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

Bin Chen (陈彬), University of Virginia

Thesis Committee: Tim Bastian (NRAO, thesis advisor), Dale Gary (NJIT), Zhi-Yun Li (UVa), Phil Arras (UVa), Bob Johnson (UVa)
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

**Interferometers:** radio images

PHOENIX (from Bain et al. 2012)

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

Total power dynamic spectrum

Dynamic "phase spectrum" of baseline 5-6

Phase @ BL 1

Dynamic "phase spectrum" of baseline 6-7

Phase @ BL 2

Dynamic "phase spectrum" of baseline 7-5

Phase @ BL 3
Locating the Radio Source

- 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~3 MK), \( L_B \sim 3.2 \times 10^9 \) cm
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 dm Bursts

- 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 III dm bursts

Temporally resolved type III dm bursts
Results

- Detailed electron beam trajectories are derived for the first time.
- Confirm that type IIIdm 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?

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 (< few x 10^8 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!