Spectroscopic Diagnostics of Chromospheric Evaporation Using IRIS and Hinode/EIS

Ying Li (李 瑛)
M. D. Ding & J. Qiu

School of Astronomy and Space Science
Nanjing University

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Background (evaporation)

Instruments & Spectra
(EIS/EUV, IRIS/UV)

Observations & Results
(2 flare events)

Summary & Discussion
Background (1/3)

Chromospheric evaporation

— **upward mass motions** in a flaring process due to thermal pressure
  \((\text{Feldman et al. 1980; Antonucci 1982; ...})\)

— also **downward motions** (condensation)
  \((\text{Canfield et al. 1990; Fisher et al. 1985; ...})\)

\[(\text{Dennis & Schwartz 1989})\]
Two types of chromospheric evaporation according to the observed Doppler velocity

— **explosive evaporation**: blueshifts & redshifts (e.g., Milligan et al. 2006a)

— **gentle evaporation**: only blueshifts detected (e.g., Milligan et al. 2006b)

**conversion** from explosive to gentle chromospheric evaporation

**threshold** of electron flux

$\sim 10^{10} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (Fisher et al. 1985)
Some problems (discrepancies between observations and models) before/in EIS (pre-IRIS) era

--- dominant stationary component in high T (≥10 MK) lines

(Ding et al. 1996; Milligan & Dennis 2009)

explanations:

1. moving perpendicular to the line-of-sight (Faliewicz 2009)
2. from the top of the flare loop (Doschek & Warren 2005)
3. multi-strand flare loop model (Brosius 2013)
4. instrument not sensitive (Doschek & Warren 2005)

solved in the IRIS era?

--- high temperature downflows

reversal temperature from blueshift to redshift

≤ 1 MK (Kamio et al. 2005)
2 MK (Milligan 2008)
2.5-5 MK (Li & Ding 2011)

rather high energy deposition site?? (further investigated in numerical modeling??)

(Li & Ding 2011)
Instruments

Hinode/EIS (since 2006)
Extreme-ultraviolet Imaging Spectrometer

wavelength: 170–210 Å & 250–290 Å (EUV)
spectral line: log T = 4.7–7.2 K (coronal & flaring lines)
resolution: ~1”, ~sec to min, 0.022 Å/pixel
mode: raster scan & sit-and-stare

IRIS (since 2013)
Interface Region Imaging Spectrograph

wavelength: ~1400 Å & ~2800 Å (FUV/NUV)
spectral line: log T = 3.7–7.0 K (chromospheric lines)
resolution: ~0.167”, ~sec to min, 0.025 Å/pixel
mode: raster scan & sit-and-stare (SJI)
# Spectral Lines

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength (Å)</th>
<th>log $T_{max}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He II</td>
<td>256.32</td>
<td>4.7</td>
</tr>
<tr>
<td>Fe VIII</td>
<td>185.21</td>
<td>5.8</td>
</tr>
<tr>
<td>Fe X</td>
<td>184.54</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Fe XII</strong></td>
<td>195.12</td>
<td>6.1</td>
</tr>
<tr>
<td>Fe XIII</td>
<td>202.04</td>
<td>6.2</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>274.20</td>
<td>6.3</td>
</tr>
<tr>
<td>Fe XV</td>
<td>284.16</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>Fe XVI</strong></td>
<td>262.98</td>
<td>6.4</td>
</tr>
<tr>
<td>Ca XVII</td>
<td>192.82</td>
<td>6.7</td>
</tr>
<tr>
<td><strong>Fe XXIII</strong></td>
<td>263.76</td>
<td>7.1</td>
</tr>
<tr>
<td>Fe XXIV</td>
<td>192.03</td>
<td>7.2</td>
</tr>
</tbody>
</table>

### from EIS
(for the 1st flare event)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Wavelength (Å)</th>
<th>log $T_{max}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg II h</td>
<td>2803.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Mg II k</td>
<td>2796.4</td>
<td>4.0</td>
</tr>
<tr>
<td>C II</td>
<td>1334.5</td>
<td>4.3</td>
</tr>
<tr>
<td>C II</td>
<td>1335.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Si IV</td>
<td>1402.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Fe XXI</td>
<td>1354.1</td>
<td>7.0</td>
</tr>
</tbody>
</table>

### from IRIS
(+EIS for the 2nd flare event)
the 1st flare event in the EIS (pre-IRIS) era

Observations (1/2) — a C4.2 flare on 2007-01-16

three points at the flare ribbons with different magnetic polarities
Observations (2/2) — a C4.2 flare on 2007-01-16
Results (1/2) — point 1 at the positive polarity

**impulsive phase**

<table>
<thead>
<tr>
<th>Ion</th>
<th>$V_d$ (km s$^{-1}$)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>He II</td>
<td>+5</td>
<td></td>
</tr>
<tr>
<td>Fe VIII</td>
<td>-28</td>
<td></td>
</tr>
<tr>
<td>Fe X</td>
<td>-36</td>
<td></td>
</tr>
<tr>
<td>Fe XII</td>
<td>-37</td>
<td></td>
</tr>
<tr>
<td>Fe XIII</td>
<td>-68</td>
<td>1.72</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>-80</td>
<td>2.53</td>
</tr>
<tr>
<td>Fe XV</td>
<td>-89</td>
<td>2.64</td>
</tr>
<tr>
<td>Fe XVI</td>
<td>-116</td>
<td>9.95</td>
</tr>
</tbody>
</table>

**preflare phase**

**decay phase**
Results (2/2) — points 2&3 at the negative polarity

- **Point 2**
  - Impulsive phase
  - Reversal T: 2.5-5.0 MK
  - Redshift

- **Point 3**
  - Impulsive phase
  - Reversal T: ~1.5 MK
  - Blueshift
Summary — the 1st flare

(1) The line profiles at one ribbon location with positive polarity are **basically blueshifted**. — could be a gentle evaporation.
In particular, the blueshifted components dominate over the stationary ones in relatively hot lines. — evaporation region not well resolved?

(2) **Both blueshifts and redshifts** are observed at negative-polarity ribbons. — explosive evaporation;
Particularly, redshifts are visible in the lines of relatively high temperatures (up to 2.5–5.0 MK). — rather high energy deposition site? (or warm rain?)

(3) Flaring ribbons with different magnetic polarities show **different types of chromospheric evaporation**.
— The heating mechanisms and atmospheric conditions may vary at different locations.
the 2nd flare event
in the IRIS era (with EIS)

Observations (1/2) — an X1.0 flare on 2014-03-29
Observations (2/2) — an X1.0 flare on 2014-03-29
Results (1/4) — profiles of hot (\(\geq 10\) MK) lines (IRIS vs. EIS)

at the flare ribbons

IRIS Fe XXI
quite symmetric & entirely blueshifted

EIS Fe XXIII
blueshifted + stationary components

using multiple Gaussian fitting

with blending

no blending
Results (2/4) — spatio-temporal variation (IRIS vs. EIS)

IRIS Fe XXI & Si IV

A pair of blueshift/redshift fronts cospatial and coincident with separating ribbons

EIS Fe XXIII & He II

Similar trend with a lower resolution
Results (3/4) —** temperature dependence (IRIS + EIS)**

**IRIS & EIS multi-T lines**

*a conversion from gentle to explosive evaporation*

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**Doppler velocity (km s⁻¹)**

- 

**Temperature (K)**

- Less than or close to 1 MK

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**Location 1 at 17:44:36**

**Location 2 at 17:46:50**

**Location 3 at 17:46:50**

**Location 4 at 17:51:18**

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**redshift**

**blueshift**
Results (4/4) — profiles of cool lines (from IRIS)

IRIS C II & Mg II
singly peaked & red asymmetric at the flare ribbon
Summary — the 2nd flare

Using the high-resolution observations from IRIS:

(1) We find that **the hot Fe XXI line (~10 MK) is entirely blueshifted** at the flare ribbon, which **well matches the prediction of evaporation model**.

(2) **The blueshifts are cospatial and coincident with separating ribbons**, suggesting that reconnection/evaporation proceeds well into the decay phase of the flare.

(3) Different ribbon locations show **different types of evaporation**, and there is **a conversion from gentle to explosive evaporation** as flare evolves.
Summary for the two flare events

cromospheric evaporation & condensation
— dynamics at the flare ribbons

<table>
<thead>
<tr>
<th>event</th>
<th>GOES class</th>
<th>evaporation type</th>
<th>blueshifts (hot lines)</th>
<th>redshifts (cool lines)</th>
<th>flow reversal temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st flare in EIS era</td>
<td>C4.2</td>
<td>gentle &amp; explosive (x)</td>
<td>dominant components (e.g., Fe XXIII)</td>
<td>entirely redshifted (e.g., He II)</td>
<td>2.5–5.0 or ~1 MK</td>
</tr>
<tr>
<td>2nd flare in IRIS era</td>
<td>X1.0</td>
<td>gentle &amp; explosive (x, t)</td>
<td><strong>entirely blueshifted</strong> (Fe XXI)</td>
<td>red asymmetry (C II &amp; Mg II)</td>
<td>~1 MK</td>
</tr>
</tbody>
</table>

also reported by many other nice studies…

still going on?
**Perspectives in Diagnosing Chromospheric Evaporation**

(“pros and cons” of EIS & IRIS)

<table>
<thead>
<tr>
<th><strong>EIS</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>con:</strong> relatively low spatial resolution</td>
<td></td>
</tr>
<tr>
<td><strong>pro:</strong> multiple spectral lines covering a wide T range</td>
<td></td>
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<tr>
<td>—&gt; temperature dependence (energy deposition site)</td>
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</table>

<table>
<thead>
<tr>
<th><strong>IRIS</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>con:</strong> few hot spectral lines</td>
<td></td>
</tr>
<tr>
<td><strong>pro:</strong> multiple cool lines (formed in the chromosphere) in particular, high spatial and temporal resolution</td>
<td></td>
</tr>
<tr>
<td>—&gt; spatio-temporal variation &amp; chromospheric condensation</td>
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</tbody>
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**EIS + IRIS + modeling**

—> help study **flare dynamics** and further **flare heating** (function, mechanisms,...)
Thanks for your attention!