Jovian Magnetospheres Beyond the Solar System

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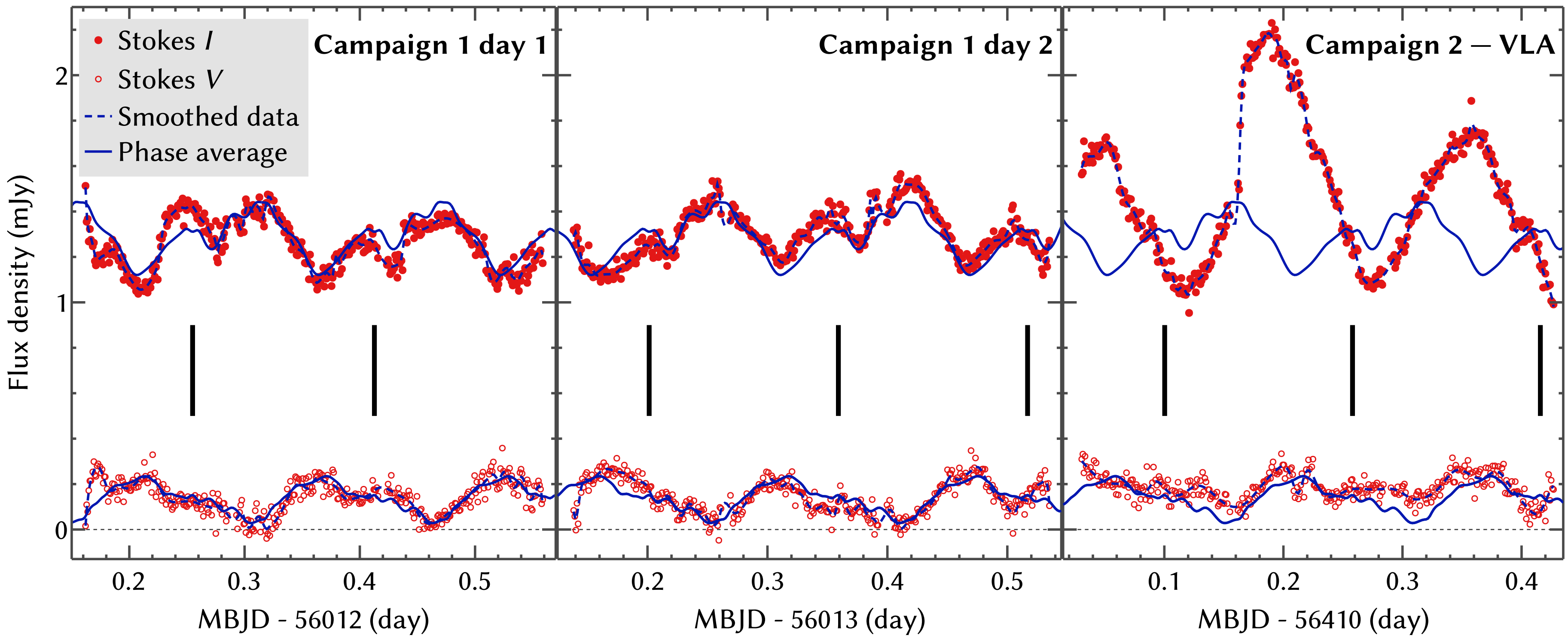
Radio Stars – 2017 Nov 2 – MIT Haystack Observatory

Chris Wiseman, NASA

UCDs show non-bursting radio emission.

The emission varies over many time scales.

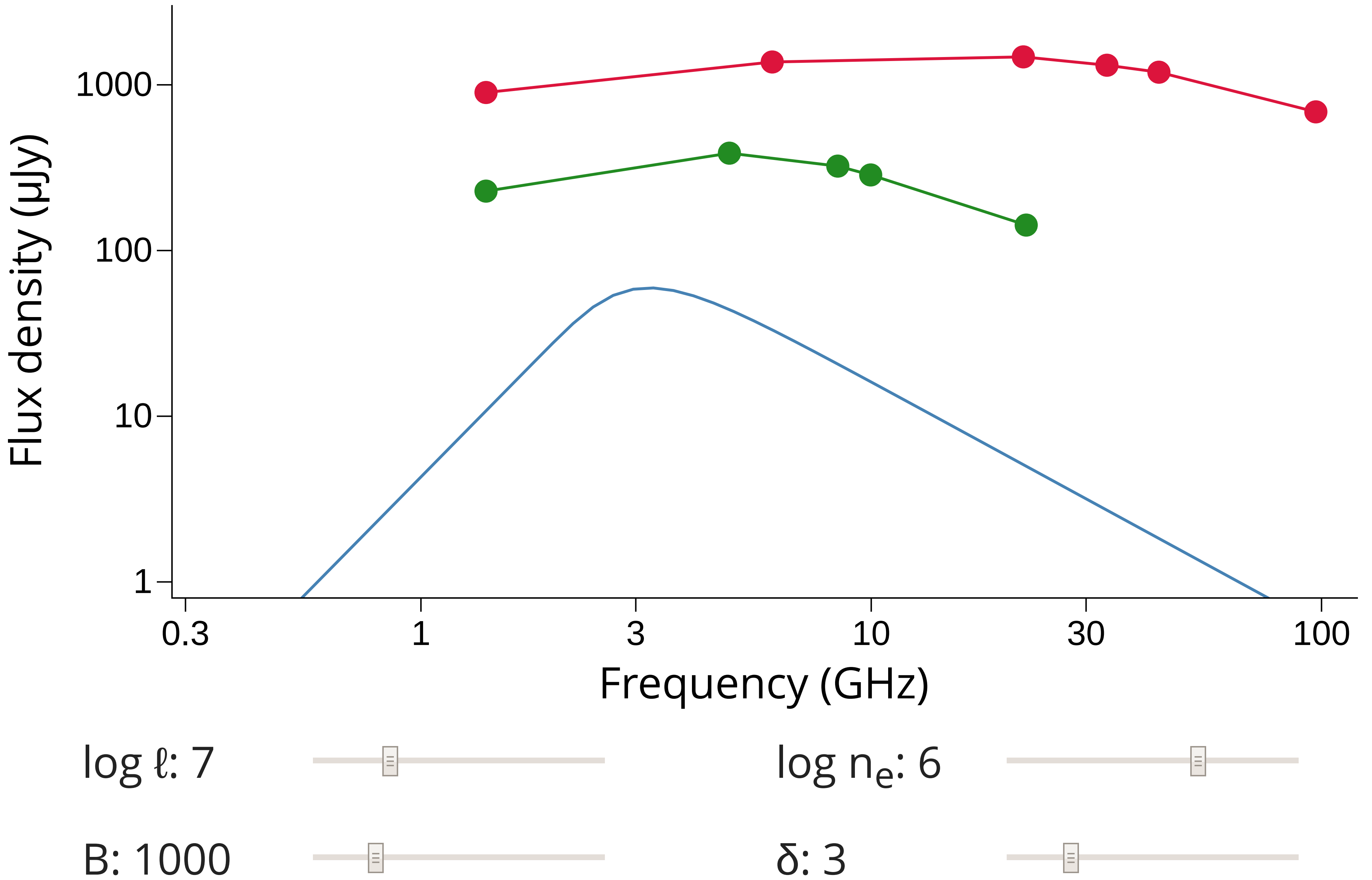
Below, data from the benchmark binary NLTT 33370 AB (M7+M7):



NLTT 33370 B (M7) • adapted from PKGW+ (2015).

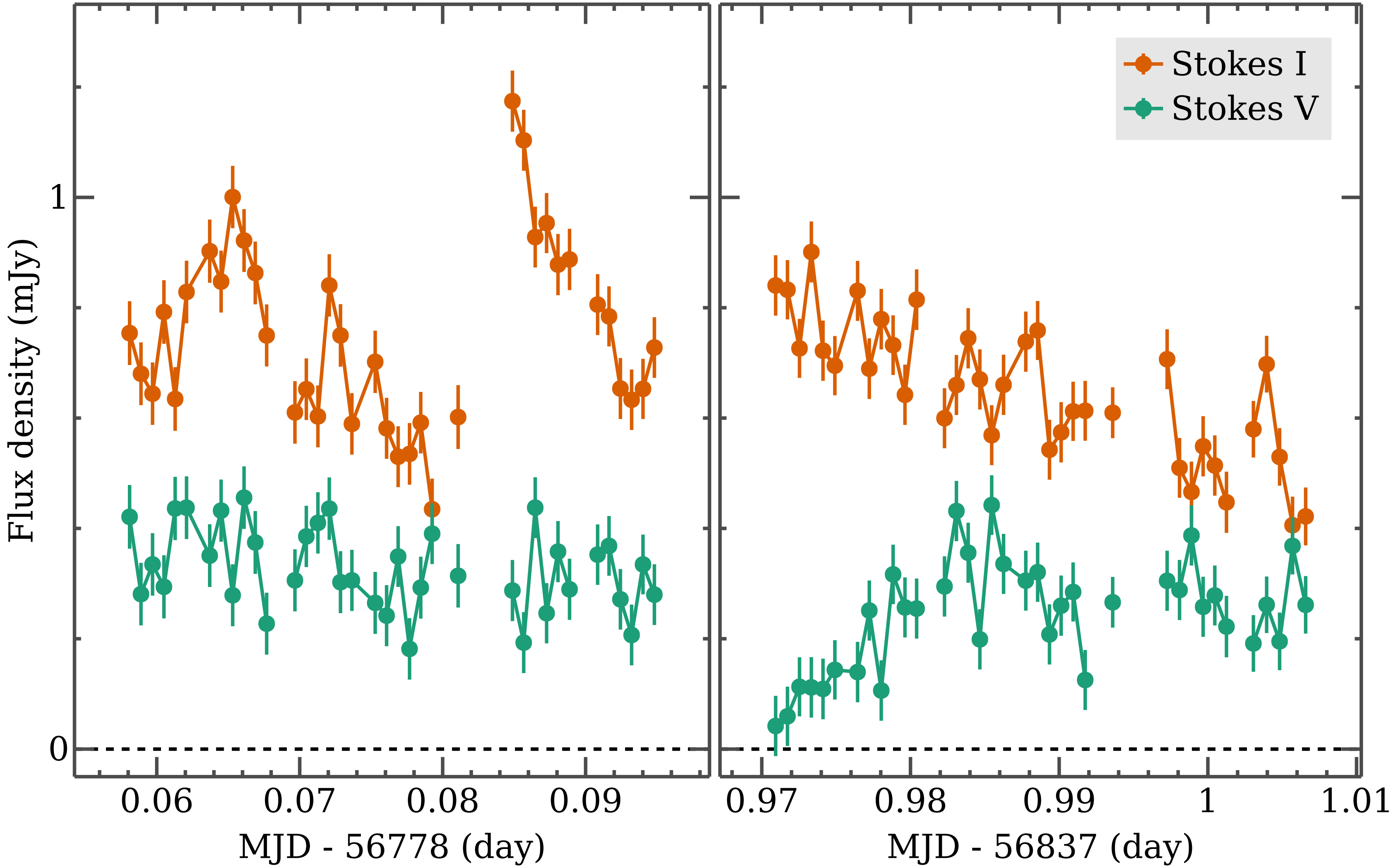
See Williams 2017 (arxiv:1707.04264) for a concise review of "Radio Emission from Ultra-Cool Dwarfs"!

Simple models don't adequately fit the data.



High-frequency data further challenge our models.

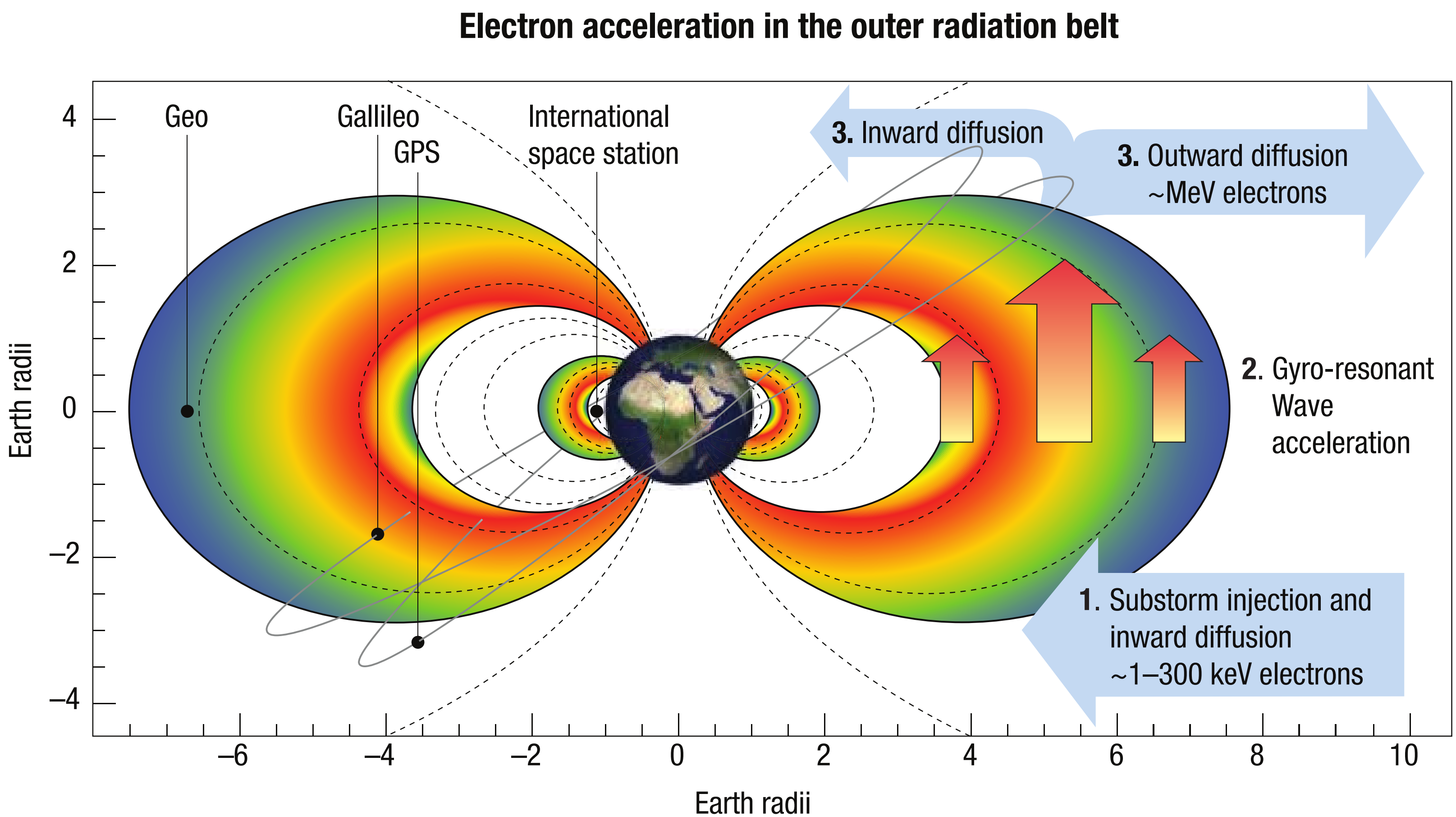
30% circular polarization … with ALMA, at 100 GHz??



PKGW+ in prep • see also PKGW+ 2015

I think this emission comes from *van Allen belts*.

AKA "radiation belts" — energetic particles trapped in a dipolar magnetosphere.

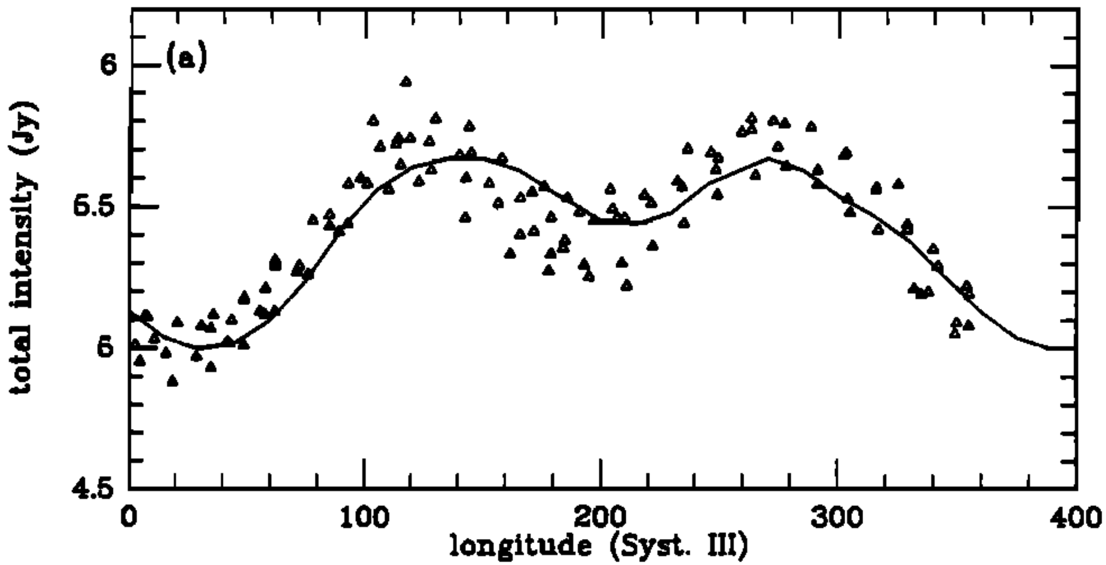


Horne 2007

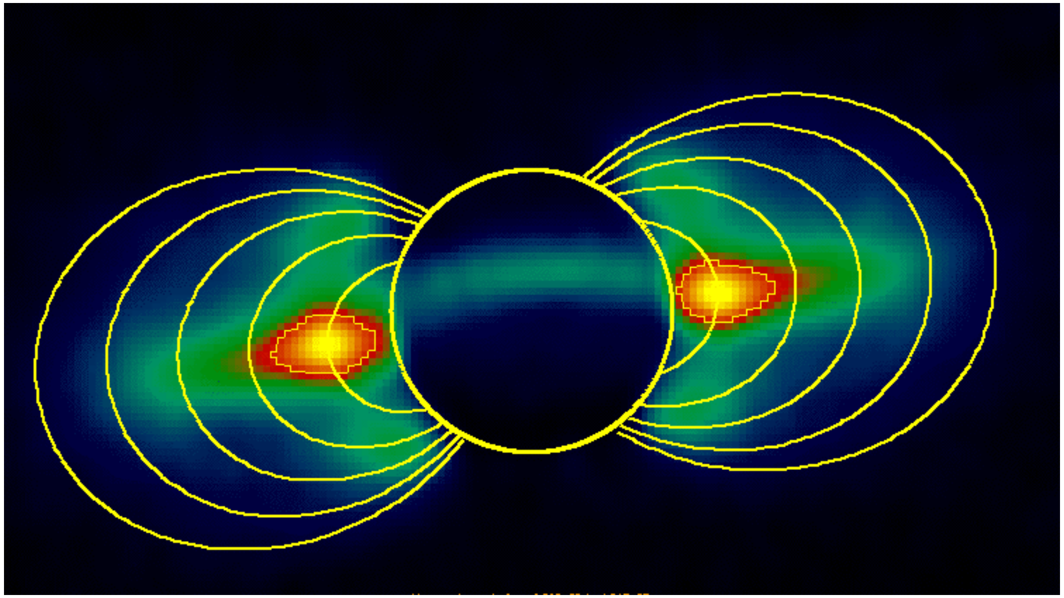
Requires stable magnetospheres very unlike those of Sun-like stars.

Jupiter's belts have the right variability.

Asymmetry in magnetosphere generates double-humped variation →

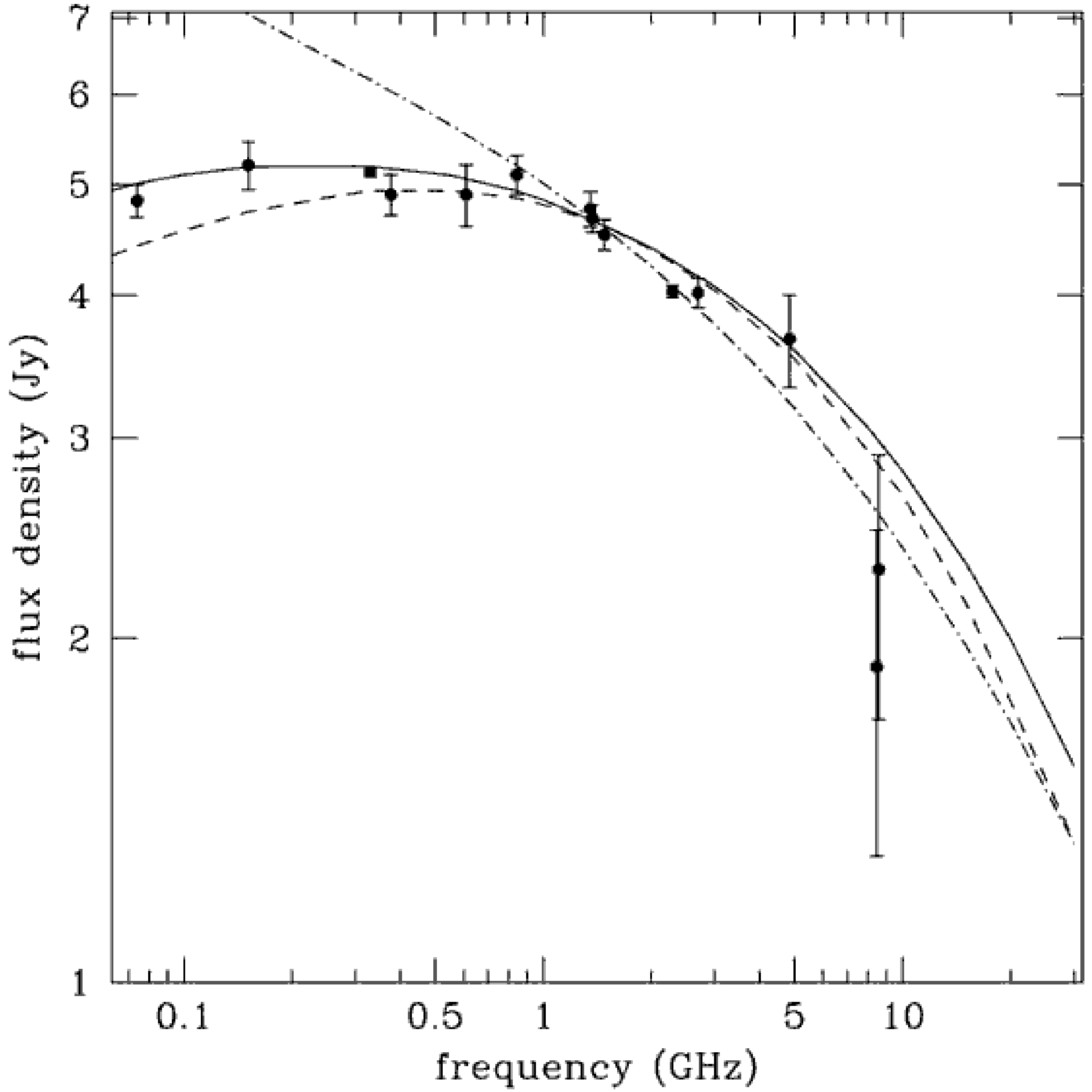


De Pater+ 1997



NASA/JPL — Caltech (source)

Jupiter's belts have the right spectrum, too.



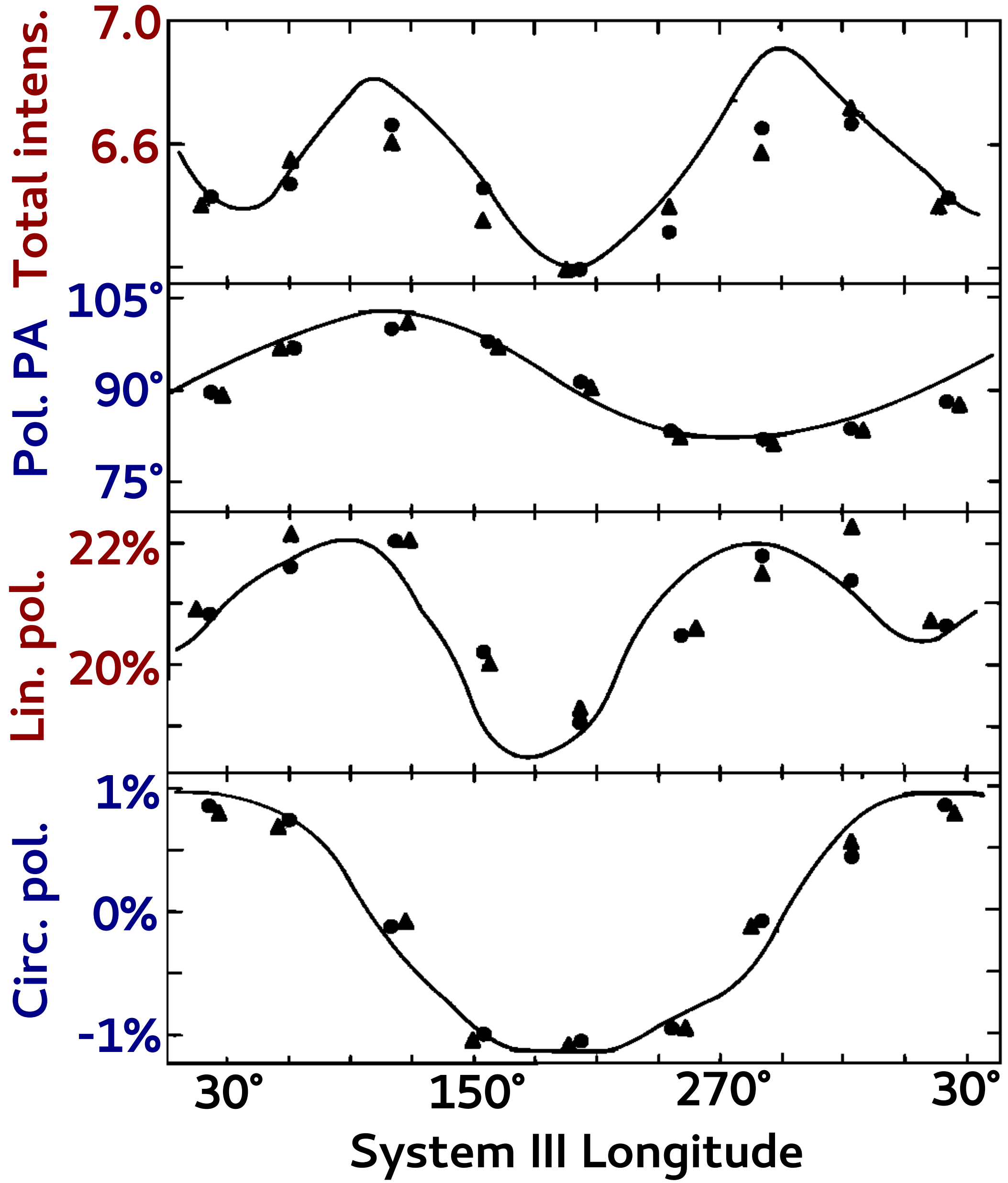
De Pater+ 2003

Jupiter's polarization could be … more similar.

Linear polarization ~20%.

Circular polarization ~1%.

UCDs are the opposite: ~20% circular, <1% linear.



de Pater+ 1981

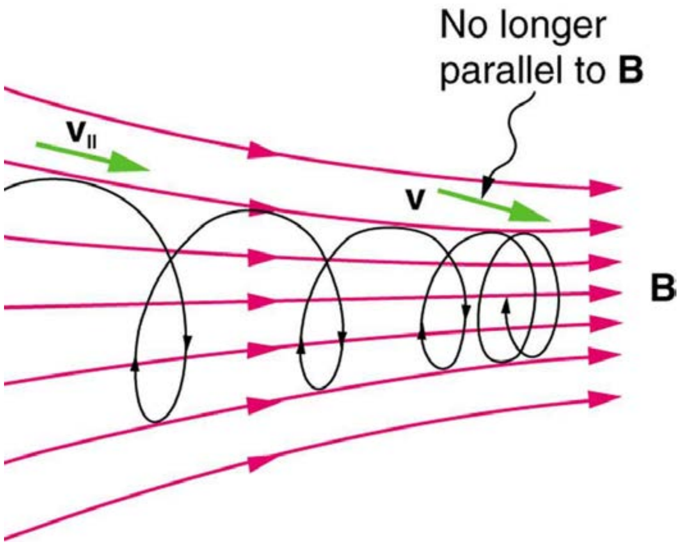
The Van Allen model is pleasingly tractable.

The particle motion has three action-angle coordinates:

Motion	Timescale
Gyromotion	μs
Latitudinal bounce	seconds
Longitudinal drift	days

The particle evolution is often dominated by two othogonal diffusion processes:

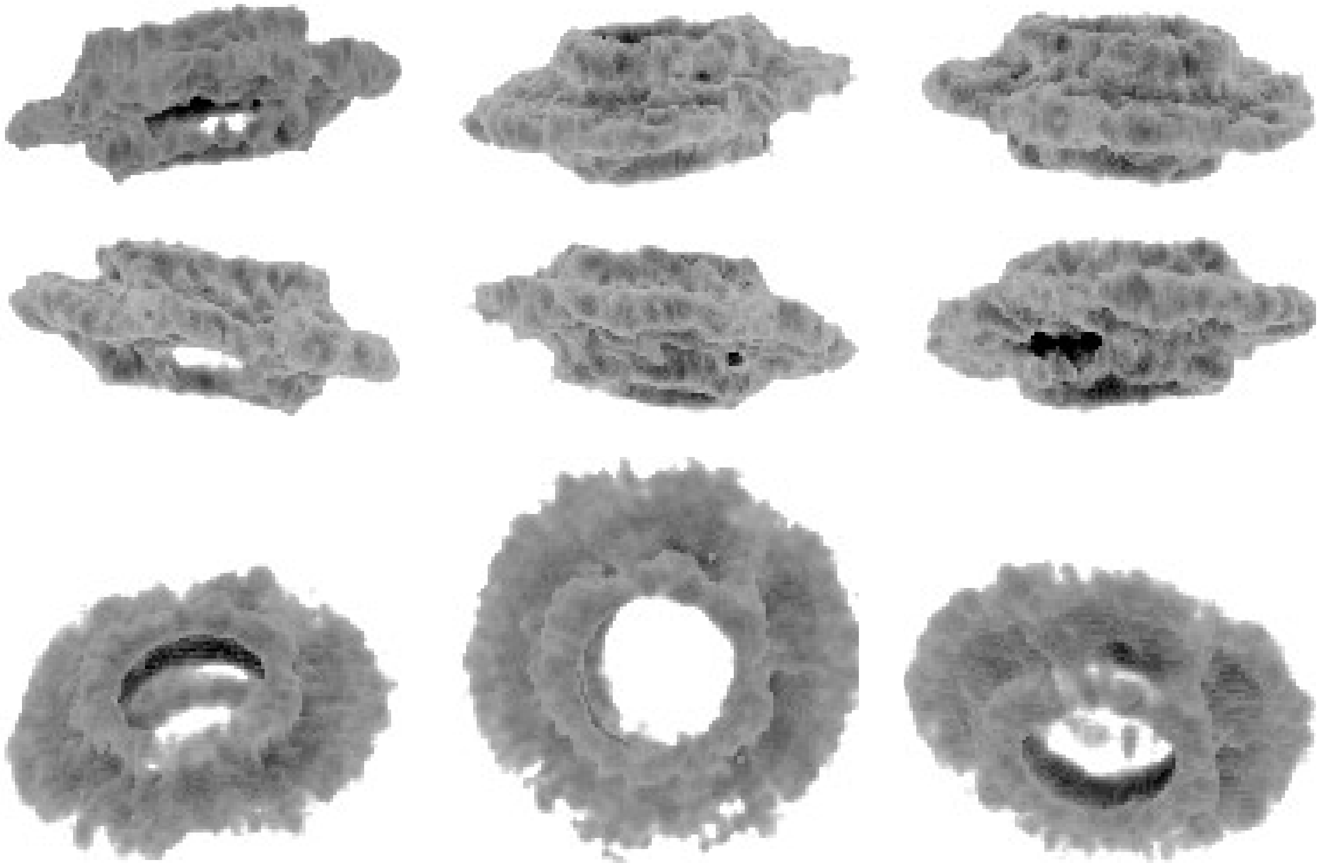
- Radial diffusion (1D)
- Energy/pitch-angle diffusion (2D)



OpenStax College Physics

All sorts of details can come into play!

Jupiter's innermost moon Amalthea scatters inward-drifting electrons in pitch-angle space.



Sault+ 1997

Santos-Costa & Bolton (2008): you cannot reproduce Jupiter's synchrotron spectrum without modeling its moons!

Existing simulation codes are not openly available.

And they all (?) use simplistic prescriptions for synchrotron radiative transfer.

I’ve set out to fix that: the **vernon** project.

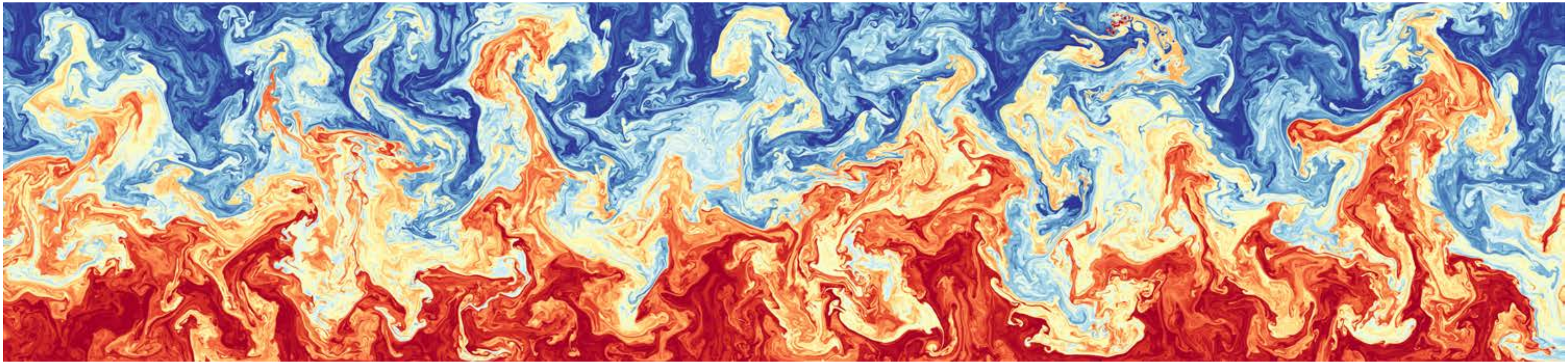
The gameplan:

1. Solve the steady-state Fokker-Planck equation to get particle distributions.
2. Do the radiative transfer to model the resulting emission.

Do it all with open-source software and an open development model. Python, GitHub, *etc.*

Particle distributions are solved using Dedalus.

Toolkit for efficient, accurate solution of differential equations in Python with MPI. Collab. with J. Oishi (Bates), K. Burns (MIT).



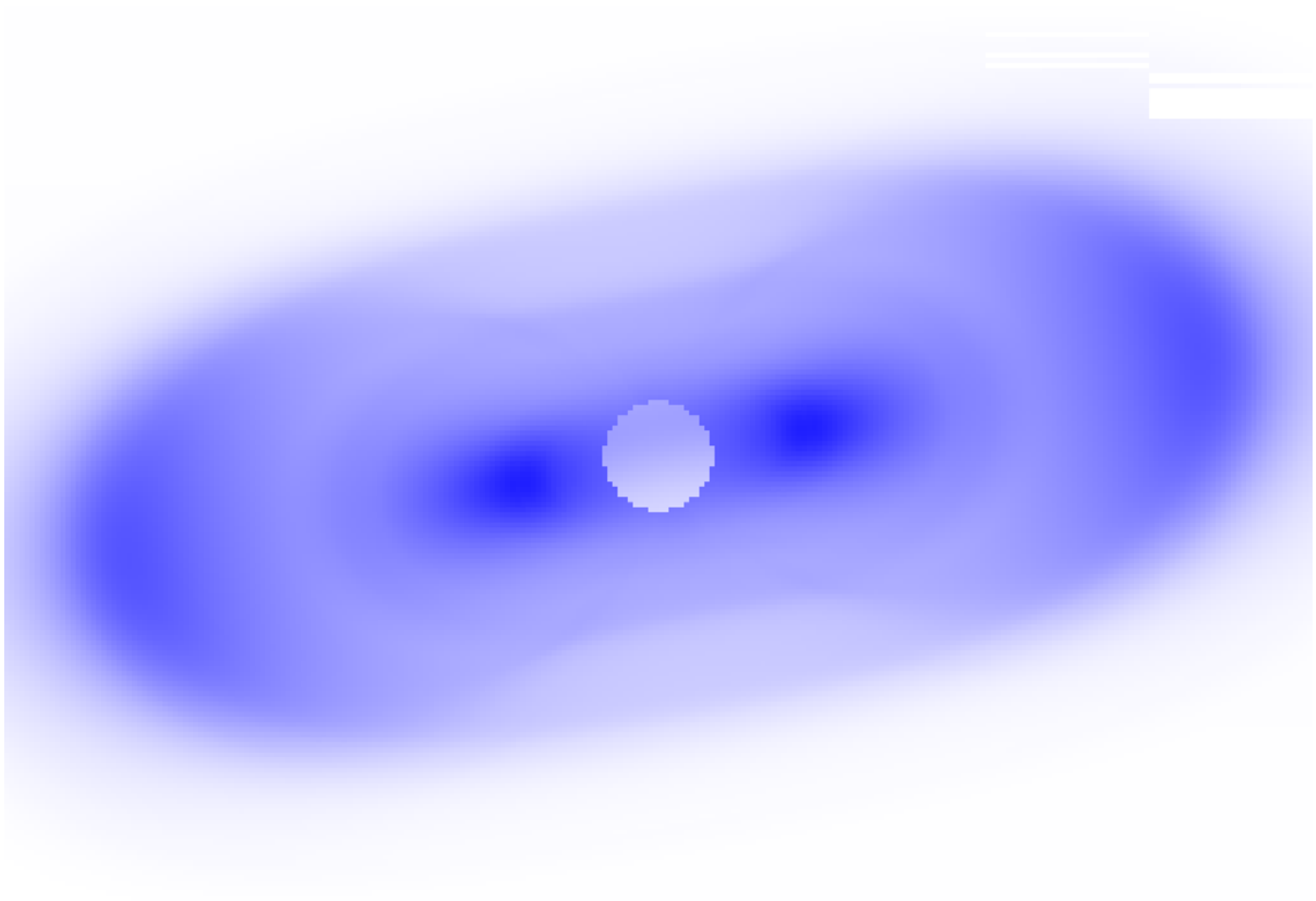
Coordinate system of Subbotin & Shprits (2012).

Energy/pitch-angle diffusion coefficients of Summers (2005).

[Cool movie goes here]

We can test with an analytic model of Jupiter.

Divine & Garrett (1983) model has closed-form expressions for the full (6D) phase-space distribution.



PKGW+ in prep.

Synchrotron coefficients come from Symphony.

The fully generic polarized radiative transfer equation is:

$$\frac{\mathrm{d}}{\mathrm{d}s}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \boxed{j_I} \\ \boxed{j_Q} \\ 0 \\ \boxed{j_V} \end{pmatrix} - \begin{pmatrix} \boxed{\alpha_I} & \boxed{\alpha_Q} & 0 & \boxed{\alpha_V} \\ \alpha_Q & \alpha_I & \boxed{\rho_V} & 0 \\ 0 & -\rho_V & \alpha_I & \boxed{\rho_Q} \\ \alpha_V & 0 & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

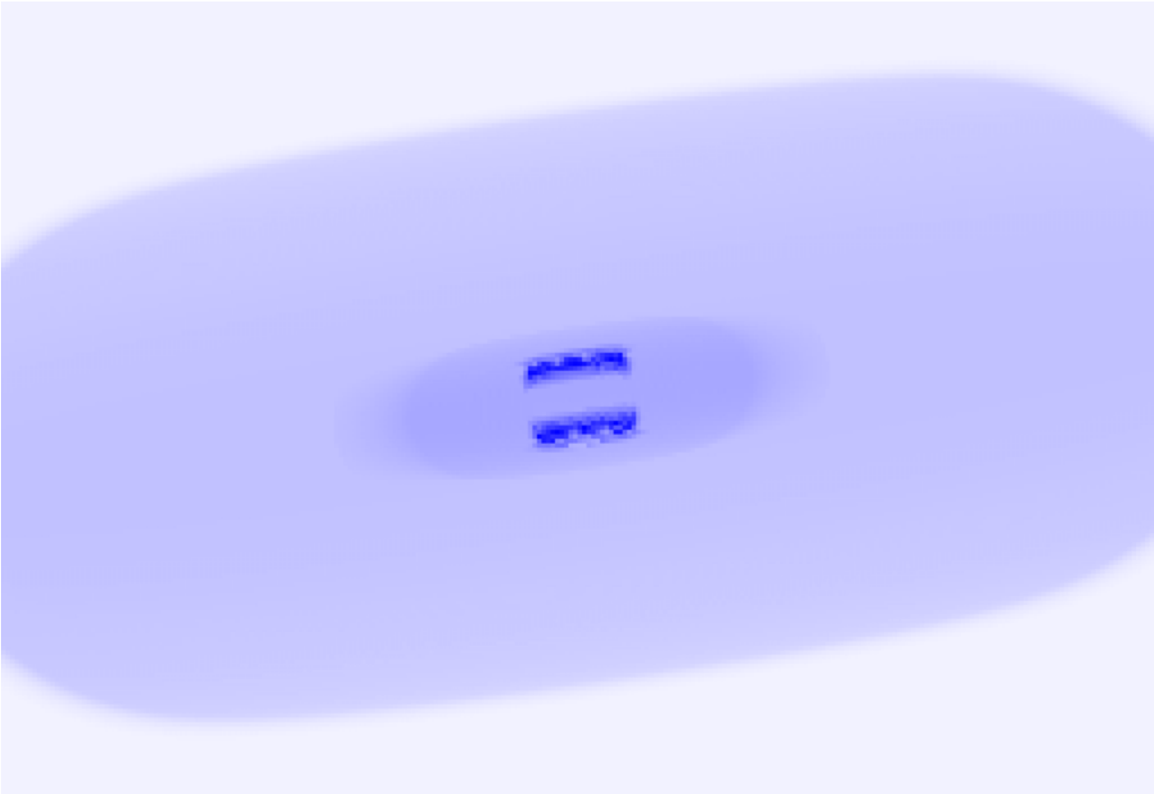
We can choose the linear polarization basis such that there are just *eight* unique coefficients.

The name of the game: given a population of electrons, calculate these eight numbers.

The *Symphony* code (Pandya+ 2016) does just this.

Well, actually, they come from “rimphony”.

Symphony only supports isotropic distributions, but anisotropy is important in radiation belts:



PKGW+ in prep.

I extended the code to support anisotropy.

https://github.com/pkgw/rimphony

With a lot of new code for the Faraday terms.

New code to compute Faraday conversion and rotation coefficients using the formalism of Heyvaerts+ 2013.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

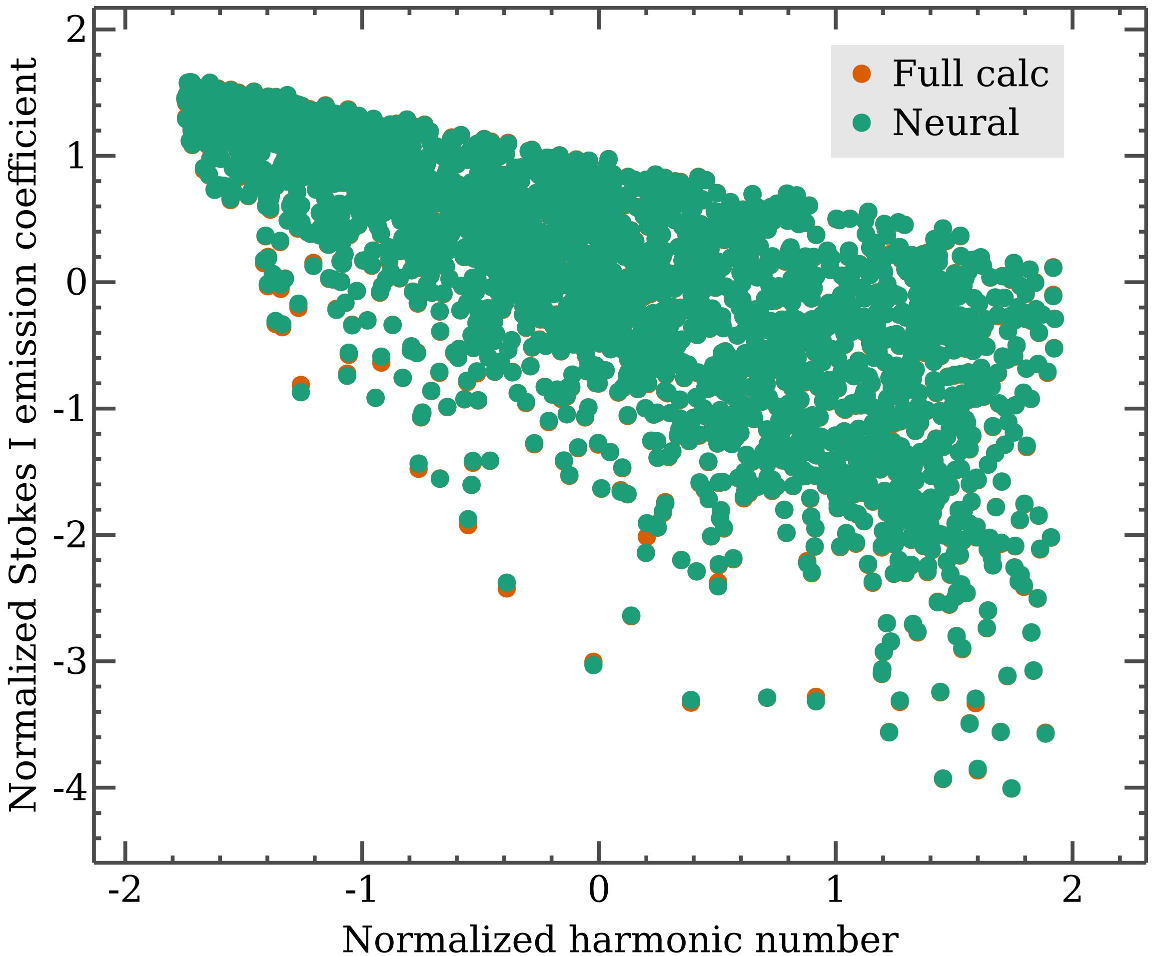
APPENDIX A: VARIABLES SUITED TO THE RELATIVISTIC PARTICLE-WAVE INTERACTION
APPENDIX B: THE CONTINUOUS-SPECTRUM REPRESENTATION OF THE CONDUCTIVITY
APPENDIX C: THE DISTRIBUTION ASSOCIATED WITH MULTIPLE RESONANCES
APPENDIX D: THE TRANSVERSE COMPONENTS OF THE CONDUCTIVITY
APPENDIX E: RESIDUAL PRINCIPLE VALUE TERMS ARE NEGLIGIBLE
APPENDIX F: NICHOLSON'S APPROXIMATION
APPENDIX G: OLVER UNIFORM ASYMPTOTIC EXPANSION OF BESSEL FUNCTIONS
APPENDIX H: COMPARISON OF QUASI-RESONANT AND NON-RESONANT CONTRIBUTIONS
APPENDIX I: KERNELS OF HIGHER MULTIPOLAR ORDERS FOR FARADAY COEFFICIENTS AT HIGH-FREQUENCY
APPENDIX J: FARADAY CONVERSION COEFFICIENT IN THE LOW-FREQUENCY LIMIT
APPENDIX K: FARADAY ROTATION COEFFICIENT IN THE LOW-FREQUENCY LIMIT
APPENDIX L: TRANSFER COEFFICIENTS FROM INTERPOLATED ISOTROPIC KERNELS

Heyvaerts+ 2013

Results agree with previous high-frequency limits, but can handle arbitrary anisotropic distributions.

And a neural network approximator for speed.

Neural networks can be good at approximating functions.

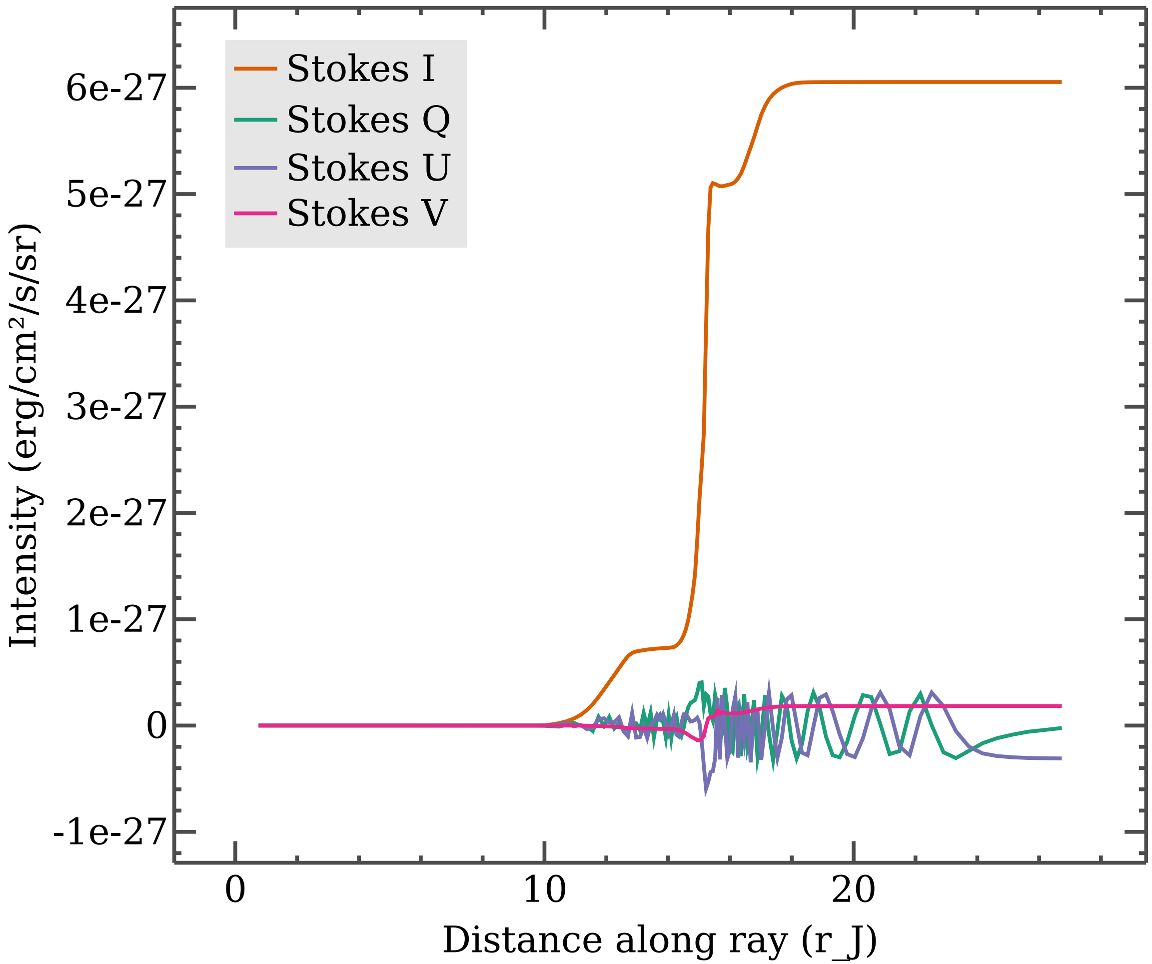


PKGW+ in prep.

~10^5 speedup, much more consistent computational cost.

The RT integration is done with "grtrans".

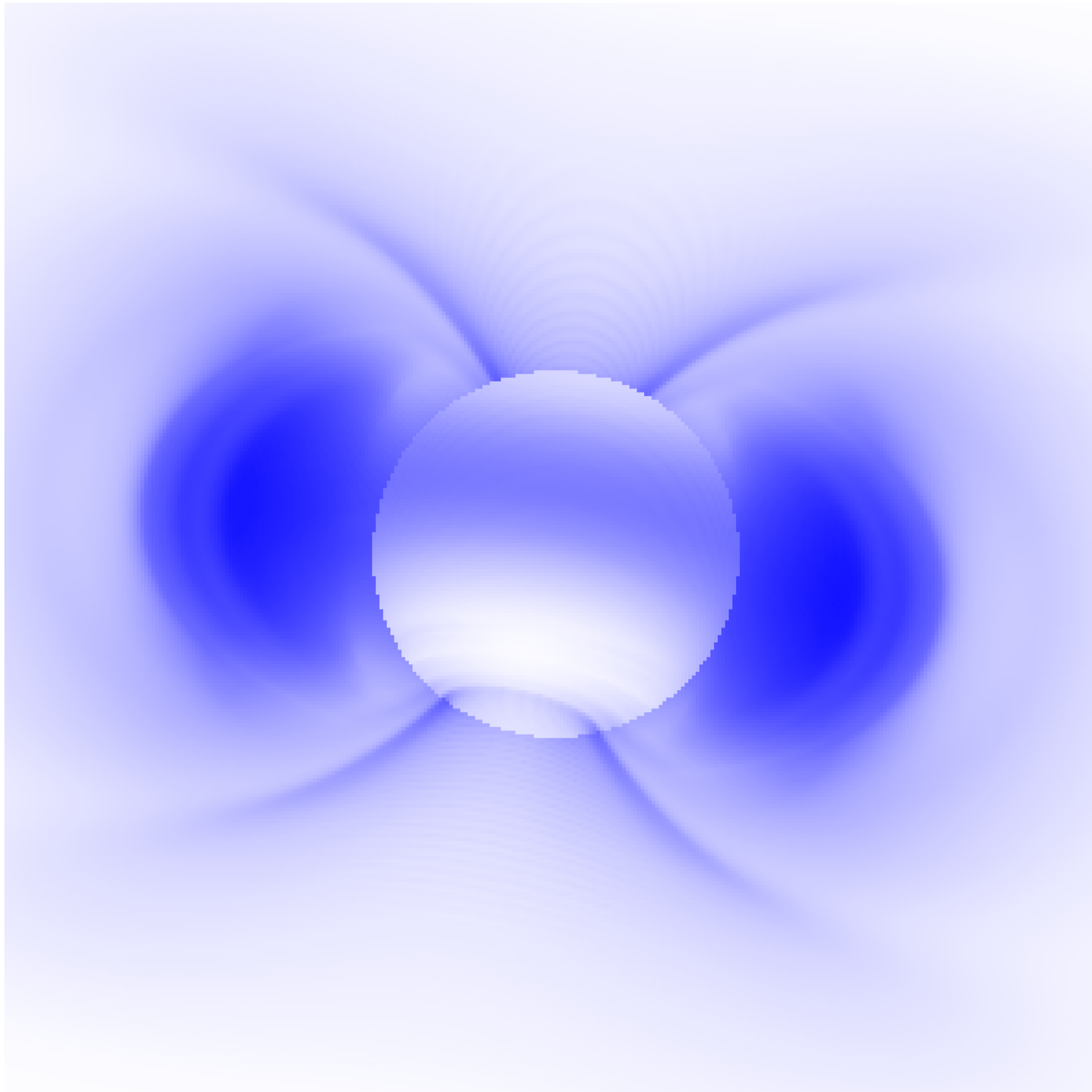
An open, full-Stokes radiative transfer code (Dexter 2016).



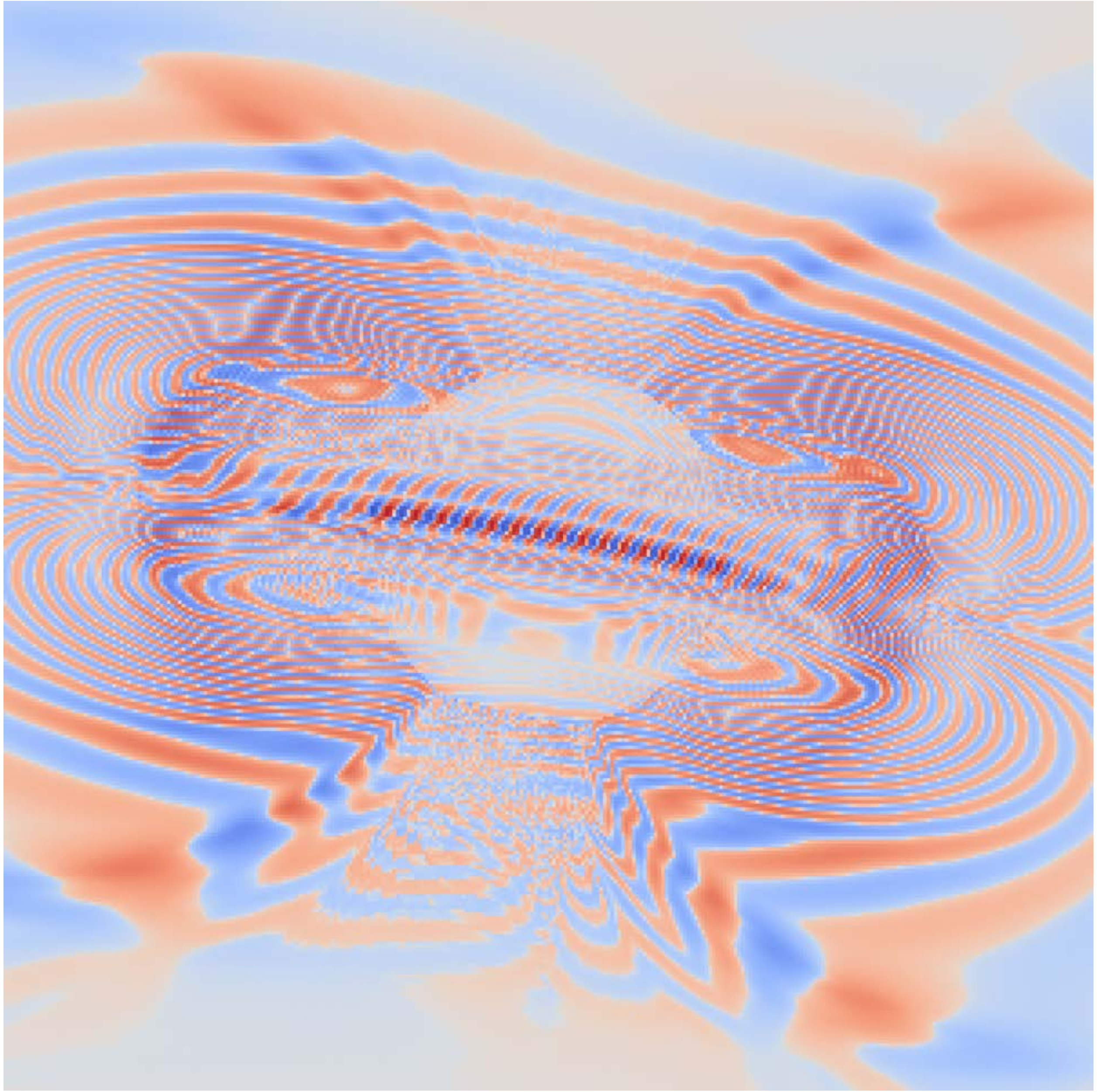
PKGW+ in prep.

Integration can be difficult when rays have large “Faraday depth”.

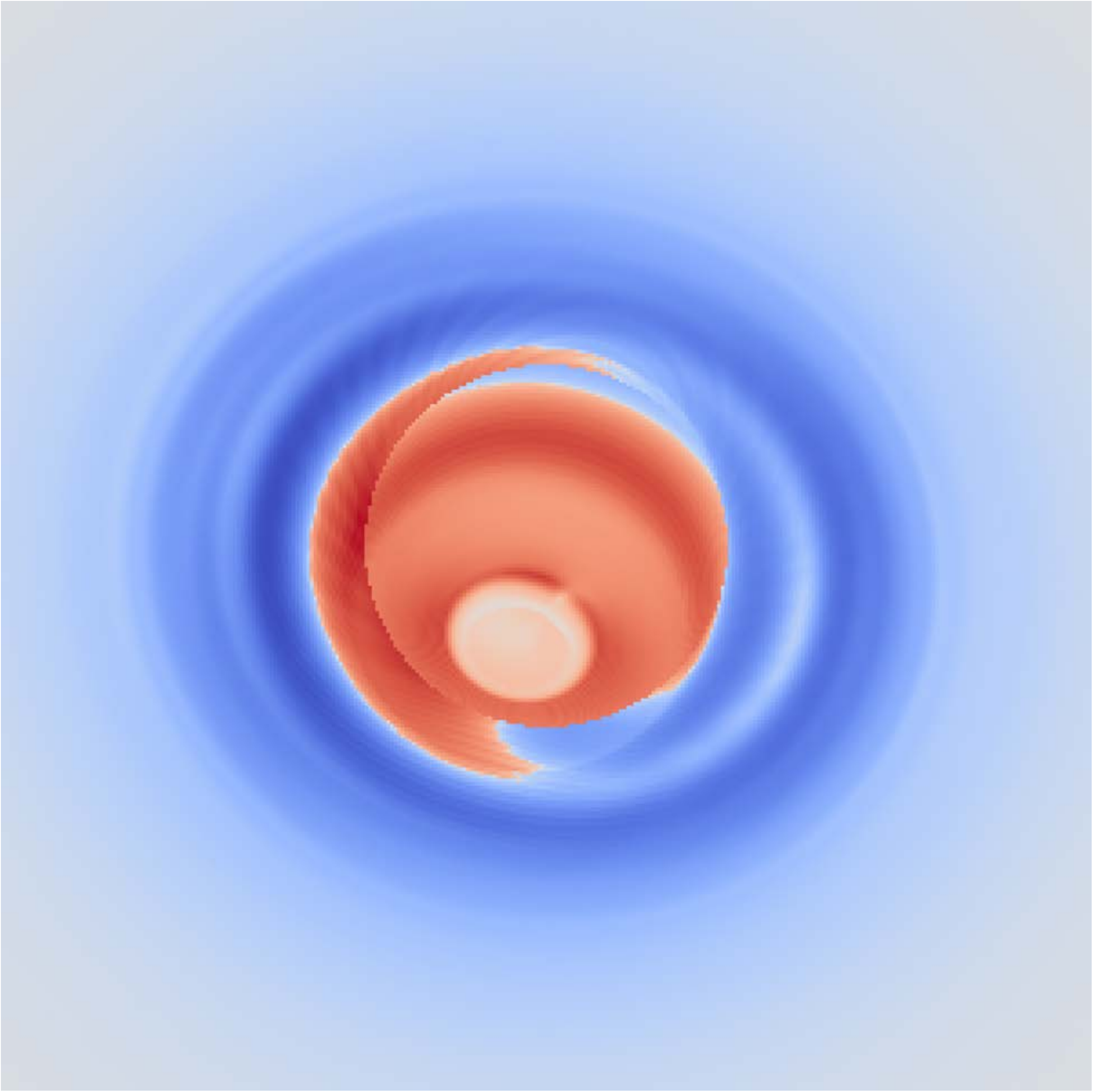
In the end, Jupiter looks pretty respectable.



Low-frequency linear polarization washes out.



Pole-on views might explain the brown dwarf data.



Here's a summary.

- The Van Allen model is a tractable paradigm for thinking about radio-emitting magnetospheres.
- You can use **vernon**/**rimphony** to do fully-polarized RT for arbitrary particle distributions.
- But stay aware of the model's limitations.

Thanks for your attention!

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HTML talk info: https://tinyurl.com/htmltalk • *Design credits*: Hakim El Hattab (“white” theme), Julieta Ulanovsky (Montserrat font), Steve Matteson (Open Sans font) • *Tech credits*: git, reveal.js, KaTeX, Firefox developer tools, d3.js.

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