RHESSI investigation of HXR coronal sources during decay phase of solar flares: I. observations

T. Mrozek, Z. Kołtun, S. Kołomański, U. Bąk-Stęślicka
Astronomical Institute
University of Wrocław
 definitions

**Long Duration Events (LDE)** – large structures, slowly evolving during decay phase; last up to several dozen hours; high temperatures (Skylab, Yohkoh observations) can be explain only if the energy is continuously released during decay phase.

**Loop top sources (LTS, LTK)** – regions of emission, located close to the top of flaring loop; except the impulsive phase their emission is dominant; internal structure is unknown.
why LDE?

- Existence of LDE is a great challenge for flare models (long durations, hours of energy release)
- Present models of a solar flare show that LTS should be located very close to the energy release site
results (Yohkoh)

02.11.1992, X9.0
Harra-Murnion et al. (1998)

- over 21h of decay in SXR

-HXR emission observed 3 hours after the maximum (14-23 keV)

-source of HXR emission located close, above the source of SXR emission

-observed HXR source is large: 20-45”

-the LTS is larger and observed higher in the corona for consecutive time intervals
27.04.1998, X1.0
Kołomański (2007)

- over 20h of decay in SXR

-HXR emission observed 50 min. after the maximum (14-23 keV)

-source of HXR emission located close above the source of SXR emission

-unknown nature of HXR source (unsufficient spectral resolution)
-12h of decay in SXR range
- emission sources of energy 3-6keV and 6-12 keV observed 11 h after maximum
-altitude of the source is rising with time
-source is large: 20’’
why RHESSI?

Pros:
- spatial resolution
- dynamical range
- sensitivity
- spectral resolution

Cons:
- pile-up
- attenuators
- orbital background (SAA, radiation belts)
## High diversity: location, class, duration

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum</th>
<th>Duration [hours] (GOES)</th>
<th>GOES Class</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Oct 2002</td>
<td>17:47</td>
<td>12</td>
<td>M1.5</td>
<td>N36W09</td>
</tr>
<tr>
<td>25 Aug 2003</td>
<td>02:59</td>
<td>7</td>
<td>C3.6</td>
<td>S11E41</td>
</tr>
<tr>
<td>11 Nov 2003</td>
<td>13:51</td>
<td>15</td>
<td>M1.6</td>
<td>N0E89</td>
</tr>
<tr>
<td>5 Jan 2004</td>
<td>03:45</td>
<td>34</td>
<td>M6.9</td>
<td>S05E57</td>
</tr>
<tr>
<td>20 Jan 2005</td>
<td>07:01</td>
<td>48</td>
<td>X7.1</td>
<td>N18W74</td>
</tr>
<tr>
<td>30 Jul 2005</td>
<td>06:36</td>
<td>11</td>
<td>X1.3</td>
<td>N10E59</td>
</tr>
<tr>
<td>22 Aug 2005</td>
<td>01:34</td>
<td>11</td>
<td>M2.7</td>
<td>S10W52</td>
</tr>
<tr>
<td>29 Nov 2005</td>
<td>17:09</td>
<td>8.5</td>
<td>C4.0</td>
<td>S14W45</td>
</tr>
<tr>
<td>25 Jan 2007</td>
<td>07:15</td>
<td>17</td>
<td>C6.3</td>
<td>S07E90</td>
</tr>
</tbody>
</table>
For a group of events we reconstructed images with 1 keV energy resolution

Images were reconstructed as far as was possible with this energy resolution

Image spectroscopy for observed sources - temperature and emission measure

Estimation of other parameters like altitude, size

The problem: sources are very weak
**RHESSI and weak sources**

- 9 pairs of grids of different slits size
- 9 germanium detectors measuring energy and time for each photon
- Rotation of a satellite, ~15 times per minute

---

<table>
<thead>
<tr>
<th>pairs of rotating grids cause changes in transmission function</th>
<th>thus, the detector measures only changes of intensity</th>
<th>changes of intensity + time = modulation pattern</th>
<th>intensity + position angle of grid for different times = image</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotation of a grid</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### RHESSI and weak sources

#### Ideal RMC Profiles of Gaussian Sources

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Point source, unit flux</td>
<td>Unit flux, FWHM=0, (R,φ)=(8·P,0) (P=Pitch=68&quot;)</td>
</tr>
<tr>
<td>2. Point source, half-unit flux</td>
<td>Half-unit flux, FWHM=0, (R,φ)=(8·P,0)</td>
</tr>
<tr>
<td>3. Point source, position change (angle)</td>
<td>Unit flux, FWHM=0, (R,φ)=(8·P,π/4)</td>
</tr>
<tr>
<td>4. Point source, position change (radial)</td>
<td>Unit flux, FWHM=0, (R,φ)=(8·P,0)</td>
</tr>
<tr>
<td>5. Point source, position change (radial)</td>
<td>Unit flux, FWHM=P/2, (R,φ)=(8·P,0)</td>
</tr>
<tr>
<td>6. Point source, position change (radial)</td>
<td>Unit flux, FWHM=P, (R,φ)=(8·P,0)</td>
</tr>
<tr>
<td>7. Unknown source distribution</td>
<td>Unknown source distribution</td>
</tr>
</tbody>
</table>

- **Point source, unit flux**: The source is a point source with unit flux.
- **Point source, half-unit flux**: The source is a point source with half-unit flux.
- **Point source, position change (angle)**: The source has a position change with respect to angle.
- **Point source, position change (radial)**: The source has a position change with respect to radial position.
- **Size of the source = pitch/2**: The size of the source is equal to the pitch divided by 2.
- **Size of the source = pitch**: The size of the source is equal to the pitch.
- **Source too large for given pitch will not produce a modulation**: If the source is too large for the given pitch, it will not produce a modulation.

---

**Note:**

- **Pitch**: The pitch is the distance between the points in the sequence.
- **FWHM**: Full Width at Half Maximum.
For image reconstruction we took only grids which show reliable sources.

Such flexible-grid method greatly improves convergence of the reconstruction.

Similar method is used in the ForwardFitting method, but it estimates shapes with arbitrary, simple figures – for single source it is the best method for estimating the size (we used it to verify PIXON results).
**main problem: size**

- If size, then from FWHM of grid we have lower boundary of size estimation.

Low signal is not a problem if we take longer integration times.
No attenuators. The source is weaker, but measured size is lower – size is well controlled by choosing different grids.

Attenuator change (A1-A0) causes drastic change in measured size (finer grid show modulation again). For A1 state the dominant is weak signal.
**image reconstruction: parameters**

**PIXON parameters:**
- background model
- phase stacker (for long integration times)
- uniform weighting

Size – area within a contour of 50% of brightest pixel. Eventually compared to Vis Ffit.
an example: 21 Aug 2005

date: 21.08.2005
AR: 10798
location: S10 W54
class: M2.6
start: ~0:40 UT
max.: 1:33 UT
decay: ~10.5 h
an example: 21 Aug 2005

**Image reconstruction**
- grids from 5th to 9th (except 7th)
- method: PIXON
- time intervals: 1-8 min
- energy resolution: 1 keV
an example: 21 Aug 2005

03:24 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)

LTS1
LTS2
an example: 21 Aug 2005

04:22 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)

[Diagram of SOHO EIT 195 Å on 22 Aug 2005 04:24:10.559 UT with LTS1 and LTS2 labeled]

[Graph of HESSI Observing Summary Count Rates, Corrected with Det 1,3,4,5,6,9 6-12 keV and 7000-20000 keV, Start Time (21-Aug-05 23:00:00)]
an example: 21 Aug 2005

04:46 UT
EIT 195 Å
RHESSI (6-7 keV, contours 30%, 50%, 70%, 90%)

LTS1, LTS2
an example: 21 Aug 2005

05:50 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)
an example: 21 Aug 2005

06:36 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)

LTS2
LTS3
an example: 21 Aug 2005

07:29 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)
an example: 21 Aug 2005

08:08 UT
EIT 195 Å
RHESSI (6-7 keV, contours 10%, 30%, 50%, 70%, 90%)
an example: 21 Aug 2005

goals:
- nature of a source
- geometry
- physical parameters
- energy balance

fitted with thermal+lines model
an example: 21 Aug 2005

**LTS1**: physical and geometrical parameters

<table>
<thead>
<tr>
<th></th>
<th>03:24</th>
<th>04:22</th>
<th>04:46</th>
<th>05:50</th>
</tr>
</thead>
<tbody>
<tr>
<td>h [Mm]</td>
<td>36.4</td>
<td>44.4</td>
<td>47.5</td>
<td>53.3</td>
</tr>
<tr>
<td>T [MK]</td>
<td>12.3</td>
<td>11.1</td>
<td>10.2</td>
<td>9.9</td>
</tr>
<tr>
<td>EM ([10^{47} \text{ cm}^{-3}])</td>
<td>3.8</td>
<td>1.6</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>r [Mm]</td>
<td>8.8</td>
<td>12.0</td>
<td>11.9</td>
<td>8.7</td>
</tr>
<tr>
<td>N ([10^9 \text{ cm}^{-3}])</td>
<td>7.2</td>
<td>3.0</td>
<td>2.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**LTS2**: physical and geometrical parameters

<table>
<thead>
<tr>
<th></th>
<th>03:24</th>
<th>04:22</th>
<th>04:46</th>
<th>05:50</th>
</tr>
</thead>
<tbody>
<tr>
<td>h [Mm]</td>
<td>59.5</td>
<td>79.4</td>
<td>73.8</td>
<td>77.0</td>
</tr>
<tr>
<td>T [MK]</td>
<td>12.3</td>
<td>11.2</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>EM ([10^{47} \text{ cm}^{-3}])</td>
<td>3.5</td>
<td>1.8</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>r [Mm]</td>
<td>4.7</td>
<td>6.4</td>
<td>8.8</td>
<td>6.8</td>
</tr>
<tr>
<td>N ([10^9 \text{ cm}^{-3}])</td>
<td>17.9</td>
<td>8.0</td>
<td>5.0</td>
<td>3.9</td>
</tr>
</tbody>
</table>
an example: 21 Aug 2005

**LTS3**: physical and geometrical parameters

<table>
<thead>
<tr>
<th></th>
<th>05:50</th>
<th>06:36</th>
<th>07:29</th>
<th>08:08</th>
</tr>
</thead>
<tbody>
<tr>
<td>h [Mm]</td>
<td>82.0</td>
<td>76.2</td>
<td>81.2</td>
<td>81.5</td>
</tr>
<tr>
<td>T [MK]</td>
<td>12.4</td>
<td>11.1</td>
<td>9.2</td>
<td>9.9</td>
</tr>
<tr>
<td>EM [$10^{47}$ cm$^{-3}$]</td>
<td>0.23</td>
<td>0.82</td>
<td>0.71</td>
<td>0.85</td>
</tr>
<tr>
<td>r [Mm]</td>
<td>9.8</td>
<td>25.3</td>
<td>28.0</td>
<td>31.1</td>
</tr>
<tr>
<td>N [$10^9$ cm$^{-3}$]</td>
<td>1.5</td>
<td>0.69</td>
<td>0.55</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Very large size for late phase. Probably overestimated.
## Results: Decay Times

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum</th>
<th>Duration [hours] (GOES)</th>
<th>Duration (RHESSI)</th>
<th>GOES Class</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Oct 2002</td>
<td>17:47</td>
<td>12</td>
<td>14</td>
<td>M1.5</td>
<td>N36W09</td>
</tr>
<tr>
<td>25 Aug 2003</td>
<td>02:59</td>
<td>7</td>
<td>7.5</td>
<td>C3.6</td>
<td>S11E41</td>
</tr>
<tr>
<td>11 Nov 2003</td>
<td>13:51</td>
<td>15</td>
<td>13.5</td>
<td>M1.6</td>
<td>N0E89</td>
</tr>
<tr>
<td>5 Jan 2004</td>
<td>03:45</td>
<td>34</td>
<td>26+</td>
<td>M6.9</td>
<td>S05E57</td>
</tr>
<tr>
<td>20 Jan 2005</td>
<td>07:01</td>
<td>48</td>
<td>31+</td>
<td>X7.1</td>
<td>N18W74</td>
</tr>
<tr>
<td>30 Jul 2005</td>
<td>06:36</td>
<td>11</td>
<td>10</td>
<td>X1.3</td>
<td>N10E59</td>
</tr>
<tr>
<td>22 Aug 2005</td>
<td>01:34</td>
<td>11</td>
<td>10.5</td>
<td>M2.7</td>
<td>S10W52</td>
</tr>
<tr>
<td>29 Nov 2005</td>
<td>17:09</td>
<td>8.5</td>
<td>6.5</td>
<td>C4.0</td>
<td>S14W45</td>
</tr>
<tr>
<td>25 Jan 2007</td>
<td>07:15</td>
<td>17</td>
<td>13</td>
<td>C6.3</td>
<td>S07E90</td>
</tr>
</tbody>
</table>
temperature decay

\[ Ae^{-\frac{t}{\tau}} + b \]

\[
\begin{array}{|c|c|}
\hline
\text{Date} & \tau \text{ [hours]} \\
\hline
25 Oct 2002 & 2.7 \\
25 Aug 2003 & 2.5 \\
11 Nov 2003 & 1.2 \\
5 Jan 2004 & 2.1 \\
20 Jan 2005 & 1.9 \\
30 Jul 2005 & 3.6 \\
22 Aug 2005 & 1.7 \\
29 Nov 2005 & 0.4 \\
25 Jan 2007 & 0.5 \\
\hline
\end{array}
\]

25 Oct 2002

\( \tau \)-characteristic time

for typical flare (not LDE) < 10 min.
## Results

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration (RHESSI)</th>
<th>T [MK]</th>
<th>EM [$10^{47}$]</th>
<th>$\tau$ [hours]</th>
<th>radius [Mm]</th>
<th>altitude [Mm]</th>
<th>non-th</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Oct 2002</td>
<td>14 3</td>
<td>14.6-6.7</td>
<td>7.9-1.0</td>
<td>2.7</td>
<td>30 – 47</td>
<td>68 – 271</td>
<td>+</td>
</tr>
<tr>
<td>25 Aug 2003</td>
<td>7.5 1</td>
<td>12.3-6.7</td>
<td>6.0-0.6</td>
<td>2.5</td>
<td>5 – 40</td>
<td>54 – 86</td>
<td>+</td>
</tr>
<tr>
<td>11 Nov 2003</td>
<td>13.5 3.5</td>
<td>25.8-7.8</td>
<td>1.5-0.3</td>
<td>1.2</td>
<td>10 – 48</td>
<td>41 – 103</td>
<td>+</td>
</tr>
<tr>
<td>5 Jan 2004</td>
<td>26+ 9</td>
<td>26.9-9.0</td>
<td>45.0-2.9</td>
<td>2.1</td>
<td>14 – 42</td>
<td>64 – 181</td>
<td>+</td>
</tr>
<tr>
<td>20 Jan 2005</td>
<td>31+ 19</td>
<td>19.0-7.8</td>
<td>71.0-3.1</td>
<td>1.9</td>
<td>17 – 32</td>
<td>13 – 74</td>
<td>+</td>
</tr>
<tr>
<td>30 Jul 2005</td>
<td>10 6</td>
<td>11.6-7.1</td>
<td>3.2-1.9</td>
<td>3.6</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>22 Aug 2005</td>
<td>10.5 3.5</td>
<td>12.4-9.9</td>
<td>3.8-0.2</td>
<td>1.7</td>
<td>5 – 31</td>
<td>36 – 82</td>
<td>-</td>
</tr>
<tr>
<td>29 Nov 2005</td>
<td>6.5 1</td>
<td>10.1-7.8</td>
<td>29.4-0.9</td>
<td>0.4</td>
<td>12 – 43</td>
<td>29 – 48</td>
<td>-</td>
</tr>
<tr>
<td>25 Jan 2007</td>
<td>13 1.5</td>
<td>13.3-9.9</td>
<td>13.5-0.2</td>
<td>0.5</td>
<td>9 – 18</td>
<td>31 – 73</td>
<td>-</td>
</tr>
</tbody>
</table>

Ranges present first and last of obtained values

Non-thermal component is very weak and steep (gamma between values of 8.5 and 10.0) and is observed within the same region
LDEs are well observed by RHESSI. The analysis is complicated due to attenuators, radiation belts, SAA, but not impossible.

The size of X-ray sources is most uncertain parameter. However, there is no doubt that sources are large structures and grow with time.

Long-lasting X-ray sources are located above structures observed in the EUV range.

Usually the sources are dominated by thermal emission. Non-thermal component is weak and very steep.

Obtained observational values give strong and demanding constraints for models of a solar flare.

The observed features demand the existence of the energy release process lasting several hours.