ALMA Polarimetry

- From Astrophysical Sources to Correlated Data

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References

- References:
  - Synthesis Imaging II: Lecture 6, also parts of 1, 3, 5, 32
  - Born and Wolf: Principle of Optics, Chapters 1 and 10
  - Rolfs and Wilson: Tools of Radio Astronomy, Chapter 2
  - Thompson, Moran and Swenson: Interferometry and Synthesis in Radio Astronomy, Chapter 4
  - Tinbergen: Astronomical Polarimetry. All Chapters.
  - J.P. Hamaker et al., A&A, 117, 137 (1996) and series of papers

  This report based on
  - Steve Myers, Polarization, NRAO summer school, 2010
  - Michael Brentjens, Radio Polarization, NRAO summer school 2012

Great care must be taken in studying these references – conventions vary between them.

Outline of talk

EM fields and EM radiation fundamentals

Maxwell Equation for near and far fields

EM field description

Use of Stokes Parameteres

Properties of astrophysical fields

mechanism, stochastic fields, polarization, and medium

Examples of Polarized Radio Emission

The measured visibility function and lead to calibration

Formation of EM Field(1)

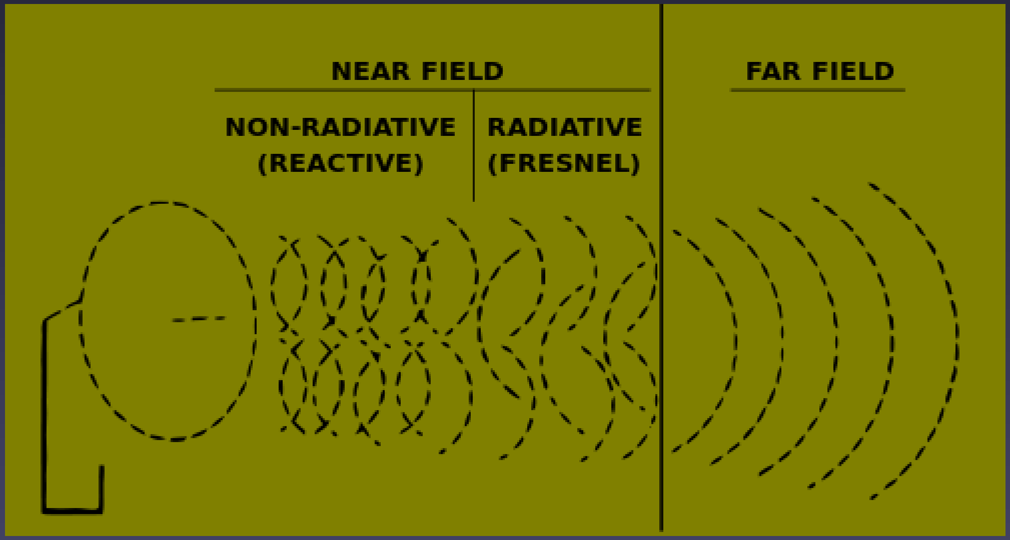
Motion of charges, currents in static fields

Produce electric and magnetic fields.

Leinard-Wiechert potential description of the fields produced by a moving particle

Electric/magnetic radiation is complicated near radiator

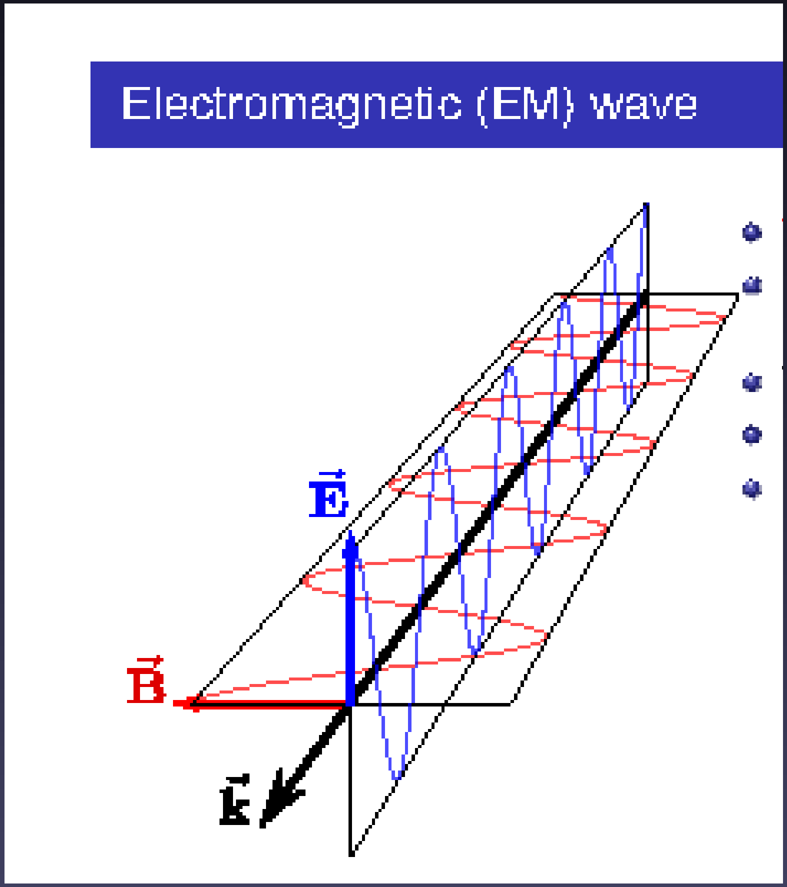
The EM radiation is more organized in the far field and Is called the EM field.



Formation of EM Field(2)

Far field E and B wave may still be spherical

Very far field E and B fields becomes transverse wave



Wave Properties:

- k is the direction of motion
  - E is the Electric field
  - B is the magnetic field
  - Self-generating
  - Ratio depends on medium

Only relevant for the emission of one particle at one instant.

Always Polarized.

Description of EM field(1)

$$E_x = A_x \cos(2\pi\nu t + \delta_x)$$

$$E_y = A_y \cos(2\pi\nu t + \delta_y)$$

Three parameters needed: A_x, A_y, $\delta_x - \delta_y = \delta xy$

The tip of the electric field follows a path:

$\delta_x - \delta_y = 0$: Components in phase

Produces linear variations in a plane

$\delta_x - \delta_y = \pi/2$: Components in quadrature

Produces circular variations in a plane

Otherwise, called elliptical polarization

Could define E_r and E_l as bases components

$$E_r = A_r \cos(2\pi\nu t + \delta_r)$$

$$E_l = A_l \sin(2\pi\nu t + \delta_l)$$

Description of EM field(2)

Stokes (1856) Parameters: Alternative Description:

Chandresekhar (1946): Used in astronomy

I, Q, U, V called Stokes parameters

$I^2 = Q^2 + U^2 + V^2$ Three power parameters

$I = A_x^2 + A_y^2$

$A_r^2 + A_l^2$:

$Q = A_x^2 - A_y^2$

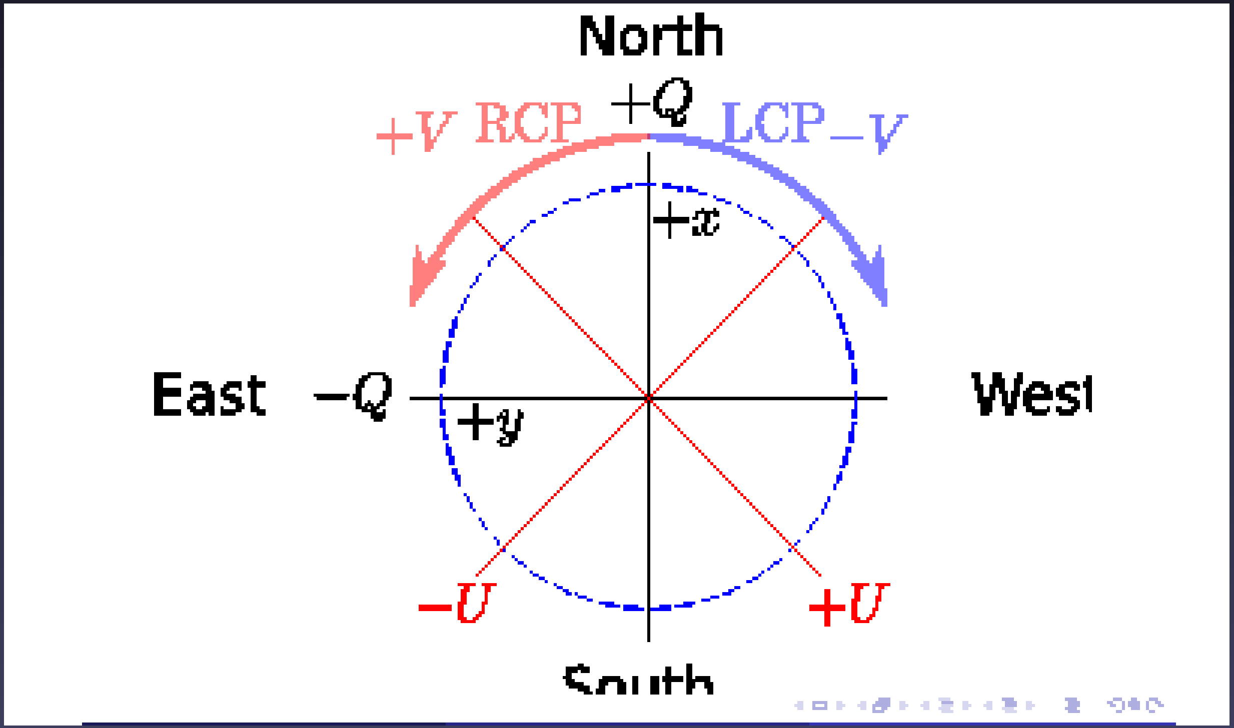
$2A_lA_r \cos(\delta xy)$

$U = 2A_xA_y \cos(\delta xy)$

$2A_lA_r \sin(\delta xy)$

$V = 2A_xA_y \sin(\delta xy)$

$A_l^2 - A_r^2$



Astrophysical EM fields(1)

Thermal Radiation: Free charged particles accelerating.
Usually free electrons interacting with denser matter.

Synchrotron Radiation: Energetic electrons spiralling in
A magnetic field

Discrete Spectral Radiation: Energy emitted by electrons
changing states (beta decay).

Many more.

The previous EM wave description is only valid for any
one of the uncountable emissions occuring in the
line of site of an observation.

Astrophysical EM fields(2)

What is observed is the 'vector' sum of uncountable superposed EM waves at different frequencies and relative phases in the line of site of the obs.

Hence,

$$E_x = \Sigma A_x \cos(2\pi\nu t + \delta_x) = \text{stochastic variable}$$

$$E_y = \Sigma A_y \cos(2\pi\nu t + \delta_y) = \text{stochastic variable}$$

What is measured by astronomical instruments are

$$I_x = \int E_x(t)^* E_x(t)\, dt \quad I_y = \int E_y(t)^* E_y(t)\, dt \;=== \langle E_x^2 \rangle$$

Intensity over one or both polarization states:

(could use circular bases, E_r, E_l as well)

Astrophysical EM Fields(3)

Since I_x and I_y (I_r, I_l) are random, stochastic variables, there is no polarization, preferential alignment?

Not true: Despite the chaos, polarization still exists, but is not complete – partial polarization is common.

Effect of Intervening material:

The stochastic properties of the EM field are changed as it passes through the media to the antennas. Any anisotropies in the media can preferentially affect one of the polarized states and change (initiate) a polarization of the received EM field.

Astrophysical EM Fields(4)

Analysis of stochastic emission

Use <Ex²> and <Ey²> as basic observables

Stokes Parameter Extension to incoherent emission

I_u = unpolarized emission; I_p = polarized emission

$I_t = I_u + I_p$ subscript t means total intensity

$I = E_x^2 + E_y^2$

$E_r^2 + E_l^2$

$Q = E_x^2 - E_y^2$

$2E_lE_r \cos(\delta xy)$

$U = 2E_xE_y \cos(\delta xy)$

$2E_lE_r \sin(\delta xy)$

$V = 2E_xE_y \sin(\delta xy)$

Why Use Stokes Parameters

- Tradition
- They are scalar quantities, independent of basis XY, RL
- They have units of power (flux density when calibrated)
- They are simply related to actual antenna measurements.
- They easily accommodate the notion of partial polarization of non-monochromatic signals.
- We can make images of the I, Q, U, and V intensities directly from measurements made from an interferometer.
- These I,Q,U, and V images can then be combined to make images of the linear, circular, or elliptical characteristics of the radiation.
- But, no too useful for some calibration steps.

Astrophysical Polarization Results

Some results that depend on the polarized properties of the emission are now shown.

How to obtain these images from radio arrays touched on later, but mainly George and Hiroshi will cover this.

For linear polarization, plots usually contain

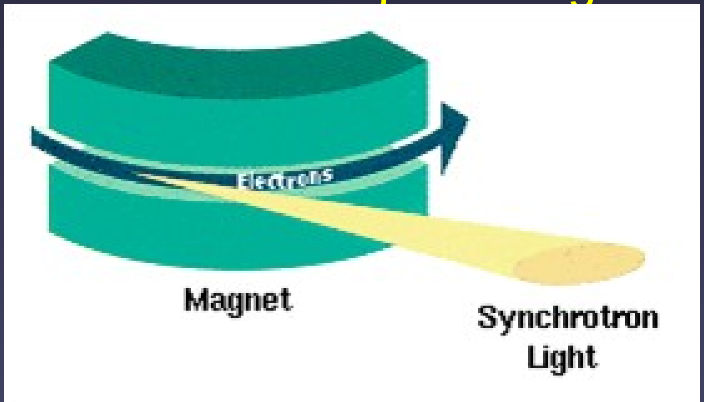
Contour and/or raster plots of total intensity I_t

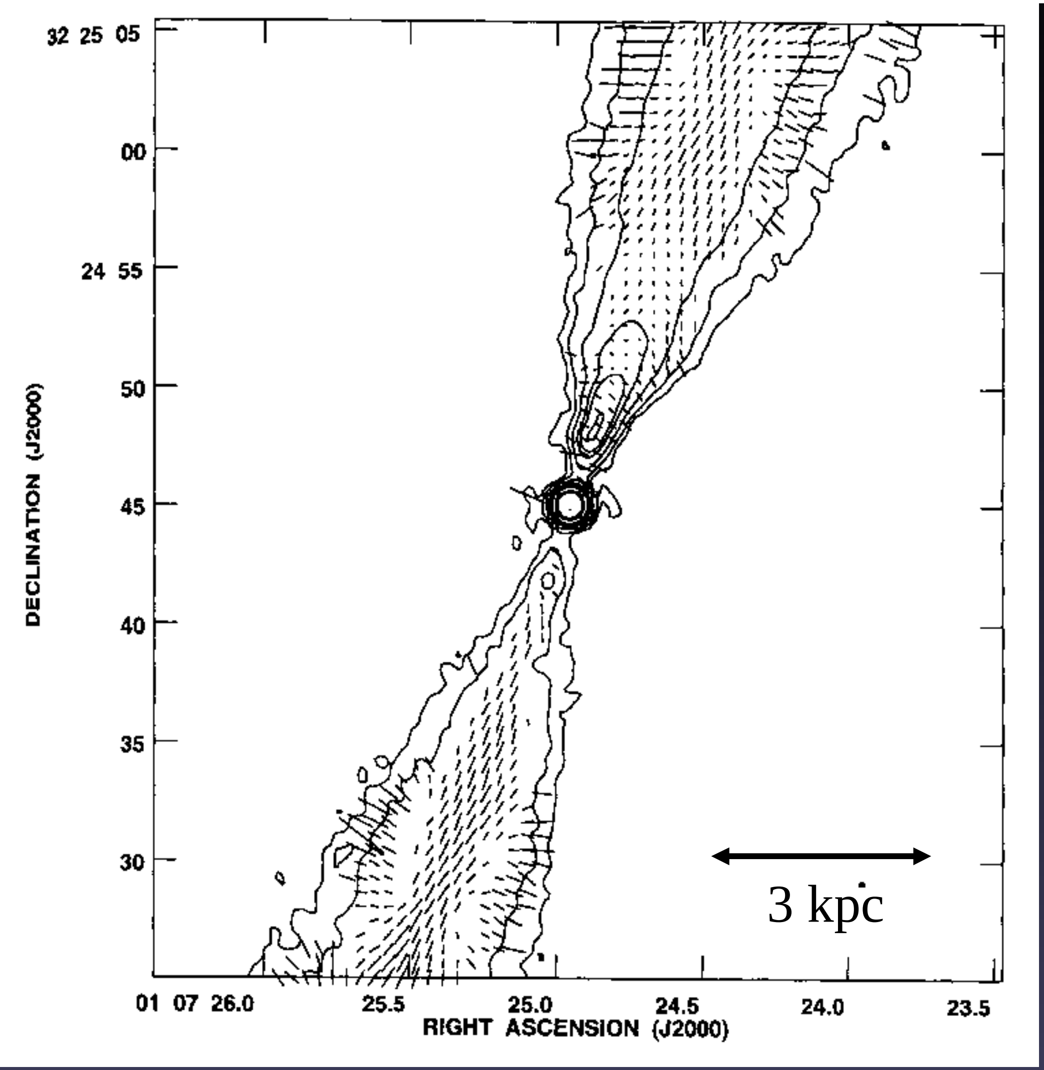
Superposed line segments of

length ~ I_p or I_p/I_t . Orientation that of the pol angle

Example: Radio Jets in Galaxy 3C31

- VLA @ 8.4 GHz
  - Laing (1996)
- Synchrotron radiation
  - relativistic plasma
  - jet from central "engine"
  - from pc to kpc scales
  - feeding >10kpc "lobes"
- E-vectors
  - along core of jet
  - radial to jet at edge



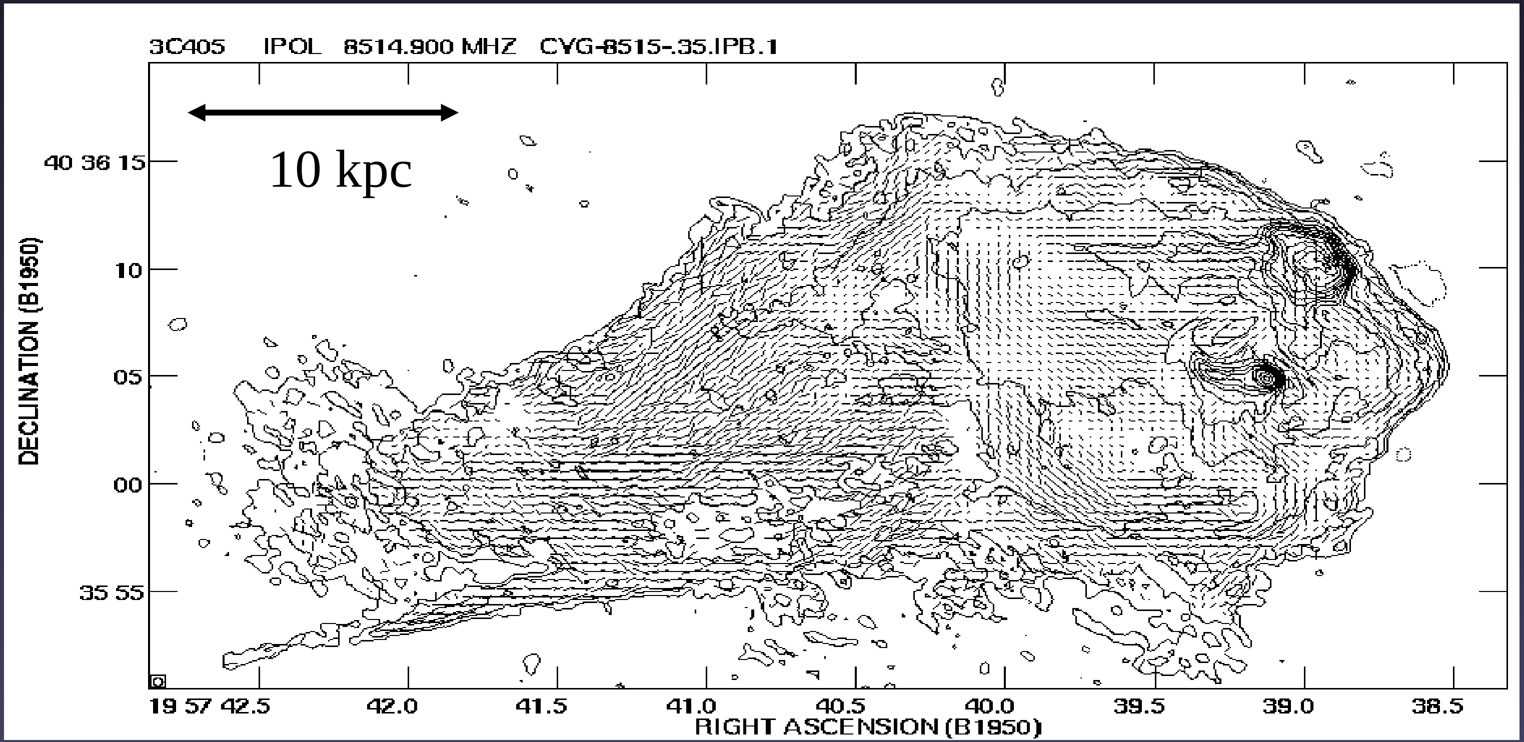


Example: Radio Lobe in Cygnus A

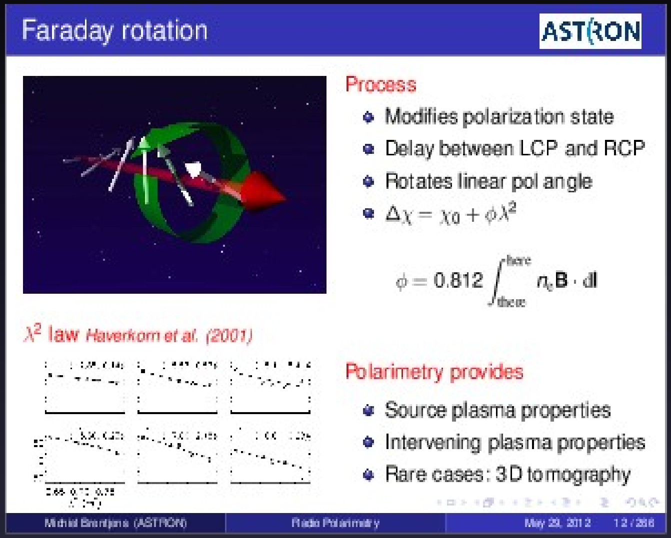
Observation and interpretation can provide:

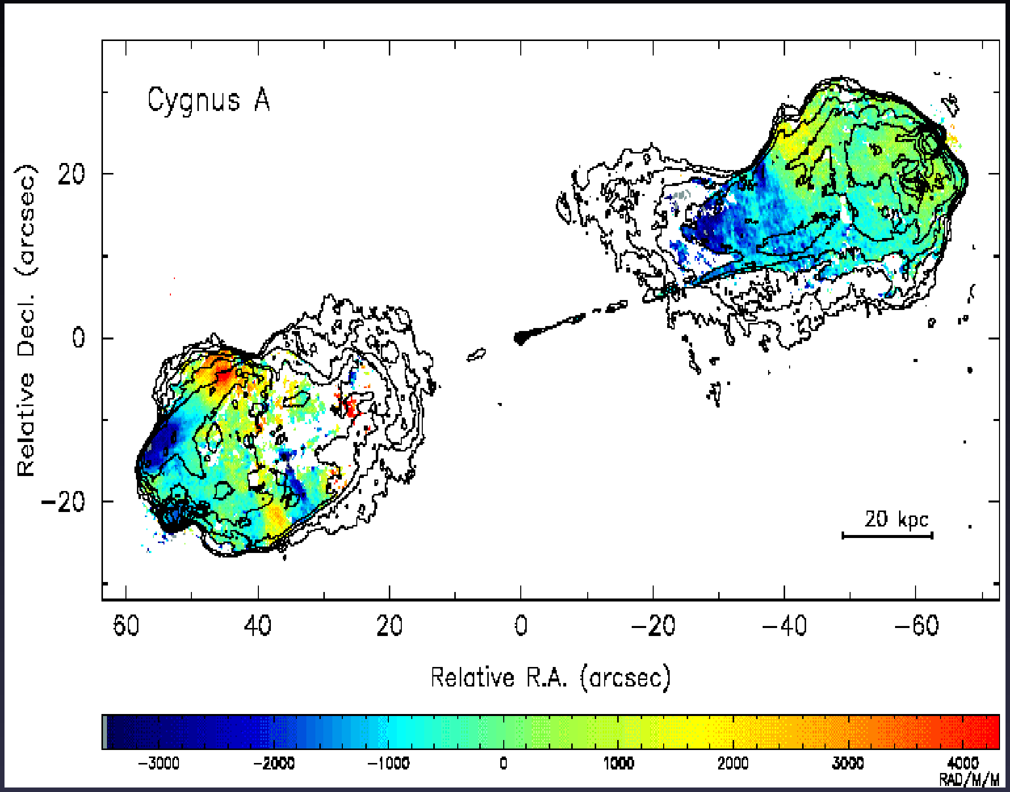
- B-field direction and strength (with additional assumptions)
- Degree of turbulence

VLA @ 8.5 GHz B-vectors Perley & Carilli (1996)



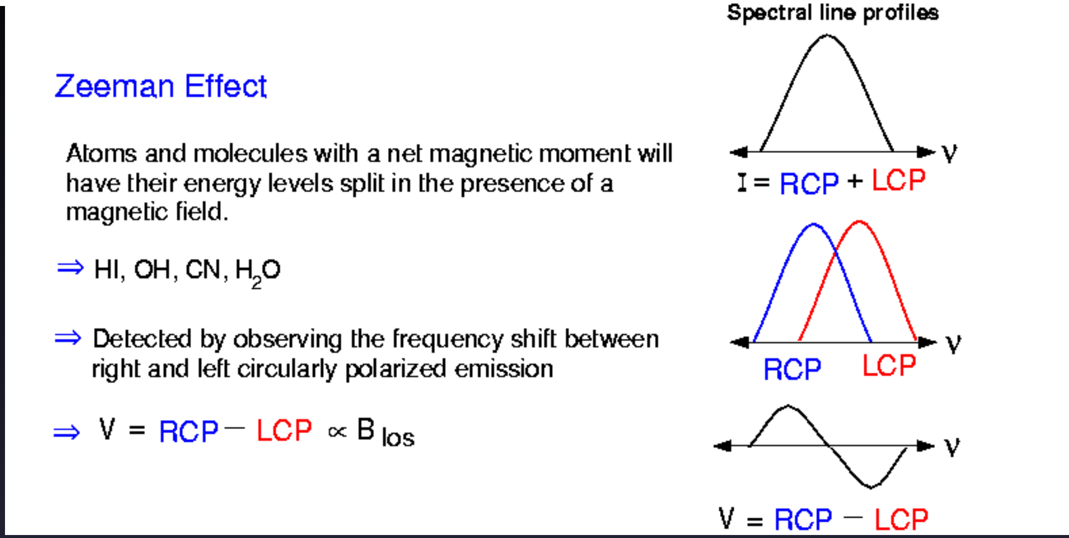
Example: Faraday rotation of CygA

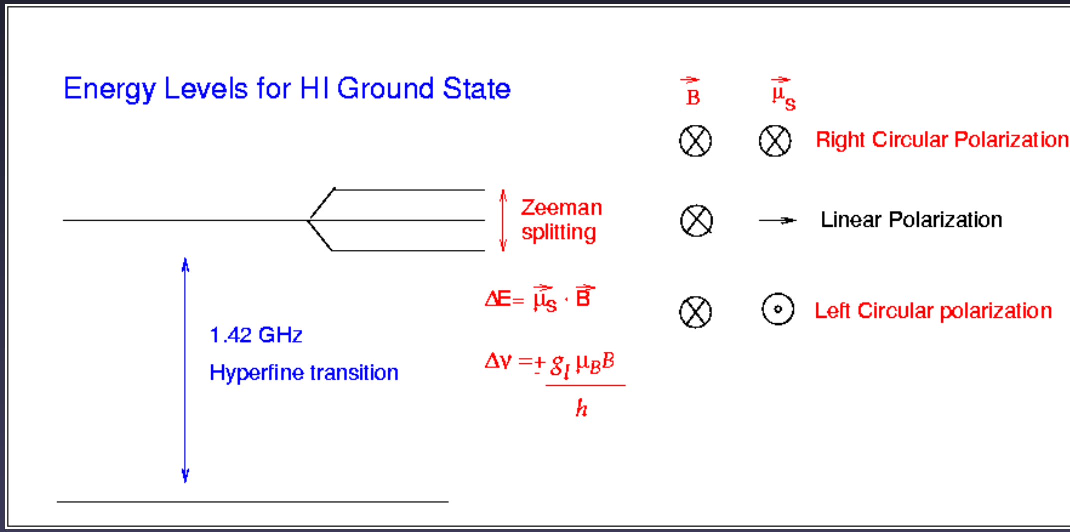


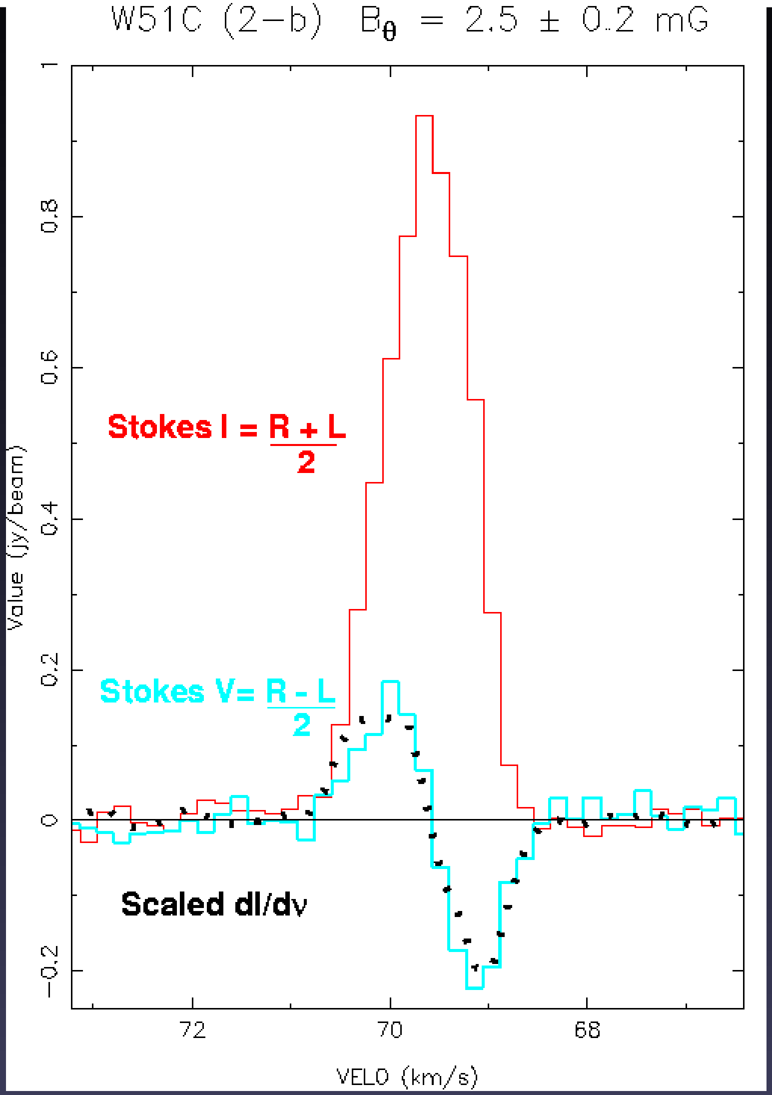


See review of “Cluster Magnetic Fields” by Carilli & Taylor 2002)

Example: Zeeman effect







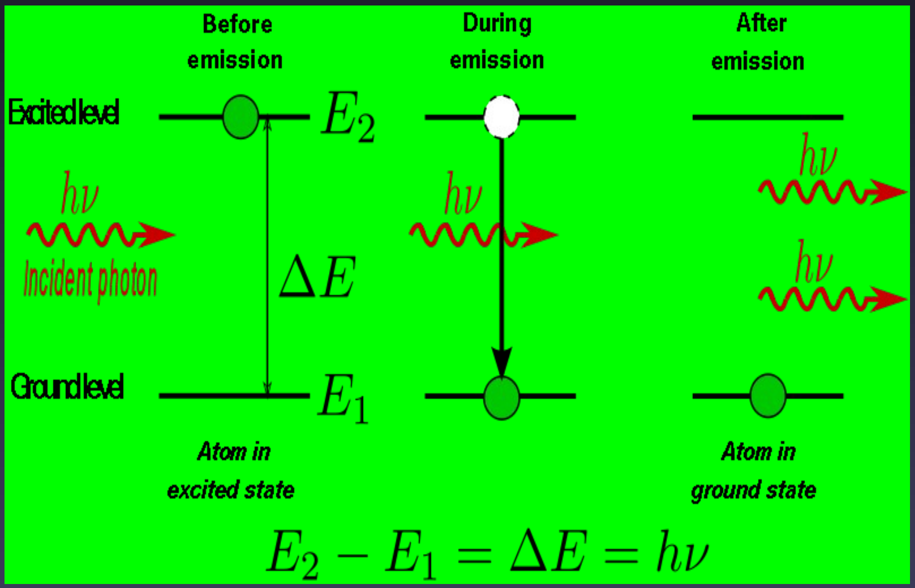
Example: Maser Polarized Emission

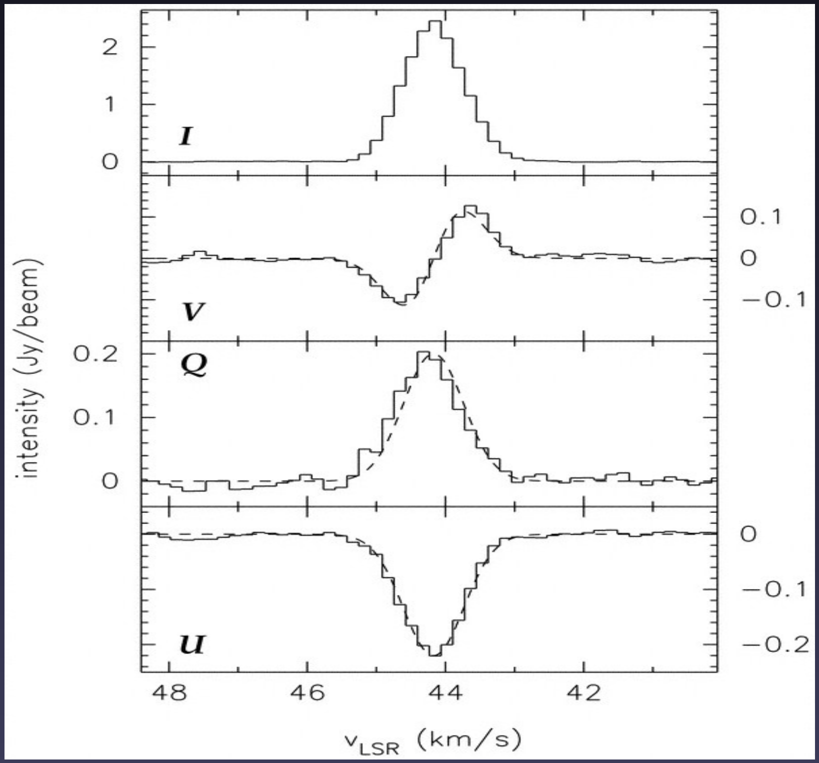
E11A maser in W44 SNR Hoffmann et al (2007)

Vpol fit to 0.61 mG Zeeman effect on 1720 MHz OH

Q,U polarization of 13% in synchrotron of gas

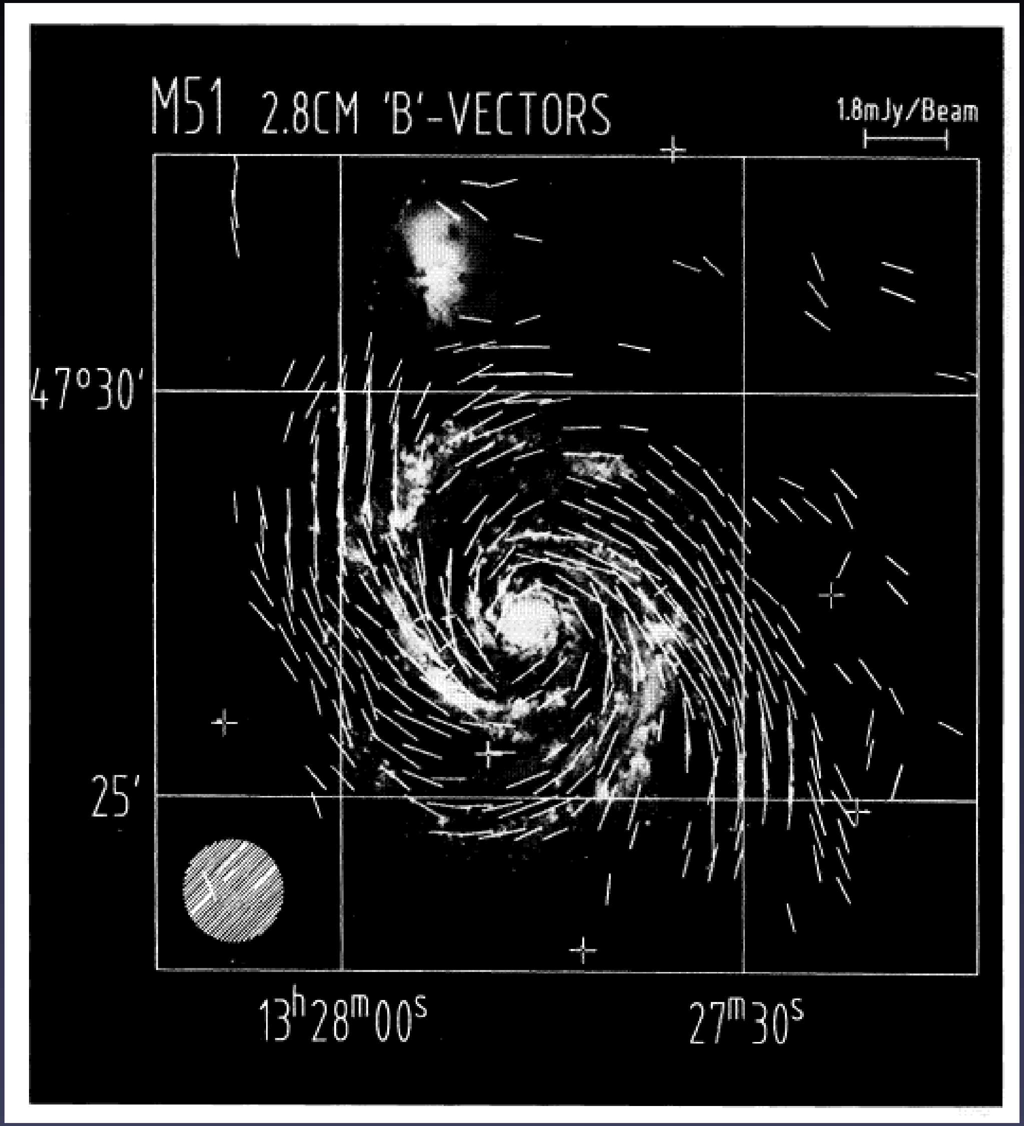
Maser boosting.........................





Example: the ISM of M51

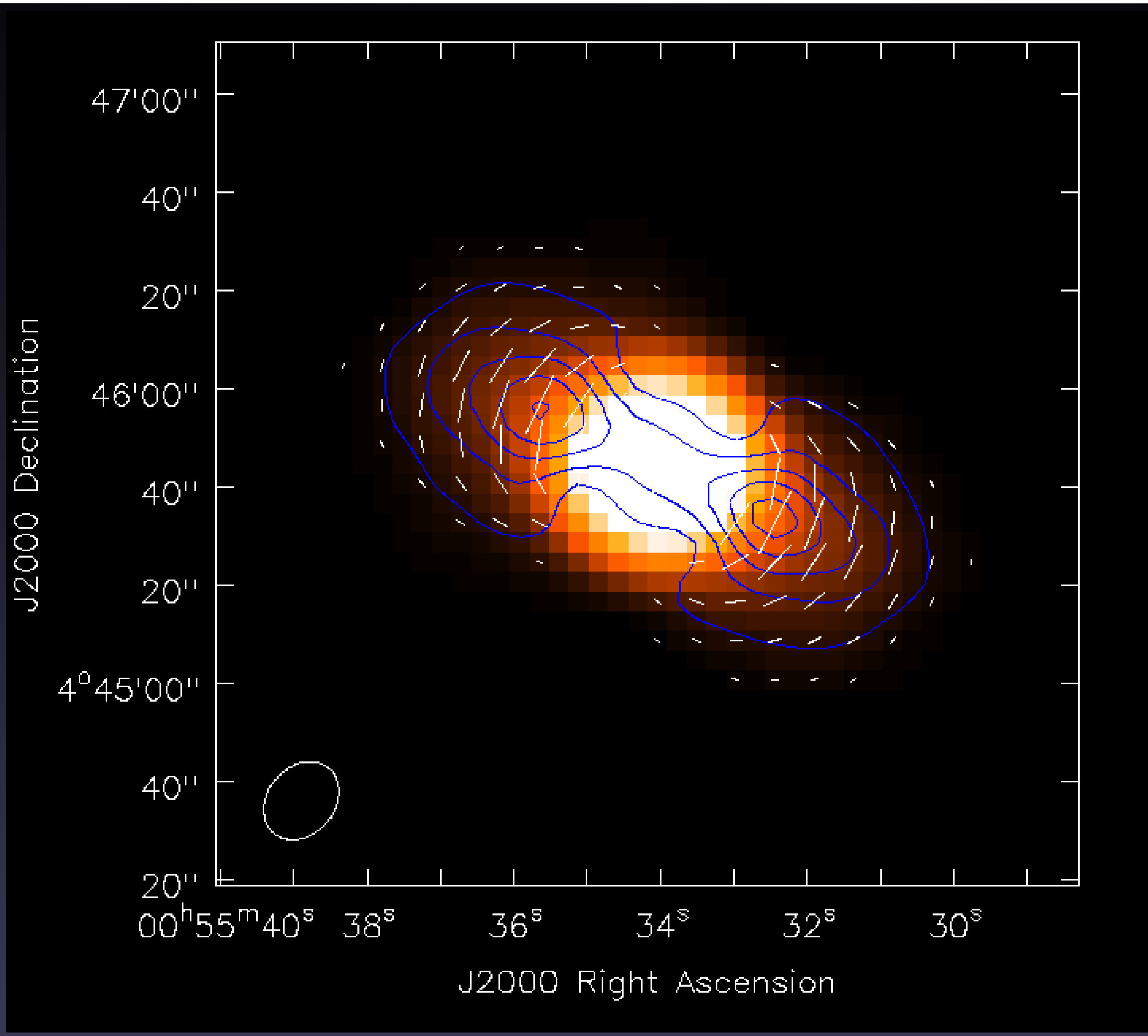
- Trace magnetic field structure in galaxies
  - follow spiral structure
  - Synchrotron?
  - Field amplified
    in dynamo?
    by shocks?



Neininger (1992)

Example: Non-thermal Emission from Jupiter

- Apr 1999 VLA 5 GHz data
- D-config resolution is 14”
- Jupiter emits thermal radiation from atmosphere, plus polarized synchrotron radiation from particles in its magnetic field
- Shown is the I image (intensity) with polarization vectors rotated by 90° (to show B-vectors) and polarized intensity (blue contours)
- The polarization vectors trace Jupiter’s dipole
- Polarized intensity linked to the Io plasma torus



Example: Non-thermal Emission from Mars

Mars VLA 23.4 GHz (Perley)

Mostly thermal emission

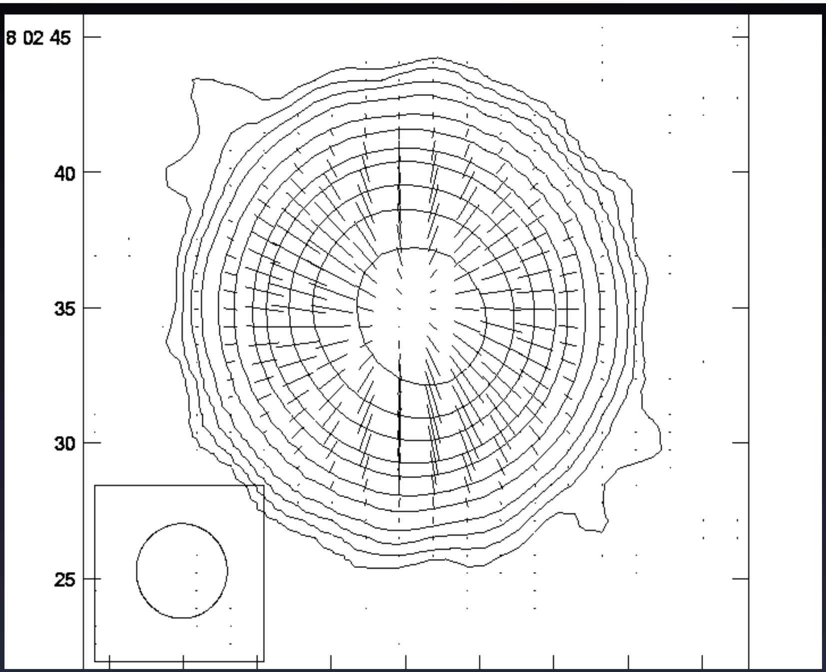
Peak polarization ~3%

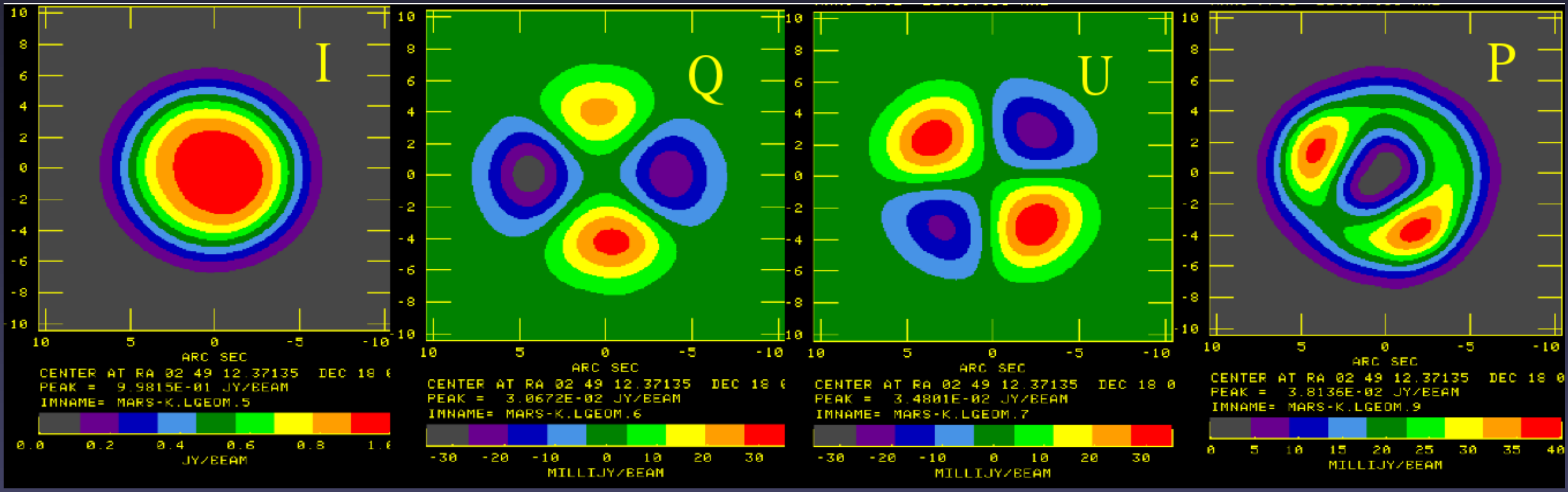
Why is it polarized?

- Little magnetic field
- Dust in atmosphere?

Observed with ALMA at 350 GHz

- <2% polarized.





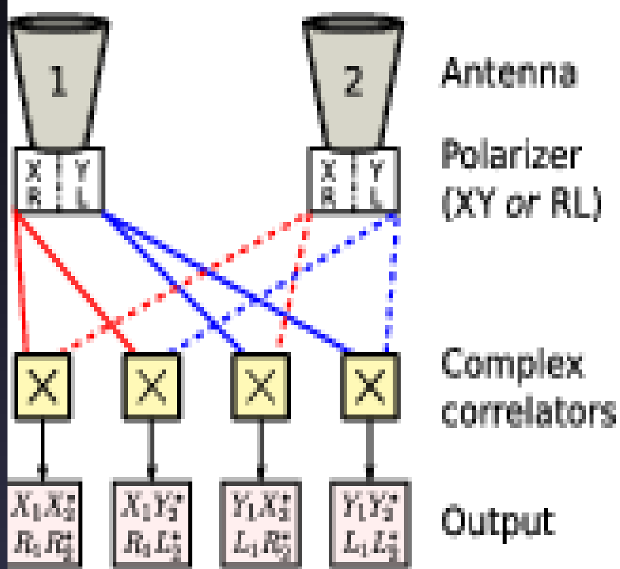
Polarization and the Array

George and Hiroshi will go into details about how the incoming polarization signals are modified. Observing/cal Methods used to remove these effects are one of the main topics for this workshop.

Polarization Array Cross-Correlation

Four cross-products per baseline

Visibility Functions



Cartesian

$$\mathcal{I} = x_1x_2^* + y_1y_2^*$$
$$\mathcal{Q} = x_1x_2^* - y_1y_2^*$$
$$\mathcal{U} = x_1y_2^* + y_1x_2^*$$
$$\mathcal{V} = \mathrm{i}\,(x_1y_2^* - y_1x_2^*)$$

Circular

$$\mathcal{I} = r_1r_2^* + l_1l_2^*$$
$$\mathcal{Q} = r_1l_2^* + l_1r_2^*$$
$$\mathcal{U} = \mathrm{i}\,(r_1l_2^* - l_1r_2^*)$$
$$\mathcal{V} = r_1r_2^* - l_1l_2^*$$

- From here on, $\langle\cdot\rangle$ is implied for correlator outputs.

Polarization Array Cross-Correlation

Output used in George's Talk

$V_{XX} = x_1 x_2^*$; $V_{XY} = x_1 y_2^*$; $V_{YX} = y_1 x_2^*$; $V_{YY} = y_1 y_2^*$

Correlator output per baseline is denoted as:

$V_{XX} = I + Q$	$V_{RR} = I + V$
$V_{XY} = U + iV$	$V_{RL} = Q + iU$
$V_{YX} = U - iV$	$V_{LR} = Q - iU$
$V_{YY} = I - Q$	$V_{RR} = I - V$

Polarization Array Calibrations

Remove corruptions of the measured visibility function by the ant/electronic system.

$V_{XX} = x_1x_2^*$; $V_{XY}=x_1y_2^*$; $V_{YX} = y_1x_2^*$; $V_{YY}=y_1y_2^*$

Define $\boldsymbol{V}_{obs} = \{V_{XX},V_{XY},V_{YX},V_{YY}\}$ as 4-vector correlations

Then,

$$\boldsymbol{V}_{\boldsymbol{obs}} = \mathrm{BGDPT}\, \boldsymbol{V}_{\mathrm{true}}$$

$$\boldsymbol{V}_{\boldsymbol{corr}} = \boldsymbol{T}^{-1}\boldsymbol{P}^{-1}\boldsymbol{D}^{-1}\boldsymbol{G}^{-1}\boldsymbol{B}^{-1}\, \boldsymbol{V}_{\mathrm{obs}}$$

B=bandpass; G = temporal gain; D = polar. leakage,

P=parallactic angle, T= troposphere

Summary

How astrophysical polarization is obtained

Stokes description is most useful for incoherent
polarized emission

Many examples of polarization images

Leading up to removing of polarization
contamination from antenna/receivers