



Radio and X-ray Diagnostics of Energy Release in Solar Flares

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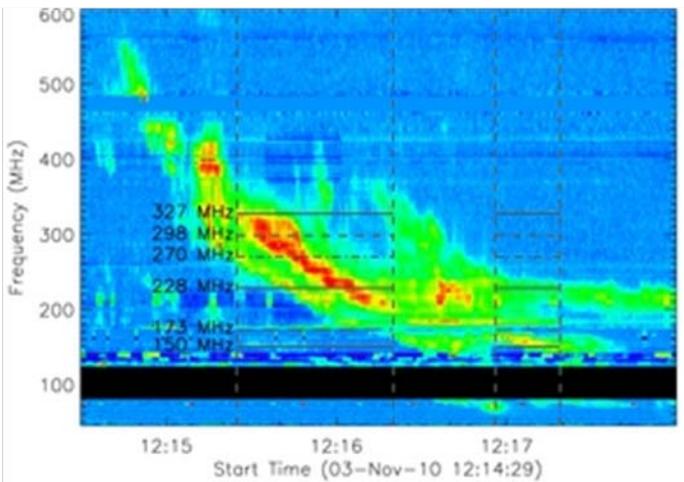
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Motivation and Methods

- Motivation: to understand flare energy release
 - Where and how is the energy released?
 - What are the properties in and around the energy release site
- Methods: multi-wavelength observations as diagnostic tools
 - Radio bursts
 - Coherent emission, highly sensitive to energetic electrons
 - Carry important information of flare energy release
 - X-ray emission
 - Especially powerful in deducing properties of accelerated electrons
 - Context information: magnetic, optical, UV/EUV, etc.

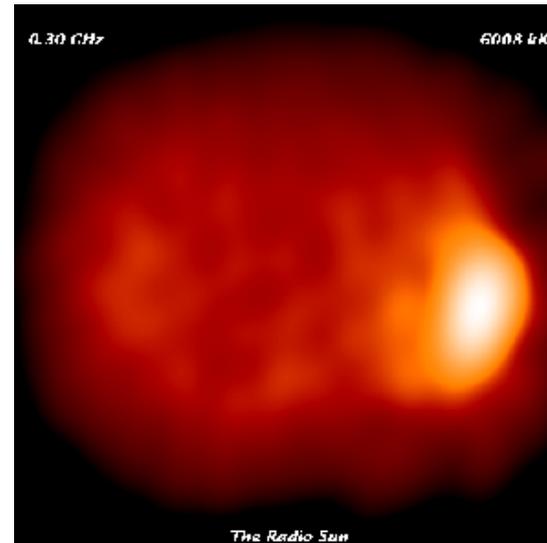
Solar Radio Bursts

Spectrographs:
total-power dynamic spectra



PHOENIX (from Bain et al. 2012)

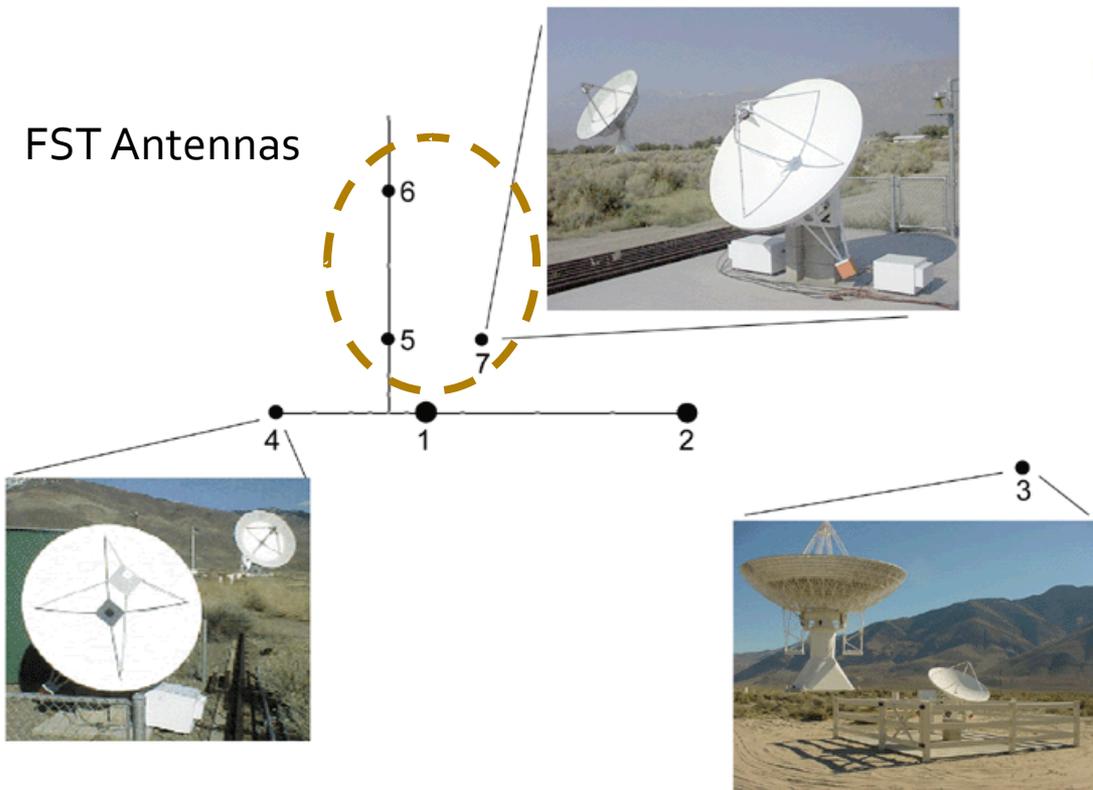
Interferometers: radio images



Very Large Array (credit: Stephen White)

Dynamic
Imaging
Spectroscopy

First Step Towards Dynamic Imaging Spectroscopy



- FASR Subsystem Testbed (FST)

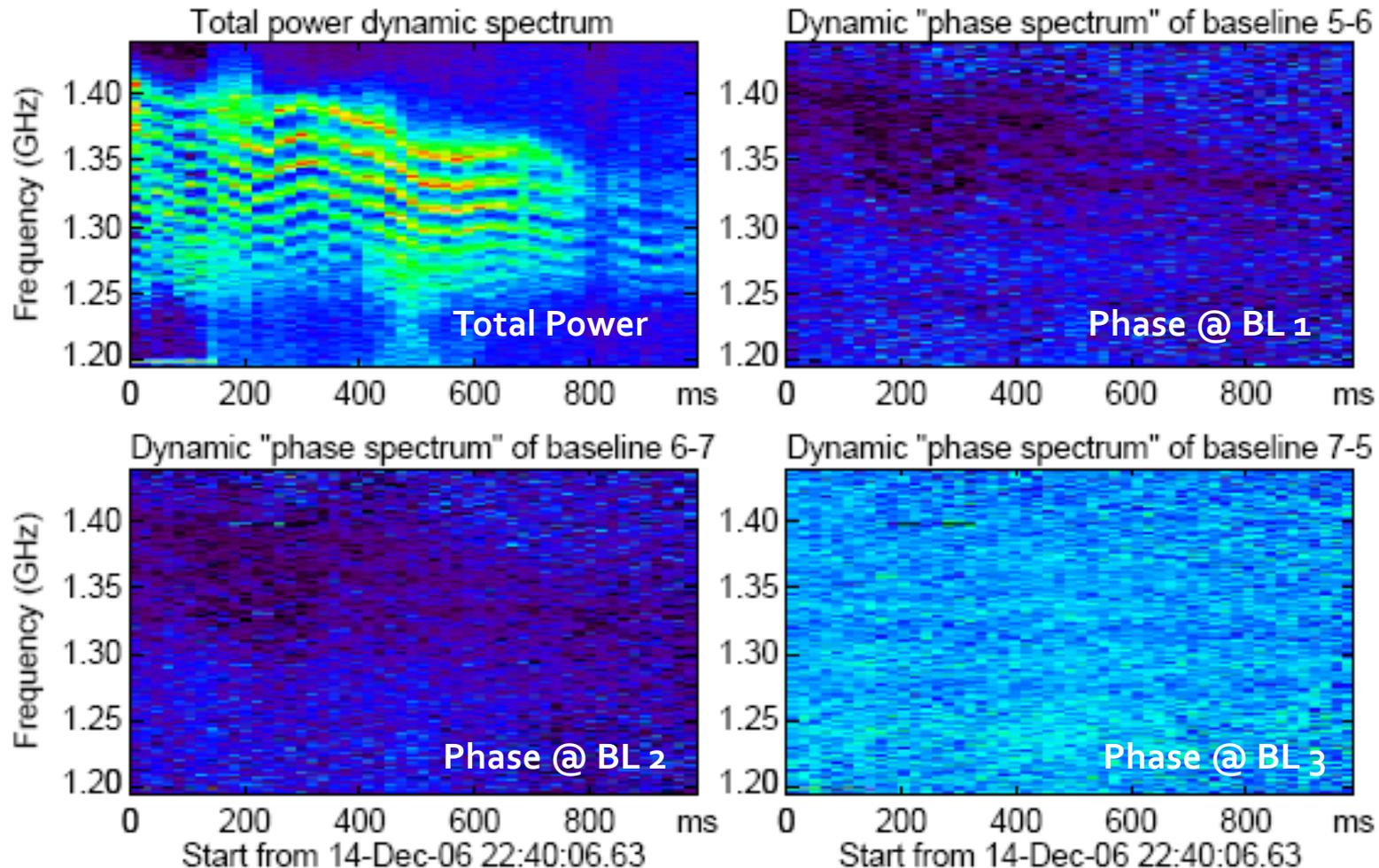
- ❖ 512 frequency channels between 1-1.5 GHz
- ❖ 20 ms time resolution

Enables dynamic spectroscopy

- ❖ Consists of three OVSA antennas

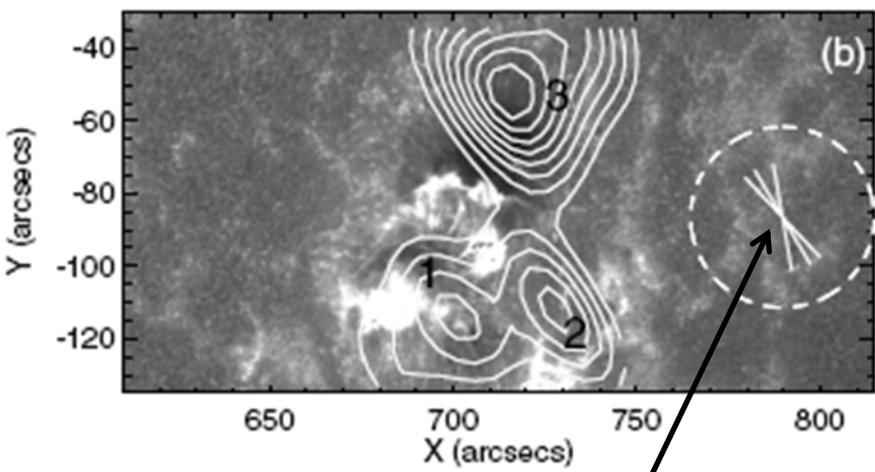
Provides simultaneous spatial information (but not yet imaging)

The Radio Burst – Zebra Pattern



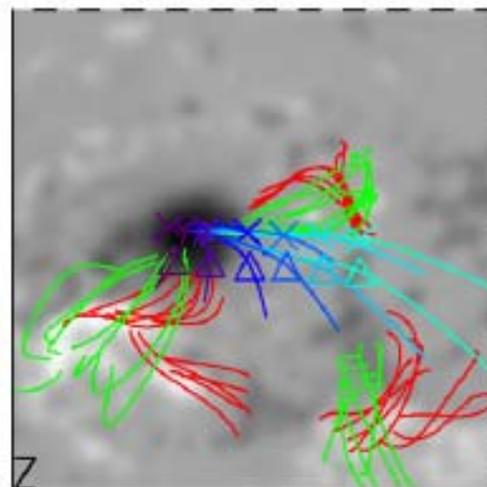
Locating the Radio Source

SOT Ca II H 22:37:35 UT

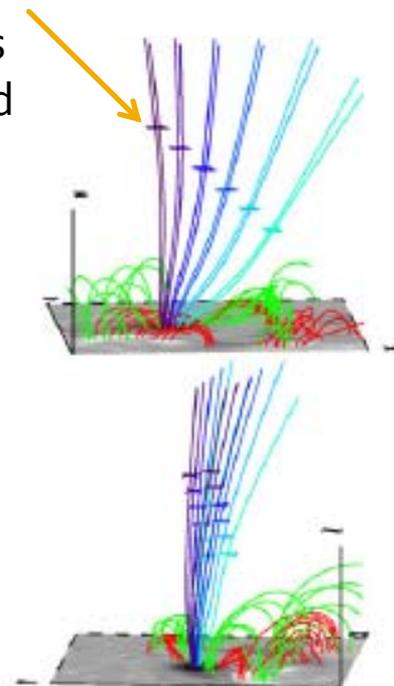


Radio source
centroid location

Possible 3D source locations
in the coronal magnetic field



LOS direction



- ❖ Produced by energetic particles originated from an energy release region high up
- ❖ Double plasma resonance is the most favorable emission model
- ❖ Source parameters: $H \sim 57-75$ Mm, $B \sim 35-62$ G, $L_N \sim 1.4 \times 10^{10}$ cm ($T \sim 3$ MK), $L_B \sim 3.2 \times 10^9$ cm

Dynamic Imaging Spectroscopy with the Very Large Array

- The recently upgraded VLA provides the first (and currently the only) opportunity to perform true radio dynamic imaging spectroscopy
 - Large instantaneous bandwidth: several GHz
 - Fine spectral resolution
 - Up to x10 ms time resolution
 - Full imaging ability

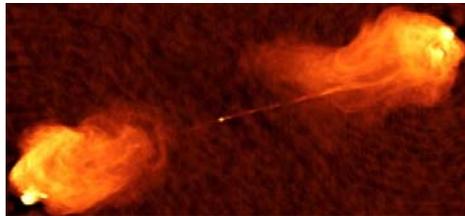


Karl G. Jansky Very Large Array, consisting of 27 25-m antennas (image credit: D. Finley, NRAO/AUI)

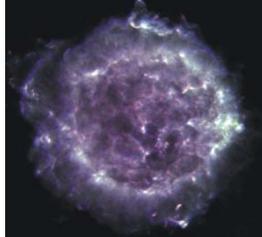
Observing the Sun with the VLA

- What does the VLA usually observe?

Radio
Galaxies:



Supernovae
Remnants:



Star forming
Regions:

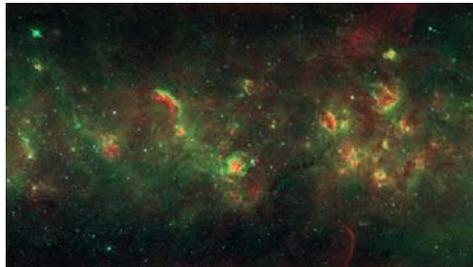
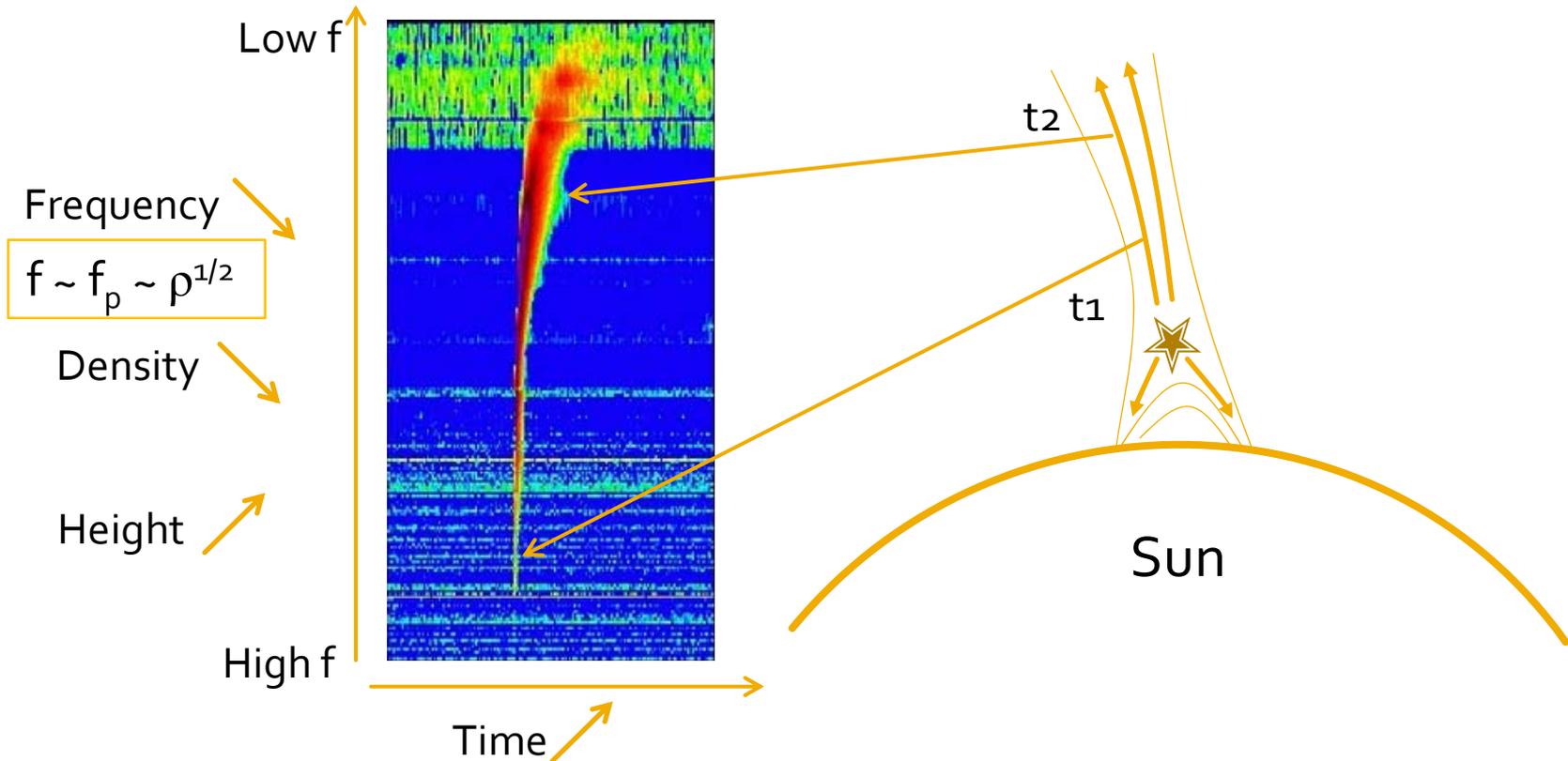


Image credit: NRAO/AUI

- Challenges:
 - Enormous increase in system temperature
 - Highly variable source, esp. during flares
 - Solar data calibration
- Solar Mode Commissioning
 - I served as the primary resident observer to carry out the commissioning
 - Hardware tests
 - Observing and calibration strategies developed

The Sun is orders of magnitudes brighter!

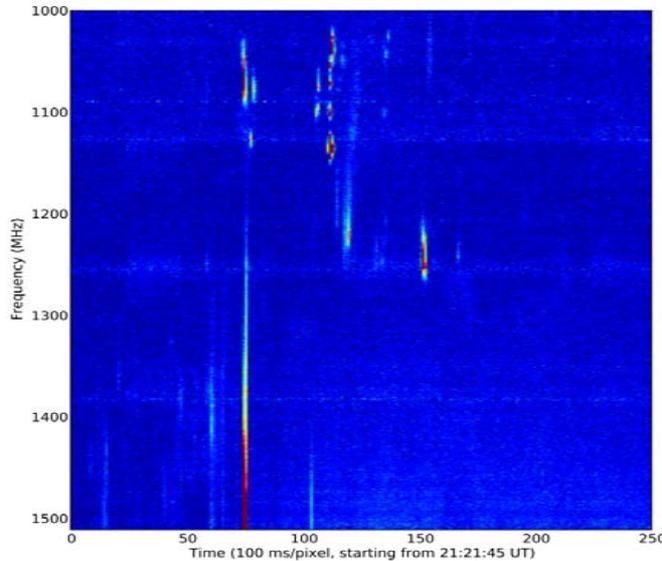
A First Experiment: $dm-\lambda$ Type III Radio Bursts



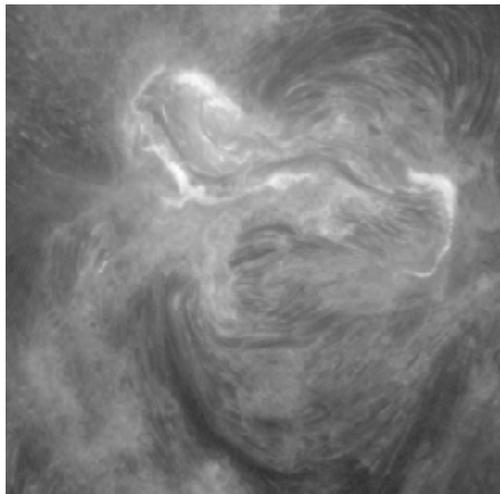
$dm-\lambda$ type III bursts are suspected to be closely associated with magnetic energy release for nearly three decades

Jet Associated Type III Bursts

Type III bursts



EUV jet

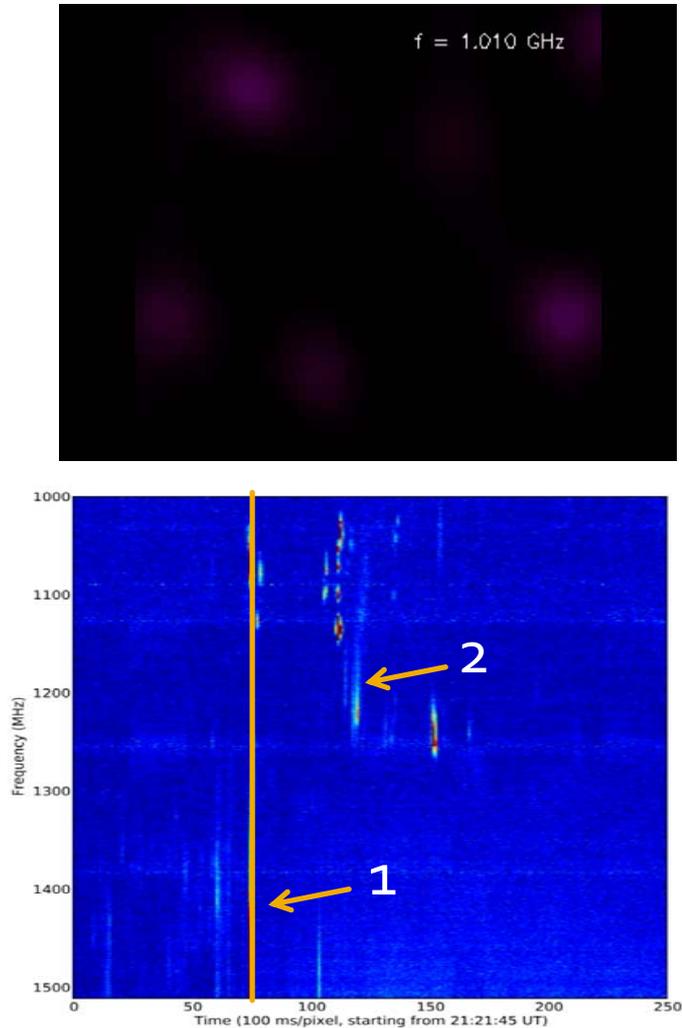


- ❖ 17 antennas, longest baseline 1 km
- ❖ 1024 1 MHz spectral channels in 1-2 GHz
- ❖ Dual polarization
- ❖ 100 ms time resolution

An image is available for each integration time and frequency:
>10,000 snapshot images/sec !

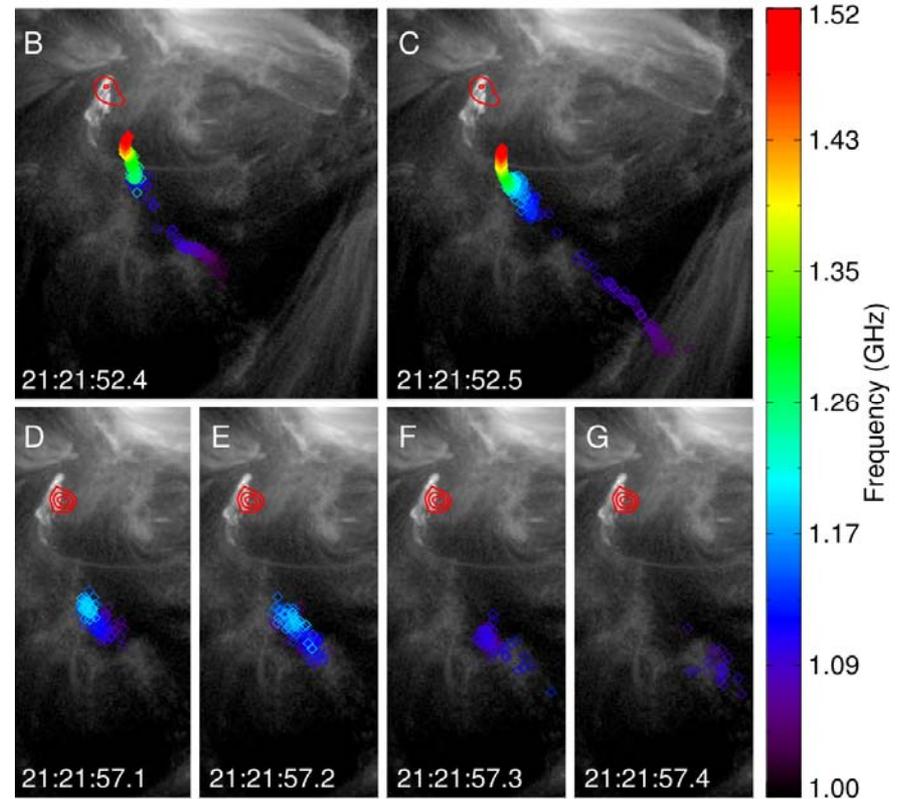
Chen et al. 2013, ApJL, 763, 21
(appeared in [NRAO Science Highlights](#))

Dynamic Imaging Spectroscopy of Type IIIIdm bursts



1

2



Temporally resolved type IIIIdm bursts

Results

- Detailed electron beam trajectories are derived for the first time.
- Confirm that type III dm bursts are closely correlated with footpoint X-ray emission, suggesting simultaneous upward and downward beam production.
- Beam speed $0.3c$; density along the trajectories derived; loop temperature inferred.
- No AIA counterparts! -- beams propagate in **extremely fine strands** (<100 km in diameter) that are cooler (3x) and denser (10x) relative to the background corona.
- Flare energy release is fragmentary in both time and space

Role of ICS in Coronal X-Ray Emission?

- The bremsstrahlung mechanism has long been favored for solar X-ray emission. Nevertheless, ICS may play a role under certain circumstances.
- Interest in ICS has been renewed with reports of certain coronal HXR sources – some require essentially ALL particles in the source to be accelerated to non-thermal energies, if interpreted in terms of bremsstrahlung!
- Questions:
 - ❖ Is ICS on ultra-relativistic electrons upscattering optical photons relevant?
 - ❖ Is there a role for ICS on mildly relativistic electrons upscattering EUV photons? (Previously overlooked)
 - ❖ What are the consequences of anisotropic electron distributions for ICS?

Results

- UR ICS may have played an important role in some super flares – it is energetically more favorable than bremsstrahlung.
- MR ICS produces a steeper spectrum than the UR case – its relevance may not be restricted to extremely hard photon spectra.
- Anisotropies in the electron distribution function yield enhanced emission relative to the isotropic case for favorable viewing geometries, esp. for ICS
- ICS may be a factor, perhaps even the dominant mechanism, for coronal sources in which the ambient density is low ($< \text{few} \times 10^8 \text{ cm}^{-3}$).

Summary

- What I have done:
 - Explored spatially resolved dynamic spectroscopy to study zebra bursts
 - Commissioned the upgraded VLA to allow solar observations
 - Exploited dynamic imaging spectroscopy using the VLA to observe dm- λ type III radio bursts
 - Investigated the role of ICS in coronal X-ray emission
- What I have learned:
 - Relation of the studied radio bursts to flare energy release with the new spatial information available
 - Emission mechanisms: zebra-pattern bursts, coronal X-ray emission. Important in using them as diagnostics
 - Properties of flare energy release and surrounding environment

Thank you for your attention!