



Polarimetry I: The astrophysics of polarisation

Ryan Shannon (based on slides from Jimi Green and Rick Perley)

Astronomy and Space Science
www.csiro.au



Why you are interested

- The Universe is magnetised!
 - Magnetism plays an important role in understanding the evolution of structure in the Universe.
 - Polarimetry allows us to study magnetic fields
 - The origin, structure and evolution of magnetic fields are key open questions in astrophysics
- Within our Galaxy:
 - *Interstellar medium (ISM), stars, **pulsars**, HII regions, masers*
- *Within other galaxies:*
 - *radio galaxies*
- *Cosmic Magnetism:*
 - *the inter-galactic medium, cosmic web, fast radio bursts?*
- Inflationary gravitational waves potentially polarise the CMB!

Outline

- Electromagnetic waves
 - Basis states and Stokes parameters
- Processes that generate polarised emission
- Examples in astrophysics
 - They are everywhere!



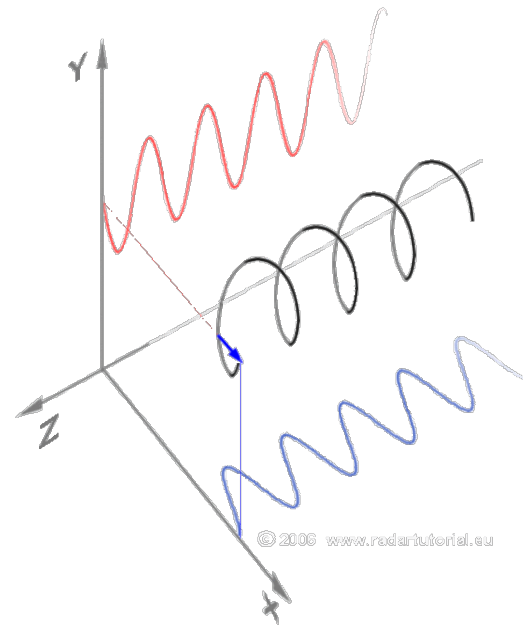
This is not a radio telescope

What is polarisation?

- One of the fundamental properties of electromagnetic waves:
 - Amplitude, direction of propagation, frequency, polarisation
- Radio telescopes sensitive to electric-field portion of electromagnetic waves
- The instantaneous electric field is comprised of two components which are completely independent.
 - EM waves: dipole radiation, basis vectors are “90-degrees” separated
 - Gravitational waves: quadropolar radiation, particle 45 degree separation between modes)
- The two components can be described in terms of orthogonal linear (E_x and E_y), or opposite circular (E_r and E_l).

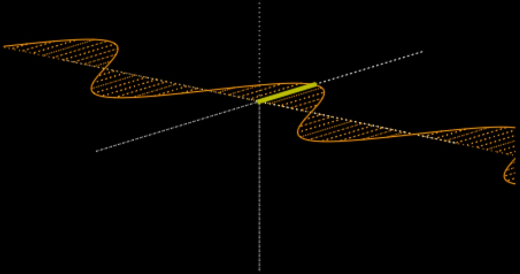
What is polarisation?

- **Linear:** orthogonal components in phase with constant ratio of strengths giving constant direction of electric vector.
- **Circular:** orthogonal components 90° out of phase with equal amplitudes – electric vector traces circle.
- Linearly polarised wave can be decomposed into two opposite handed circular waves
- Sum of two circular waves of unequal amplitude is elliptical.
- Sum of two orthogonal linears with a phase difference of between 0 and $\pi/2$ is also elliptical.



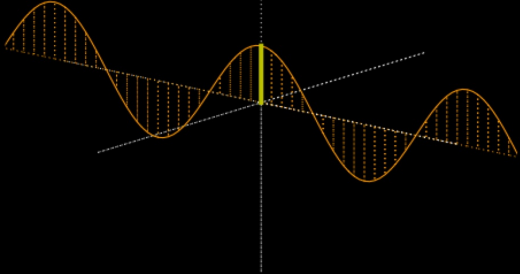
What is polarisation?

Linear



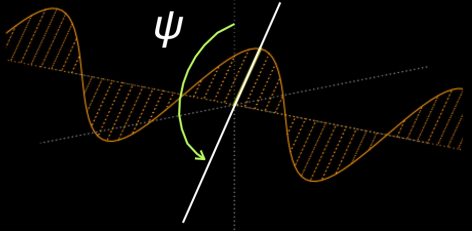
$$\mathbf{E} = E_x \cos(\omega t - kz) \hat{x}$$

Linear



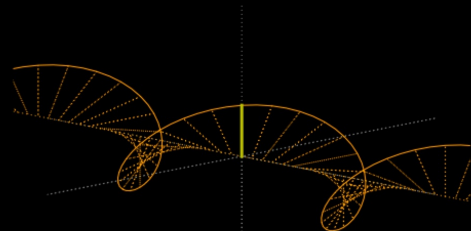
$$\mathbf{E} = E_y \cos(\omega t - kz) \hat{y}$$

Position Angle



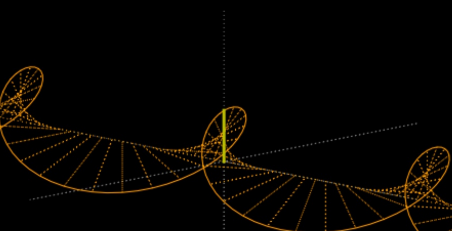
$$\mathbf{E} = E_x \cos(\omega t - kz) \hat{x} + E_y \cos(\omega t - kz) \hat{y}$$

Right Hand Circular

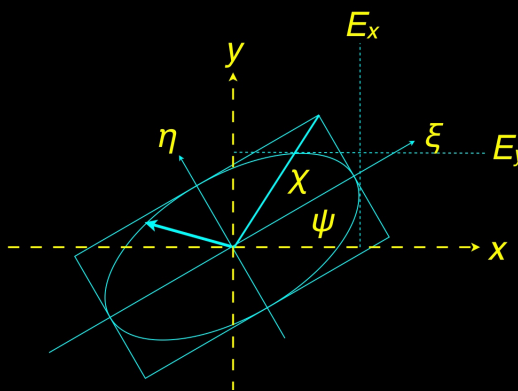


$$\mathbf{E} = E \cos(\omega t - kz) \hat{x} + E \sin(\omega t - kz) \hat{y}$$

Left Hand Circular



$$\mathbf{E} = E \cos(\omega t - kz) \hat{x} + E \cos(\omega t - kz + \frac{\pi}{2}) \hat{y}$$



Polarisation Ellipse

[slide credit D. McConnell]

Visualising polarisation

The Poincaré Definition:

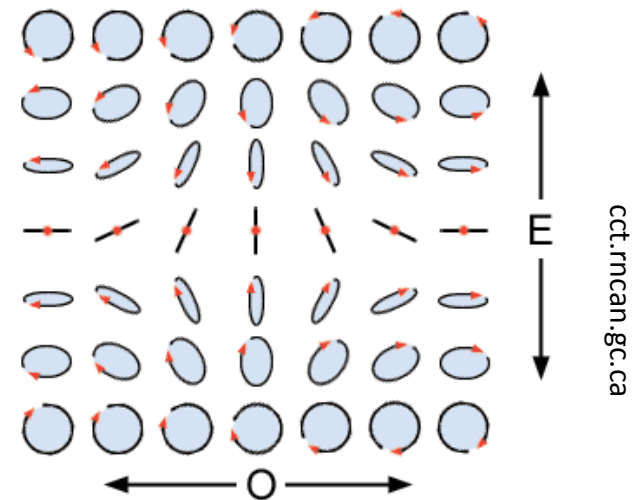
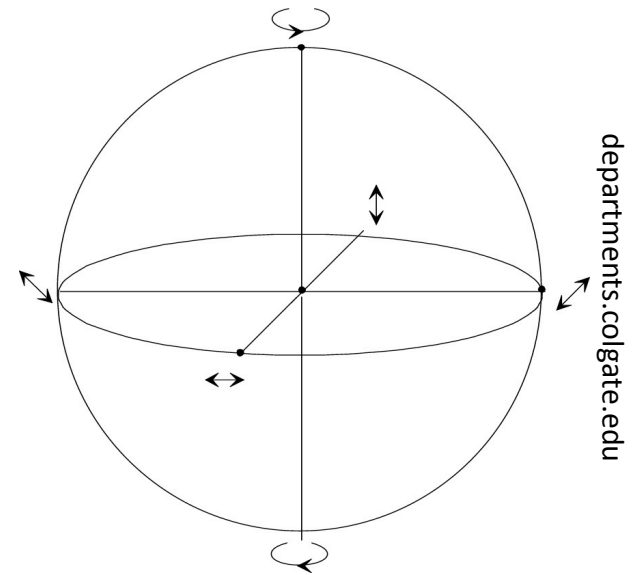
Spherical surface occupied by completely polarised states in the space of the vector

Poles represent circular polarisations

- * Upper-hemisphere LHCP
- * Lower-hemisphere RHCP

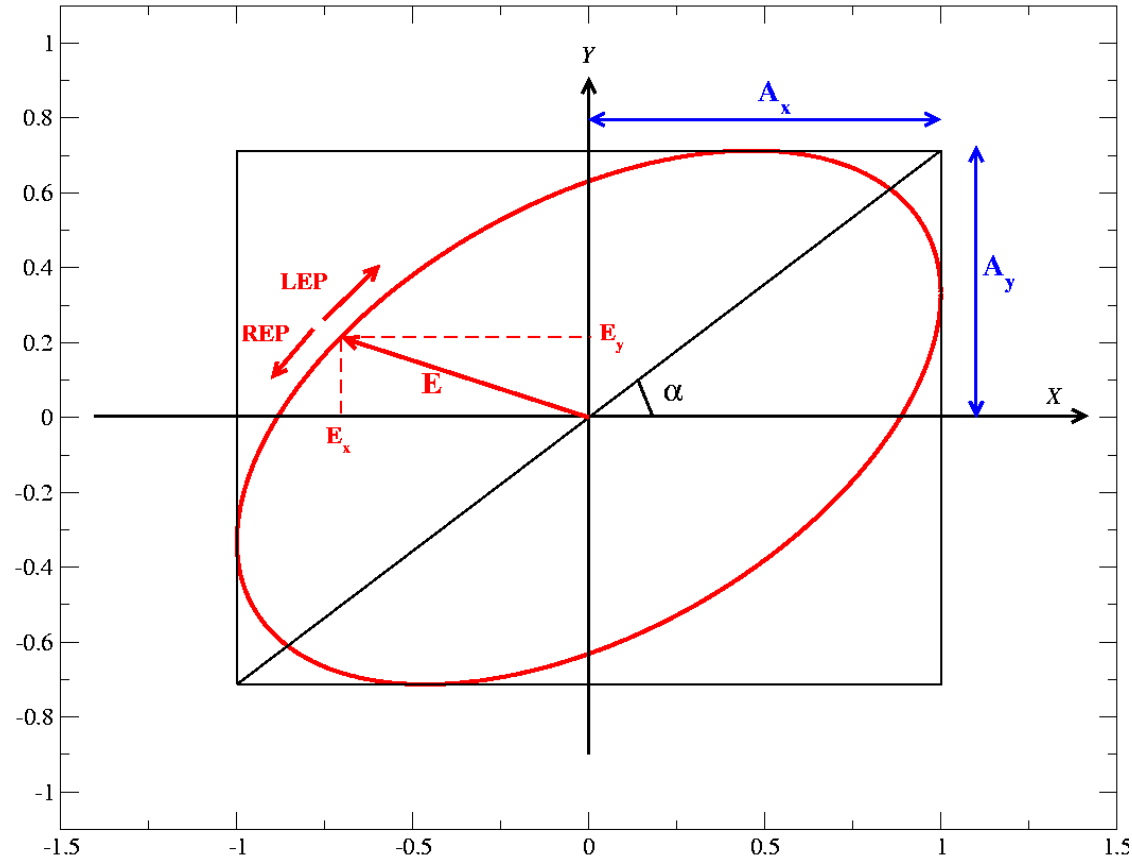
Equator represents linear polarisations with longitude representing tilt angle

Latitude represents axial ratio

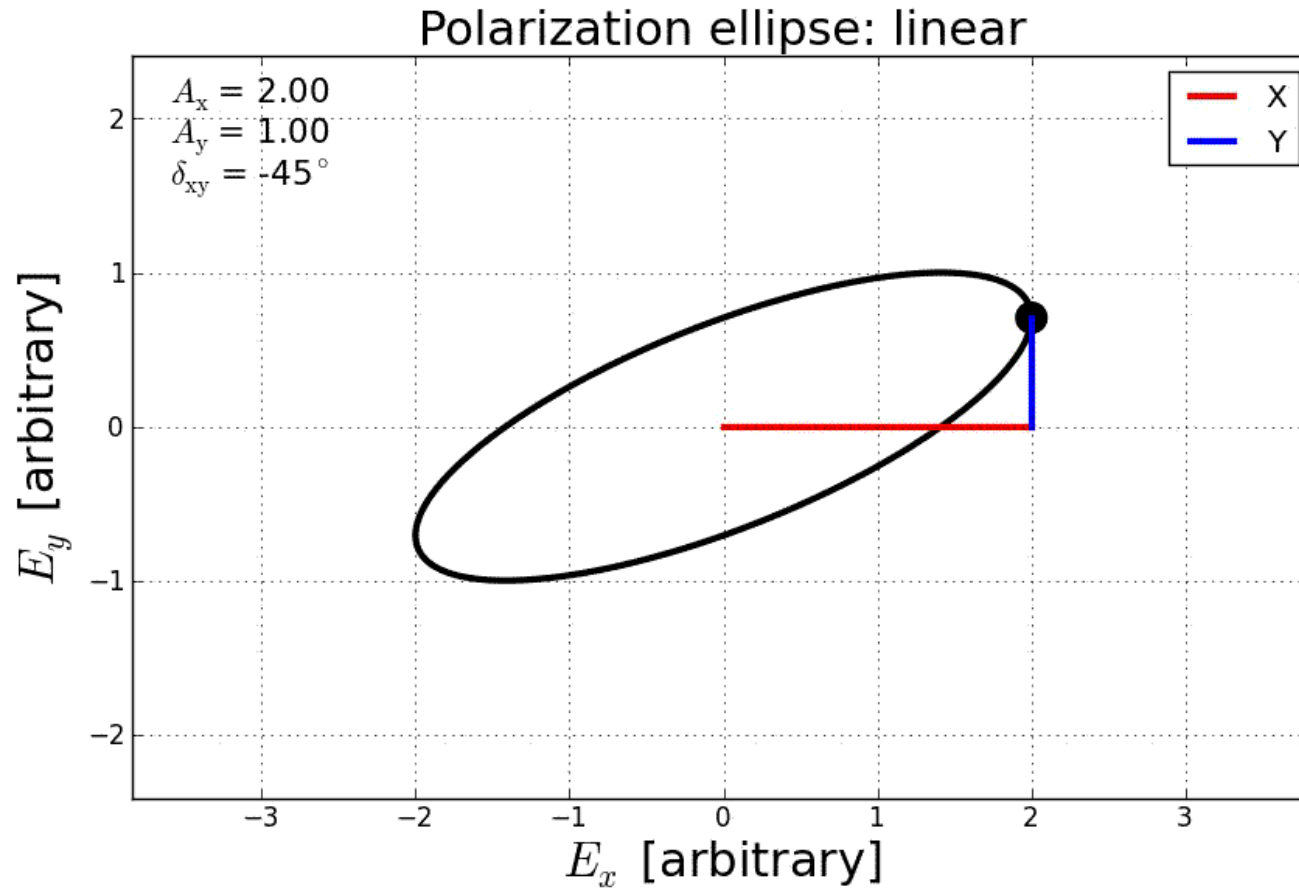


Elliptically Polarized Monochromatic Wave

- Electromagnetic waves are in general elliptically polarized.
 - Three parameters are needed to describe the ellipse:
 - A_x – X-axis amplitude max
 - A_y – Y-axis amplitude max
 - $a = \text{atan}(A_y/A_x)$ – an angle describing the orientation
- If the E vector is rotating:
- Clockwise, the wave is Left Elliptically Polarized:
 - Anti-clockwise, the wave is Right Elliptically Polarized.

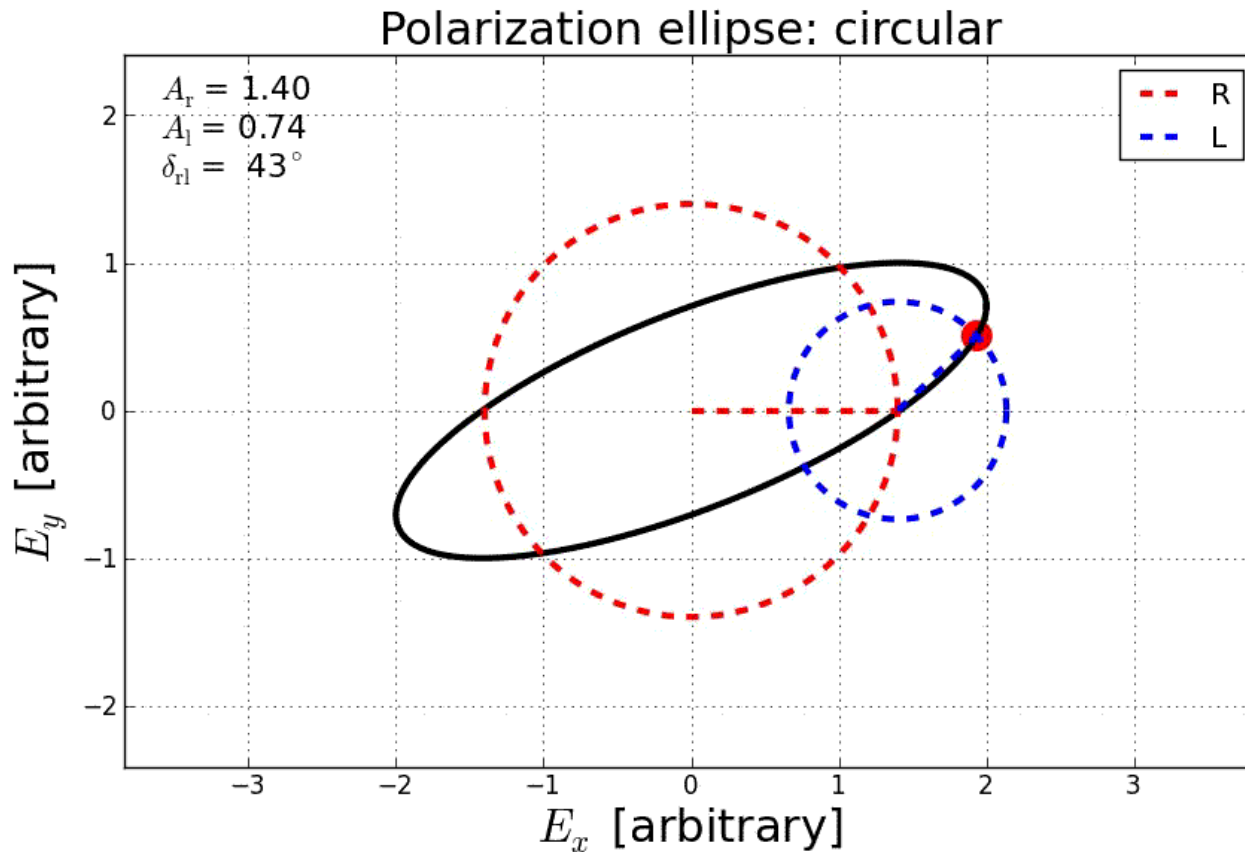


Example: Decomposition into Linear components



Example: decomposition into circular components

- The same ellipse, but now decomposed into oppositely-rotating circular components.



Stokes Parameters

- Defined by Stokes in 1852, adopted for astronomy by Chandrasehkar in 1947.
- Not vector-like quantities: Deals with power instead of electric field amplitudes.
- Parameters measured in units of flux density
- Can be used for partially polarised radiation.
- A (auto)correlator can effectively produce **all** Stokes parameters simultaneously (not easy in optical astronomy!)
 - After calibration

Stokes Parameters

- I – total intensity and sum of any two orthogonal polarisations
- Q and U – completely specify linear polarisation
- V – completely specifies circular polarisation
- $I^2 \leq Q^2 + U^2 + V^2$
- The total linearly polarised intensity is defined as: $P = \sqrt{U^2 + Q^2}$
- A linearly polarised source will have an intrinsic position angle on the sky that is given by:
$$\psi = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right)$$
- Stokes parameters often presented as percentages of the total intensity.
- Since radio sources are never fully polarised, then the fractional linear and circular polarisation will always be <1

Stokes Parameters for wide-band radiation

- In the quasi-monochromatic approximation, the incoming EM wave can be described, for a period $\Delta t \sim 1/\Delta\nu$, by two amplitudes, A_p and A_q , and a phase difference, δ_{pq} .
- With one measurement in Δt , $\Delta\nu$ sample will be 100% polarised (this has fooled a pulsar astronomer or two)
- For the orthogonal linear, and opposite circular bases, we have:

$$I = \langle A_X^2 \rangle + \langle A_Y^2 \rangle = \langle A_R^2 \rangle + \langle A_L^2 \rangle$$

$$Q = \langle A_X^2 \rangle - \langle A_Y^2 \rangle = \langle 2 A_R A_L \cos \delta_{RL} \rangle$$

$$U = \langle 2 A_X A_Y \cos \delta_{XY} \rangle = \langle 2 A_R A_L \sin \delta_{RL} \rangle$$

$$V = \langle 2 A_X A_Y \sin \delta_{XY} \rangle = \langle A_R^2 \rangle - \langle A_L^2 \rangle$$

- The angle brackets $\langle \rangle$ denote an average over a time much longer than the coherence time $1/\Delta\nu$.
- These four real numbers are a complete description of the polarization state of the incoming radiation.

Interpreting the Meaning of I, V, Q, and U

$$I = A_x^2 + A_y^2 = A_R^2 + A_L^2$$

$$V = A_R^2 - A_L^2$$

$$Q = A_X^2 - A_Y^2$$

$$U = 2A_X A_Y \cos \delta_{XY}$$

- I is the total power.
- V is the difference between the power in RCP and LCP components.
- Q is the difference between vertical and horizontal power.
- U is the difference between orthogonal components in a frame rotated by 45 degrees.

For a monochromatic wave:

- If $\mathbf{V} = \mathbf{0}$, the wave is 100% Linearly Polarized
- If $\mathbf{Q}=\mathbf{U}=\mathbf{0}$, the wave is 100% Circularly Polarized
- In general, the wave is Elliptically Polarized

How do we measure polarisation?

- Radio feeds sensitive to different polarisations (either linear or circular, though in practice cross coupling makes the feeds elliptical)
- Combine the information we receive from the two feeds, **after appropriate calibration**, to determine the polarisation of detected emission
- Linear polarisation probes the magnetic field in the plane of the sky
- Circular polarisation – magnetic field along the line of sight (can also determine the field along the line of sight from the rotation of linear polarisation..)



Examples processes

- **Synchrotron emission:** Up to $\sim 80\%$ linearly polarized, with no circular polarization. Measurement provides information on strength and orientation of magnetic fields, level of turbulence.
- **Pulsar emission:** up to 0-100% linear polarisation, can also show high levels of circular polarisation (as classmate Hong how it is produced)
- **Zeeman-line splitting:** Presence of B-field splits RCP and LCP components of spectral lines by amount proportional to the field strength.
- **Faraday rotation:** Magneto-ionic region rotates plane of linear polarization. Measurement of rotation, combined with density estimate, gives B-field estimate.
- **Free-electron scattering:** Induces a linear polarization which can indicate the origin of the scattered radiation.

What do we measure with polarisation?

- **Rotation measures (RM)** – provide integrated magnetic fields through Faraday rotation of linear polarisation – integral along the line of sight of the electron density and line-of-sight magnetic field

$$\text{RM} = 0.81 \int_{\text{source}}^{\text{observer}} n_e(l) B_{\parallel} dl \text{ rad m}^{-2}.$$

- **Extension: Rotation-measure synthesis**

- **Zeeman splitting** – provides in-situ magnetic fields through the splitting of a spectral line into several components in the presence of a magnetic field – compare with lab measurements (splitting factor) to find magnetic field strength

$$RR = I + V$$

$$LL = I - V$$

$$\Delta E = \mu_b B$$

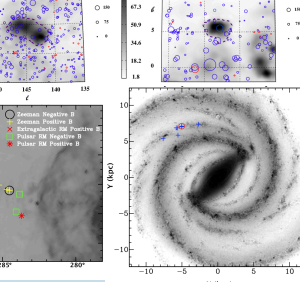
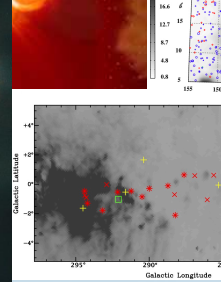
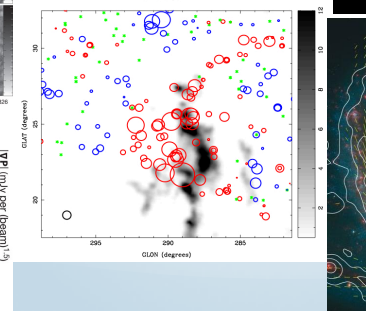
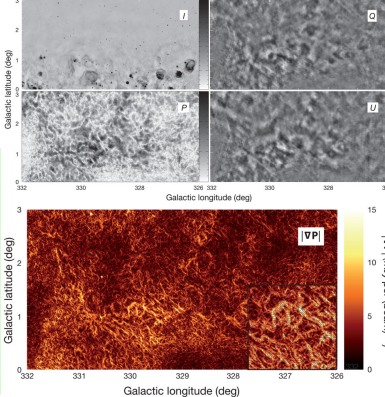
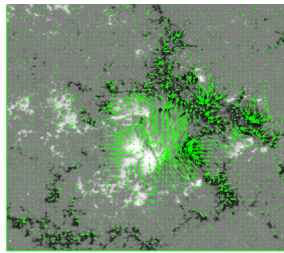
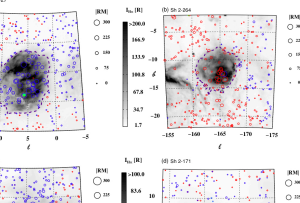
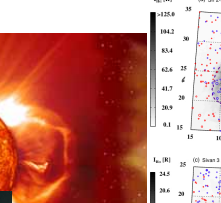
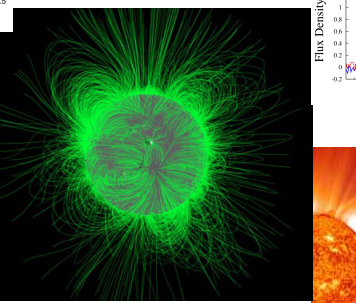
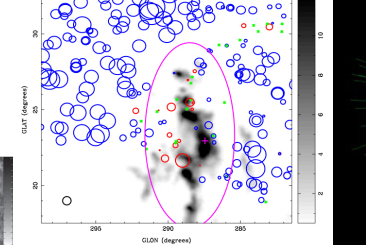
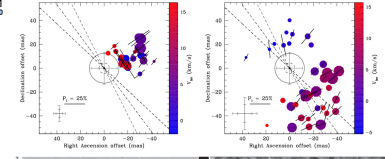
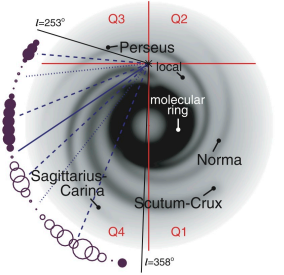
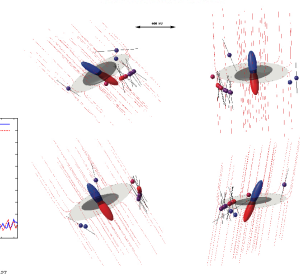
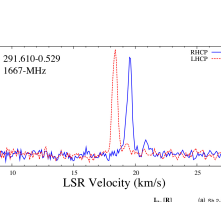
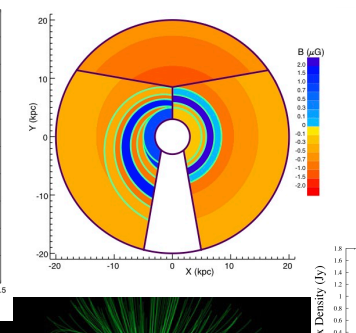
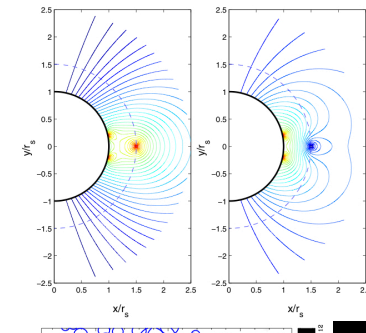
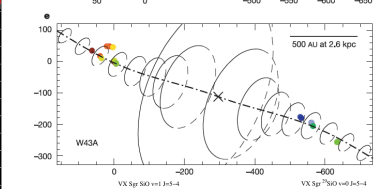
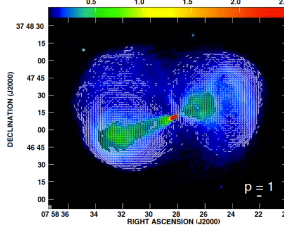
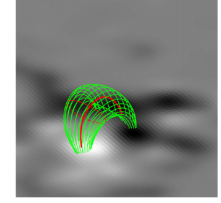
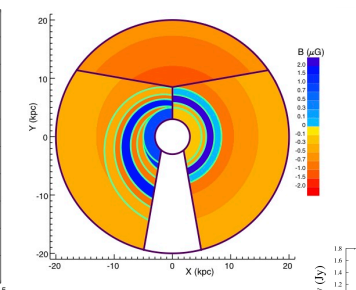
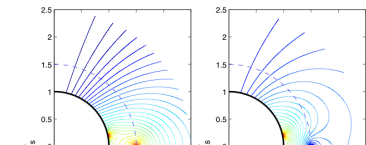
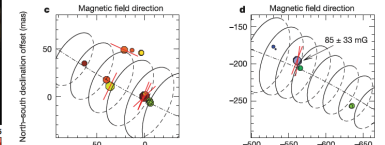
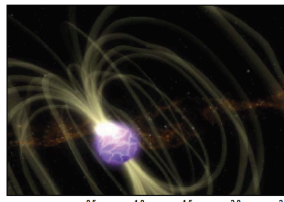
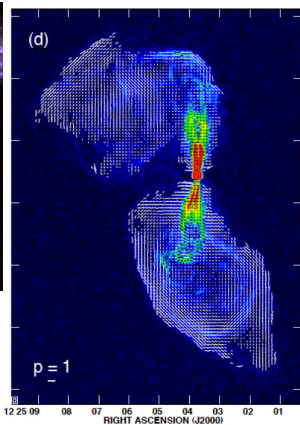
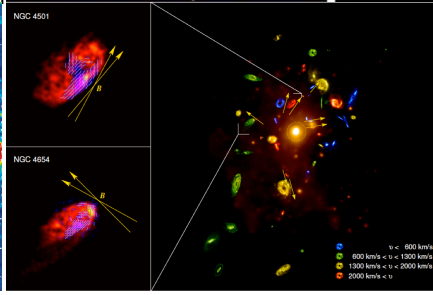
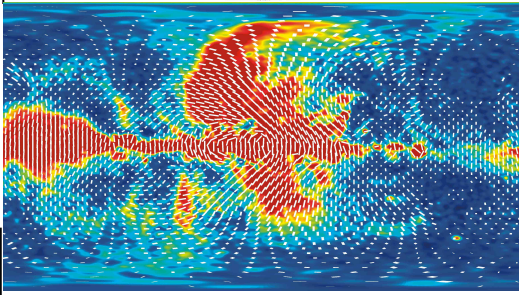
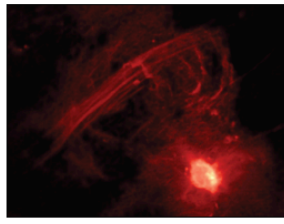
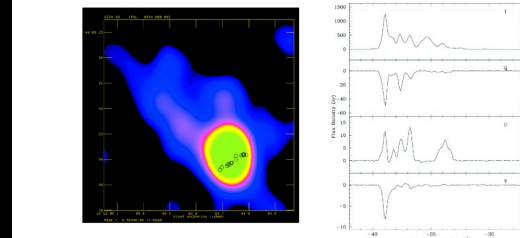
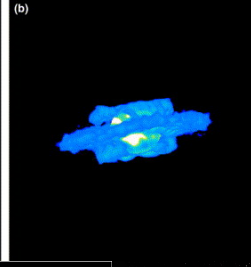
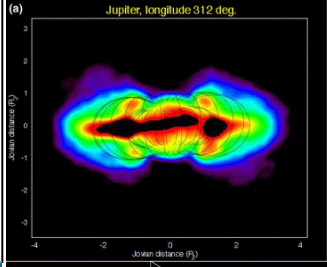
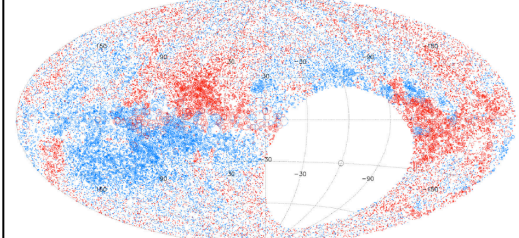
What do we measure with polarisation?

- **Polarisation vectors** – provide field strength and direction in plane of sky through computation of measured Stokes Q and U to obtain linear polarisation and polarisation angle
- **Gradient of Stokes Q and U** – provide direct imaging of interstellar turbulence – changing of magnetic field orientation with gas motions
- **Circular polarisation** from synchrotron emission (it has a small, <0.1% Stokes I, component in Stokes V) – provide direct measurement of field strength and direction

$$P = \sqrt{U^2 + Q^2} \quad \Theta = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right)$$

$$|\nabla P| = \sqrt{\left(\frac{\partial Q}{\partial x} \right)^2 + \left(\frac{\partial U}{\partial x} \right)^2 + \left(\frac{\partial Q}{\partial y} \right)^2 + \left(\frac{\partial U}{\partial y} \right)^2}$$

$$m_c = \epsilon_\alpha^v \left(\frac{v_{B\perp}}{v} \right)^{0.5} \frac{B_{u, \text{los}}}{B_\perp^{\text{rms}}}$$



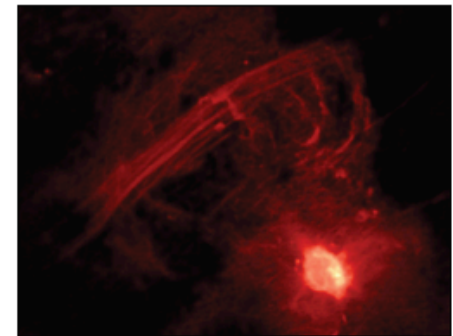
* The range of Magnetic fields

[Fridge Magnet = 50 G]

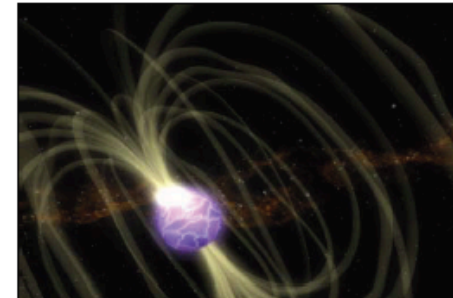
- › High-z seed fields
(Widrow 2002; Subramanian 2007) $B \sim 10^{-30} - 10^{-20}$ G
- › Intergalactic Medium $B \sim 1-10$ nG ?
- › Intracluster Medium $B \sim 0.1-1$ μ G
- › Interstellar medium $B \sim 1$ μ G – 10 mG
- › Galactic Centre $B \sim 50$ μ G – 1 mG
(Crocker et al. 2010; Ferrière 2010)
- › Main sequence star: HD 215441 $B_0 \approx 34$ kG
(Babcock 1960)
- › White dwarf: PG 1031+234 $B_0 \approx 10^9$ G
(Schmidt et al. 1986)
- › Pulsar: PSR J1847-0130 $B_0 \approx 9 \times 10^{13}$ G
(McLaughlin et al. 2003)
- › Magnetar: SGR 1806-20 $B_0 \approx 2 \times 10^{15}$ G,
(Kouveliotou et al. 1998, Israel et al. 2005) $B_i \approx 10^{16}$ G
- › Cosmic strings (Ostriker et al. 1986) $B \sim 10^{30}$ G
- › Planck-mass monopoles $B \sim 10^{55}$ G
(Duncan et al. 2000)



Magnetic filaments in Perseus A
(Fabian et al. 2008)



Galactic Centre
(Yusef-Zadeh et al. 1984)

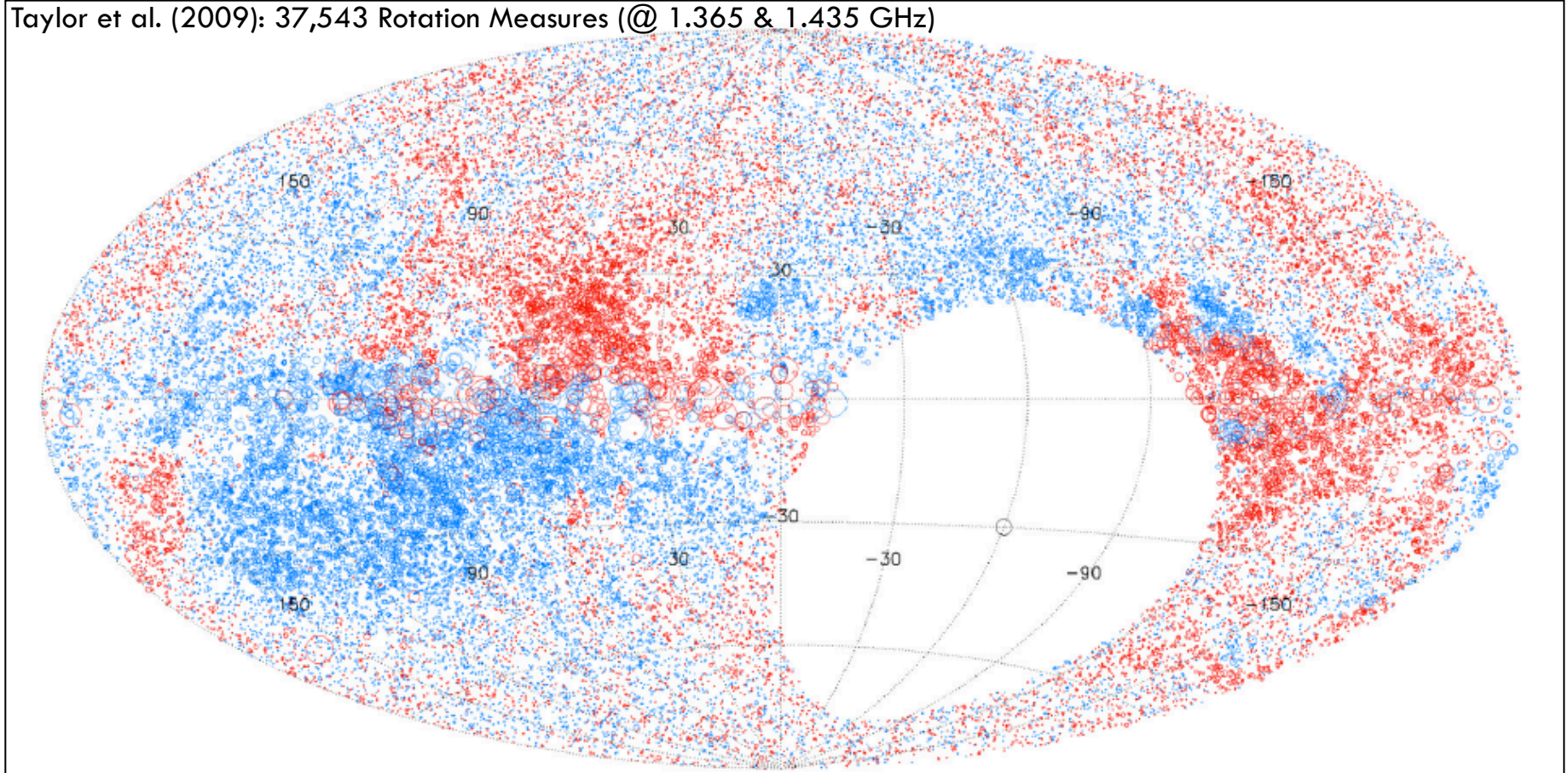


SGR 1806-20 giant flare
(NASA)

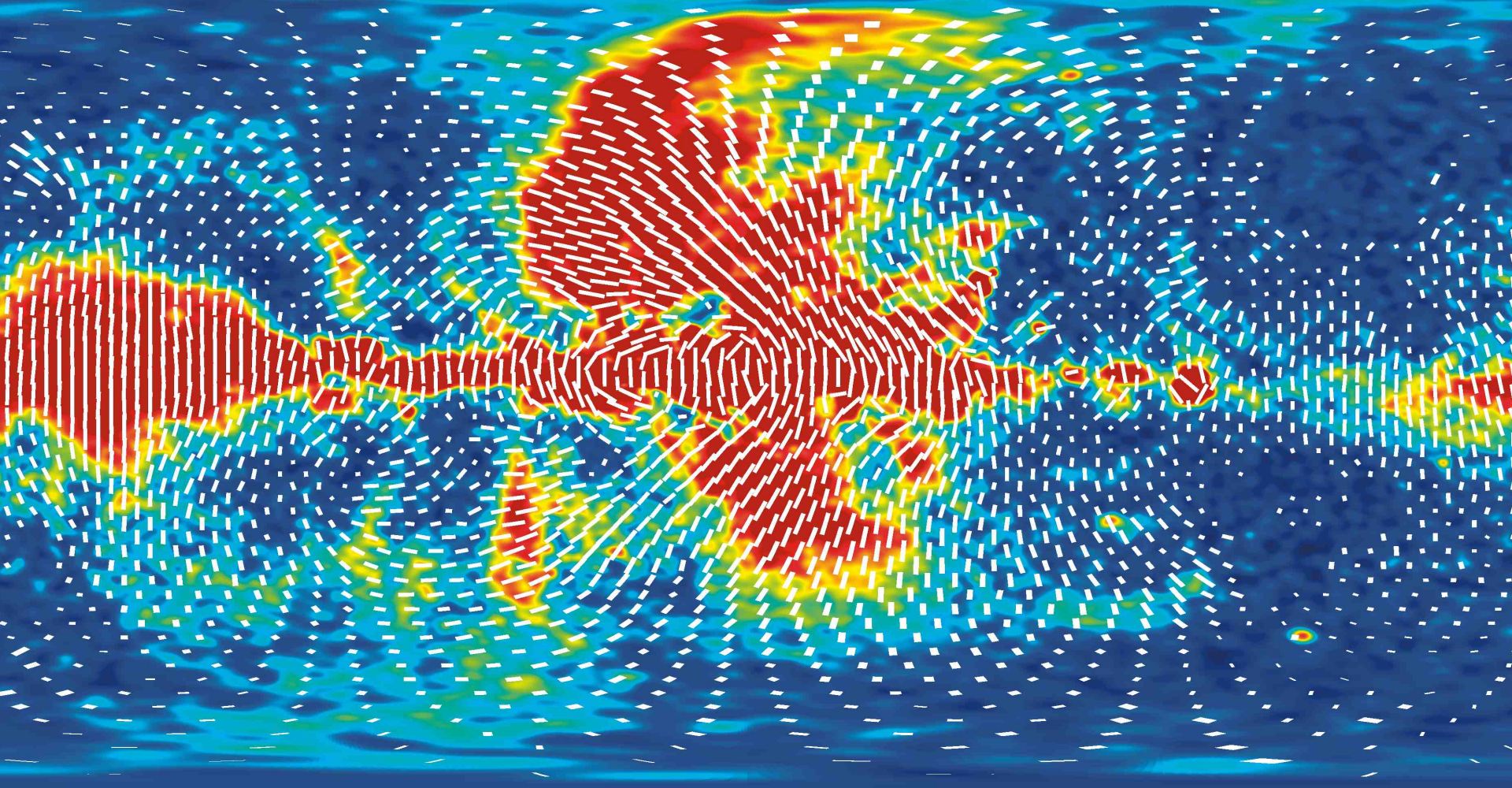
[slide credit B. Gaensler]

* Magnetism across the sky

Taylor et al. (2009): 37,543 Rotation Measures (@ 1.365 & 1.435 GHz)

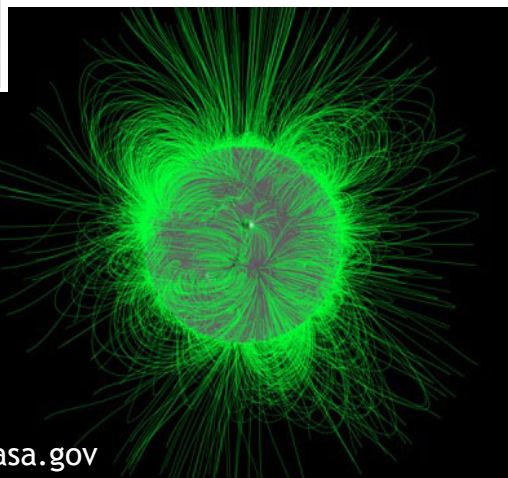
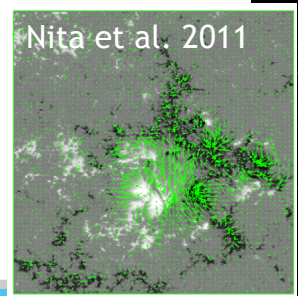
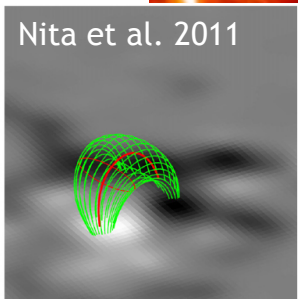
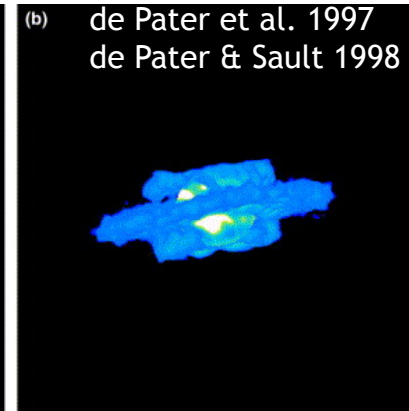
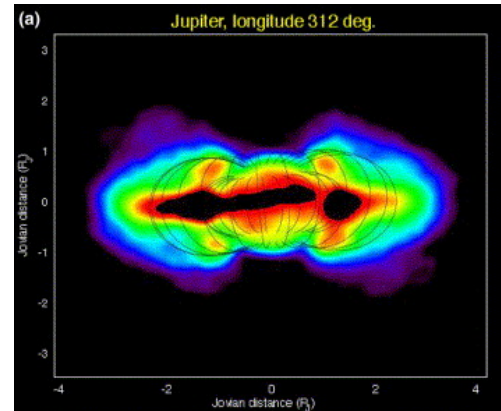
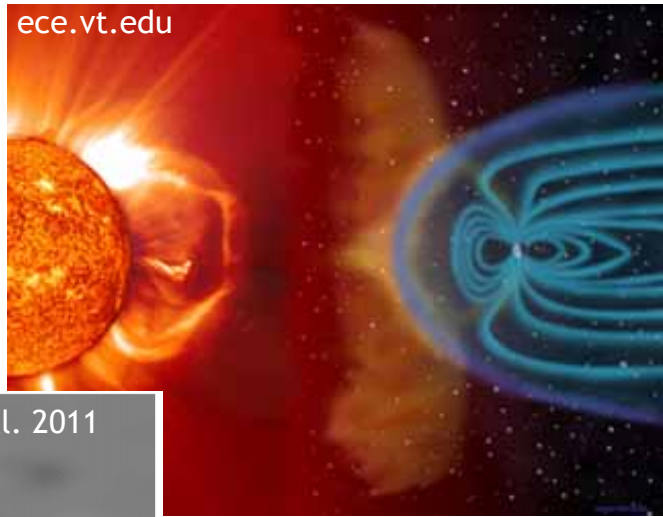


WMAP 23-GHz polarised emission (intensity and direction)



Within our Galaxy

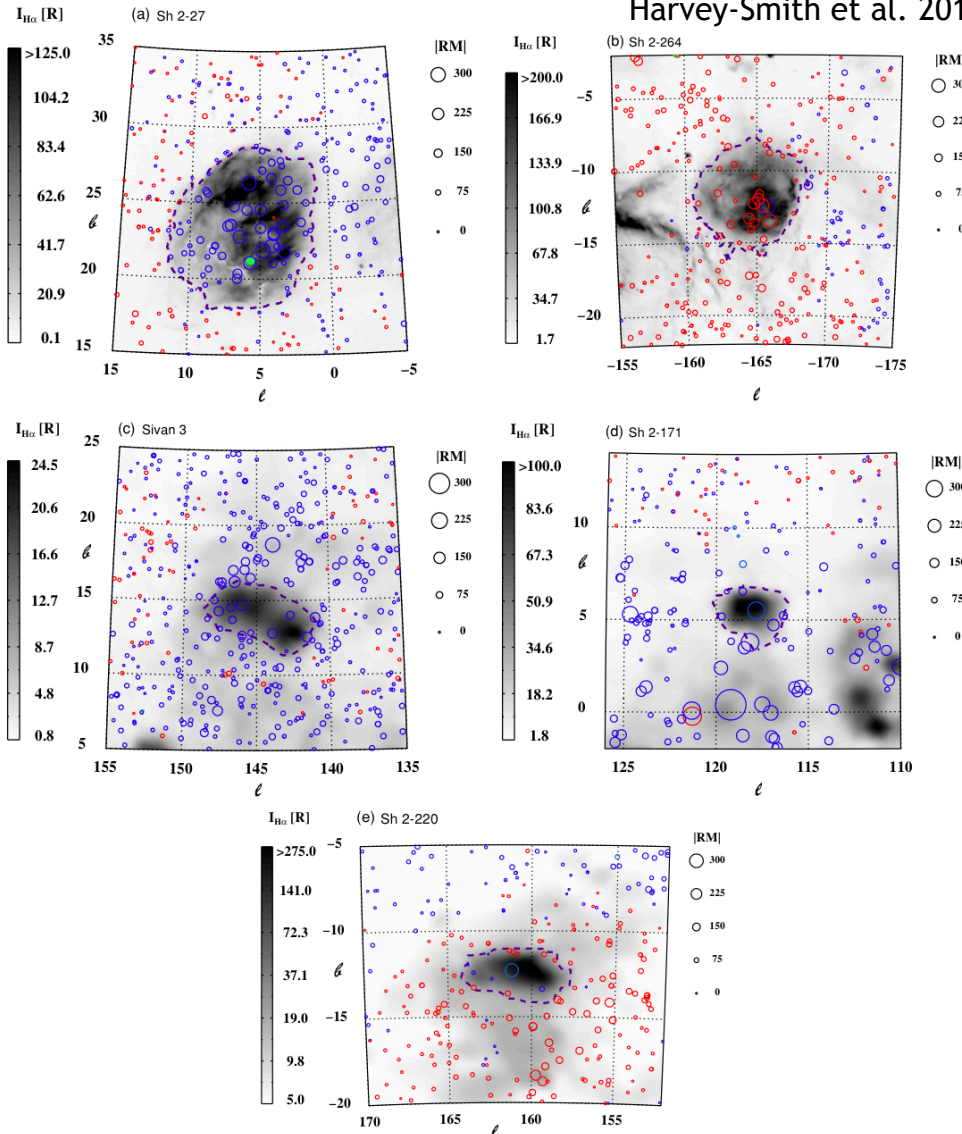
* The solar system



- Earth
- Mars
- Around the Sun (the solar wind)
- Around Jupiter

HII regions

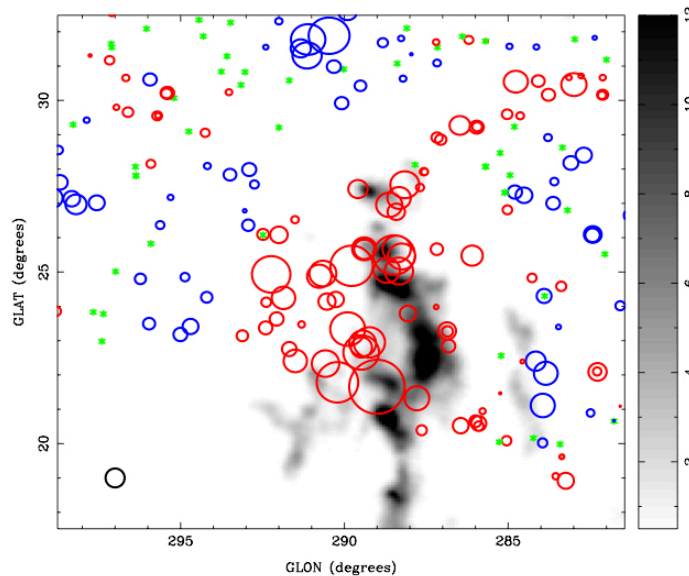
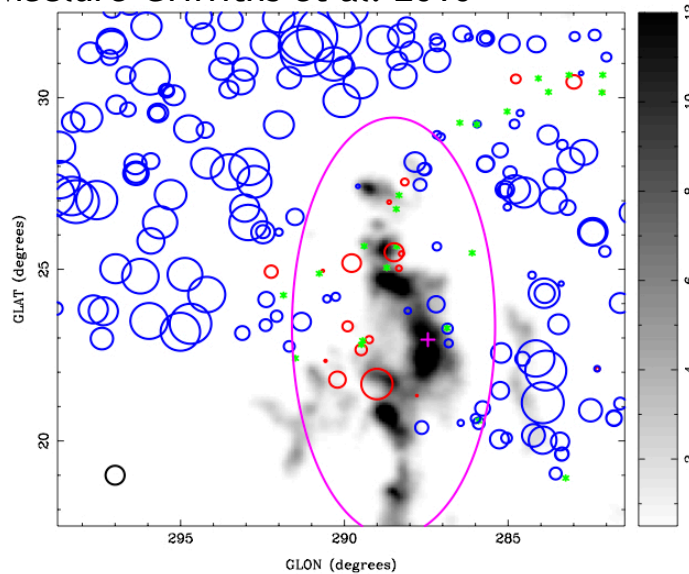
Harvey-Smith et al. 2011



- Magnetic fields in large HII regions (star forming regions)
- Measurement of rotation of polarisation along line of sight, using background polarised sources.
- See coherent fields within the HII regions
- *Do HII regions stir up larger scale fields or simply compress them?*
- *Related to Galactic scale magnetic fields?*

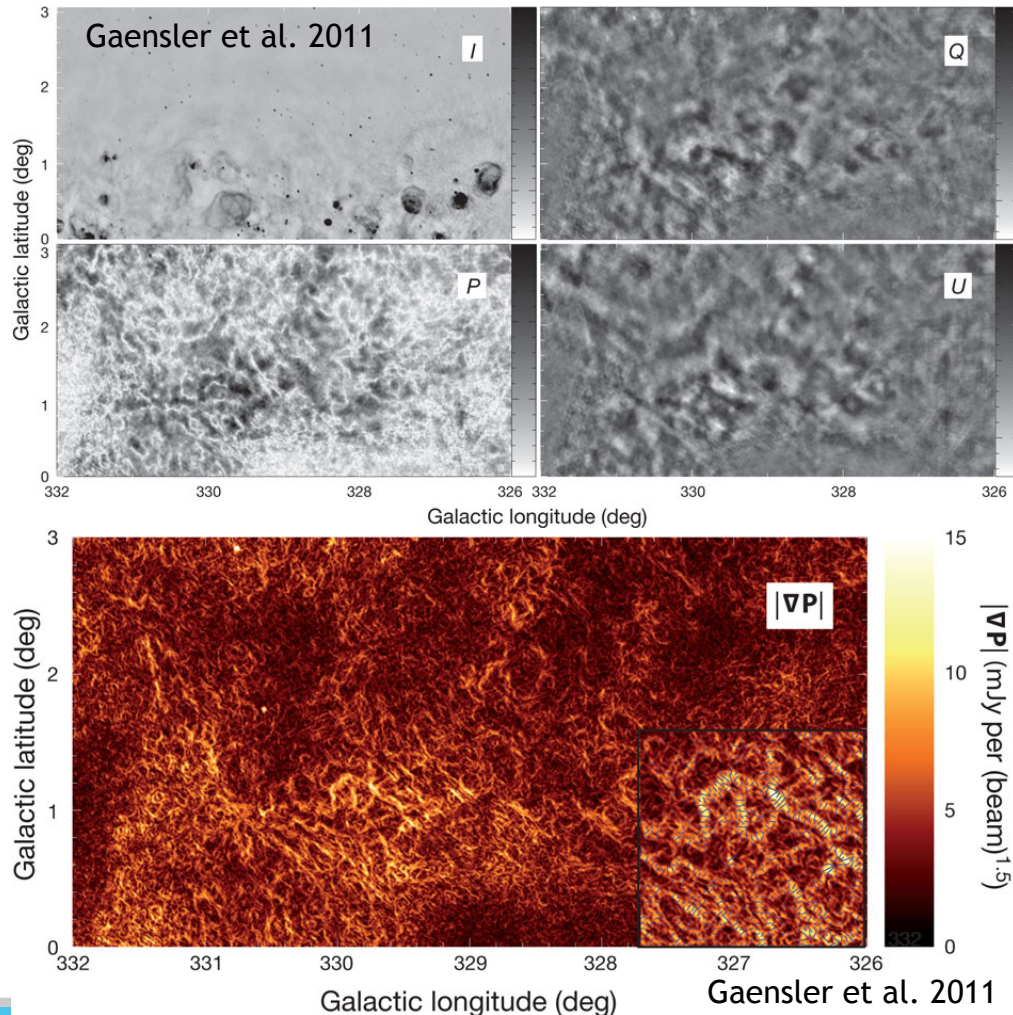
High-Velocity Clouds

McClure-Griffiths et al. 2010



- Magnetic fields in high velocity clouds
- Measurement of rotation of polarisation along line-of-sight, using background polarised sources.
- *Are clouds entraining magnetic fields?*
- *Magnetic fields sustaining cloud?*
- *Milky Way mass accretion?*
- *More rotation measures needed, HI Zeeman splitting?*

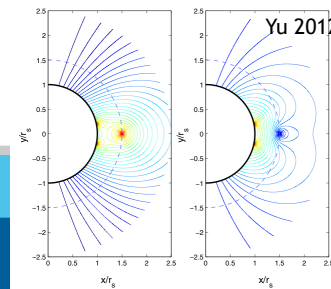
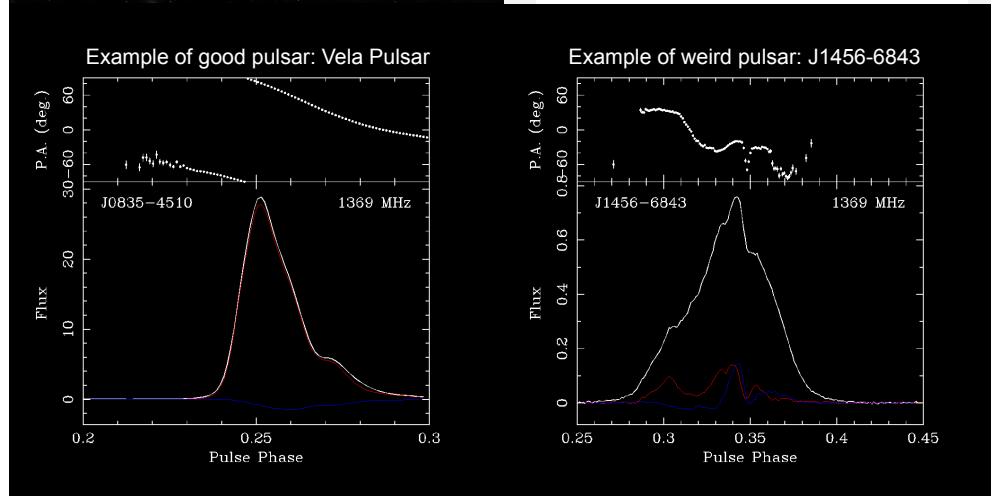
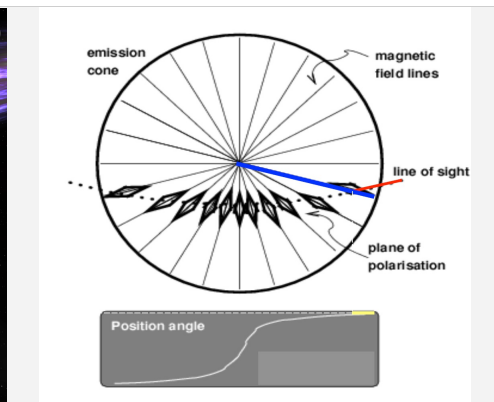
Fields within the ISM



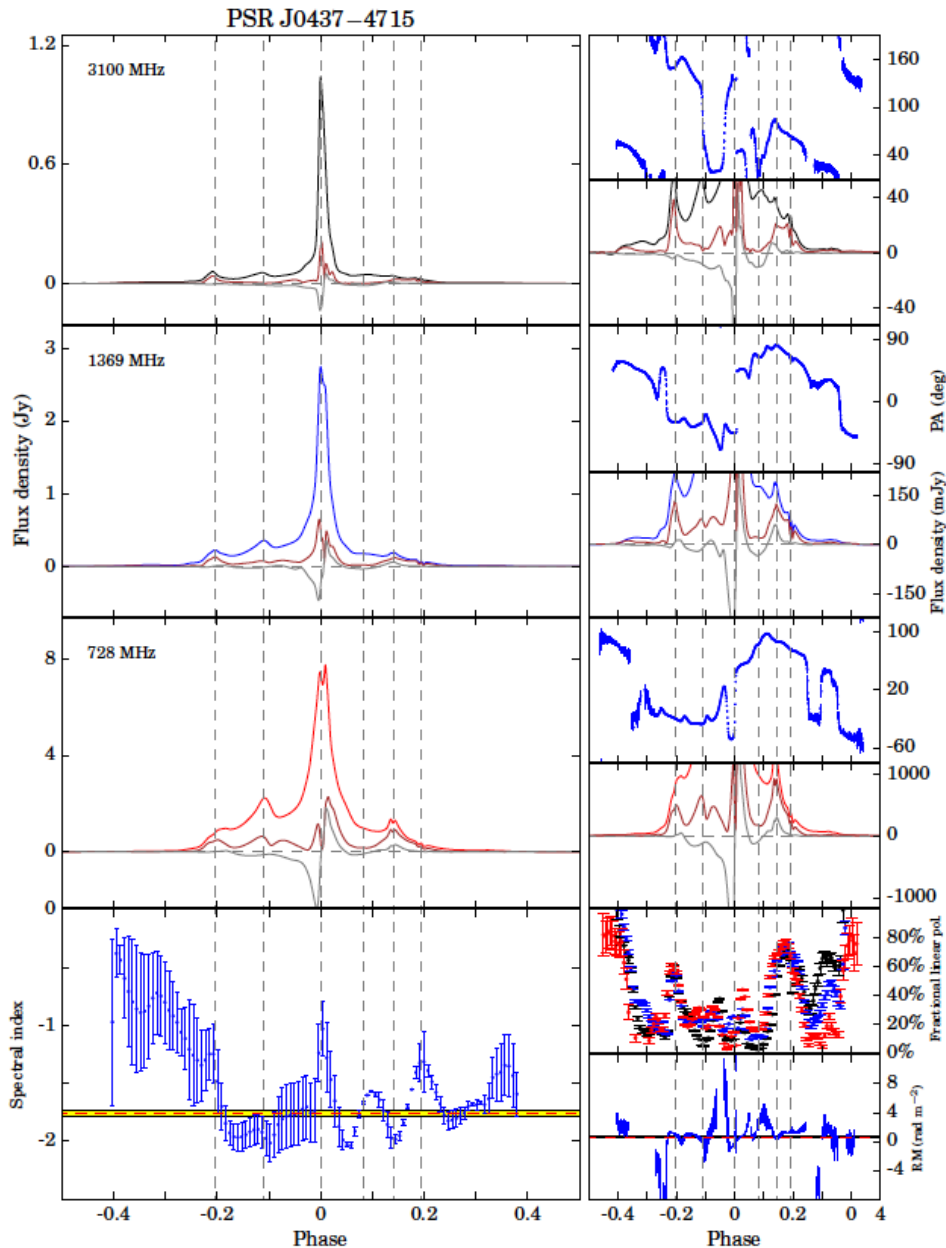
- Gaensler et al.'s *Snakes in the Plane*
- Emil Lenc et al.'s *Dragons out of the plane* (or suitable pun)
- Magnetised turbulent interstellar medium
- Gradient of change of linear polarisation (Stokes Q and U)
- *What are we seeing?*
- *What does this tell us about the processes of the interstellar medium?*

Pulsars/Magnetars/Fast-Radio Bursts

- Pulsars: high levels of polarised radiation
- All properties of polarisation change versus pulse phase
 - Some pulsars obey “rotating vector” model
- For many pulsars, the polarisation doesn't follow expected model: they can emit in two orthogonal senses of polarization simultaneously
- Due to the spread of pulsars across the sky, they can be used as rotation measures to map magnetic fields of the Galaxy and Solar system, e.g. solar wind.

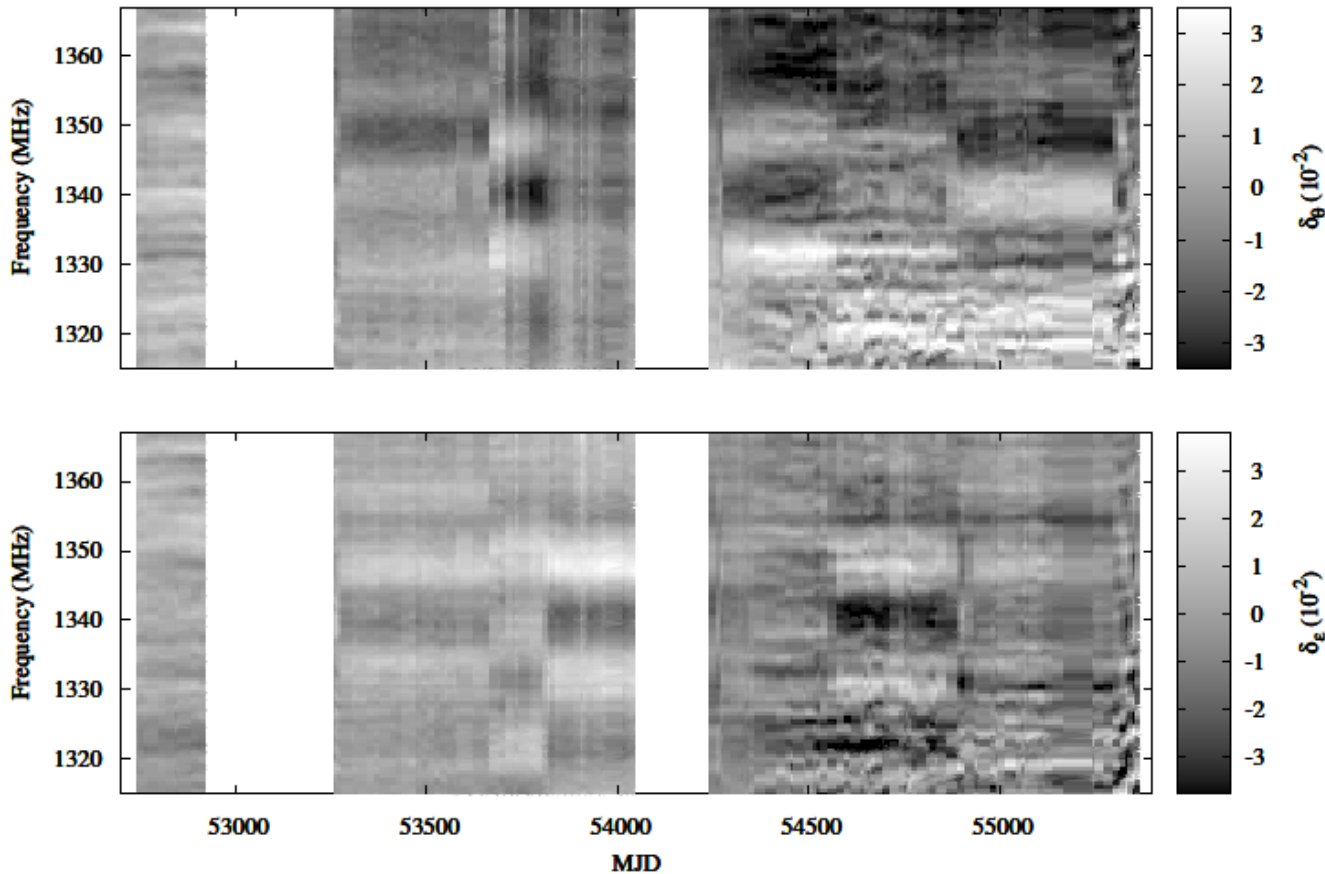


Example: Polarisation of pulse profile



- Observations from Parkes of bright millisecond pulsar J0437-4715, analysed by Ph.D. student Shi Dai (100 hours of observations).
- Position angle of linear polarisation
- Linear and circular polarisation
- Phase-dependent Rotation Measure?

Instrumental Polarisation can be a nuisance!



Cross-coupling and ellipticity of Parkes multibeam receiver

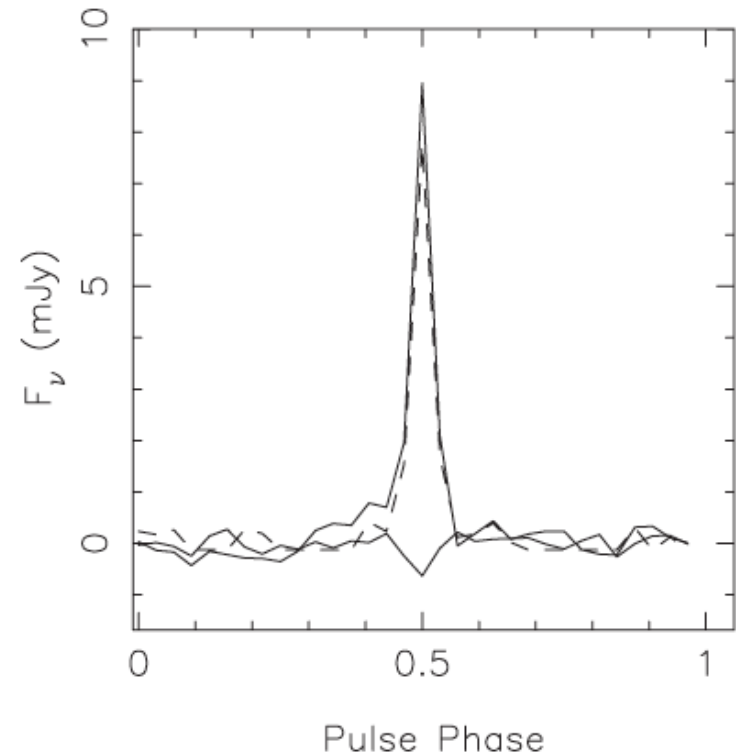
Changes with time

Can cause issues with precision pulsar timing (distorts shapes of highly polarised pulses)

Emil yesterday: check to see if calibration is sane by imaging other Stokes parameters

Rotation measures and the Galactic Centre

- Magnetar J1745-2900 (high magnetic field pulsar) discovered near Galactic Centre
 - Unlike most pulsars, magnetars can have flat spectrum
- Observations of ATCA at 4.5-8.5 GHz and 16-20 GHz
- $RM \sim -67,000 \text{ rad m}^{-2}$
- Rotation measure can depolarise emission



ATCA observations of J1745-2900 at 17 GHz (Shannon & Johnston 2013)

Example: Rotation measures

- Magnetar J1745-2900 (high magnetic field pulsar) discovered near Galactic Centre
 - Unlike most pulsars, magnetars can have flat spectra
- Observations of ATCA at 4.5-8.5 GHz and 16-20 GHz
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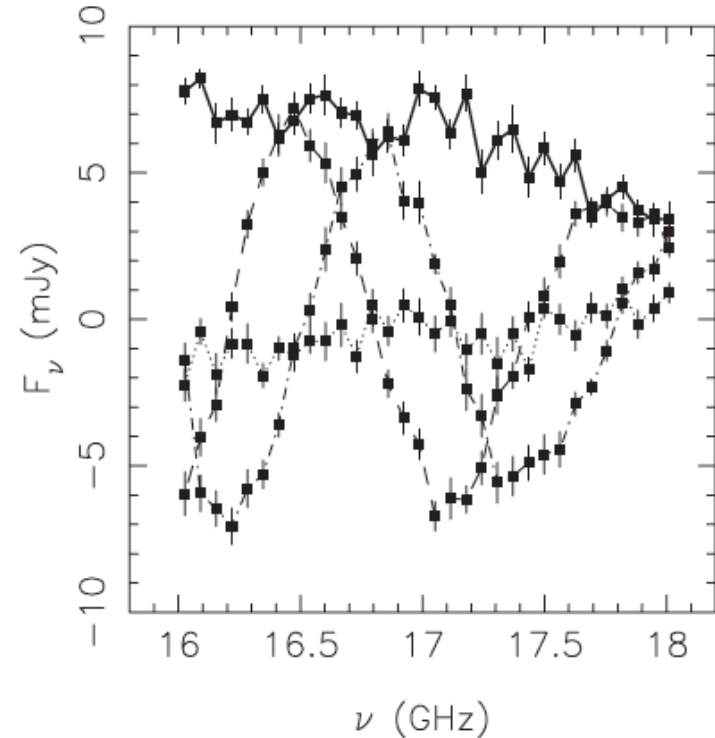
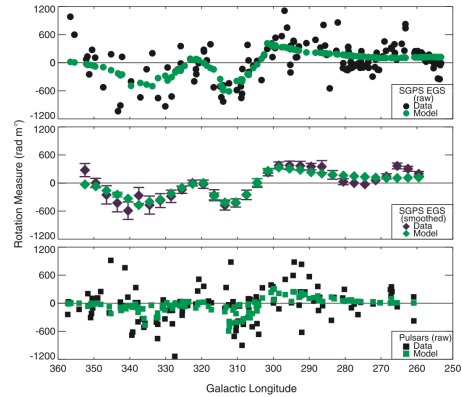
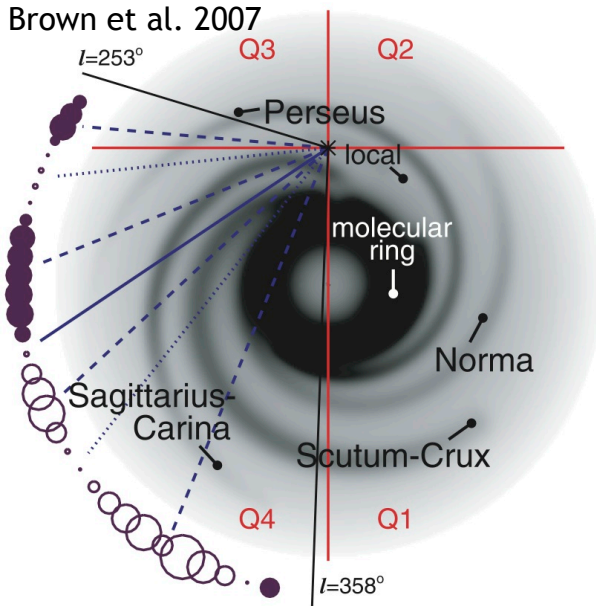


Figure 2. Flux density of the Stokes parameters in the peak bin of the profile as a function of observing frequency. The thick solid line shows Stoke *I*, Stokes *Q* and *U* are shown as the dashed and dash-dotted lines and Stoke *V* is shown as the thin solid line.

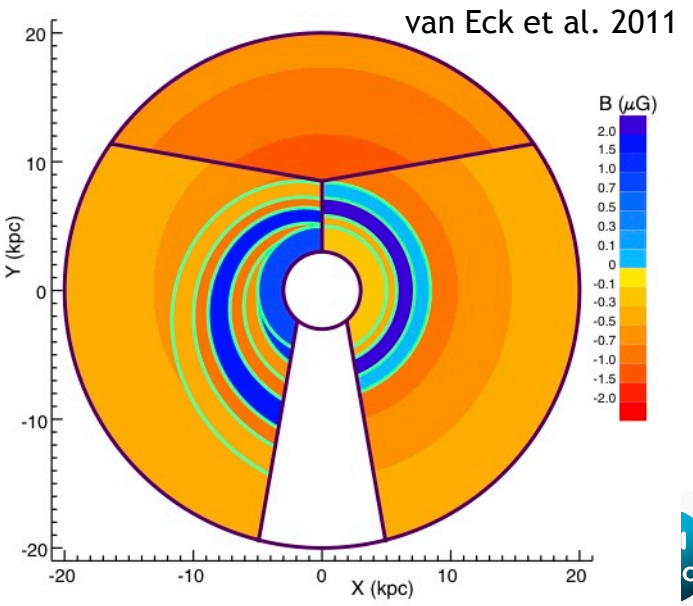
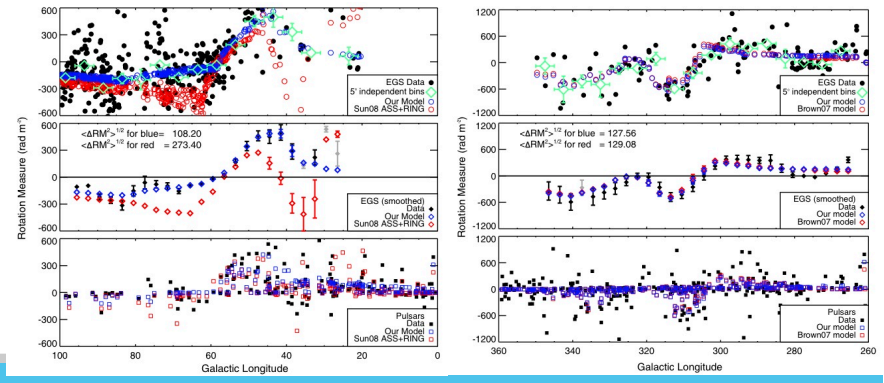
Galactic Magnetic Field



Rotation measures (Pulsars and extragalactic) across Galaxy used to examine Milky Way magnetic field.

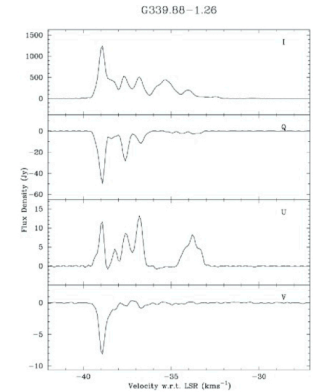
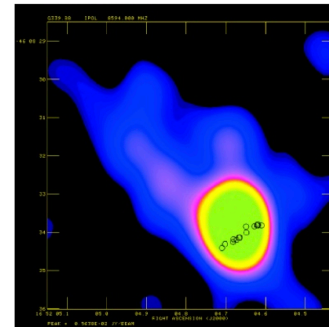
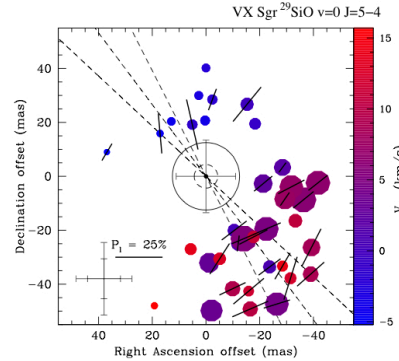
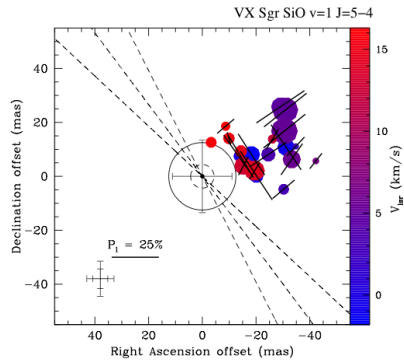
Do fields follow spiral arms?

Are there field reversals? (where are they?)



Masers

Vlemmings et al. 2011

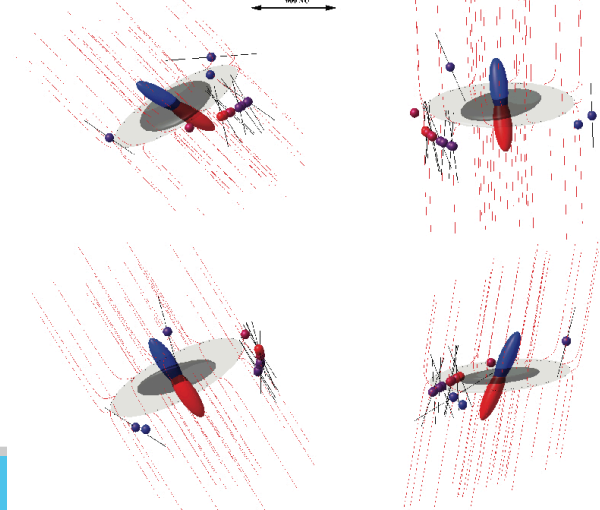


Ellingsen 2002

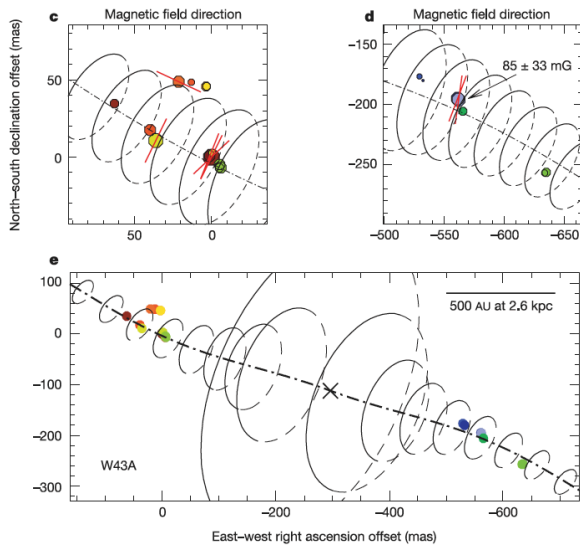
- Maser emission shows linear and circular polarisation – in situ magnetic fields in plane of sky and line-of-sight
- Found in range of astrophysical objects

What can we learn about the objects traced?

Vlemmings et al. 2010

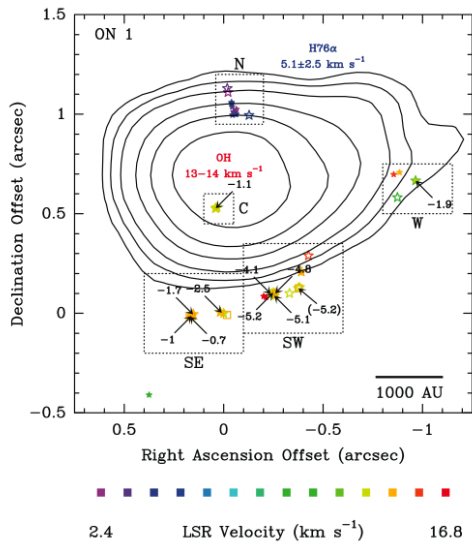


Vlemmings et al. 2006

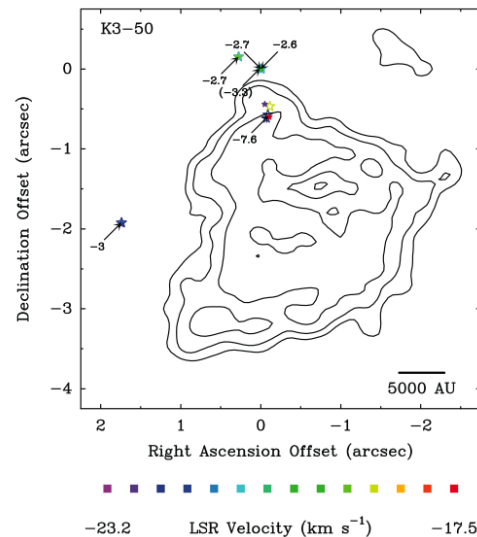


Masers

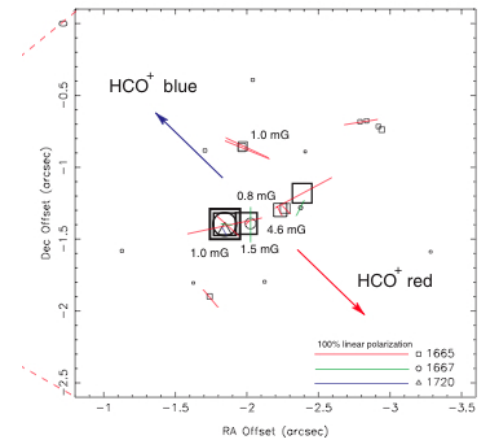
- Masers typically exhibit consistent line-of-sight magnetic field orientations with comparable field strengths (of a few mG)
- Examples: Fish & Reid 2007, Nammahachak et al. 2006, Caswell et al. 2010, Vlemmings et al. 2010



Fish & Reid 2007

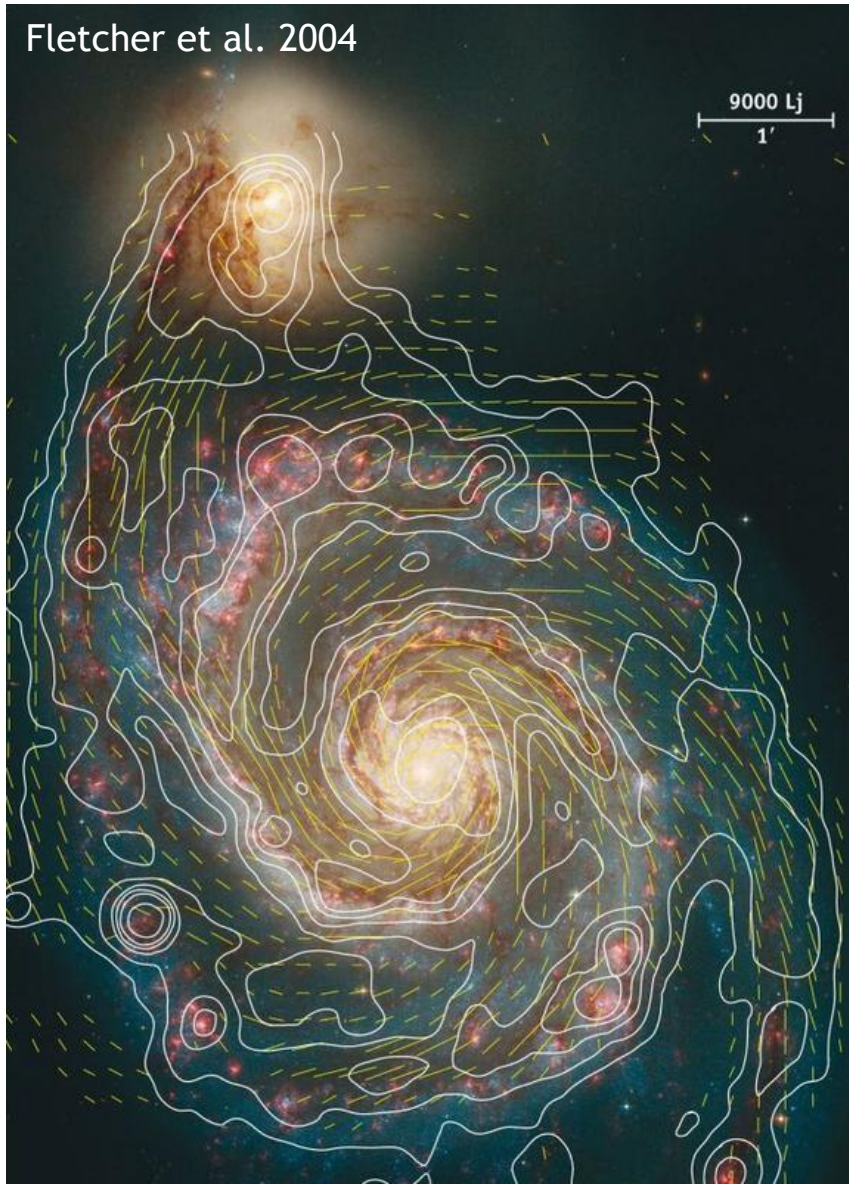


Fish & Reid 2007



Nammahachak et al. 2006

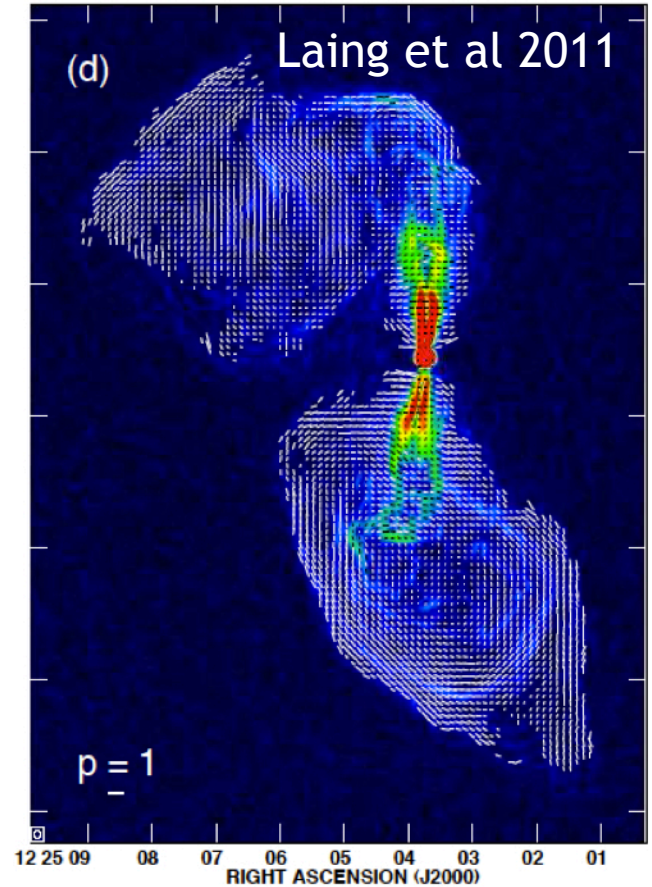
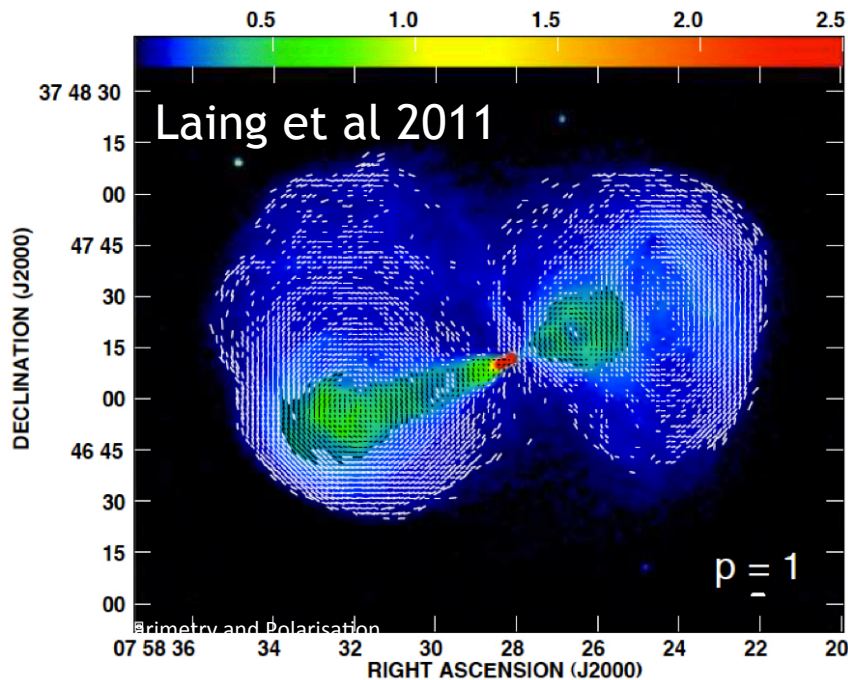
Fletcher et al. 2004



Galaxies

Galaxies

- Polarised emission in jets
- *How are such strong magnetic fields created near black holes?*
- *What is composition of outflow?*
- *What effect does the outflow have on galaxy?*



Electron Scattering in S106

- Example of polarised emission due to electron scattering.
- This is a $2.2\mu\text{m}$ image of the bipolar HII nebula S106
- Center peak is IR source IRS4.
- Contours show emission intensity
- Lines show the apparent E-field.
- Azimuthal orientation shows the emission is scattered light from the central source.

Aspin et al. (1990)

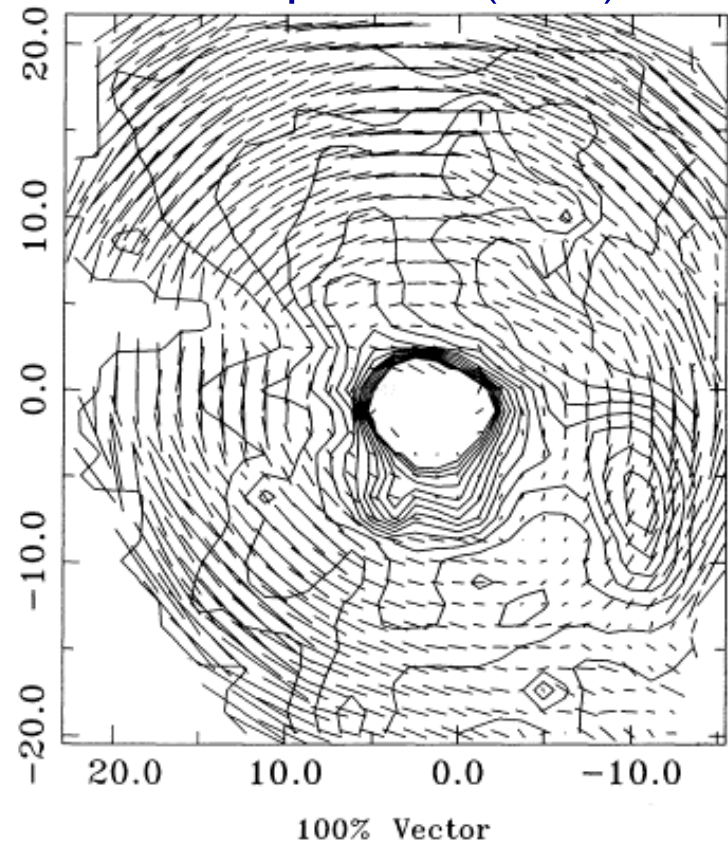
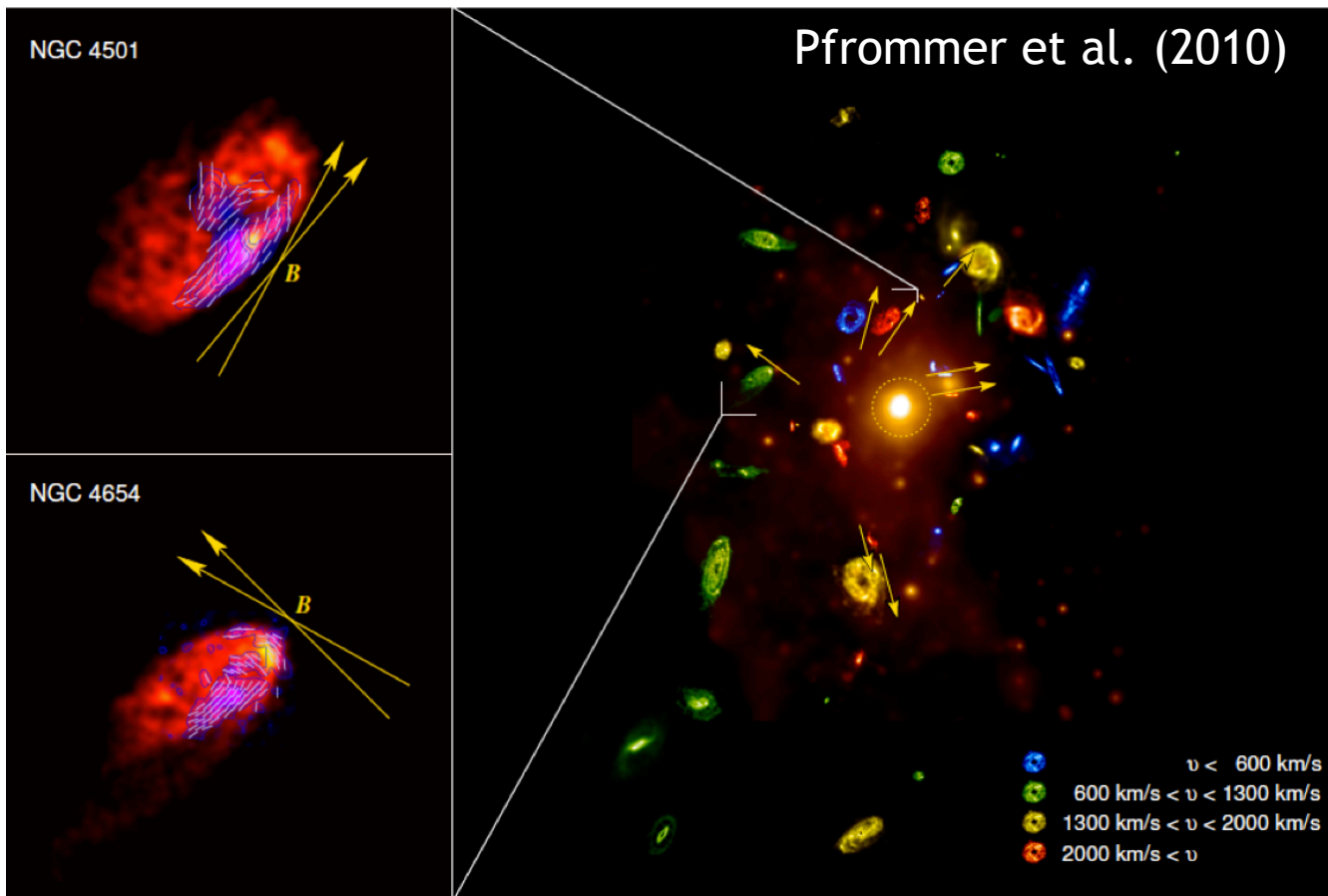
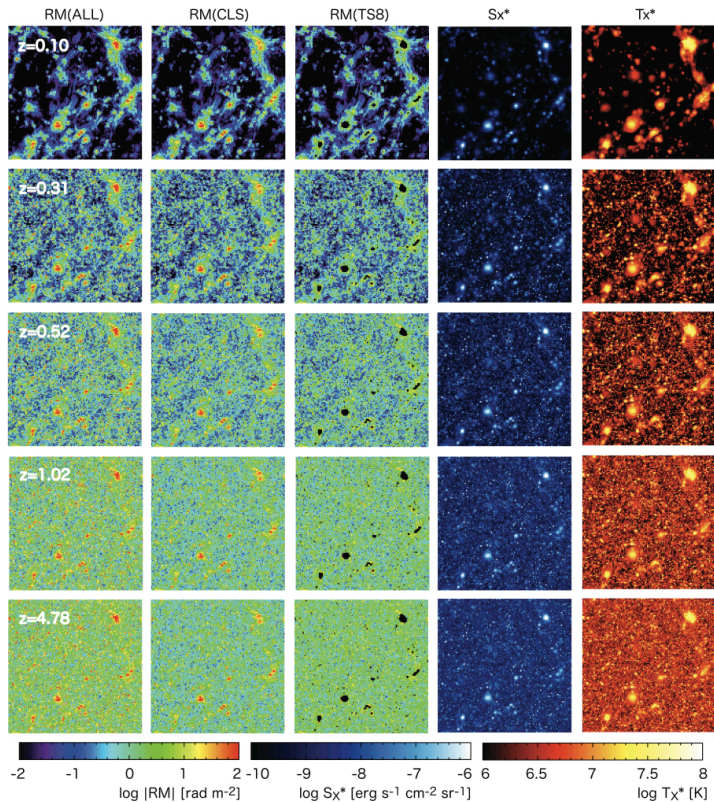


Figure 4. *K* polarization-vector map. Here, the *K* polarization-vector map of the region is overlaid on the *K* intensity contours. Axes offsets are in arcsec from IRS4 (0, 0) and the 100 per cent polarization-vector map is shown for reference.



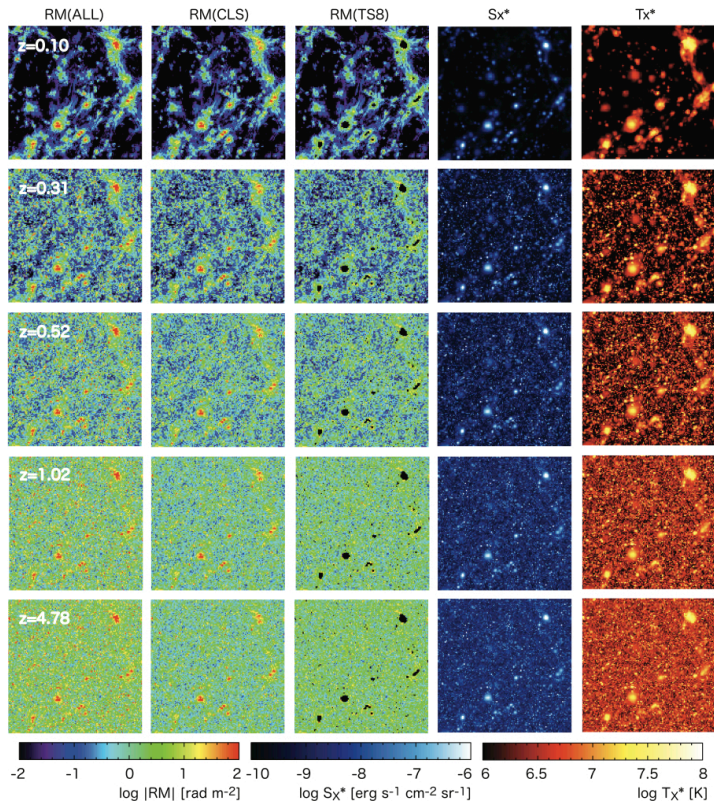
Cosmic magnetism: clusters of galaxies and beyond

Cosmic magnetism



- Goal: discover the inter-galactic medium magnetic fields
- relate magnetic fields to structures, clusters of galaxies
- can trace and/or regulate the formation of structure in the early universe
- size scale of fields can differentiate generation mechanisms
- synchrotron cosmic web?
- primordial magnetic fields?
- Probe with fast radio bursts (FRBs)?

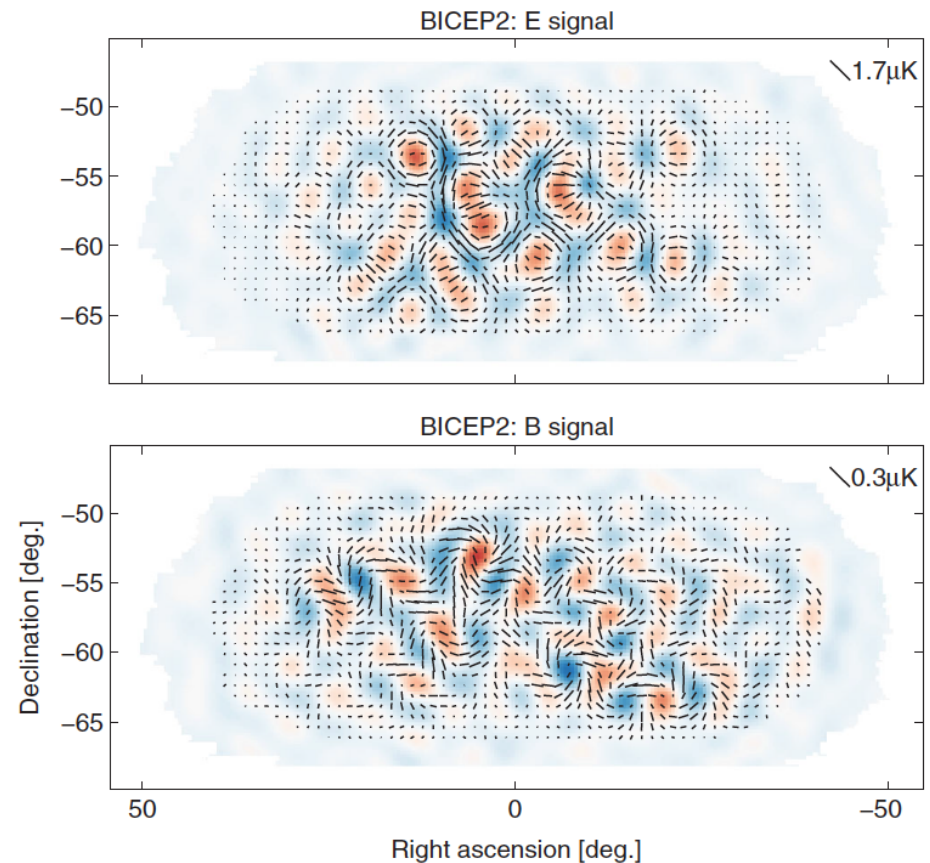
Cosmic magnetism



- Models of rotation measures at different cosmological ages (e.g. Akahori & Ryu 2011, left)
- Next generation instruments allow for these type of measurements
- Trying to determine origin of magnetism

Gravitational Waves and BICEP2

- Cosmic microwave background is weakly polarised
- Temperature variations cause linear polarisation to shear (accepted)
- Primordial gravitational waves cause curl
 - GWs produced in epoch of inflation
- Issue: can foreground cause same shear?
 - Foreground has different spectral index than, so can hope to cancel it out through multi-frequency observations



Summary

- Polarisation and magnetic fields are a fundamental part of radio astronomy
- Careful measurement and understanding of polarised emission tells us a wealth of information about the magnetic fields present in a whole range of astrophysical objects
- So, what about magnetic fields?
- Thank you!