Solar and Heliospheric Physics with the ngVLA

T. S. Bastian (NRAO) on behalf of the solar community

Solar Physics

The ngVLA will contribute to a number of outstanding problems in solar physics. A few of these are outlined here.

Coronal Magnetography

Quantitative measurements of the Sun's chromospheric and coronal magnetic field is key to understanding a range of outstanding problems: non-radiative heating; solar flares and coronal mass ejections; and the solar wind. A variety of powerful techniques unique to radio wavelengths at cm to mm wavelengths can be exploited to place quantitative constraints on the Sun's magnetic field as summarized in Table 1.

Table 1

Diagnostic	Application
Thermal gyroresonance	Active regions ($\|\mathbf{B}\| \rightarrow \mathbf{B}$)
Non-thermal gyrosynchrotron	Flares & CMEs ($\|\mathbf{B}\| \rightarrow \mathbf{B}$)
Thermal free-free	Quiet sun, active regions ($B_{\parallel}$)
Loop oscillations	Flares (discrete loops)
Mode coupling	Active region corona (topological)
Propagation Techniques	Corona & solar wind

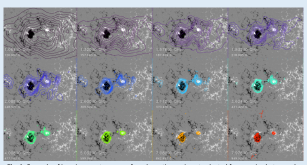


Fig. 1: Example of imaging spectroscopy of a solar active region at selected frequencies between 1-8 GHz, observed on 18 November 2014 by the Jansky VLA.. The photospheric magnetogram is shown in greyscale. The color contours show the isogauss surface at each frequency. At the lowest frequency, free-free emission dominates, rapidly giving way to gyroresonance emission as the frequency increases above 1.5 GHz (from Bastian + 2018)

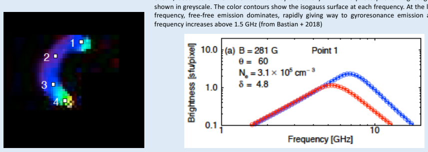
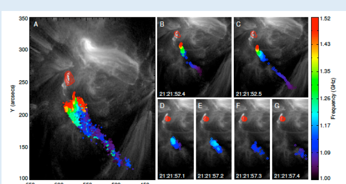


Fig. 2: Simulation of imaging spectroscopy of a flaring magnetic loop between 1-20 GHz. Mildly relativistic ($\gamma \sim 2$-5) accelerated during magnetic energy release. Measurement of the of the polarized microwave spectrum along each line of sight (left) allows the electron magnetic field to be mapped in the flaring loop (right). Forward fitting allows a number of other parameters to be fit, including the ambient plasma density the spatio-temporal evolution of the electron distribution function, allowing powerful constraints to be placed on acceleration and transport mechanisms. (from Gary + 2013)

Magnetic Energy Release

The source of free energy for a variety of transient energetic phenomena on the Sun is non-potential magnetic fields. The details of the conversion of magnetic energy to plasma heating and particle acceleration via 3D magnetic reconnection remains an outstanding problem (e.g., Shibata & Takasao 2016). The Jansky VLA offers a new tool with which to probe magnetic energy release - dynamic imaging spectroscopy. Two recent examples: 1) mapping electron beam trajectories to constrain the magnetic energy release site (Chen + 2013); 2) mapping stochastic spike bursts to trace a termination shock during a solar flare (Chen + 2015). These techniques will be deployed more comprehensively with the ngVLA.



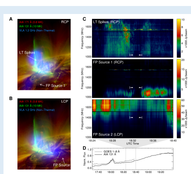
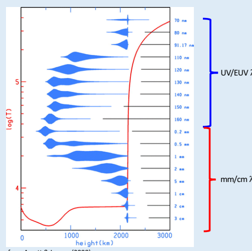


Fig 3: *Above:* Example of the ensemble of electron beam trajectories mapped via type III radio bursts using the Jansky VLA between 1.0-1.5 GHz (Chen + 2013). The radio emission is the result of plasma radiation, the frequency of which is proportional to $n_e^{1/2}$; right: example of vector dynamic spectra observed during the course of an solar flare accompanied by a fast coronal mass ejection. The "loop top" source is associated with the termination shock resulting from the fast plasma outflow from the fast magnetic energy release. Details may be found in Chen + (2015).

Non-radiative Heating

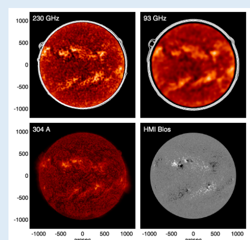
A long-standing problem is understanding the heating and dynamics of the solar chromosphere and corona. Observations from submillimeter to centimeter wavelengths serve as an ideal probe of the thermodynamic state of the Sun's atmosphere. Emission at these wavelengths is due to thermal free-free H and H^- opacity; the source function is Planckian and, owing to the Rayleigh-Jeans approximation, observations at these wavelengths provide a convenient linear thermometer. By tuning across a wide range of ngVLA frequencies, the solar chromosphere and low corona will be sampled over heights that are complementary to those sampled by ALMA (Figs. 3,4). Detailed comparisons with observations at UV/EUV wavelengths from space-based platforms will provide additional perspective (Bastian + 2017).



from Avrett & Loeser (2008)

Fig. 3 Schematic of the variation of temperature with height from the solar photosphere up through the chromosphere and the low corona. The contribution functions to the observed emission from material at different heights are shown in blue. Radiation at submm, mm, and cm wavelengths is in LTE and the source function is Planckian, allowing emission at these wavelengths to be used as a linear "thermometer". In contrast, radiation at UV/EUV wavelengths is in non-LTE and is less straightforward to interpret. Continuum radio and UV/EUV observations together allow powerful constraints to be placed on models of the chromospheric heating.

Fig. 4 Example of ALMA fast-scan total power maps of the solar chromosphere at 230 GHz (1.3 mm) and 93 GHz (3.2 mm). ALMA and ngVLA observations will be highly complementary, probing the full extent of the chromosphere from the temperature minimum region up into the corona.



from White + (2017)

Implications for ngVLA Requirements

The primary interest in the ngVLA for solar physics is the excellent snapshot *uv* coverage provided by the core of the array and the broad frequency coverage. For solar wind studies, the most attractive attributes of the ngVLA are baselines extending to several X 100 km and the enormous sensitivity of the array. Requirements may be summarized as follows:

Solar Requirements

- Core baselines to 3 km (1″ @ 20 GHz)
- Ephemeris tracking with OTF and mosaicing support
- Support of up to six **independent** science subarrays simultaneously
- Robust flux calibration of the time-variable signal
- Total Power Measurements
- Spectral resolution $\Delta\nu/\nu \sim 0.01\%$ (to 4 GHz); 0.1% otherwise
- Full polarimetry
- Time resolution to 10 ms

Solar Wind Requirements

- Baseline coverage to ~1000 km
- Frequency coverage to 30 GHz
- Full continuum sensitivity
- Full polarimetry
- Time resolution to 10 ms

The Solar Wind

With its unprecedented sensitivity, angular resolution, and frequency bandwidth the ngVLA will be an outstanding tool for solar wind studies which, in turn, will inform our understanding of mass loss on other stars. Outstanding problems include the acceleration of fast and slow solar wind, solar wind turbulence, transient disturbances such as coronal mass ejections and the creation of solar energetic particles.

Solar Wind Diagnostics

The ngVLA's enormous continuum sensitivity will enable large numbers of numbers of background sources to be exploited as probes of the foreground solar wind and corona at various solar elongations and position angles. The interaction of the incident radio waves with large scale gradients in the solar-wind/coronal electron density and with the spatial spectrum of the electron number density $\Phi_{ne}(q) = C_n^2 q^{-(\alpha+2)} \exp[-(q l_o/2)^2]$ result in a variety of propagation phenomena that can be used to leverage information about both, as detailed in Table 2.

Table 2

Observation/Technique	Plasma Property
Group delay	Mean electron number density n_e
Refraction	Electron density gradient ∇n_e
Angular broadening	Index α of Φ_n on scales of km to 100s of km Inner scale l_o, degree of anisotropy, B orientation
Spectral broadening	Index α of Φ_n on scales of km to 100s of km Inner scale l_{in}
Phase scintillations	Index α of Φ_n on scales of 100s to 1000s of km Outer scale l_{out}
Doppler (freq) scintillations	Index α of Φ_n on scales of km to 100s of km Solar wind velocity v_{sw}
Intensity scintillations	Index α of Φ_n on scales of km to 100s of km Solar wind velocity v_{sw}, δv
Faraday rotation	$B_{\parallel}$, n_e
Faraday fluctuations	Magnetic field fluctuations δB

Solar Wind Fluctuations

As an example, interplanetary scintillations (IPS) can be exploited on baselines of 100s to ~1000 km to measure the solar wind speed (both fast SW and slow SW) as well as fluctuations therein. This will allow important global constraints to be placed on SW acceleration and the development of SW turbulence. Of particular interest is the region in the vicinity of the Alfven radius, where the $v_{SW} \sim v_A$, at r ~ 10-20 $R_\odot$ (Fig. 5).

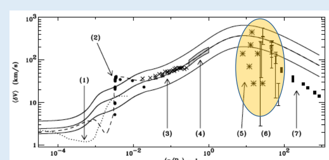


Fig. 5 Comparison of velocity fluctuation amplitudes with a model of Alvenic turbulence (Cranmer and van Ballegooijen (2005). The sources of the velocity fluctuation measurements include microturbulence (1) and nonthermal UV line broadening on the disk (2) and above the limb using SOHO SUMER (3) and UVCS (4), interplanetary scintillations (5, 6), and in situ measurements (7).

Space Weather

IPS and differential measurements of Faraday Rotation have the potential to be powerful probes of space weather drivers such as coronal mass ejections (CMEs). The former place density constrains on the CME whereas the latter place critical constraints on the CME magnetic field. (e.g., Kooi + 2017 and AAS 231 poster #238.05).

ngvla NRAO NSF Associated Universities, Inc.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.