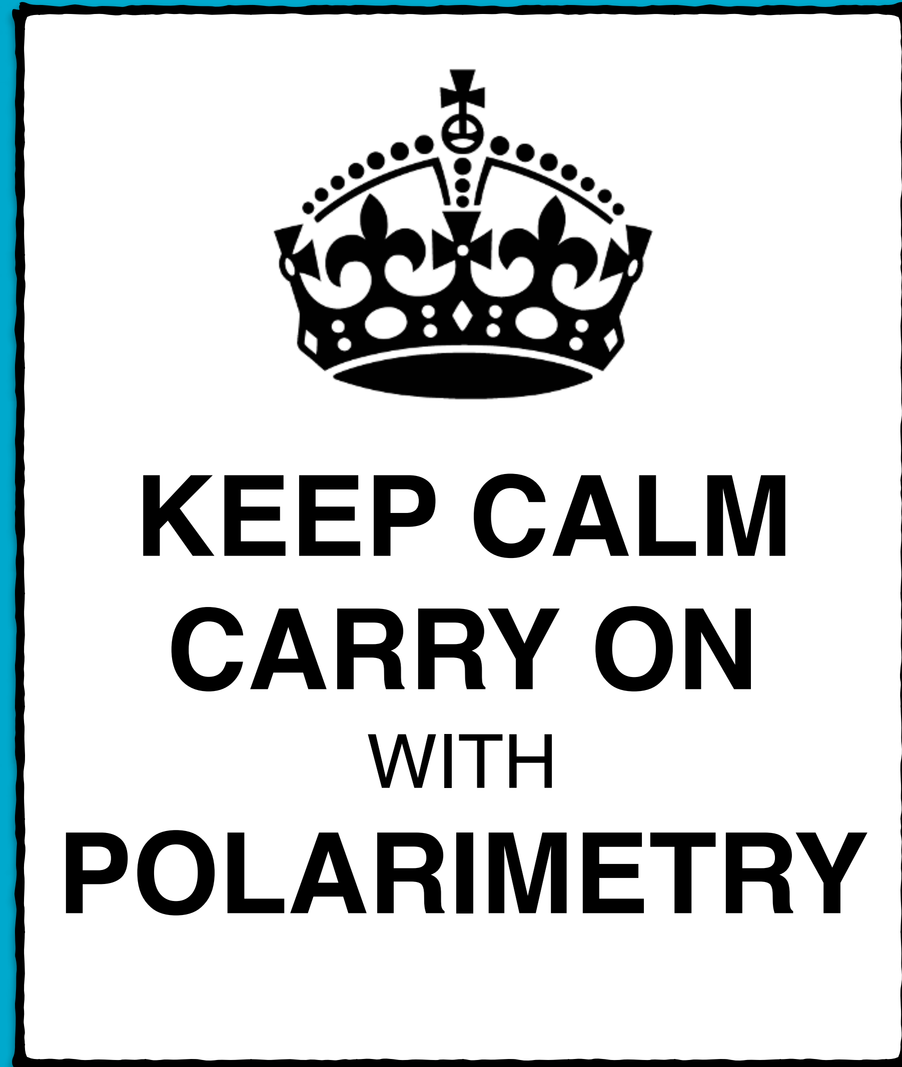


Polarimetry

2018 ICRAR/CASS Radio School

Emil Lenc | Senior Research Scientist

05 October 2018

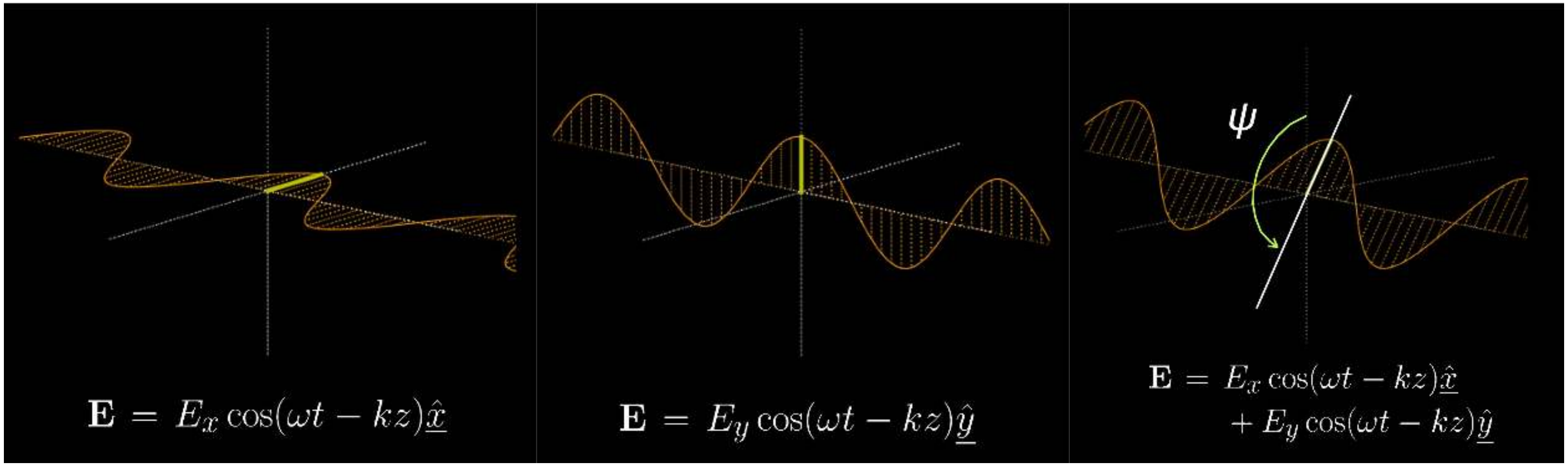
Polarimetry

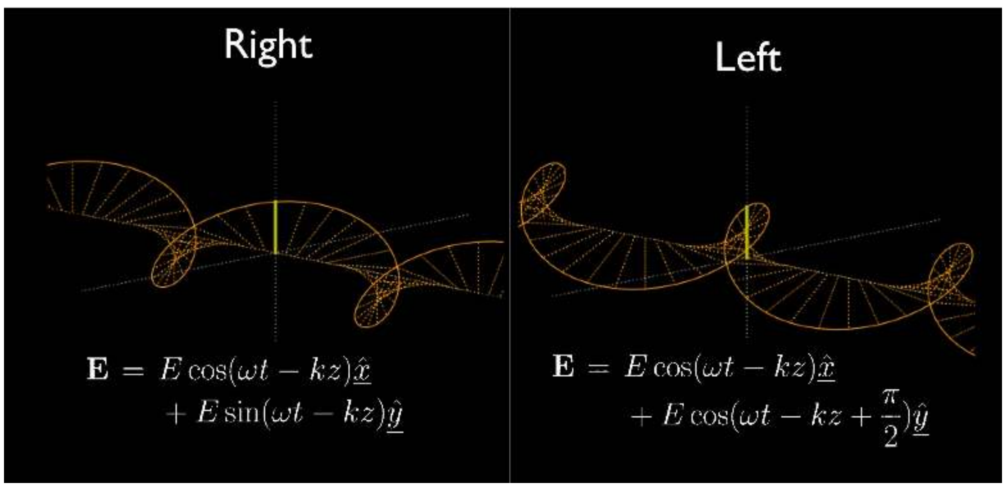
- What is it?
- Why study it?
- How do we measure things
- Things to worry about
- Pop Quiz

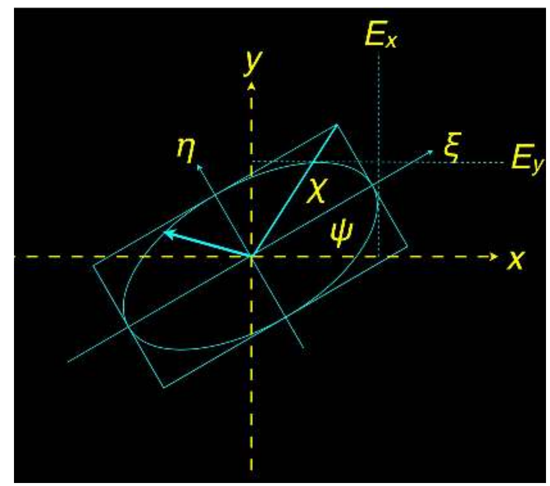
Polarimetry - What is it?

- Electromagnetic waves can be polarised and the polarisation can be defined as the behaviour of the electric field with time.
- Natural radiation tends to be randomly polarised, such that the orientation of the electric field is completely random with respect to time.
- Astrophysical processes like synchrotron radiation can emit partially polarised emission, but never 100% polarised.
- Interstellar matter can polarise random background emission or de-polarise polarised background emission.
- Waves can be linearly and/or circularly polarised

Polarimetry - What is it?



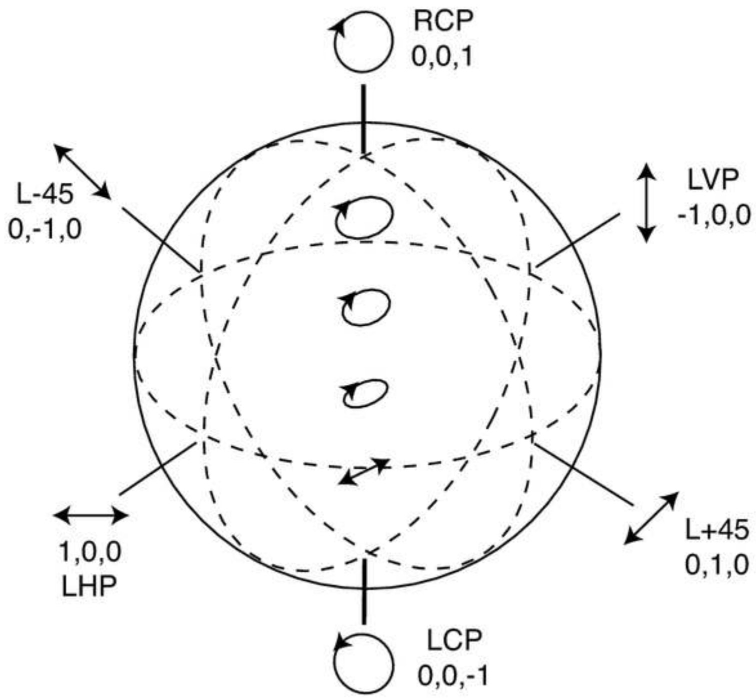




χ is the ellipticity; ψ is the position angle

Credit: D. McConnell

Polarimetry - What is it?



- Poles represent circular polarisation
- Equator represents linear polarisation
- Longitude represents tilt angle
- Latitude represents axial ratio

Poincaré Sphere

Polarimetry - What is it?

- Poles represent circular polarisation
- Equator represents linear polarisation
- Longitude represents tilt angle
- Latitude represents axial ratio

Poincaré Sphere

Polarimetry - What is it?

For imaging, convenient to have parameters with units of power rather than amplitudes, angles and ratios.

Stokes Parameters

$$I = E_X^2 + E_Y^2$$

$$Q = E_X^2 - E_Y^2$$

$$U = 2E_XE_Y\cos(\delta_{XY})$$

$$V = 2E_XE_Y\sin(\delta_{XY})$$

$$I = E_R^2 + E_L^2$$

$$Q = 2E_RE_L\cos(\delta_{RL})$$

$$U = 2E_RE_L\sin(\delta_{RL})$$

$$V = E_R^2 - E_L^2$$

Polarimetry - What is it?

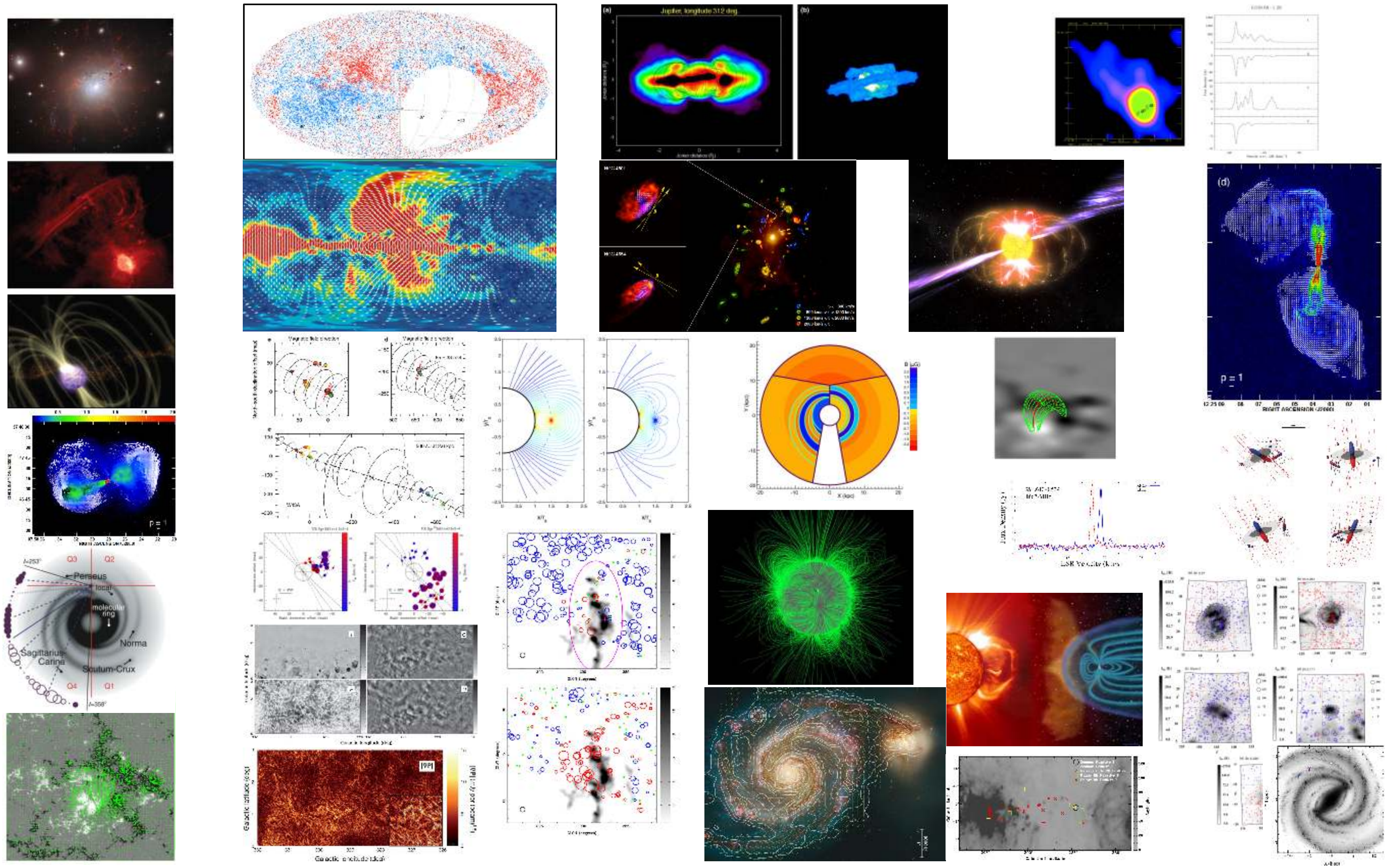
Stokes I - Total intensity

Stokes Q and U - Completely specify linear polarisation

Stokes V - Completely specifies circular polarisation

$$I^2 = Q^2 + U^2 + V^2$$

Why do Polarimetry?



Why do Polarimetry?

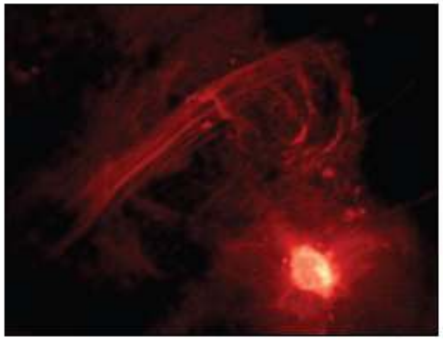
- The Universe is magnetised!
  - Polarimetric observations provide insight into magnetic fields.
  - Magnetism is a fundamental force.
  - The origin, structure and evolution of magnetic fields are key open questions in astrophysics.
- Within our galaxy
  - Interstellar medium (ISM), stars, pulsars, HII regions, masers.
- Within other galaxies
  - Radio galaxies, lobes, hot-spot interaction, radio lobes
- Cosmic Magnetism
  - The inter-galactic medium, the cosmic web

Why do Polarimetry?

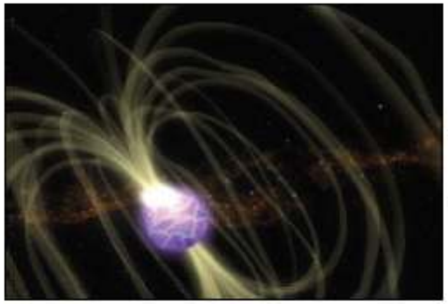
- High-z seed fields (Widrow 2002; Subramanian 2007) — $B \sim 10^{-30} - 10^{-20}$ G
- Intergalactic Medium — $B \sim$ 1-10 nG ?
- Intracluster Medium — $B \sim$ 0.1-1 μG
- Interstellar medium — $B \sim$ 1 μG – 10 mG
- Galactic Centre (Crocker et al. 2010; Ferrière 2010) — $B \sim$ 50 μG – 1 mG
- Main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

** Fridge Magnet ~50 G

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



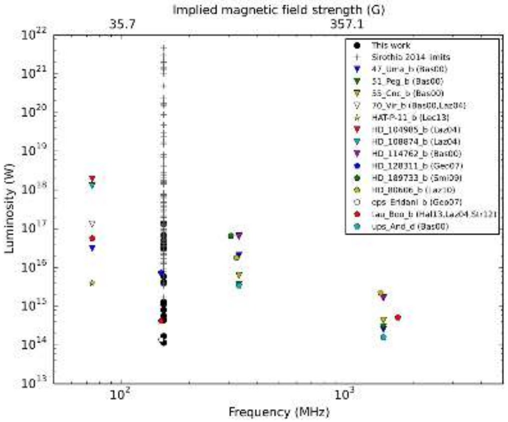
Galactic Centre (Yusef-Zadeh et al. 1984)



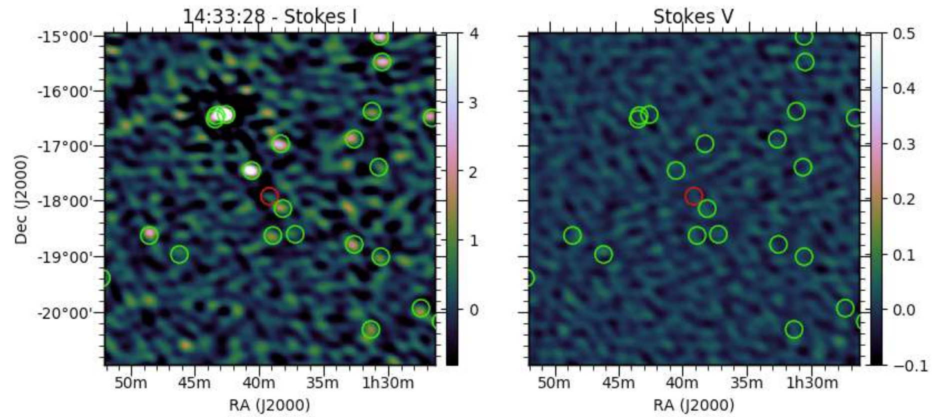
SGR 1806-20 giant flare (NASA)

Credit: B.M. Gaensler

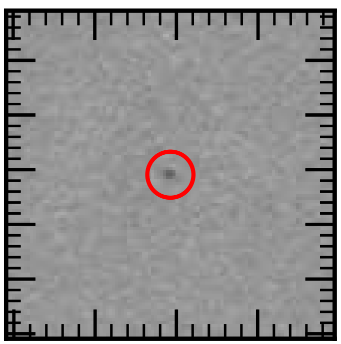
Circular polarisation



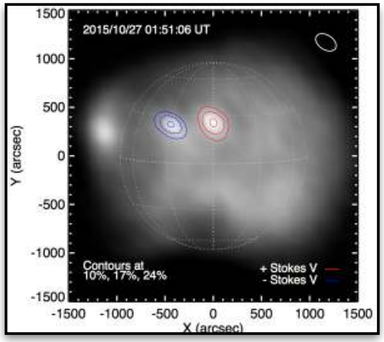
Planets & Exoplanets
Seaquist (1969)
Murphy et al. (2015)
Lenc et al. (2017)



Flare stars
Lynch et al. (2017)
Lenc et al. (2017)

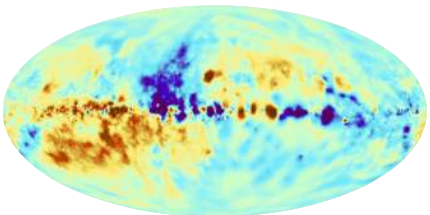


Pulsars
You & Han (2006)
Noutsos et al. (2015)
Johnston & Kerr (2017)
Lenc et al. (2017, 2018)

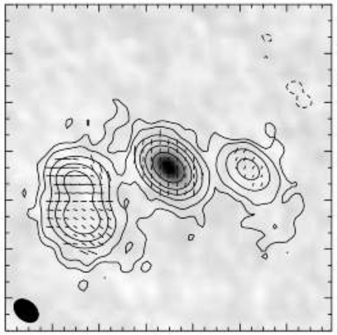


Solar
Lenc et al. (2017)
McCauley et al. (in prep)

Weakly polarised

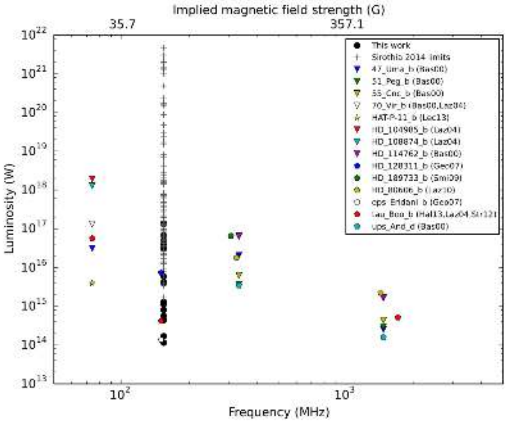


Galactic?
Enßlin et al. (2017)



AGN
Seaquist (1969), Komesaroff et al. (1984)
Rayner et al. (2000), Macquart et al. (2000)
Aller & Aller (2012), Myserlis et al. (2017), etc.

Circular polarisation



Planets & Exoplanets
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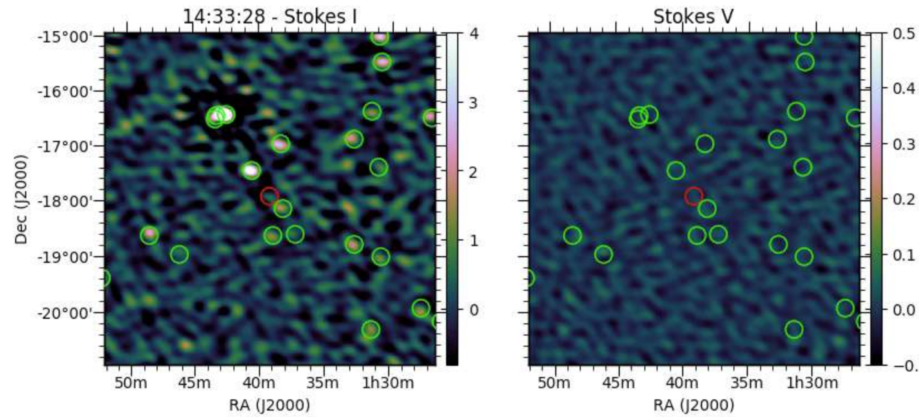
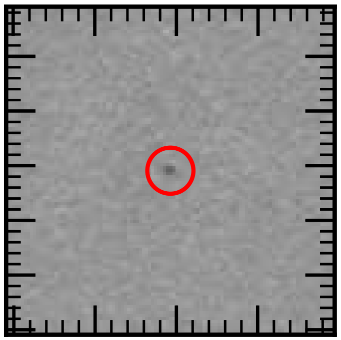
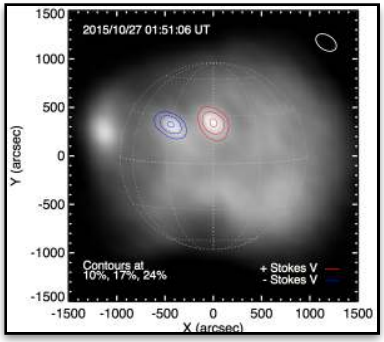
Lenc et al. (2017)



Flare stars
Lynch et al. (2017)
Lenc et al. (2017)



Pulsars
You & Han (2006)
Noutsos et al. (2015)
Johnston & Kerr (2017)
Lenc et al. (2017, 2018)



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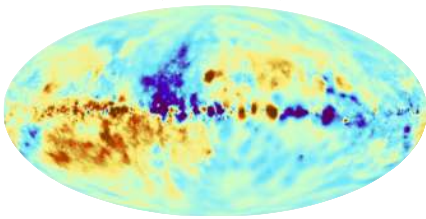
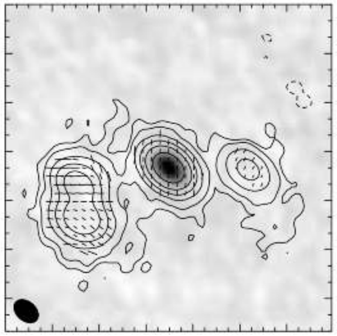


Galactic?
Enßlin et al. (2017)



AGN
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How do we measure with polarisation? Faraday rotation

$$\beta = RM\,\lambda^2$$

$$RM = \int n_e \mathbf{B}\, dl$$

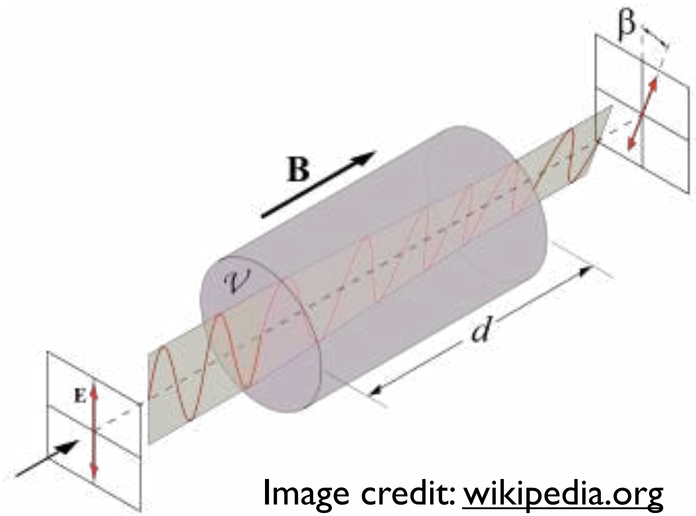
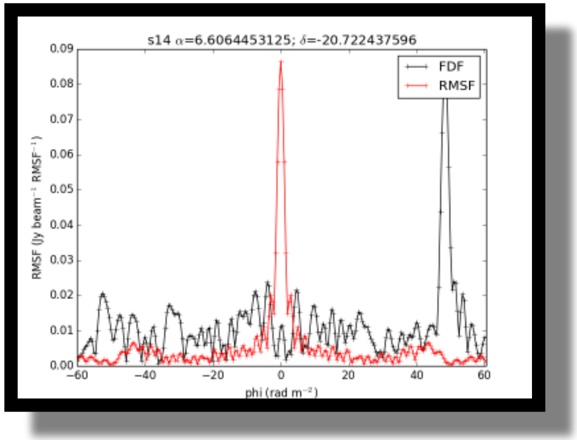


Image credit: wikipedia.org



Rotation Measure (RM) Synthesis

Long wavelength observations exhibit higher rotation!

NB: MWA range is ~1-4 metres

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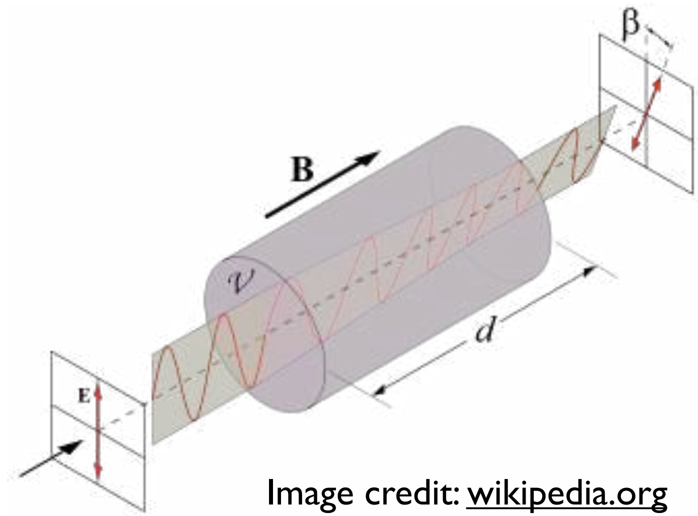
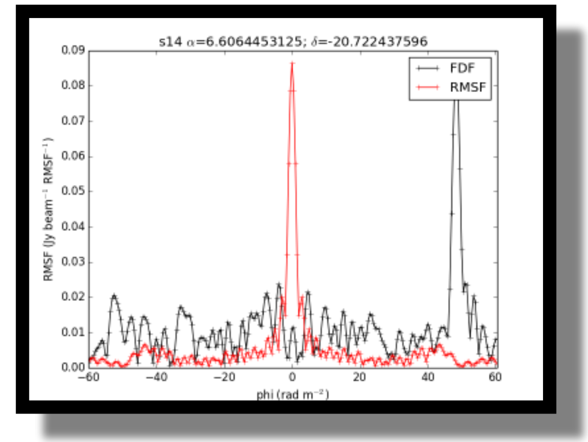


Image credit: wikipedia.org



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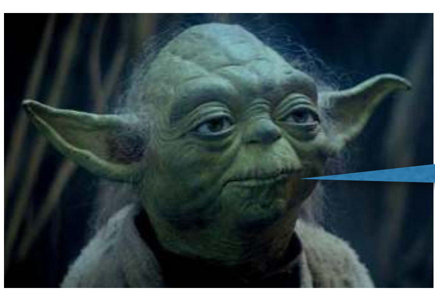
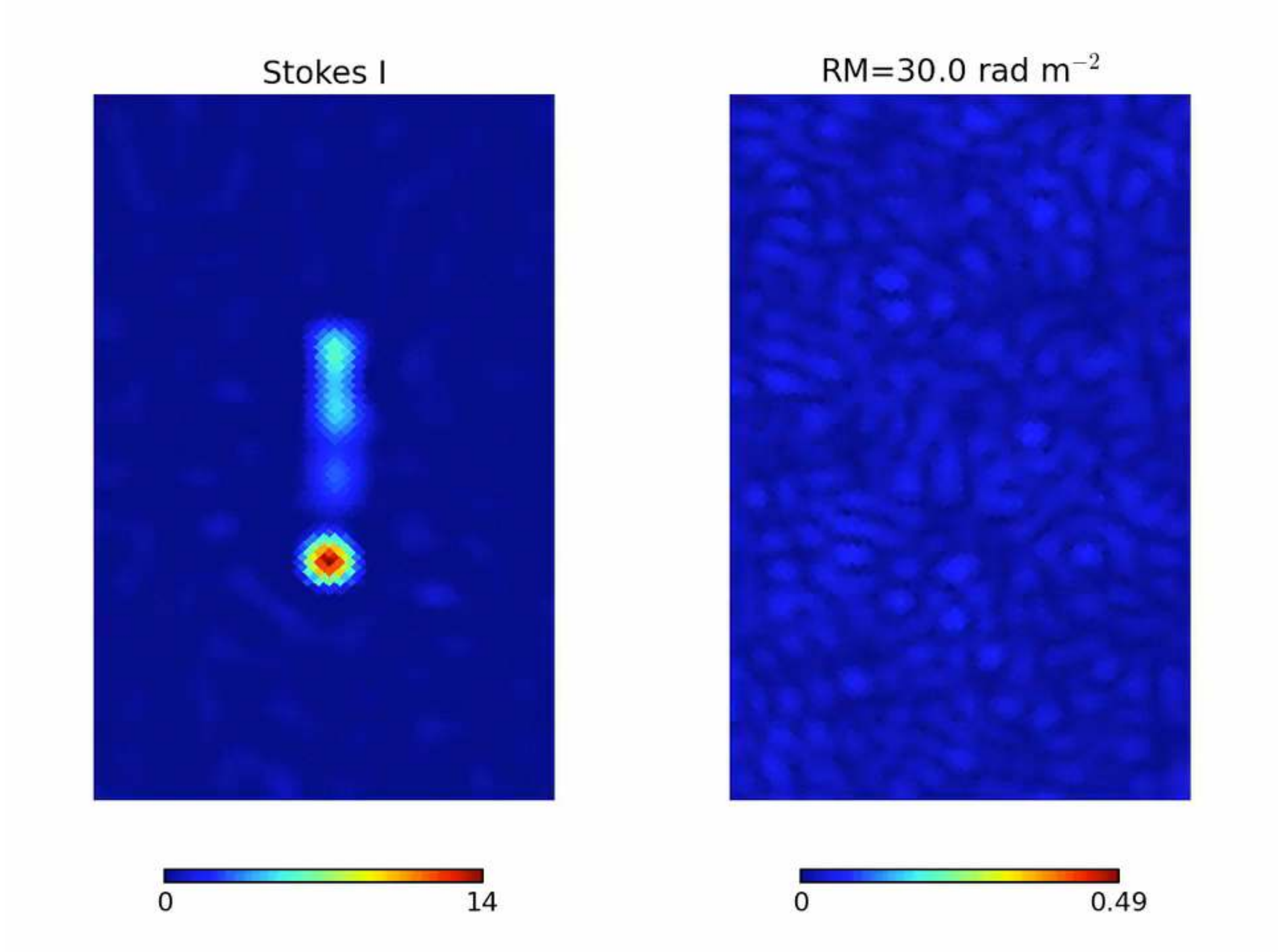
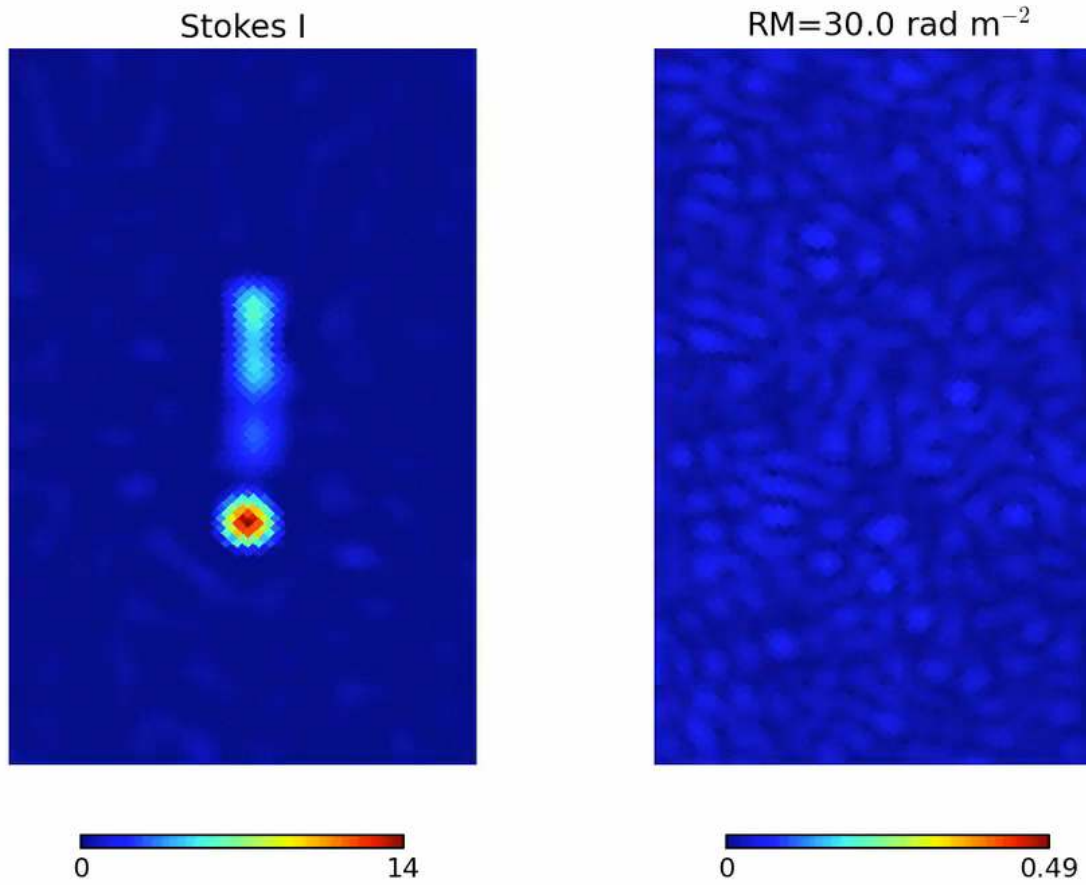


Average the channels, you must not. Yes, hmmm.

Faraday rotation (MWA)



Faraday rotation (MWA)



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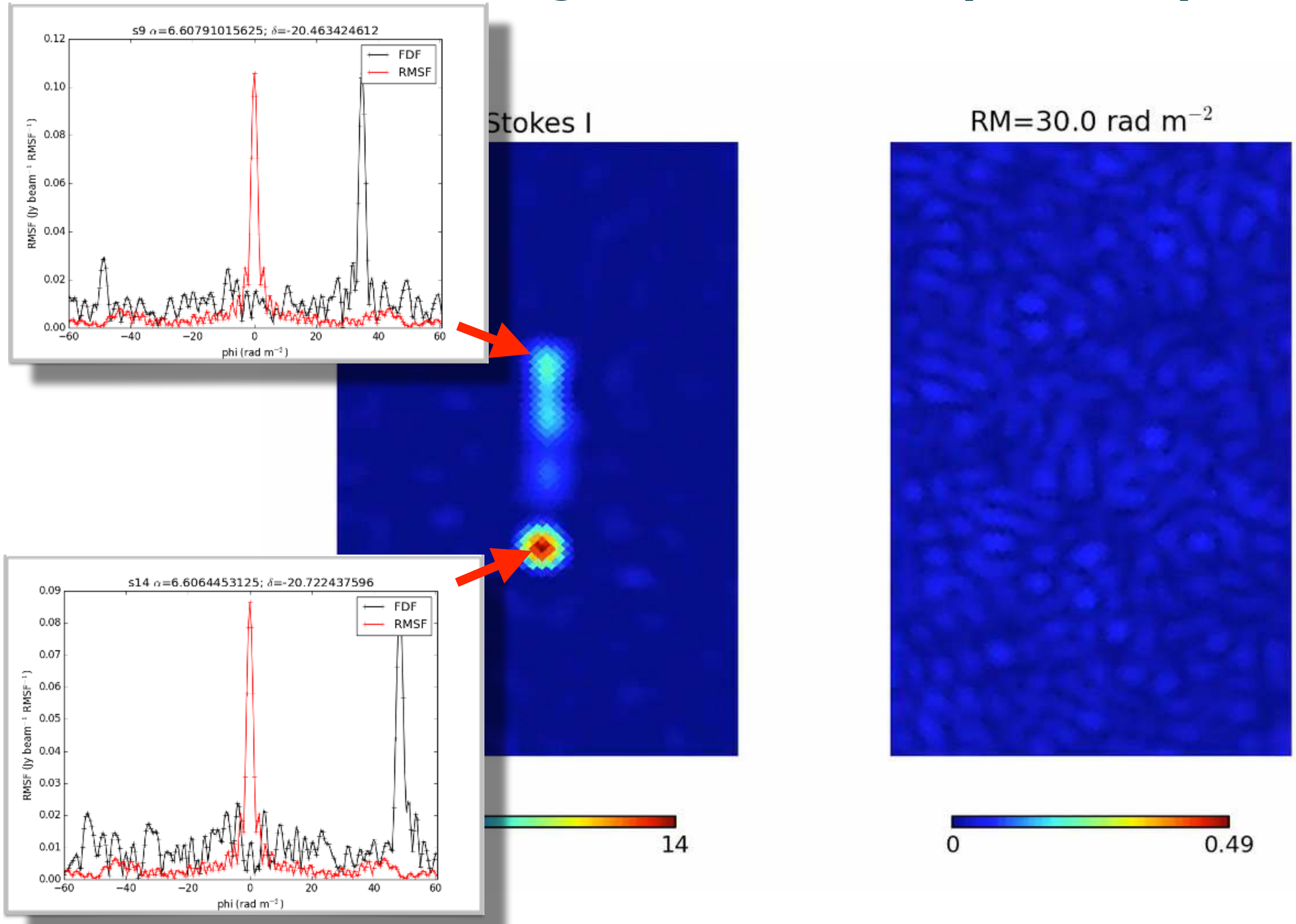
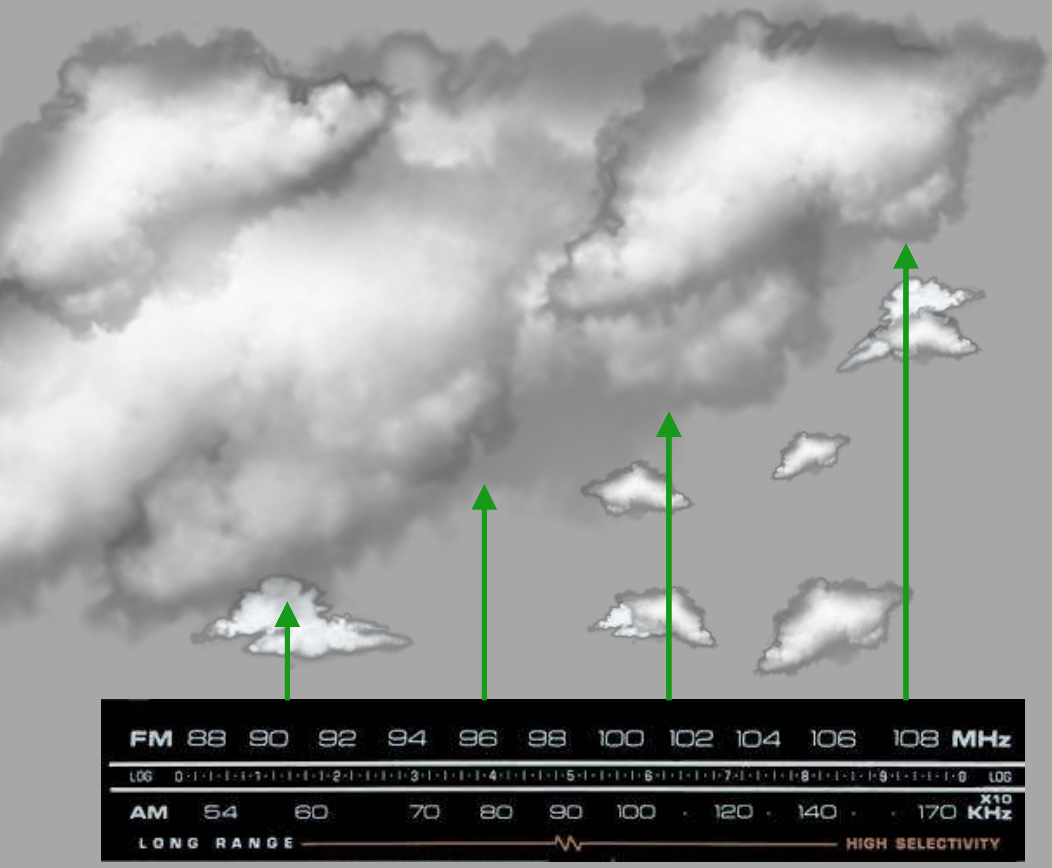
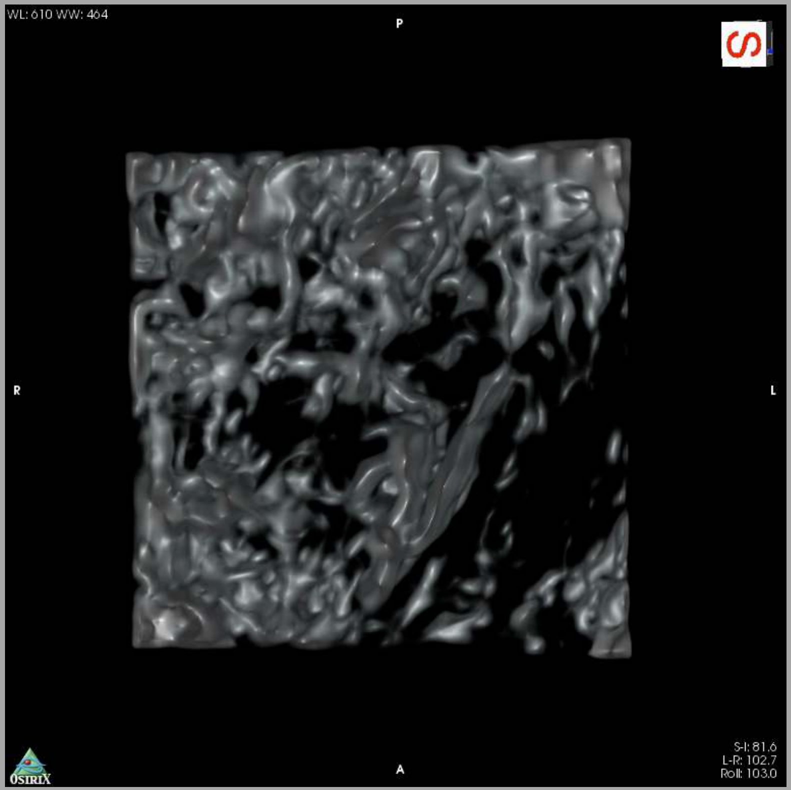


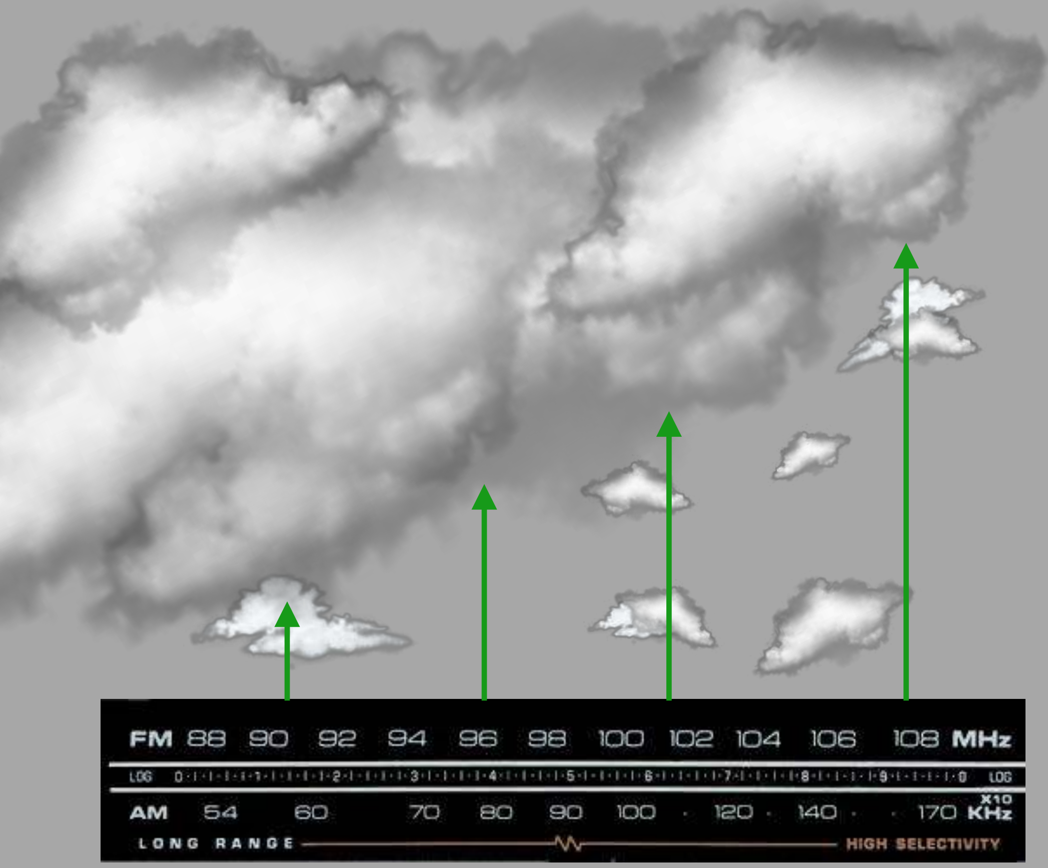
How do we measure with polarisation? Faraday tomography

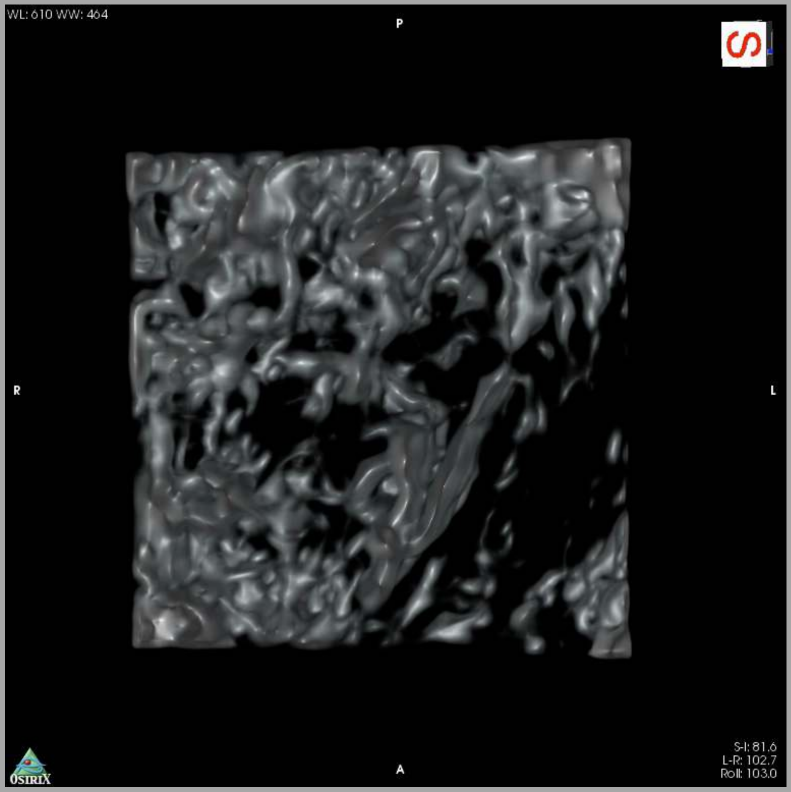




Lenc et al. (2016)

How do we measure with polarisation?
Faraday tomography



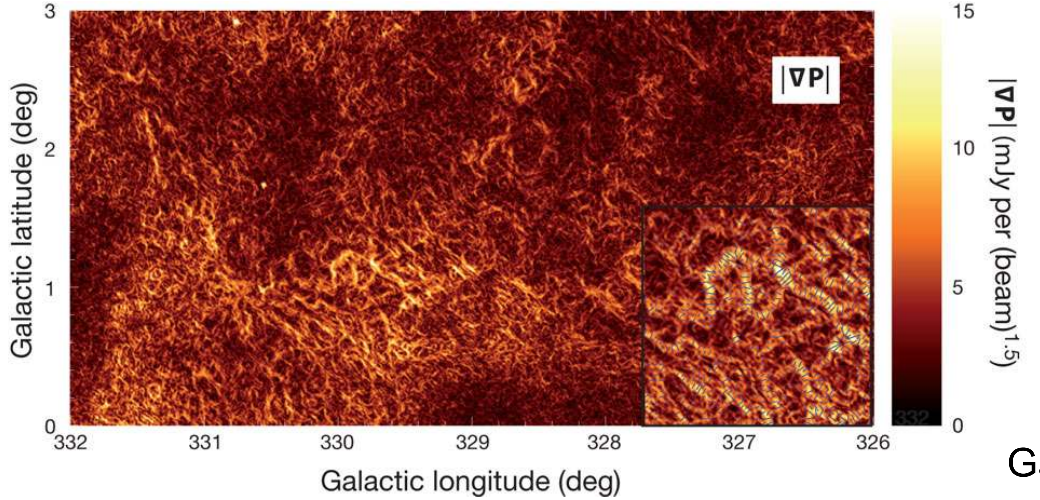


Lenc et al. (2016)

How do we measure with polarisation? Gradient of Stokes Q/U

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

Gradient of Stokes Q and U provides direct imaging of interstellar turbulence - changing of magnetic field orientation with gas motions



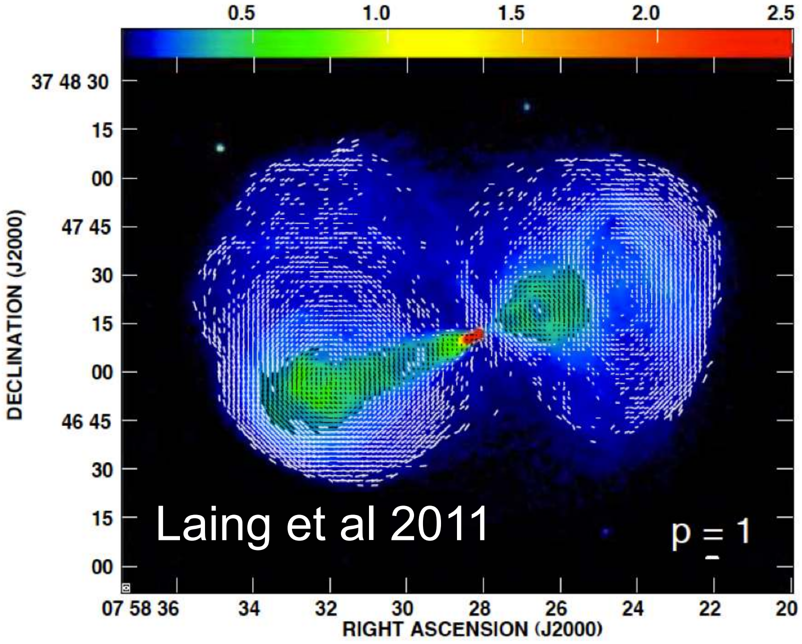
Gaensler et al. 2011

How do we measure with polarisation? Polarisation vectors

Total linearly polarised intensity is defined as: $P = \sqrt{U^2 + Q^2}$

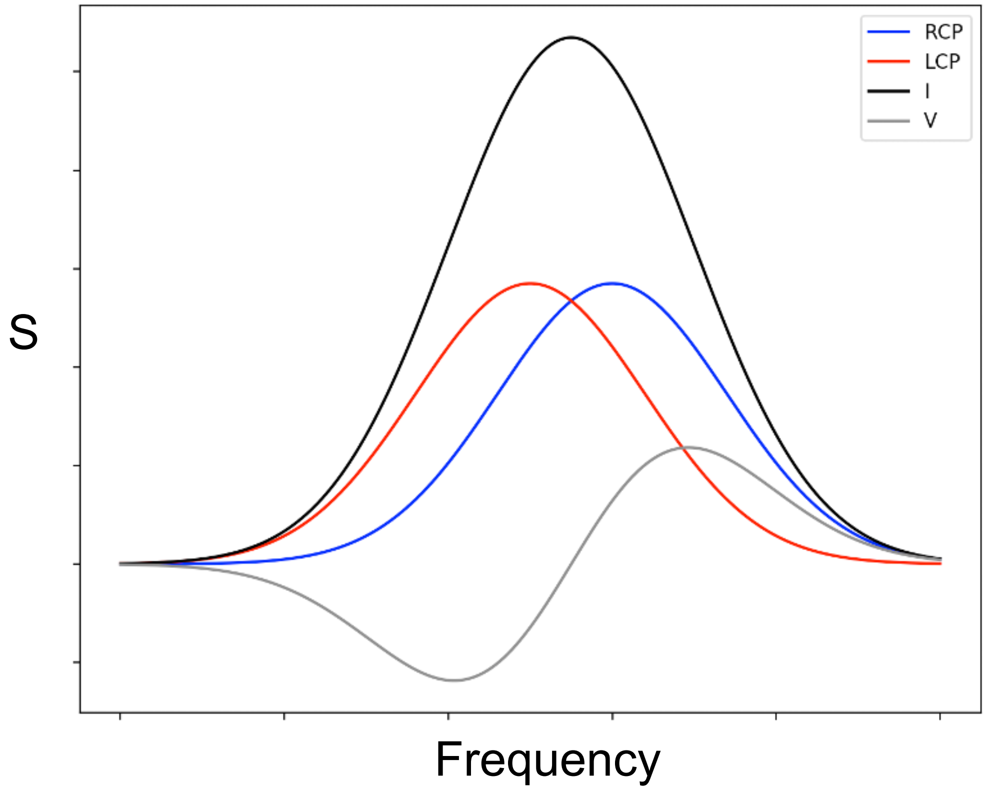
A linearly polarised source will have an intrinsic position angle on the sky that is given by:

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$



Together these provide field strength and direction in plane of sky

How do we measure with polarisation? Zeeman splitting



Measure in magnetic field strength through splitting of spectral line into several components in presence of magnetic field

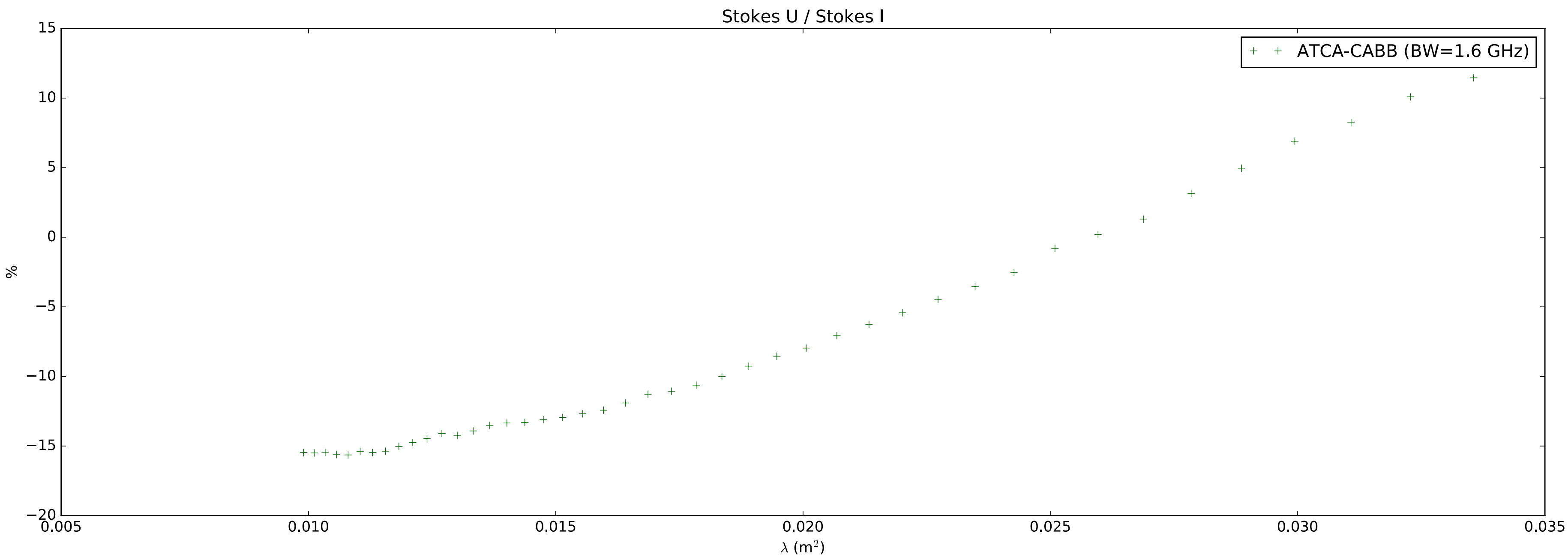
$V = RCP - LCP \propto B_{los}$

How do we measure with polarisation? Circular polarisation from synchrotron emission

Circular polarisation from synchrotron emission can provide a direct measurement of field strength and direction (effect is small and is less than 0.1% of the Stokes I component).

Things to worry about
Bandwidth depolarisation

Observations of PKS J0636-2041



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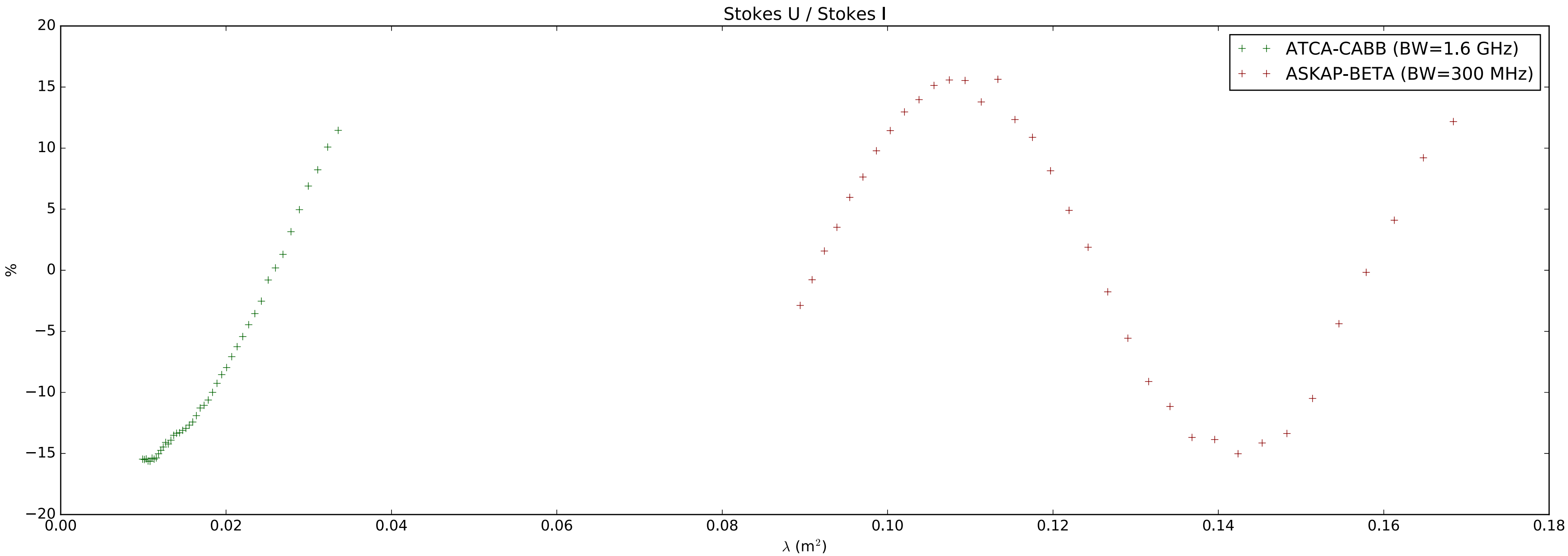

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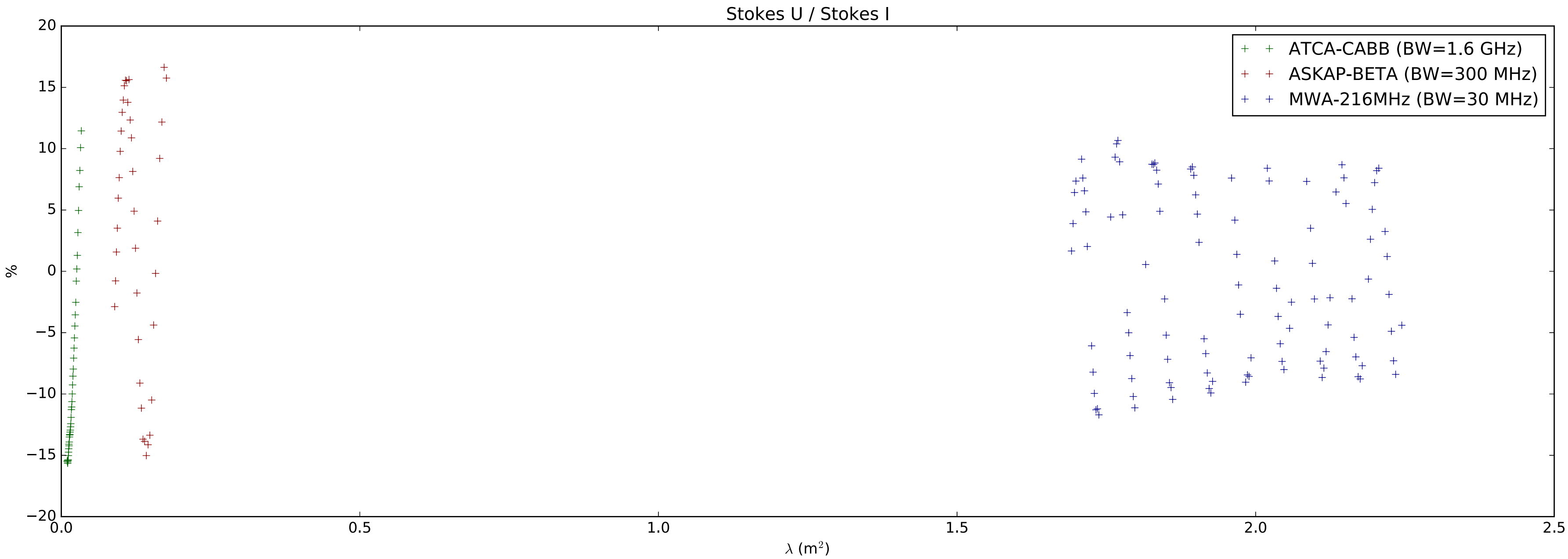

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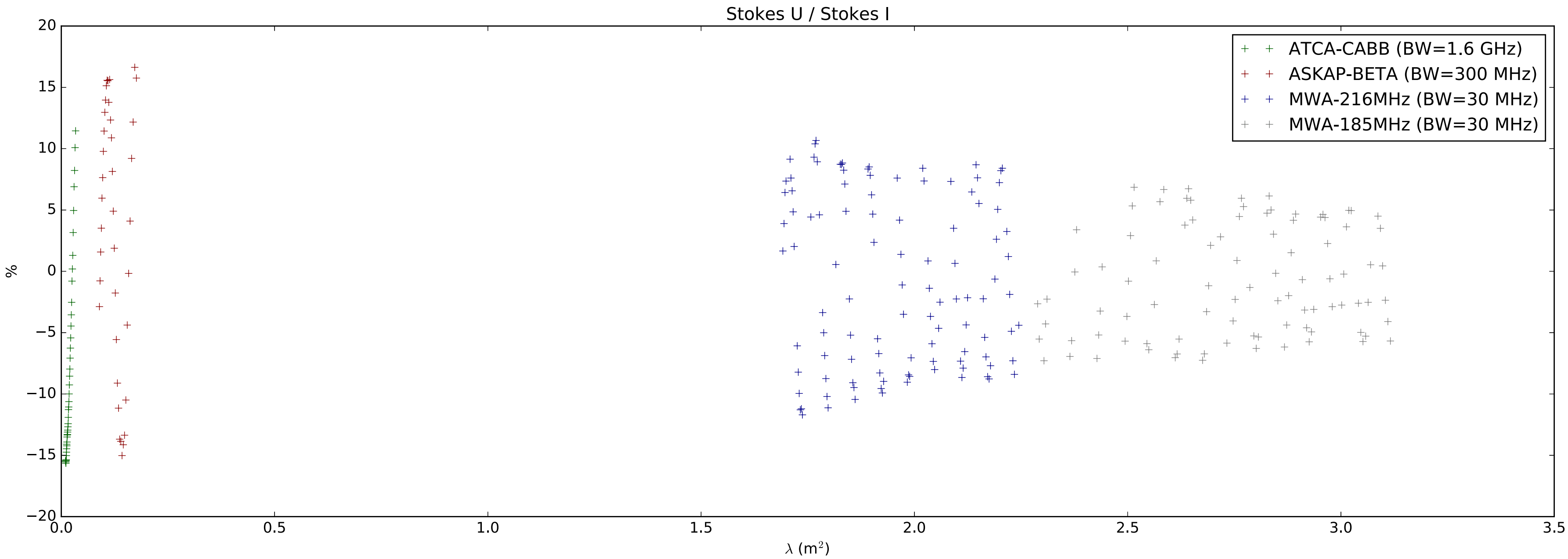

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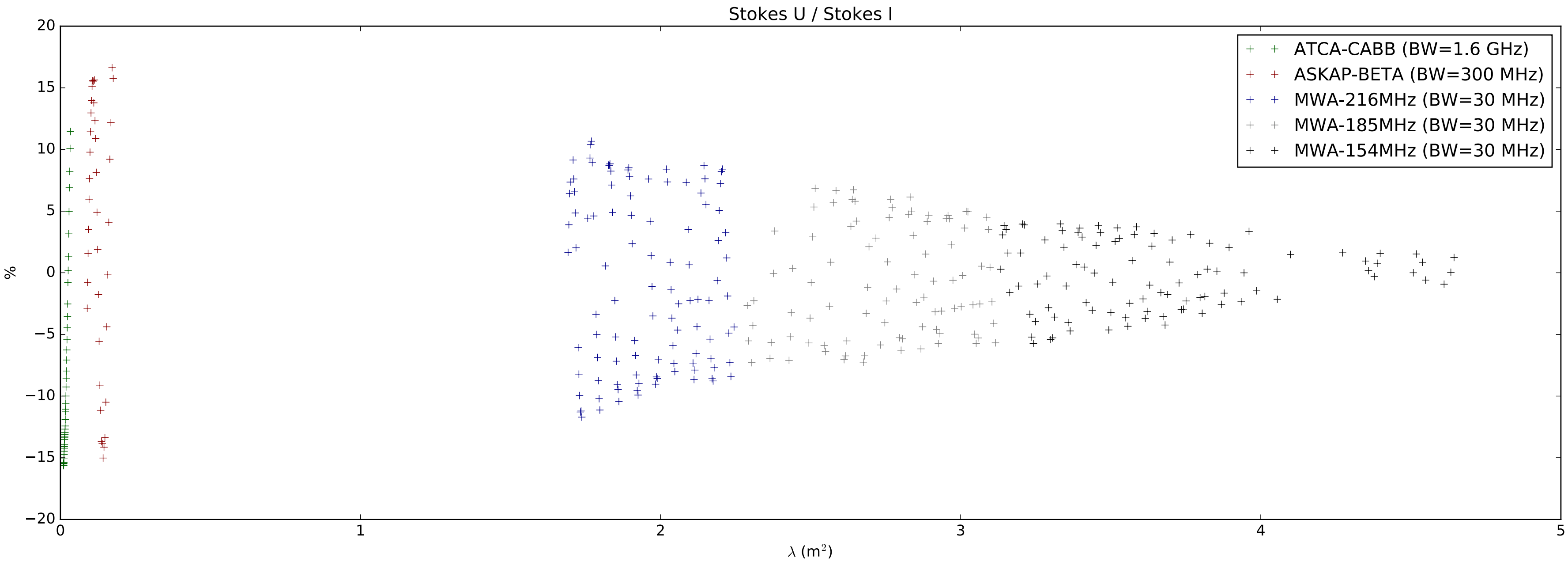

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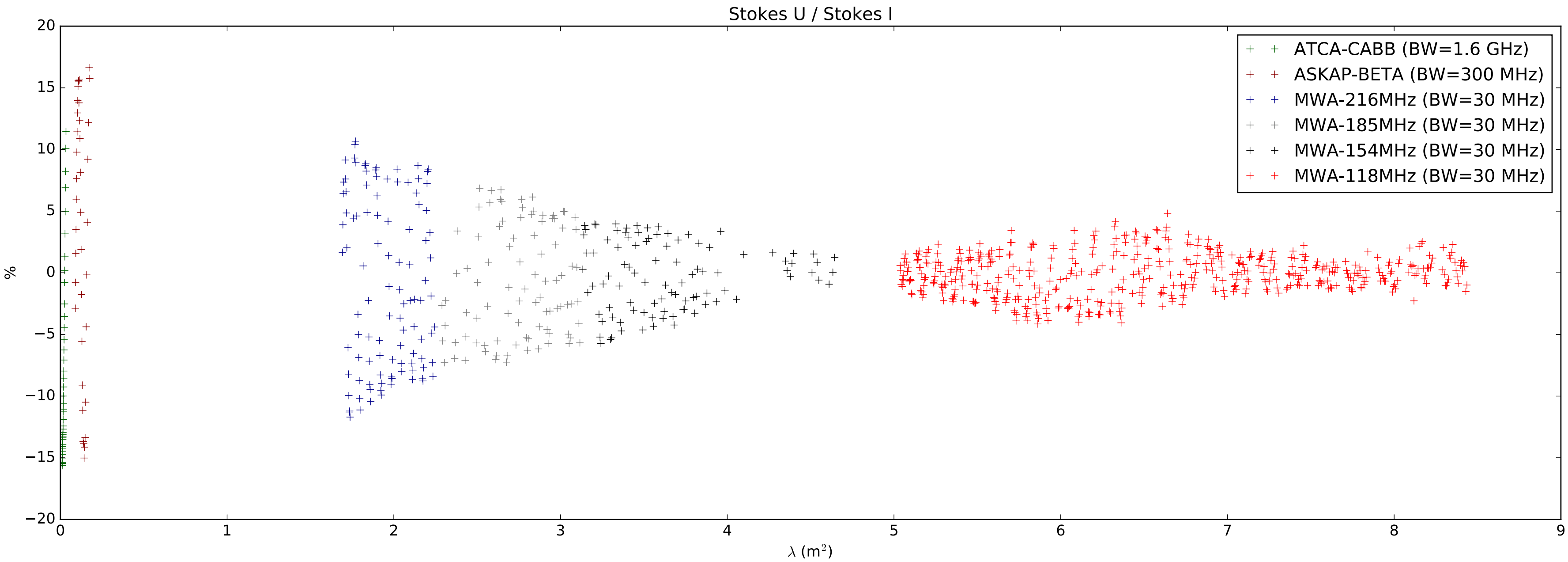

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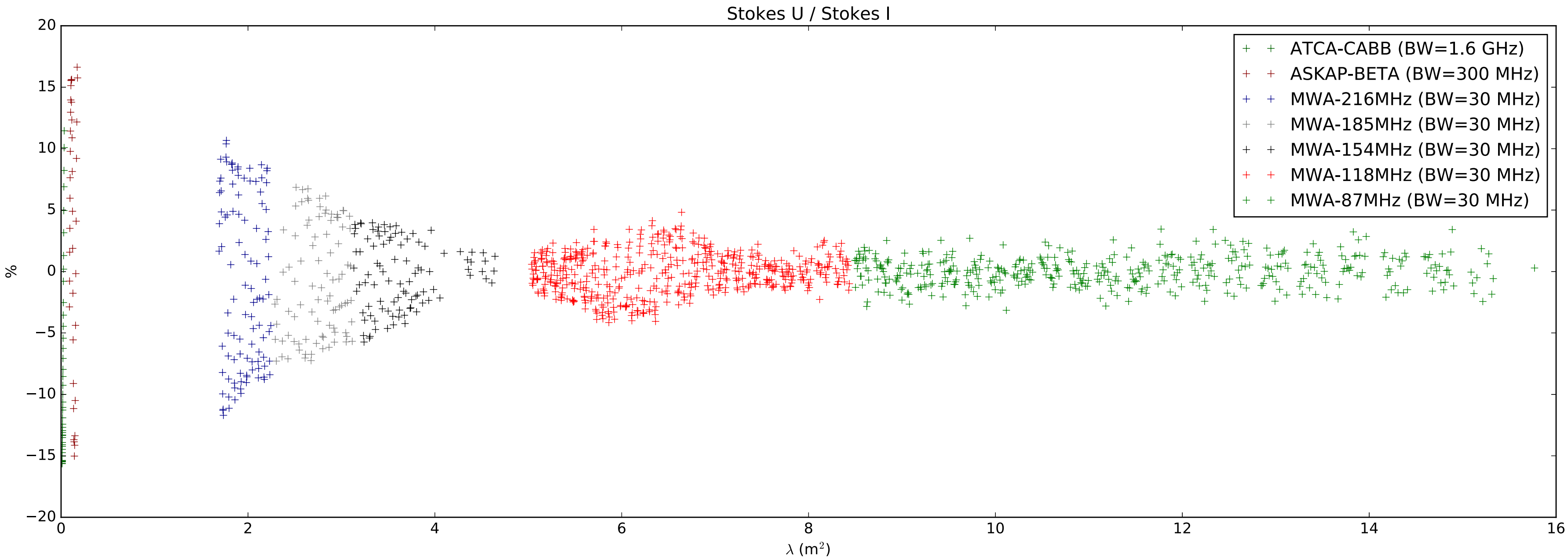
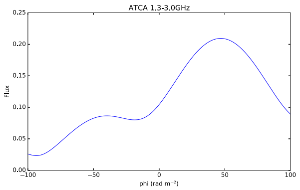
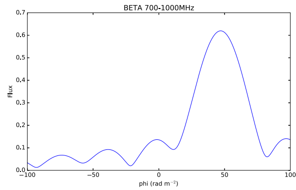


Things to worry about Bandwidth depolarisation





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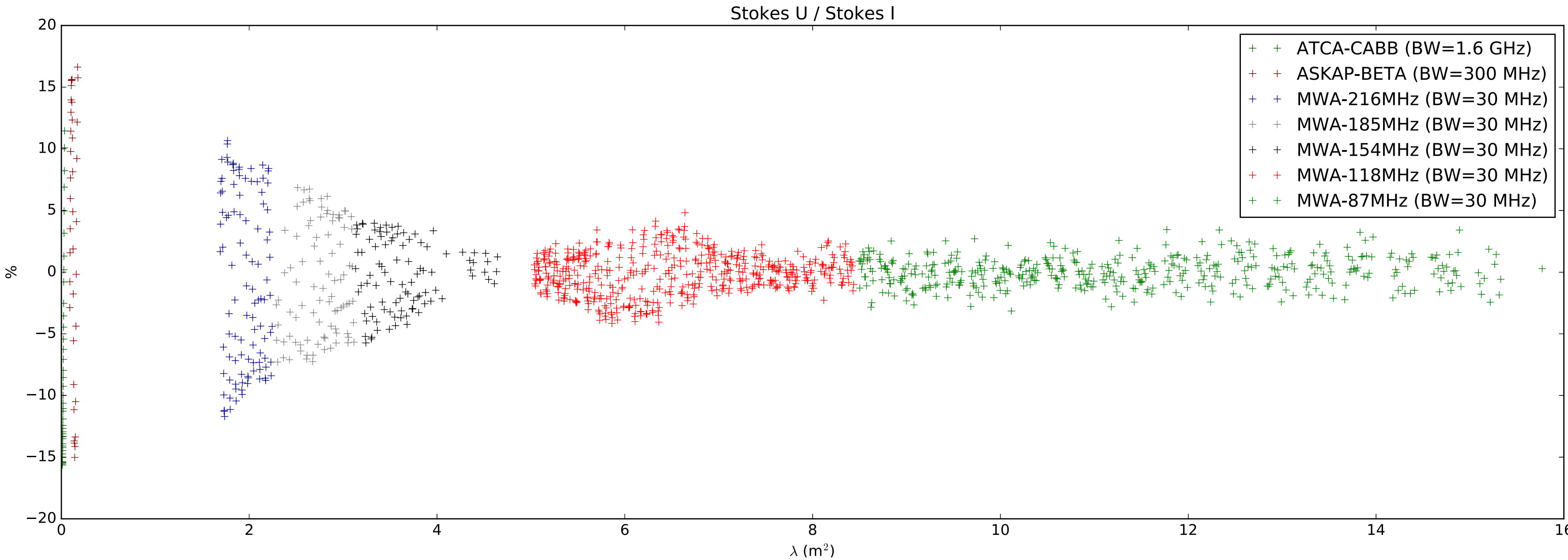
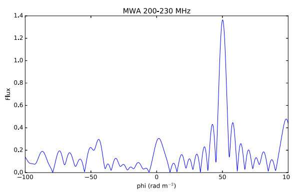
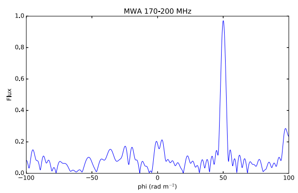
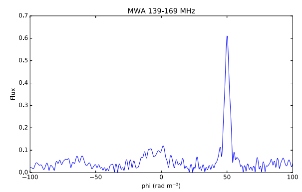
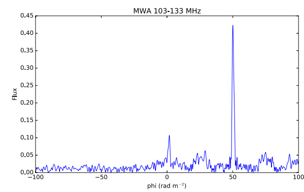
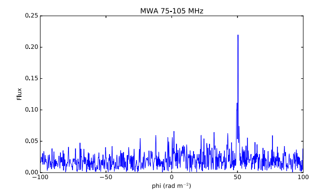






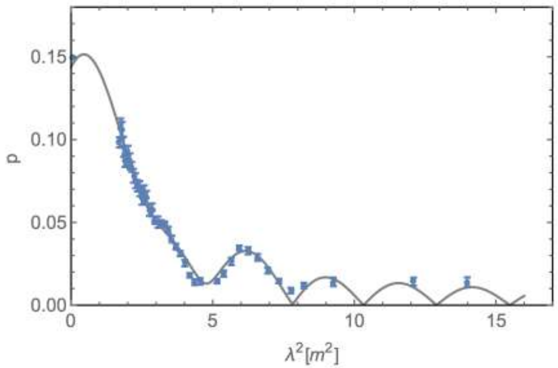


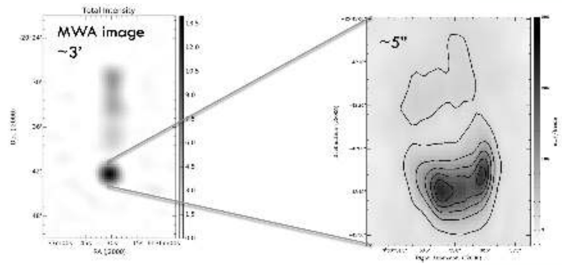




Faraday rotation - Broadband modelling

$$p_{01}\, e^{2i(\chi_{01}+\mathrm{RM}_1\lambda^2)}\,\frac{\sin \Delta\mathrm{RM}_1\lambda^2}{\Delta\mathrm{RM}_1\lambda^2} + p_{02}\, e^{2i(\chi_{02}+\mathrm{RM}_2\lambda^2)}\, e^{-2\sigma^2_{\mathrm{RM}_2}\lambda^4}$$





Observations of PKS J0636-2041

Source depolarisation
O'Sullivan et al. (2018)

Things to worry about - the ionosphere
Things that ionise the atmosphere

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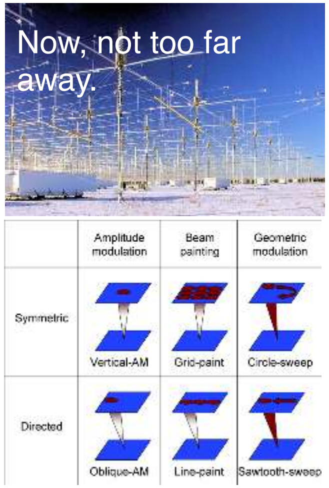
Things to worry about - the ionosphere
Things that ionise the atmosphere

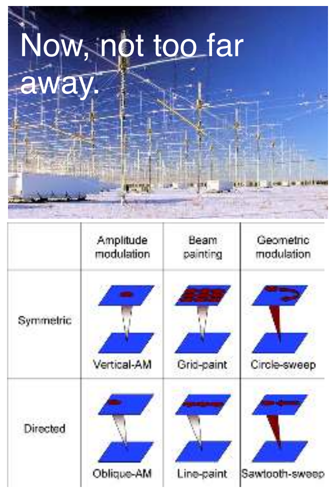


HAARP

Things to worry about - the ionosphere
Things that ionise the atmosphere

During the initial setting-up period for the polarization survey, a violent disturbance of the ionosphere occurred during the observations. This was produced by the explosion at 1210 U.T. (2210 E.A.S.T.) on November 1, 1962, of a 1 megaton bomb 10 km above Johnston Island.

- Mathewson & Milne



HAARP

Things to worry about - the ionosphere
Things that ionise the atmosphere

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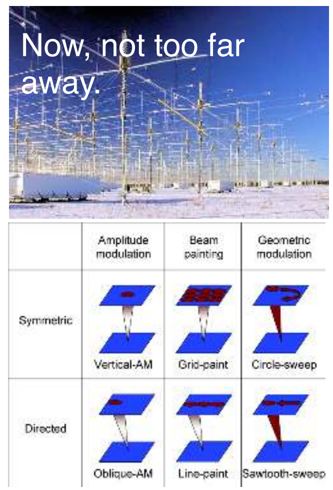
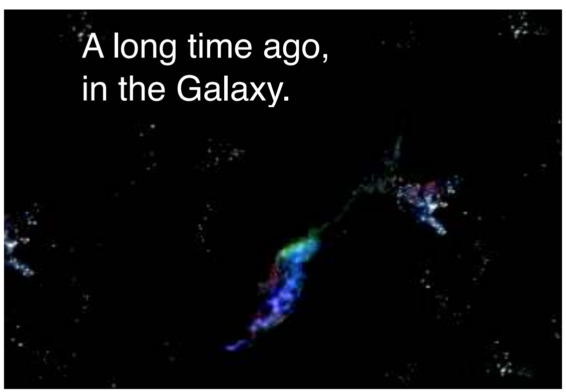


HAARP



Things to worry about - the ionosphere
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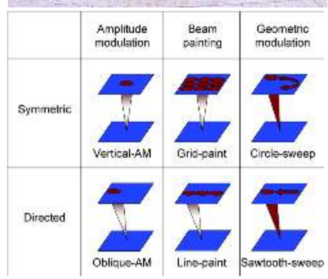
- Mathewson & Milne

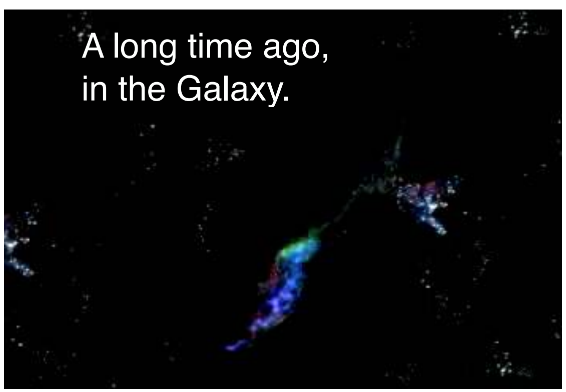
Not too long ago,
nearby.

Now, not too far
away.



HAARP

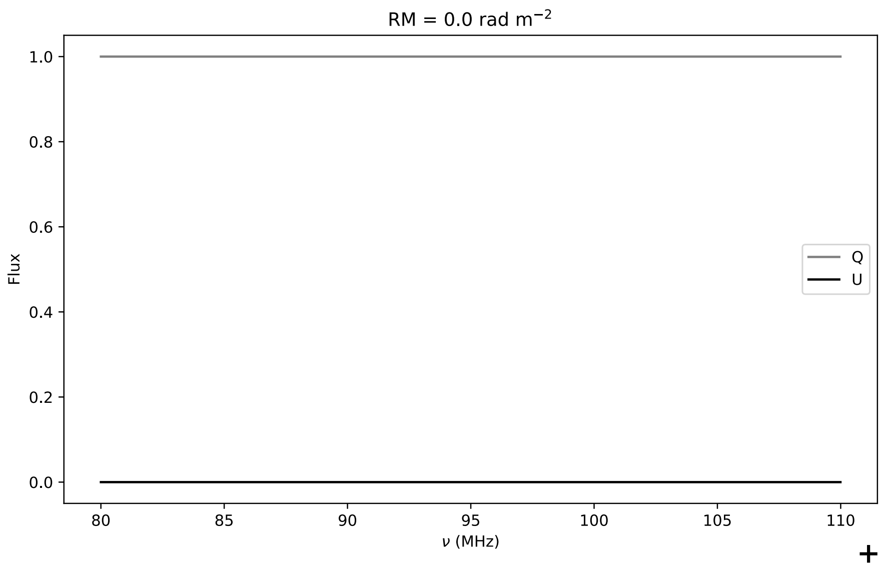
A while ago,
too close for comfort.

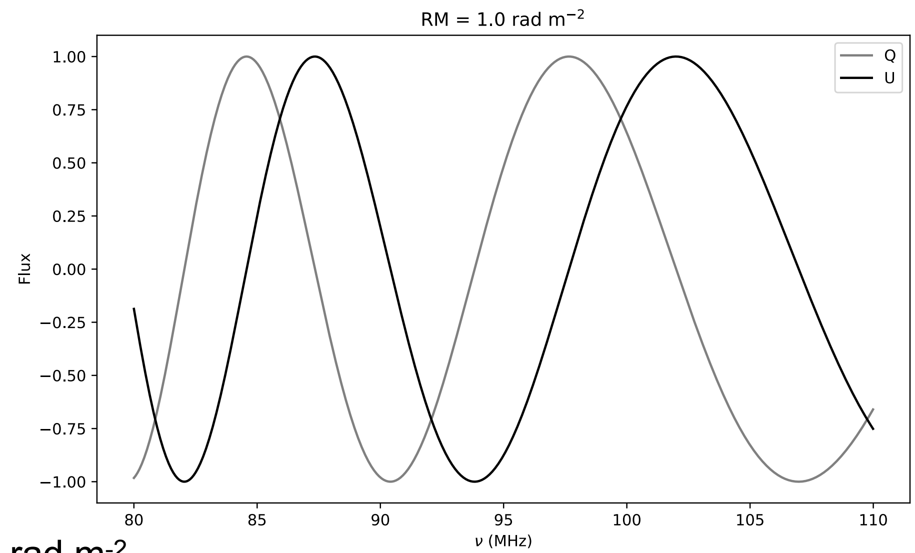


A long time ago,
in the Galaxy.

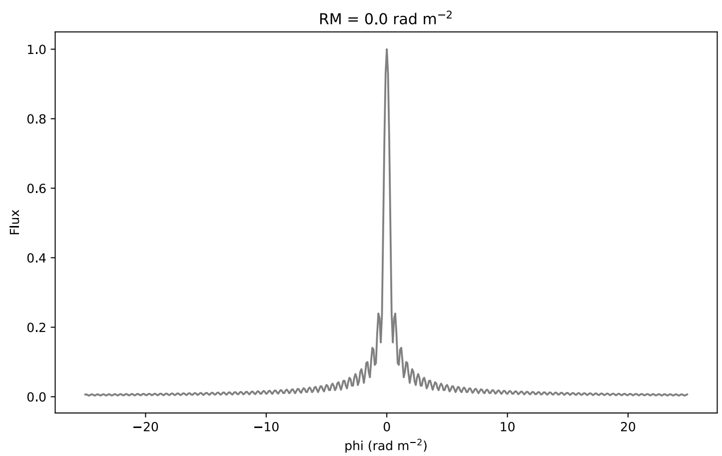
A long time ago,
in a galaxy far, far away.

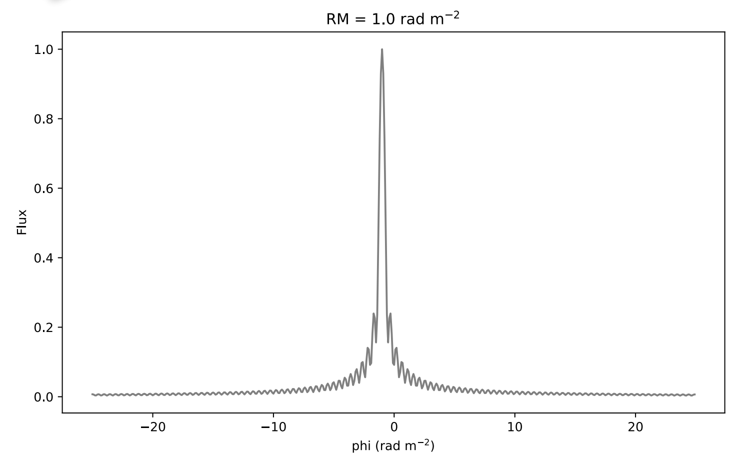
Effect of ionospheric Faraday rotation



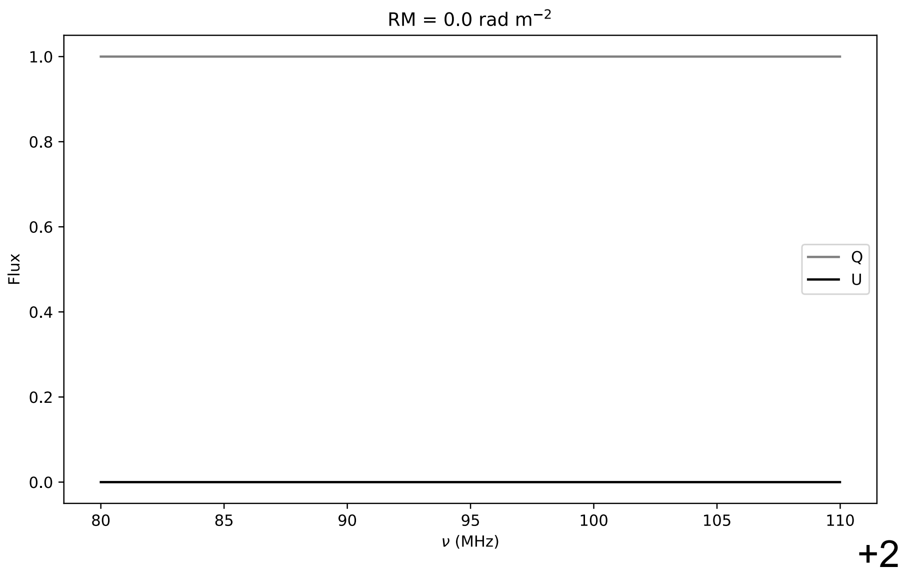


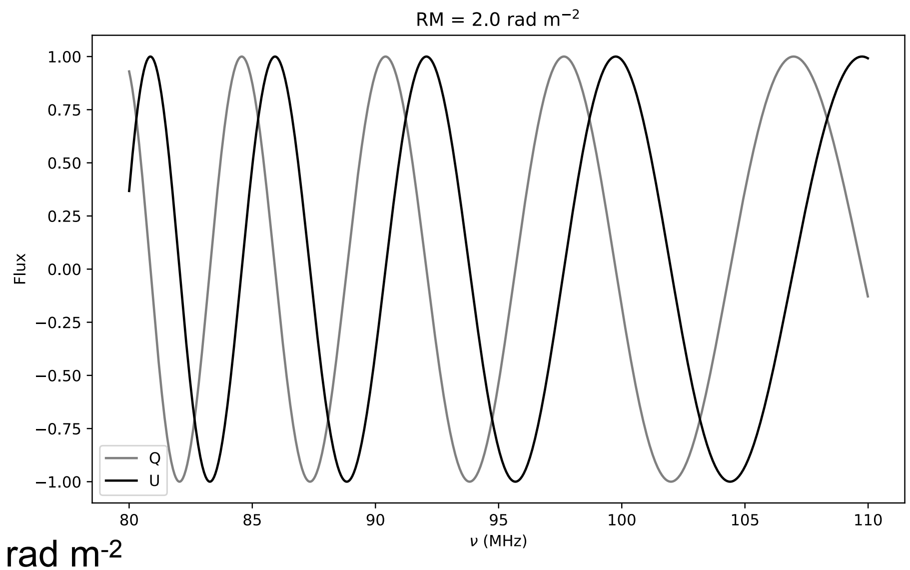
+1.0 rad m^{-2}



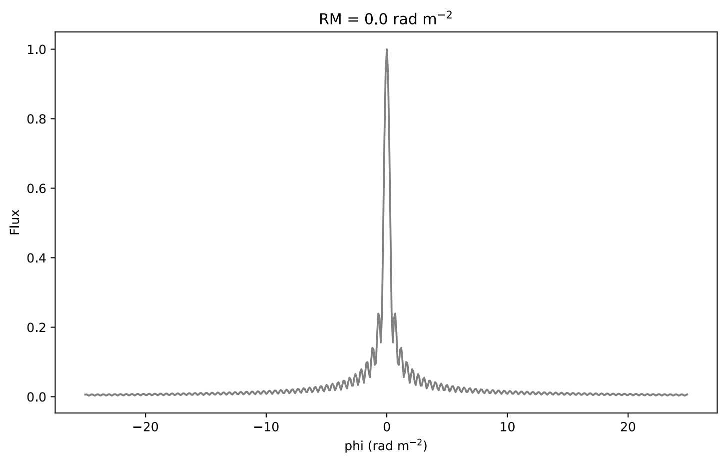


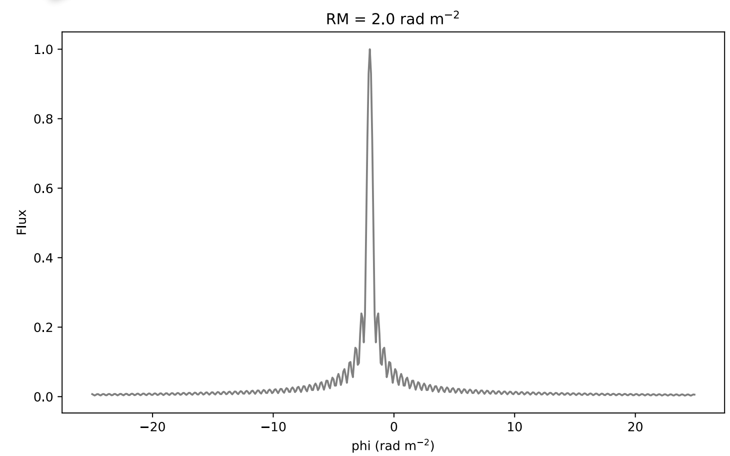
Effect of ionospheric Faraday rotation



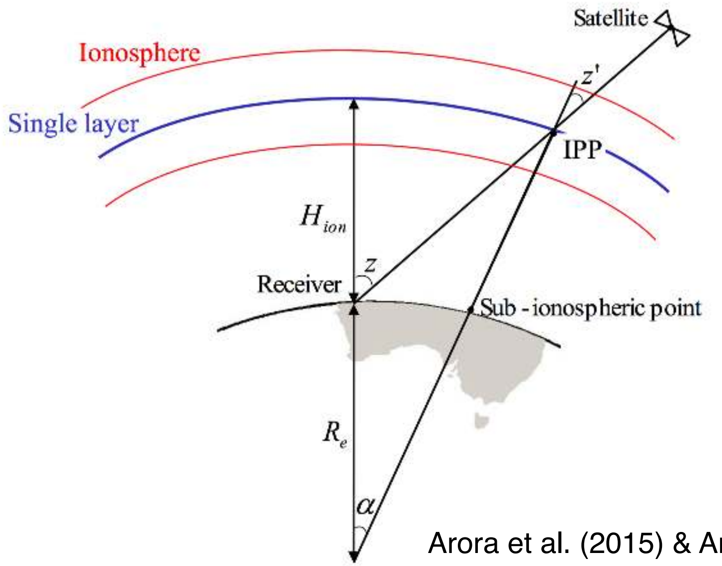


+2.0 rad m^{-2}





Correcting for the ionosphere

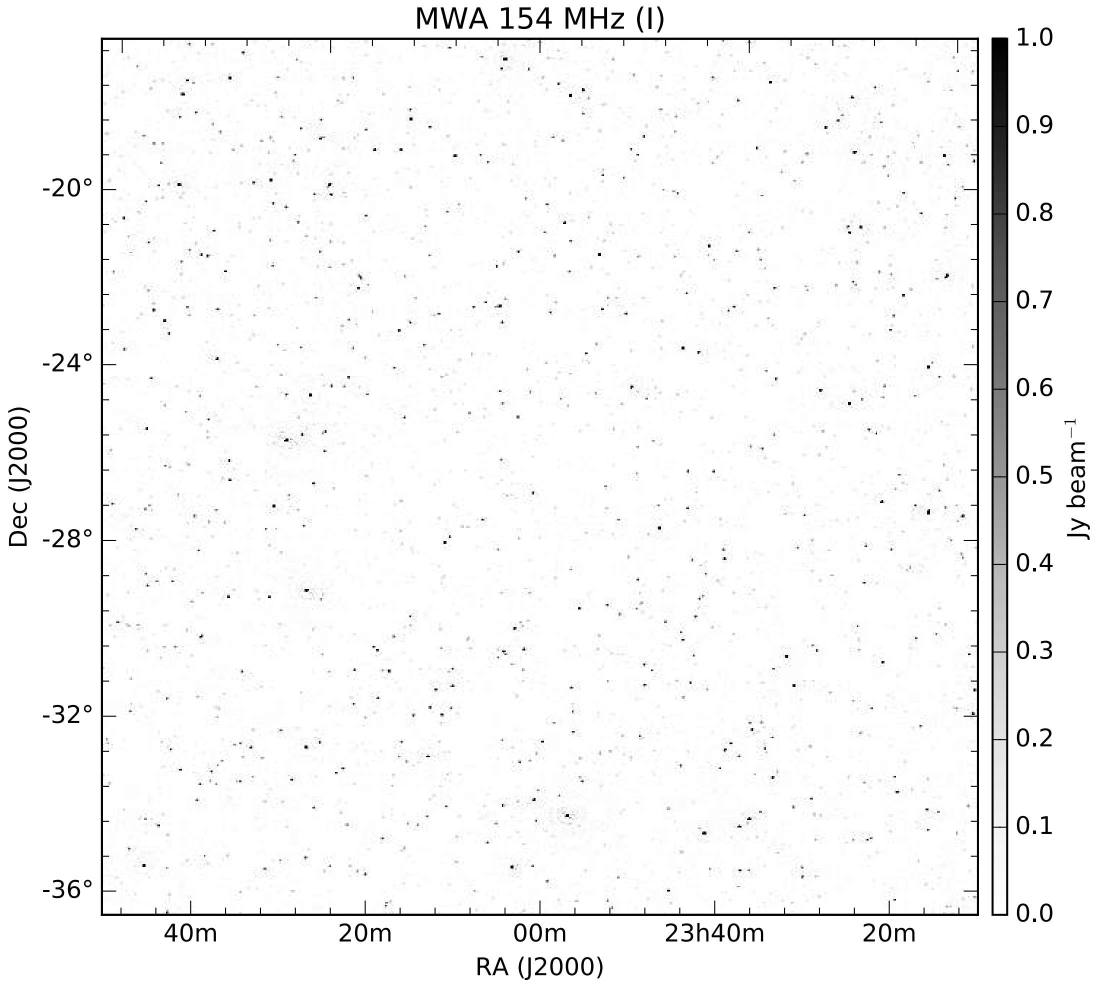


Arora et al. (2015) & Arora et al. (2016)

Tools of the trade:
- ionFR
- RMextract
- ALBUS

- Accurate to line of sight to satellite.
- Generally simplistic models (but improving).
- Many receivers and satellites required to improve model.
- Data is coarse in time (2 h) and spatially (2.5-5 deg).
- Data not available in real-time.

Calibrating for ionosphere against polarised point sources?



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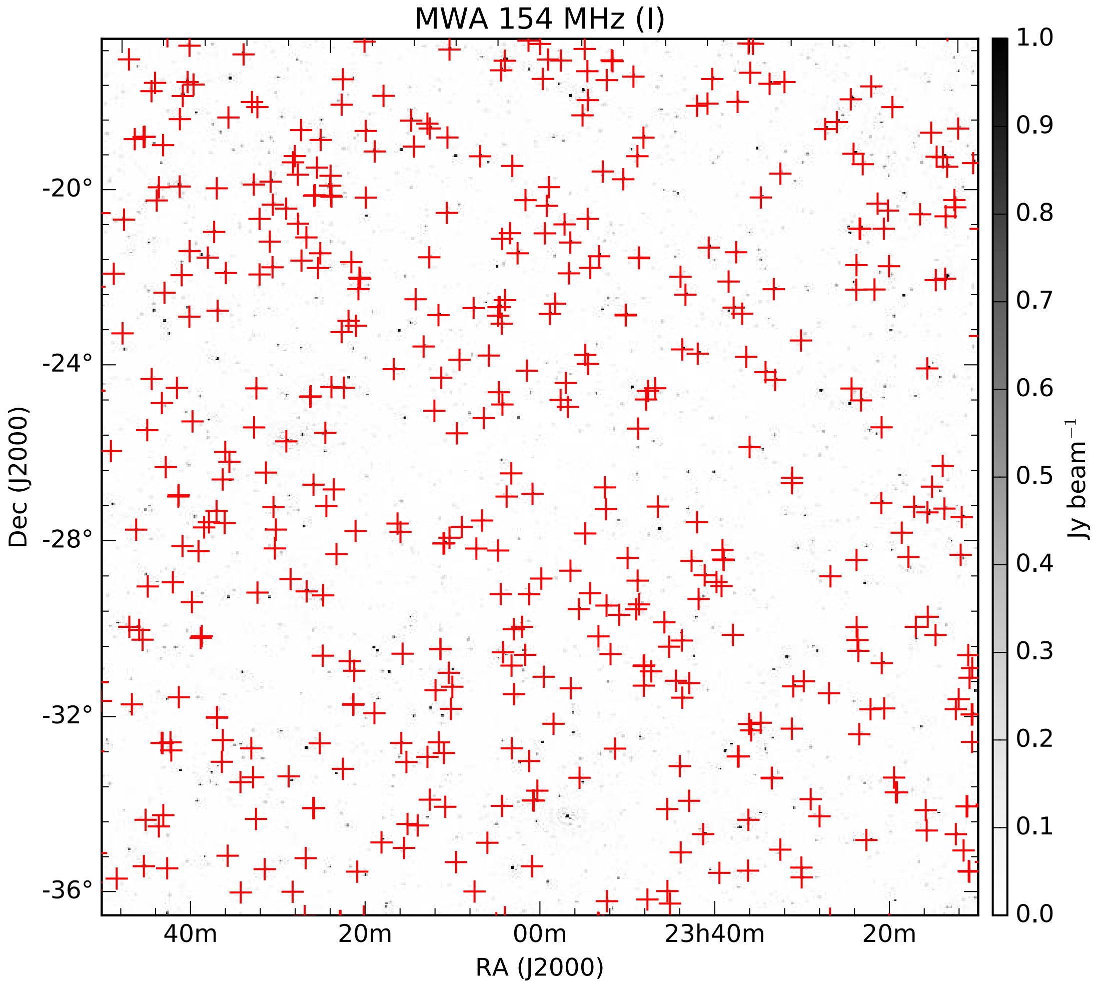

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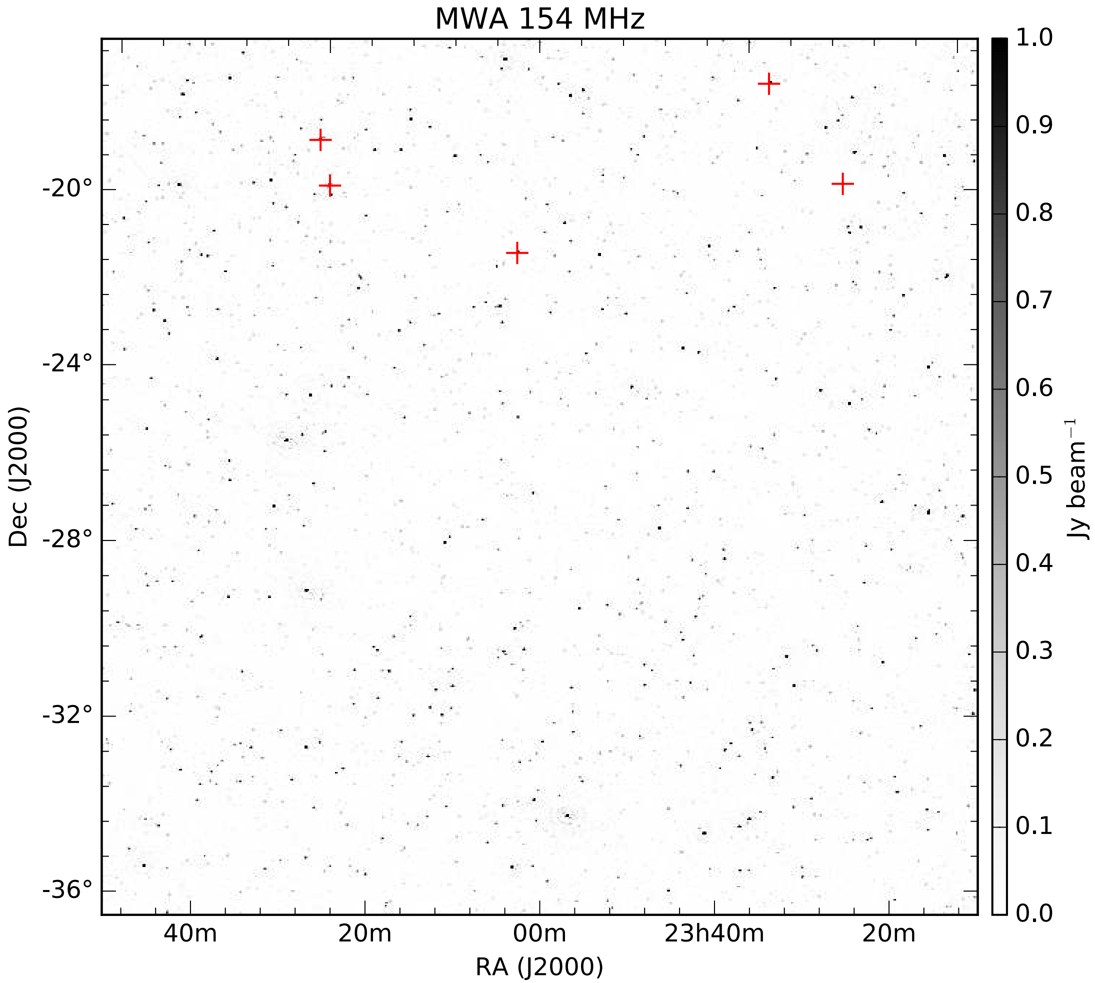
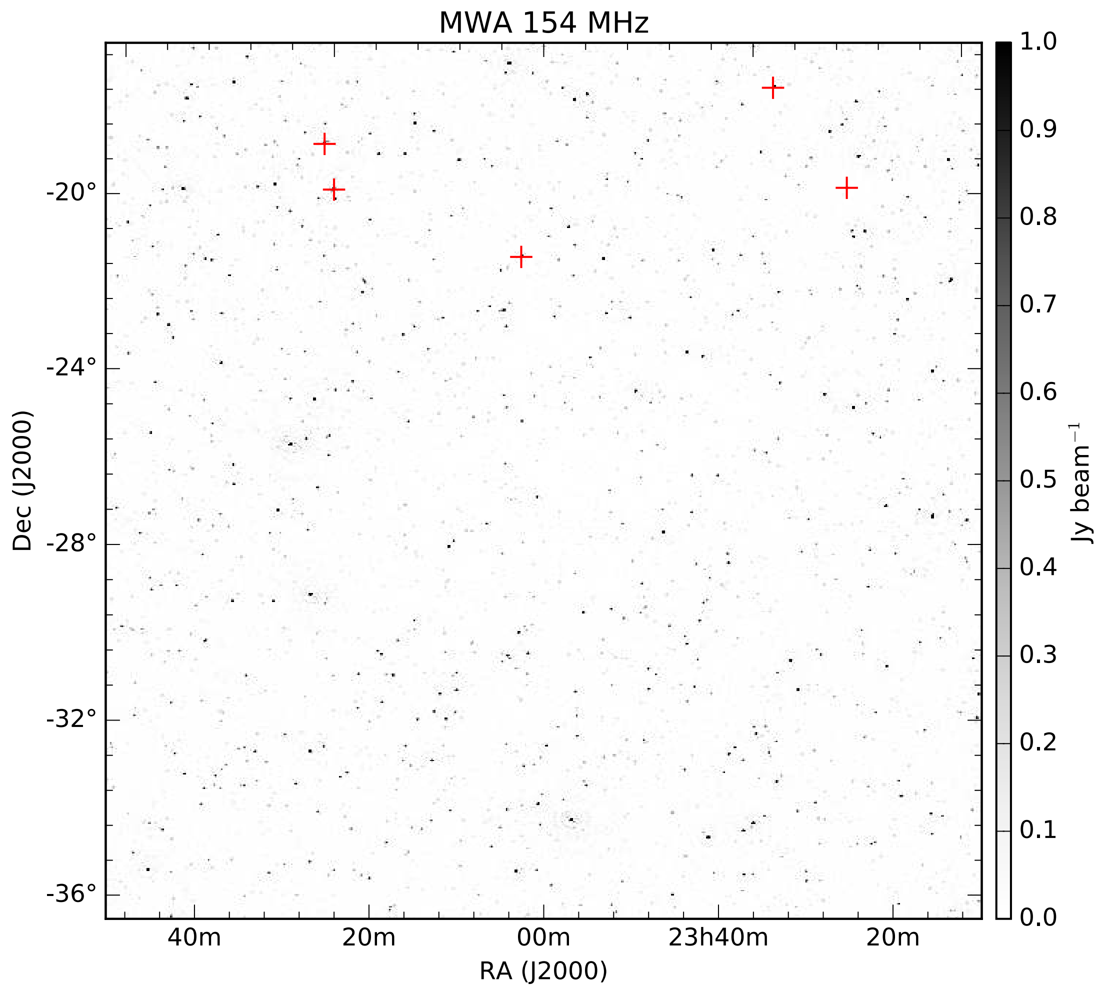
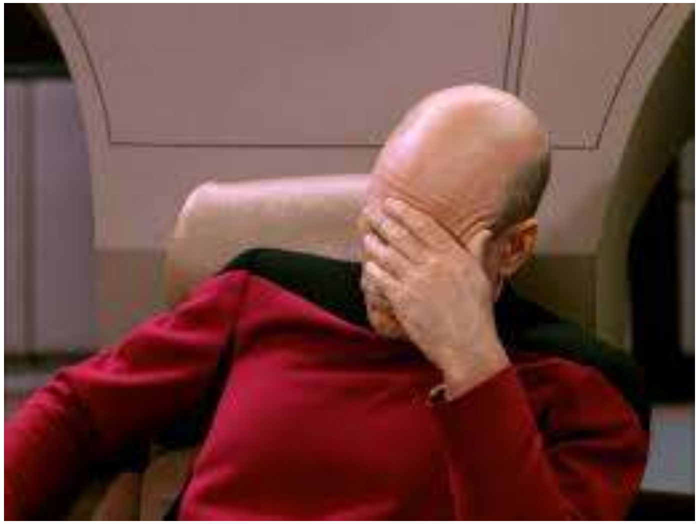


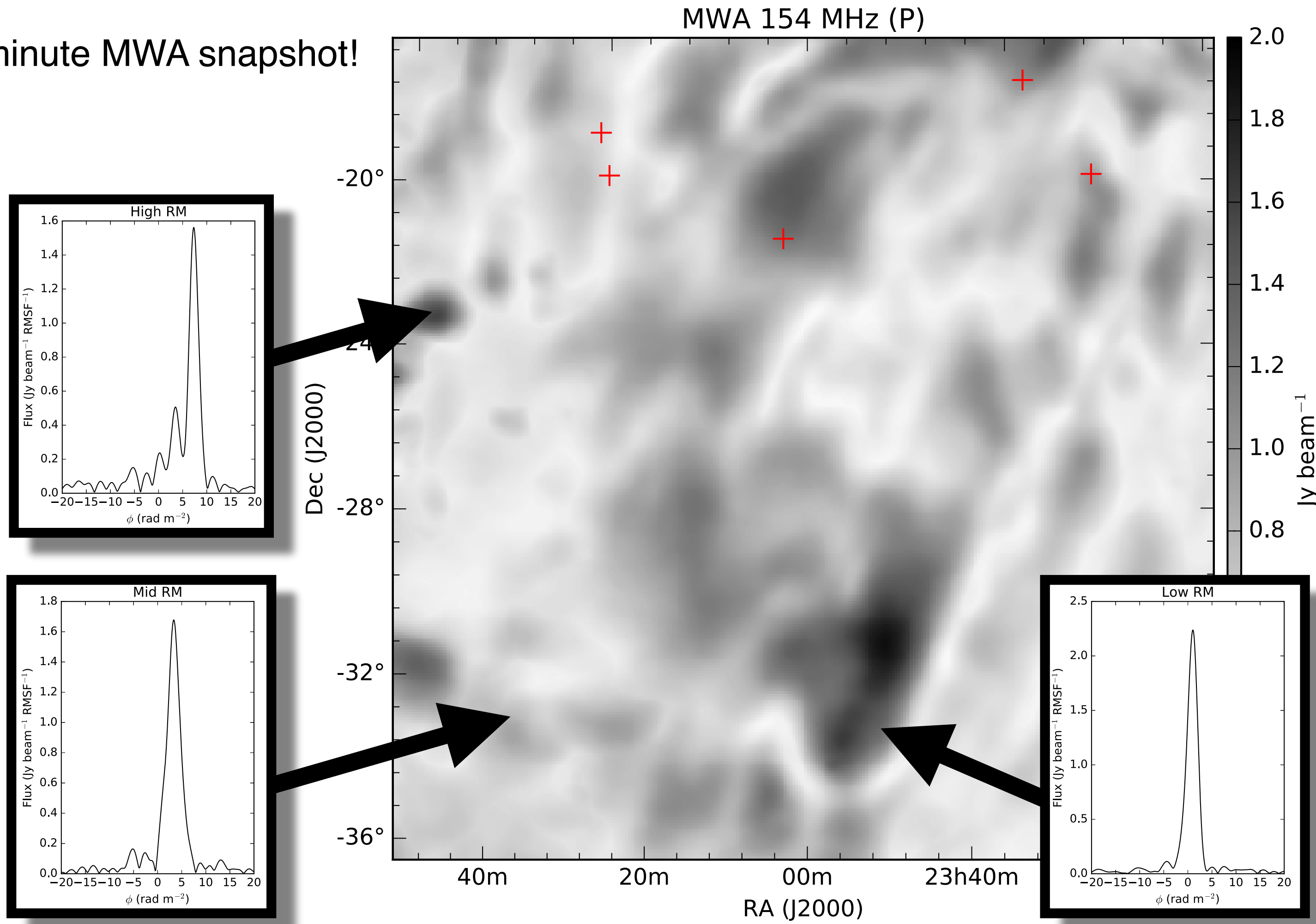
Calibrating for ionosphere against polarised point sources? Maybe not.



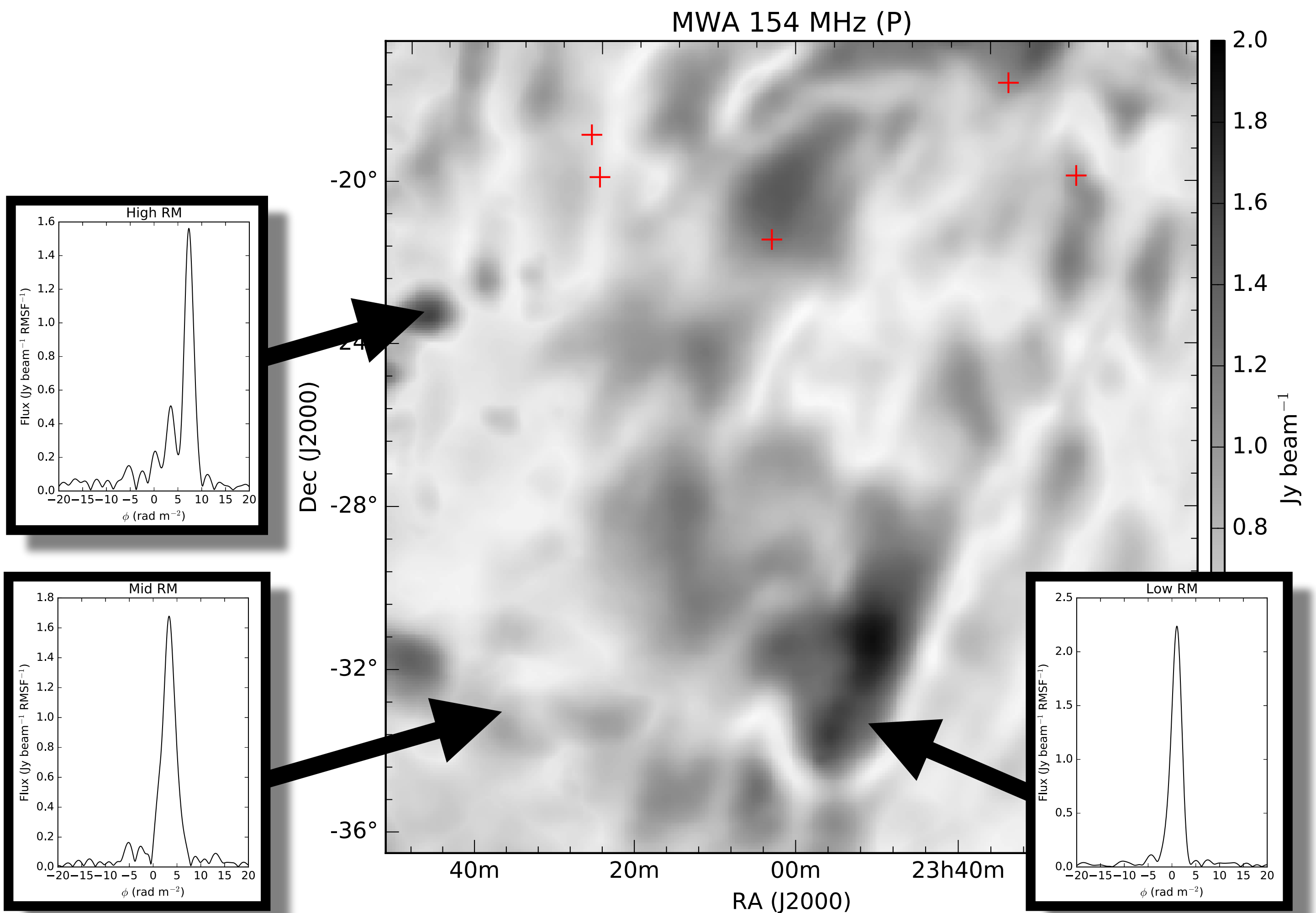


Calibrating for ionosphere against diffuse polarised background

2-minute MWA snapshot!

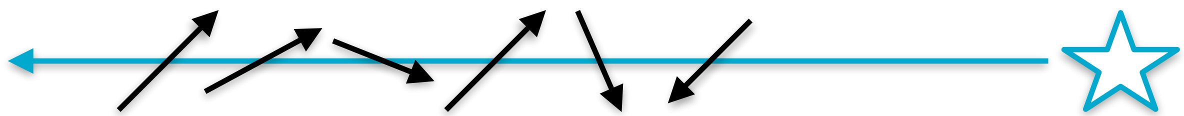


Things to worry about
Beam depolarisation

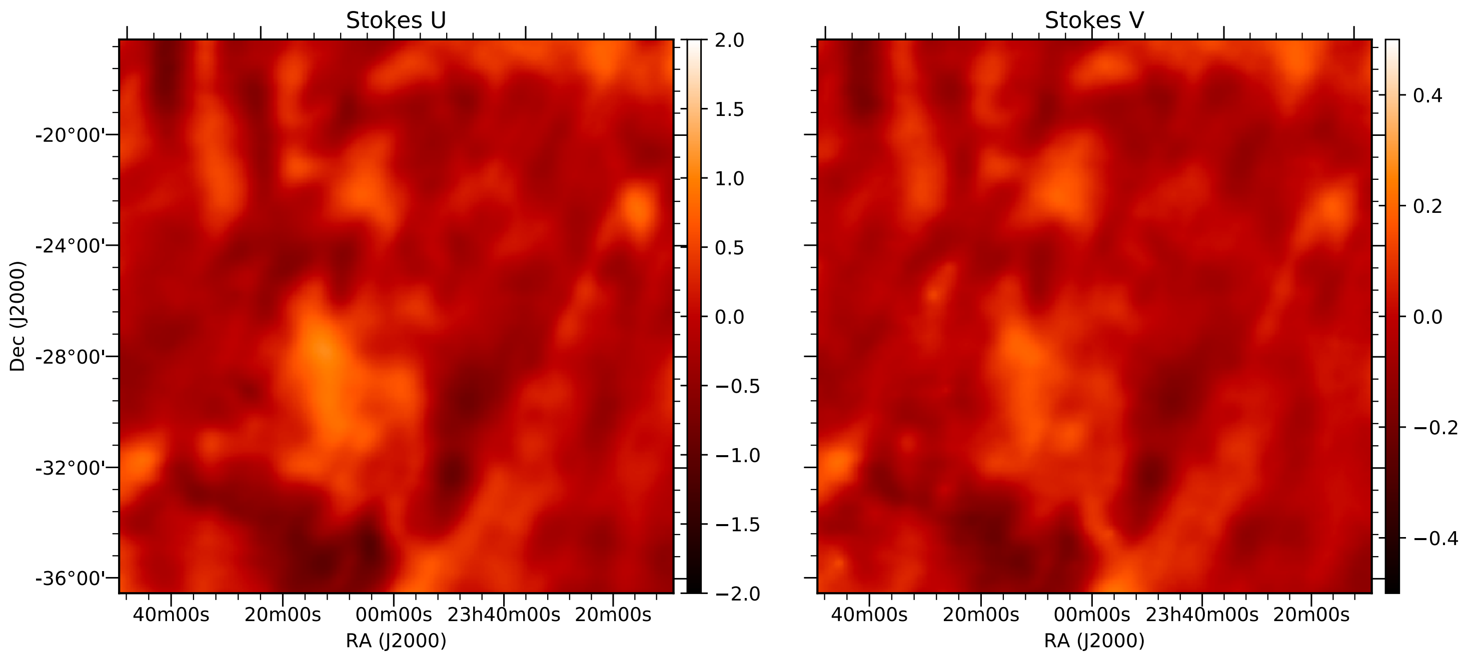


Things to worry about
Depth depolarisation

- Similar to beam depolarisation except that it occurs along the line of sight.
- Fluctuations in polarisation angle act to depolarise the signal
- It is particularly prominent at long wavelengths.

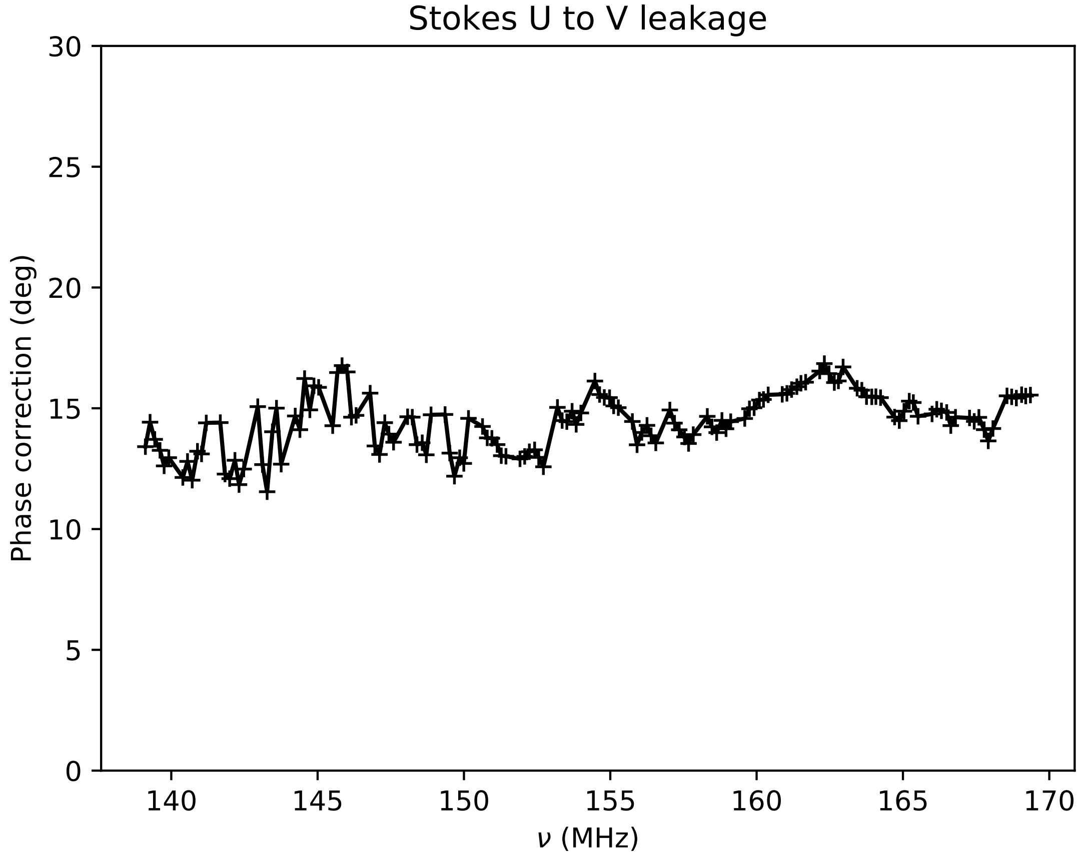


Things to worry about XY-phase calibration



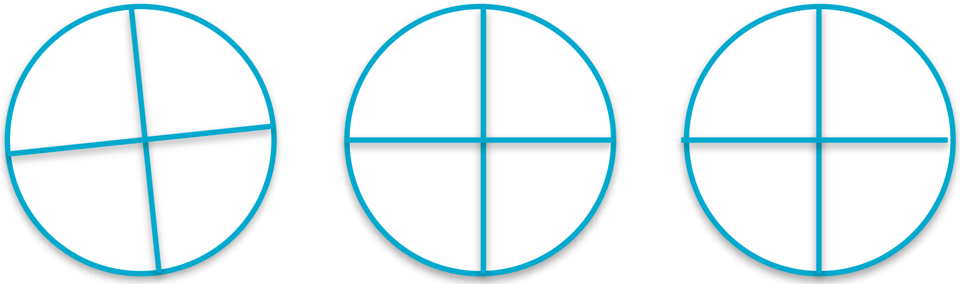
- An uncalibrated XY-phase can result in leakage from Stokes U to Stokes V

MWA XY-phase calibration



Assume sky not circularly polarised and rotate Stokes V back into Stokes U

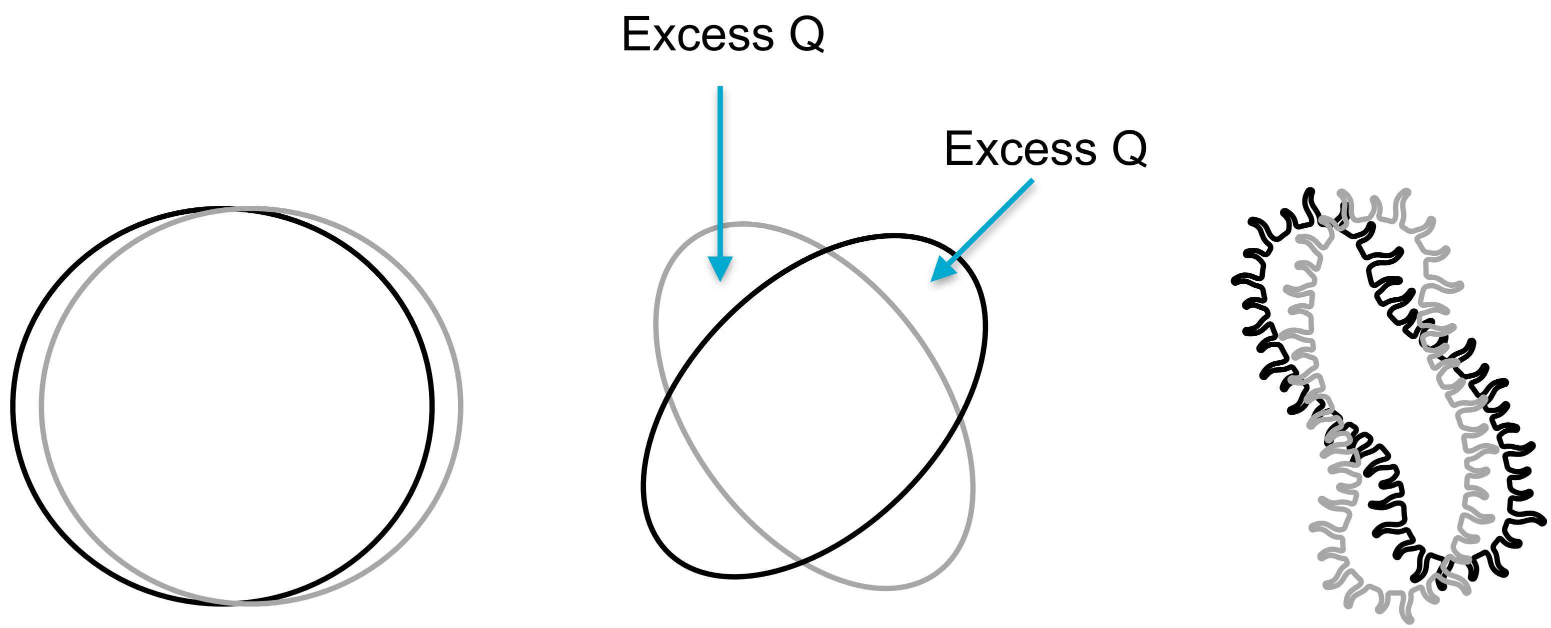
ASKAP XY-phase calibration



- Rotate 3rd axis on one antenna to induce polarisation in to unpolarised sources.
- Or, use on-dish calibrator source to correct for XY-phase (currently in test).

Things to worry about
Beam model errors

- The beam shape is important for polarisation calibration.
- Poor understanding of beam leads to false polarisation i.e. Q = XX-YY



Things to worry about
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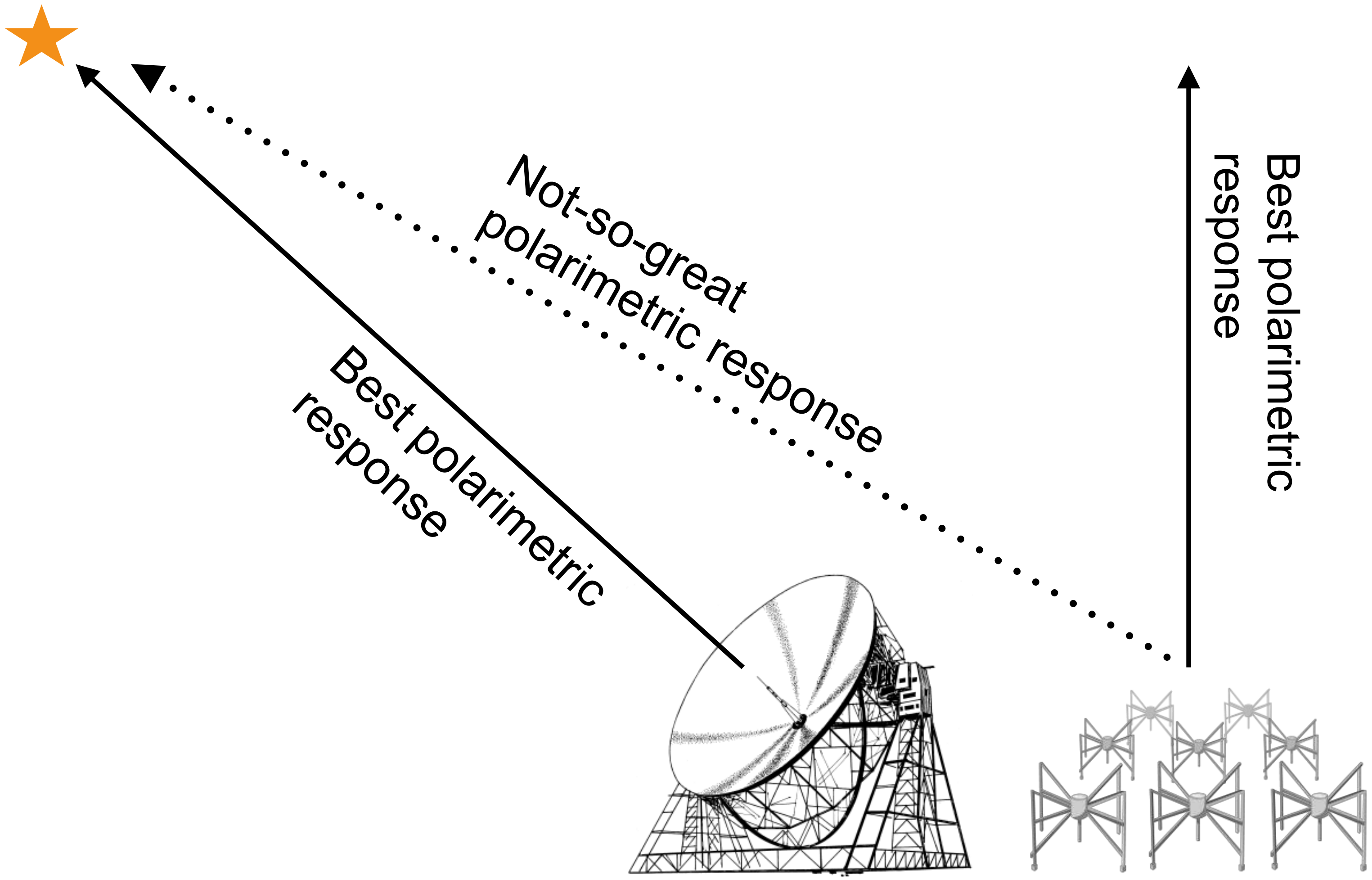
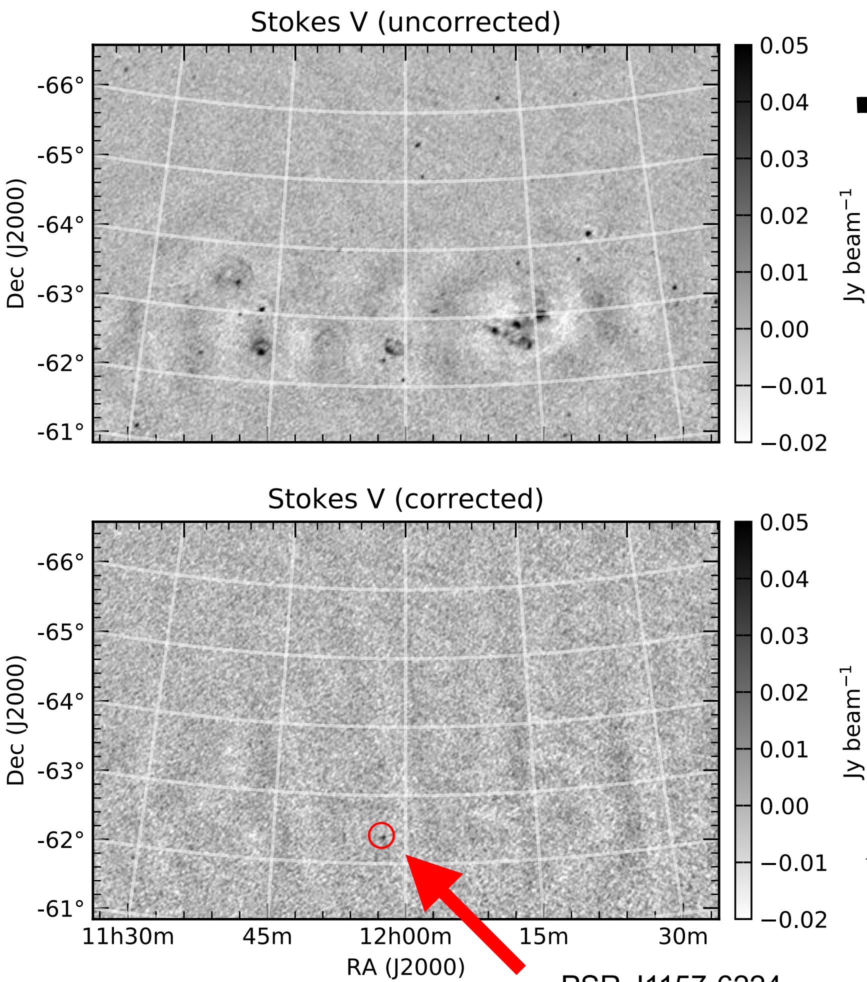
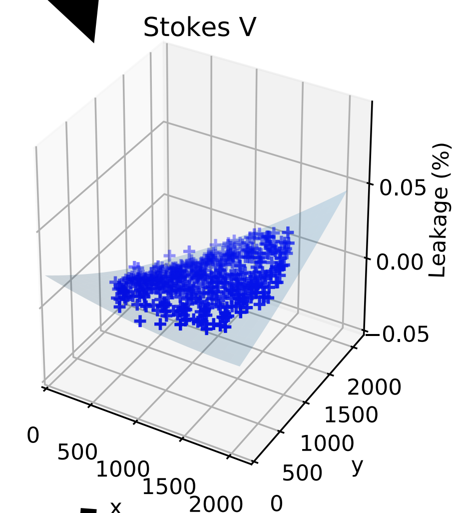


Things to worry about
Beam model errors



Model Stokes I to Stokes V leakage for each beam-former setting

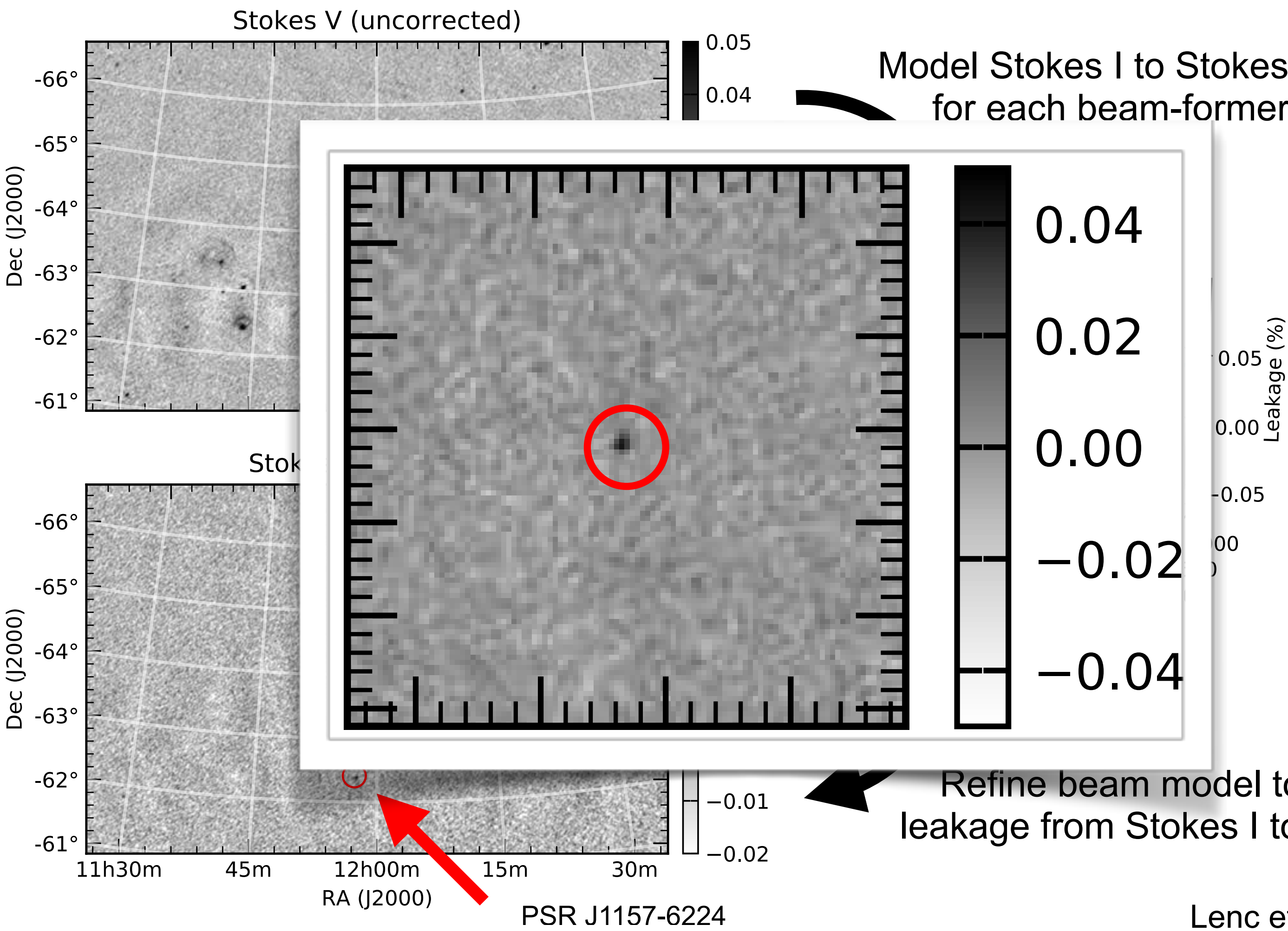


Refine beam model to reduce leakage from Stokes I to Stokes V.

PSR J1157-6224

Lenc et al. (2018)

Things to worry about
Beam model errors



Model Stokes I to Stokes V leakage
for each beam-former setting

Refine beam model to reduce
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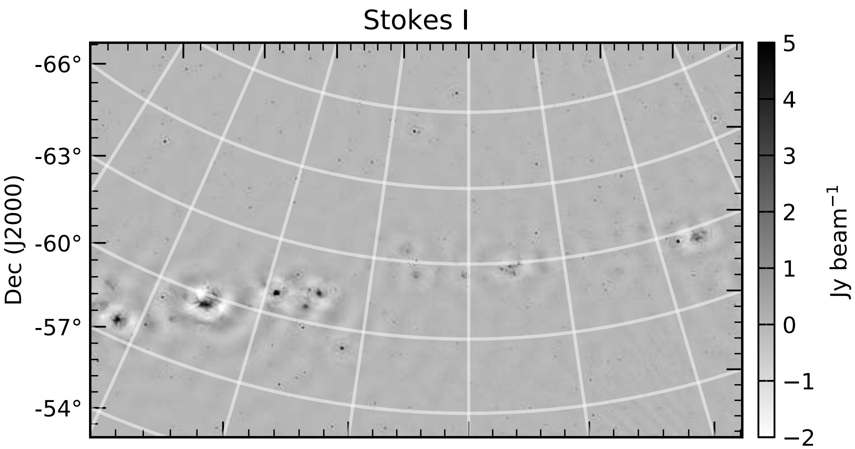
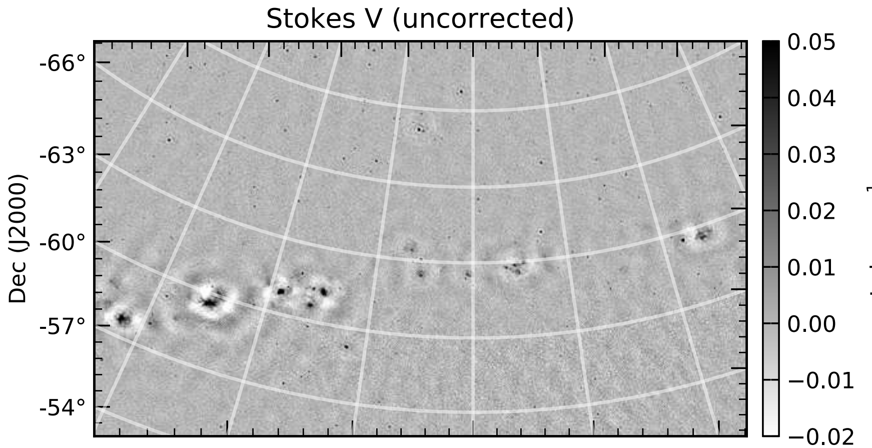
Lenc et al. (2018)


POP
QUIZ!

1. Can this be real? What are we seeing?





A. Ionospheric effects
B. Faraday rotation
C. Polarisation leakage
D. Galactic circular polarisation

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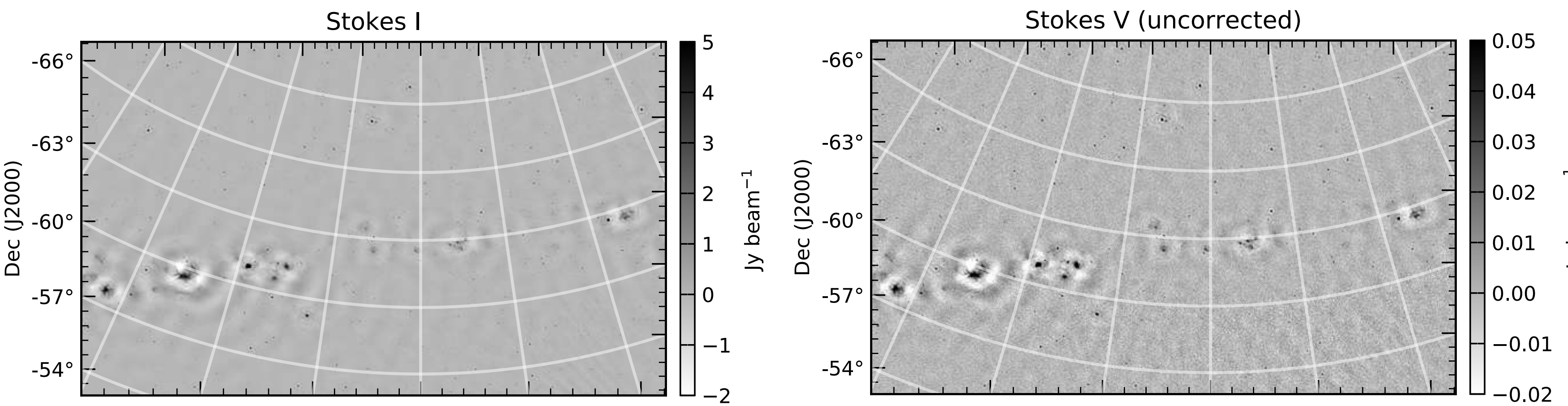

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B. Faraday rotation
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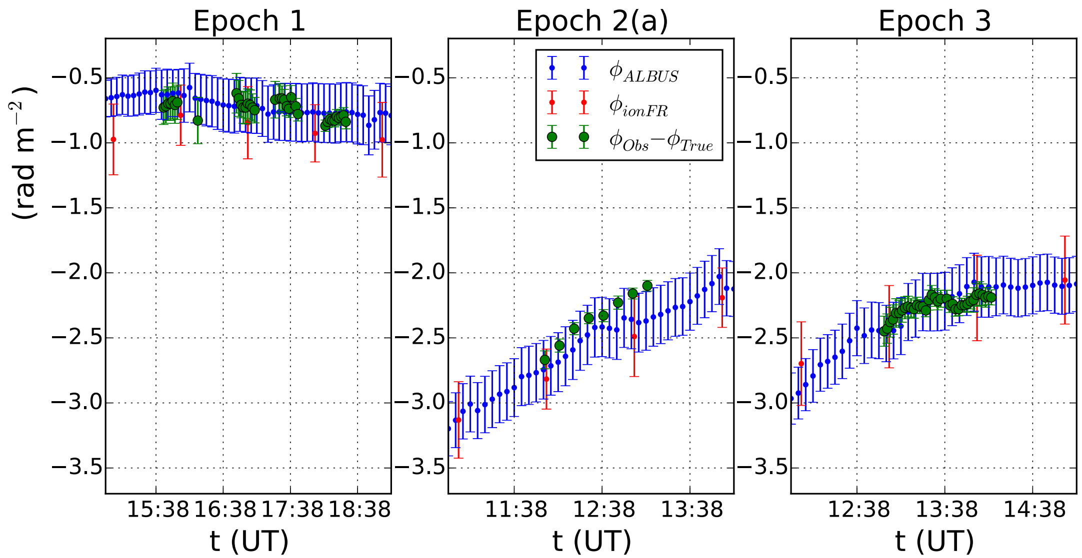
2. Are you able to identify the cause?



A. Ionospheric Faraday rotation
B. Google stock prices
C. PAF temperatures
D. Intrinsic source RM

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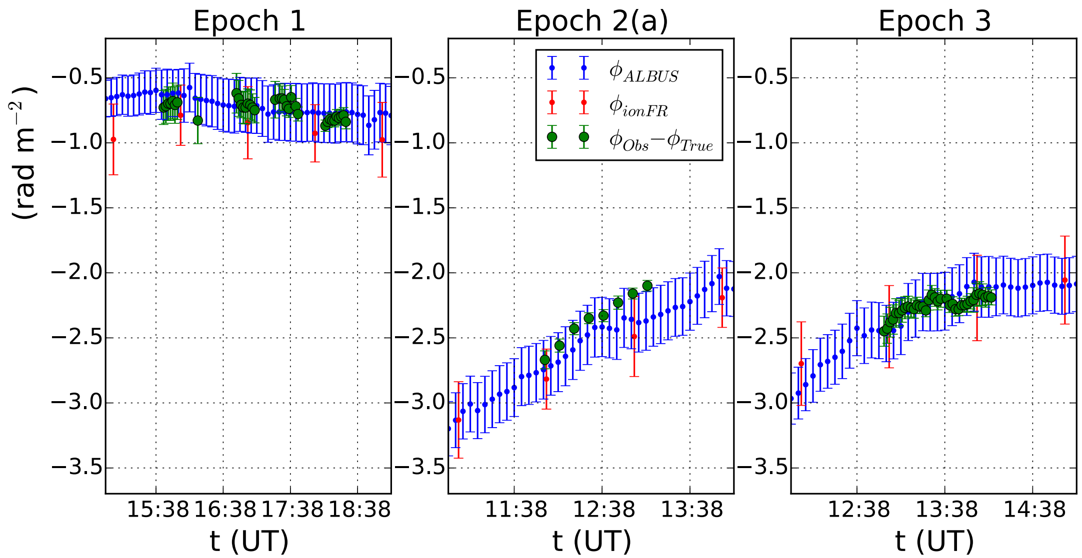

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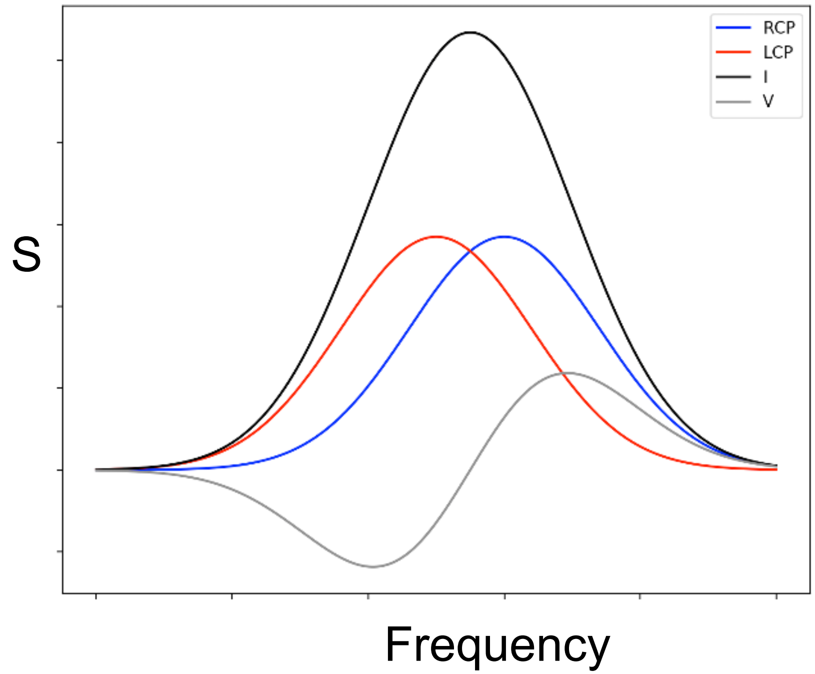
CSIRO

3. Dare to solve this … What is being shown here?



A. Ionospheric Faraday rotation
B. Linear polarisation
C. Rotation measure synthesis
D. Zeeman splitting

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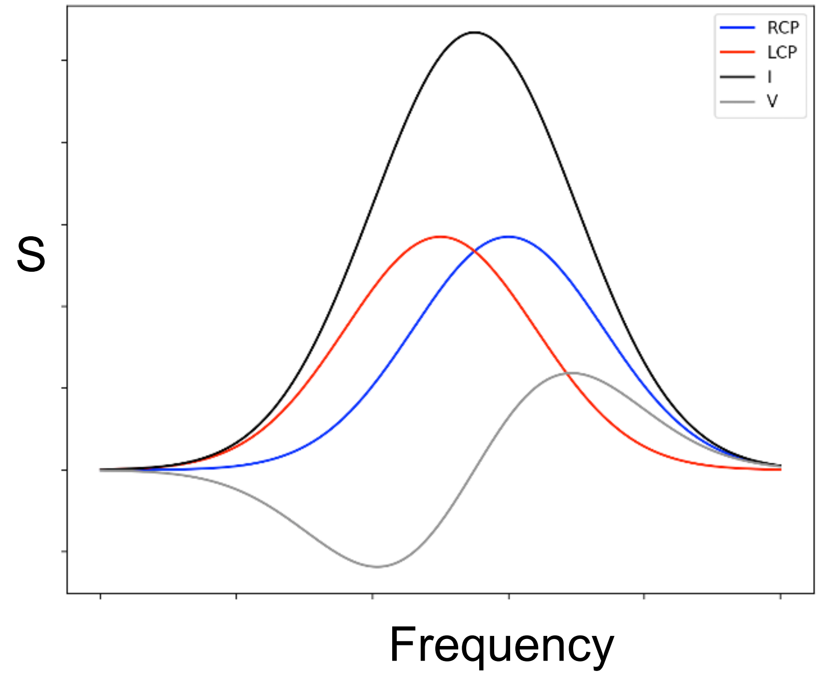

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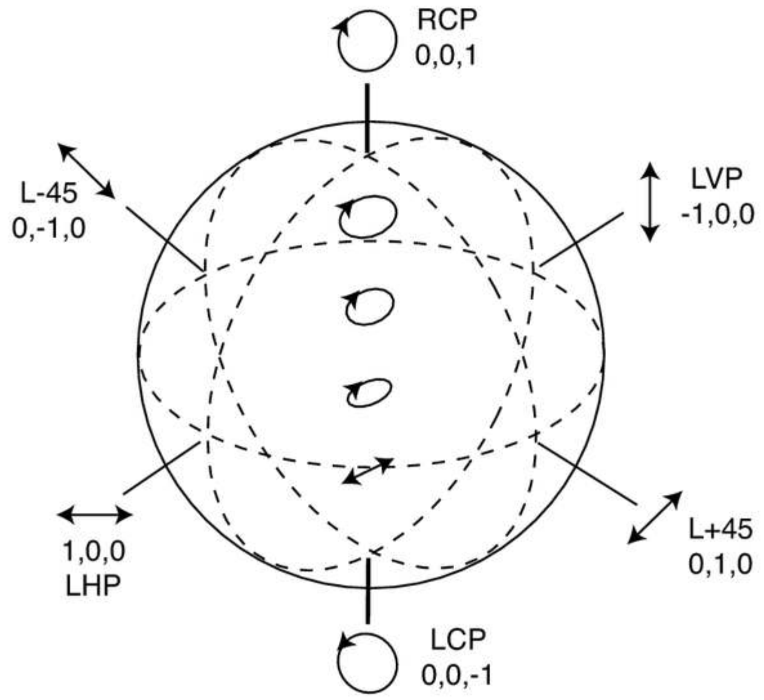
4. Be adventurous … What is this?



A. Solar convection model
B. A Poincaré Sphere
C. A Death Star
D. Faraday rotation

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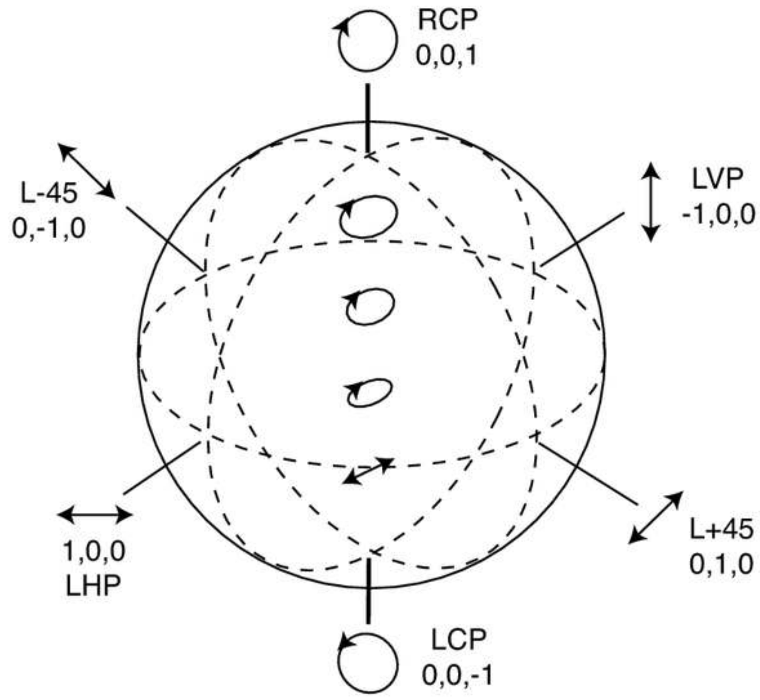

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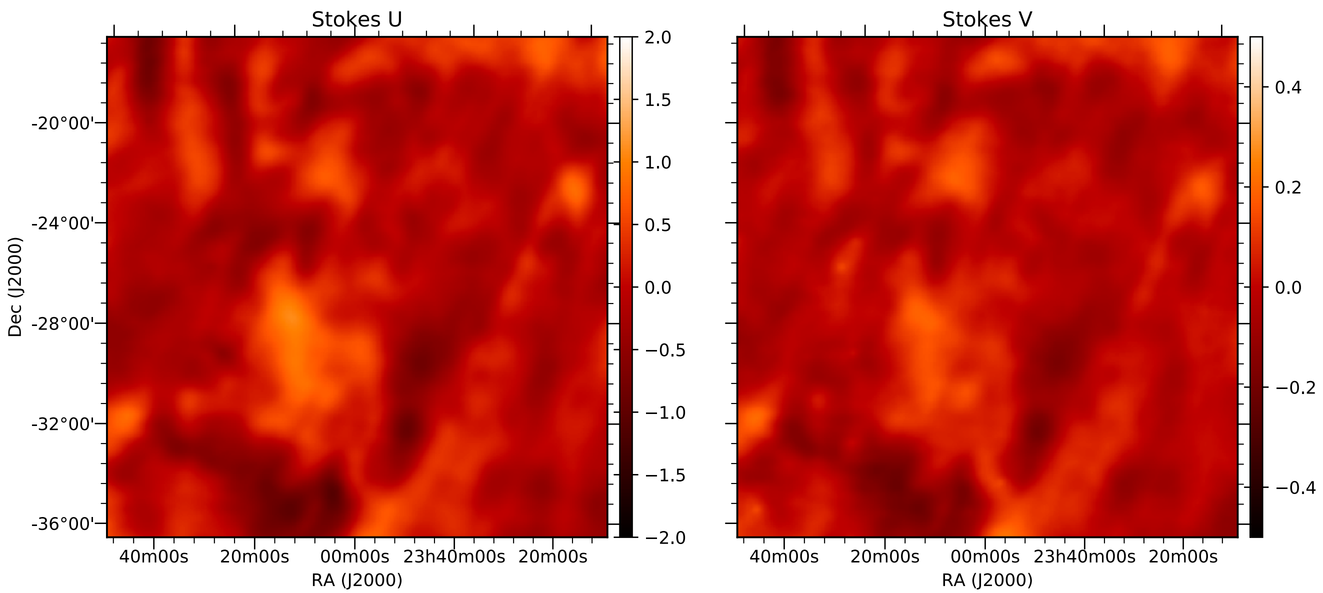
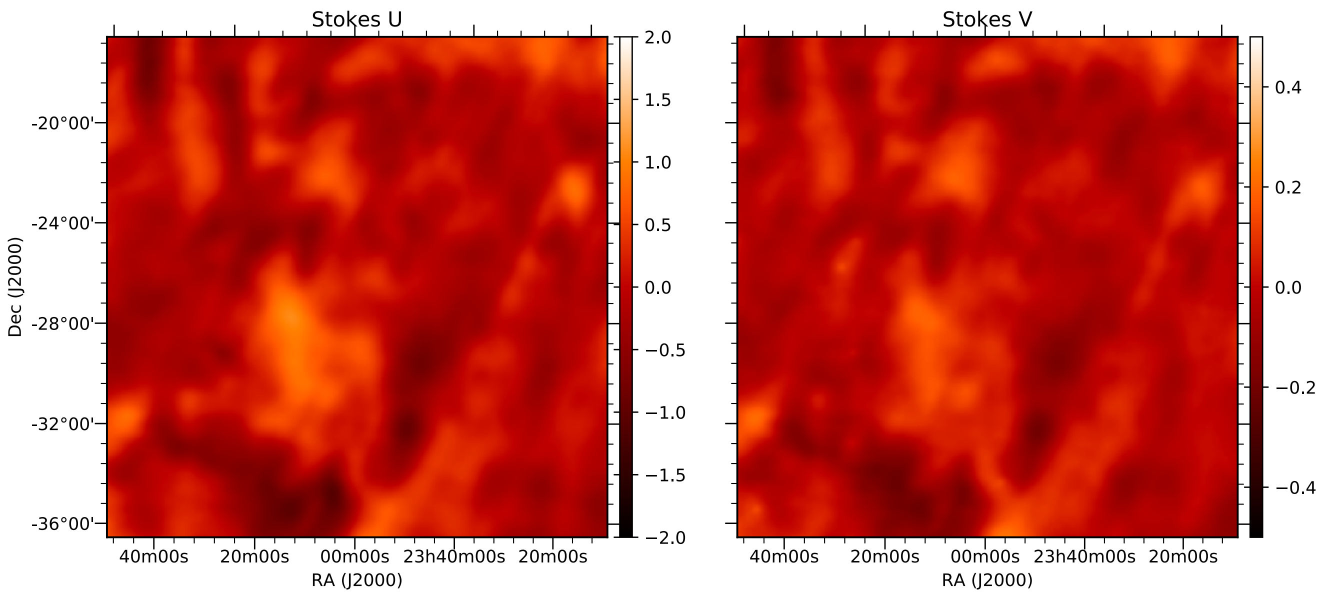
D. Faraday rotation

5. A tricky problem? What's the cause?



A. An uncorrected XY-phase
B. Stokes I to U leakage
C. Ionospheric Faraday rotation
D. Circularly polarised dust on the telescope

5. A tricky problem? What's the cause?



- ✔A. An uncorrected XY-phase
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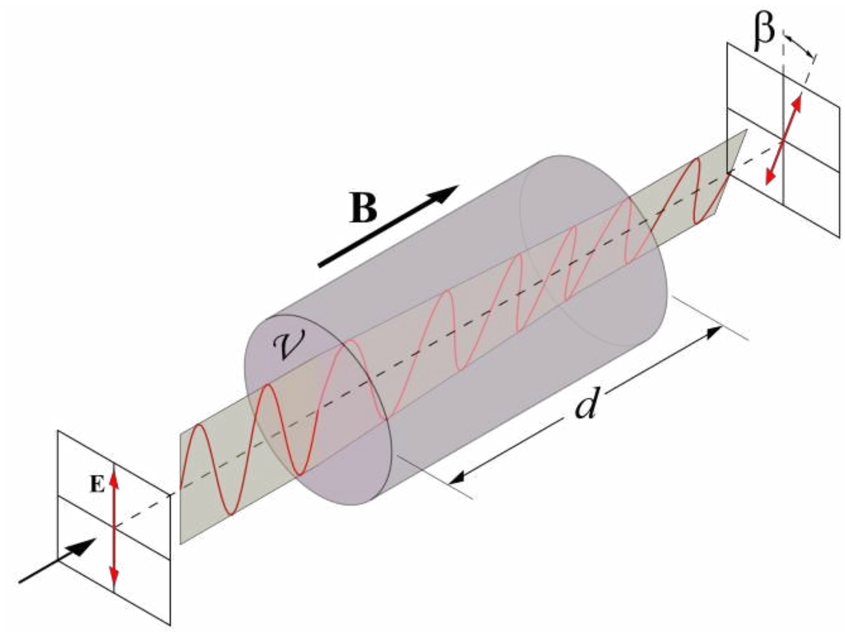
6. Don’t give up! What’s this showing?



A. Beta radiation
B. Circular polarisation
C. EM pulses
D. Faraday rotation

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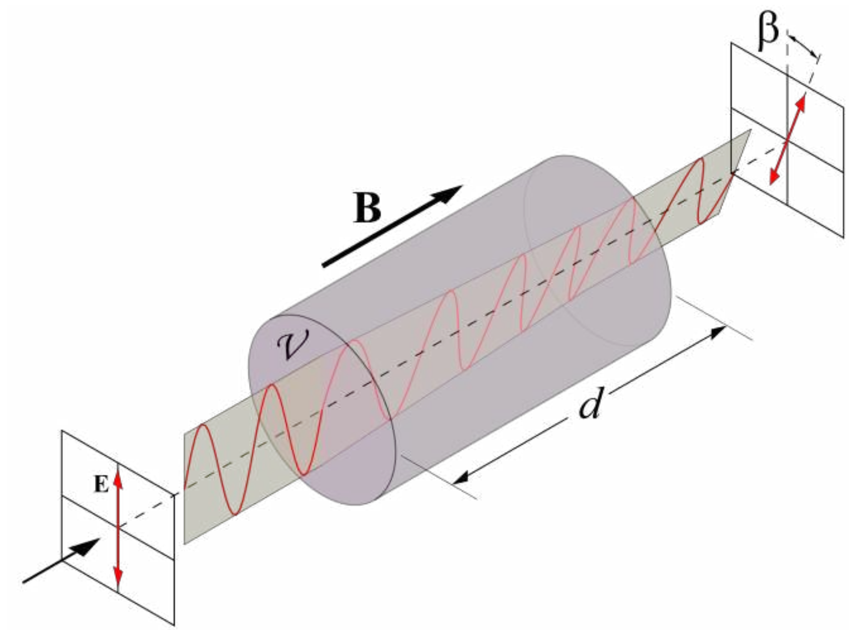

A. Beta radiation
B. Circular polarisation
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CSIRO

7. Can you identify what this is?

Stokes V

A. Linear polarisation
B. Total intensity
C. Circular polarisation
D. Velocity of polarisation

7. Can you identify what this is?

Stokes V

A. Linear polarisation
B. Total intensity
✔ C. Circular polarisation
D. Velocity of polarisation

8. Do you recognise this person?

A. Michael Faraday
B. Henri Poincaré
C. Abraham Lincoln
D. George Stokes

8. Can you identify this person?

A. Michael Faraday
B. Henri Poincaré
C. Abraham Lincoln
✔D. George Stokes

9. End of Game Question.
What is the typical strength of a fridge magnet?

A. 50 fG
B. 50 μG
C. 50 kG
D. 50 MG
E. 50 G

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Reading Material

- Cotton, W.D., "Polarization in Interferometry", Synthesis Imaging in Radio Astronomy II, 1999 : http://adsabs.harvard.edu/abs/1999ASPC..180..111C - Fundamentals
- Heiles, C., "A Heuristic Introduction to Radioastronomical Polarisation", 2002, ASP, 278 :
- Tinbergen, J., "Astronomical Polarimetry", 1996, Cambridge University Press (Cambridge UK)
- Stutzman, W., "Polarisation in Electromagnetic Systems", 1993, Artech House (Norwood, MA, USA)
- Radhakrishnan, "Polarisation", URSI proceedings, 1990, pp.34
- Hamaker et al., "Understanding radio polarimetry. I. Mathematical foundations. Astronomy and Astrophysics Supplement (1996) vol. 117 pp. 137
- 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
- Lenc, E. Et al., 2017, "The Challenges of Low-Frequency Radio Polarimetry: Lessons from the Murchison Widefield Array", PASA, 34, 40 : http://adsabs.harvard.edu/abs/2017PASA...34...40L
- Lenc, E. et al., 2018, "An all-sky survey of circular polarization at 200 MHz", MNRAS, 478, 2835 : http://adsabs.harvard.edu/abs/2018MNRAS.478.2835L - demonstration of how to reduce the effects of Stokes I into V leakage as a result of poorly defined beams
- Riseley, C. et al., 2018, "The POlarised GLEAM Survey (POGS) I: First Results from a Low-Frequency Radio Linear Polarisation Survey of the Southern Sky", PASA, accepted : http://adsabs.harvard.edu/abs/2018arXiv180909327R - demonstration of how to reduce the effects of Stokes I leakage into Q/U as a result of poorly defined beams.
- Sault, R.J., 2014, "Initial characterisation of BETA polarimetric response", ASKAP MEMO : ftp://ftp.atnf.csiro.au/pub/people/sau078/memos/askap-1.pdf - example of using a beam rotation to calibrate polarisation.

Look up previous NRAO and ATNF Radio School presentations - there is so much to talk about in polarisation and everyone has their own take on the subject.

CSIRO

Thank you

CSIRO Astronomy & Space Science
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Senior Research Scientist

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