Radio Measurements Of Coronal Magnetic Fields

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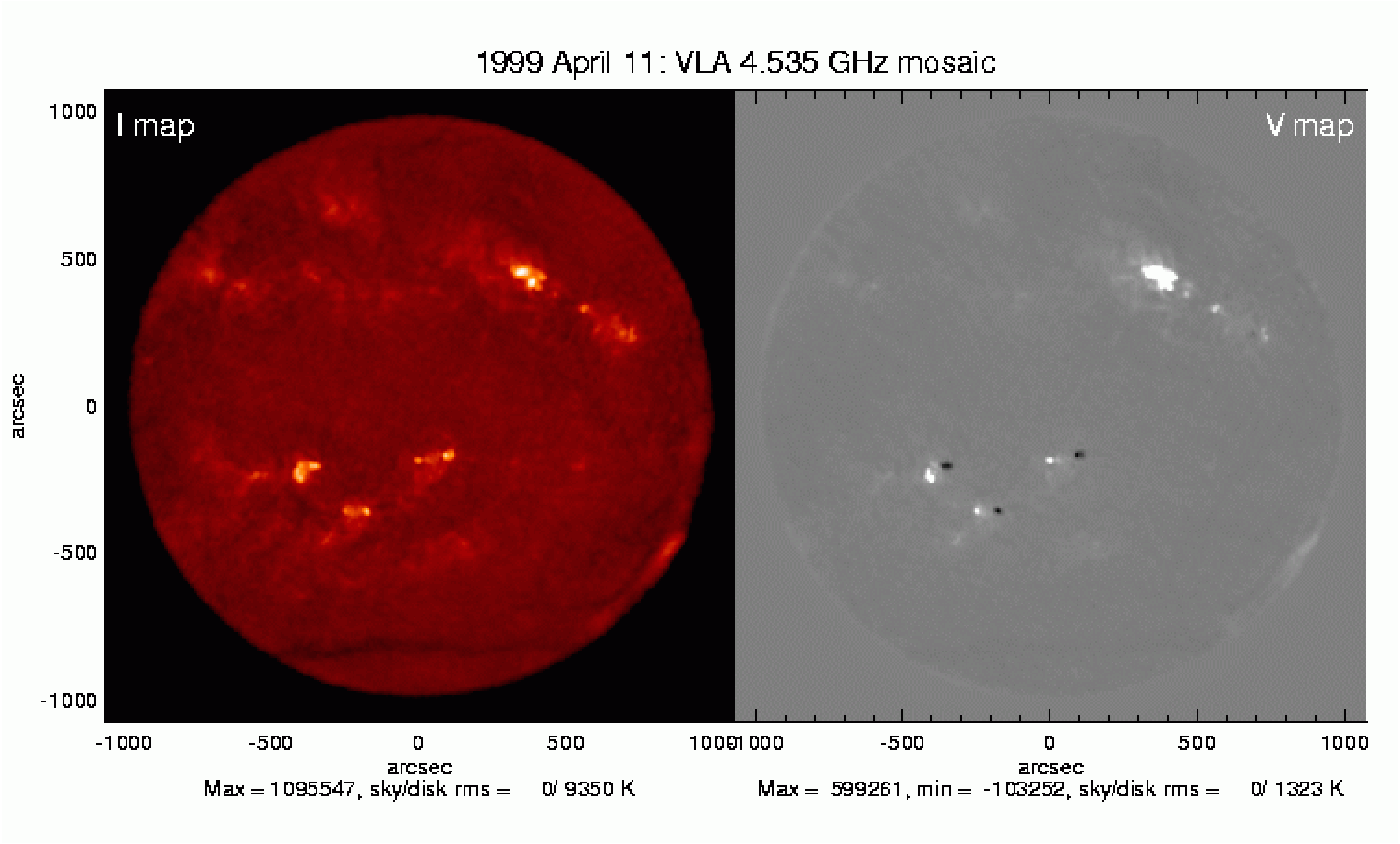
Radio Emission and the Coronal Magnetic Field

- “Anthroporadiomorphic” principle: radio astronomers are lucky that God, or whoever, decreed that the range of magnetic fields in the corona is such that electrons gyrate at frequencies exactly in the band easily accessible to radio astronomers from the ground.
- Magnetic fields operate on radio emission in two ways:
  - Gyro motion of electrons as a direct source of opacity: gyroresonance emission
  - Gyro motion of electrons modifying the response of plasma to electromagnetic fields and thus determining wave properties, e.g. refractive index, polarization
- Polarization is usually the key to unlocking B
- We do not measure linear polarization (Faraday rotn.)

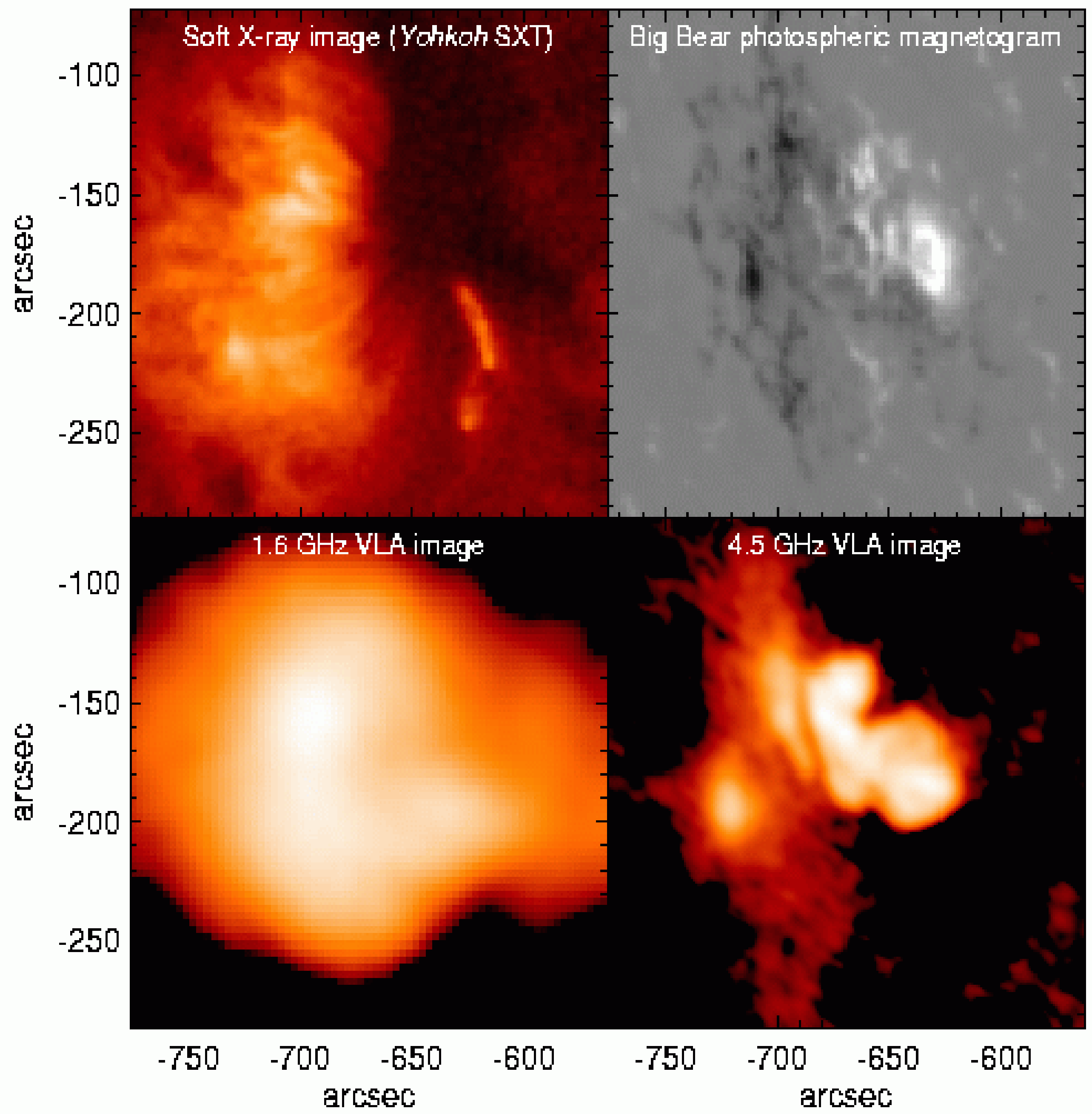
The Radio Sun



Radio Emission Mechanisms

- **Bremsstrahlung** due to thermal plasma occurs throughout the solar atmosphere and is the dominant mechanism in most of the corona. It is optically thin above a few GHz and usually weakly polarized (plasma response).
- **Gyroresonance emission** (emission from nonrelativistic thermal plasma at low harmonics of the electron gyrofrequency 2.8 B MHz) is strong wherever B > 300 G in the corona and produces optically thick emission in active regions which may be highly polarized.
- **Gyrosynchrotron emission** (emission by mildly relativistic electrons at harmonics 10-100 of the gyrofrequency) is produced by nonthermal electrons in flares; broad frequency response.
- **Plasma emission** is produced by energetic electrons at low harmonics of the plasma frequency $f_p=9000n^{1/2}$: produces bright highly polarized bursts at low frequencies. In the presence of magnetic fields, fundamental plasma emission is highly polarized.

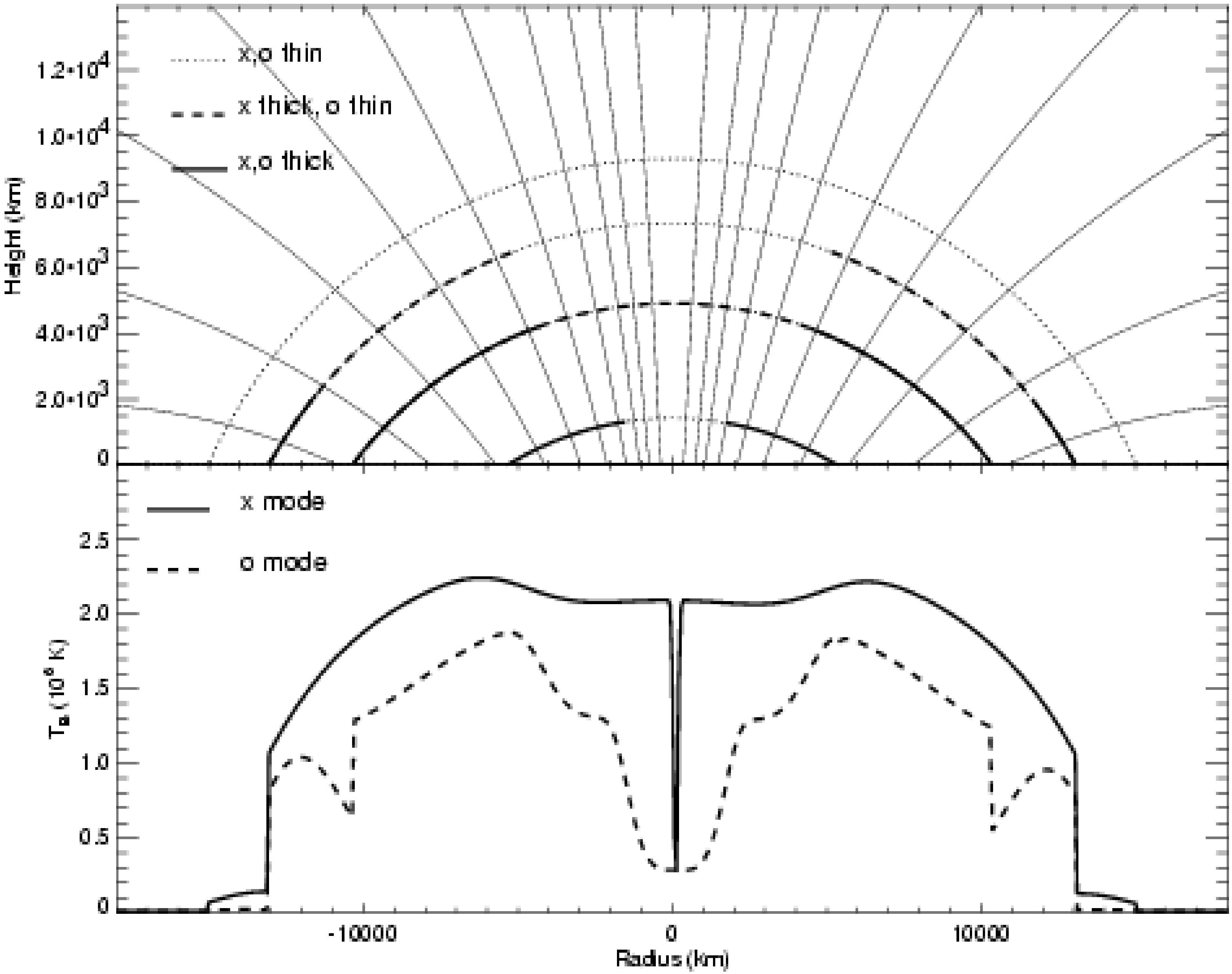
Active regions at different radio frequencies



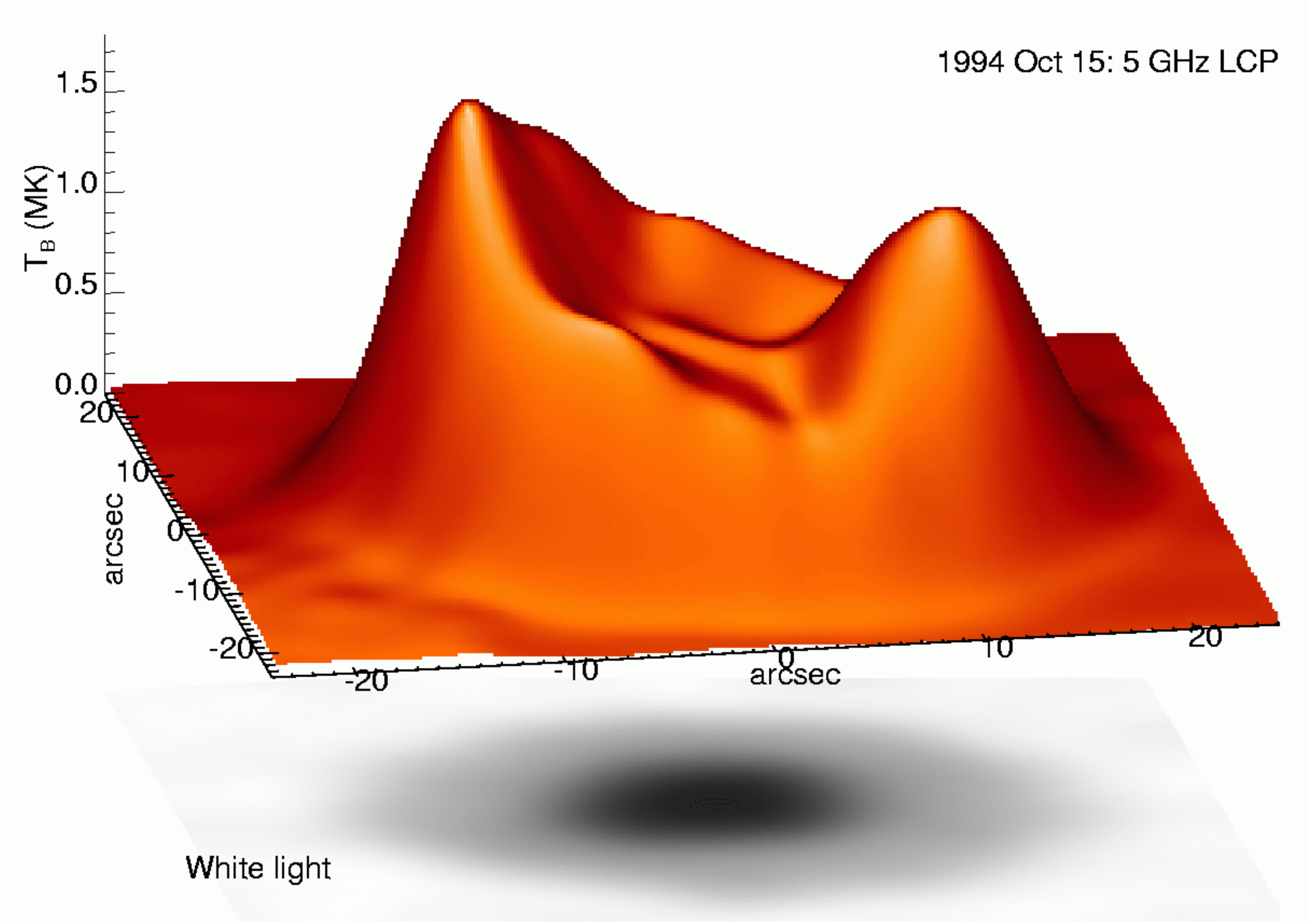
Gyroresonance emission

- Opacity results from electrons gyrating in coronal magnetic fields at $f_B = 2.8\ 10^6$ B Hz: linear scaling of B with frequency.
- In the non-flare (non-relativistic) corona this produces narrow resonances, i.e. physically very thin layers (tens of km).
- Opacity $\propto$ n B/(∂B/∂l) $(T/mc^2 \sin^2\theta)^{s-1}$ where s = 1, 2, 3, … is the harmonic
- Because T/mc^2 is 1/3000, opacity drops by 3 orders of magnitude from one layer to the next
- Big difference in opacity of two polarizations of electromagnetic waves: extraordinary mode interacts more with electrons than ordinary mode

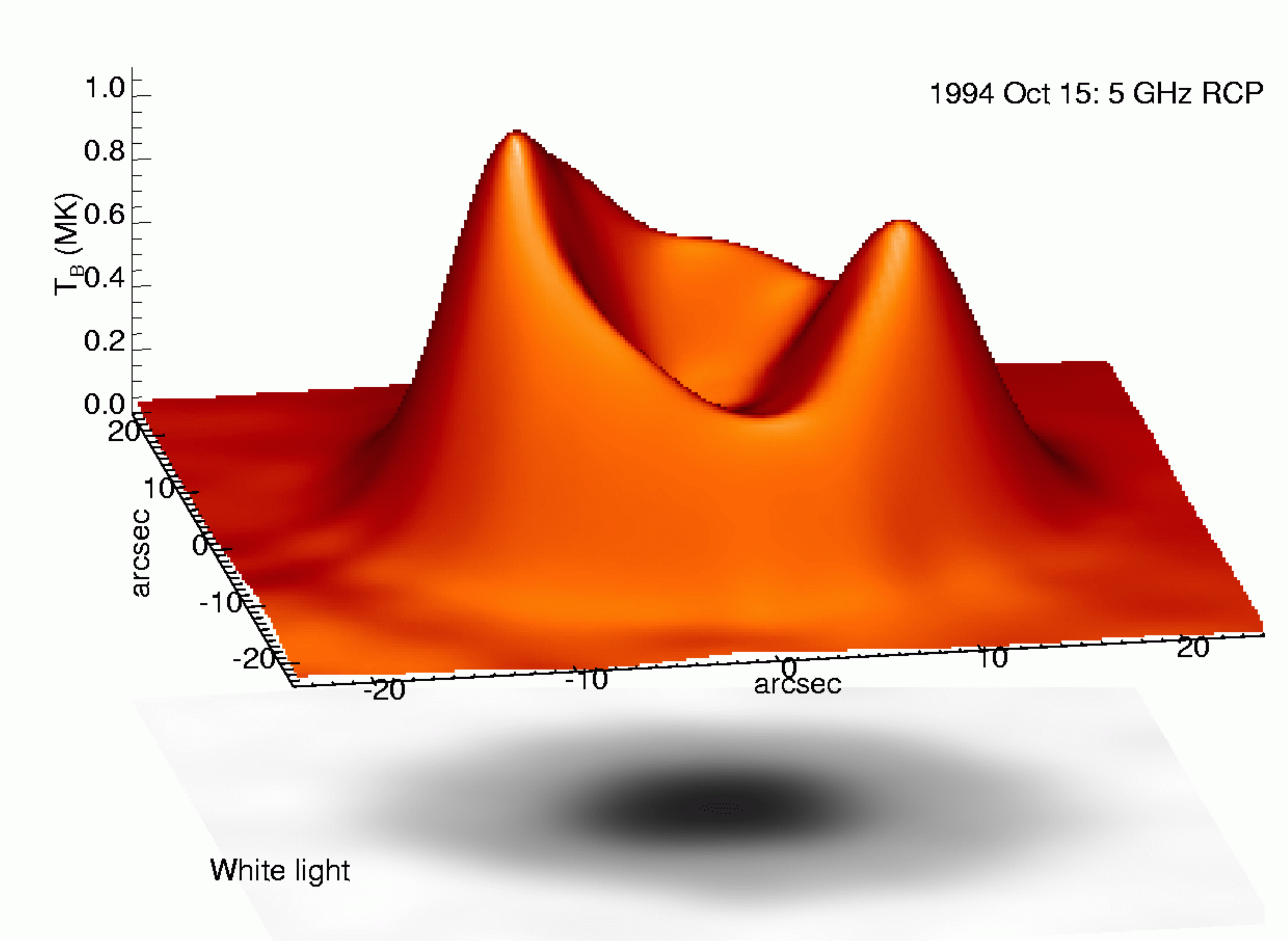
Model sunspot gyroresonance layers



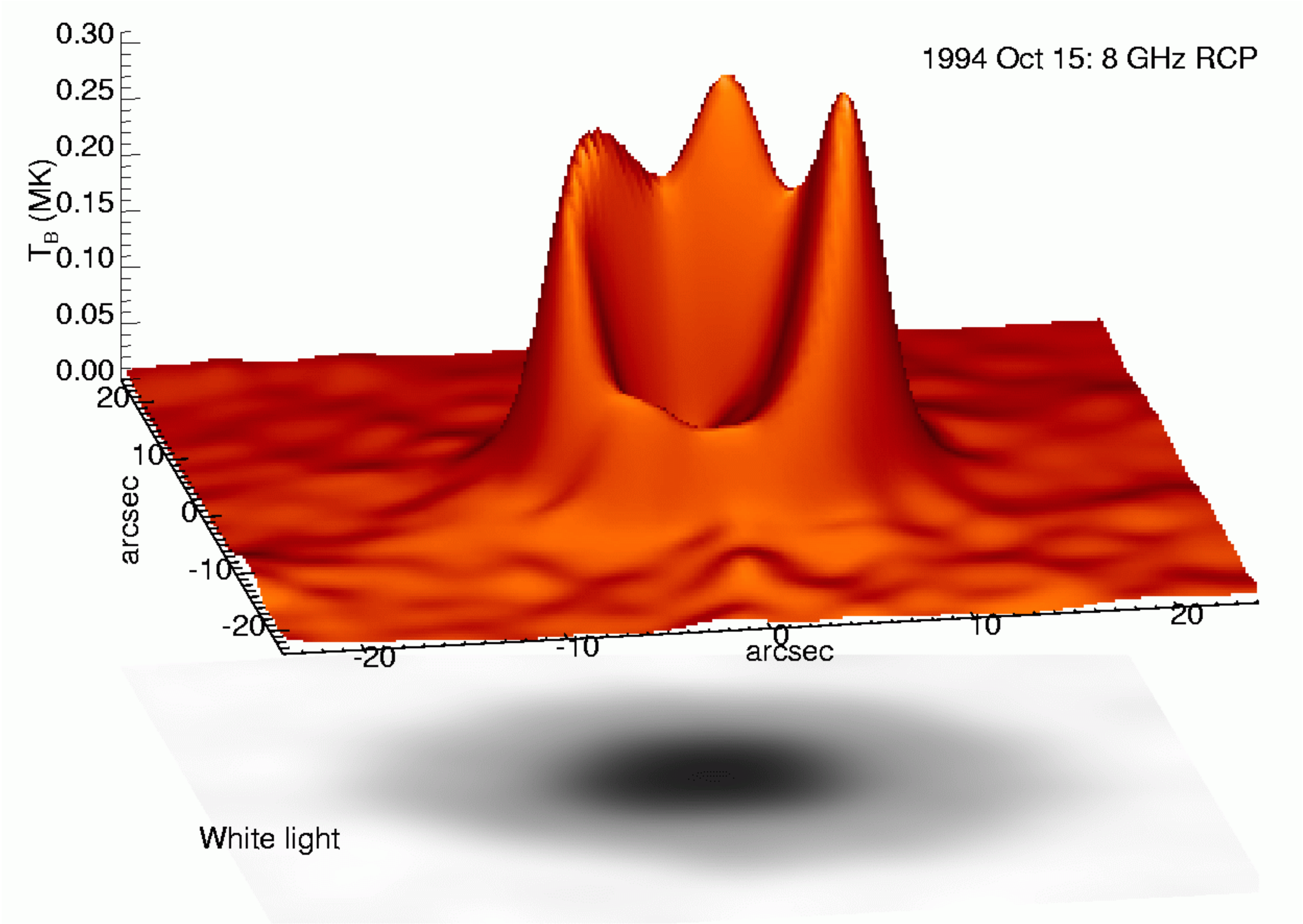
A sunspot near disk center: 5 GHz x mode



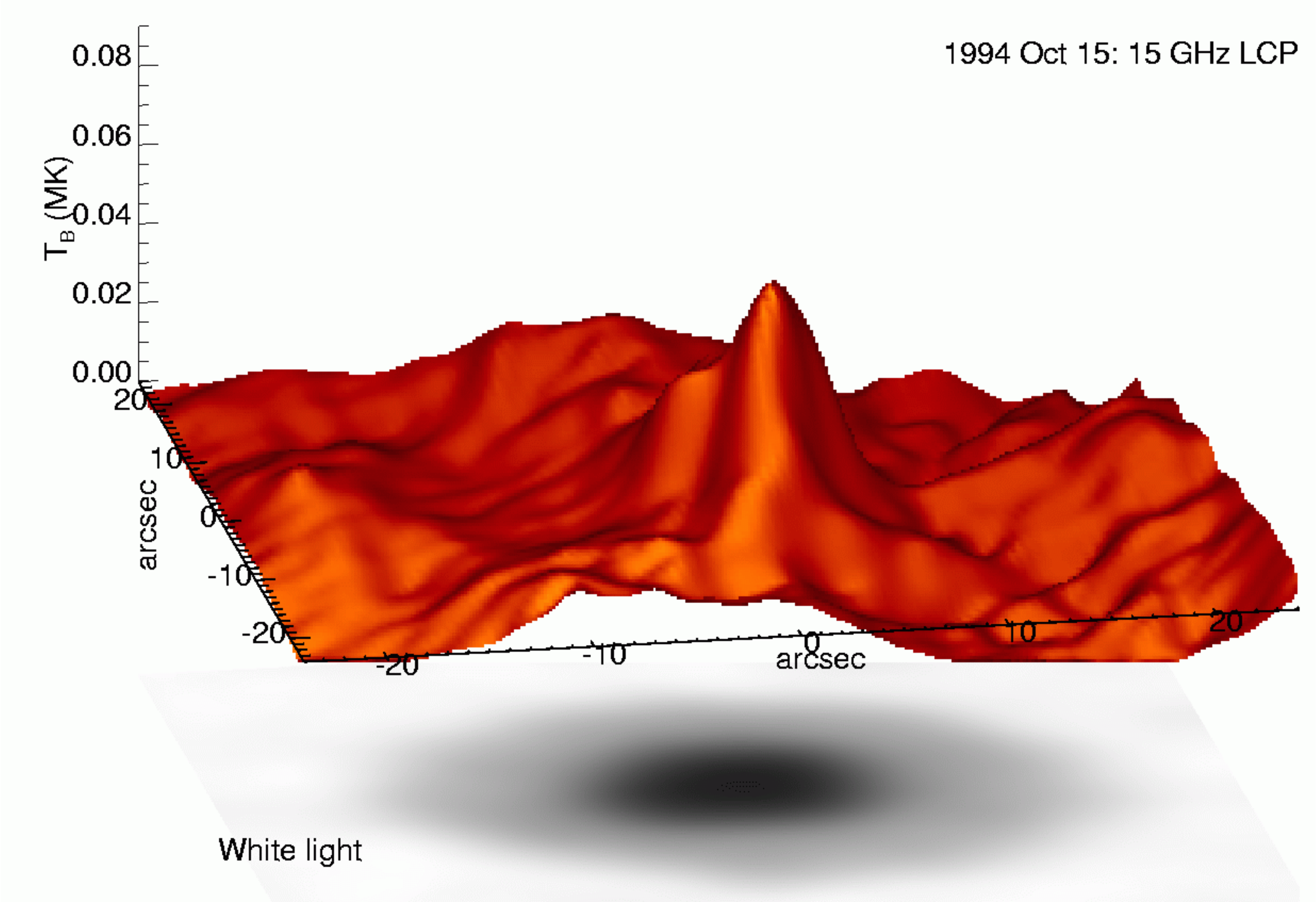
A sunspot near disk center: 5 GHz o mode



A sunspot near disk center: 8 GHz o mode

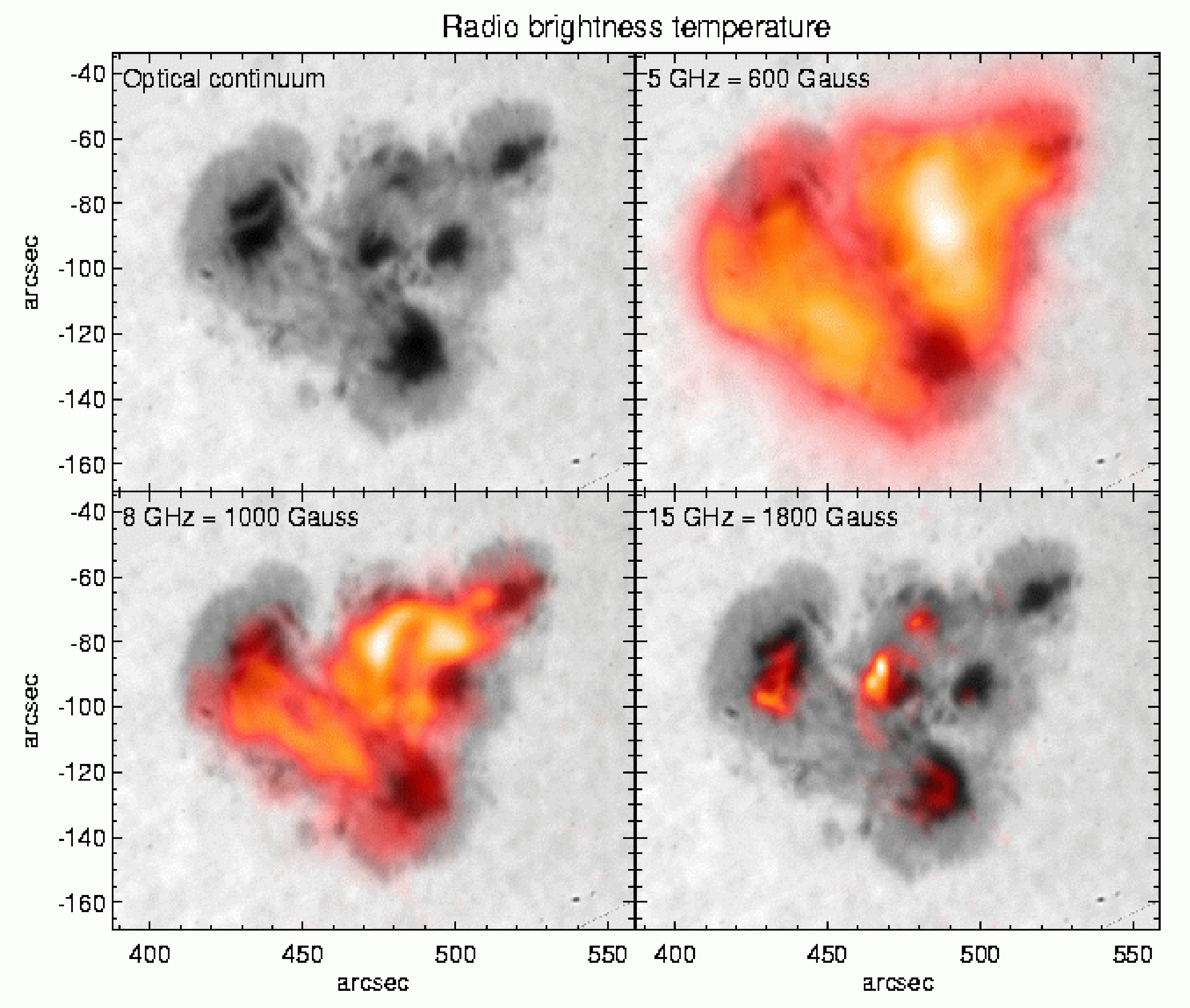


A sunspot near disk center: 15 GHz



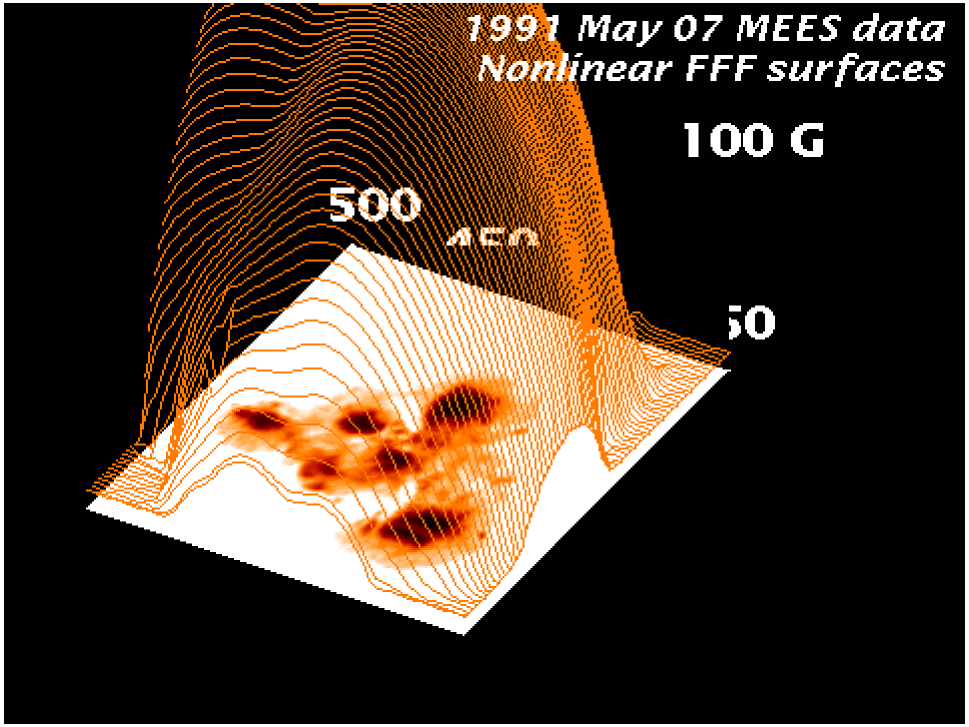
Radio Emission from Coronal Magnetic Fields

Region showing strong shear: radio images show high B and very high temperatures exactly where the magnetic field is non-potential



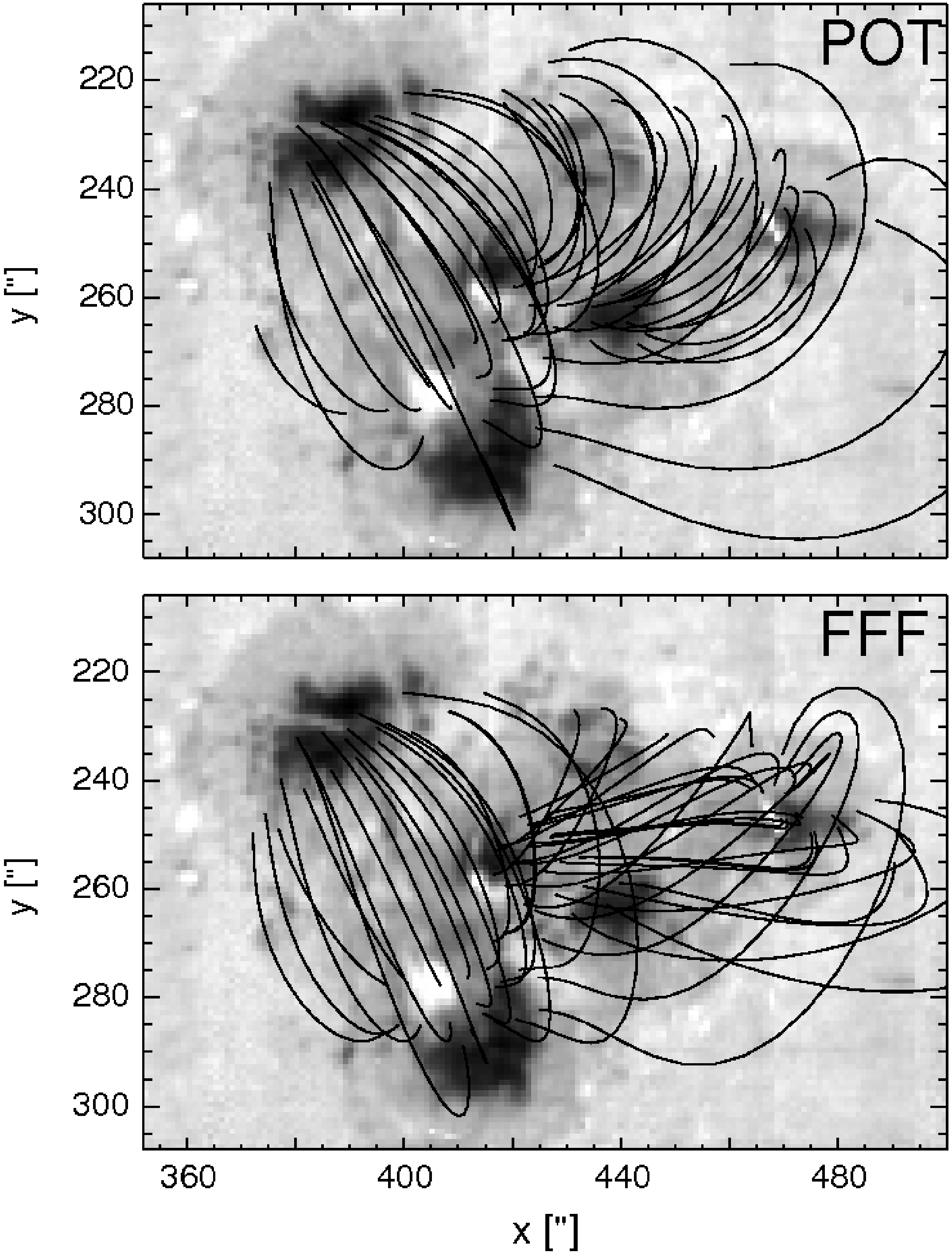
Coronal Magnetic Fields: Strong Shear

Region showing strong magnetic shear: extrapolations of surface field show large difference between potential-field approximation and nonlinear force-free field solution in center of region where shear is strong.

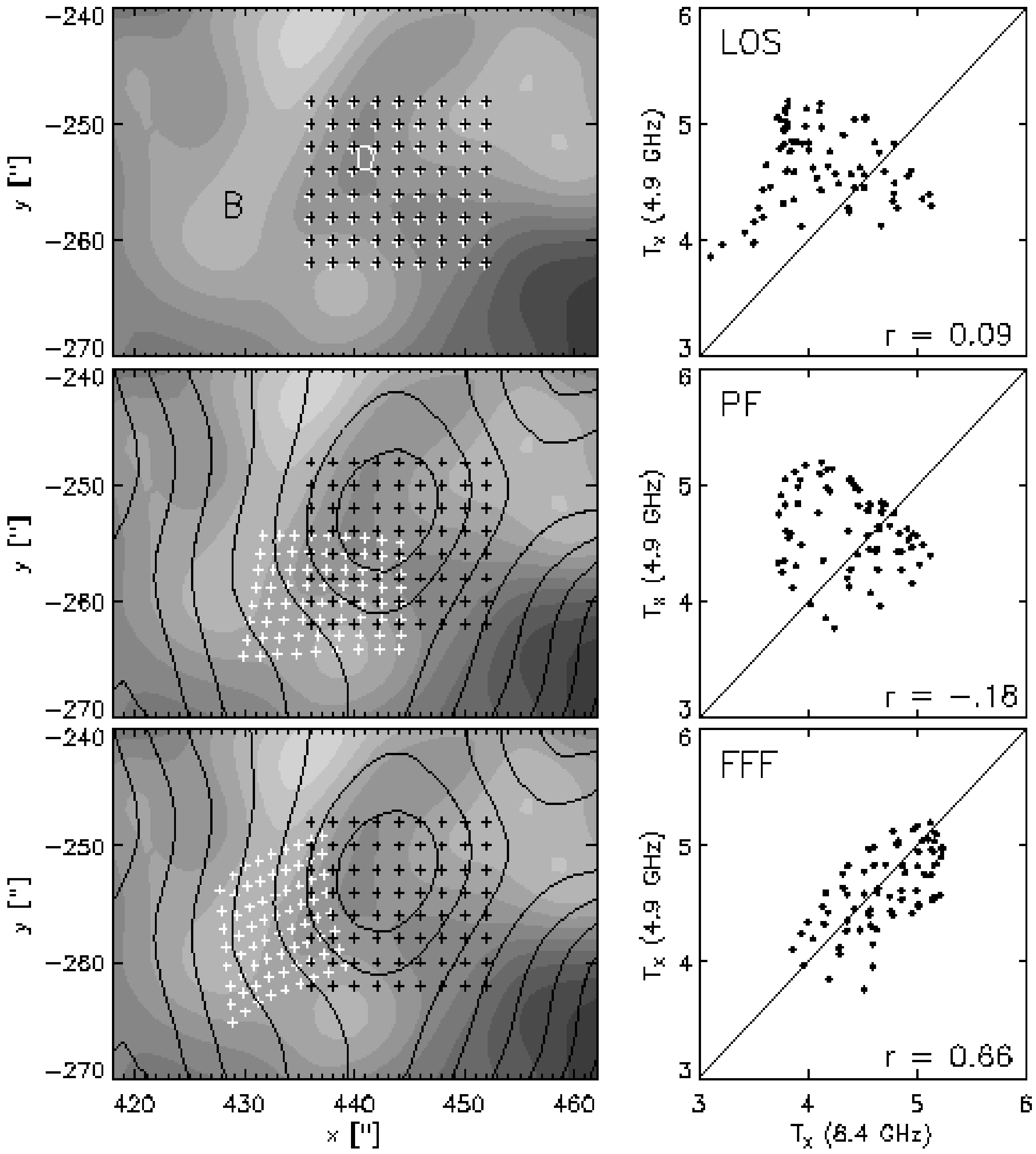


Coronal Magnetic Fieldlines

Region showing strong shear: magnetic connectivity very different in reality from what potential approximation predicts



Tests of magnetic field extrapolations



- Use field lines from extrapolations to connect points in 600 G gyroresonance surface (5 GHz) with 1000 G surface (8 GHz) and compare temperatures

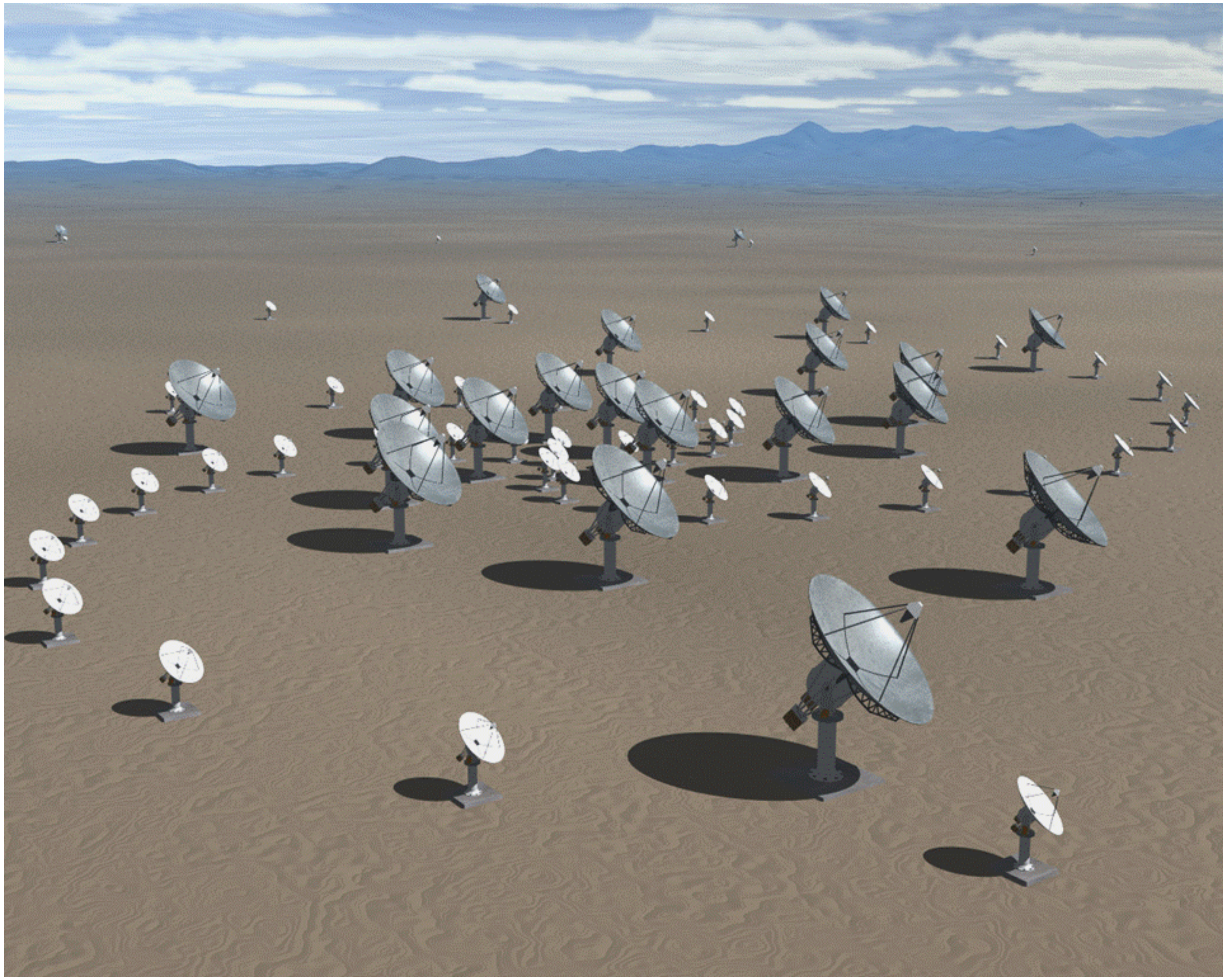
- Find good correlation only for nonlinear force-free extrapolation (Mikic)

Coronal magnetic fields: intrinsically 3D

- Everyone wants to measure coronal magnetic fields: flares, coronal heating, CMEs, ….
- Most of us come from Flatland: we are accustomed to 2D photospheric field measurements.
- The corona is different: intrinsically 3D. Have to think differently. Optically thin diagnostics have line-of-sight problems to deal with; here radio has an advantage because it is optically thick: get different layers of the corona at different frequencies.
- Extrapolations of surface fields will be just as crucial because we don't measure the height of the gyroresonance layers. Extrapolations need radio measurements to help resolve ambiguities, issues with non-force-free photospheric field data.
- For radio measurements to be useful we need a telescope that makes high-quality, high-resolution maps of the Sun at many frequencies simultaneously, to measure a wide range of B strengths

FASR

FREQUENCY-AGILE SOLAR RADIOTELESCOPE



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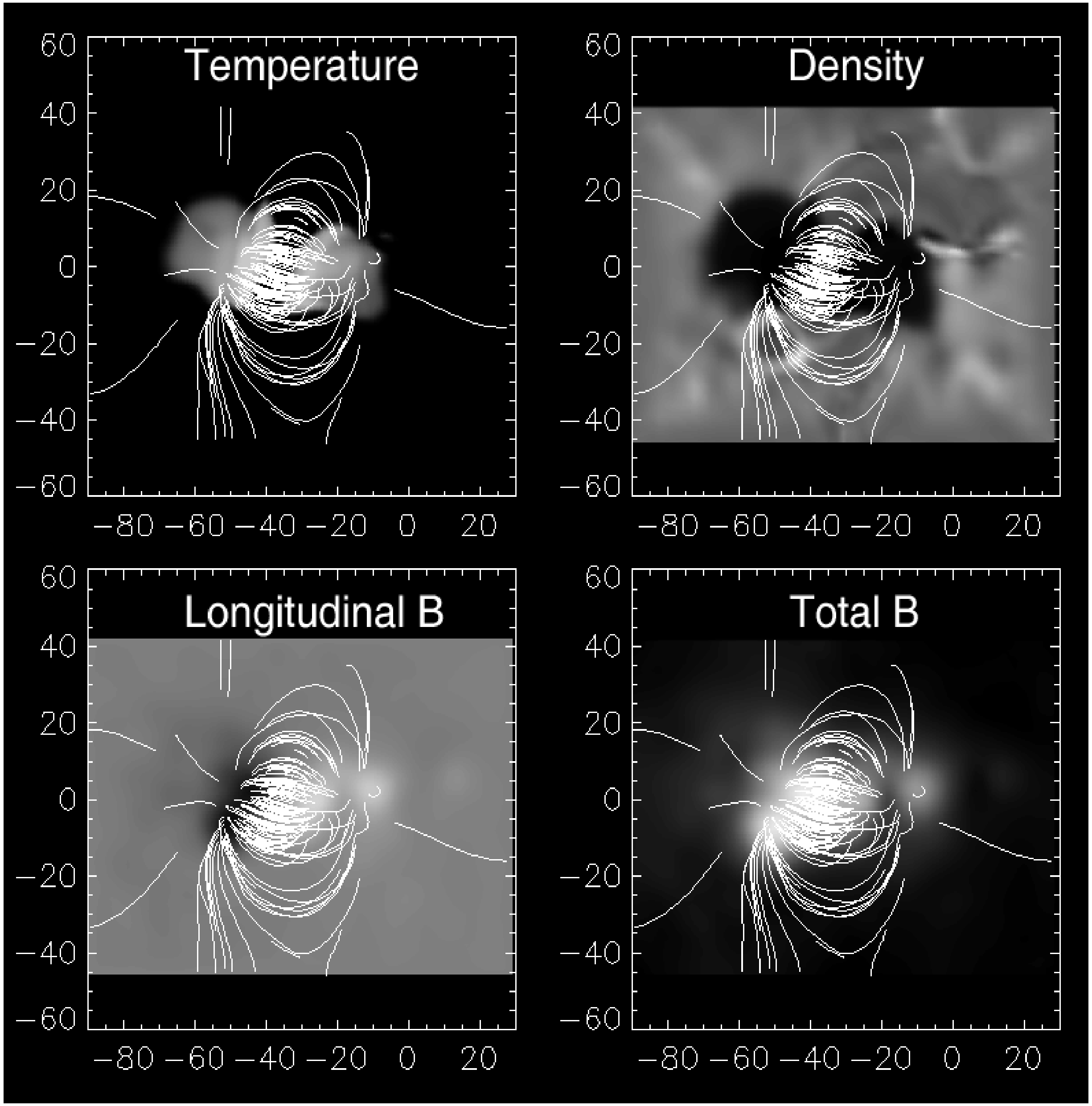
~ 100 antennas, 3 separate arrays to cover 300-20000 MHz,
VLA-like spatial resolution with high spectral resolution,
(hopefully to be) funded by NSF Atmospheric Sciences

Magnetogram at the base of the corona: how do we measure it?

Use the fact that gyroresonance emission is optically thick, so where the isogauss surface drops out of the corona the brightness temperature shows a sudden drop. This produces sharp features in the radio spectrum that reveal the magnetic field.

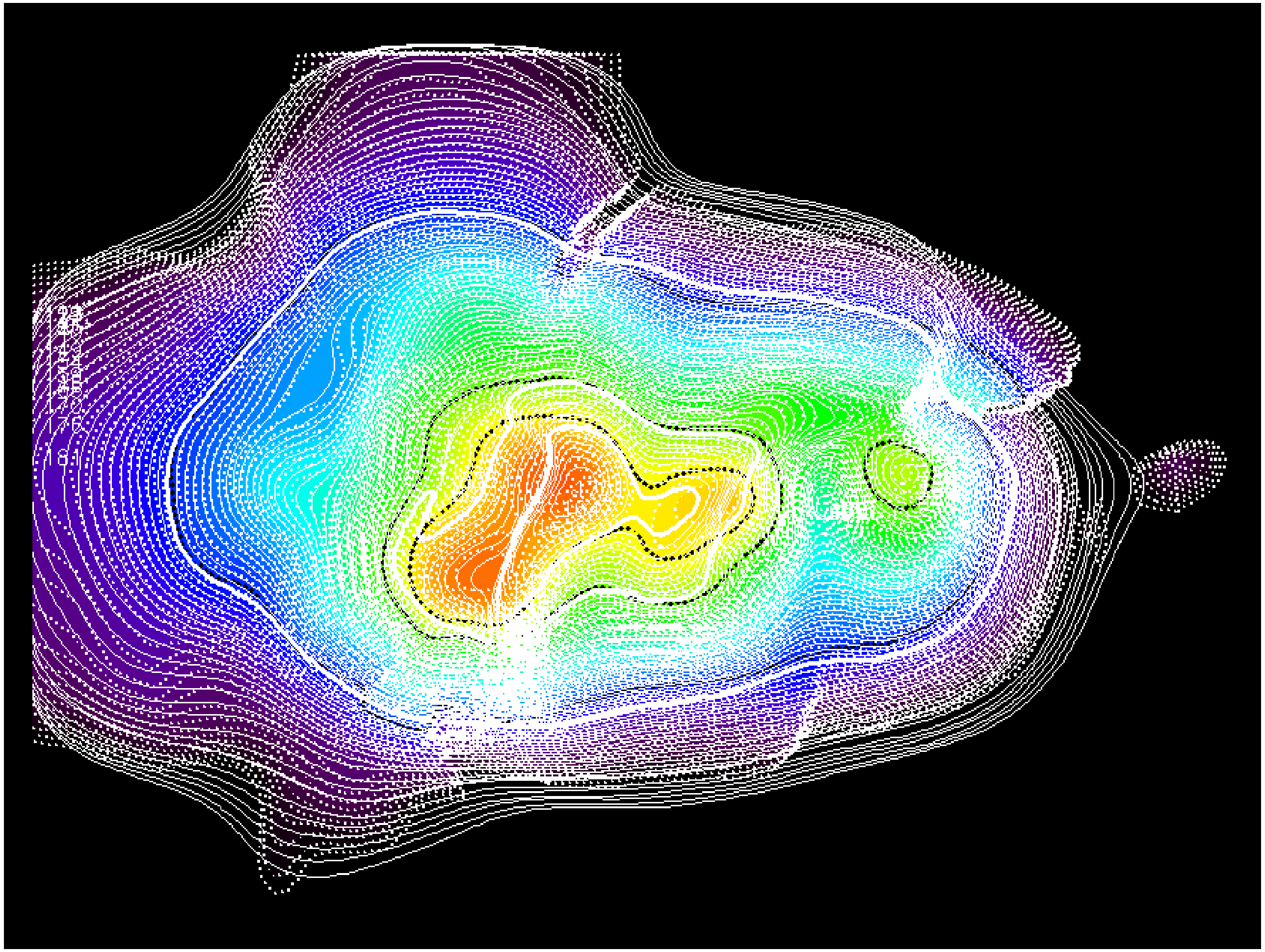
Test model active region



The physical model is a potential field model extrapolated from a vector magnetogram, whose thermal structure was computed self-consistently assuming a plasma heating model in which the volumetric heating rate is directly proportional to the local magnetic field strength

Mok et al (2003).

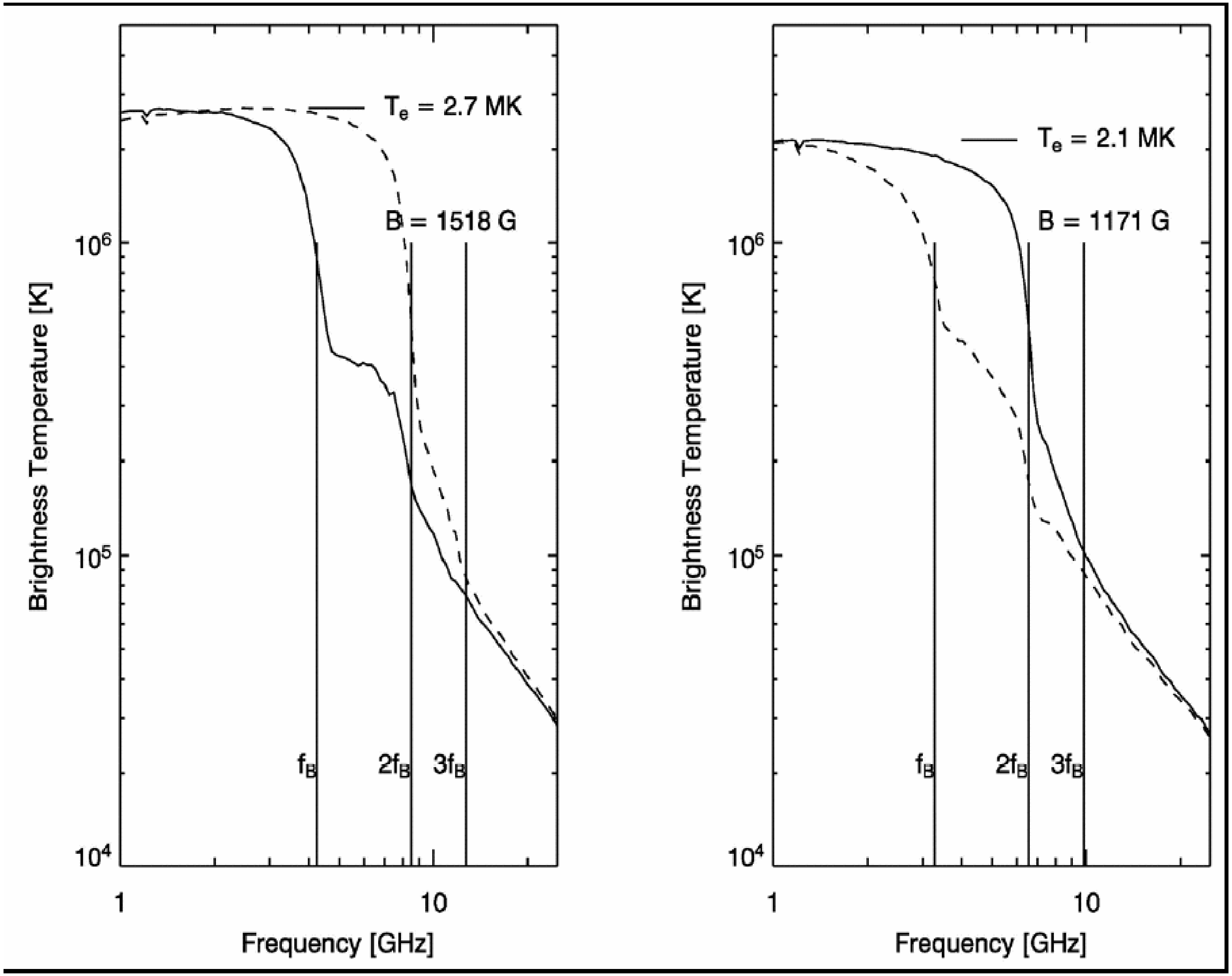
Model radio images



Gary, Lee, Giordano, Mok

- Start with vector field measurements
- Perform force-free field extrapolation
- Assume heating function proportional to B
- Derive electron temperature and density distribution on each field line
- Produce sampled 3-D grid of B, Te, ne values
- Calculate radio emission at 100 frequencies (include both gyroemission and free-free emission)

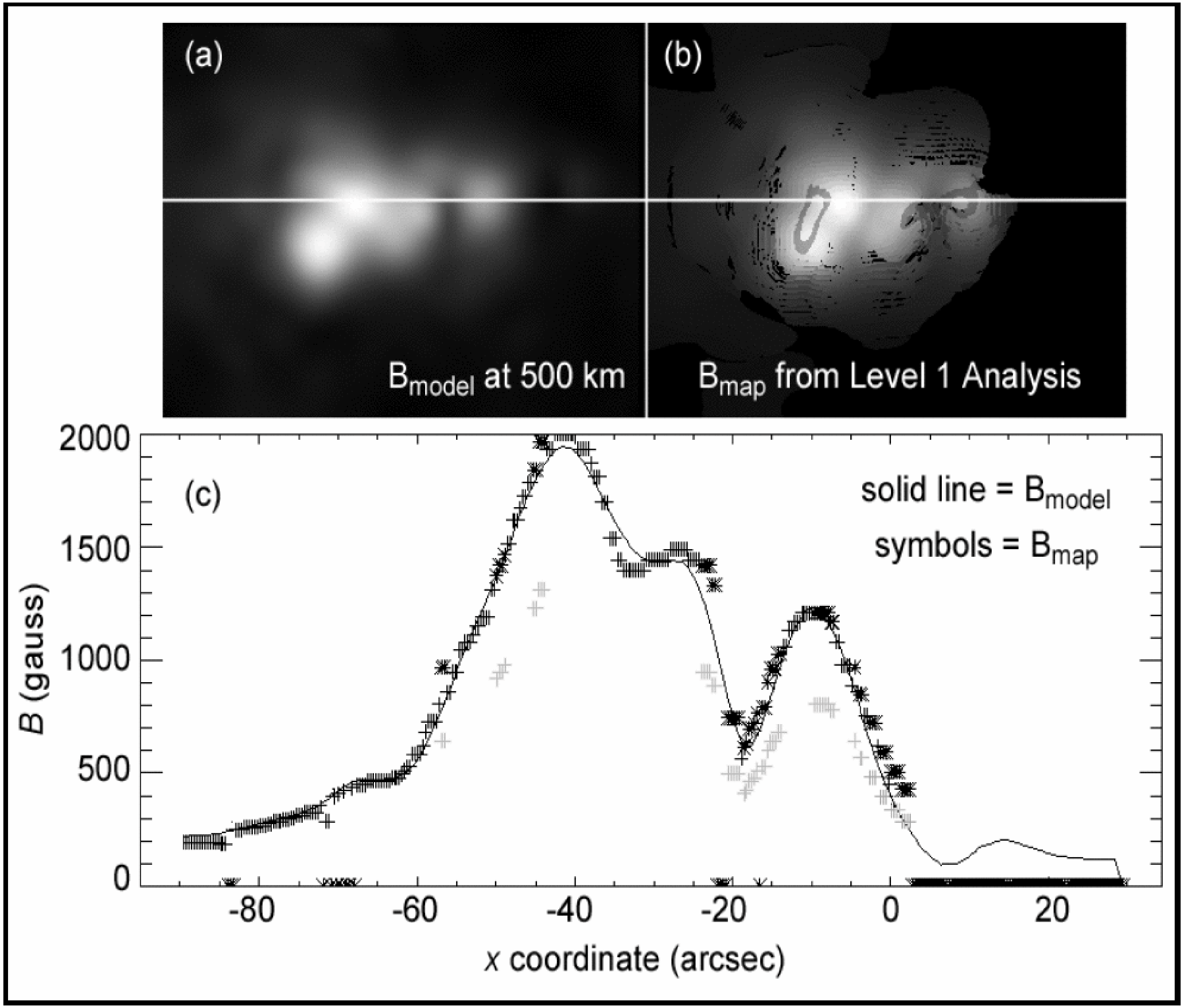
Radio spectra reveal B



The two circular polarizations (solid, dashed) are both measured and are often optically thick at different harmonics

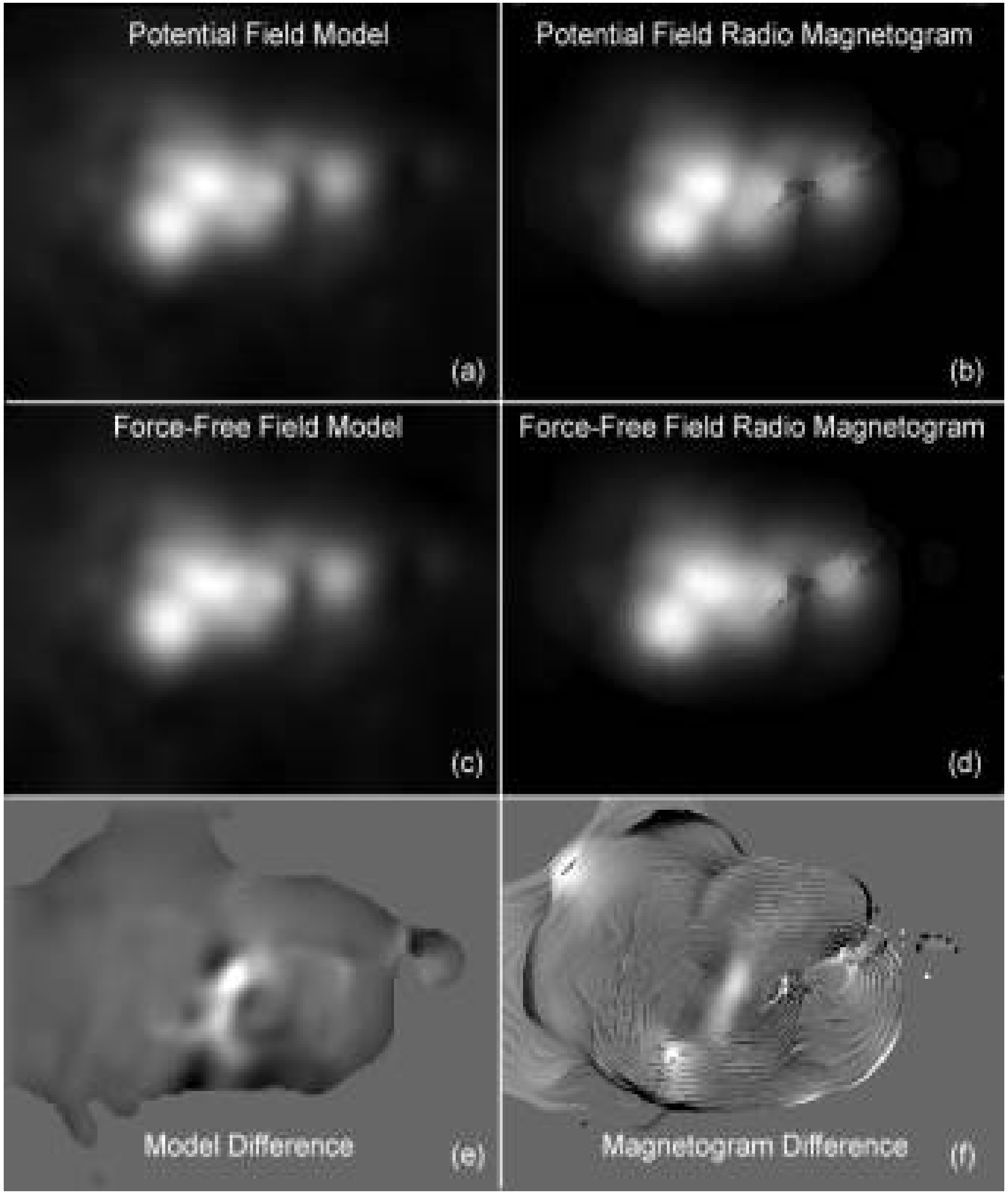
- Make “input” radio maps
- Fold radio maps through instrument response function, adding realistic noise level
- Make “output” maps at each of 100 frequencies
- Sharp edges in the radio spectra where T_B drops from coronal to chromospheric indicate harmonic jumps and hence reveal B.

Test model: determination of coronal B



Results of analysis of the radio images of the active region: determination of coronal B

Test model: determination of coronal B



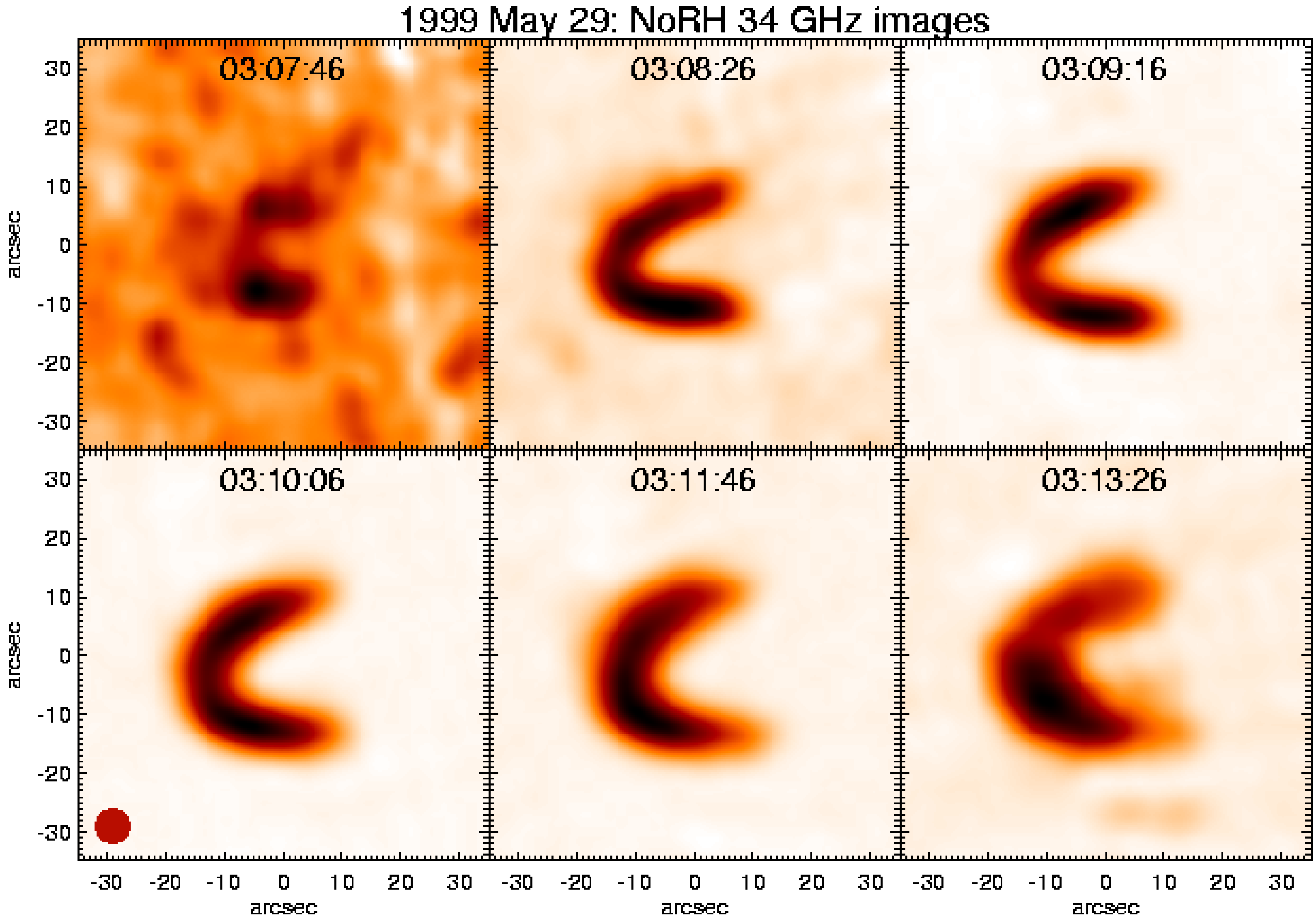
Comparison of input model coronal magnetic field (left) versus field derived from radio images via the technique described above.

Difference between FFF and potential fields are shown in the bottom panels (actual on left, radio-derived on right): region of shear clearly seen.

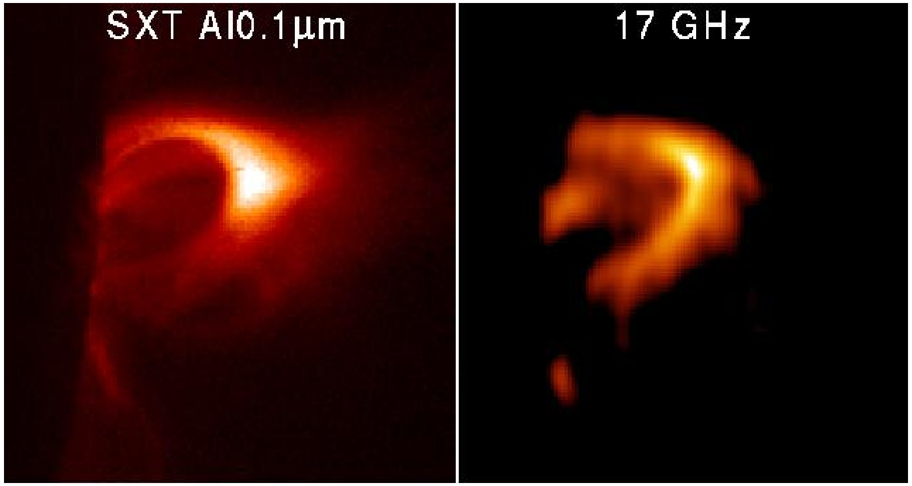
Coronal magnetography

- Radio observations can measure coronal magnetic field strengths above 300 G anywhere on the solar disk
- Measures temperatures on surface of constant field strength – directly see regions of strong heating
- Because emission is optically thick in regions of strong field, we get 3D information on fields
- Relatively insensitive to density, therefore complements other techniques which are dominated by density contrast
- Presently no absolute height information directly from the radio data: need information from other wavelengths?
- Important role in testing techniques for extrapolating surface fields into corona
- FASR will produce maps of B at the base of the corona routinely every 10 minutes or so, more data products when we understand the data better

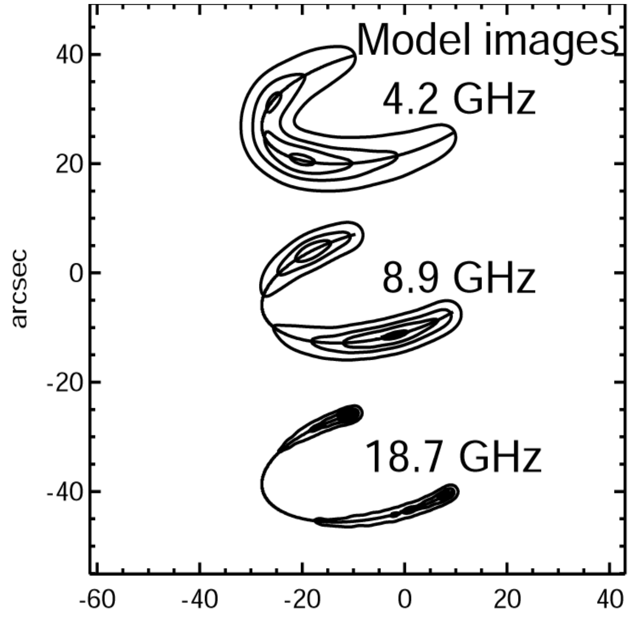
Radio Flare Loop

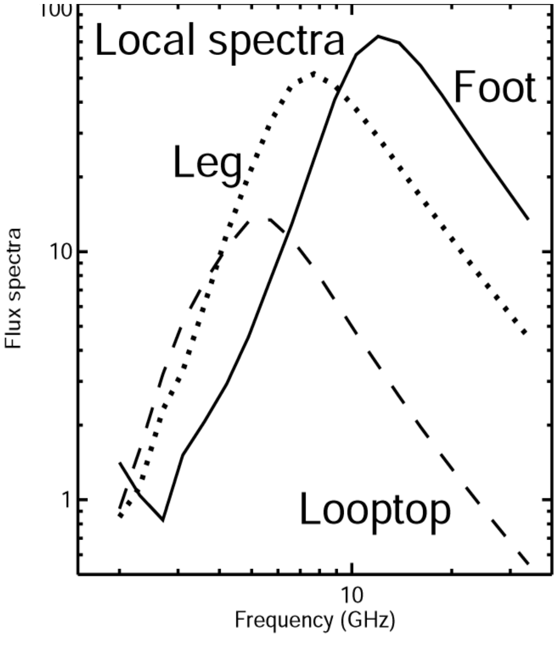


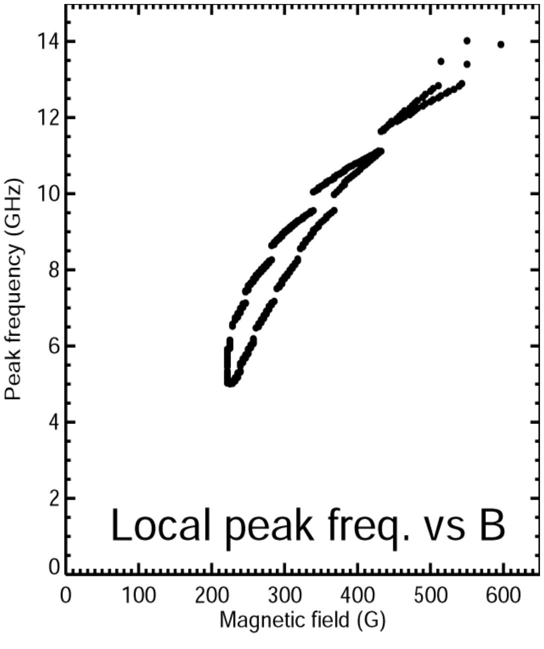
Solar Flare Diagnostics



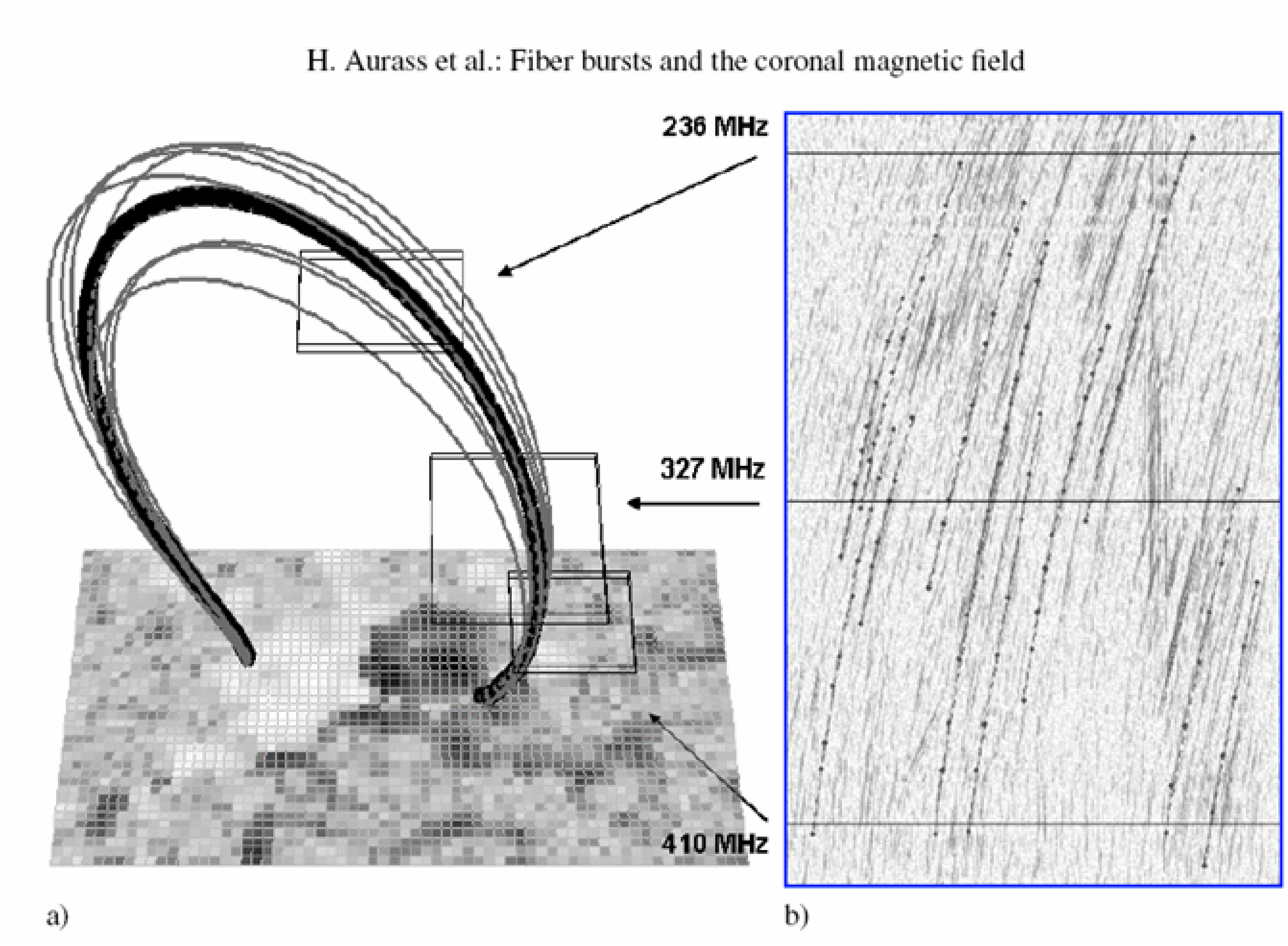
Multifrequency imaging allows spatially resolved spectral diagnostics







Using radio bursts and plasma physics

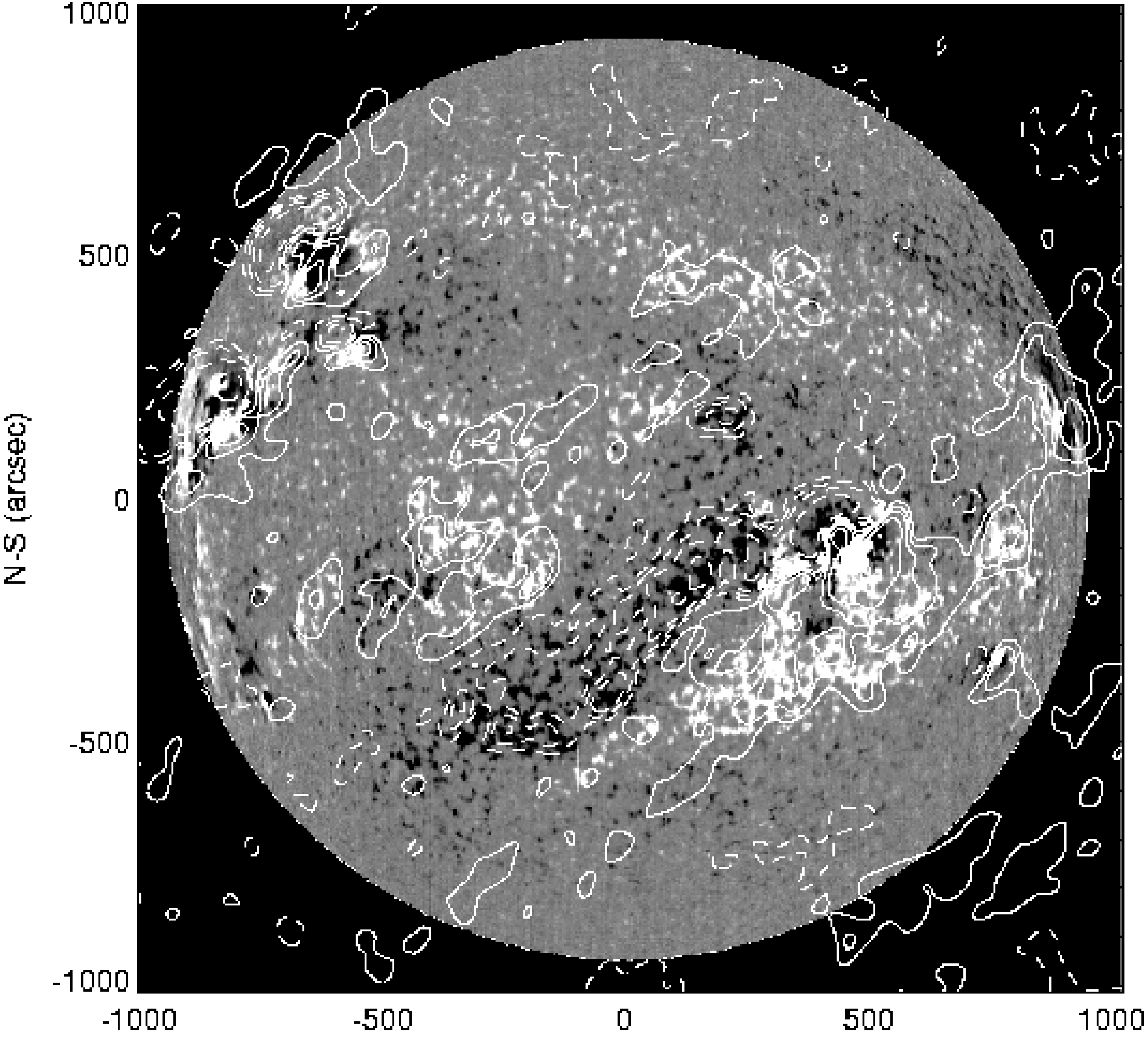


Henry Aurass
& group at
AIP Potsdam

Assume Type IV fine structure due to whistler waves moving upwards, get whistler frequency from ridge-depression separation, get density model from self-consistency, check against Nancay images at several frequencies and with field lines from extrapolation

Polarization at low frequencies: origin?

VLA 1.4 GHz V contours on KPNO magnetogram



Contours at 6.0,12.0,20.0,40.0 percent of 3.35e+05 K

- Example of large-scale polarization at 1.4 GHz where the sense of V matches the underlying large-scale plage/network field

- Weak gyro or bremsstrahlung? At 1.4 GHz need 170 G (3rd harmonic) or 125 G (4th), so gyro is unlikely

Can We Exploit It?

- Two modes are optically thick in different layers due to the magnetic field effect: the polarization of free-free emission depends sensitively on the (unknown) temperature gradient.
- Recent work by Grebinskij et al. (2000) gives a breakthrough. The basic idea is that the radio spectrum itself measures the temperature gradient!
- If we consider the local slope of the free-free emission brightness temperature spectrum, $n = d\log T/d\log \nu$, then the polarization becomes

$$P = -n\,(\nu_B/\nu)\cos\theta = -(n\,2.8\text{x}10^6/\nu)\,B_l.$$

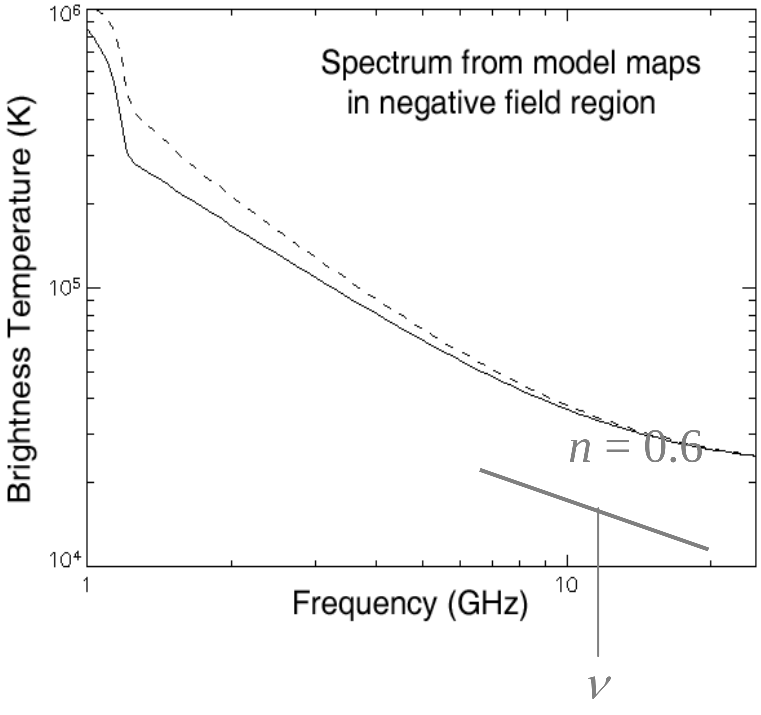
- Thus, $B_l = P\nu/(2.8\text{x}10^6\,n)$.
- This sounds too simple, but it works!

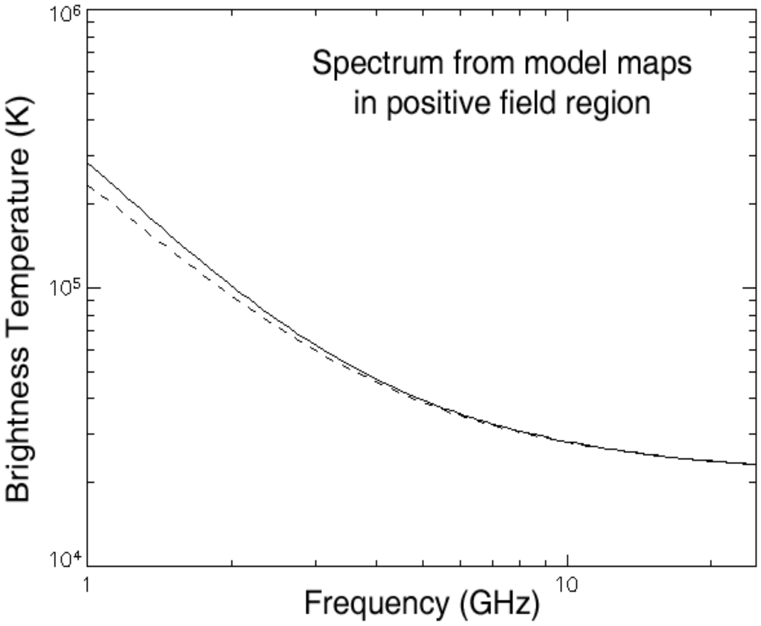
Free-free Spectra

- Measure local log-log slope, *n*, and polarization, *P*.
- Calculate longitudinal component of *B* from:

$$B_l = P\nu/(2.8\text{x}10^6\, n)$$

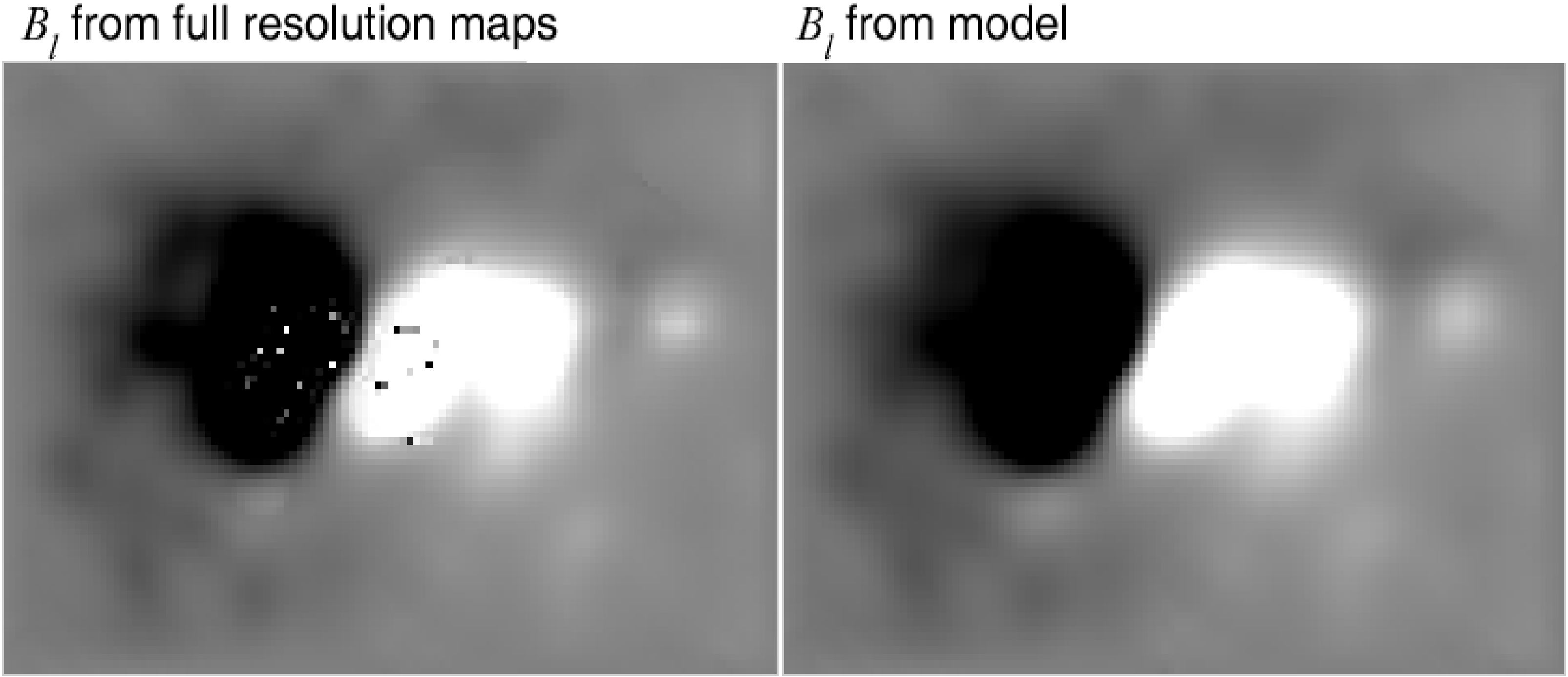
- Note that *n* and *P* both decrease with ν, keeping *B* nearly constant.





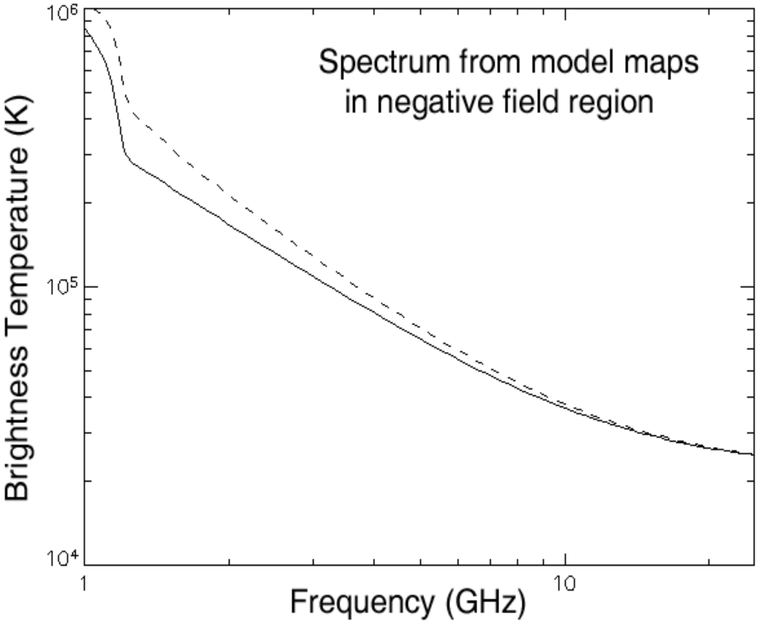
Derived Longitudinal Magnetic Field Compared with Model

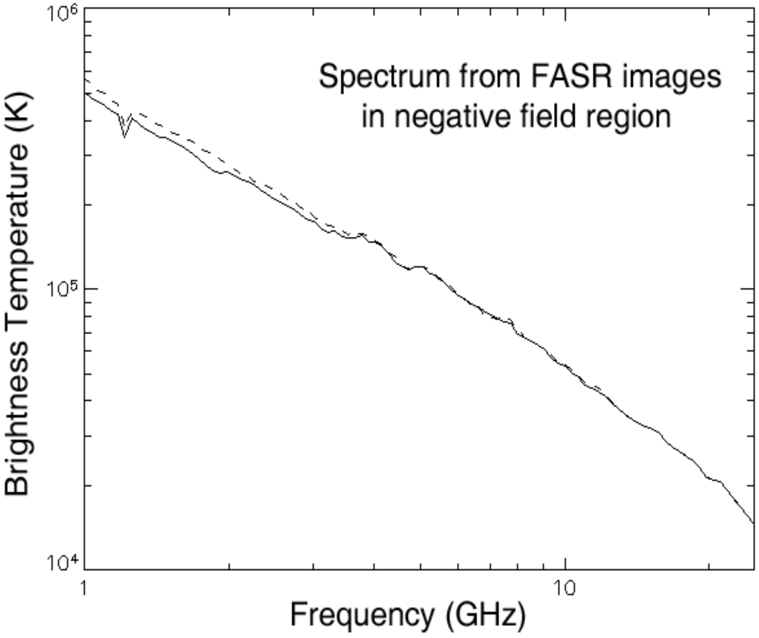
Magnetic fields from free-free emission



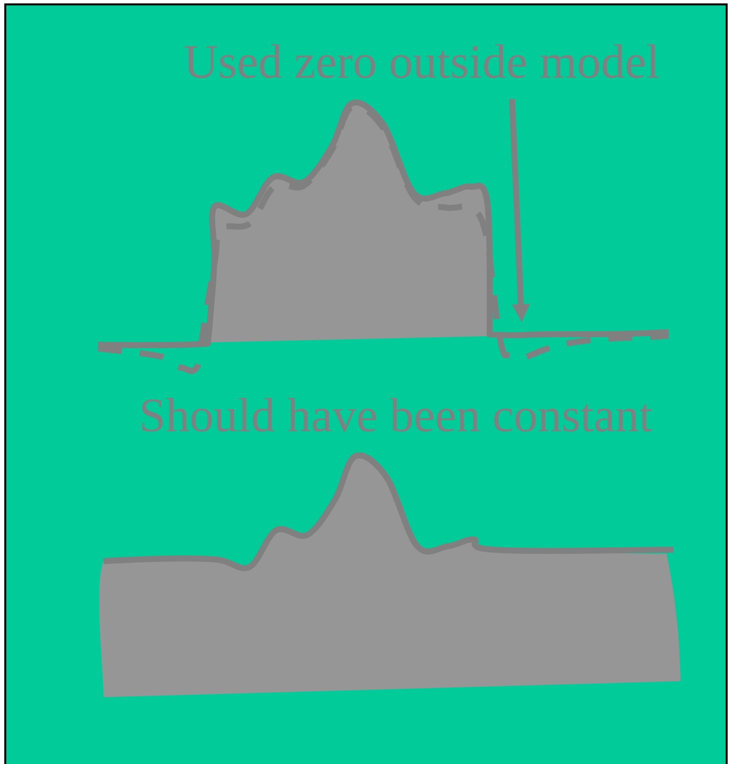
Looks good qualitatively (work by Dale Gary)

But Real Life Is Not So Simple





- After passing through the instrument response, the spectrum is much steeper, noisier, and polarization is reduced.
- Likely cause is mistakes in setting up the model, plus inexpert use of imaging software.
- Optimistic about improving these results, but this is a challenging observation. This shows importance of precision polarization measurements.



Used zero outside model

Should have been constant

Coronal magnetic fields in the near future

- Optical/IR measurements
  - at moderate spatial resolution off the solar limb:
  - field strengths mostly below 20 G,
  - no chance to compare with surface fields because of projection effects,
  - line of sight confusion issues
  - but possibility of full Stokes measurements
- Radio measurements (gyroresonance)
  - Measures magnetic field strength and line-of-sight orientation
  - Limited to fields above 100 G (other sources of opacity take over at low frequencies)
  - Therefore really only for active regions
  - Works on the disk, so can compare with surface fields
  - But don’t see weak fields, so misses flux
  - 3D information is present, but not absolute heights
  - Spatial resolution scales inversely with B
- Extrapolations, from chromospheric vector magnetograms when we have them

Coronal magnetic field measurements in the near future

- These observations will not address the biggest questions the theoreticians want the observers to answer (none of us are getting close to dissipation scales), but they are a necessary step towards these answers
- The 3D nature of the coronal magnetic field makes it infinitely more difficult in principle than the photospheric field

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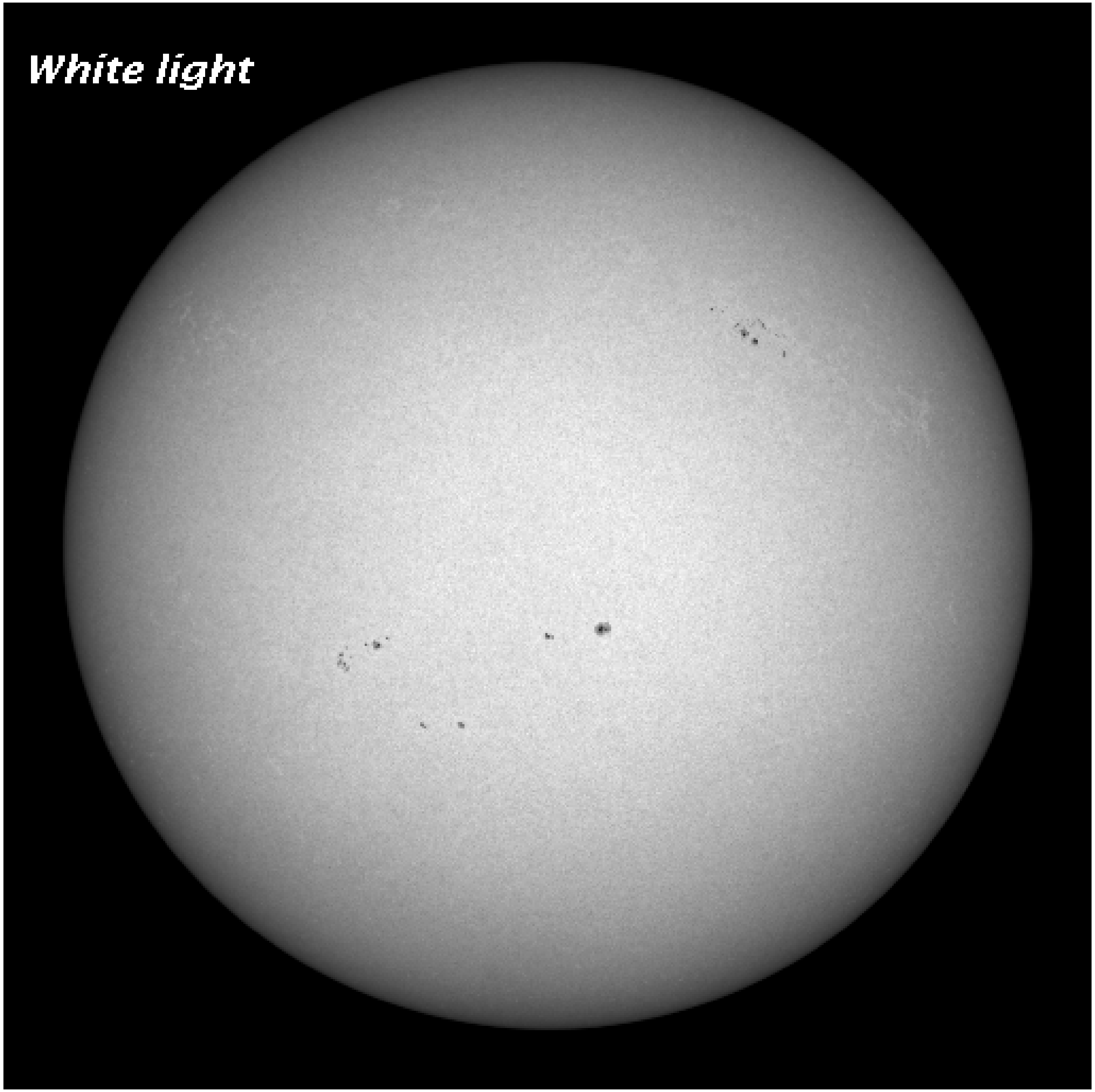

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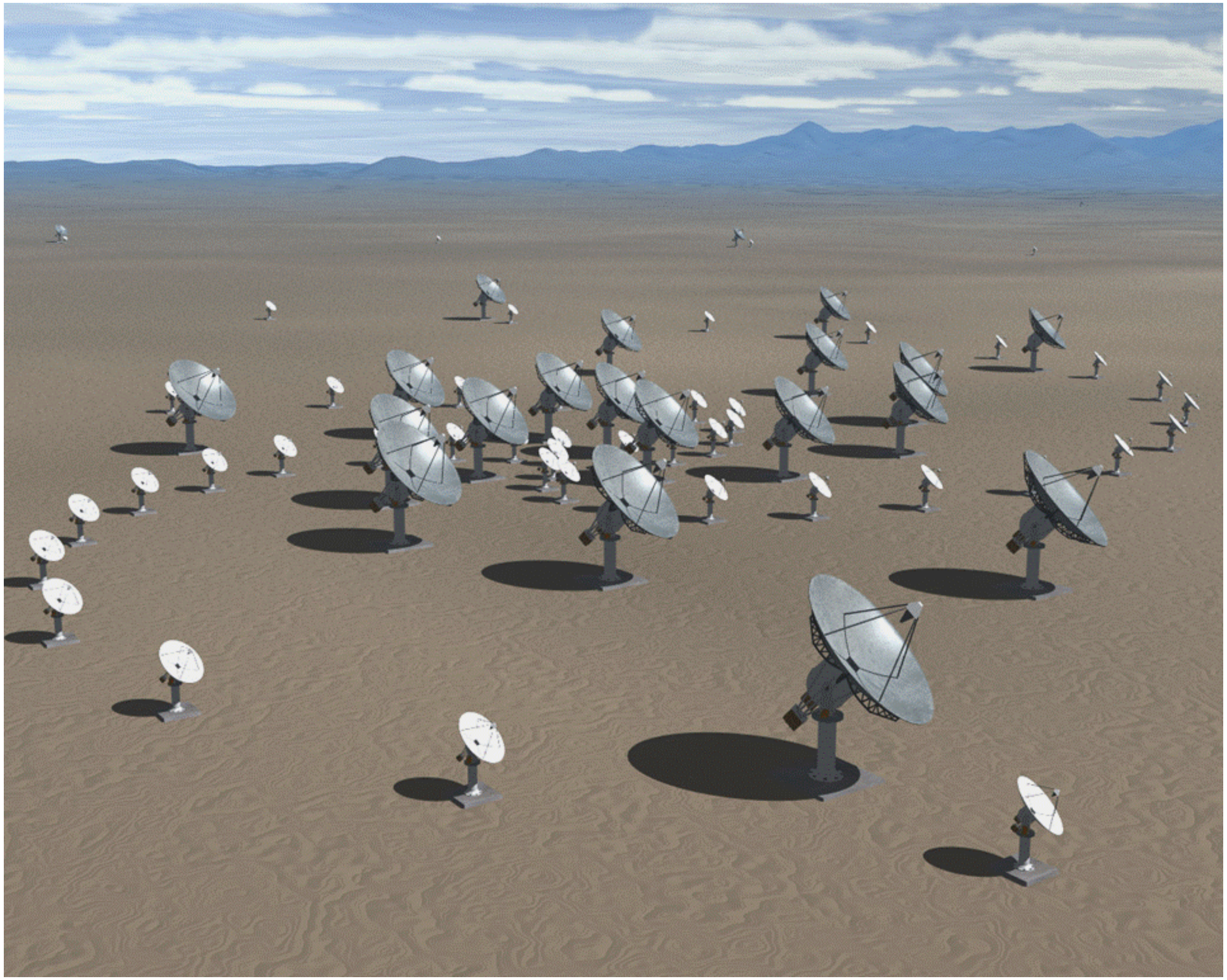

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The Sun