SSL Research on the Sun

R. P. Lin

Physics Department & Space Sciences Laboratory
University of California, Berkeley
FIG. 1. The solar-flare electron event of 8 October 1965.

Fig. 3. Two solar flare electron events observed on March 24, 1966, while the IMP 3 satellite was well within the geomagnetic tail. The delay times and buildup times for these events are no longer than those observed in interplanetary space.
Dungey, 1962
Wang et al, 2009
Reames, Lin, von Rosenvinge 1985; (see Temerin & Roth for theory)
Fig. 3. Four channels of the OGO-III detector are shown to ~10 min time resolution. The dashed lines indicate the decay slopes which were removed to obtain the spatial profiles of Figure 11. The 34 meV curve is the sum of channels 31 and 32, so the flux per meV is one half the graphed values.
Fig. 1. The interplanetary sector structure observed by IMP-1. The + signs (away from the sun) and — signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hour intervals.
Fig. 1.—A relatively broad X-ray spike observed on 1968 May 24 (1254:28 U.T.). Note the good time correlation and similarity in shape of the impulsive X-ray burst and the impulsive microwave radio burst.

Fig. 2.—Two small X-ray spikes observed on 1968 April 3 (2042:58 and 2044:05 U.T.). Notice that both the X-ray spikes are reproduced in the microwave radio emission.

Kane & Anderson, 1970
Fig. 6.—X-ray spectra observed at the maxima of three impulsive X-ray bursts. *Open circles*, observed counting rates in the different energy channels divided by their respective channel widths and the area of the detector. *Vertical bars* represent the estimated statistical uncertainty. *Filled rectangles*, computed response of the detector to an incident X-ray spectrum of the form $k_1 E^{-\gamma}$ photons cm$^{-2}$ sec$^{-1}$ keV$^{-1}$.

Kane & Anderson, 1970
Krucker, private communication, 2008
Lin et al 1985
Bastille Day 2000 Solar Flare
‘Standard’ model

This has evolved to keep pace with observations

Sturrock 1966

Tsuneta 1997

ITP Workshop Jan-18-2002
23 July 2002
X4.8 Flare
(Lin et al 2003)

Thermal Plasma
~3x10^7 K

Accelerated Electrons
~10 keV to >10s MeV

Accelerated Ions
~1 to >100s of MeV
Large solar flares are the most powerful explosions in the solar system

*Up to ~ \(10^{32} - 10^{33}\) ergs released in ~ \(10 - 10^3\) s*

*Flare-accelerated ~20-100 keV electrons contain ~10-50% of total energy released (Lin & Hudson 1971,1976)*

*In large flares, >\(\sim 1\) MeV ions contain comparable energy (Ramaty et al 1985)*

⇒ Particle acceleration is intimately related to flare energy release

*The total energy released by all flares, down to microflares/nano-flares may be significant for the heating of the solar corona*
RHESSI Imaging Spectroscopy

Spin Axis (to Sun Center within 0.2 degree)
Spin Rate ~15 RPM
Van Beek Grid (1 of 5)
Tecket Grid (1 of 4)
Solar Aspect System (SAS) Lens 4-cm dia. (1 of 3)

Metering Structure 1.5 m long x 45 cm dia.
Flexure Mount to Spacecraft (1 of 3)
Roll Angle System (RAS)
PMT RAS
Cryostat
Germanium Detector (1 of 9)
Aluminum Cover, Beryllium Windows Over Detectors
Spectrometer
Sunpower Cooler

Image Reconstruction

Count Rates in Each Detector for One Rotation

Time-Tagged Detector Counts
**HXR source motions in magnetic reconnection models**

- $v_{in}$ = coronal inflow velocity
- $B_c$ = coronal magnetic field strength
- $v_{fp}$ = HXR footpoint velocity
- $B_{fp}$ = magnetic field strength in HXR footpoint

$\sim$ photospheric value

$v_{in} B_c = v_{fp} B_{fp}$
Velocity-HXR flux correlation

Rough correlation between $v$ and HXR flux

$$d\Phi = B \, v \, a \, dt$$

Reconnection rate

$$d\Phi/dt = B \, v \, a$$

$\sim 2 \times 10^{18}$ Mx/s

$E = vB \sim 5$ kV/m

$v =$ velocity

$B =$ magnetic field strength

$a =$ footpoint diameter
Smith et al. Poster 2003, Share et al. 2003
23 July 2002 flare nuclear de-excitation lines
(Smith et al. 2003), see Smith et al poster 2.01, Shih et al talk 47.08
Protons vs Electrons

$\geq 30 \text{ MeV } p$

(2.223 MeV n-capture line)

$\geq 0.2 \text{ MeV } e$

(0.2-0.3 MeV bremsstrahlung X-rays)

e & p separated by $\sim 10^4 \text{ km, but close to flare ribbons}$
RHESSI and STEREO observations of a partially disk-occulted flare (Krucker et al, 2009)

C8 class flare on December 31, 2007
time series
(Krucker et al, 2009)

thermal emission

rapid time variations

Nobeyama observations:
thermal component
(constant spectrum)
gyro-synchrotron emission
(decreasing spectrum)
STEREO view shows flare ribbons and post flare loops

(Krucker et al, 2009)
above-the-loop-top source could be
along the flare arcade

impulsive phase

1 hour later (post flare loops)
HXR spectra

(Krucker et al, 2009)

Power-law spectrum

index $\gamma \sim 4.2$

$\Rightarrow$ accelerated electrons have power law spectrum with index $\delta \sim 3.7$
Microwave spectrum: non-thermal

(Krucker et al, 2009)

gyro-synchrotron emission
\( \alpha \sim 1.8 \)
\( \delta_\mu \text{wave} \sim 3.4 \)
\( B \sim 30-50 \text{ G} \)

RHESSI:
\( \delta_\text{thin} \sim 3.7 \)

→ power law spectrum from \(~16\text{ keV} up to the MeV range
Summary: measured parameters

- volume: $\sim 8 \cdot 10^{26}$ cm$^3$
- magnetic field strength $B$: $\sim 30-50$ G
- pre-flare density: $\sim 2 \cdot 10^9$ cm$^{-3}$
- acc. electron density: $\sim 2 \cdot 10^9$ cm$^{-3}$
- power law distribution with $\delta$: $\sim 3.4$
- from $\sim 15$ keV up to a few MeV
- pre-flare $\beta$ (T=2 MK): $\sim 0.01$
- $\beta$ during HXR burst: $\sim 1$

→ energy density of the accelerated electrons is comparable to that of the magnetic field

ions?
Discussion of models

Drake et al.:
- extended acc. region
- all electrons are acc.
- power law distribution
- $\beta \sim 1$ stops contraction
- $\beta \sim 1$ stops acceleration

Time evolution is given by acceleration and escape.

**turbulence**
(e.g. Liu et al. 2007)

**Contracting islands**
(Drake et al. 2006)
Why do we think of active regions as flux tubes? (this shape of flux tube is known as an Ω-loop)

(George Fisher & collaborators)
δ-spot active regions as twisted, kinking flux tubes (Linton, Fan)

- Properties of δ-spot regions:
  - Sunspot umbrae of opposite polarity in a common penumbra
  - Strong shear along neutral line
  - Active region rotates as it emerges
  - Large and frequent flares and CMEs
  - Kinked geometry explains rotation, shear along neutral line
  - Flares/CMEs might be explained by reconnection between the 2 legs of the intertwined loop structure
Mewaldt et al 2005
Kahler 1994:
Compare ion release time near Sun with CME front altitude
→ CME is already several Solar radii away from the Sun
Solar Reconnection – Breakout CME Model

- 3D simulation
- Null-point ahead of ejected plasmoid
- Bipolar reconnection behind
2002 Oct 27 flare

MARS: GRS

RHESSI
15-25 keV

giant flare seen by GRS (MARS) from Earth view:
tiny thermal emission, but large HXR burst

Krucker, White, & Lin 2007
October 27, 2002
CME velocity ~2000 km/s
very large source (>200 arcsec) expanding and rising

HXR emission from electrons in magnetic structures related to coronal mass ejections.

speed of CME front ~ 2000 km/s
filament behind ~ 1000 km/s


~400 km/s
~800 km/s
X-ray spectrum

14 MK, low EM (1e46 cm\(^{-3}\))
\[\Rightarrow\] density \(~10^8\) cm\(^{-3}\)

relatively hard/flat spectrum
\((\gamma\approx3.3)\)
extending down to \(~10\) keV

Number of non-thermal electrons are 10% of number of thermal electrons.
FOSXI (Focusing Optics Solar X-ray Imager) NASA Low Cost Access to Space program, PI Krucker

- ~100 times RHESSI sensitivity at 10 keV
- 12” FWHM resolution
- ~5 - 20 keV
- Si strip detectors (NeXT mission, Takahashi san)
  launch: 2010, ~7 minute flight

Science:
HXR emission from quiet corona (search for non-thermal emission from nanoflares)
GRIPS (Gamma-Ray Imaging Polarimeter for Solar Flares) balloon payload  **R. Lin, PI**

- Energy range: 20 keV-10 MeV
- Energy Res.: ~2-5 keV FWHM
- Angular Res.: ~10 arcsec
- Field of View: ~1 degree
- Polarization: ~3% in large flare

**Multi-pitch Rotating Modulator**

**3D position-sensitive germanium detectors in active shield**

**Ultra-long duration Balloon**
NASA Solar Probe Plus
ESA Solar Orbiter
NASA Solar Sentinels

Figure 4-1. Baseline Solar Probe+ trajectory.
Solar Oblateness
(Fivian, Hudson et al 2008)
Solar Oblateness
(Fivian, Hudson et al 2008)
Temperature $kT$

Magnetic Reconnection at a Magnetar (?)
(Hurley, et al., *Nature* 2005; Boggs et al., 2007)

*RHESSI*

$> 20 \text{ keV X-rays}$

Time in seconds
RHESSI TGFs: Lightcurves

Durations from 200 us to 3.5 ms; consistent with BATSE, shorter than most TLEs.