FASR and Radio Measurements Of Coronal Magnetic Fields

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Radio Emission and the Coronal Magnetic Field

- 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.)
Gyroresonance emission

- Opacity results from electrons gyrating in coronal magnetic fields at $f_B = 2.8 \times 10^6$ 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 $\propto n B/(\partial B/\partial l) (T/mc^2 \sin^2 \theta)^{s-1}$ where $s = 1, 2, 3, \ldots$ 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
Gyroresonance emission from a simple sunspot

Extraordinary (x) mode emission near disk center: $B = 1000$ G
Gyroresonance emission from a simple sunspot

Ordinary (o) mode emission near disk center: no opacity at spot center where the line of sight is parallel to B
Gyroresonance emission from a simple sunspot

Extraordinary (x) mode emission 2 days later, well to west
Gyroresonance emission from a simple sunspot

Ordinary (o) mode emission 2 days later: magnetic field over spot is more orthogonal to line of sight, less difference from x mode
- Gyroresonance opacity is the only mechanism capable of making the corona optically thick at frequencies above 4 GHz
- Emission comes from a surface of constant magnetic field in the corona
- Coronal temperatures indicate the presence of magnetic field strengths at appropriate strengths: microwaves are sensitive to fields in the range 200–3000 G.
- High levels of circular polarization also indicate presence of strong magnetic fields and can be used to measure temperature gradients
Radio images of the region show relatively simple structure consistent with extrapolated surfaces (apart from cool plume at upper center).
Coronal Magnetogram

Magnetic field at the base of the corona: contours at 600, 1000, 1800 G
The Height of the Corona

Outer boundaries of isogauss surfaces at different heights from nonlinear FFF extrapolation of radio boundaries (Leka, Mikic, SW)
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
~ 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
Endorsements

1998 NRC Task Group on Ground-based Solar Astronomy
• Highly ranked

2001 NRC Astronomy & Astrophysics Decadal Survey Committee
• Ranked as one of 17 priority projects for this decade
• one of 3 solar projects, with ATST and SDO

2003 NRC Solar and Space Physics Decadal Survey Committee
• Ranked as top priority in small (<$150 M) projects

3 workshops for community input
FASR Participants

• Associated Universities, Inc. AUI (Tim Bastian)
• National Radio Astronomy Observatory NRAO
• New Jersey Institute of Technology NJIT (Dale Gary)
• University of Maryland U Md (Stephen White)
• University of California at Berkeley UCB (Gordon Hurford)
• Paris Observatory/Nançay Observatory NRH (Monique Pick/Alain Kerdraon)
• University of Michigan UM (Thomas Zurbuchen/Chris Ruf)
• California Institute of Technology CIT
• University of New Mexico UNM
• Naval Research Laboratory NRL
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.
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

Model radio images

- 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)

Gary, Lee, Giordano, Mok
Radio spectra reveal B

- 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.

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

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

Lee et al
Coronal field lines from nonlinear FFF extrapolation
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

JW Lee, McLymont, Mikic, SW
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
2003 October 28 loop flare: TRACE/NoRH
Model spectra from a flaring loop with fitted values of B and the angle between B and the line of sight (δ and n also fit). The model parameters are generally recovered to better than 10% although there are obvious problems for small aspect angles.
Routine FASR products

- **Coronal magnetograms**: magnetograms at the base of the corona (wherever that is)

- **Coronal temperature maps**: possible wherever the corona is optically thick, i.e., every active region (relevant for flare studies). Use maximum T at any frequency in each pixel.

- **Coronal magnetic shear maps**: essentially difference between coronal magnetogram and potential field extrapolation of photospheric fields. Potentially valuable for flare prediction.

- **Emerging coronal flux**: indicates regions of rapid changes of flux entering the corona

- Eventually: **3D coronal magnetograms** in conjunction with nonlinear force-free extrapolations of surface fields
Coronal magnetic fields in the near future

- **Optical/IR measurements**
  - at locations above the solar limb
  - at present no chance to compare with surface fields because of projection effects, difficulty measuring photospheric B at limb
  - 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; bremsstrahlung may yield weaker fields
  - 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 ambiguity-resolved chromospheric vector magnetograms when we have them, if robust fast algorithm is available
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.
The End