

Solar Coronal Magnetic Fields: Quantitative Measurements at Radio Wavelengths

- Thematic Areas:**
- Planetary Systems
 - Star and Planet Formation
 - Formation and Evolution of Compact Objects
 - Cosmology and Fundamental Physics
 - Stars and Stellar Evolution
 - Resolved Stellar Populations and their Environments
 - Galaxy Evolution
 - Multi-Messenger Astronomy and Astrophysics

Principal Author:

Gregory D. Fleishman, New Jersey Institute of Technology

Email: dgary@njit.edu

Phone: (973) 642-7878

Co-authors:

Timothy S. Bastian, National Radio Astronomy Observatory

Bin Chen, New Jersey Institute of Technology

Dale E. Gary, New Jersey Institute of Technology

Lindsay Glesener, University of Minnesota

Gelu Nita, New Jersey Institute of Technology

Pascal Saint-Hilaire, University of California, Berkeley

Stephen M. White, Air Force Research Laboratory

Abstract

The solar corona and upper chromosphere represent an important and unique testbed for studying universal physical processes occurring in astrophysical plasmas. For example, energy stored in the magnetic field in the solar atmosphere above active regions is a key driver of all solar activity including particle acceleration and transport in solar flares and coronal mass ejections, some of which can have a profound effect on Earth. Yet, quantitative measurements of coronal and chromospheric magnetic field is currently in its infancy. However, a number of important diagnostics of coronal and chromospheric magnetic fields may be enabled by exploiting well-understood techniques offered through ultra-broadband imaging spectropolarimetry at radio wavelengths. Such observations will provide unique measurements of coronal and chromospheric magnetic fields and their evolution, which is a key input for MHD numerical models of the solar atmosphere and eruptive processes, and a key link between lower layers of the solar atmosphere and the heliosphere.

1 Introduction

Magnetic fields are of critical importance in a variety of astrophysical contexts. The release of energy stored in magnetic fields is central to many problems of astrophysics, such as the origin of the radio arc in the galactic center [1], quasar superluminal sources [2], the hot component of the galactic ridge X-ray emission [3], particle acceleration in the accretion disks of AGNs [4], and solar-analogous problems in stellar astrophysics, such as how stellar atmospheres are heated and nonthermal particles are produced in active, highly magnetized stars [5]. Thanks to its proximity and an extensive system of space- and ground-based observing facilities across a wide range of wavelengths, the Sun is arguably the best astrophysical laboratory for obtaining clues to the fundamental processes underlying magnetic field generation and emergence (the dynamo), its structure and evolution, and its transport and conversion to other forms of energy.

Quantitative knowledge of coronal magnetic fields is fundamental to understanding essentially all solar phenomena above the photosphere, including the structure and evolution of active regions, prompt energy release, charged particle acceleration, flares, coronal mass ejections (CMEs), filaments, coronal heating, and acceleration of the solar wind. Coronal magnetography has been, and remains, a priority of the wider solar physics community.

Currently available space- and ground-based solar optical telescopes are already capable of vector measurements of the photospheric magnetic field with sub-arcsecond angular resolution and high temporal resolution using the Zeeman effect (e.g., SDO/HMI). Yet direct quantitative measurements of chromospheric and coronal magnetic fields have been limited or unavailable. Thus, considerable resources are devoted to indirect means of constraining the magnetic field above the photosphere. Vector magnetic field measurements at photospheric heights can be numerically extrapolated into the upper chromosphere and corona using nonlinear force-free field extrapolation techniques. However, such extrapolations depend sensitively on measurement errors [6] and rely on assumptions whose validity is questionable (see, e.g., [7] for a critical assessment). Hence, new observational techniques for directly measuring the coronal magnetic fields are being vigorously pursued. At optical/IR wavelengths, the Hanle and Zeeman effects [8] are being measured for this purpose. Next generation instruments like the Daniel K. Inouye Solar Telescope (DKIST) [9] will exploit such measurements using near-IR coronal spectral lines [10], but these will only be effective above the solar limb. As we show here, radio observations are positioned to be a powerful, versatile, and complementary diagnostic of chromospheric and coronal magnetic fields both on the disk and above the limb.

2 Sensitivity of Radio Emission to Magnetic Fields

Radio emission processes are well known to depend strongly on the magnetic field strength in the source region due to two effects: (1) the $\mathbf{v} \times \mathbf{B}$ Lorentz force causes the emitting electrons to spiral in the magnetic field to produce gyroemission, which takes the form of gyroresonance (GR) emission for thermal electrons in the hot corona of active regions, and gyrosynchrotron (GS) emission for mildly-relativistic electrons in flares; and (2) the plasma itself is birefringent, with differing indices of refraction [11] for the ordinary (o) and extraordinary (x) magnetoionic modes,

which leads to a magnetic-field-dependent polarization of each type of emission, including free-free (FF) bremsstrahlung emission [12]. Hence, both Stokes I and V polarization parameters must be observed.¹

We emphasize measurements of chromospheric and coronal magnetic fields in solar active regions here but comment briefly on other applications and contexts in § 3. For active regions, the two emission mechanisms relevant for the chromosphere and corona are the GR and FF mechanisms, both of which are well understood. **To exploit them fully, broadband imaging spectropolarimetric observations are required** (§ 4). As described in [13], spatially-resolved polarized brightness temperature spectra $T_b(f)$ along a line of sight (LOS) to the source provide temperature as a function of frequency, $T(f) = T_b(f)$ for the x- and o-mode. The contribution of FF and GR to a given polarized spectrum depends on temperature, density, and magnetic field strength and orientation along the LOS. The optical depth of FF emission varies as $n_e^2 f^{-2} T^{-1.5}$ and therefore favors denser, cooler, regions and low frequencies whereas GR strongly favors high magnetic fields and higher plasma temperatures. The corona is seldom optically thick to free-free absorption at frequencies $\gtrsim 3$ GHz, at which point optically thick GR emission becomes relevant if the coronal magnetic field is sufficiently strong. Typically, GR emission has a significant optical depth at the lowest few harmonics $s = 1, 2, 3$ (more seldom 4 or 5) of the gyrofrequency f_B , $f = sf_B = 2.8sB$ MHz, which allows the conversion $T(f) \Rightarrow T(sB)$; [14, 15, 16]. Given that the temperature of the solar atmosphere drops precipitously at the base of the corona, the T_b spectrum likewise cuts off and it is then straightforward to deduce the magnetic field strength $|B|$ at the base of the corona [17].

Wang et al. (2015) demonstrated the technique by creating a realistic 3-dimensional model of an active region, calculating the radio images from it including both GR and FF emission, and then using the technique describe above. The derived magnetic field strength could then be compared directly with the “known” magnetic field strength in the model, to assess the differences, as shown in Figure 1c. Such measurements require high-resolution spectra along each line of sight to determine which harmonic s is optically thick to GR and to disentangle FF from GR emission. Wherever the magnetic field is low, or the plasma density is particularly high, the dominant contribution to the radio emission comes from the FF process. The intensity of the FF emission is determined by the plasma temperature, while it only weakly depends on the magnetic field. In contrast, the polarization does depend on the line-of-sight magnetic field. [18, 19, 20]. Hence, in addition to $|B|$ provided by GR, B_{los} is available from FF emission.

Although 2D mapping of $|B|$ in solar active regions at the base of the corona is straightforward, 3D mapping is a research frontier. The problem of mapping coronal magnetic fields and tracking their evolution in 3D will require close collaboration with IR and UV/EUV observers measuring coronal lines as well as modelers extrapolating photospheric (or chromospheric) magnetic field measurements into the corona. It is important to note that the GR measurement in the corona yields a radio brightness of a given optically thick layer, where the optical depth is determined primarily by the magnetic field, while the brightness is determined by the plasma temperature at this layer. This means, that the thermal and magnetic structures of the corona are strongly coupled in the GR process; thus, to decouple them, additional thermal diagnostics are required.

¹The Faraday depth of the corona is so large that Stokes Q and U are unobservable except, possibly, under special circumstances. See Allisandrakis & Chiuderi-Drago 1995.

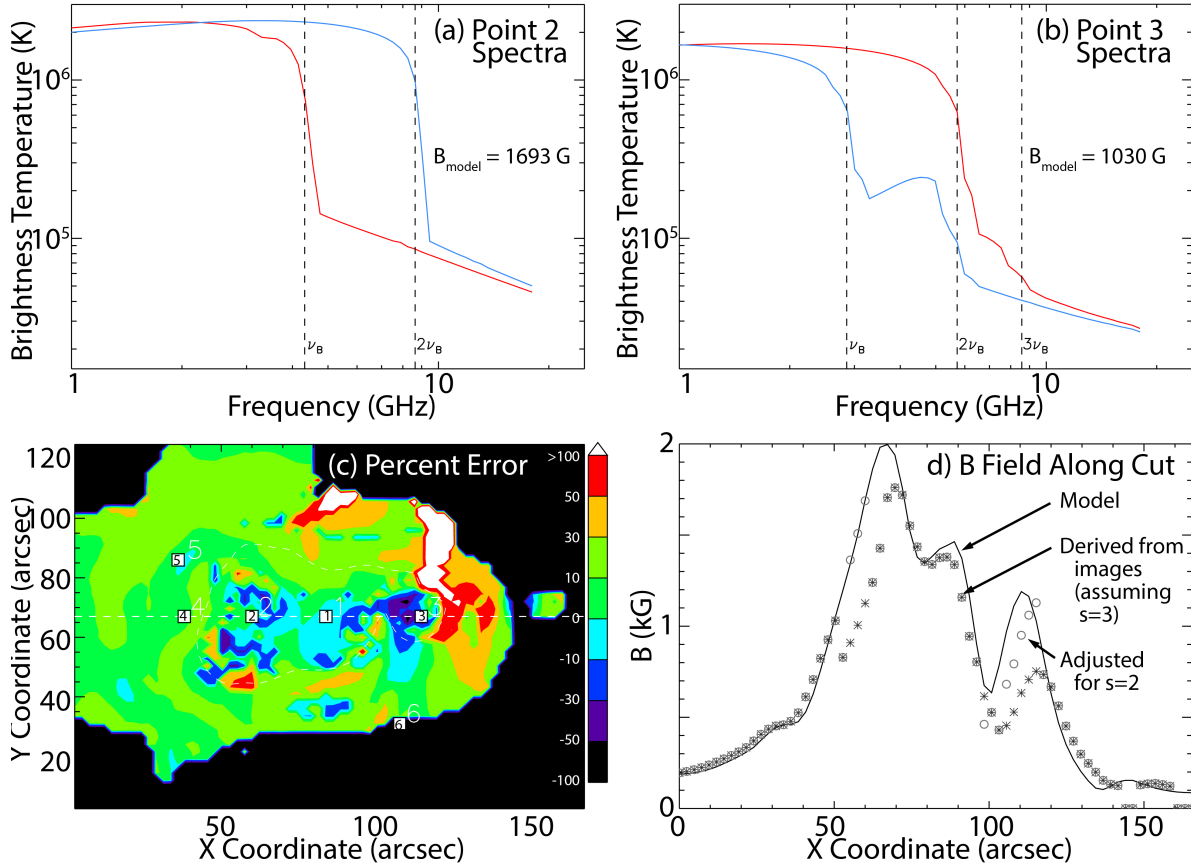


Figure 1: Results obtained from simulated images derived from an active region model. (a) Example spectra from point 2 marked in (c), in right-circular polarization (RCP, red) and left-circular polarization (LCP, blue). Two harmonics are apparent from breaks in the spectrum; (b) Same as (a), for point 3 marked in (c). Note that the polarity of the field is opposite to that in panel (a). Here again two harmonics are apparent from the spectra, with a slight indication of the third harmonic in RCP; (c) Spectra along each LOS over the entire region have been used to derive the magnetic field strength, which was then compared with the model assuming the third harmonic emission ($s = 3$). Plotted is the percent error of the measurements relative to the model; (d) Asterisks show the derived magnetic field along the cut indicated by the white dashed line in (c), assuming $s = 3$ compared with the model (black curve). Points corrected to account for $s = 2$ derived from the spectra are shown as open circles, showing much better agreement. Adapted from Wang et al. (2015).

The characteristic thermal emissions from the solar corona occur in UV, EUV, and soft X-ray wavelengths, as currently observed by IRIS, SDO/AIA and Hinode/XRT. Such data complement the magnetic field measurements made with radio data, and the combination of multi-wavelength regimes with sophisticated modeling can provide the full specification of density, temperature and magnetic field needed to describe the energetics of the Sun’s atmosphere.

To summarize, FF and GR emission from active regions can together be used to measure the magnetic field strength $|B|$ and/or B_{los} . FF emission is relevant everywhere that GR is optically thin. It is therefore a key diagnostic of B_{los} in the chromosphere and corona wherever the magnetic field is weak or the frequency is high (e.g., ALMA). GR is key to measuring strong ($\sim 150 - 2000\text{G}$) magnetic fields in active regions at centimeter wavelengths. Radio observations provide unique and complementary measurements to off-limb observations made at O/IR wavelengths and to UV/EUV/SXR observations of chromosphere and corona.

3 Other Applications

While we have emphasized the utility of radio observations to measure magnetic fields, both $|B|$ and B_{los} , in active regions above, radio observations can play a key role in quantitative measurements of other phenomena on the Sun. We briefly summarize several examples here:

- *Solar Flares:* As noted above, GS emission is produced by mildly relativistic electrons (100s of keV to MeV). Radio imaging spectropolarimetry of GS emission is wholly unique in its ability to measure coronal magnetic fields in flaring plasma [21, 22, 23].
- *Coronal Mass Ejections:* GS emission from MeV electrons has been imaged in fast CMEs associated with solar energetic particle events [24, 25]. Again, such measurements are currently unique in their ability to measure magnetic fields in CMEs.
- *Quiet Sun:* The quiet solar atmosphere is permeated by weak magnetic fields. Coronal holes (CH) are regions that are magnetically open to the interplanetary medium and are the source of fast solar wind streams. The magnetic and density structure of CH differs from that of surrounding QS. Polarized imaging spectroscopy is needed to probe the 3D structure in detail as recently highlighted by recent observations made by the Murchison Widefield Array (McCauley et al., priv. comm.).

4 Enabling Radio Magnetography of the Sun

To exploit radio observations to make quantitative measurements of the magnetic field of the solar chromosphere and corona requires specialized instrumentation with a number of attributes:

- *Extremely broad frequency coverage:* from 50 MHz to ~ 50 GHz to allow FF, GR, and GS emission to be exploited fully to measure magnetic fields from chromospheric to coronal heights for both quiet Sun and active Sun phenomena.

- Time resolution: Time resolution requirements are to image this frequency range in 10 s for quiet Sun phenomena and 1 s for active Sun phenomena.
- Spectral coverage and resolution: continuous frequency coverage is needed to measure and disentangle contributions from multiple sources and emission mechanisms. Spectral resolution of 1% is needed.
- Polarization: Support of full polarimetry is needed. In most cases only the Stokes I and V parameters will be needed since the Faraday depth of the corona washes out linearly polarized emission. Stokes V embodies information about the chromospheric and coronal magnetic field.
- Angular resolution: scattering in the Sun's corona constrains the usable angular resolution to roughly $20''/\nu_9$ where ν_9 is the frequency in GHz; i.e., 1'' at 20 GHz.
- Field of view: Full disk imaging at cm- λ and imaging to several solar radii at dm- to m- λ .
- High-dynamic-range imaging: in order to exploit broadband 3D imaging of the Sun's atmosphere it must be possible to see faint phenomena such as "EIT waves" and radio CMEs in the presence of bright flare-related or radio-burst emission, requiring a dynamic range of order $10^4 : 1$.

These requirements are in fact met by a next-generation radioheliograph that is known as the *Frequency Agile Solar Radiotelescope* (FASR), a facility that has been recommended as a priority by previous decadal surveys, both the Astronomy & Astrophysics decadals and the Solar & Space Physics decadals. As a mid-scale-sized project, funding mechanisms have not been available to move this priority project forward. Until now. With the implementation of NSF's Mid-scale Research Infrastructure program, FASR can now be made a reality. Separate project submissions will describe the instrument in detail.

References

- [1] Y. Sofue, H. Kigure, and K. Shibata, “Magnetic-Reconnection and Current-Sheet Model for the Radio Arc and Threads in the Galactic Center,” *Publications of the Astronomical Society of Japan*, vol. 57, pp. L39–L43, Oct. 2005.
- [2] E. M. de Gouveia dal Pino and A. Lazarian, “Production of the large scale superluminal ejections of the microquasar GRS 1915+105 by violent magnetic reconnection,” *Astronomy and Astrophysics*, vol. 441, pp. 845–853, Oct. 2005.
- [3] S. Tanuma, T. Yokoyama, T. Kudoh, R. Matsumoto, K. Shibata, and K. Makishima, “Magnetic Reconnection as the Origin of Galactic-Ridge X-Ray Emission,” *Publications of the Astronomical Society of Japan*, vol. 51, pp. 161–172, Feb. 1999.
- [4] R. Schopper, H. Lesch, and G. T. Birk, “Magnetic reconnection and particle acceleration in active galactic nuclei,” *Astronomy and Astrophysics*, vol. 335, pp. 26–32, July 1998.
- [5] K. Hurley, S. E. Boggs, D. M. Smith, R. C. Duncan, R. Lin, A. Zoglauer, S. Krucker, G. Hurford, H. Hudson, C. Wigger, W. Hajdas, C. Thompson, I. Mitrofanov, A. Sanin, W. Boynton, C. Fellows, A. von Kienlin, G. Lichti, A. Rau, and T. Cline, “An exceptionally bright flare from SGR 1806-20 and the origins of short-duration γ -ray bursts,” *Nature*, vol. 434, pp. 1098–1103, Apr. 2005.
- [6] T. Wiegmann, L. Yelles Chaouche, S. K. Solanki, and A. Lagg, “Nonlinear force-free modelling: influence of inaccuracies in the measured magnetic vector,” *Astronomy and Astrophysics*, vol. 511, p. A4, Feb. 2010.
- [7] M. L. De Rosa, C. J. Schrijver, G. Barnes, K. D. Leka, B. W. Lites, M. J. Aschwanden, T. Amari, A. Canou, J. M. McTiernan, S. Régnier, J. K. Thalmann, G. Valori, M. S. Wheatland, T. Wiegmann, M. C. M. Cheung, P. A. Conlon, M. Fuhrmann, B. Inhester, and T. Tadesse, “A Critical Assessment of Nonlinear Force-Free Field Modeling of the Solar Corona for Active Region 10953,” *The Astrophysical Journal*, vol. 696, pp. 1780–1791, May 2009.
- [8] J. O. Stenflo, “Stokes polarimetry of the Zeeman and Hanle effects,” *ISSI Scientific Reports Series*, vol. 9, pp. 543–557, 2010.
- [9] A. Tritschler, T. R. Rimmele, S. Berukoff, R. Casini, J. R. Kuhn, H. Lin, M. P. Rast, J. P. McMullin, W. Schmidt, F. Wöger, and DKIST Team, “Daniel K. Inouye Solar Telescope: High-resolution observing of the dynamic Sun,” *Astronomische Nachrichten*, vol. 337, p. 1064, Nov. 2016.
- [10] G. Del Zanna and E. E. DeLuca, “Solar Coronal Lines in the Visible and Infrared: A Rough Guide,” *The Astrophysical Journal*, vol. 852, p. 52, Jan. 2018.
- [11] G. D. Fleishman and I. N. Toptygin, *Cosmic Electrodynamics*. 2013.

- [12] G. B. Gelfreikh, “Coronal Magnetic Field Measurements Through Bremsstrahlung Emission,” in *Astrophysics and Space Science Library* (D. E. Gary and C. U. Keller, eds.), vol. 314 of *Astrophysics and Space Science Library*, p. 115, Sept. 2004.
- [13] D. E. Gary and G. J. Hurford, “Radio Spectral Diagnostics,” in *Astrophysics and Space Science Library* (D. E. Gary and C. U. Keller, eds.), vol. 314 of *Astrophysics and Space Science Library*, p. 71, Sept. 2004.
- [14] S. D. Tun, D. E. Gary, and M. K. Georgoulis, “Three-dimensional Structure of a Solar Active Region from Spatially and Spectrally Resolved Microwave Observations,” *The Astrophysical Journal*, vol. 728, p. 1, Feb. 2011.
- [15] G. M. Nita, G. D. Fleishman, J. Jing, S. V. Lesovoi, V. M. Bogod, L. V. Yasnov, H. Wang, and D. E. Gary, “Three-dimensional Structure of Microwave Sources from Solar Rotation Stereoscopy Versus Magnetic Extrapolations,” *The Astrophysical Journal*, vol. 737, p. 82, Aug. 2011.
- [16] Z. Wang, D. E. Gary, G. D. Fleishman, and S. M. White, “Coronal Magnetography of a Simulated Solar Active Region from Microwave Imaging Spectropolarimetry,” *The Astrophysical Journal*, vol. 805, p. 93, June 2015.
- [17] J. Lee, “Radio Emissions from Solar Active Regions,” *Space Science Reviews*, vol. 133, pp. 73–102, Dec. 2007.
- [18] V. M. Bogod and G. B. Gelfreikh, “Measurements of the magnetic field and the gradient of temperature in the solar atmosphere above a flocculus using radio observations,” *Solar Physics*, vol. 67, pp. 29–46, Aug. 1980.
- [19] G. Fleishman, M. Loukitcheva, and G. Nita, “Solar ALMA: Observation-Based Simulations of the mm and sub-mm Emissions from Active Regions,” in *Revolution in Astronomy with ALMA: The Third Year* (D. Iono, K. Tatematsu, A. Wootten, and L. Testi, eds.), vol. 499 of *Astronomical Society of the Pacific Conference Series*, p. 351, Dec. 2015.
- [20] M. Loukitcheva, S. M. White, S. K. Solanki, G. D. Fleishman, and M. Carlsson, “Millimeter radiation from a 3D model of the solar atmosphere. II. Chromospheric magnetic field,” *Astronomy and Astrophysics*, vol. 601, p. A43, May 2017.
- [21] D. E. Gary, G. D. Fleishman, and G. M. Nita, “Magnetography of Solar Flaring Loops with Microwave Imaging Spectropolarimetry,” *Solar Physics*, vol. 288, pp. 549–565, Dec. 2013.
- [22] G. M. Nita, G. D. Fleishman, A. A. Kuznetsov, E. P. Kontar, and D. E. Gary, “Three-dimensional Radio and X-Ray Modeling and Data Analysis Software: Revealing Flare Complexity,” *The Astrophysical Journal*, vol. 799, p. 236, Feb. 2015.
- [23] N. Kuroda, D. E. Gary, H. Wang, G. D. Fleishman, G. M. Nita, and J. Jing, “Three-dimensional Forward-fit Modeling of the Hard X-Ray and Microwave Emissions of the 2015 June 22 M6.5 Flare,” *The Astrophysical Journal*, vol. 852, p. 32, Jan. 2018.

- [24] T. S. Bastian, M. Pick, A. Kerdraon, D. Maia, and A. Vourlidas, “The Coronal Mass Ejection of 1998 April 20: Direct Imaging at Radio Wavelengths,” *The Astrophysical Journal, Letters*, vol. 558, pp. L65–L69, Sept. 2001.
- [25] D. J. F. Maia, R. Gama, C. Mercier, M. Pick, A. Kerdraon, and M. Karlický, “The Radio-Coronal Mass Ejection Event on 2001 April 15,” *The Astrophysical Journal*, vol. 660, pp. 874–881, May 2007.