Solar and Space Weather Radiophysics

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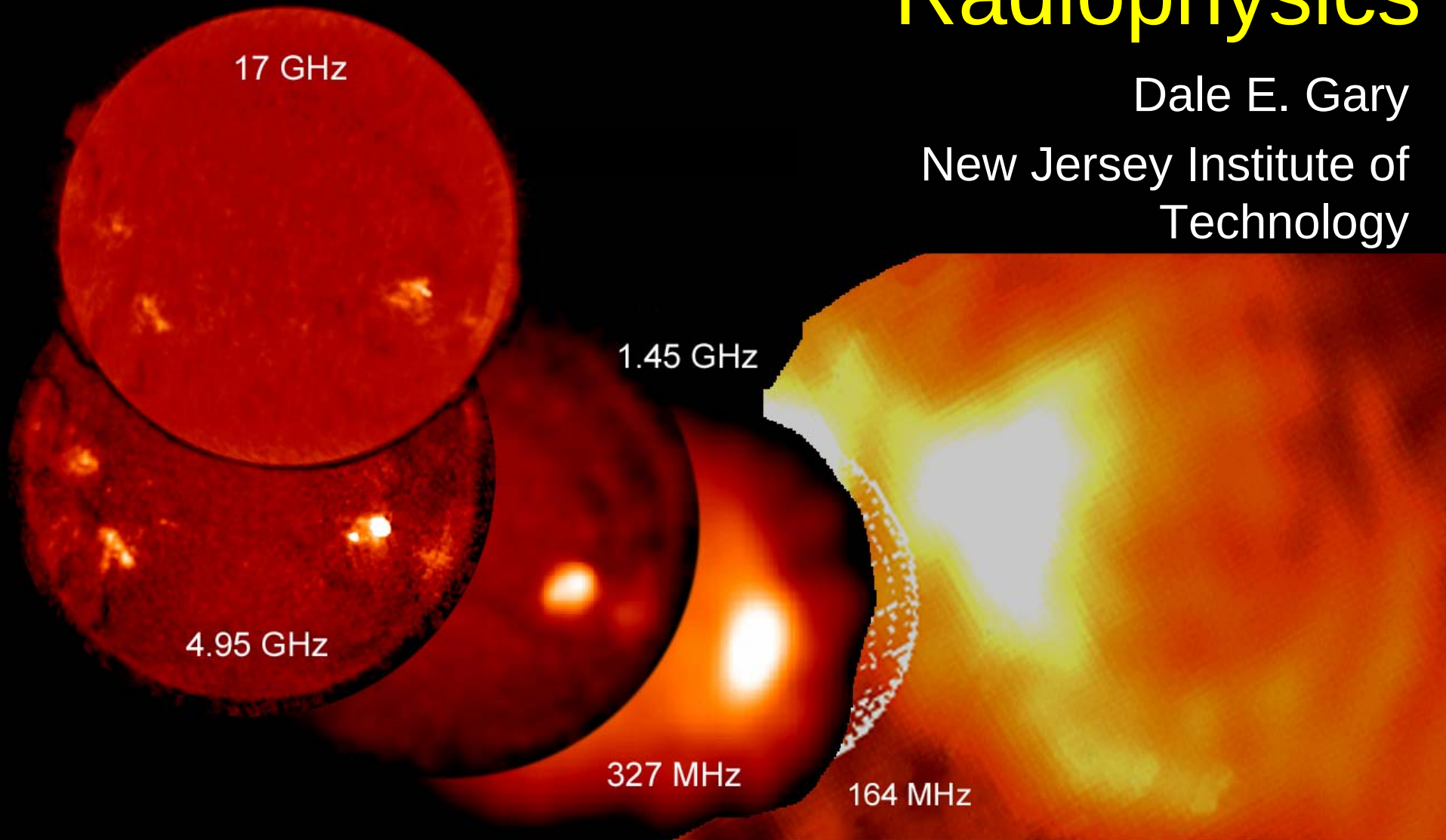


Motivation for this Talk

- International Workshop on Science with FASR (*Frequency Agile Solar Radiotelescope*), 2002 May, Green Bank, WV
- Special session, 2002 *American Astronomical Society* meeting
- Kluwer ASSL* Book: *Solar & Space-Weather Radiophysics* (17 chapters on all aspects of radiophysics of the Sun and inner heliosphere, to be published in September, 2004)

**Astrophysics & Space Science Library*

Radio Emission Mechanisms

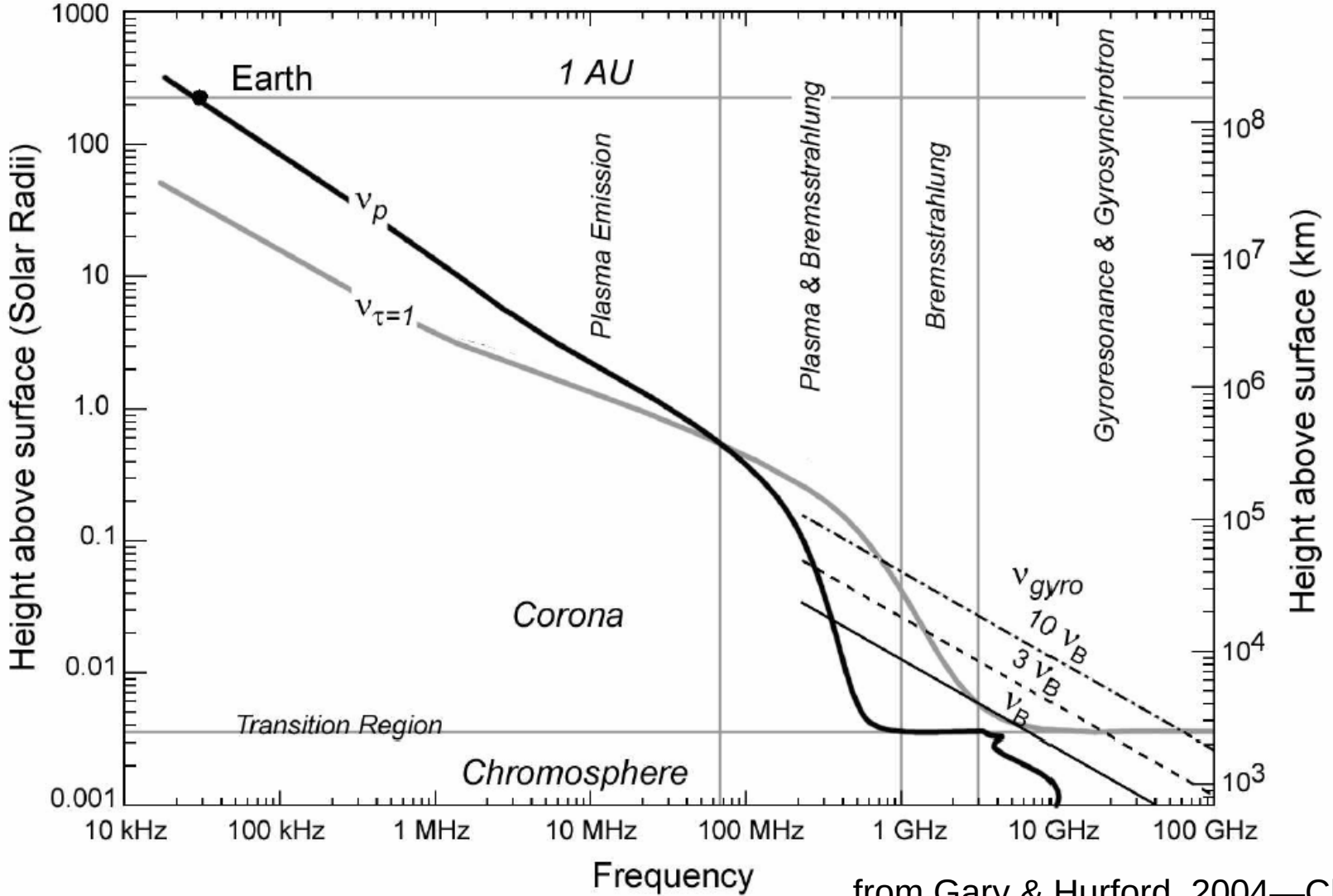
- Emission due to electrons—any acceleration process will do!
- Collisions between electrons and ions—free-free (bremsstrahlung) emission
- Gyro-emission (electrons spiralling in magnetic field)
- Plasma emission (collective oscillations at electron plasma frequency and 2nd harmonic
- Other coherent and incoherent mechanisms

Sensitivity to Magnetic Field

- Due to inherent magnetic field dependence, i.e. gyro-emission—allows direct determination of B field.
- Due to radiation propagation effects
  - Free-free emission (line of sight B field)
  - Plasma emission (sense of B only)
- Dependence of exciter on B
  - Electron beam trajectories
  - Shock wave propagation

Sensitivity to Particle Distribution

- Brightness of thermal emission is directly proportional to electron temperature
- Spectrum of nonthermal emission is directly related to energy and pitch-angle distribution
- Time profile of emission is directly related to lifetime of electrons—can study acceleration and decay processes
- Location of the emission gives location of accelerated electrons—can study particle acceleration region, or propagation of exciters (shocks, electron beams)



from Gary & Hurford, 2004—Ch. 4

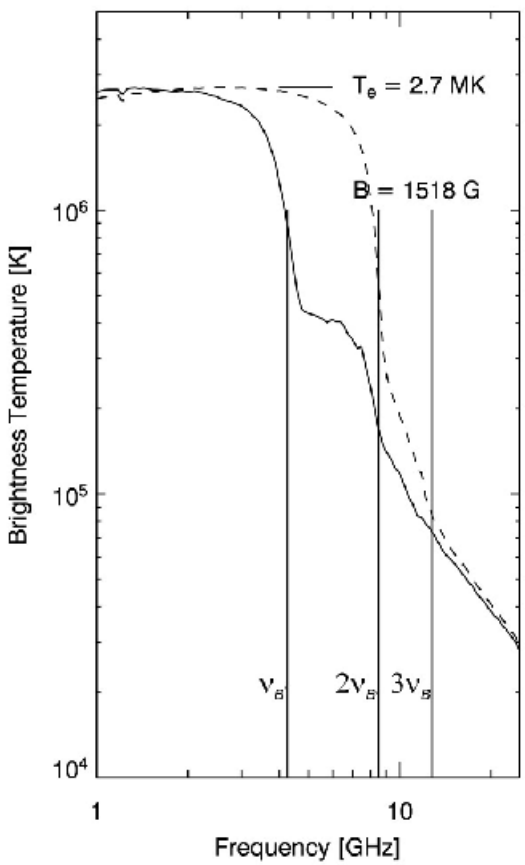
Radio Science Capabilities

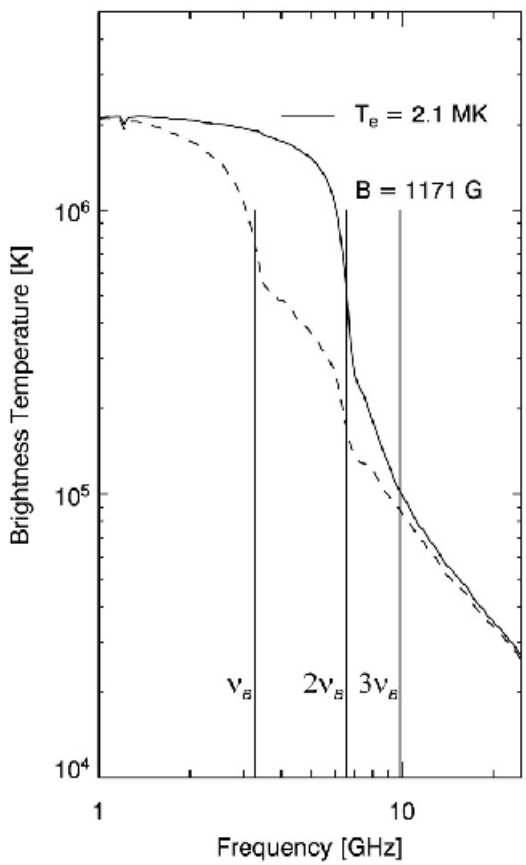
1. Directly measure coronal magnetic fields
2. Image Coronal Mass Ejections (CMEs)
3. Obtain radio spectral diagnostics of particle acceleration / energy release
4. Image radio emission from shocks (type II), electron beams (type III), and other bursts over heights 1-2.5 R_s
5. Construct 3D solar atmospheric structure (T, B, n_e) over a wide range of heights

Direct Measurement of Coronal Magnetic Fields

- Active region corona (120 G < B < 2400 G)
- Corona outside of active regions (B_l > 20 G)
- Coronal cavities
- Solar flares/CMEs

Magnetic Field Spectral Diagnostics



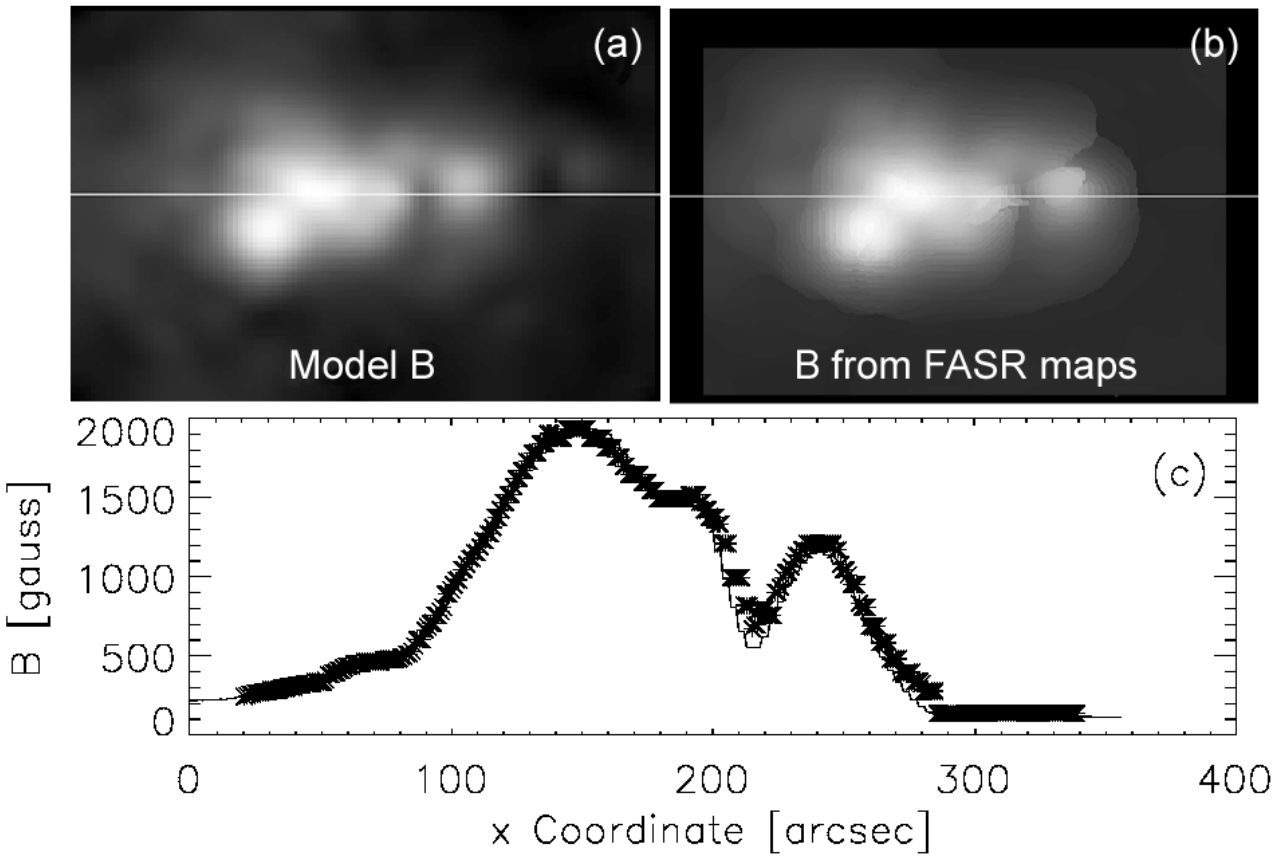


- Model spectra along 2 lines of sight: *a*) negative polarity sunspot, *b*) positive polarity sunspot.
- The coronal temperature and the magnetic field strength can be read directly from the spectra.

Model from Mok et al., 2004;

Simulation from Gary et al. 2004

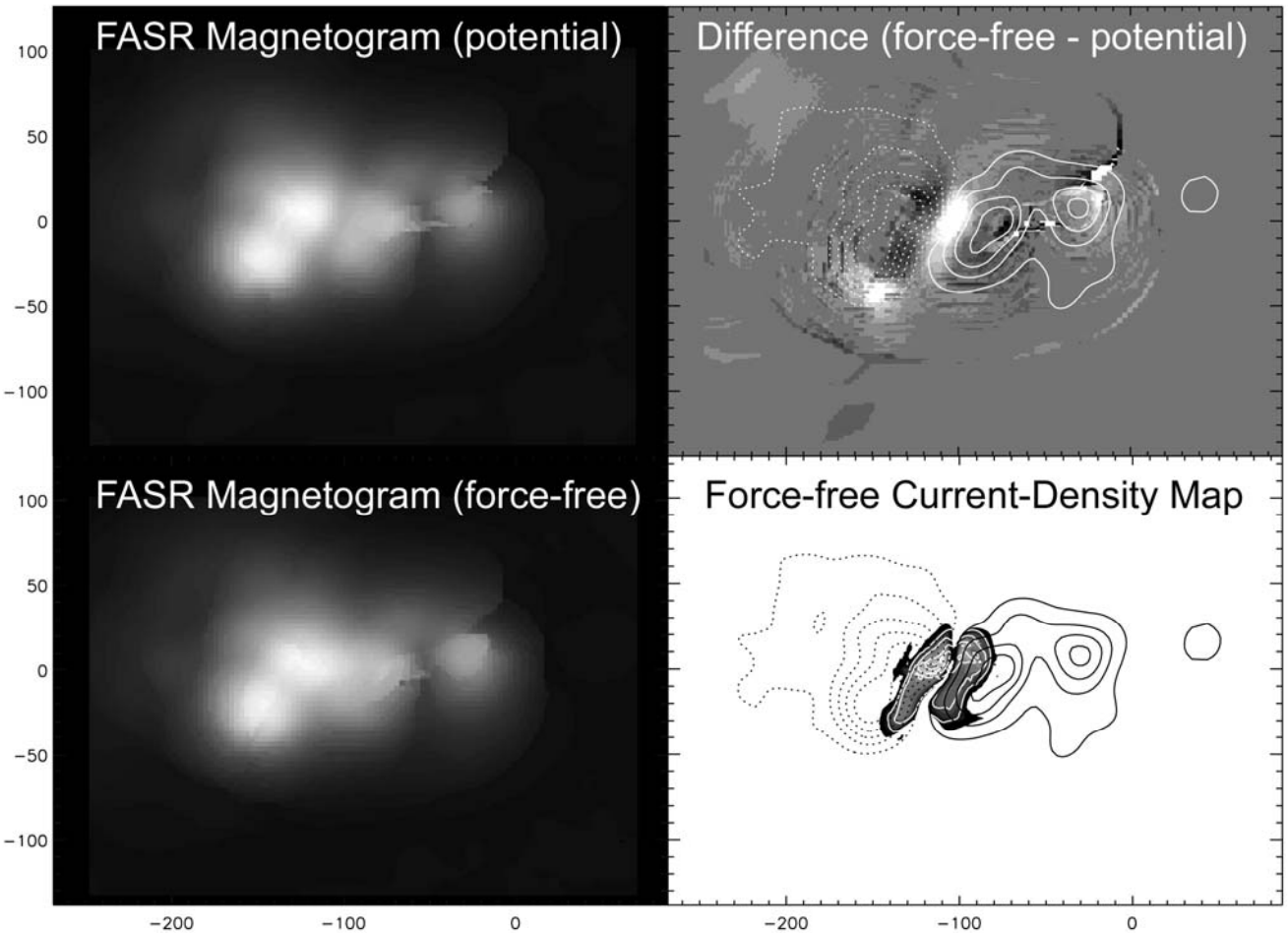
2D Magnetogram



from Gary et al. 2004

- *B* map deduced from 1—24 GHz spectra (*b*) match the model (*a*) very well, everywhere in the region. (*c*) is a comparison along a line through the center of the region.
- The fit only works down to 119 G (corresponding to $f = 3\ f_B = 1$ GHz)

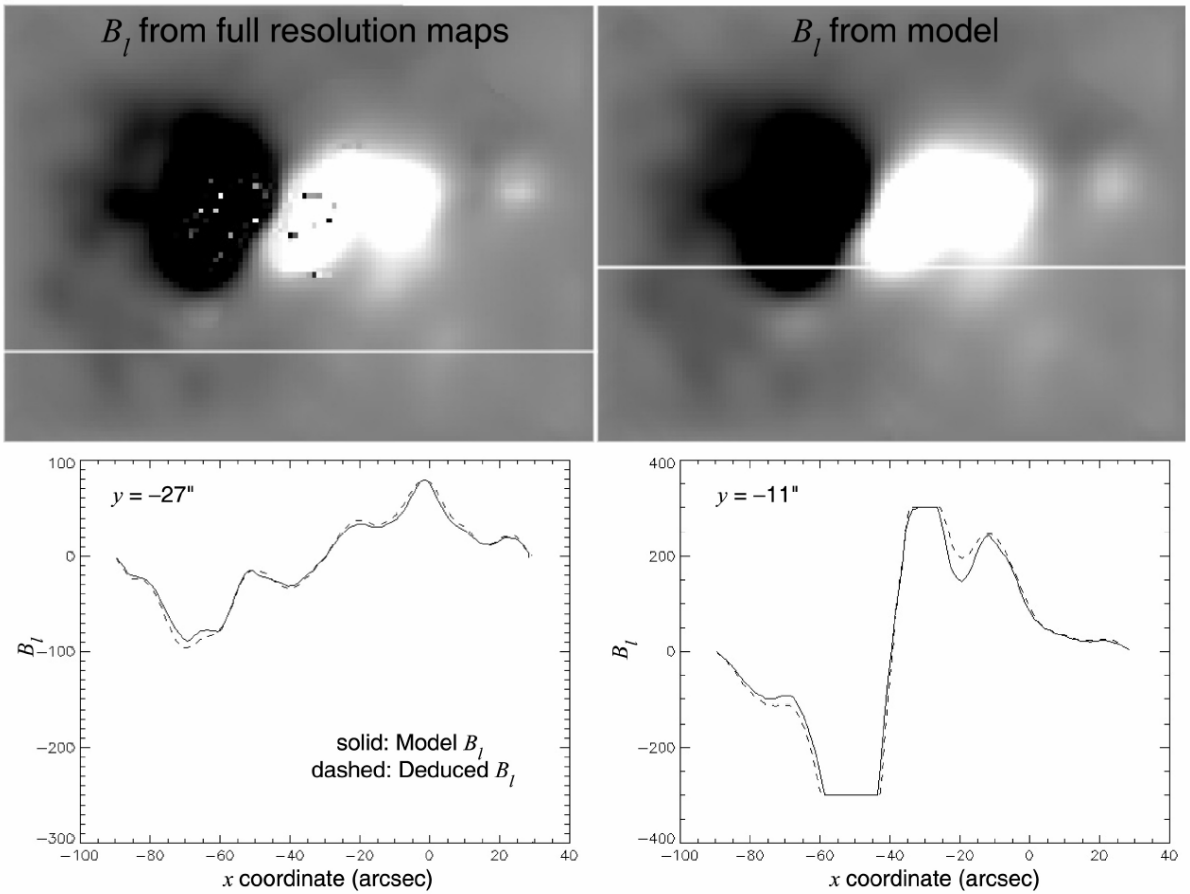
Coronal Magnetograms



Accurate simulation of FASR coronal magnetograms of potential and non-potential active region, and difference compared with current-density map from the model.

from Gary et al. 2004

B_l from Free-Free Emission



from Gary & Hurford, 2004—Chapter 4

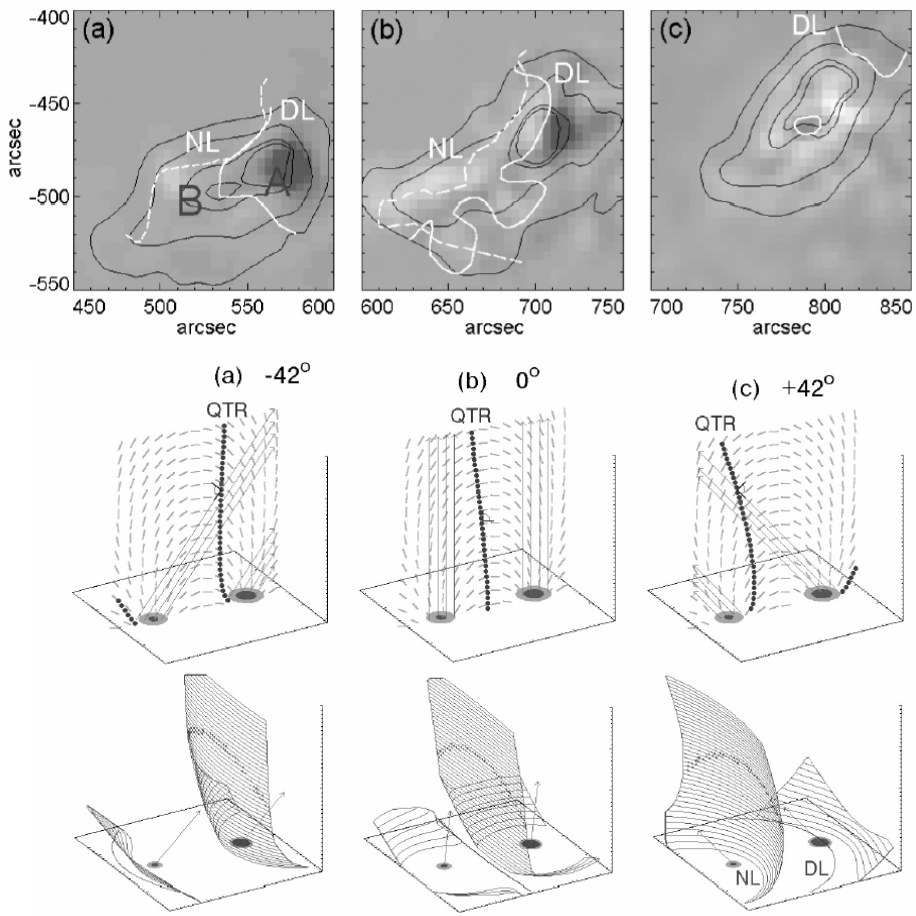
- This capability remains speculative, but with sufficient polarization sensitivity, B_l can be deduced everywhere down to ~ 20 G using:

$$B_l = \frac{107}{\lambda \cdot n} P\% \ .$$

where n is the spectral index

from Gelfreikh, 2004—Ch. 6

Magnetic Topology from QT Layer



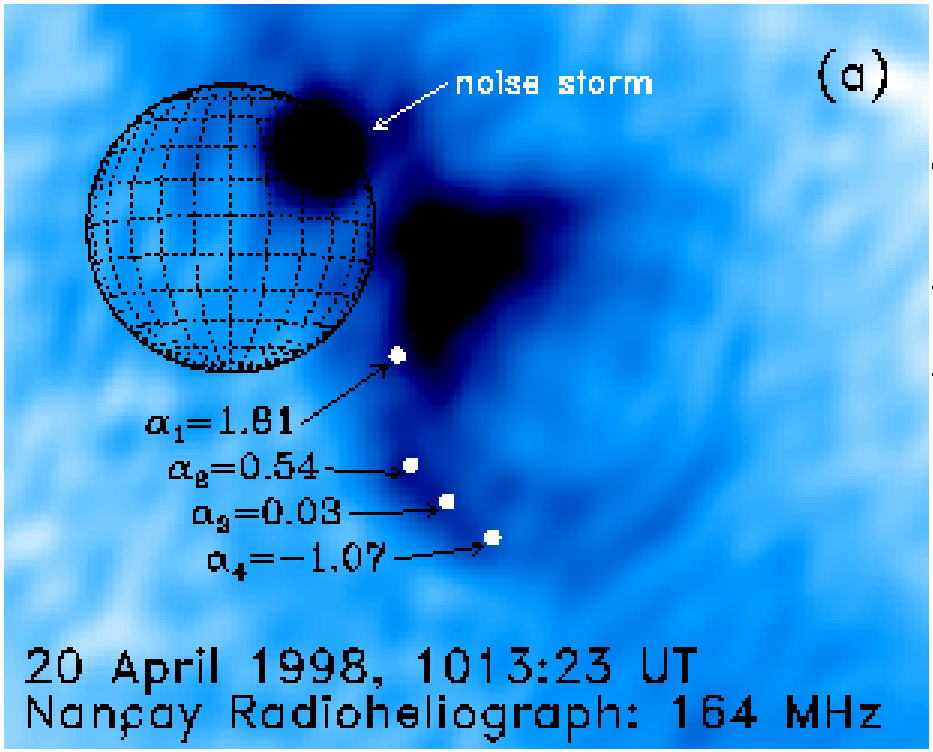
- Upper panels show radio "depolarization line" (DL) at a single frequency due to mode-conversion at a quasi-transverse (QT) layer, vs. photospheric neutral line (NL).
- Using FASR's many frequencies, a QT surface can be mapped in projection. The surface changes greatly with viewing angle.

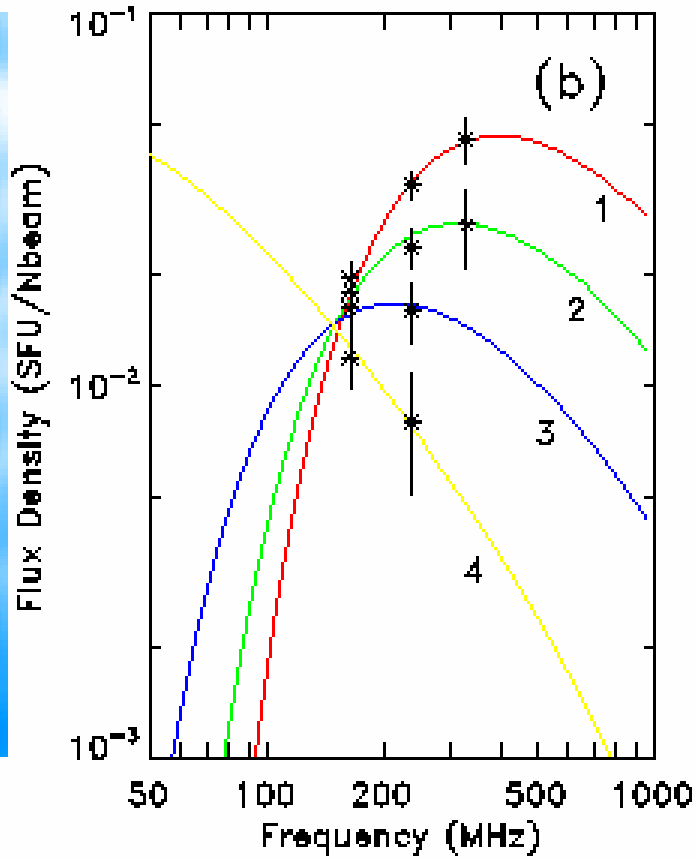
from Ryabov, 2004—Chapter 7

Radio Science Capability (2)

- Image CMEs both on the disk and off the limb
  - Observe non-thermal electrons in CMEs easily
  - Possibly detect free-free emission in some CMEs
  - Relate other forms of activity (both thermal and nonthermal) that take place simultaneously, with perfect co-registration
  - Observe analog of EIT/Moreton waves/coronal dimmings, filaments, type II bursts, and CMEs all in one panoramic view!
  - No occulting disk!

Observed CME Spectrum





from Bastian et al. 2001

Imaging the CME Density Enhancement via Free-Free

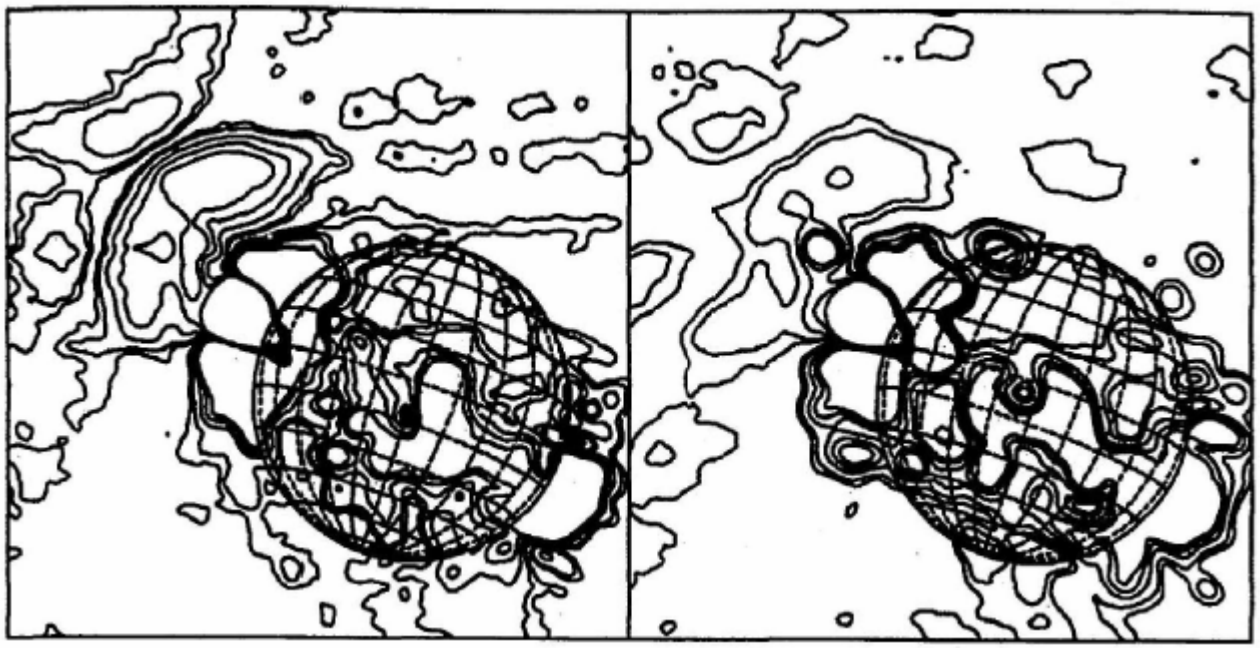


Image simulated with 73-element array

Image simulated with 37 element array

from Bastian & Gary 1997

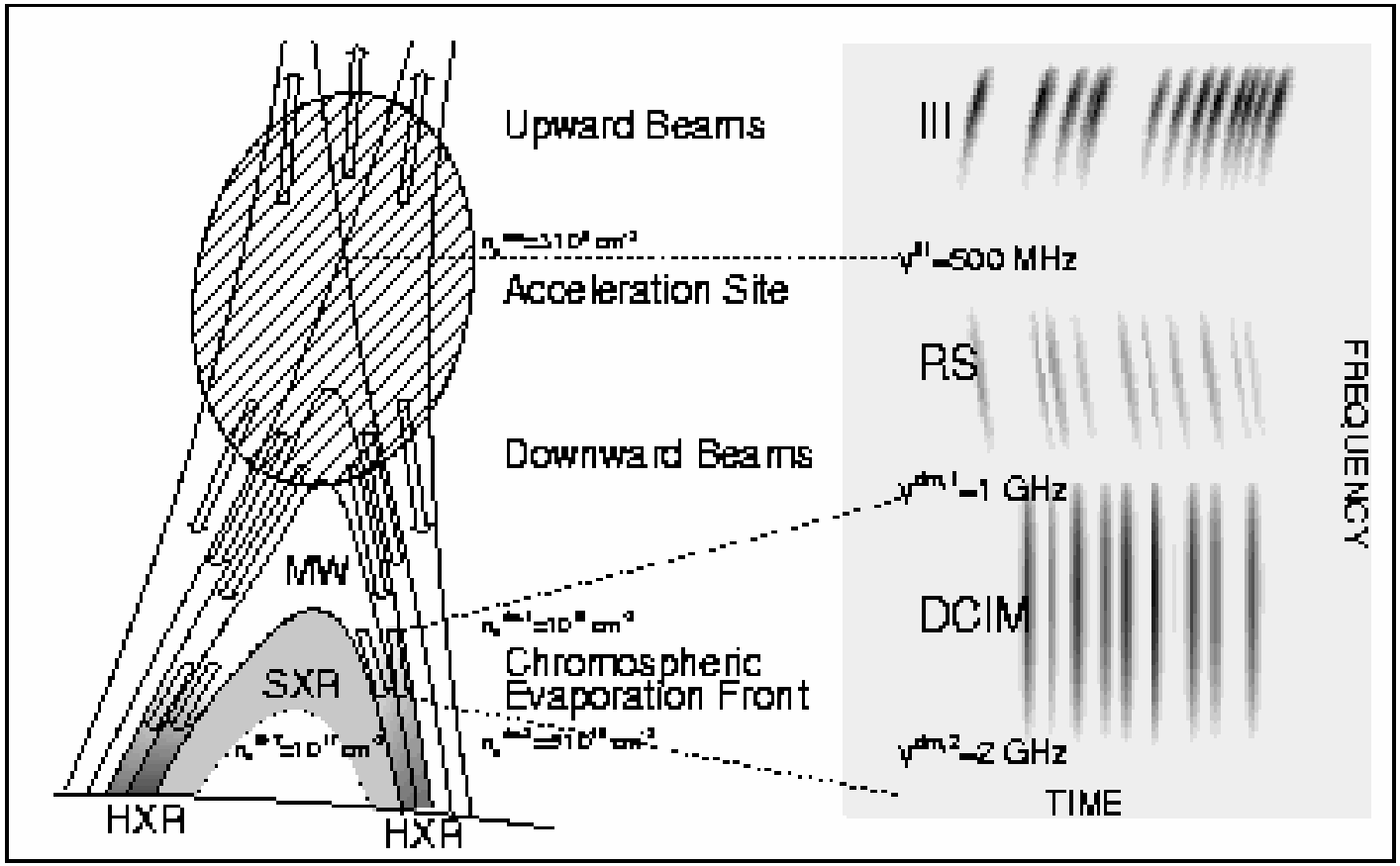
- Early FASR simulation
- New simulations are underway by Vourlidas and Marque

see Vourlidas, 2004—Chapter 11

Radio Science Capability (3)

- Radio spectral diagnostics of particle acceleration & energy release, with excellent spatial and temporal resolution
  - Directly image energy release region
  - Follow evolution of electrons from acceleration, through transport, and escape or thermalization
  - Obtain spectral diagnostics of energy/pitch angle distributions

Energy Release and Particle Acceleration

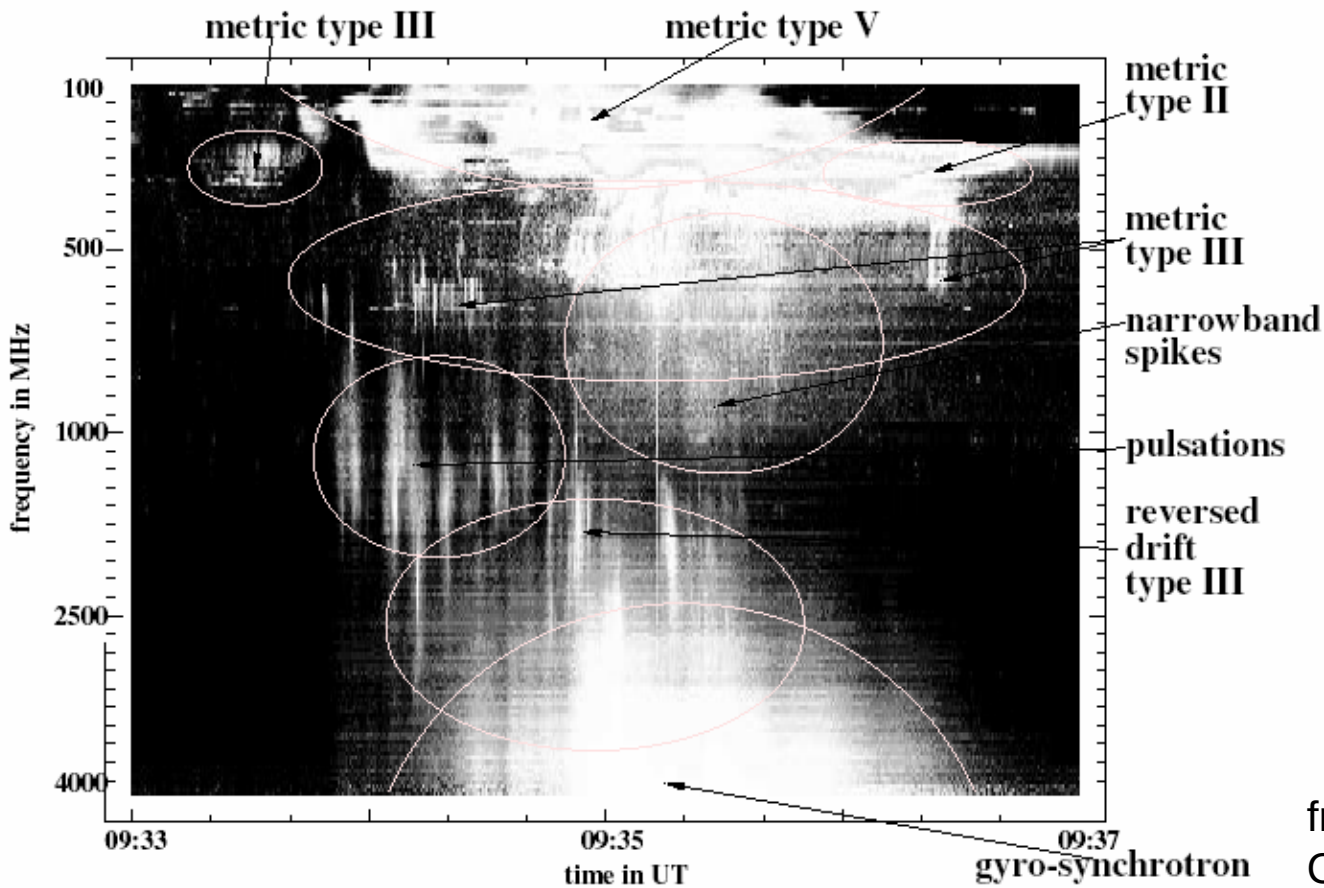


Subsecond timescales, with rapid frequency drift over 100s of MHz.

The decimetric part of the spectrum has *never* been imaged.

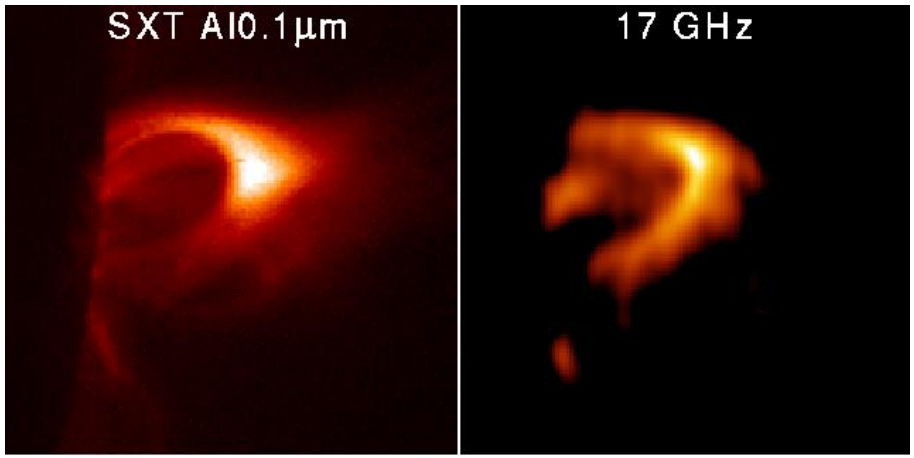
from Aschwanden et al. 1996

Panoramic View Proffered by Radio Emission

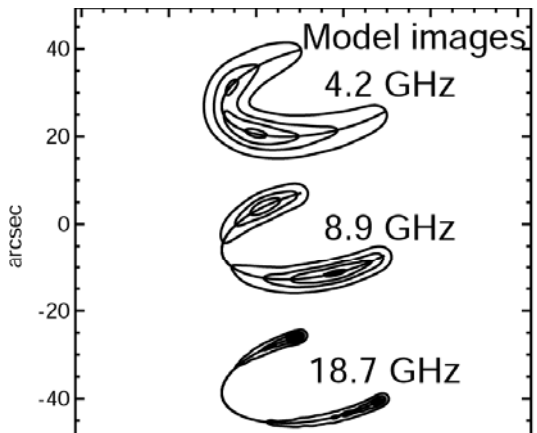


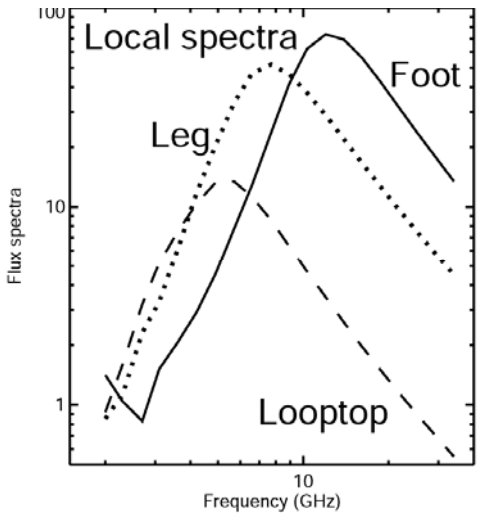
from Benz, 2004—Chapter 10

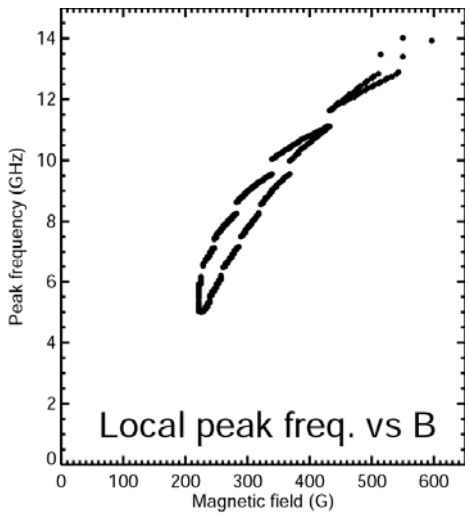
Solar Flare Diagnostics



Multifrequency imaging allows spatially resolved spectral diagnostics



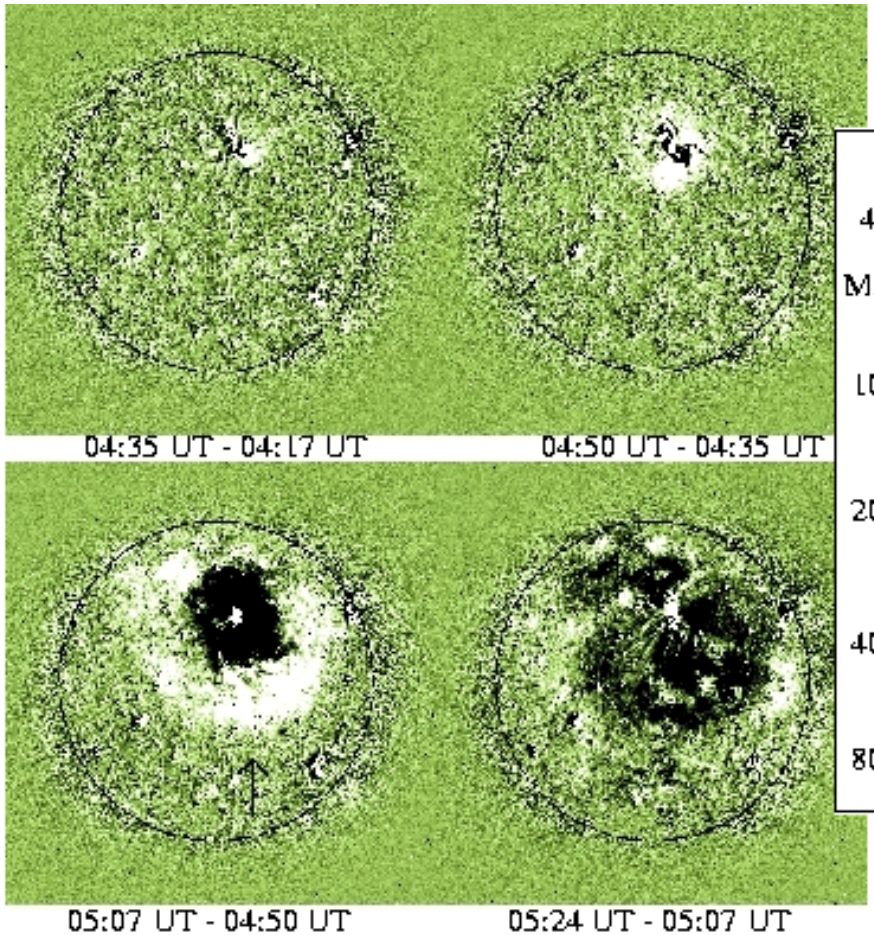


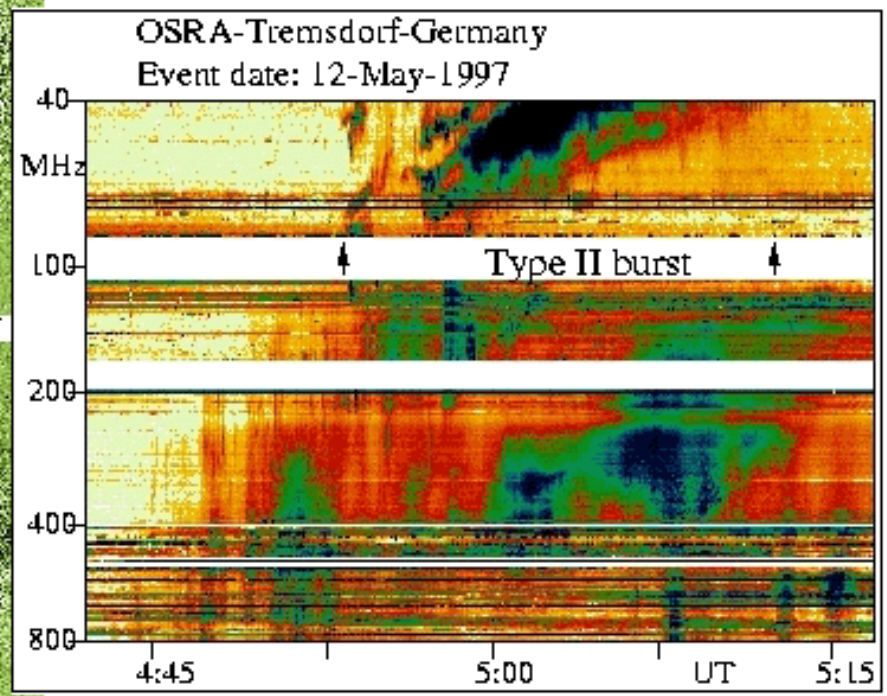


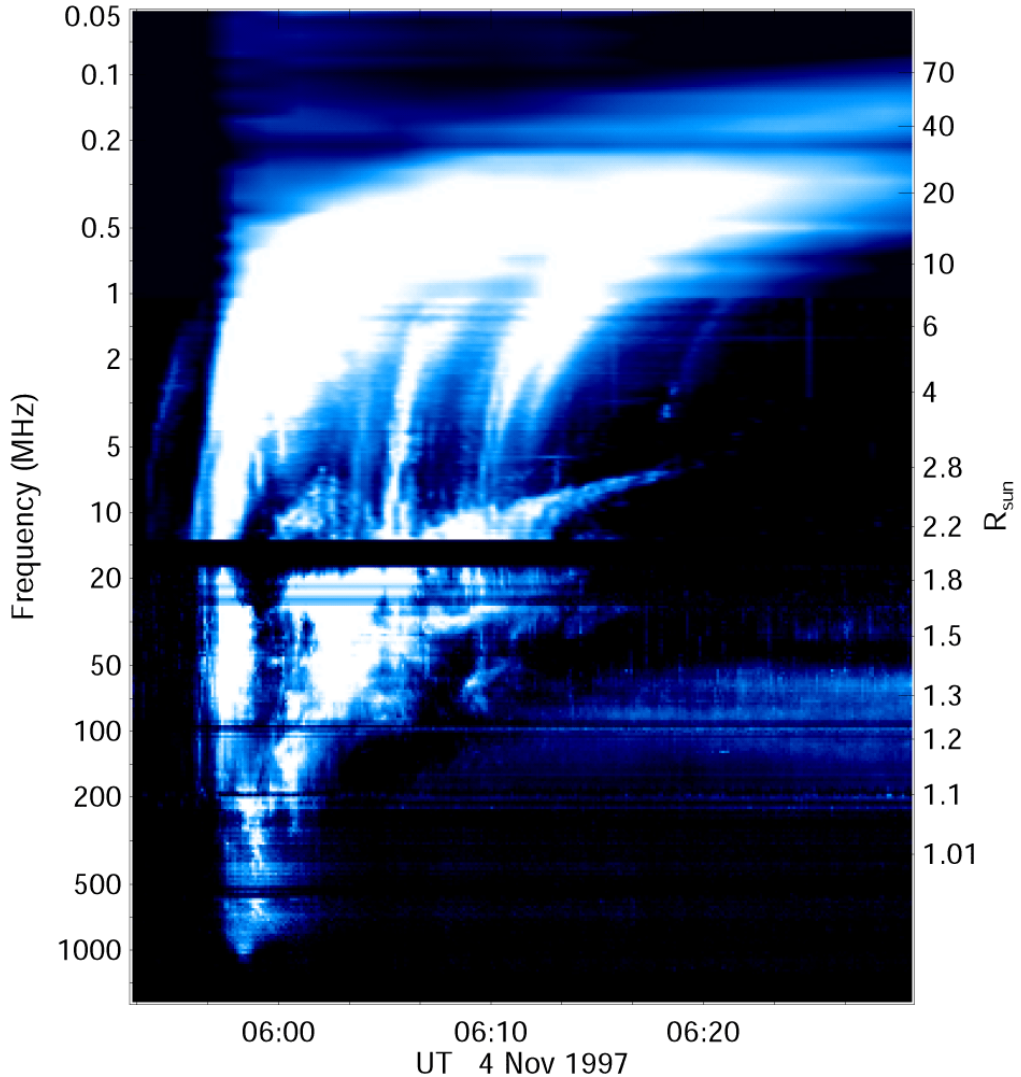
Radio Science Capability (4)

- Image radio emission from shocks (type II), electron beams (type III), and other bursts over heights 1-2.5 R_s
  - Global view of type II emission (multi-frequency gives multiple plasma layers)
  - Relate type II to CME, waves, accelerated particles
  - Follow type III (and U-burst) trajectories throughout frequency, and hence height

EIT Waves and Shocks





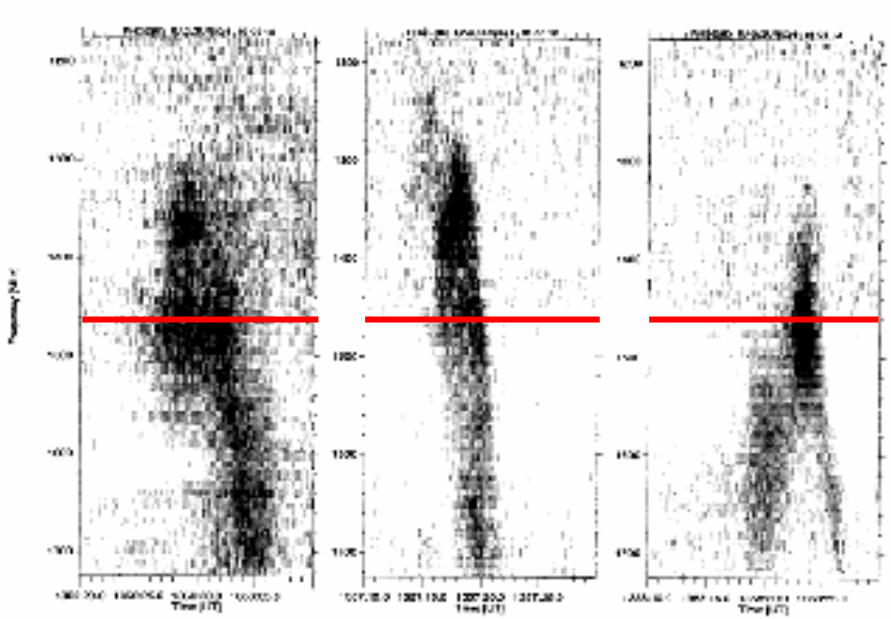


High Spectral and Temporal Resolution

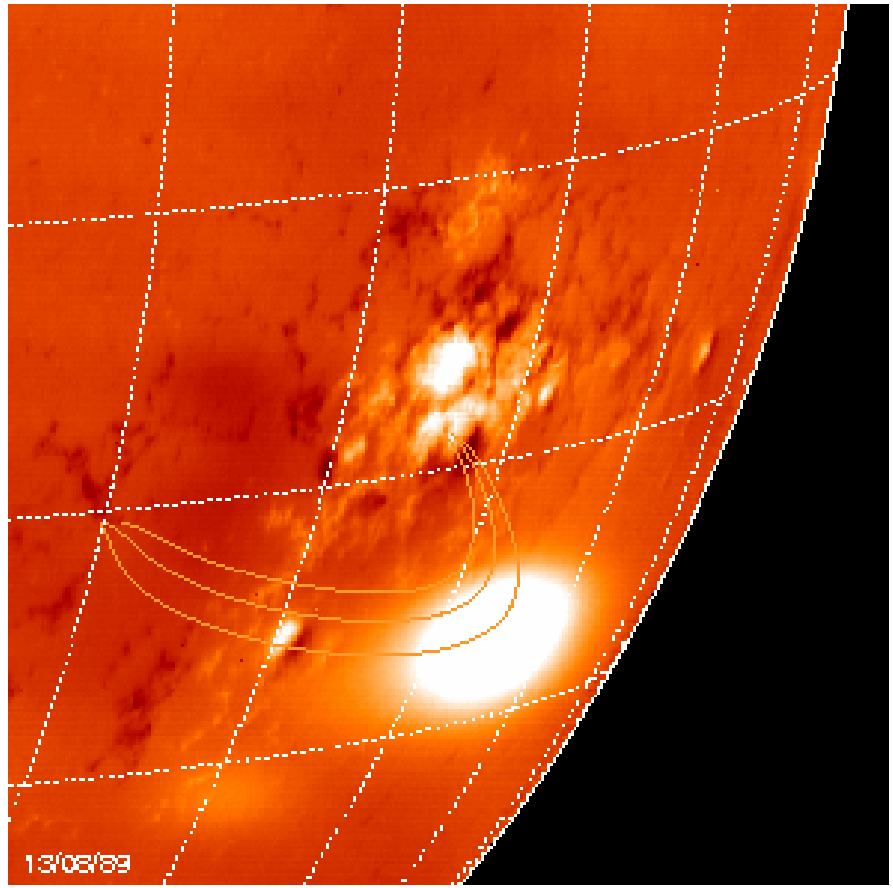
Complete imaging over a wide frequency range that connects solar and IP events.

Integrated view of thermal, nonthermal, flare, CME, shocks, electron beams.

Particle Trajectories

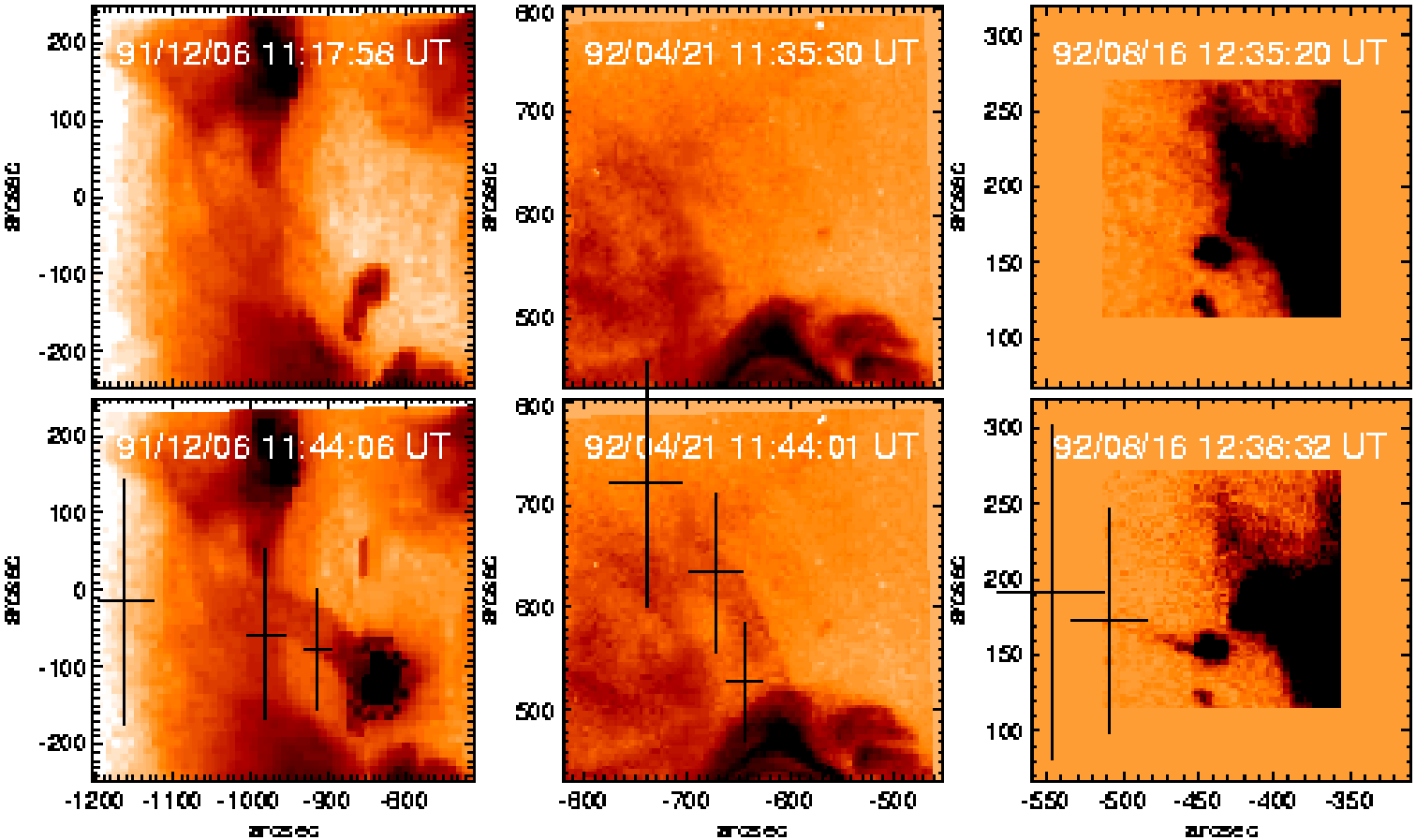


Type U bursts observed by Phoenix/ETH and the VLA.



from Aschwanden et al. (1992)

Particle Trajectories

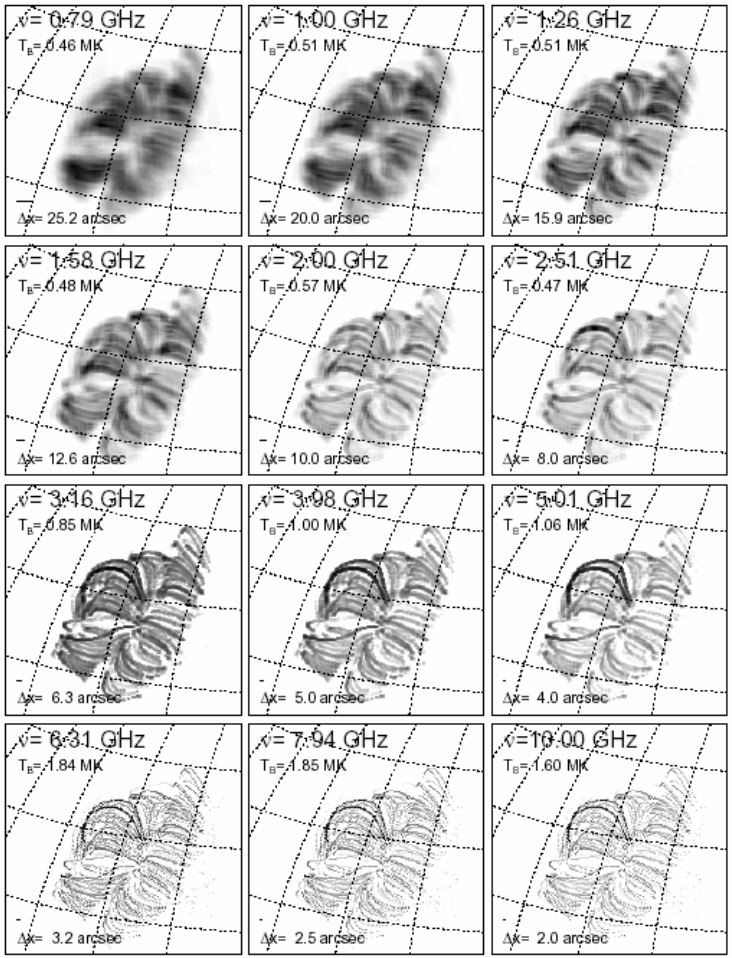


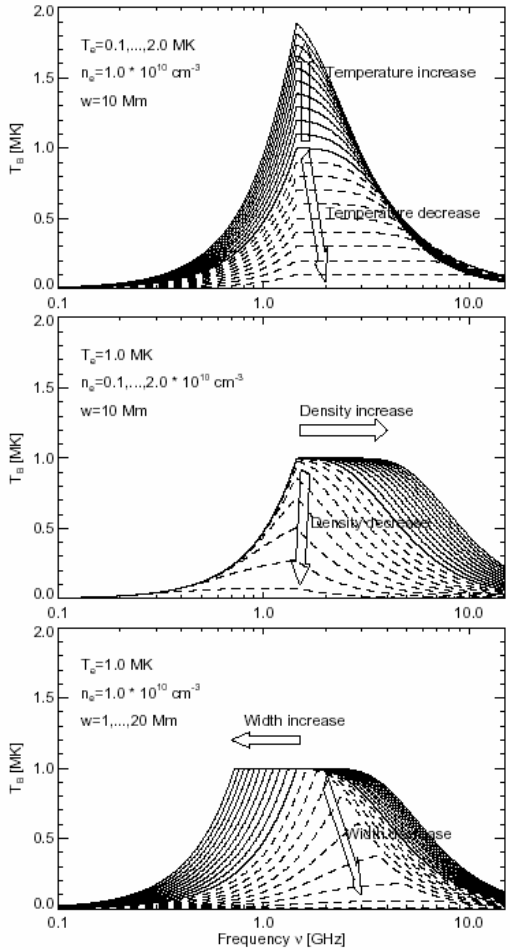
from Raulin et al. (1996)

Radio Science Capability (5)

- Construct 3D solar atmospheric structure (T, B, n_e) over a wide range of heights
  - Image individual heated loops
  - Image filaments, filament channels, eruptions, with spectral diagnostics
  - Combine radio, EUV, X-ray diagnostics for complete model of 3D structure

Diagnostics of Loop Heating

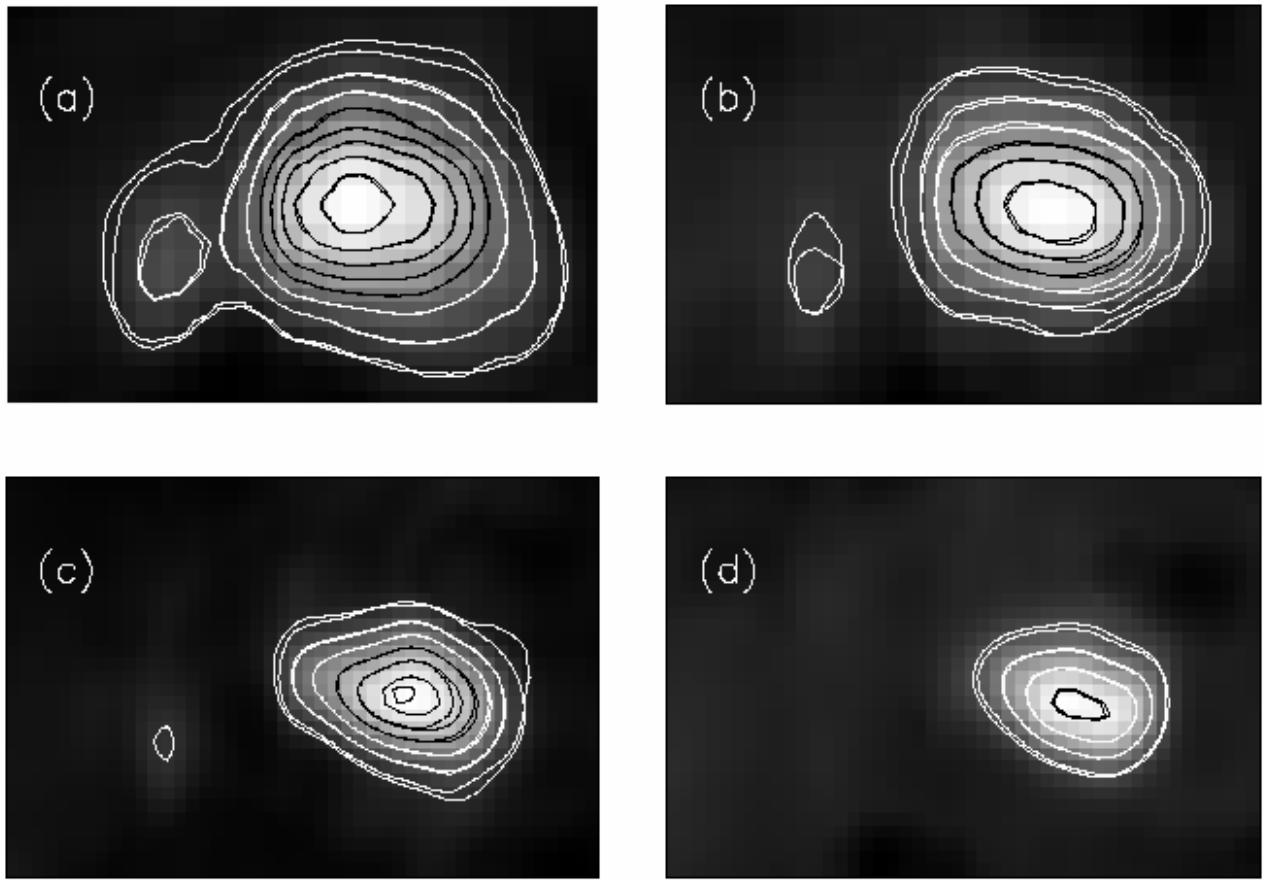




Simulated spectra of individually imaged hot loops yield detailed diagnostics

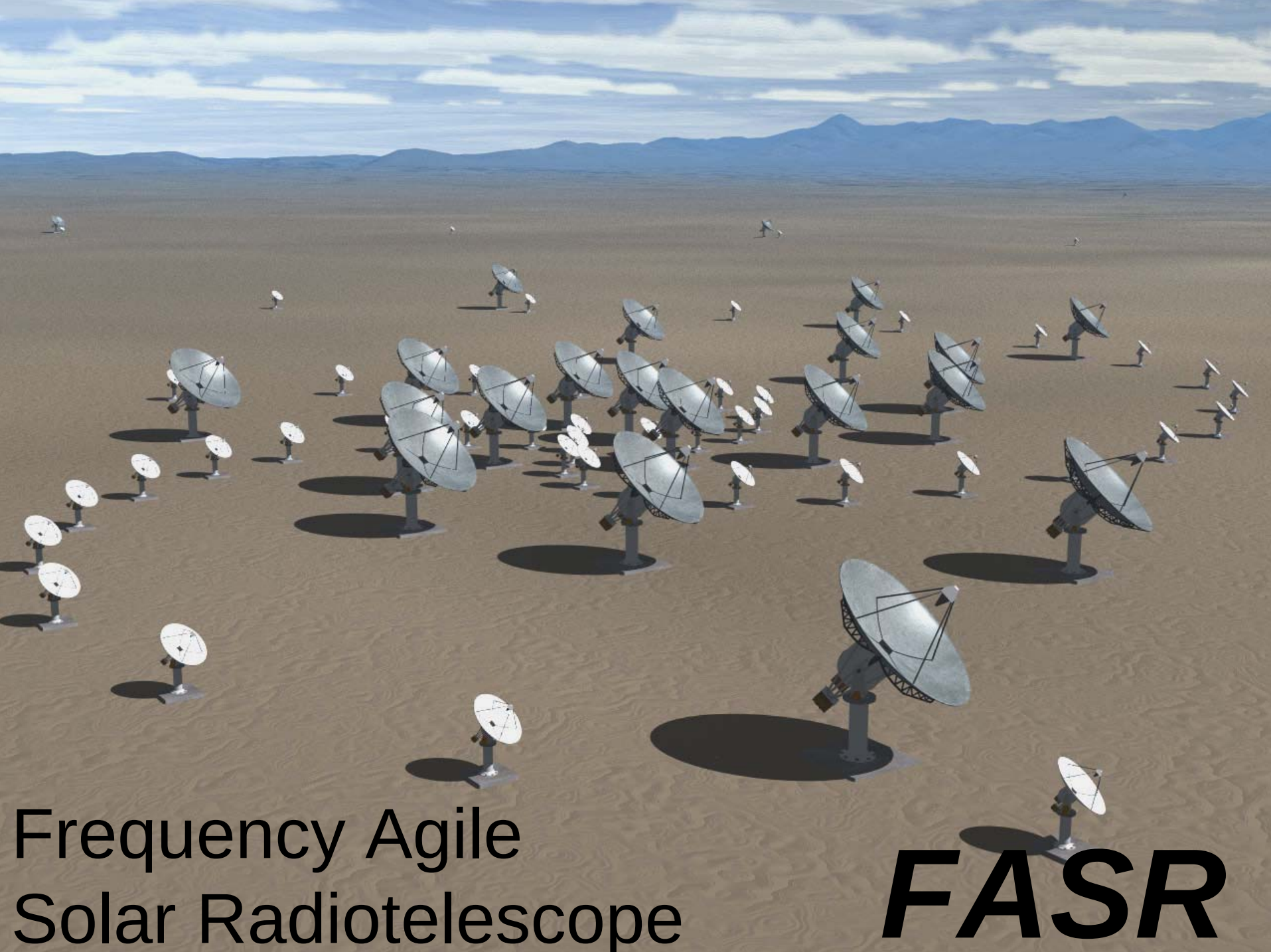
from Achwanden et al., 2004—Chapter 12

3D Model Using VLA/SERTS/EIT



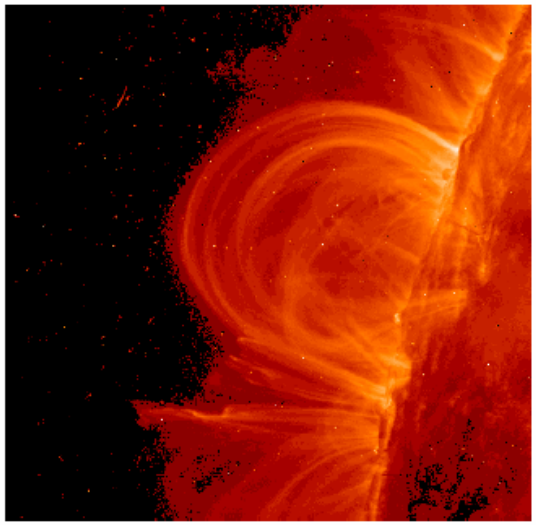
- Model simultaneously fits radio brightness, EUV DEM, temperature and density parameters

from Brosius 2004—Chapter 13


Frequency Agile
Solar Radiotelescope
FASR

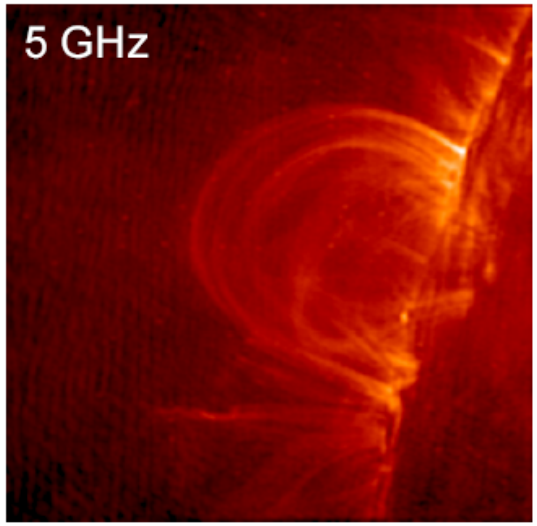
Imaging

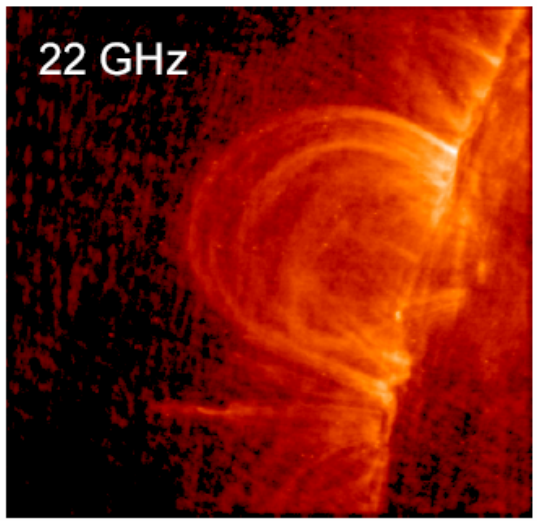
model



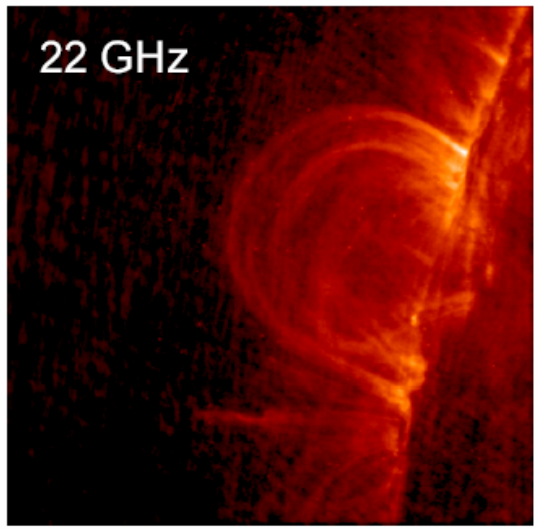
TRACE: 6 Nov 1999

snapshots





10 min synth.



102 antenna log-spiral in three arms

(noiseless data)

FASR Instrument (Antennas)

Three arrays, 6 km baselines

Array Designation	Number of Antennas	Frequency Range	Antenna Size
HFA High Frequency Array	~100	2-24 GHz	2 m
LFA Low Frequency Array	~60	0.2-3 GHz	6 m
LPDA Log-Periodic Dipole Array	~40	20-300 MHz	Log-dipole

FASR Instrument (Receivers)

Broadband RF transmission, Digital FX Correlator

Quantity	Spec
Frequency Resolution	0.1% (LFA) 1% (HFA)
Time Resolution	10 ms (LFA) 100 ms (HFA)
Polarization	Stokes IV (QU)
Instantaneous Bandwidth	~1 GHz

Conclusion

- Radio emission offers a number of key solar and space weather science capabilities, including unique sensitivity to magnetic fields.
- Past and current instruments have not put together the two essential elements to realize these capabilities: imaging and spectroscopy.
- FASR is being designed to address this extremely rich range of solar science, utilizing state-of-the-art technology.

FASR Endorsements

2001 Astronomy & Astrophysics Survey Committee

- Ranked as one of 17 priority projects for this decade
- one of 3 solar projects, with ATST and SDO

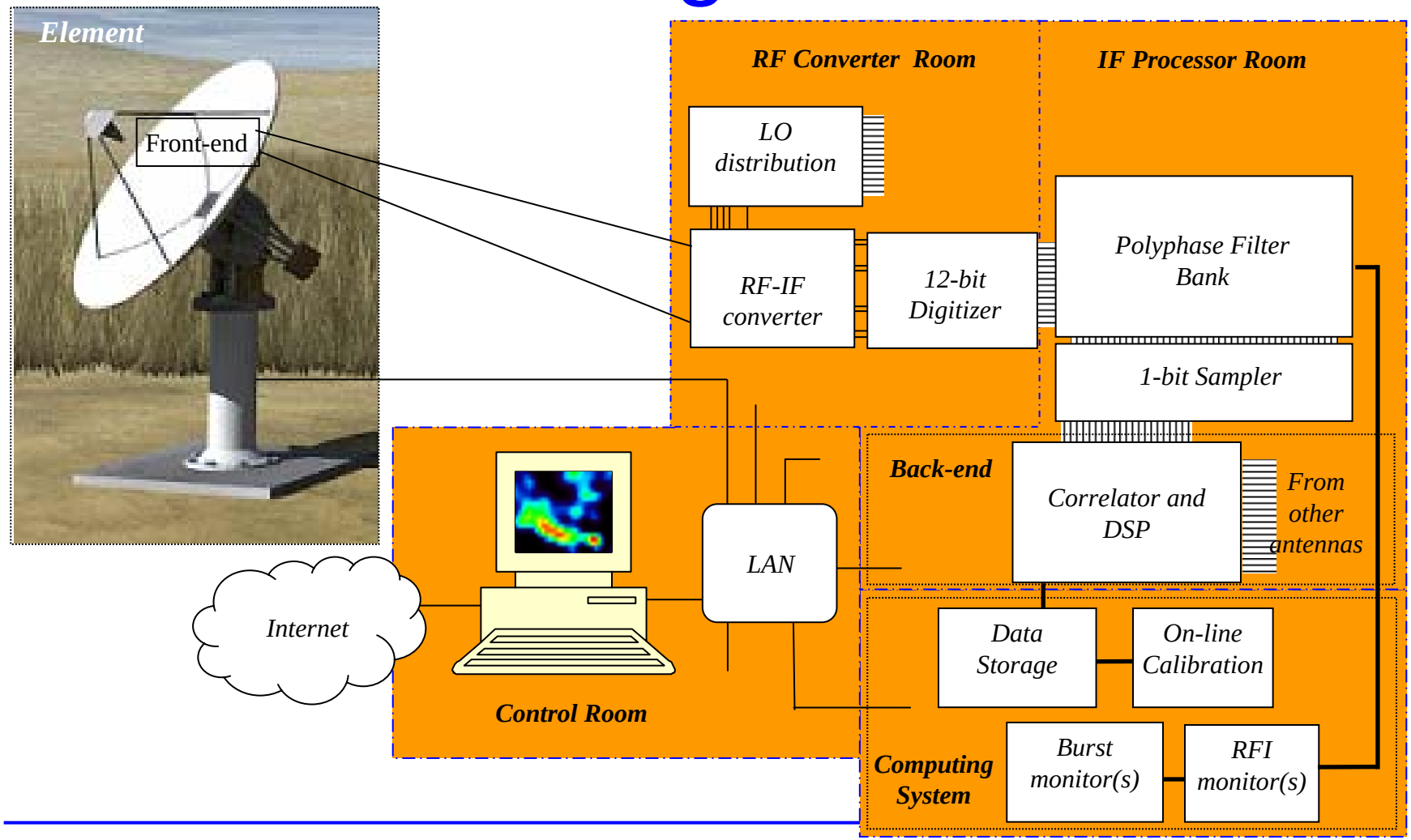
2003 Solar and Space Physics Survey Committee

- Ranked as top priority in small (<$150 M) projects

2002-2004: Design Study (NSF/ATI): NJIT (lead), NRAO, UMd, UC/Berkeley

- 3 workshops for community input (Kluwer ASSL book publication)
- Science consensus, hardware and software design options, and development of management plan.

2004-2006: FASR Prototyping Grant (NSF/ATI): NJIT (lead), UMd, UC/Berkeley, Caltech

2005-2006: FASR Phase B Study: AUI, NJIT, UMd, UMich, UC/Berkeley

FASR Signal Path