Polarization

- If there are magnetic fields (Synchrotron, Cyclotron ...) involved we can get a preferred direction of radiation - polarization
- We normally use Stokes parameters to show thes (I,Q,U,V) -total intensity (I), 2 orthogonal linear polarizations (Q,U), circular polarization (V)
- To measure these we need measure 2 orthogonal polarizations in our receiver (either linear X,Y or circular R,L polarizations)

Description

- Polarization can be described several other ways
  - Jones matrix
  - Poincaré sphere
  - cohererency matrix
- Radio astronomers use the RADIO definition for circular polarization (opposite to that used optically)

Orders of magnitude

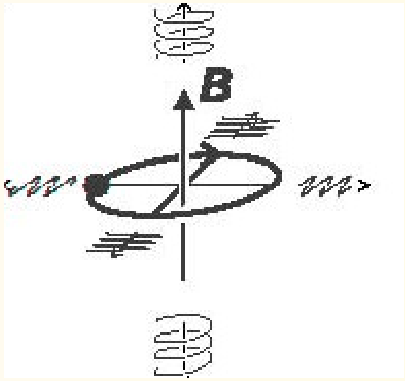
- Free-free and thermal sources are unpolarized
- Synchrotron sources can have linear polarization from 0-60%, typically 0-10% (depends on ordering of the magnetic field)
  - their circular polarization is typically 0-0.1%
- Pulsars have high linear polarization but direction changes throughout the pulse
- Maser sources can have extremely high polarization (they are coherent)
- Man made (interference) is usually 100% polarized

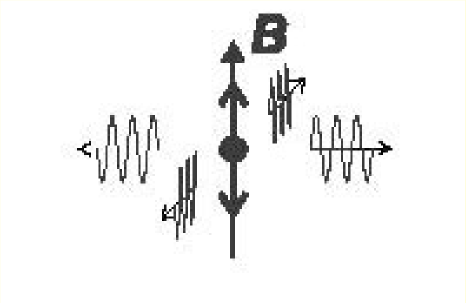
Zeeman splitting

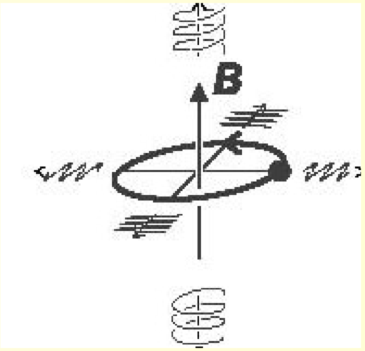
- The hyperfine transitions are magnetic
- So magnetic fields will split a single spectral line into a triplet in frequency (for an 's' level electron)
- BUT it also makes it polarized
  - Δm =0 is has vectors parallel to the field
  - Δm =+/- 1 has vectors orthogonal to the field

Zeeman and polarization

- like this







Stokes Parameters vs Electric Field

- If the electric field in 2 orthogonal linear directions is E_x and E_y we can represent that as voltages $e_x(t)\cos[\omega t+\delta_x]$
  and $e_y(t)\cos[\omega t+\delta_y]$

  That gives the Stokes parameters as powers

$$I = \langle e_x^2(t)\rangle + \langle e_y^2(t)\rangle$$

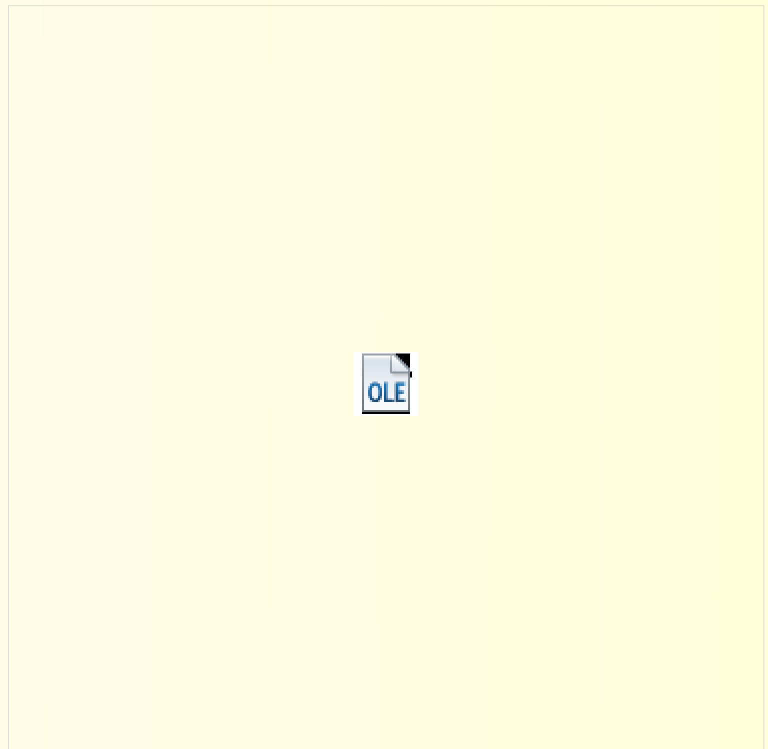
$$Q = \langle e_x^2(t)\rangle - \langle e_y^2(t)\rangle$$

$$U = 2\langle e_x(t)\, e_y(t)\cos[\delta_x - \delta_y]\rangle$$

$$V = 2\langle e_x(t)\, e_y(t)\sin[\delta_x - \delta_y]\rangle$$

where angle brackets denote time average

movie



We can convert these measures

- More convenient are fractional polarization and polarization angle

$$m_l = \frac{\sqrt{Q^2 + U^2}}{I}$$ fractional linear polarization

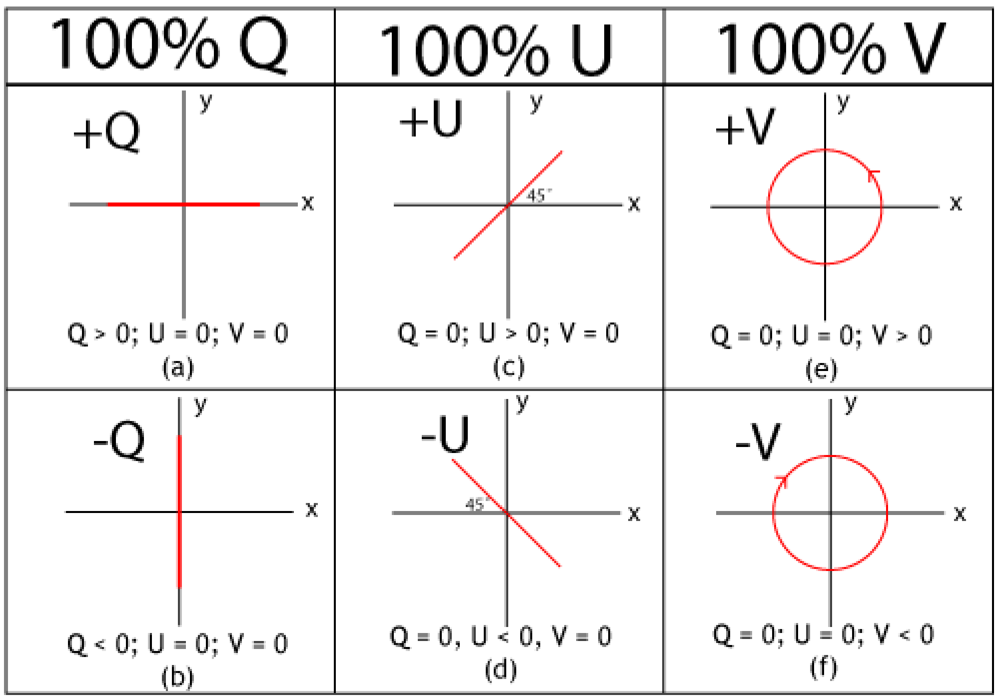
$$m_c = \frac{V}{I}$$ fractional circular polarization

$$m_t = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$ fractional polarization

$$\chi = \frac{1}{2} \tan^{-1}\left(\frac{U}{Q}\right)$$ position angle of the plane of polarization

Polarization angle

- Q,U,V can be negative
- Rotation of Q or U by 90° changes their signs
- Rotation by 45° changes U to Q
- Mirrors change V to -V (left<->right hand)



How do these relate to measurement

- For orthogonal linear feeds (with standard X=N-S,Y=E-W coordinates), not rotating with respect to the sky
  - XX = I+Q
  - YY = I-Q
  - XY= U+iV
  - YX = U-iV
- It is simpler to treat these in matrix formulations

For circular

- For circularly polarized feeds
  - RR = I+V
  - LL = I-V
  - RL = Q+iU
  - LR = Q- iU
- Unfortunately no feeds are perfect (in general you have an elliptical polarization and they are not perfectly othogonal)
- For Alt-Az mounts we need to worry about rotation of the sky (parallactic angle)

Beam patterns

- Unfortunately **any** asymmetries give different beam patterns in different directions
  - Usually they are matched on axis but get progressively worse off-axis
  - This makes unpolarized sources appear polarized
  - Internal reflections (off feed legs etc.) exacerbate this
  - So we usually only get good polarization data close to the field centre

Leakage

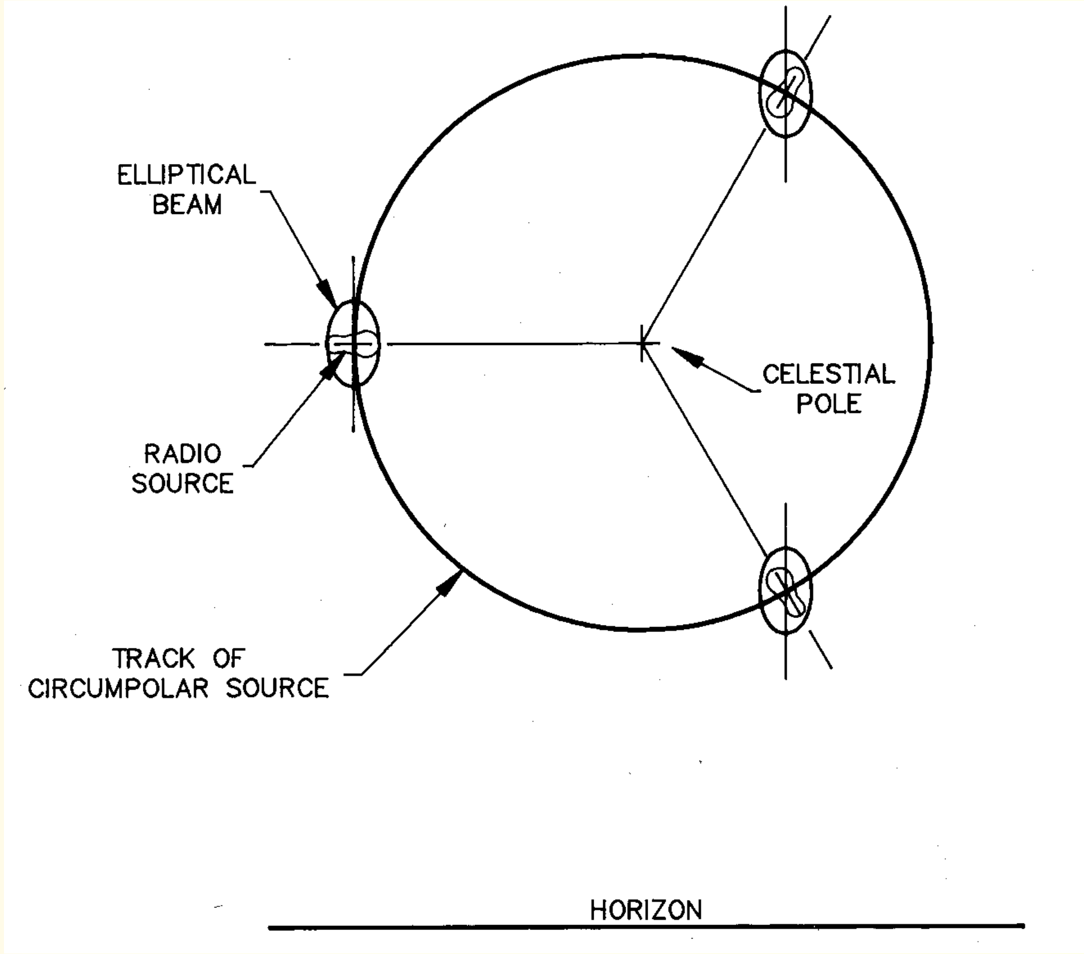
- We can get one polarization leaking into the other
  - via internal cross-talk (bad electronics)
  - via unwanted reflections (bad dishes)

parallactic angle

- If the telescope has an alt-az mount the sky rotates with respect to the telescope axis. This rotation angle is called the parallactic angle
  - if the hour angle is H, declination δ, telescope latitude L we get a rotation ψ_p

$$\tan\psi_p = \frac{\cos L \sin H}{\sin L - \cos\delta - \cos L \sin\delta \sin H}$$

Parallactic Angle

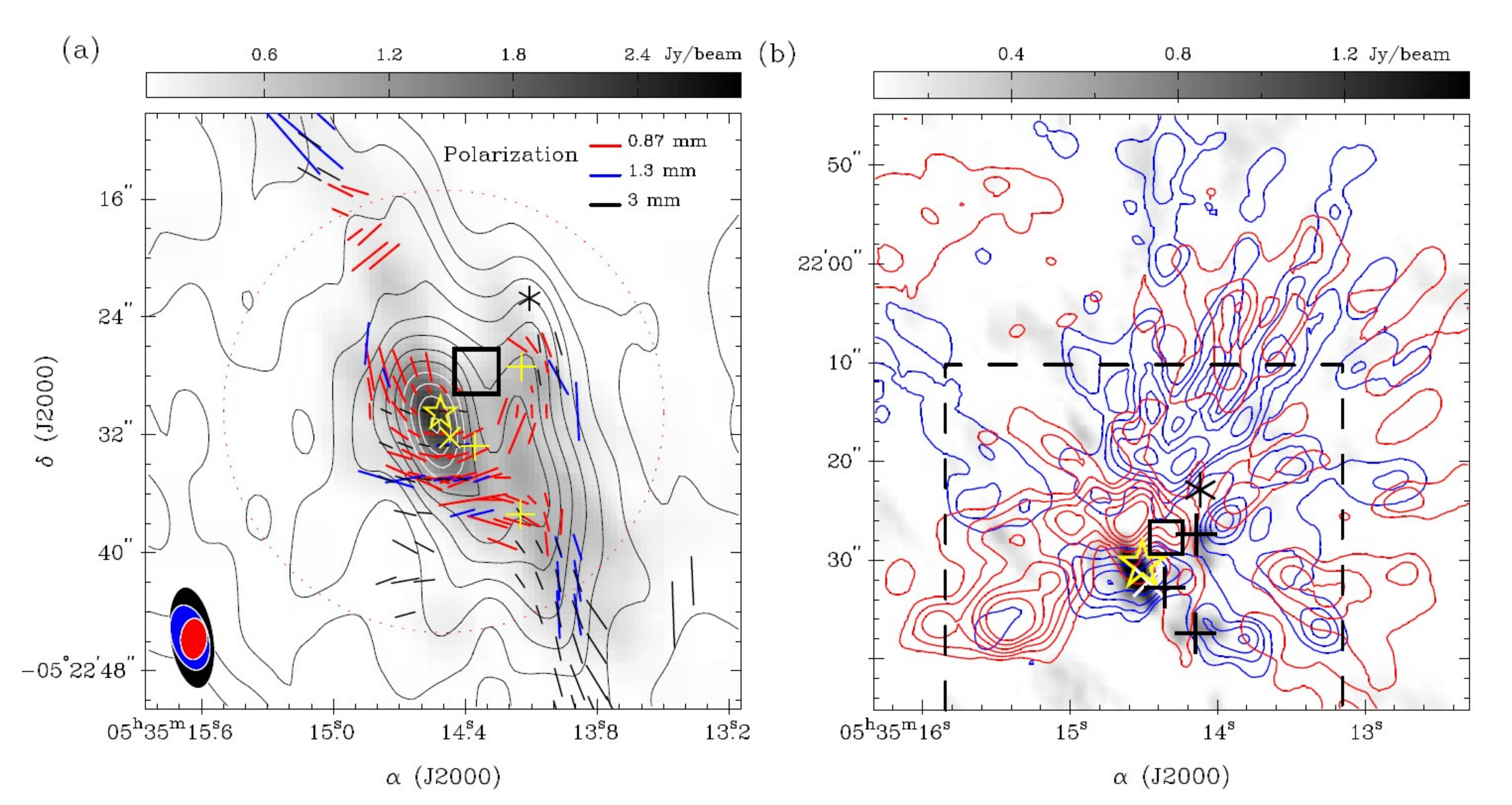


In practice

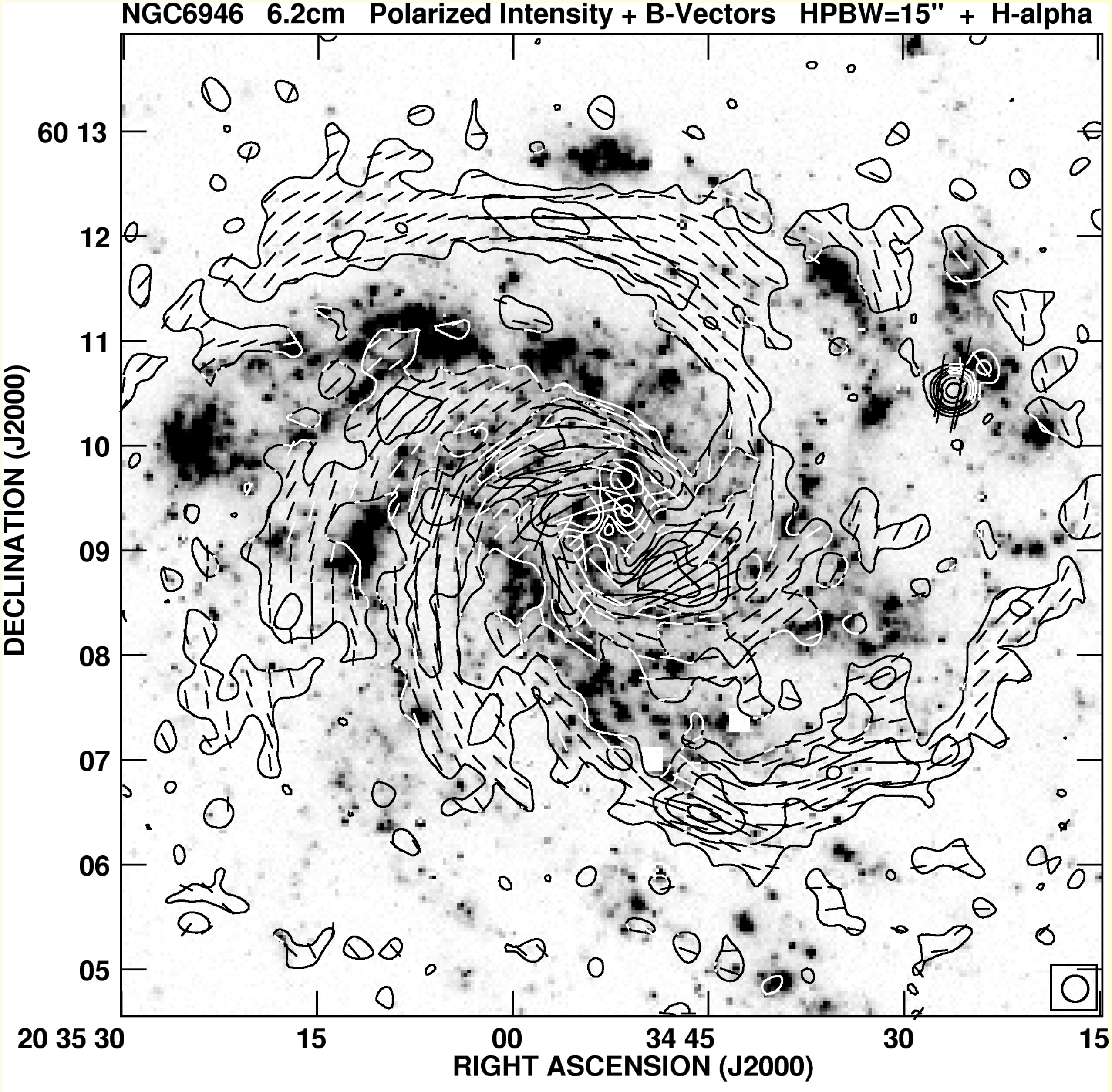
- Most synchrotron sources are linearly polarized to some degree somewhere (1%-60%)
- But typical circular polarization is small (<0.1%)
- By measuring the polarization we can measure magnetic field directions
- Some maser source have high degrees of circular polarization

Images

- Polarized rotating dust (and CO outflow) in Orion BN/KL region

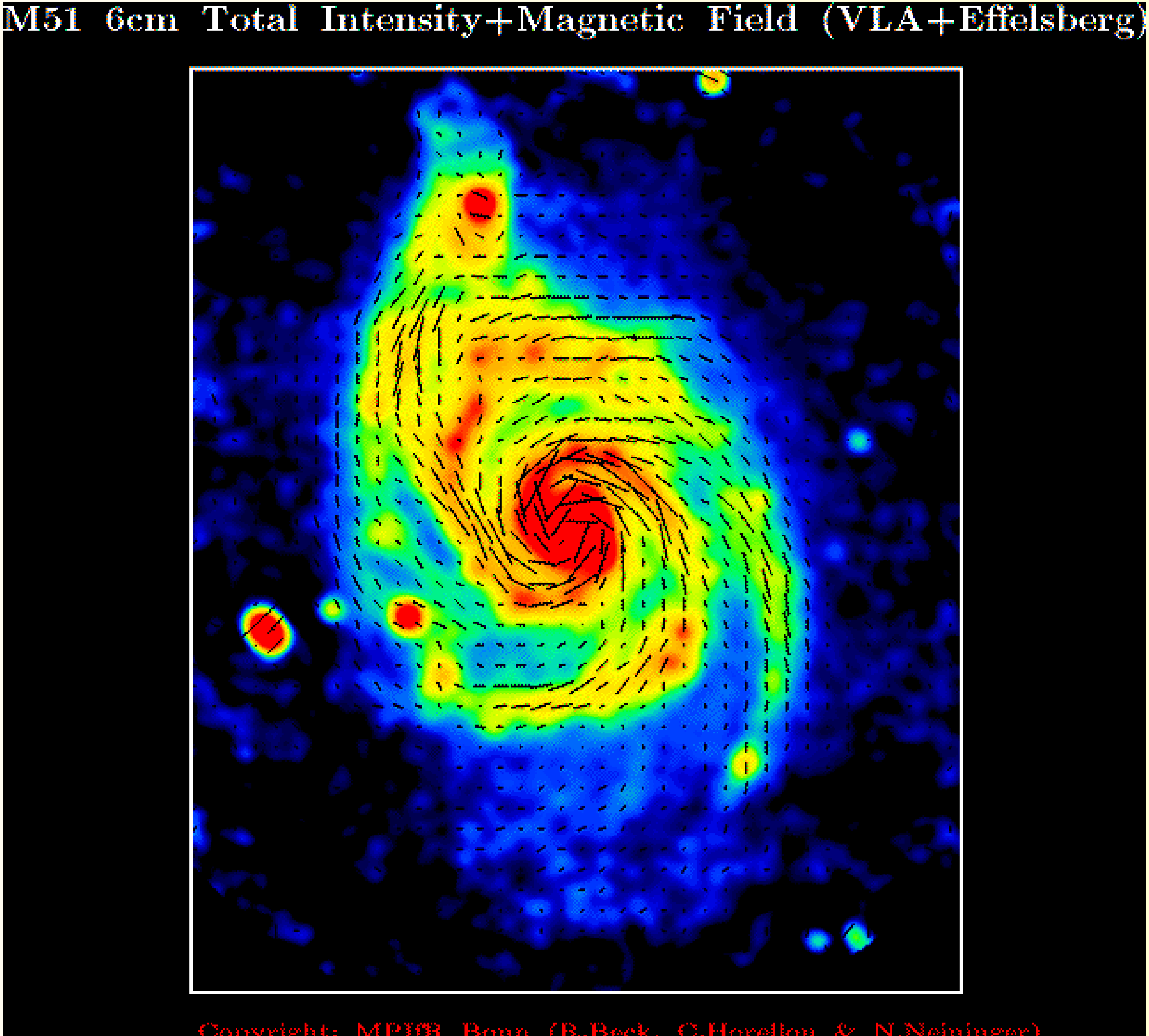


Galaxy Hα under radio pol



Peak contour flux = 5.5283E-04 JY/BEAM
Levs = 6.000E-05 * (1, 2, 3, 4, 6, 8, 12)
Pol line 1 arcsec = 8.3333E-06 JY/BEAM

Synchrotron



Faraday Rotation

- If the signal transverses a magnetized plasma the plane of linear polarization rotates
  - The amount varies with λ^2
  - This can be interstellar
  - There is Faraday rotation in out own ionosphere
    - For accurate work this must be removed
  - Depending on the field direction this can be positive or negative
  - Total intensity and circular polarization are not affected

Faraday rotation 2

- If the Faraday rotation is purely between the source and us (not internal to the source). If the rotation is χ

$$E_x' = E_x \cos\chi + E_Y \sin\chi$$
$$E_y' = -E_x \sin\chi + E_y \cos\chi$$

Or in terms of Stokes parameters

$$I' = I$$
$$V' = V$$
$$Q' = Q\cos 2\chi + U\, sin2\chi$$
$$U' = -Q\sin 2\chi + U\cos 2\chi$$

How much

- Ionosphere is typically 1-2 radians/m^2
  - depending on where you are and what direction you are observing it can be positive or negative
- Interstellar can be much larger (in astronomer units

$$RM = 810 \int \boldsymbol{B}_{\parallel} n_e \, dl$$

RM in $Radian\ m^{-2}$ $\quad$ n_e electron density in cm^{-3}

parallel magnetic field $\boldsymbol{B}_{\parallel}$ in $\mu\, Gauss$ $\quad$ dl in kpc

- If it is not all external (i.e. some part is within the source) you need to do 'Rotation Measure Synthesis'

Rotation Measure synthesis

If we represent orthogonal polarizations Q, U
with complex linear polarization

$$P = Q + iU = p\,I\,e^{2i\chi} \quad \text{where} \quad \chi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right),$$

p is fractional linear polarization

$$RM = \frac{d\chi(\lambda^2)}{d\lambda^2}$$

$$P(\lambda^2) = \int_{-\infty}^{\infty} F(\phi)\,e^{2i\phi\lambda^2}\,d\phi$$

where $F(\phi)$ is the complex polarized surface brightness
per unit Faraday depth ϕ
This is another Fourier transform