Probing Fine Time Scale Variations in the Quiet Sun Brightness Temperature at Metrewaves

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Nature of Radio Emission

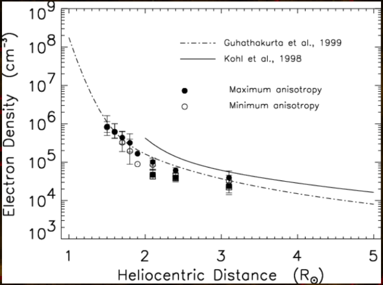
+ Quiet Sun emission

- Thermal free-free emission background.
- Brightness Temperature, $T_B = T_e(1 - e^{-\tau})$, Optical depth $\tau = \int \kappa ds$. s is the line of sight distance.

$$\kappa = \frac{10^{-11} N_e^2}{n f^2 T_e^{3/2}}$$

κ: Absorption coefficient
N$_e$: Electron density
T$_e$: Electron temperature
n: Refractive index
f: Frequency of the observation

- Optical depth of solar corona at low radio frequencies ($\tau \leq 1$).
- Plasma frequency ($\nu_p \propto \sqrt{N_e}$)



Advantages of Solar Radio Observations

- Active emission is produced from plasma emission processes, which are coherent.
- Direct detection of non-thermal emission.
- Larger contrast in spectrum/images.
- **Ideal to study weak heating emission/events.**
- Coronal Heating/Nanoflare hypothesis.

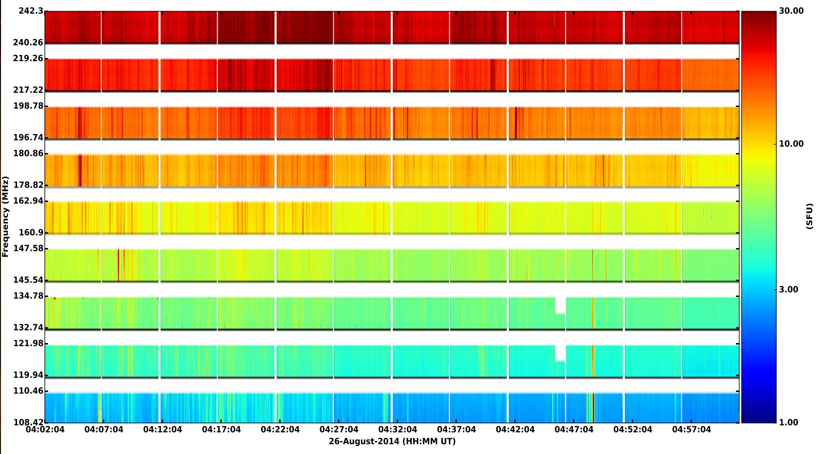
Technological challenges

- Radio Sun is more dynamic (variability < 1 sec, < 1 MHz), morphologically complex.
- Synthesis imaging averages over time and frequency. Snapshot imaging with high frequency and time resolution.
- New generation interferometers like Murchison Widefield Array (MWA), Square Kilometre Array (SKA)1-Low are closer to ideal solar instrument.

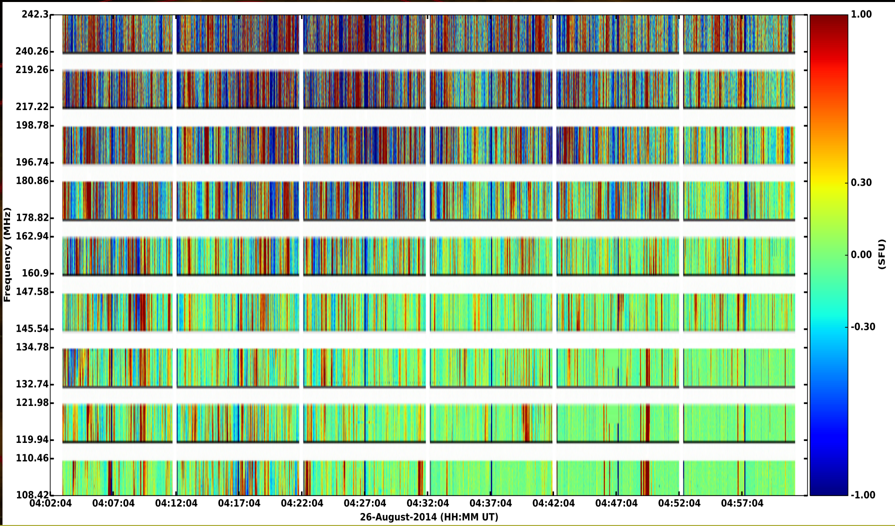
Weaker Emission Features - Disc Integrated Spectrum

(Oberoi, D., Sharma, R. & Rogers, A.E.E. Sol Phys (2017) 292: 75)

1 Solar Flux Unit (SFU) $= 10^{-19}$ ergs cm^{-2} sec^{-1} Hz^{-1} $= 10^{4}$ Jansky



Impulsive Features



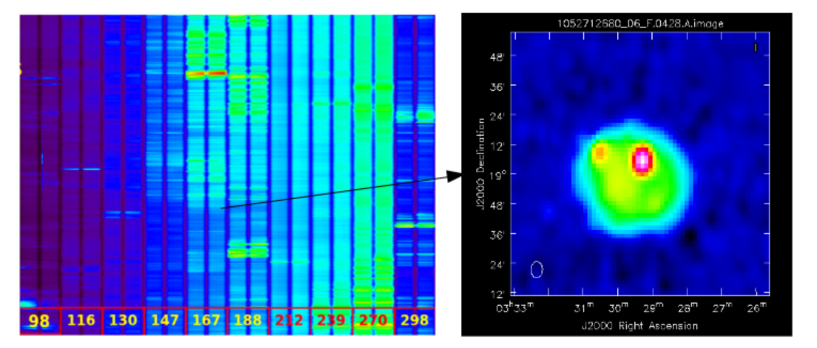
Results - Disk Integrated Spectrum

- Earlier studies with MWA reports impulsive fluxes of 10 - 100 SFU for weaker features. Typical Type-III bursts $\sim 10 - 1000$ SFU. (Suresh A., Sharma R., Oberoi D., & MWA collaboration 2017, ApJ)
- Typical range of brightness temperature 10^9 - 10^{12} K (Saint-Hillaire et al. 2013).
- 1 SFU $= 10^{-19}$ ergs cm^{-2} sec^{-1} Hz^{-1}

Frequency (MHz)	Continuum Flux (SFU)	Impulsive Flux (SFU)	Impulsive Fraction	T_B (K)	Impulsive Energy (ergs)
109.0	2.74 ± 0.34	5.43 ± 0.07	0.25 ± 0.01	3.7e+07	4.6×10^{15}
121.0	3.68 ± 1.31	4.62 ± 0.13	0.24 ± 0.00	3.2e+07	3.9×10^{15}
134.0	4.84 ± 1.46	3.33 ± 0.13	0.26 ± 0.02	2.3e+07	2.8×10^{15}
147.0	6.24 ± 0.74	5.77 ± 0.13	0.42 ± 0.07	3.9e+07	4.9×10^{15}
162.0	8.14 ± 1.07	5.79 ± 0.03	0.17 ± 0.00	4.0e+07	4.9×10^{15}
180.0	10.65 ± 1.62	10.44 ± 0.71	0.31 ± 0.03	7.3e+07	8.8×10^{15}
198.0	13.54 ± 2.34	13.35 ± 0.89	0.33 ± 0.02	9.2e+07	1.1×10^{16}
218.0	17.75 ± 3.02	12.96 ± 0.43	0.45 ± 0.05	8.9e+07	1.1×10^{16}
241.0	23.35 ± 3.38	16.24 ± 0.60	0.28 ± 0.04	1.1e+08	1.4×10^{16}

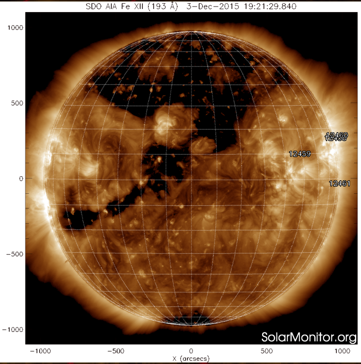
Advantages of Imaging

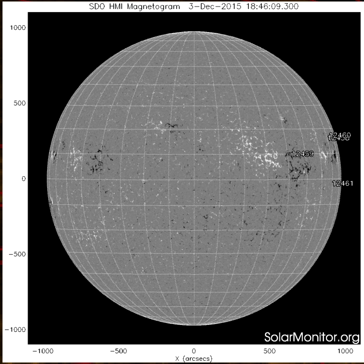
- Each pixel can make an image.
- Flux obtained from spectrum is distributed on the image.
- Weaker variability can be detected.



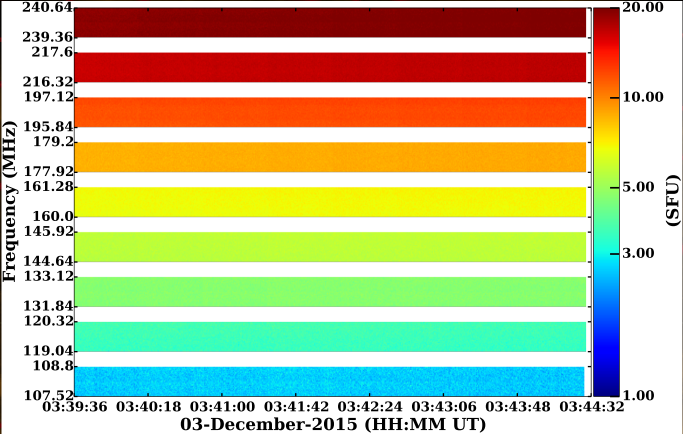
Data Description

- Quiet period.
- 9 frequency band between 110 and 240 MHz.
- Time: 03:39:36 - 03:44:32 UT



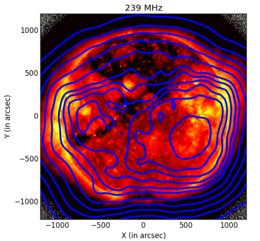


Solar Flux Spectrum

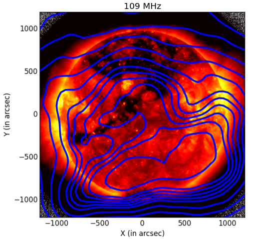


Imaging - Results

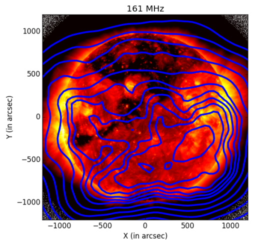
239 MHz



109 MHz



161 MHz

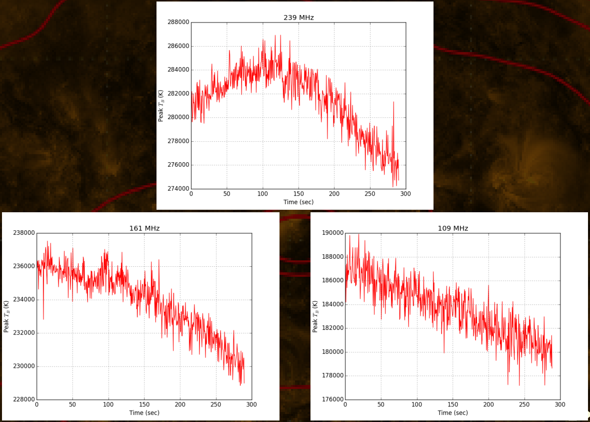


Typical coronal heights are:

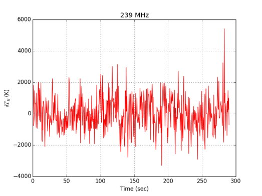
- 239 MHz corresponds to 1.021 $R_\odot$ or 14 Mm from photosphere.
- 161 MHz corresponds to 1.2 $R_\odot$ or 147 Mm from photosphere.
- 109 MHz corresponds to 1.4 $R_\odot$ or 280 Mm from photosphere.

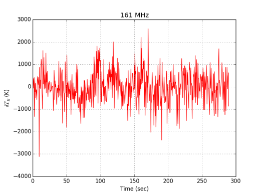
Imaging - Slowly Varying Component

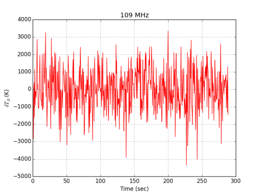
- Slowly varying component and fluctuations.
- 1-2 % variation in brightness temperature / flux.
- Mean T_B is **0.183, 0.234 & 0.281 MK** at 109, 161 & 239 MHz respectively.



Imaging - Result







Frequency (MHz)	Mean T_B (MK)	1 σ variation(K)	Fractional RMS	Noise $\sim \sqrt{2\delta\nu\delta t}$
109	0.183	1219	0.67 %	0.06%
161	0.234	709	0.30 %	0.06%
239	0.281	1056	0.38 %	0.06%

- Isotropic impulsive energy $\sim 10^{13}$ ergs.
- Type-III bursts - $10^{18} - 10^{23}$ ergs (Saint-Hilaire et al. 2013)
- Type-I bursts - 10^{21} ergs (Mercier & Trottet 1997)

Summary

Non-Imaging Studies

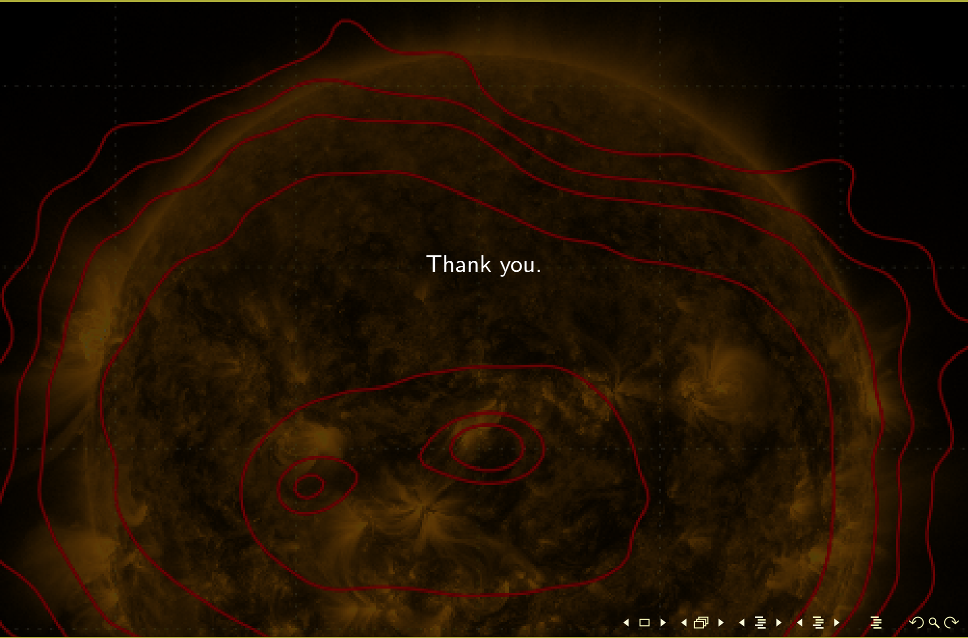
- We have detected weak impulsive features. Flux scales $\lesssim$ 10 SFU. $T_B > 10^7 - 10^8$ K. Isotropic impulsive power $\sim 10^{15}$ ergs.
- Flux emitted in impulsive features is significant in energy and fraction.
- No particular trend with frequencies / coronal heights.

Imaging Studies

- Going two order of magnitude deeper in the energies. Flux scales $\lesssim$ 1 SFU. Isotropic power $\sim 10^{13}$ ergs.
- Minute timescale slowly varying component ($\sim 1 - 2\%$) on mean T_B 0.18-0.28 MK.
- RMS variation in Brightness temperature $< 1\%$ detected, i.e $\Delta T_B \lesssim 10^3$ K.

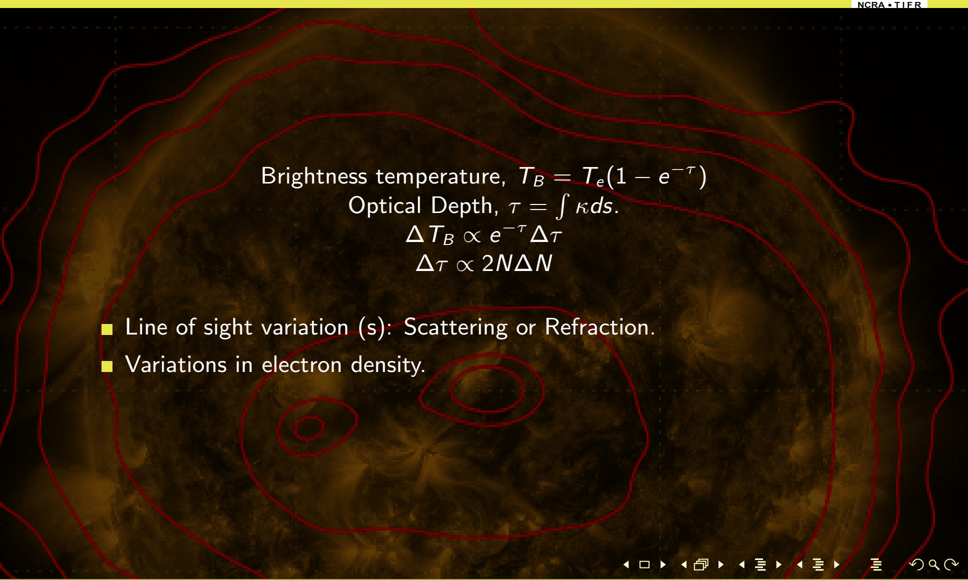
Implications of variabilities

- Electron density fluctuations / weak heating.
- Missing piece of heat generation/transportation.



Thank you.

Interpretation



$$\text{Brightness temperature, } T_B = T_e(1 - e^{-\tau})$$

$$\text{Optical Depth, } \tau = \int \kappa ds.$$

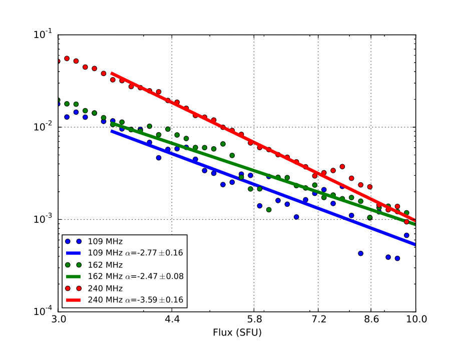
$$\Delta T_B \propto e^{-\tau} \Delta \tau$$

$$\Delta \tau \propto 2N \Delta N$$

- Line of sight variation (s): Scattering or Refraction.
- Variations in electron density.

Occurrence Rate (β)

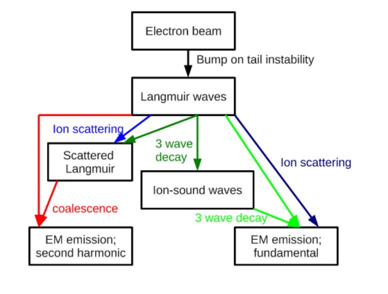
$$N(S) \propto S^{\beta}$$



Frequency (MHz)	β	$\delta\beta$
109.0	-2.77 ± 0.16	0.02
121.0	-2.32 ± 0.1	0.03
134.0	-1.91 ± 0.16	0.05
147.0	-2.54 ± 0.11	0.03
162.0	-2.47 ± 0.09	0.05
180.0	-2.48 ± 0.07	0.05
198.0	-2.54 ± 0.06	0.03
218.0	-2.52 ± 0.05	0.02
241.0	-3.59 ± 0.23	0.13

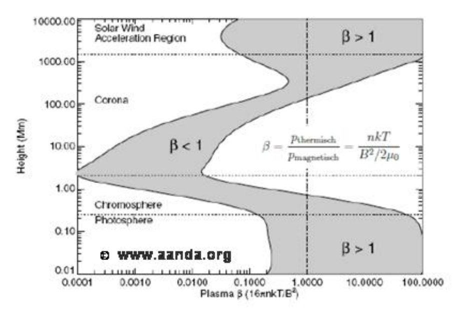
- Hudson et al. 1991 calculates rate to be < -2.0.

Plasma Emission Process



Ratcliffe, H. 2013

Plasma Beta



Gary, G.A. Solar Physics (2001) 203: 71

Typical Non-Thermal Power

Assuming isotropic emission, total average impulsive power radiated,

$$W = 4\pi D^2 \Delta\nu \Delta t S_\odot \quad (1)$$