Radio emission from the Sun:
Recent advances at high frequencies

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Solar Radio Emission

• Produced by different sources via a variety of emission processes
• Provides rich diagnostics for both thermal plasma and nonthermal electrons

Bremsstrahlung

- Nucleus
- $e^{-}$
- $\gamma$
- Thermal plasma

Gyromagnetic Radiation

- Energetic electrons
- Magnetic field
- Thermal plasma
- $\gamma$
- $B$

Coherent Radiation

- Energetic electrons
- Background plasma
- $\gamma$
Figure 4.1. Characteristic radio frequencies for the solar atmosphere. The upper-most characteristic frequency at a given frequency determines the dominant emission mechanism. The plot is meant to be schematic only, and is based on a model of temperature, density, and magnetic field as follows: The density is based on the VAL model \( B \) (Vernazza et al. 1981), extended to \( 10^5 \) km by requiring hydrostatic equilibrium, and then matched by a scale factor to agree with \( 5 \times \) the Saito et al. (1970) minimum corona model above that height (the factor of 5 was chosen to give 30 kHz as the 1 AU plasma frequency). Temperature was based on the VAL model to about \( 10^5 \) km, then extended to \( 2 \times 10^6 \) K by a hydrostatic equilibrium model. The temperature is then taken to be constant to 1 AU. The magnetic field strength was taken to be the typical value for active regions given by Dulk & McLean (1978), \( B = 0.5 \left( \frac{R}{R_\odot} \right) \). For the \( \int \) \( \theta \) \( \phi = 1 \) curve, a scale height \( L \) is needed. We used \( L = H_0 \left( \frac{T}{T_0} \right) \left( \frac{R}{R_\odot} \right)^2 \) where \( H_0 = 0.1 \). 

Near the Sun, the curves apply to active regions. Third harmonic \( \int = 3 \int \). Figure 1 shows that the \( 3 \int \) line lies above the \( \theta \) \( \phi = 1 \) level down to 1–2 GHz, and extends up in frequency to \( \approx 20 \) GHz—both of which agree well with the observed range. During bursts, gyroemission is more typically at \( \int = 10 \int \), from which we see that gyroemission during bursts can extend to 800–900 MHz in the decimetric range. At mm wavelengths \( \approx 100 \) GHz, bursts can be dominated by either free-free or gyroemission, depending on the number and energy of emitting particles. Outside of flares, the emission above 20 GHz is entirely due to free-free emission. From D. Gary
Dynamic Spectroscopy

In most cases, our spectral resolution and cadence are not limited by sensitivity, but by the instrumentation capability.
Solar Radio Observing Techniques:
Radio Synthesis Imaging

Radio Interferometer

Credit: S. White
When Imaging Meets Dynamic Spectroscopy

EUV, X-ray, and radio images

VLA “vector” dynamic spectrum

X-ray light curve

VLA cross-power dynamic spectrum

VLA “vector” dynamic spectrum
New generation radio facilities: Jansky VLA

- General purpose radio observatory
- Microwave range: 1–8 GHz (currently available for solar observing)
- Probes low solar corona (<~1.15 R\text{sun}). Great for solar flare and active region science.
  - 27 25-meter antennas
  - ~20”/GHz for C configuration
  - Instantaneous bandwidth up to 2 GHz
  - Full Stokes polarization
  - \textit{Up to 50 ms and 1 MHz resolution}
New generation radio facilities: EOVSA

Expanded Owens Valley Solar Array

- Located at OVRO/Caltech, operated by NJIT
- Fully commissioned in 2017

- **Solar-dedicated** radio observatory
- Microwave range 1–18 GHz (now 2.5–18 GHz due to RFI)
- Probes low corona (<~1.15 $R_{\text{sun}}$). Great for solar flare and active region science

- 13 2.1-m antennas + 1 27-m antenna for calibration
- Max baseline 1.56 km (typically ~60”/GHz)
- Full Stokes correlation
- Sweeps 1–18 GHz *in 1 second*
New generation radio facilities: ALMA

Atacama Large Millimeter Array

Solar observing started in 2016 (Cycle 4)

- General purpose radio observatory
- Bands 3 and 6 currently available for solar observing (~100 GHz & 230 GHz, Bands 7 & 9 being commissioned)
- Probes solar chromosphere (~1–1.003 $R_{\text{sun}}$). Great for observing detailed thermal structures in chromosphere
  - ~50 antennas for INT and 3 antennas for total-power fast scan
  - **Sub-arcsecond spatial resolution!**
Solar flare and Coronal Mass Ejections

CME (white light)

Flare signatures near the surface

From T. Bastian
Unified flare-CME model

Outstanding Questions

- When, where, and how do major space weather drivers such as solar flares and coronal mass ejections occur?

- Solar flares and CMEs are excellent laboratories to study catastrophic magnetic energy release processes that also occur on other stars
  - Where and how does magnetic energy store and release?
  - How are charged particles accelerated to relativistic speeds?
  - How is plasma heated to multiple millions of degrees?
  - How does energy transport in the highly-coupled solar atmosphere?
Recent Examples from EOVSA:

*Imaging flare loops filled with energetic electrons*

X8.1 flare on 2017 Sep 10
Recent Examples from EOVSA:

*Imaging flare loops filled with energetic electrons*
Spatially Resolved Gyrosynchrotron Spectra
Recent Examples from EOVSA:  
**Mapping Solar Active Regions**

- Solar active regions are the *source for all major solar activities*
- Measuring B field in the *corona* remains a *major challenge* at all other wavelengths, but *readily accessible from radio gyroresonance radiation*
- Requires *wide frequency coverage* to sample B field in active regions (100s to 1000s G)

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Background: SDO/HMI magnetogram (*photosphere*)
Contours: EOVSA radio map at ~5 GHz (*corona*)
Recent Examples from EOVSA: Mapping Solar Active Regions

"Isogauss" gyroresonance layers: $f = s f_{ce} = 2.8 \times 10^6 sB$

From D. Gary
Recent Examples from EOVSA:

Mapping Solar Active Regions

B ~ 350 G  402 G  415 G  472 G  530 G  594 G

Assuming s=3

From D. Gary
Examples of Solar Studies with JVLA

• Mapping solar flare termination shock
  – Chen et al. 2015, *Science*, 350, 1238

• Tracing fast electron beams
  – Chen et al. 2017, in prep
Solar Flare Termination Shock

- TSs suggested as one mechanism for accelerating electrons in flares
- However, solid observational evidence remains elusive
Radio Emission at a Termination Shock

Reconnection
Outflow

\[ V_{\text{downflow}} > C_{ms} \]

Turbulence/Fluctuations

Accelerated Electrons

Langmuir waves:
\[ f \sim n^{1/2} \]

\[ e^- \]

\[ f_1 \]

\[ f_2 \]

Flux

frequency
Radio and HXR source at the front of reconnection downflows

Drifting structure consisting of numerous short-lived, narrowband coherent radio bursts

VLA 1-2 GHz
Main results:

- First convincing observational identification of a solar flare termination shock
- Demonstrated its role in accelerating electrons

Chen et al. 2015, *Science*, 350, 1238
Examples of Solar Studies with JVLA

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Dm-\(\lambda\) type III radio bursts from fast electron beams

\[ f \sim 1 \text{ or } 2 f_{pe} = 9n_e^{1/2} \text{ kHz} \]

\[ n_e \sim 10^9-10^{10} \text{ cm}^{-3} \]
Snapshot of a Beam Trajectory

High-resolution Dynamic spectrum

Channel-by-channel spectral imaging

Electron beam trajectory

Erupting Jet-Reconnection Scenario

Radio, EUV, and X-ray Observations

Pinpointing the magnetic reconnection/electron acceleration site

Chen et al., in prep
Recent Examples from ALMA:

*Imaging detailed structures in chromosphere*

Thermal structure & magnetic field (Stephen’s talk)

Credit: ALMA (NRAO/ESO/NAOJ)
Recent Examples from ALMA:

*Probing dynamics in chromosphere*
Concluding Remarks

• Solar radio astronomy has *entered a new era*, thanks to new instrumentation that offers *broadband dynamic spectral imaging*, opening up new opportunities for solar physics and space weather research.

• Provides detailed studies of magnetic energy storage and release, particle acceleration, emission processes, as well as structure, dynamics, and magnetic field of the solar atmosphere.
Thank you