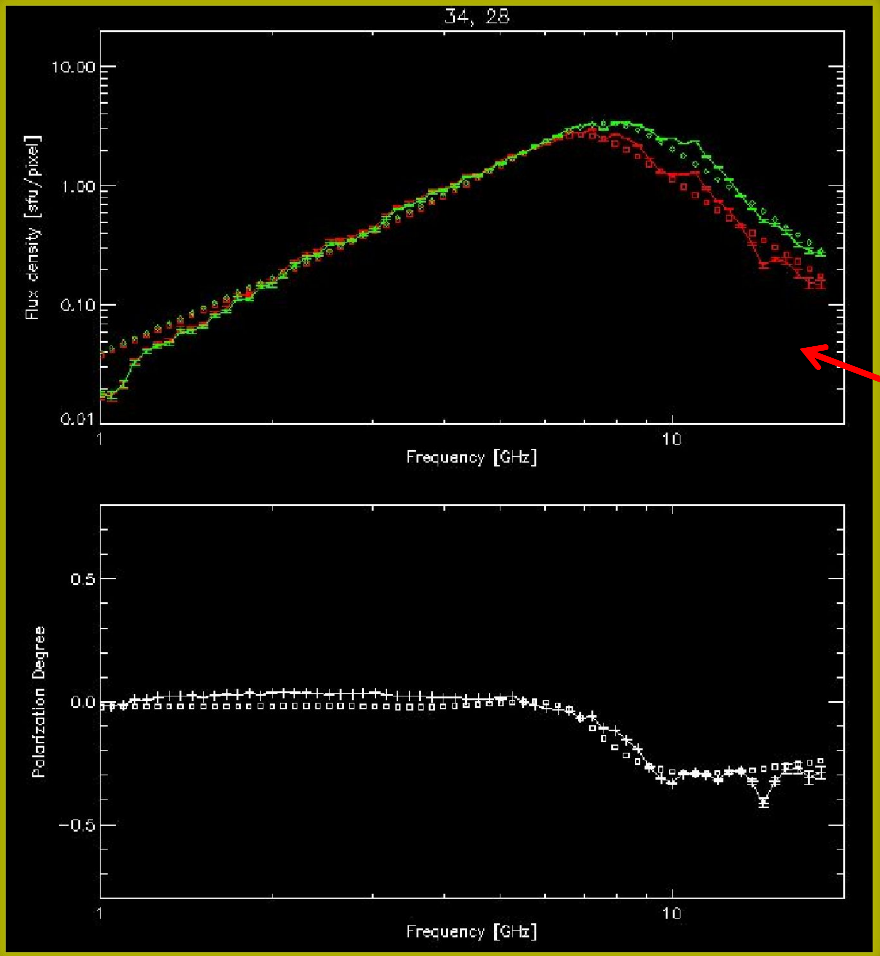
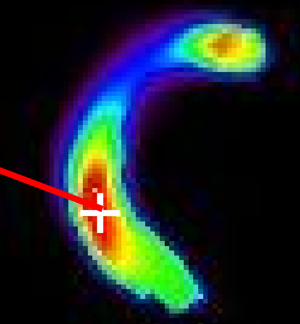
COSMIC MAGNETOBREMSSTRAHLUNG: FAST COMPUTING CODES AND 3D MODELING TOOLS





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Relevance

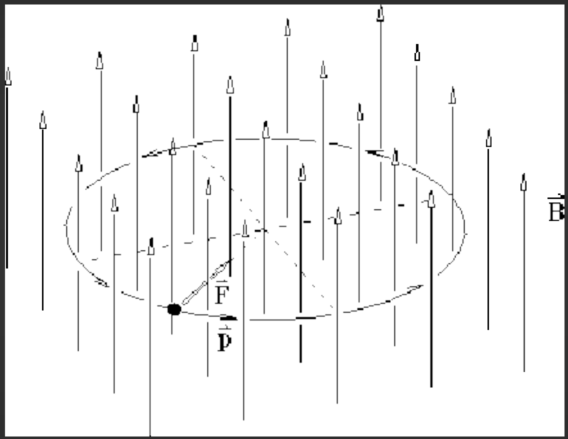
- ***Vitaly Ginzburg was among the very first scientists who recognized a fundamentally important role of the synchrotron radiation in astrophysics; moreover, he was the most enthusiastic 'promoter' of this emission mechanism during 50ies, which ensured that the synchrotron theory became commonly accepted in the radio astronomy and then well beyond that. His fundamental pioneering review paper 'Cosmic Magnetobremsstrahlung (synchrotron Radiation)' published along with Sergei Syrovatskii in ARR&A in 1965 remains an up-to-date and actively used (and cited) paper on the topic.***

Outline

- Radio emission mechanism and magnetic fields
- Fast codes for calculating radio emission
- Interactive realistic 3D modeling tools
- Fitting brightness temperature radio spectra for quantitative measurement of parameters, including B
- Observations needed to measure radio brightness temperature spectra

Magnetobremsstrahlung/Gyroemission

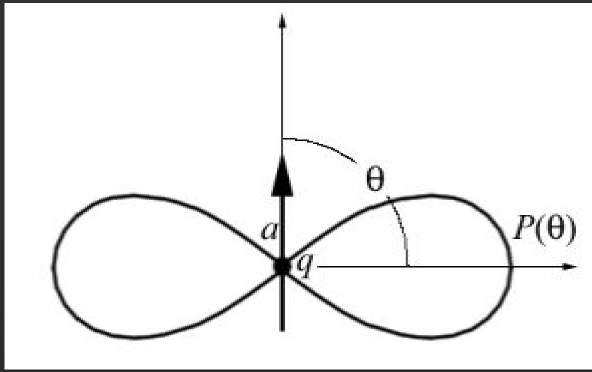
- Radio emission is produced by charged particles undergoing acceleration.
- One type of acceleration is due to the magnetic Lorentz force, i.e. particles spiraling in a magnetic field.
- The power radiated (given by the Larmor formula) is proportional to a^2, hence electrons are more efficient than protons by the ratio $(m_p/m_e)^2$ (more than 10^6 times more efficient).



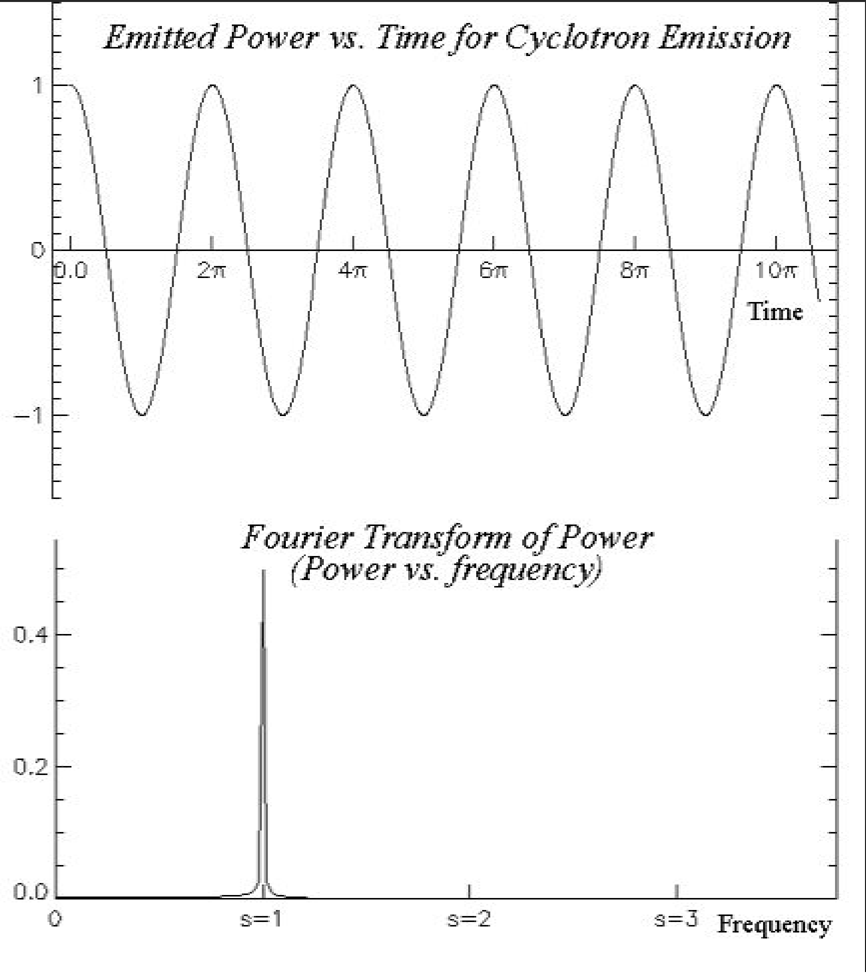
Motion of an electron (negative charge) in a uniform magnetic field.

Cyclotron Emission

- The lowest energy electrons undergoing acceleration by the Lorentz force have a nice, symmetric dipole radiation pattern.

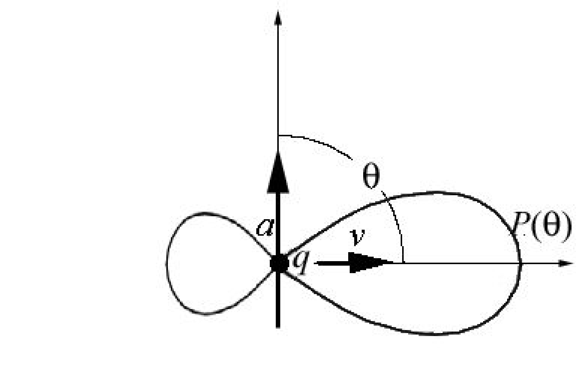


- This produces a pure sinusoidal electric field at the cyclotron frequency, ν_B, whose Fourier transform is a single spectral line at $s = \nu / \nu_B = 1$.

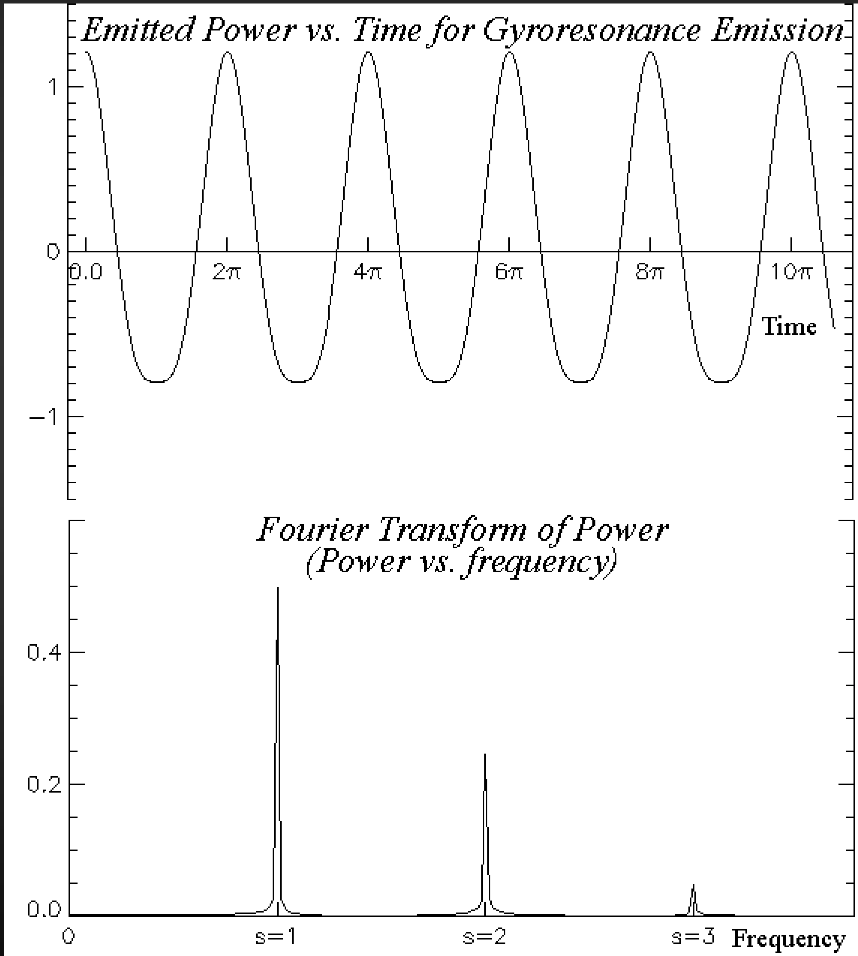


Gyroresonance Emission

- Higher energy electrons (say those at 10^6 K) begin to have a markedly asymmetric radiation pattern.

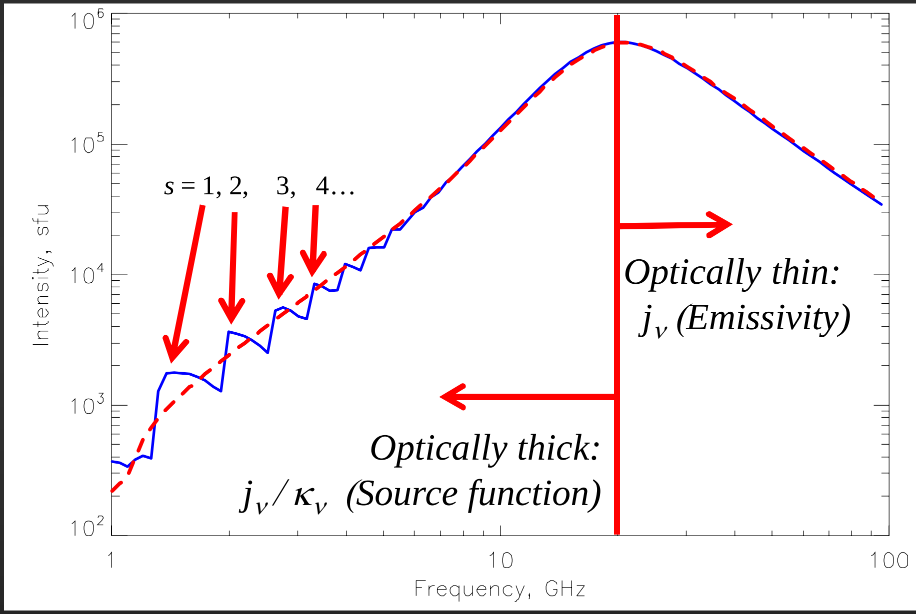


- This produces a mainly sinusoidal electric field, but with asymmetric peaks and valleys.
- The Fourier transform is a series of spectral lines at $s = \nu/\nu_B = 1, 2, 3...$



Gyrosynchrotron Emission

- At mildly relativistic energies (effective temperatures of 10^8 K or higher) the asymmetry in the radiation pattern becomes more pronounced.
- This produces an even more peaked (pulsed) electric field, containing many harmonics that now blend into a continuum spectrum.
- The spectrum turns over at low frequencies due to self-absorption.
- This is the spectrum from flares that we want to use for magnetic field diagnostics.



Exact formalism for the gyrosynchrotron emission
(V.Ya. Eidman 1958; R. Ramaty 1969; D.B. Melrose 1968):

Emission intensity:

$$J_\sigma(\nu,\theta) = \frac{j_\sigma(\nu,\theta)}{\varkappa_\sigma(\nu,\theta)}\left[1 - e^{-\varkappa_\sigma(\nu,\theta)L}\right],$$

Plasma emissivity:

$$j_\sigma(\nu,\theta) = \frac{2\pi e^2}{c}\frac{N_\sigma \nu^2}{1+T_\sigma^2}\sum_{s=-\infty}^{\infty}\int\left[\frac{T_\sigma(\cos\theta - N_\sigma\beta_z) + L_\sigma\sin\theta}{N_\sigma\beta_\perp\sin\theta}J_s(\lambda) + J_s'(\lambda)\right]^2 \times \beta_\perp^2 f_{\mathbf{p}}(\mathbf{p})\delta\left(\nu - \frac{s\nu_B}{\Gamma} - \frac{k_z v_z}{2\pi}\right)\mathrm{d}^3\mathbf{p},$$

Absorption coefficient:

$$\varkappa_\sigma(\nu,\theta) = -\frac{2\pi e^2}{N_\sigma(1+T_\sigma^2)}\sum_{s=-\infty}^{\infty}\int\left[\frac{T_\sigma(\cos\theta - N_\sigma\beta_z) + L_\sigma\sin\theta}{N_\sigma\beta_\perp\sin\theta}J_s(\lambda) + J_s'(\lambda)\right]^2 \times\left[\sin\alpha\frac{\partial f_{\mathbf{p}}(\mathbf{p})}{\partial p} + \frac{\cos\alpha - N_\sigma\beta\cos\theta}{p}\frac{\partial f_{\mathbf{p}}(\mathbf{p})}{\partial\alpha}\right]\beta_\perp\delta\left(\nu - \frac{s\nu_B}{\Gamma} - \frac{k_z v_z}{2\pi}\right)\mathrm{d}^3\mathbf{p}.$$

Calculations become very slow when $\nu/\nu_B >> 1$.

Fast Gyrosynchrotron Codes

- Fleishman & Kuznetsov (2010) made a breakthrough in fast calculation of gyrosynchrotron spectra that has enabled this field to proceed in an exciting new direction—enabling practical forward fitting.

Emissivity

$$j_\nu \simeq \frac{2\pi e^2}{c}\frac{\nu}{n(1+T^2)\sin^2\theta}\int_{p_1}^{p_2} u(p)p^2\,\mathrm{d}p\int_{-1}^{1} g(\mu)Z^{2s}Q\,\mathrm{d}\mu$$

energy (or momentum) distribution function

pitch-angle distribution function

factor arising from Bessel functions

factor describing the wave polarization

Absorption Coefficient

$$\varkappa \simeq -\frac{2\pi e^2 m_e c}{n^3\nu(1+T^2)\sin^2\theta}\int_{p_1}^{p_2} u(p)\Gamma\,\mathrm{d}p\int_{-1}^{1} g(\mu)Z^{2s}QR\,\mathrm{d}\mu$$

factor with derivatives of the distribution function

Fast Gyrosynchrotron Codes

- This breakthrough consists of extending approximations by Petrosian (1981) and Klein (1987) and making them far more accurate and more widely applicable.
- The calculations were made more accurate and applicable by using a gaussian approximation over pitch angle and locating the peak emissivity more accurately, by numerical means.
- The calculations were also made more accurate and widely applicable by melding exact calculations at low harmonics with approximate calculations at high harmonics.

Strongly anisotropic (pancake-like) distribution

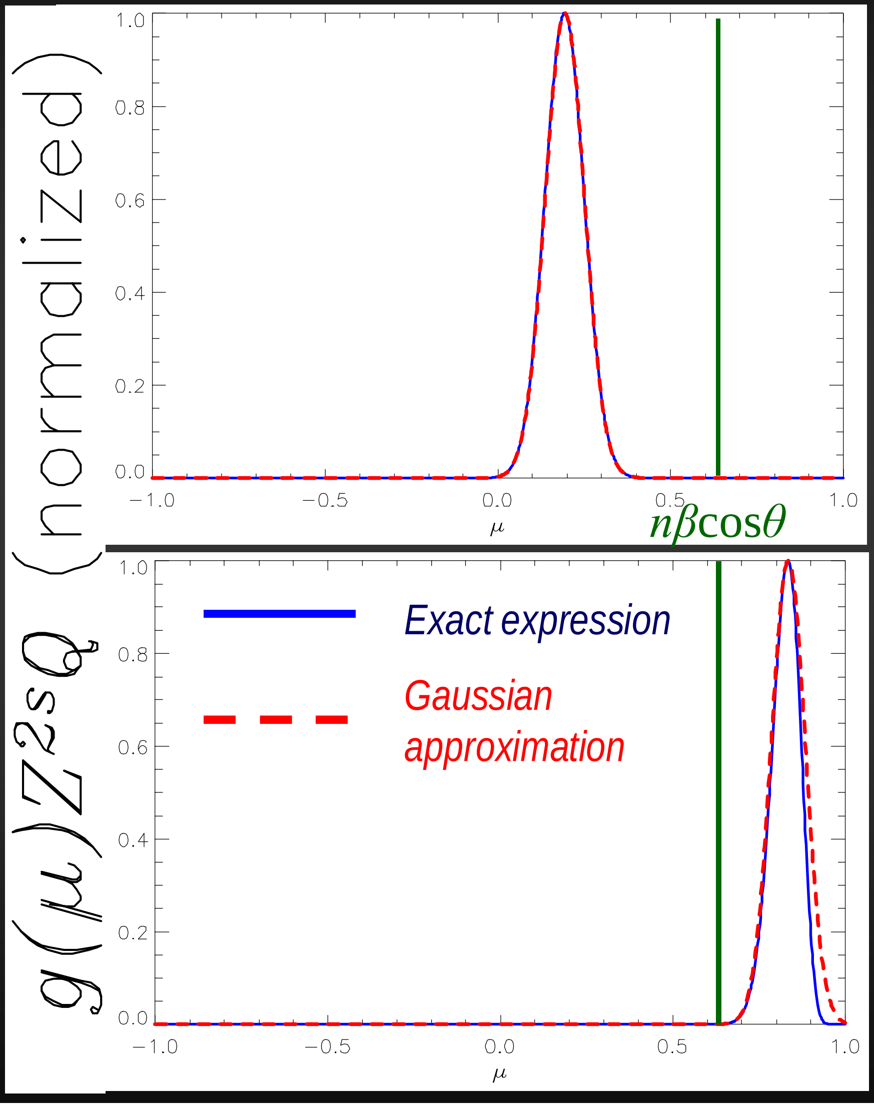
$$g(\mu) = \exp\left(-\frac{\mu^2}{\Delta\mu^2}\right)$$

Δμ=0.1

Strongly anisotropic (beam-like) distribution

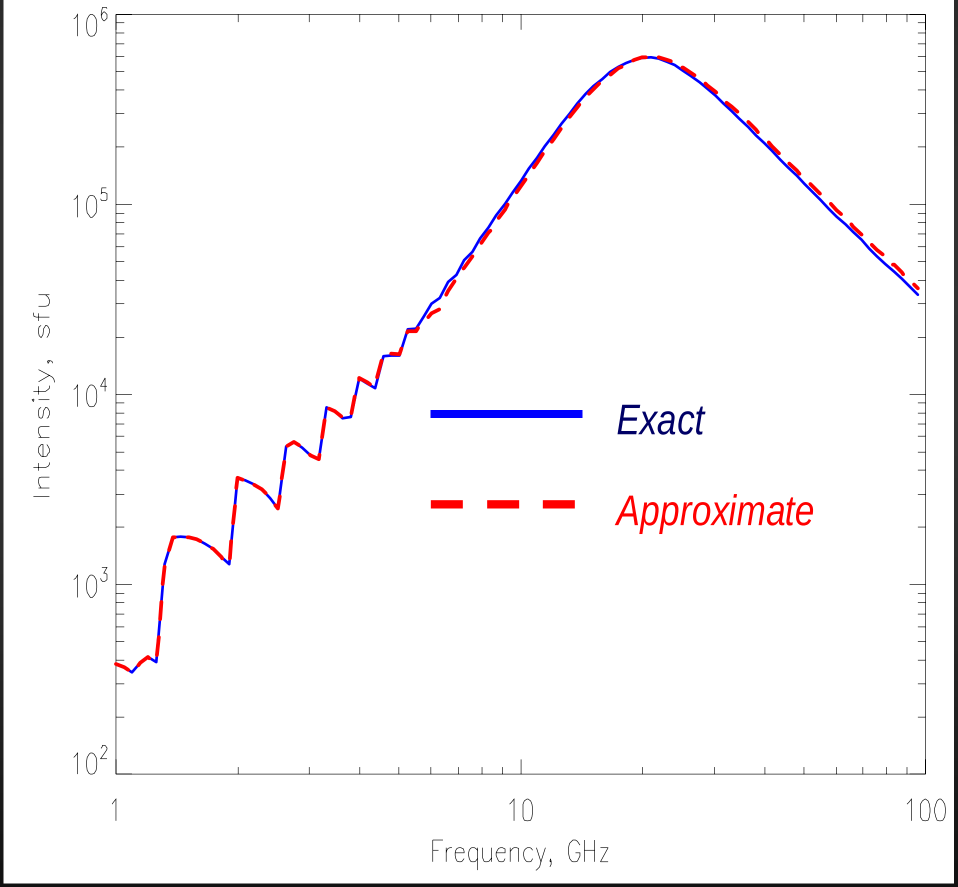
$$g(\mu) = \exp\left[-\frac{(\mu-1)^2}{\Delta\mu^2}\right]$$

Δμ=0.1



Fast Gyrosynchrotron Codes

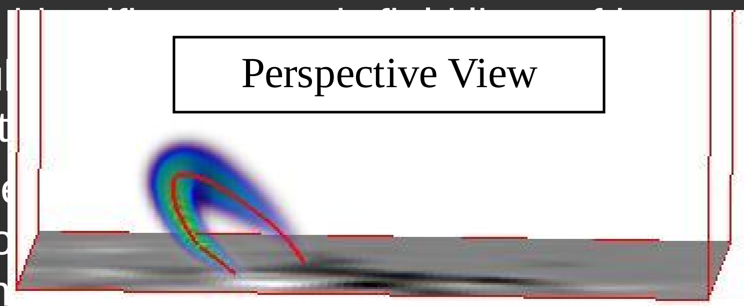
- Here is a demonstration of the performance of the exact vs. approximate codes.
- Note that this is for a homogeneous source. For a real source, there is another integration to do—that along the line of sight.
- To investigate this in a realistic source, a model flaring loop model was constructed.



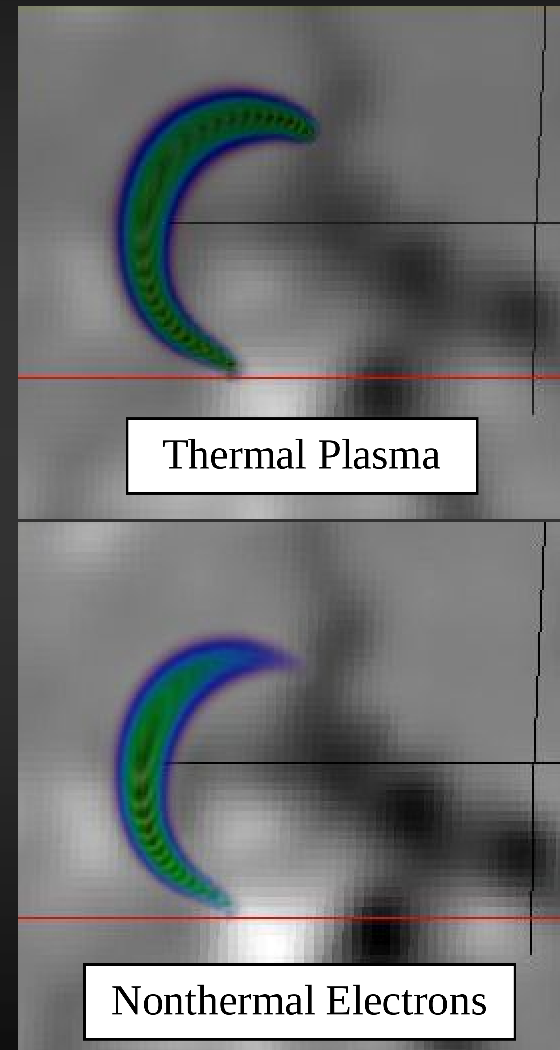
Calculation time (for the same parameters and accuracy):

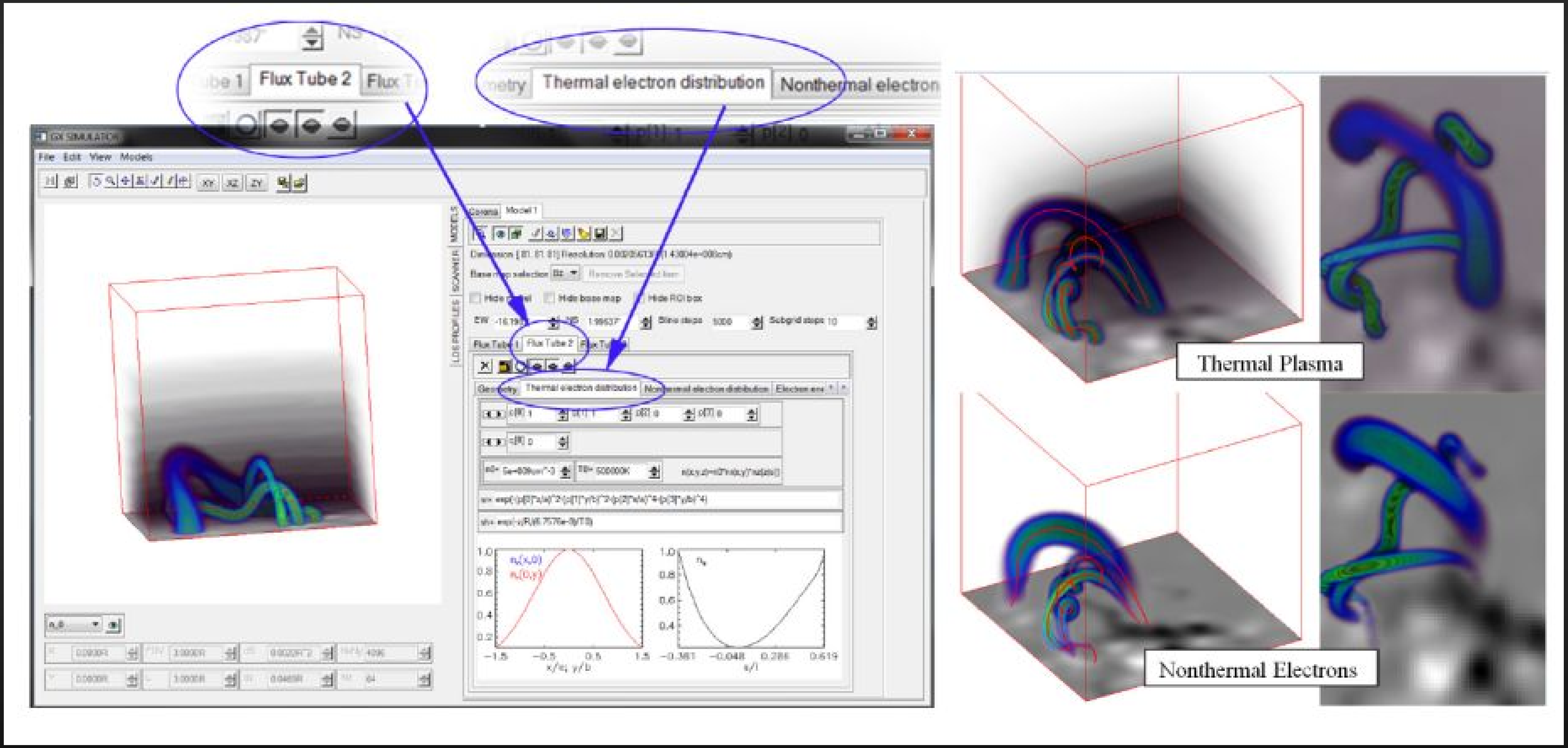
Multifrequency Radio

- In order to investigate what actual radio observations can hope to do, we have developed a general tool called GX Simulator. Using the intuitive graphical environment, the user reads in a magnetic model (e.g. a NLFFF extrapolation), t, and then popul tubes) with bot cles.
- Once the mode e gyrosynchrotro emission) from (or multi-energy) images.

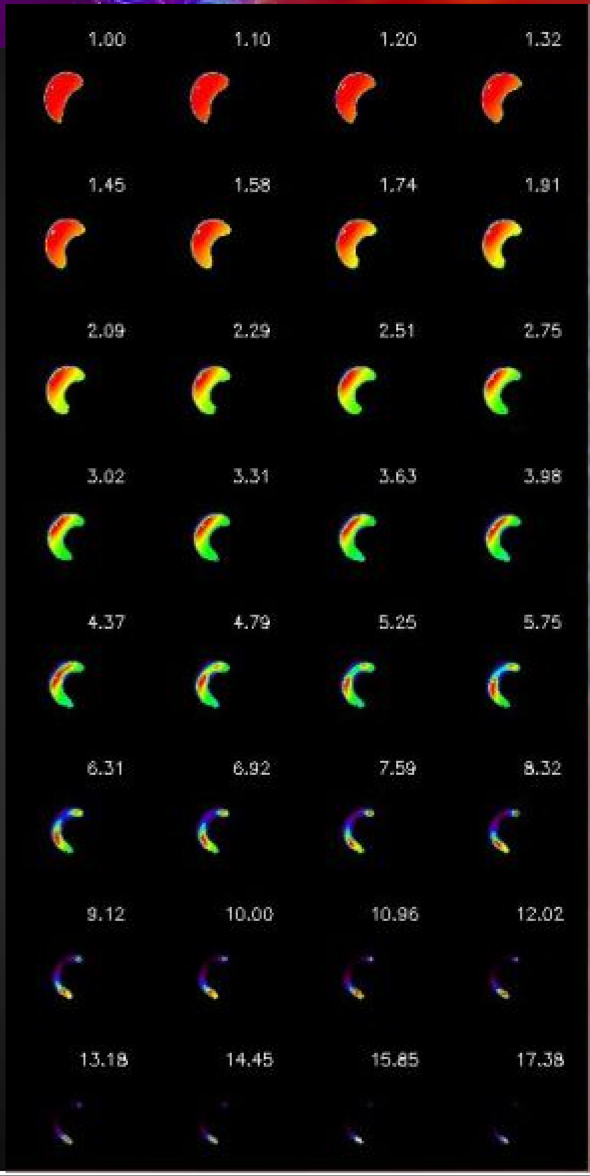


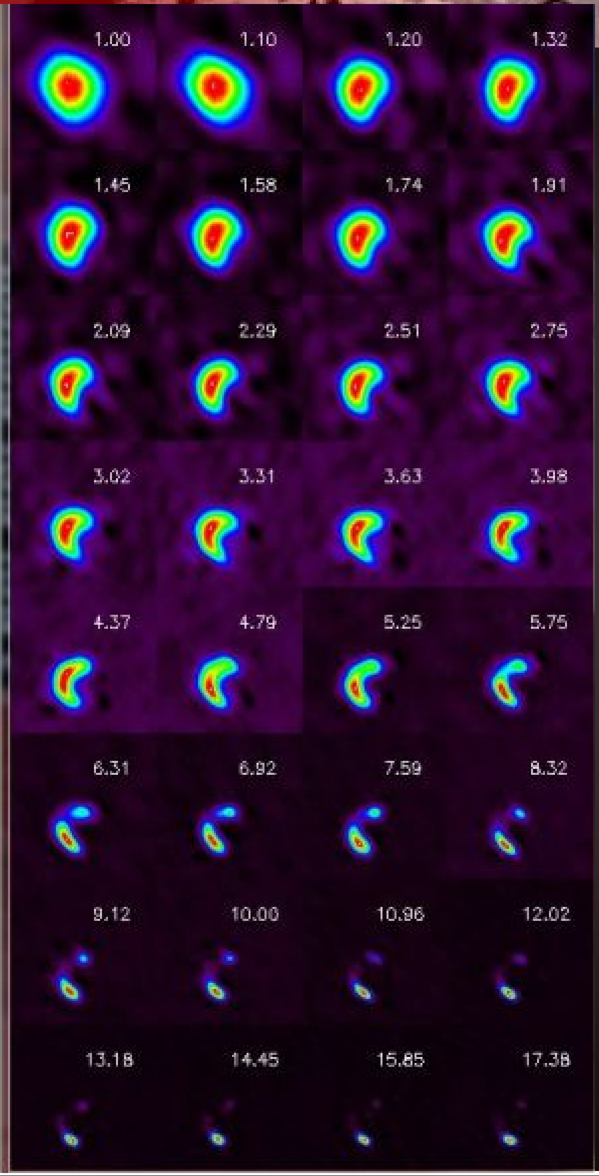
- Those images can then be folded through any instrument, to generate images as seen by the instrument.
- We will now show an example.





Flux Tube 2
Thermal electron distribution
Nonthermal electron
Thermal Plasma
Nonthermal Electrons


1.00 1.10 1.20 1.32
1.45 1.58 1.74 1.91
2.09 2.29 2.51 2.75
3.02 3.31 3.63 3.98
4.37 4.79 5.25 5.75
6.31 6.92 7.59 8.32
9.12 10.00 10.96 12.02
13.18 14.45 15.85 17.38


1.00 1.10 1.20 1.32
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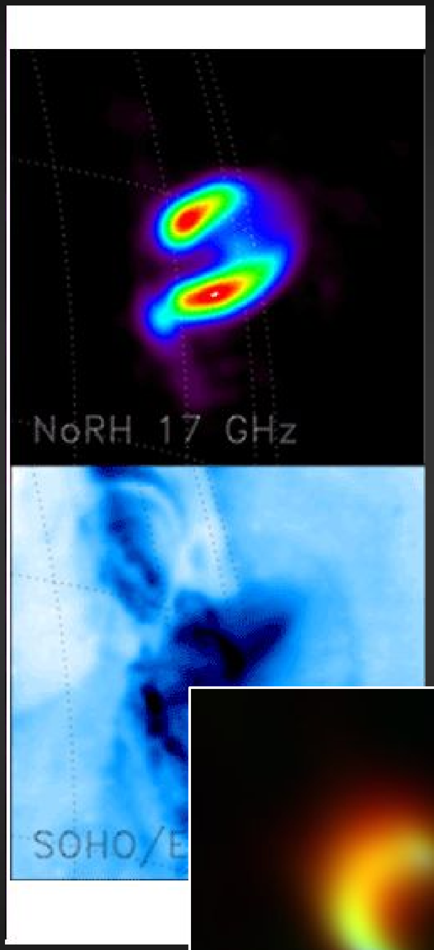
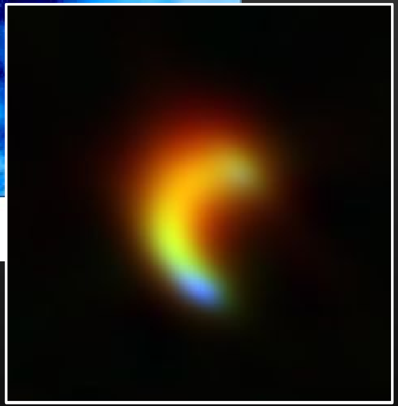
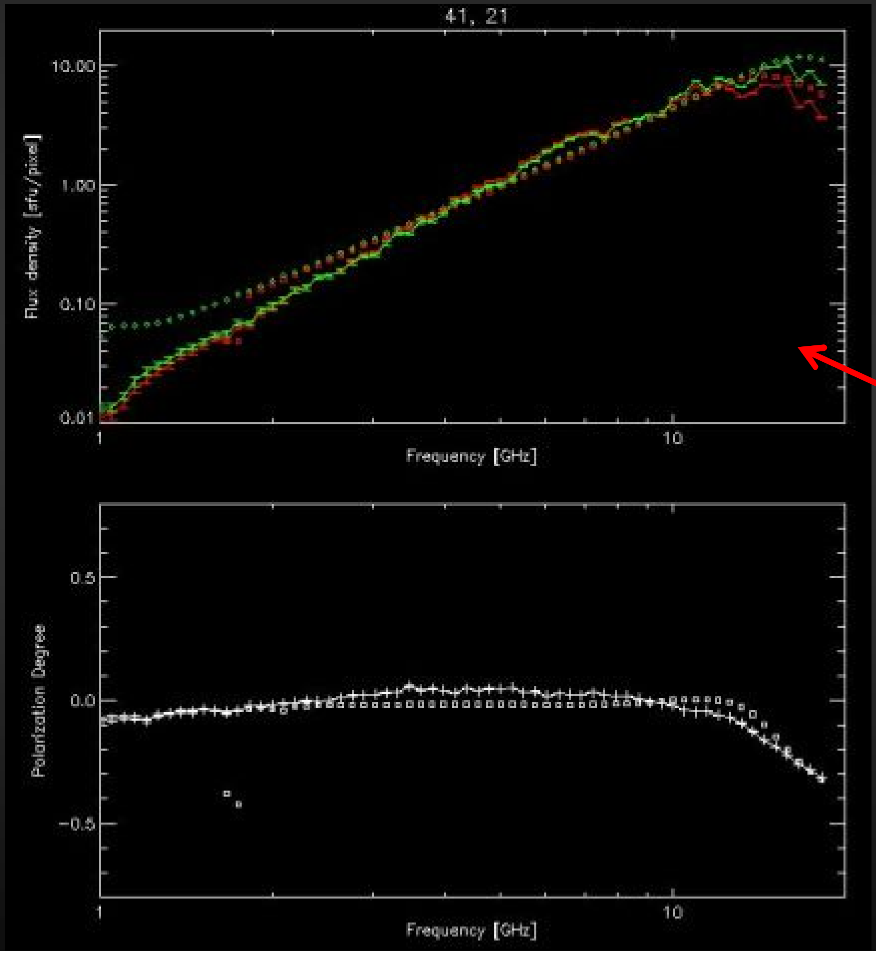
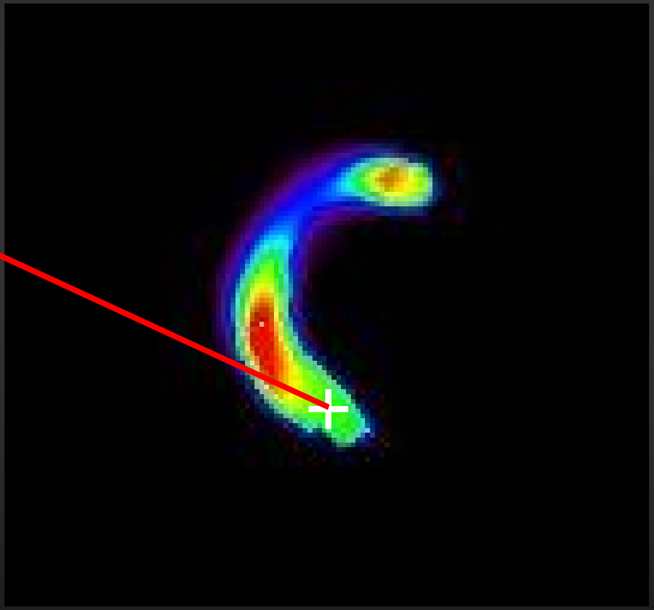

NoRH 17 GHz

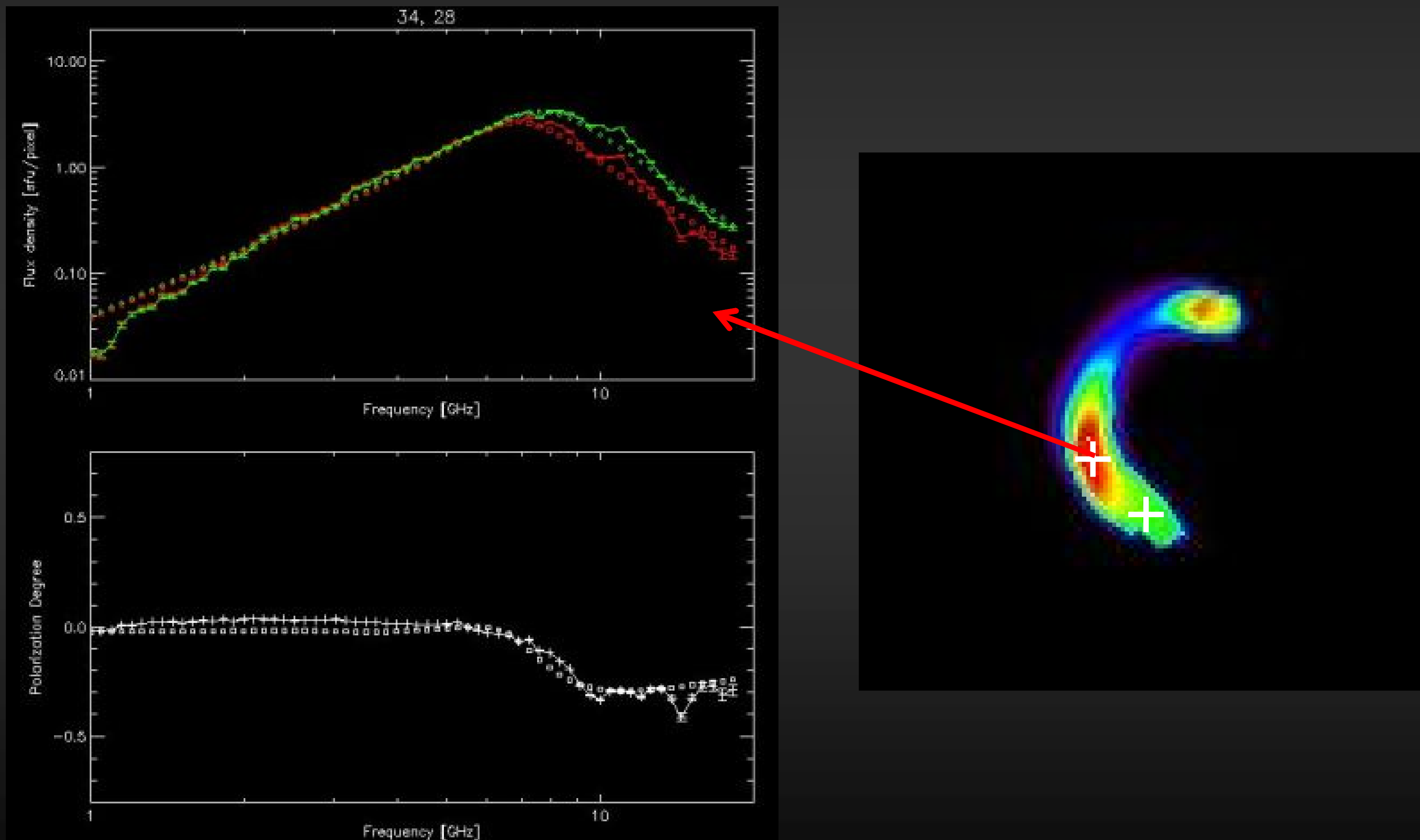


High-Field Footpoint

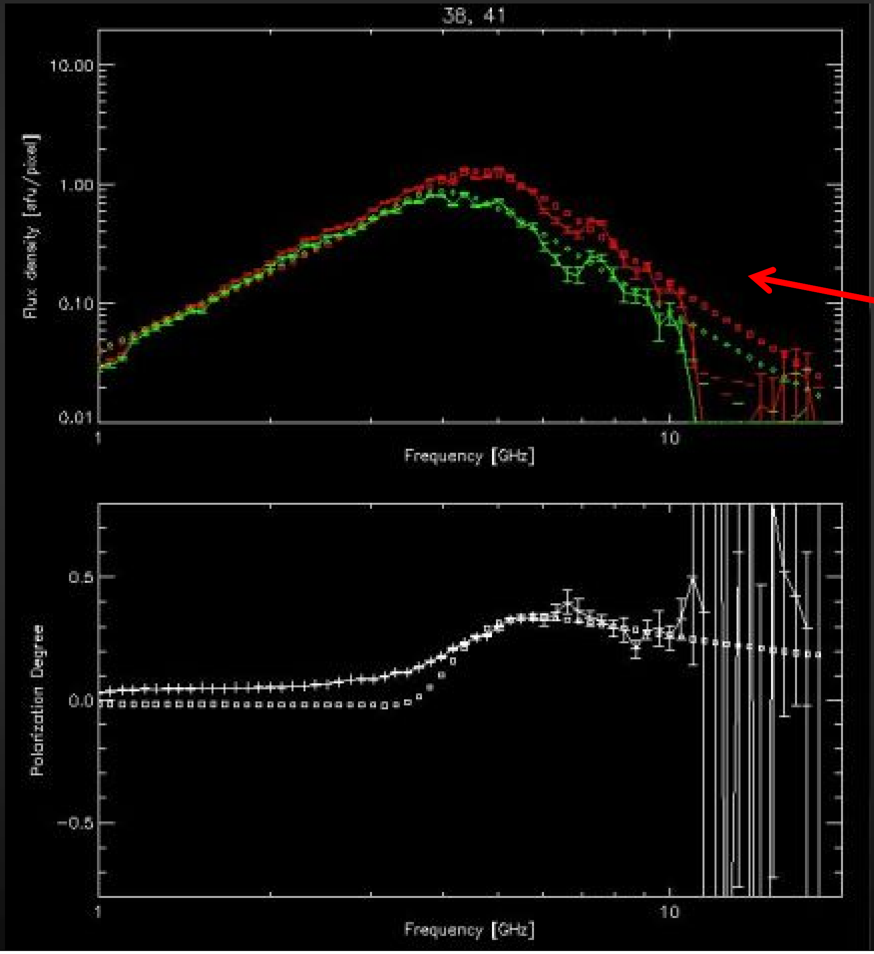




Part-way Up Loop Leg



Looptop


38, 41
10.00
1.00
0.10
0.01
Flux density [sfu/pixel]
1
10
Frequency [GHz]
0.5
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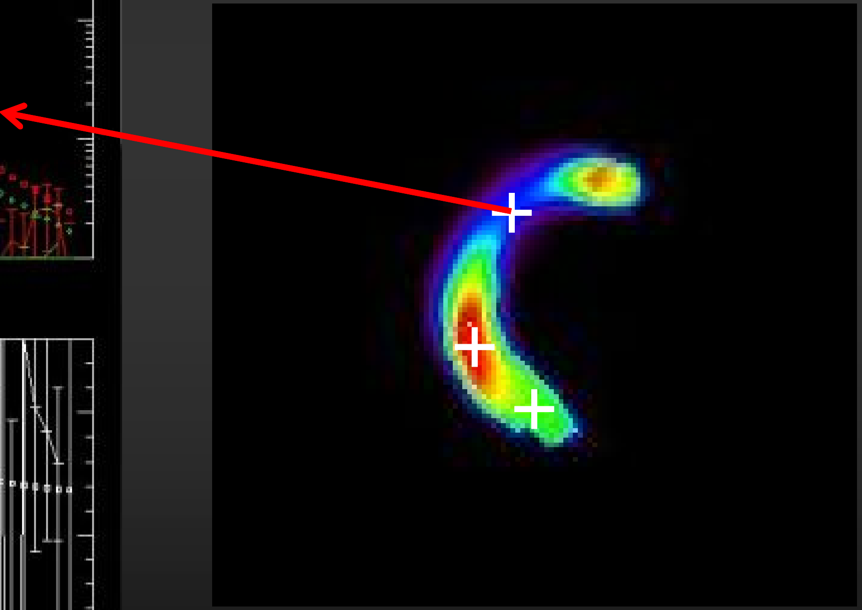
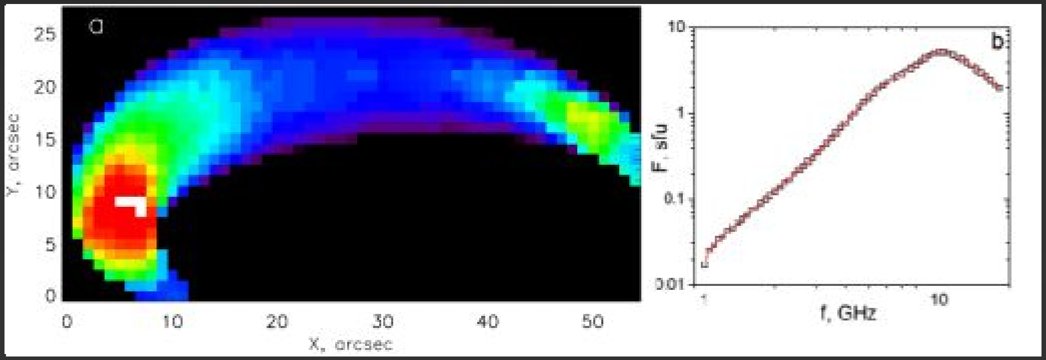
-0.5
Polarization Degree
1
10
Frequency [GHz]



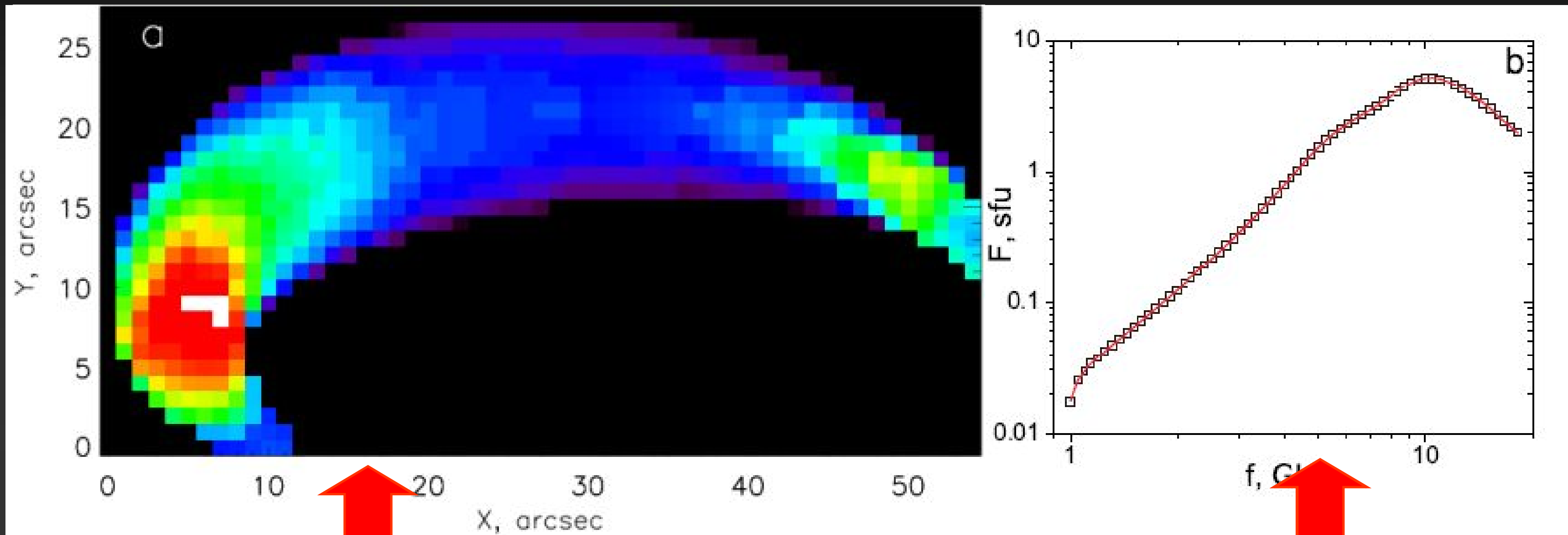
Multifrequency Radio Imaging

- The foregoing demonstration used “perfect” model data consisting of radio spectra at 100 frequencies from 1-20 GHz along each line of sight with 1” resolution.



- This is equivalent to images with 1” resolution at 100 frequencies, i.e. high-resolution multifrequency radio imaging. Is such a thing possible?
- Yes, with one major caveat: the spatial resolution of any radio array will be frequency dependent. Over a factor of 20 in radio frequency, the resolution will degrade by a like factor. 1” at 20 GHz implies 20” at 1 GHz.
- In addition, there will be other limitations including coronal scattering, additive noise, calibration issues, and the imaging properties of the radio array.

Fast Codes and 3D Modeling

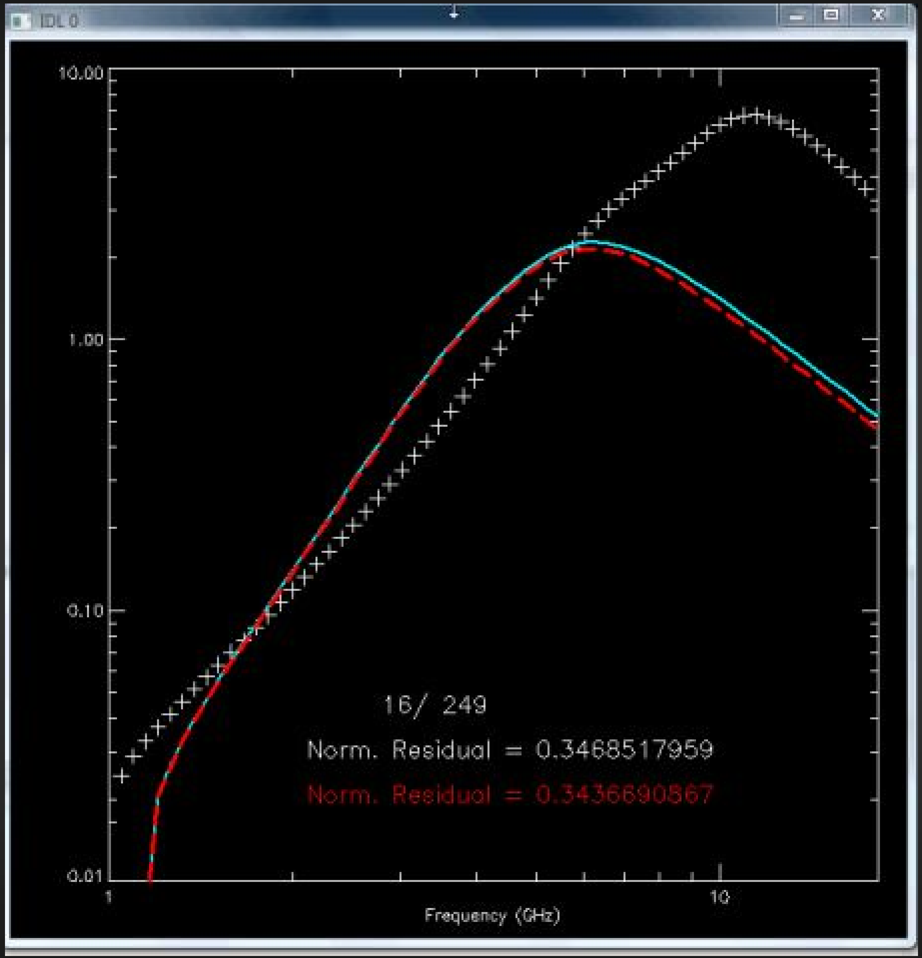


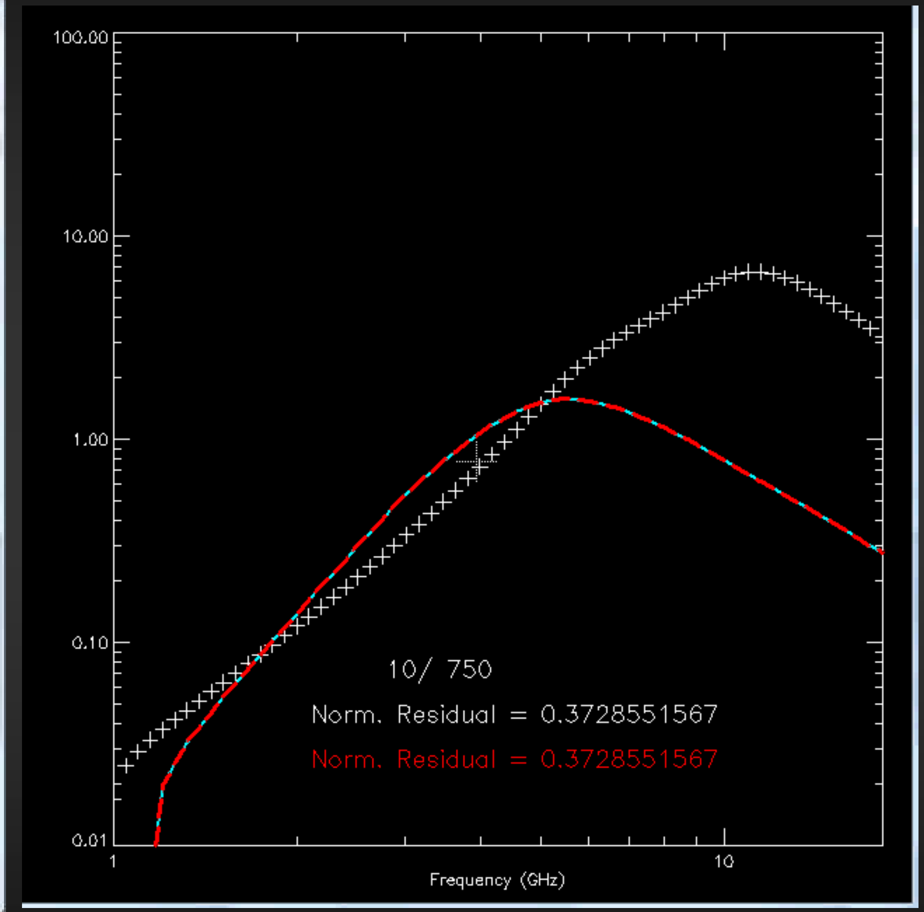
Equation of radiation transfer is solved numerically for each line of sight using fast GS codes

Fitted by

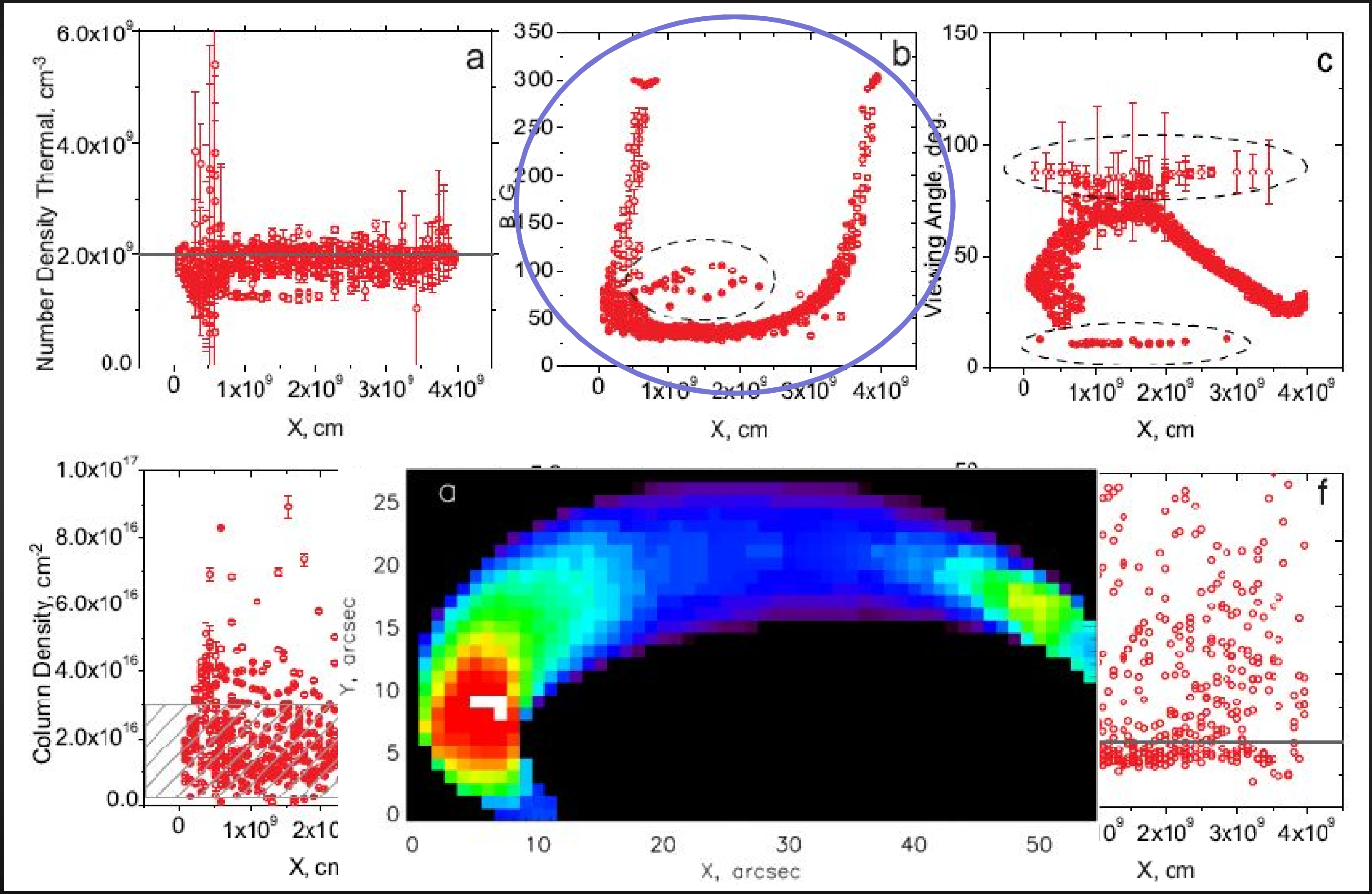
$$J_\sigma(\omega,\vartheta) = \frac{j_\sigma(\omega,\vartheta)}{\varkappa_\sigma(\omega,\vartheta)}\left(1 - e^{-\tau_\sigma}\right)$$

Note: Brightness temperature spectra (spatially resolved spectra or equivalently multifrequency images) are produced

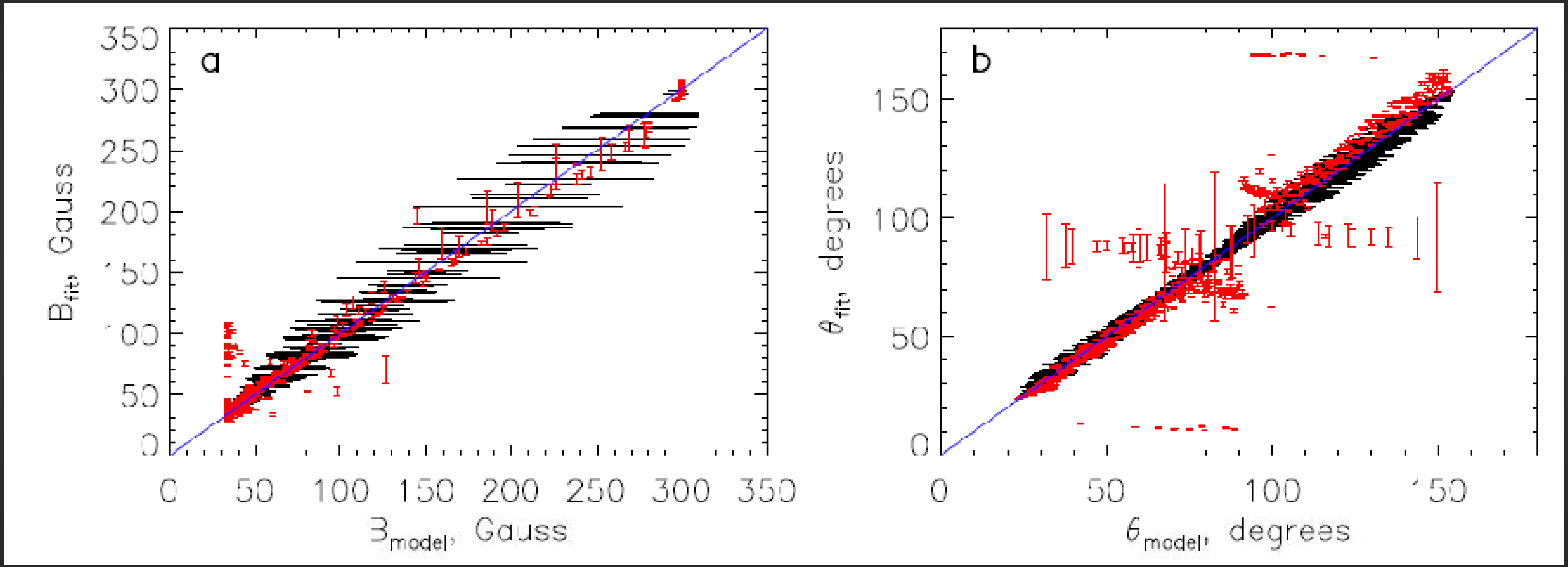




Note: 250 spectra in one case, 750 in the other => fast codes required!


a
b
c
f
Number Density Thermal, cm-3
B, G
Viewing Angle, deg.
Column Density, cm-2
X, cm
Y, arcsec
X, arcsec

Fit to Model Comparison



Conclusion: Solar radio spectra can be forward fit in principle, to determine magnetic field strength and inclination in flaring loops.

Summary

- We have fast GS codes and built the 3D tools to calculate radio emission in complex, realistic geometries.
- We have demonstrated the proof-of-concept for forward fitting spatially resolved gyrosynchrotron brightness temperature spectra to measure magnetic field in flaring loops.
- We have shown that the concept remains promising when sampled with a realizable instrument, with its finite resolution, image quality, and additive noise.
- Recall that everything I have shown is for a single snapshot in time. Obtaining such data with high time resolution will allow dynamic measurement of magnetic field strength and direction (as well as the other important parameters of the accelerated electron population) as the flare develops in time.
- All that remains is to build an instrument capable of making such observations. Enter EOVSA, now under construction.