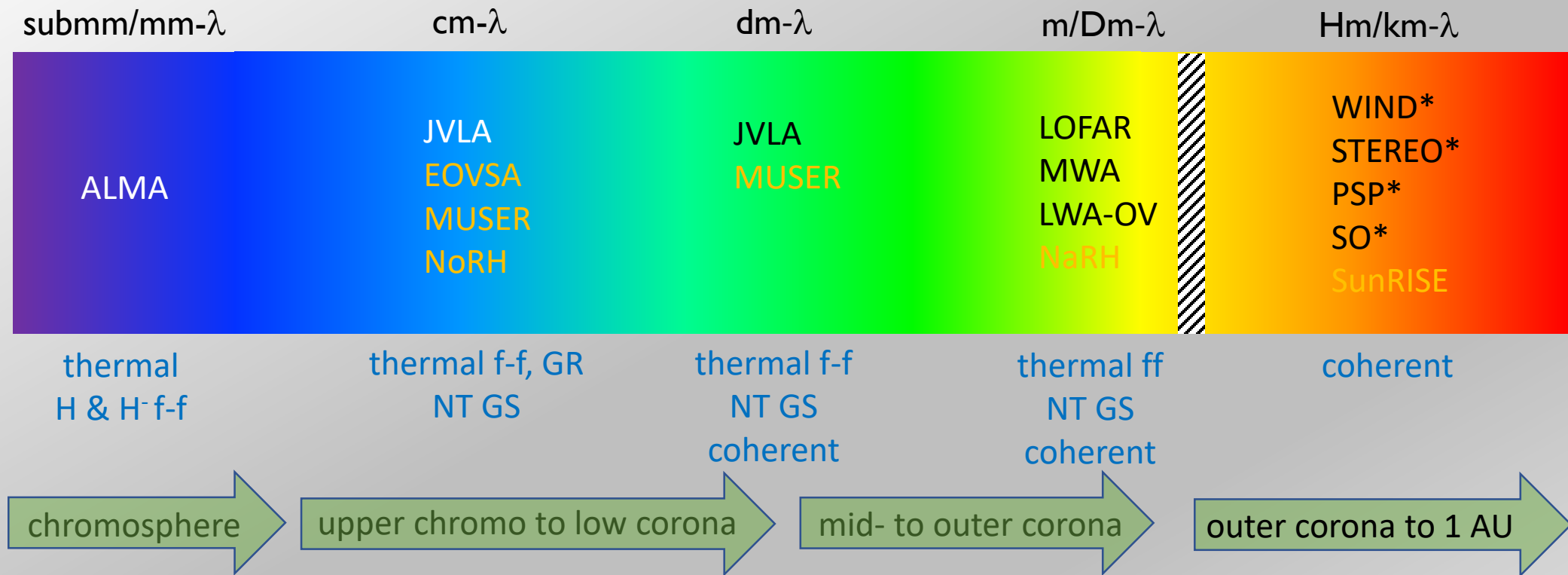


Radio Inputs to Space Weather Operations and Research

T. S. Bastian

National Radio Astronomy Observatory





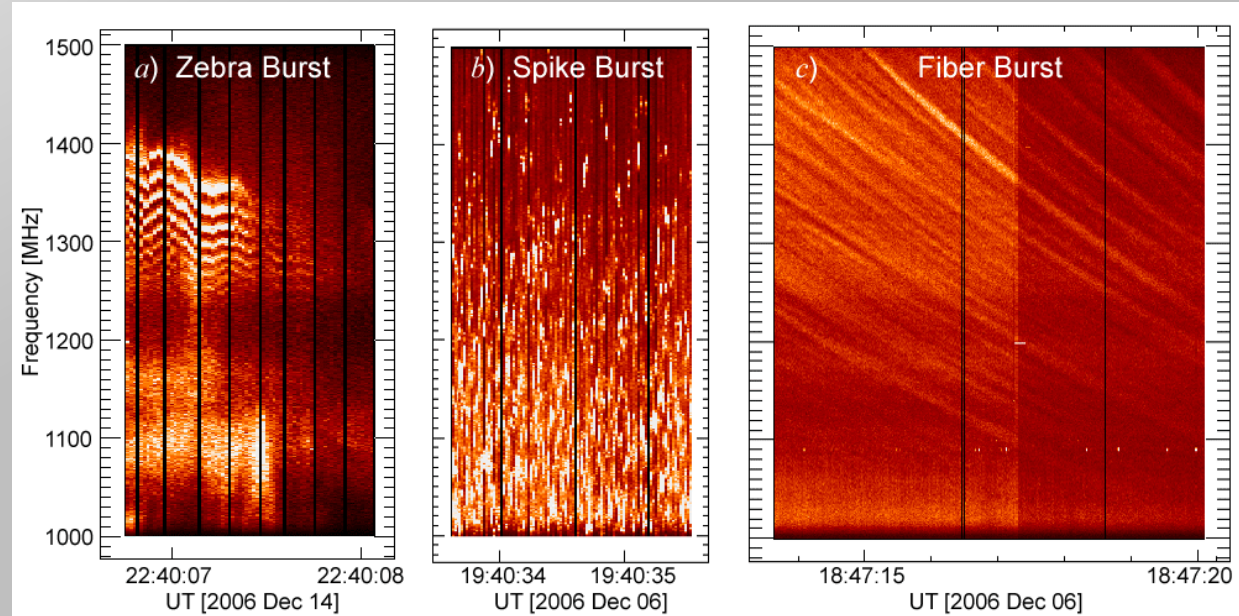
Outline

- Space weather impacts at radio wavelengths
 - ✓ Solar radio bursts
- Tracers of space weather drivers
 - ✓ type II/IV and type III radio bursts
- Gaps in available observational infrastructure & recommendations I
- Science of space weather
 - ✓ Uniqueness space
 - ✓ Examples
- Gaps in research infrastructure & recommendations II
- The broader view

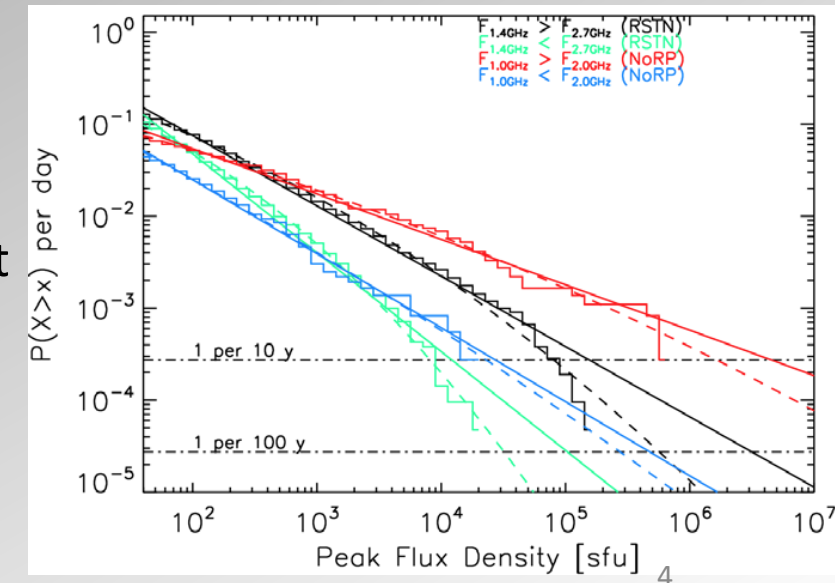
Solar Radio Bursts

- SRBs affect many different navigation and communication systems.
- The disturbances occur without warning, simultaneously over a large region (over the entire sunlit hemisphere in the case of GPS).
- Events producing high radio noise levels can be modest in other non-radio classifications.
- High radio flux density occurs in relatively narrow frequency ranges, so monitoring a few widely spaced frequencies is not sufficient. Their polarization state is not currently monitored, yet it can be essential to gauge effects on some systems such as GPS.
- Comparison of well-calibrated radio measurements with reports from radio monitoring systems shows large discrepancies, so that we do not have good statistics of the occurrence rate of extreme events.

from IDA Group Report NS GR-10982: Next Step Space Weather Benchmarks



See Gary & Bastian 2020



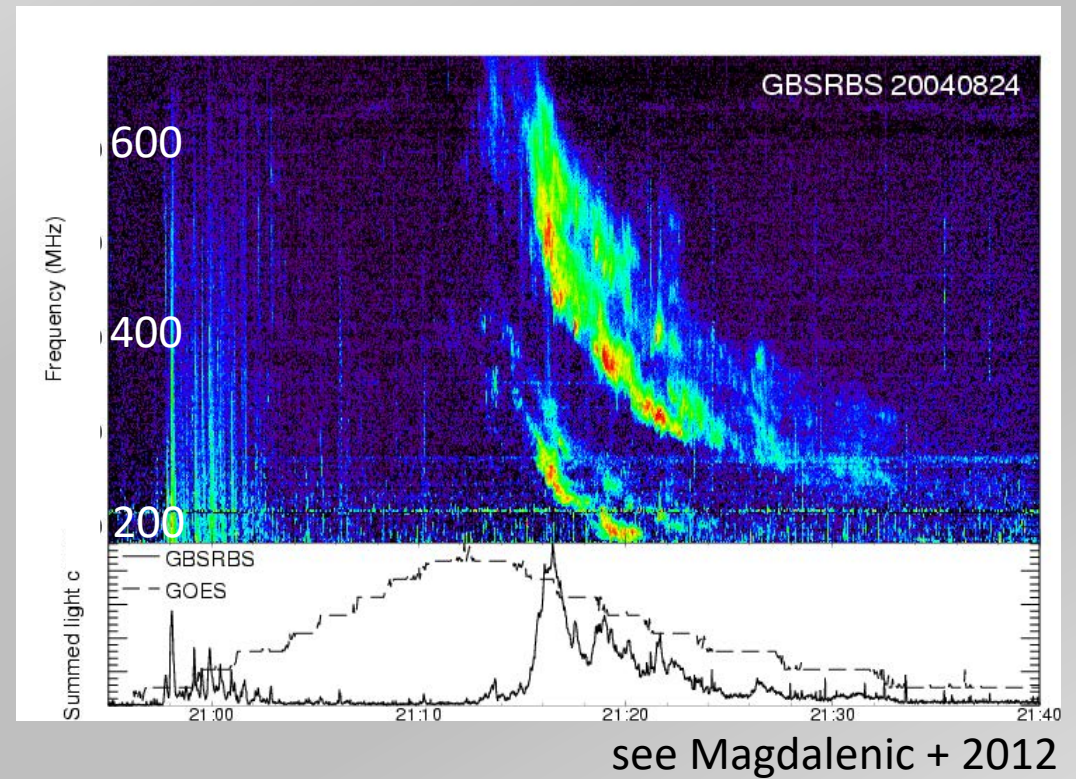
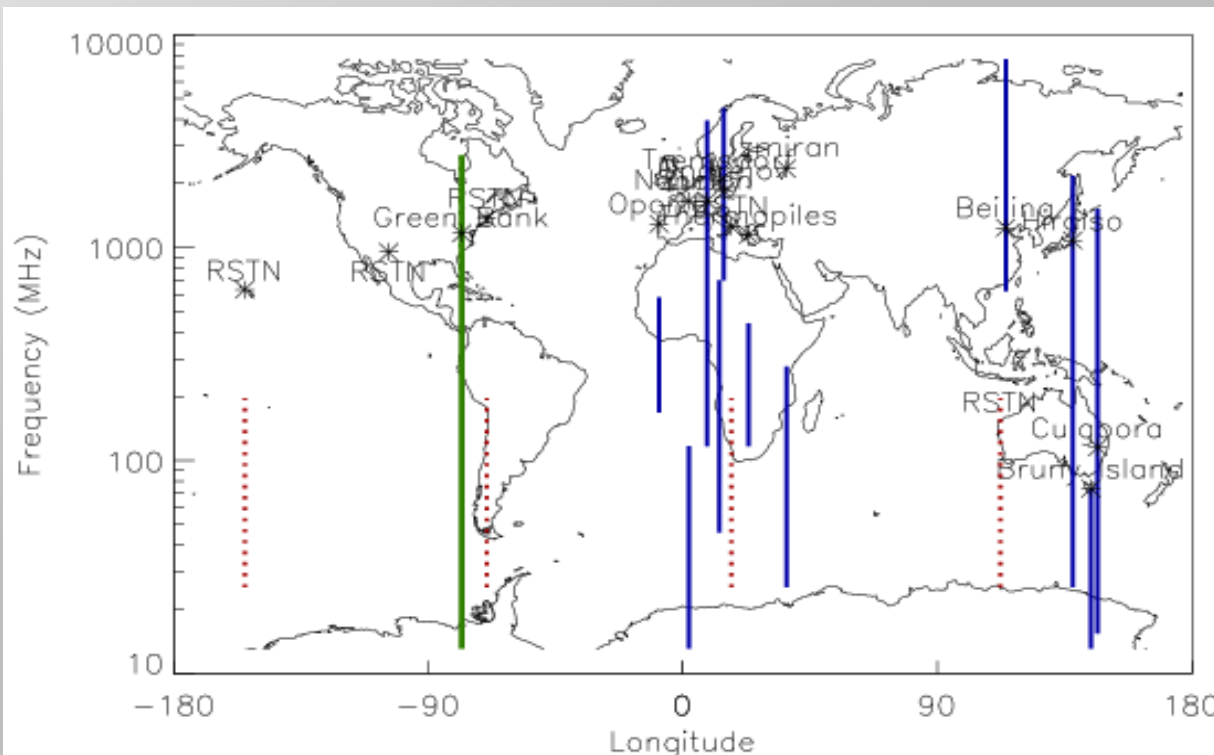
Gaps to be Addressed

1. Extant data are heavily weighted to RSTN measurements, which lack polarization information and also saturate for bursts greater than 100,000 sfu, undercounting the tail of the distribution.
2. The data are limited to a small number of discrete frequencies [8], whereas the extreme flux densities are known to occur in narrow (and unpredictable) frequency ranges that have been demonstrated to be missed by the standard frequencies.
3. In certain cases the reported flux densities in the RSTN database are lower than reported by other well-calibrated instruments—sometimes, but not always, due to saturation effects.

In other words, existing data sources are over-reliant on a system that saturates on large events, has sparse frequency coverage, does not measure the degree or sense of circular polarization, and is in any case poorly calibrated.

SWx Radio Proxies

- Coronal and IP type II radio bursts – produced by a shock driven by a fast CME or flare ejecta
- Coronal and IP type III radio bursts – produced by electron beams likely associated with magnetic energy release



GB Infrastructure for spectroscopic monitoring

- USAF/RSTN: swept frequency spectrometers – limited coverage
- A number of spectrometers available in Europe and Asia – those in US now defunct
- Space-based instruments (STEREO, PSP, SO)

Long-term Recommendations I

Improve Operational Infrastructure

- Worldwide (24/7) coverage of the Sun (3 or 4 identical stations around the globe).
- Broad frequency coverage (20 MHz–20 GHz) to address the full range of vulnerabilities of current wireless communication and navigation systems. Future systems may require extending the high-frequency limit to 35 GHz or even higher.
- To address gap #2: Continuous frequency coverage over the above range with at least 5% frequency resolution.
- To address gap #1: Dual circular polarization, for assessment of impact on GNSS, whose signals are right-hand circularly polarized.
- To address gap #1: Large dynamic range ($>10^6$ sfu) to minimize saturation effects.
- To address gap #3: Implementation of a regularly executed absolute and cross-calibration plan.

from IDA Group Report NS GR-10982: Next Step Space Weather Benchmarks

The Science of Space Weather

Radio observations occupy a substantial uniqueness space:

- Sensitivity to chromospheric and coronal magnetic fields
- Sensitivity to thermal, nonthermal (keV-MeV electrons), and coherent emissions
- Ability to image phenomena on the solar disk and above the limb
- Ability to observe the solar atmosphere as a system

Rich potential for new diagnostics of space weather drivers and their impacts (R2O).

Nancay RH (Obs Paris)



JVLA (NRAO)

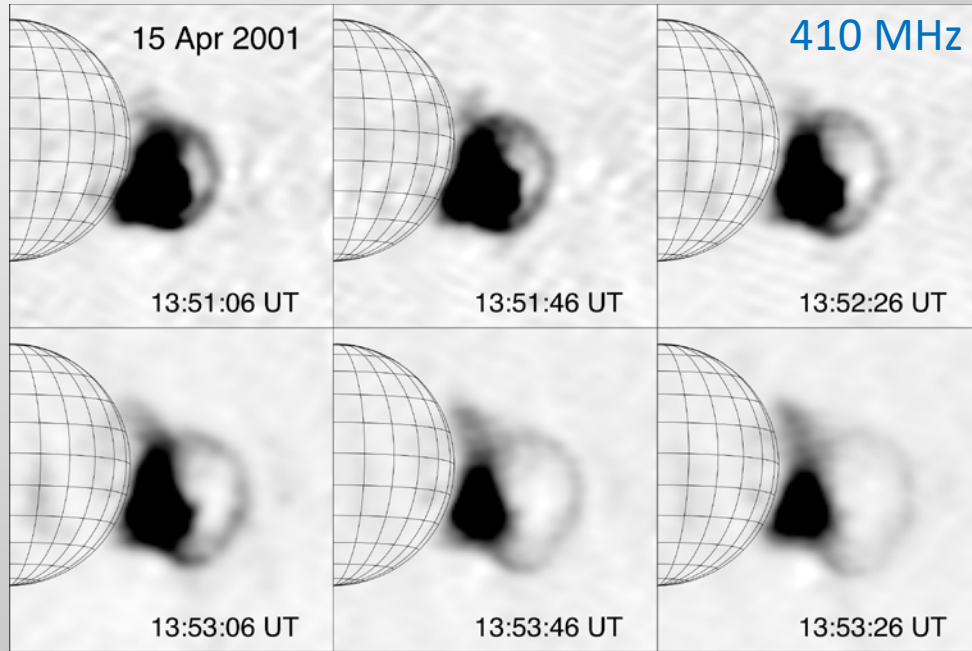


EOVSA (NJIT)



Each of these enable new science via broadband imaging spectroscopy!

The Science of Space Weather



Magnetography of Active Regions

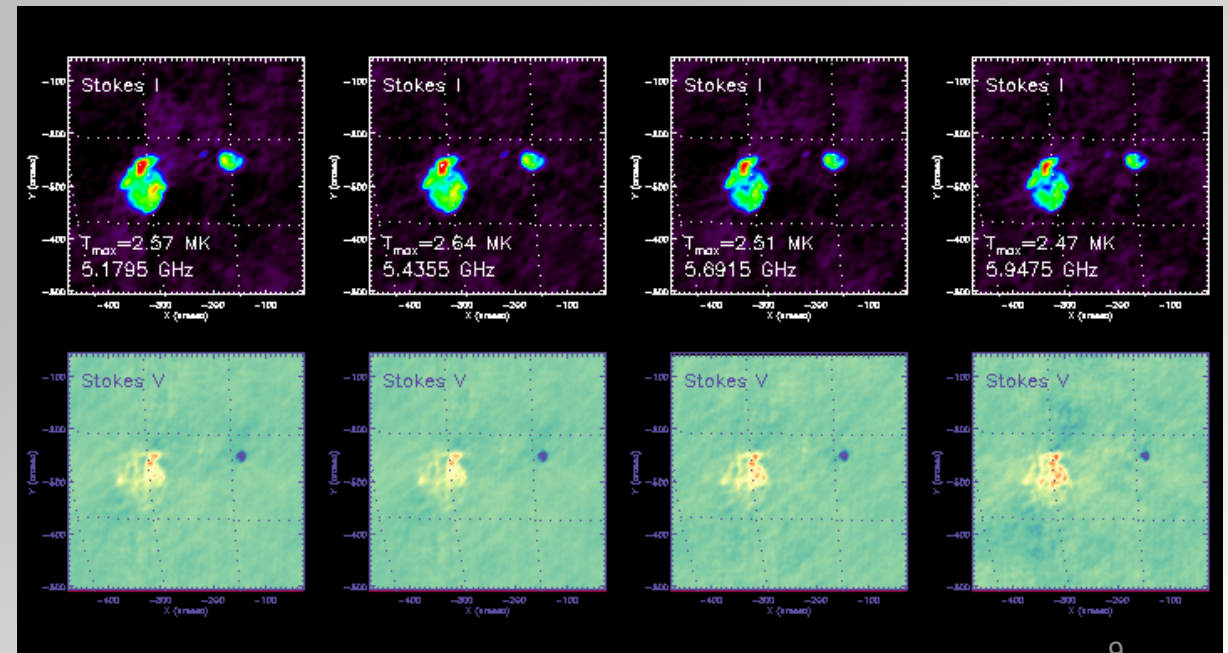
Broadband imaging spectropolarimetry enables coronal magnetic field measurements from 200-2000 G with exquisite resolution and precision.

Radio CMEs

Synchrotron emission from MeV electrons entrained in the magnetic field of the CME

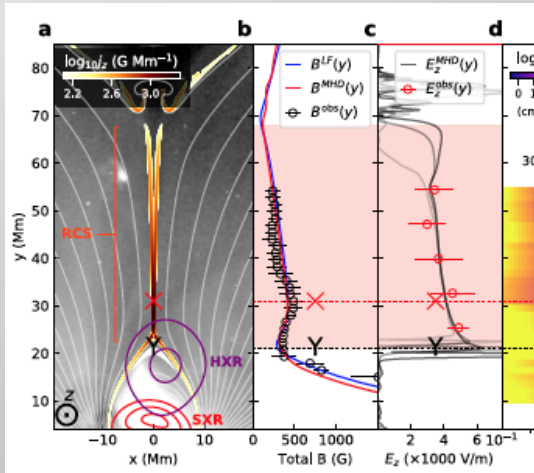
- CME B, n_{th} , $n_{rl}(E)$
- No occulting disk

e.g., Maia et al 2007; Demoulin et al 2012



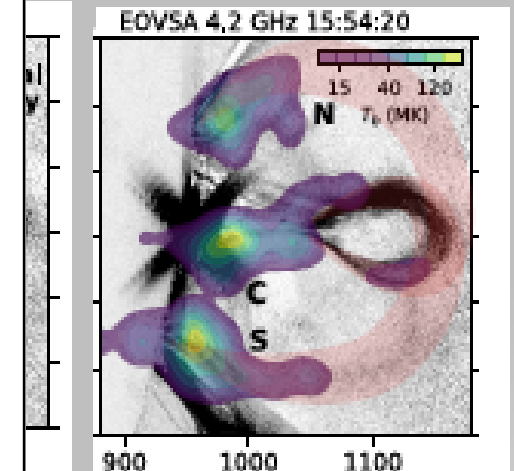
Science of

The magnetic
(Chen et al. 2010)

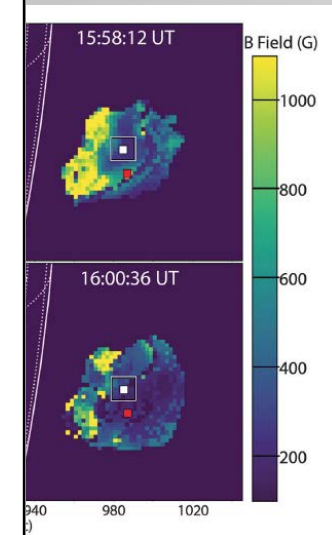


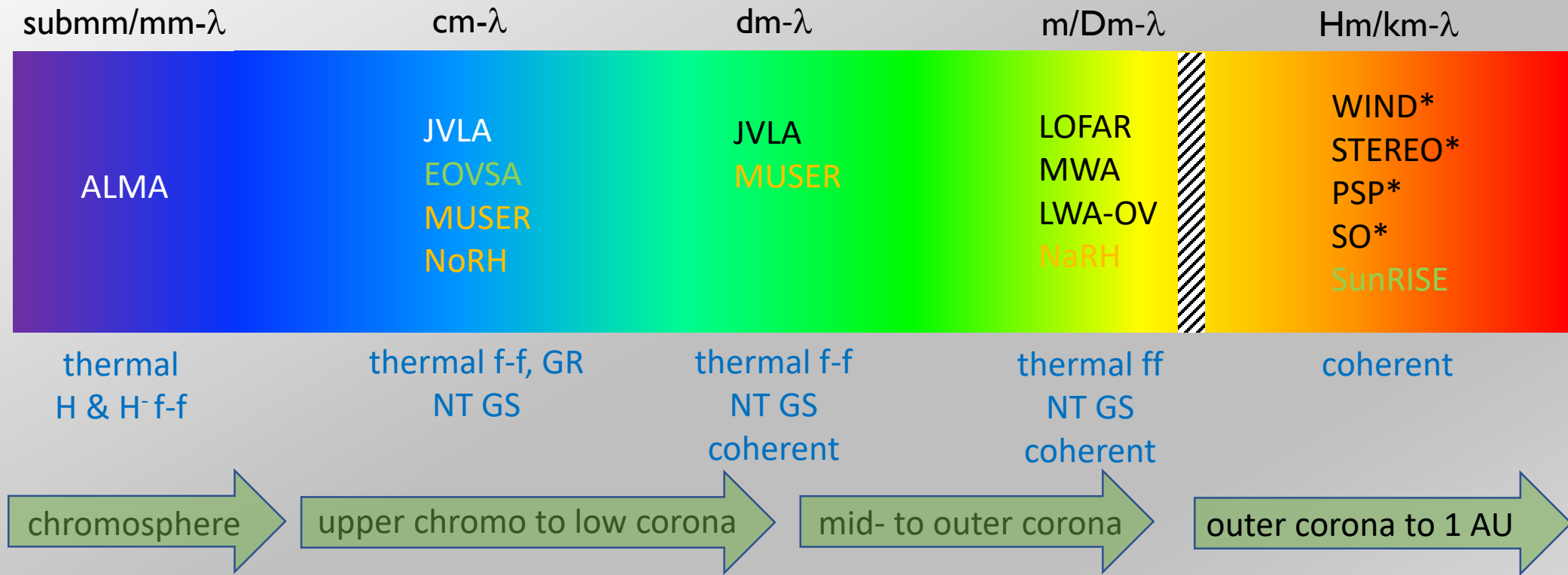
Dynamic
powering

All of these results
imaging spectroscopy.



nt sheet





Expanded Owens Valley Solar Array



- Solar-dedicated instrument—full time coverage of solar bursts.
- Thirteen 2-m antennas (78 baselines)
- One 27-m (90-ft) antennas (for calibration)
- 1-18 GHz frequency range
- High-resolution images at 500 frequencies
- High-cadence (1 s) spectral imaging of flares and other radio bursts
- Dynamic, spatially resolved spectral diagnostics of magnetic fields, thermal and nonthermal electrons, and acceleration processes in flaring loops.
- Coronal magnetography via spectral diagnostics from full-disk, multifrequency images.
- Drivers of space weather, such as eruptive events, type III bursts.
- Synoptic observations

Sun Radio Imaging Experiment (SunRISE)

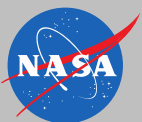
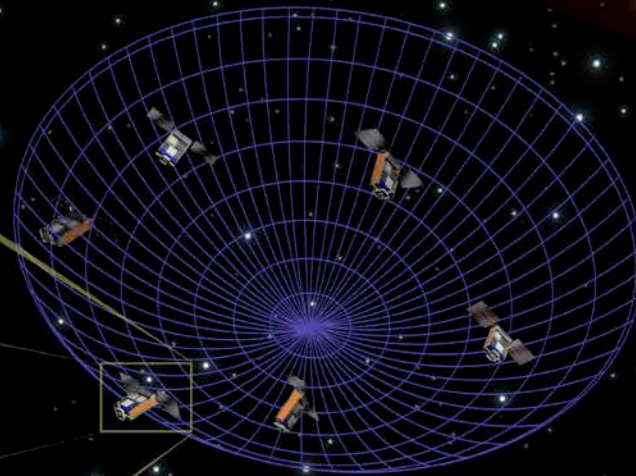
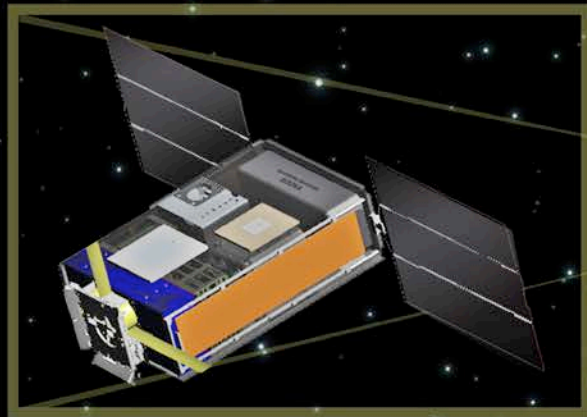
PI: Justin Kasper (U Mich & BWX)
Proj. Sci.: Joe Lazio (JPL)



Mission of Opportunity
Now in Phase B

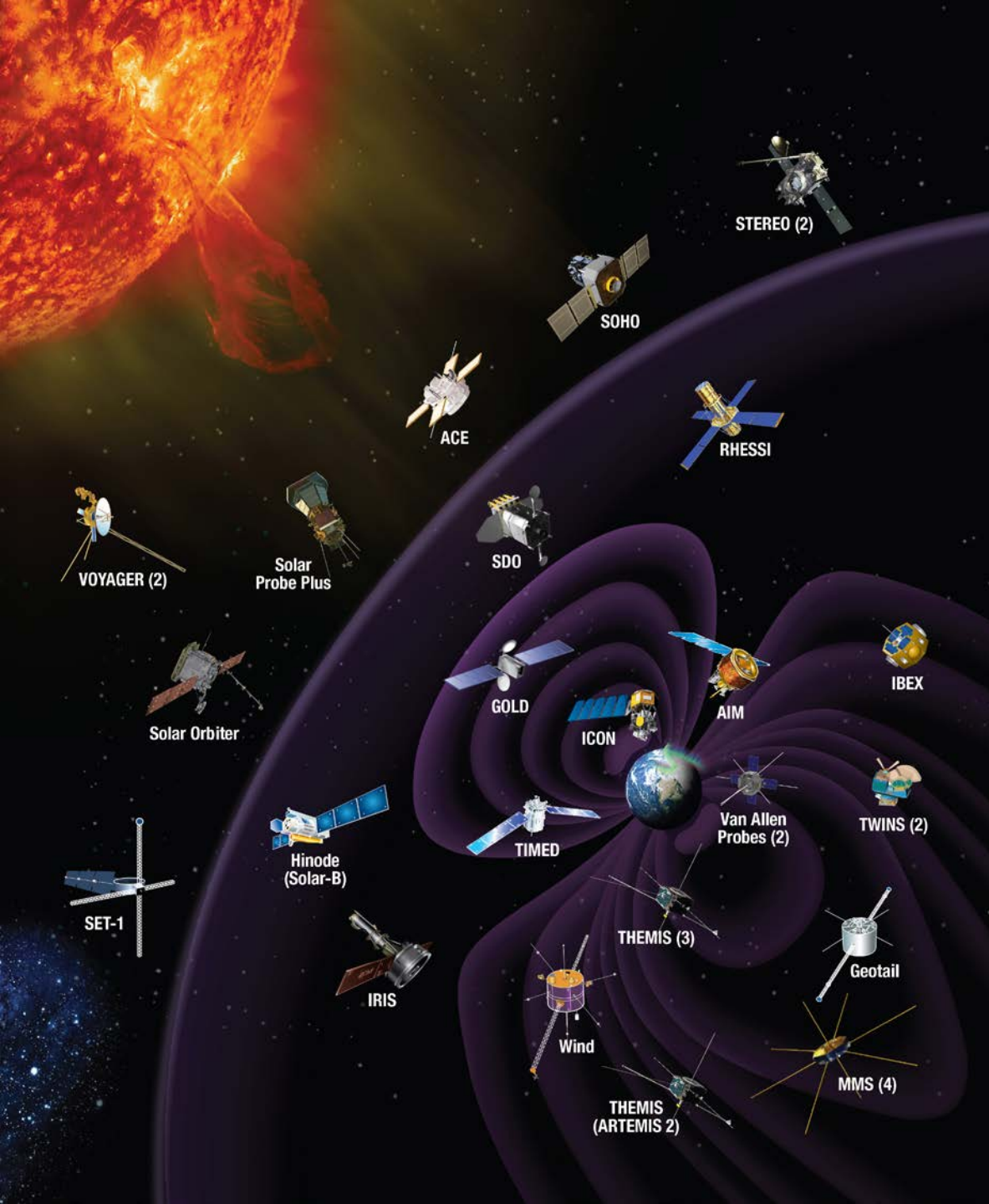
An imaging array of 6U
spacecraft operating below
the ionospheric cutoff.

Imaging the source regions
of IP type II and type III
bursts!



Jet Propulsion Laboratory
California Institute of Technology

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Government sponsorship acknowledged.



Heliophysics System Observatory

20+ space missions to monitor and study:

- Sun
- Solar wind/SEPs
- Magnetosphere/ionosphere
- Outer heliosphere

No Ground-based Counterpart

O/IR { DKIST
HAO/MLSO
University-based (BBSO)

No dedicated broadband radio imaging spectrometer!

- ngRH midscale required

Long-term Recommendations II

Invest in understanding **extreme events**

[This calls] for a new solar-dedicated radio facility beyond the capabilities of currently existing ones, e.g. the Frequency Agile Solar Radiotelescope concept that has received strong recommendations in several decadal surveys.

Invest in understanding the **science of space weather**

This, too, calls for a modern, solar-dedicated instrument like FASR capable of performing imaging spectroscopy from cm- λ to Dm- λ as a key component of the ground-based counterpart to the HSO. This will ultimately yield new, unique, and robust observables (R2O), the basis of which has already been established.

Potential Radio Contributions

Thermal emission from chromosphere to corona (3D)

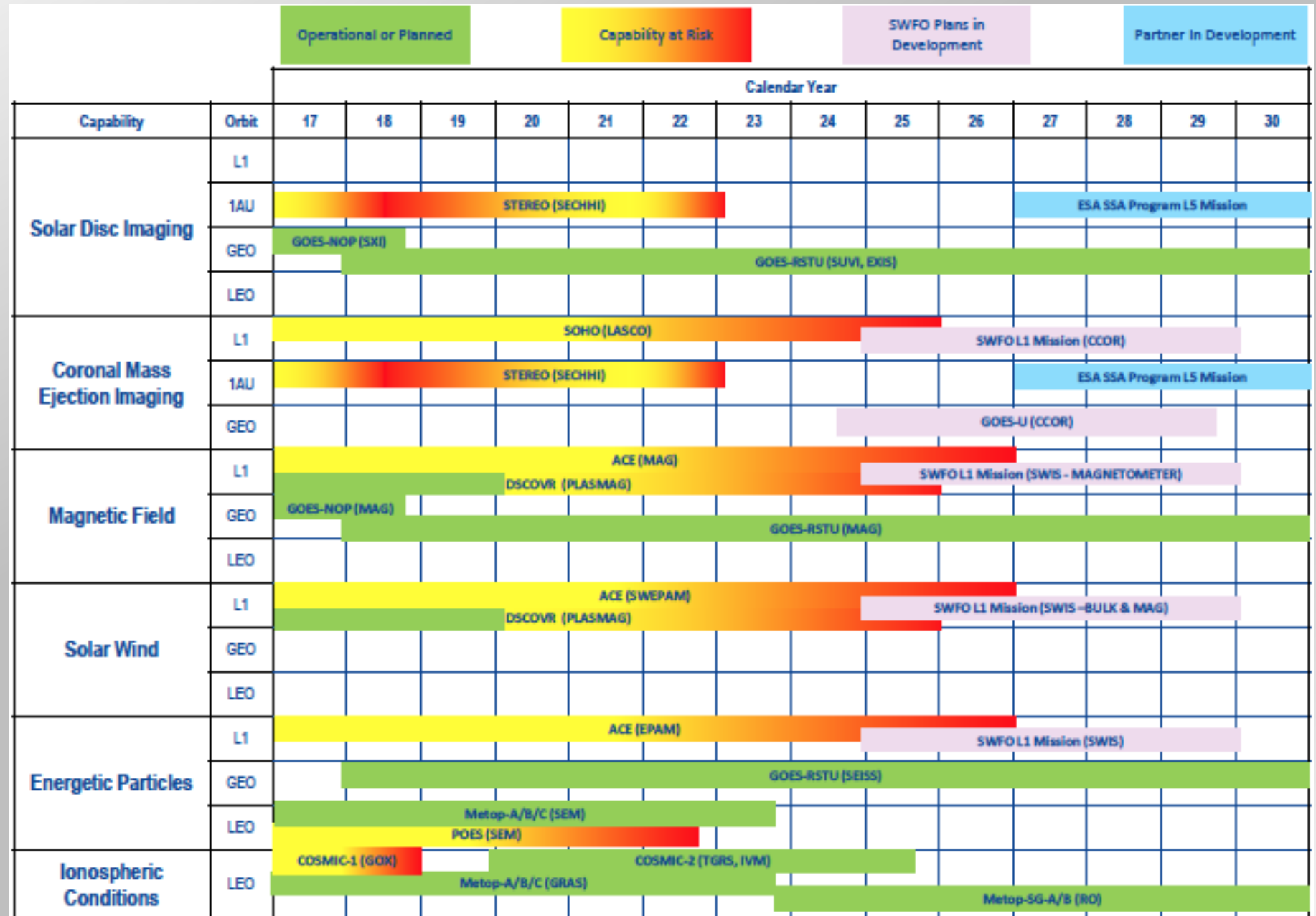
Radio CMEs plus associated type II

QS B_{los} , $|B|$ in ARs, dynamical B in flares, CMEs

[Remote sensing]

Sources of energetic electrons

F10.7



Summary

- Solar radio bursts represent a direct space weather threat to communications and navigation infrastructure
- Radio emission from, e.g., type II & type III radio bursts trace space weather phenomena (magnetic energy release, particle transport, shock initiation and propagation)
- Radio emission offers unique observables and insights into fundamental aspects of the science of space weather
- All of these require appropriate investments the construction of modern radio facilities and their sustained operation. The groundwork has been laid. Time to implement.