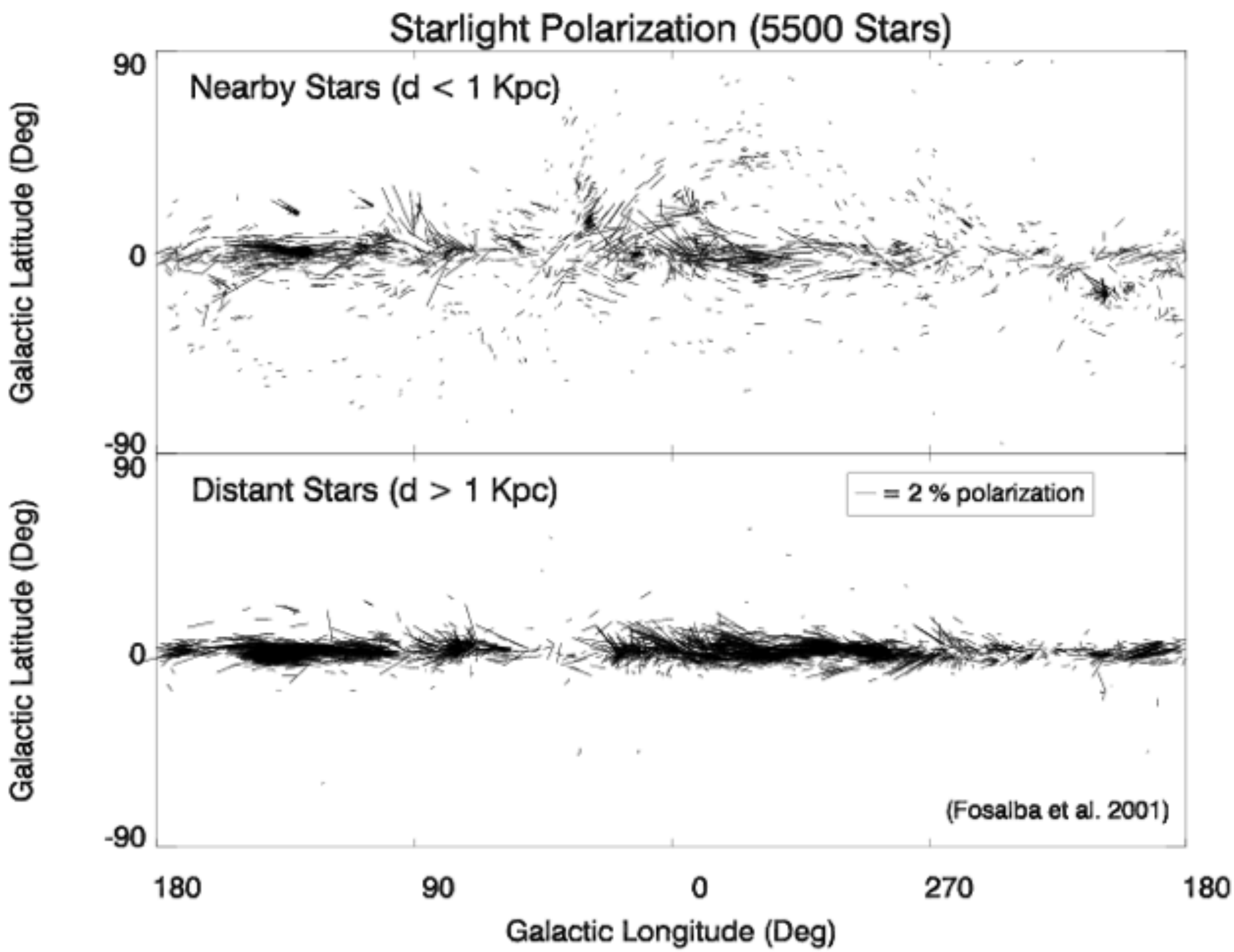
Pulsars and RMs

- Pulsars emit linearly polarized emission



Noutsos et al.

Dust Polarization



Galactic B fields

- For the Milky Way:
- the field is mainly parallel to the disk midplane,
- concentrated in the spiral arms with inter-arm reversals,
- The random component may be 50% of the ordered field.
- The median total field in the solar neighborhood is 6 μG.
- The field increases with decreasing galactic radius, and is about 10 *μG at R = 3 kpc*

- *For external galaxies:*
  - *the synchrotron emission studies show the effects of spiral structure, the existence of thin and thick disk components, and occasionally inter-arm reversals. Typical field values are 10 μG, not all that different than the Milky Way.*

Effects on the ISM

- In terms of a static disk, the most important force for consideration of large scale (kpc) structure is the gravity field generated by the stars (with a mass an order of magnitude larger than the ISM).

- Cox05 reports the following expression for the vertical gravity (exact to 2% in z=[0-10] kpc)

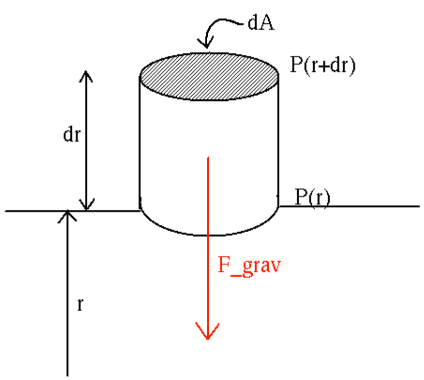
$$|g| = 10^{-9}\,\mathrm{cm\,s^{-2}}\,\{4.2[1-\exp(-|z|/165\ \mathrm{pc})] + 4.1|z|/2\ \mathrm{kpc}\}$$
$$\cdot(1-|z|/27\ \mathrm{kpc})/[1+(z/6\ \mathrm{kpc})^2]^{1/2}.$$

disk

halo stars

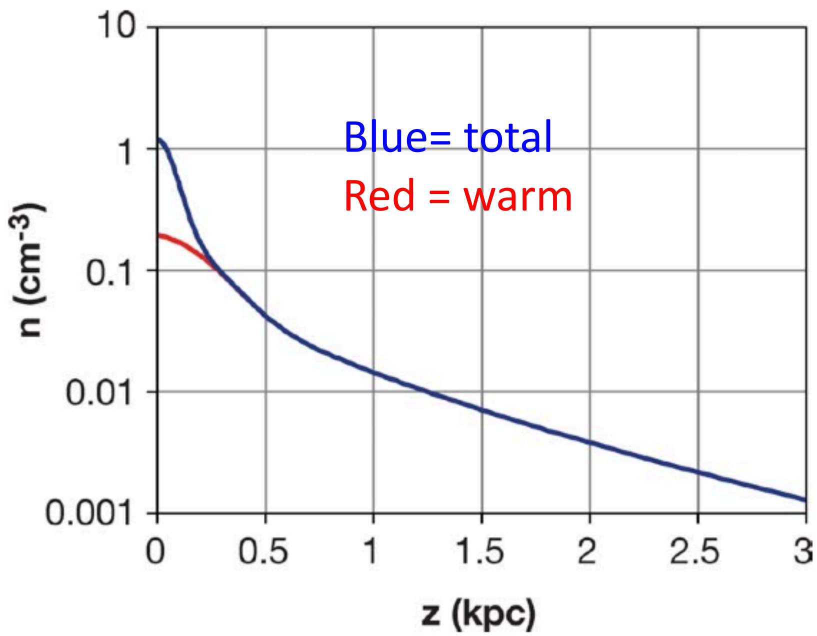
- Hydrostatic equilibrium

$$\frac{dp}{dz} = -\rho(z)\,g(z)$$



Hydrostatic equilibrium

- Hydrostatic eq. can be solved since we know the density distribution of gas and assuming p(10kpc) ~0



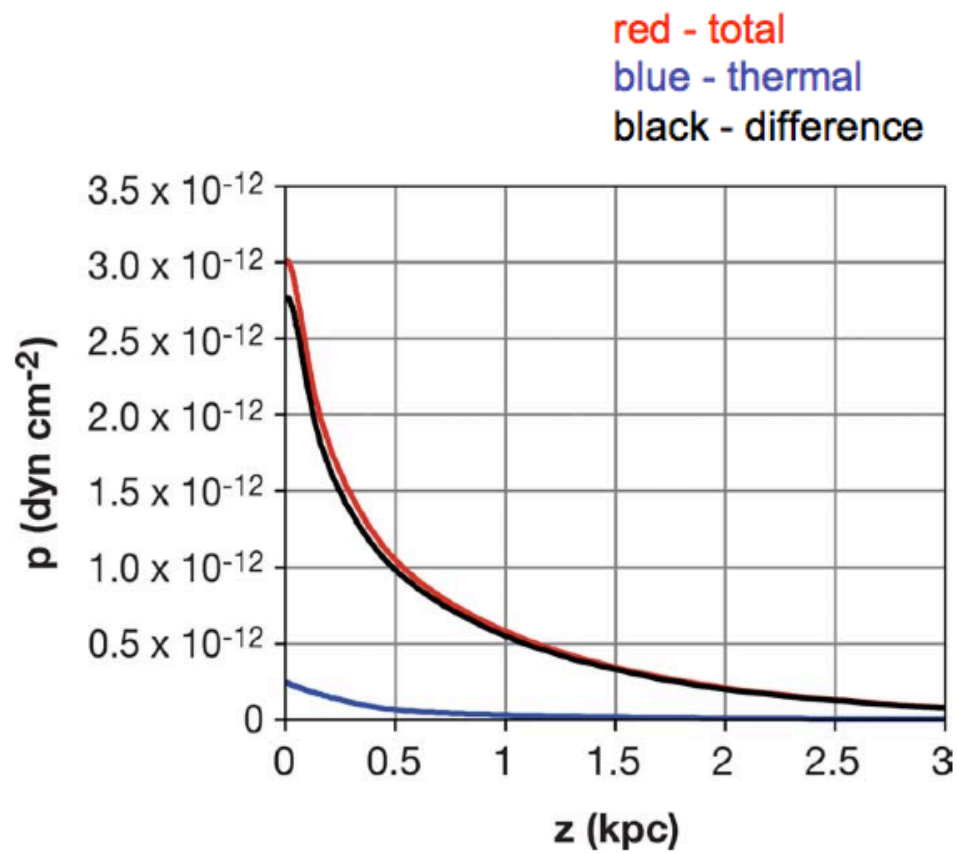


Figure 2 Comparison of the total (*red*) and volume average thermal (*blue*) pressure distributions, and their difference (*black*) interpreted as the nonthermal pressure. In this case, the total is taken from the weight distribution of the ISM. The thermal pressure neglects any contribution from the hot component.

Non thermal Pressure

- $P = p_{th} + (p_{turb} + p_{CR} + p_B + p_{dyn})$
  - Last term includes macroscopic flows

- The synchrotron emissivity implies that the cosmic rays and magnetic field persist to greater heights than would be inferred from the weight distribution of the interstellar matter considered so far (Cox05), in agreement with observations from other galaxies

- The last three terms are in rough equipartition (turbulence does not count much) and solve the `pressure' problem

Summary

- The magnetic field is an important component of galaxies
  - In equipartition with CRs and interstellar radiation fields

- Studies of polarized synchrotron emission, Faraday Rotation and dust polarizations (using background stars) show the magnetic field lines
  - Substantial B fields in the halo
  - Magnetic reversal