FASR Science Case # WG2-3

Diagnosing the Dynamics of Developing Magnetic Flux Ropes in Active Regions

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1 Science Goal(s)

Briefly summarize the key science goal(s) for this science case. A few sentences will be sufficient.

The goal is to investigate how coronal magnetic structures in the core of active regions, which may appear in the form of filament channels, sigmoids, and hot channels, evolve over time, transforming from less-energy sheared arcades to more-energy current-carrying magnetic flux ropes and leading to solar eruptions.

2 Scientific Rationale

2.1 Scientific Importance

Provide a brief discussion on the scientific importance of this science case.

Magnetic flux ropes are known to be the underlying driver of eruptive flares and CMEs. Their formation involves long-term magnetic evolution driven by shearing motion, flux cancellation, reconnection, and flux rope formation along strong-gradient polarity inversion lines. Understanding this magnetic structure and its dynamics is critical for identifying the physical mechanisms that generate eruptive magnetic configurations. The study will lead to a firm and fundamental understanding of how solar eruptions are initiated, one key scientific objective in solar physics research and space weather applications.

2.2 Uniqueness to FASR Capabilities

Is this science case uniquely addressed by FASR? Why can't other facilities address this science and achieve the same goal?

The existing observations, mostly in EUV and X-rays, lack direct diagnostics of the magnetic field in these critical structures dominated by magnetic fields. The FASR shall provide critical measurements of magnetic fields, filling a critical observational gap that has prevented progress in understanding solar eruptions.

2.3 Synergies

Describe potential synergies/complementarities between this FASR science case and those from current/future/planned facilities at all wavelengths (e.g., DKIST, MUSE, FIERCE, COSMO, ngGONG, etc.).

Studying the structure leading to solar eruptions requires observations in both large- and small-scale, in wavelengths diagnosing plasma temperature, density, magnetic field, and Doppler field, and in multi-layers of the Sun. Thus, FAST shall be synergized with other instruments, such as DKIST, MUSE, COSMO, SDO etc.

2.4 Measurements Required by FASR

Provide a description of the necessary measurements to be carried out by the FASR to adequately address this science case. Please coordinate these measurements with the Science Requirements table in Section III.

This science case requires Event-driven observations of Active Regions, Solar Flares, CMEs. Target description: Solar active regions with strong polarity inversion lines. Focusing on core regions appearing to be a filament channel, sigmoid and hot channel. Required frequency coverage: Approximately 1–15 GHz (to diagnose coronal magnetic fields via gyroresonance and gyrosynchrotron emission; broader coverage desirable if available). Shortest temporal scale of interest: Seconds. Requested polarization products: Stokes I, Stokes Q, Stokes U, Stokes V.

III. Science Requirements Tables

(A) Observational Target Description

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

(A) OBSERVATIONAL TARGET	
Type of observation (what defines a 'target')	Provide a brief description of the target [e.g., gyrosynchrotron radiation from coronal mass ejections in the low corona (< 1.5 solar radii)] Target type: Active Regions, Solar Flares, CMEs. Solar active regions with strong polarity inversion lines. Focusing on core regions appearing to be a filament channel, a sigmoid, and a hot channel.
Number of targets	1–2 active regions at a time (occasionally a few during high solar activity)
Size of a single target (arcsec x arcsec)	A few arcminutes $< 10''$-100s$''$
Distribution of all targets (arcmin x arcmin)	Up to the full active-region complex, about 10 arcmin x 10 arcmin; full-disk context desirable for eruption connectivity

(A) OBSERVATIONAL TARGET (continued)		
Peak brightness (sfu/beam or Kelvin)	A few 10^5–10^8 K, depending on flare magnitude and frequency	
RMS brightness (sfu/beam or Kelvin)	10^5 K	
Expected circularly polarized flux density	Stokes V (sfu/beam)	
	V/I	< 10% to 50%
Expected linearly polarized flux density	Stokes Q or U (sfu/beam)	N/A
	Q/I or U/I	N/A

(B) Spectro-Temporal Requirements Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

(B) SPECTRAL-TEMPORAL REQUIREMENTS	
Central Frequency (GHz)	2 to 20
Instantaneous Bandwidth (GHz/pol; max 20 GHz)	Broad simultaneous coverage across 2-20 GHz where possible.
Spectral resolution [MHz]	200
Temporal resolution (in seconds)	1

(C) Polarization Product Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

(C) POLARIZATION DATA PRODUCTS REQUIRED	
y	Stokes I
n	Stokes Q
n	Stokes U
y	Stokes V

(D) Imaging Requirements Discussion

Provide a brief discussion describing how these values are obtained/estimated, any trade-offs, interrelationships between the values, or anything else that is not captured in the following table.

A developing active-region MFR is expected to form low in the corona above a strong-gradient polarity inversion line, where shearing motions, flux cancellation, and reconnection add twist and current to an initially sheared arcade (van Ballegooijen and Martens 1989; Mackay and van Ballegooijen 2006; Green, Kliem, and Wallace 2011). EUV and soft-X-ray images can trace the sigmoid or hot-channel morphology, but they do not directly give the coronal field strength, the thermal density, or the presence of accelerated electrons (Cheng et al. 2013; Zhang, Cheng, and Ding 2012; Nindos et al. 2020). The radio diagnostic has to resolve the rope body, its legs, and the surrounding arcade while measuring the spectrum and circular polarization well enough to distinguish thermal plasma from nonthermal electrons.

In a strong active-region core, the relevant microwave emission can include thermal gyroresonance from low harmonic layers, thermal or nonthermal gyrosynchrotron emission from hot or accelerated electrons, and thermal free-free emission from dense coronal plasma. For gyroresonance and gyrosynchrotron radiation, the magnetic field scale enters through the electron gyrofrequency:

$$\nu = s\nu_{\mathrm{B}}, \qquad \nu_{\mathrm{B}} = 2.8\,B \text{ MHz}. \tag{1}$$

At the third harmonic, 2-20 GHz corresponds to fields of about 240-2400 G. Adjacent harmonics extend the sampled range to the few hundred to several thousand Gauss fields expected in active-region cores and low-lying rope legs. The higher body of the rope may contain weaker fields, but those fields can still affect the gyrosynchrotron turnover, source height, and free-free contribution if the density and temperature are high enough. EOVSA measurements of related eruptive structures fall in this range: partially erupting filament sources have yielded coronal fields of about 600-1400 G, and the slow-rise precursor studied by Kou et al. (2025) showed microwave sources along the hot channel and precursor loops with fitted fields around 500-600 G, temperatures near 3.8 MK, and thermal electron densities near 10^{10} cm^{-3} before the main flare developed a stronger nonthermal component (Chen et al. 2020a, 2020b; Wei et al. 2021). This field range requires broad microwave coverage: the high-frequency channels are needed for the strong-field footpoints and low-lying legs, while the lower-frequency channels trace weaker and more extended parts of the rope.

The continuum spectra expected from these sources do not require line-like spectral resolution. Free-free emission varies smoothly with frequency. Gyroresonance brightness changes as different harmonic layers enter the line of sight, but the useful observable is the change of brightness temperature and circular polarization over neighboring channels. Gyrosynchrotron spectra are broader still, with optically thick and optically thin slopes separated by a turnover whose width depends on the magnetic-field, density, viewing-angle, and electron-energy gradients inside the source (Dulk 1985; Bastian, Benz, and Gary 1998; Nindos, Kontar, and Alissandrakis 2020; Alissandrakis and Gary 2021; Gary 2023). Since ν scales with B, a 5-10% field variation across the beam or along the line of sight broadens a gyroresonance or gyrosynchrotron feature by a similar fractional bandwidth. That gives characteristic widths of about 100-200 MHz at 2 GHz, 300-600 MHz at 6 GHz, and 1-2 GHz at 20 GHz. A 100 MHz image channel samples the narrow end of these continuum-scale features while still providing several channels across the broader turnovers. Finer channels would be useful for coherent fine structures, but narrowband coherent bursts are not the primary diagnostic of the slowly developing MFR. About 200 image channels across the band preserve the spectral information needed for continuum fitting without making the data product unnecessarily large.

The source morphology sets the angular-resolution scale. The rope body, filament channel, or sigmoid can span tens to hundreds of arcseconds. The legs, footpoint-rooted strong-field sources, and compact reconnection sites near the PIL can be only a few arcseconds across. A $10''$ beam at 2 GHz separates the broad MFR channel and surrounding arcade from the active-region background at low frequency. Higher frequencies then provide the finer imaging needed for the strong-field legs and the sharp changes in viewing angle and magnetic field. The field of view has to cover the active-region magnetic environment around the visible rope. A $10' \times 10'$ map includes the PIL, overlying arcade, remote connections, and the early expansion of the erupting system. The pixel scale should sample the synthesized beam well enough that spectral morphology and Stokes V structure do not shift artificially from one frequency to the next.

The brightness-temperature range spans weak thermal emission and much brighter compact sources. Extended free-free emission from active-region plasma can be near 10^4-10^6 K, depending on density, temperature, and path length. Optically thick gyroresonance reaches the local electron temperature, usually MK values in active regions. Nonthermal gyrosynchrotron sources can be much brighter, often 10^6-10^9 K in flare-related structures. The observation has to recover weak extended emission in the same field as compact bright sources. An rms brightness sensitivity of order 10^5 K per image channel is sufficient for MK-level MFR and arcade emission, while a dynamic range near 1000:1 is needed when compact sources are two or three orders of magnitude brighter than the surrounding structure.

Stokes I gives the brightness-temperature spectrum, but Stokes V carries much of the magnetic information. For gyroresonance and gyrosynchrotron sources, circular polarization constrains emission mode, line-of-sight field direction, and viewing angle. Useful signals can range from a few percent to several tens of percent, so 5-10% polarization accuracy keeps calibration errors below the expected Stokes V/I diagnostic signal. Total-power or zero-spacing information is also needed, because thermal free-free and gyroresonance emission can be extended across the active-region complex. Missing that extended component would bias the brightness temperature and spectral slope. A few-percent flux-density scale is needed for the same reason: the field and electron constraints come from the shape and normalization of spatially resolved spectra, not only from the source morphology.

(D) IMAGING REQUIREMENTS	
Required angular resolution (arcsec) (single value or range)	$10''$ at 2 GHz
Largest angular scale required (arcsec)	
Mapped image size (arcmin x arcmin)	Up to $10' \times 10'$
Required pixel resolution (arcsec)	$6''$ at 1 GHz and $0.3''$ at 20 GHz
Number of output/image channels	200
Output bandwidth (minimum and maximum frequency - GHz)	20 GHz
Channel width (MHz)	100
Required rms (sfu/beam or Kelvin) [per channel] (if polarization products required define for each)	10^5 K
Dynamic range within image (if polarization products required define for each)	1000:1
Polarization accuracy (%)	5-10%

(D) IMAGING REQUIREMENTS (continued)		
Zero spacing/total power required?	y	
Required maximum latency (in seconds, or N/A)	N/A	
Required flux density scale calibration accuracy		1-3%
		5%
	x	10%
		20-50%

2.5 Other Performance or Functional Requirements

If there are any additional performance or functional requirements not captured above, describe them here. For example, beamforming array mode, phased array, etc.

3 Appendix

Please provide any other relevant material necessary to understand and substantiate this Science Case.

Reference

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