From X-ray observations of solar flare energetic electrons, to new models of particle acceleration and transport

Eduard Kontar

Department of Physics and Astronomy University of Glasgow, UK

4 November, 2009
What is RHESSI?

**Ramaty High Energy Solar Spectroscopic Imager**

is a NASA-led mission launched in **February 2002**

**RHESSI** is designed to investigate particle acceleration and energy release in solar flares through imaging and spectroscopy of hard X-ray and gamma-rays in the range from 3 keV up to 17 MeV (Lin et al 2002).
**Spectroscopy:** 9 Ge detectors with energy resolution around 1 keV;

**Imaging:** rotating modulating collimators allowing angular resolution down to 2.3 arcsec;

**Imaging spectroscopy:** spectral information in various locations

Incoming X-ray flux is modulated by a pair of grids – modulated lightcurves are used later to recover spatial information
RHESSI detectors look at the source through a pair of grids called **Rotating Modulating Collimator** (RMC)

Spacecraft spins about once every \( \sim 4 \) sec => *artificial modulation of incoming X-ray flux*
RHESSI imaging

---

RHESSI has 9 RMCs for 9 detectors

Slats/Slits spacing growing with detector (RMC) number

⇒ angular resolution from ~2.3” (RMC #1) to 180” (RMC #9)
RHESSI: ideal modulated lightcurves

Modulation profiles for various ideal sources for a grid of pitch $P$ with equal slits and slats

**Point source**

- **Half flux from the point source** => note half amplitude
- **45 degrees angle** => note change of phase

**Source further from the axis** => note change of modulation frequency

**Source size=\(P/2\)** => note change of the amplitude

**Source size=\(P\)** => note change of modulation depth (no modulation for source size $>> P$)

**Modulation encodes spatial source information:**

- Phase of the modulation => position angle
- Distance from the centre => modulation frequency
- Amplitude => source size
Fourier, Joseph, Baron
(From Britannica.com)

Stacking
(sum one roll bin over a few periods in)

RHESSI Modulation profile over three periods from (Schmahl and Hurford)
(http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&amp;article_id=39)

Each period is split into roll bins (here it is 16)

Stacking increasing signal-to-noise ratio and helps to calculate mean amplitude and phase

=> X-ray Visibilities!
X-ray Visibilities are two dimensional spatial Fourier components of X-ray source

\[ V(u, v; q) dq = \int_{x,y} \int_{c=q}^{\infty} D(q, c) I(x, y; c) e^{2\pi i (ux + vy)} dx dy \]

Note 9 circles (nine RMCs) in U,V (spatial frequencies) plane

Prato et al, 2008
Standard fare geometry

Soft X-ray emission up to ~10 - 20 keV

RHESSI spectrum

‘Standard’ flare model picture in 2D (Shibata, 1996)
X-ray emission from limb flares

Limb flare event 6 January 2004

Coronal Source

Footpoints

Spectrum 06:22:20 to 06:23:00

19MK, $2 \times 10^{48}$ cm$^{-3}$

$\delta_1 (>19$ keV$) = 3.2$

$\delta_2 (>201$ keV$) = 3.9$

Ellipse S

Circle N
1) What is the energy distribution, $F(E)$?

2) What is the angular distribution, $F(E, \Omega)$?

3) What is spatial distribution, $F(E, r)$?

From Krucker et al, 2007
X-rays and flare accelerated electrons

Resolution is $> 2.3''$

However, we can accurately measure moments of distribution:
1st moment – position
2nd moment - size

From Krucker et al, 2007
First measurements using fit to the light curves

Aschwanden et al, 2002

Higher energy sources appear lower in the chromosphere (consistent with simple collisional transport) => downward electron beaming

=> Max position with 1” accuracy
Electron transport: theory

Indeed, higher energy sources appear lower in the chromosphere (consistent with simple collisional transport) Aschwanden et al, 2002.

If we can we measure not only the positions but the sizes of X-ray sources we can learn about the transport of the electrons in the chromosphere.

If we assume collisional transport:

\[ F(E, z) = F_{IN} E \left( \sqrt{E^2 + 2KN(z)} \right)^{-\delta-1}, \]

X-ray emission at various energies should appear at different heights (Brown et al, 2002):

\[ I(\epsilon, z) = \frac{n(z)}{4\pi R^2} \int_{\epsilon}^{\infty} F(E, z) \sigma(\epsilon, E) dE \]

Indeed, higher energy sources appear lower in the chromosphere (consistent with simple collisional transport) Aschwanden et al, 2002.

If we can we measure not only the positions but the sizes of X-ray sources we can learn about the transport of the electrons in the chromosphere.
X-ray flux at different energies: theory

\[ I(\epsilon, z) = \frac{n(z)}{4\pi R^2} \int_{\epsilon}^{\infty} F(E, z)\sigma(\epsilon, E)\,dE \]

Corona

Photosphere

Corona

FWHM Source size

Normalized photon flux vs. Height [arcsec]
Hard X-ray images
Energy dependent positions

\[ n(h = r - r_0) = n_0 \exp \left( \frac{-(r - r_0)}{h_0} \right), \]

Fixed at photospheric density
Chromospheric field structure measurements

- 20-30 keV
- 70-150 keV
The simple thick target case is inaccurate

Vertical size of the footpoint, expected from collisional transport

Vertical size of the footpoint measured in 6th January event
Possible explanations

- Non-uniform magnetic field

- Strongly inhomogeneous chromosphere

- Strong pitch angle scattering (simple collisions do not work)
Non-uniform magnetic field

Constant pitch angle in the simple thick target

\[ F(E, N) = F_{\text{norm}} E \sqrt{E^2 + 2KN/\mu_0}^{(-\delta-1)} \]

- \( \mu_0 = 1 \)
- 0.9
- 0.7
- 0.5

Full semi minor axis (2b), [arcsec]

Energy [keV]
If we assume that electrons propagate along the different paths with different density profiles we can increase the vertical size of X-ray footpoint.

Vertical size of the footpoint, expected from collisional transport
Electron anisotropy: individual events

20-Aug-2002, 08:25 UT

Albedo mirror suggest close to isotropic distribution (e.g. Kontar & Brown, 2006) => The angular distribution found is inconsistent with downward beamed distributions

Collisional scattering and return current effects cannot explain the isotropy of electron distribution

=> The angular distribution found is inconsistent with downward beamed distributions
RHESSI X-ray imaging allows to infer the shape and the source positions with sub-arcsecond precision.

The characteristic **vertical and horizontal sizes of X-ray sources at various energies**.

The **size of footpoints decrease with energy** suggesting expansion of the magnetic flux tube with height and the presence of strong horizontal fields at ~900km.

The vertical variations of the magnetic field can be measured at ~0.2” scale although, but requires reference height.

The electron transport can be collisional but **strong pitch angle scattering or multiple density profiles** within the loop is needed.