“Observations and Modeling of Chromospheric Lines during a Solar Flare”

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Outline

• **Observation of a solar flare** (Tei+ 18)
  • Chromospheric lines by IRIS and Hida/DST
  • Blue wing enhancement in Mg II hk lines
  • Cool upflow scenario

• **RHD and RT modeling solar flare atmosphere** (Ongoing work)
  • Flarix + MALI
  • Qualitatively cool upflow scenario is OK
Chromospheric Line Profile in Flares — Red Asymmetry

Many observations. Mostly in the impulsive phase. In Hα/β/γ, He D3, Ca II H/K, Mg II h/k/triplet. (Ichimoto & Kurokawa 84; Shoji+95; Wulser & Marti 89; Ding & Huang 95, Kerr+15; Graham & Cauzzi 15)

Interpreted to be caused by condensation downflow in the chromosphere.
Chromospheric Evaporation & Condensation

Fisher+85; Allred+05

Reconnection

Corona
$10^6$ K

Chromosphere
$10^4$ K

thermal conduction
accelerated electrons

evaporation upflow
condensation downflow

Red asymmetry in chrom. lines

Time

Intensities

Blue $\lambda$ [km/s] Red

10
6 K

10
7 K

10
4 K
Chromospheric Line Profile in Flares — Blue Asymmetry

Sometimes reported. Mostly in early phase of a flare. In Hα/β/γ, He D3, Ca II H, Mg II k. (Svestka 62; Canfield+ 90; Heinzel+ 94; Gan+ 93; Ding & Fang 96/97; Kuridze+15/16; Kerr+15)

A few interpretations (Canfield+ 90; Heinzel+ 94) but poorly understood.

Aim of our study:
We clarify both spatial & temporal evolution of red/blue asymmetry at footpoints of a flare using chromospheric lines.
C5.4 Class Flare on 10 Nov, 2014

Focus on this bright feature

IRIS Mg II k

Fixed slit
Spectra at Flare Footpoints

IRIS (fixed slit)
- 9.5 s cadence
- 0.17"/pix

Hida/DST (raster scan)
- every 10 s
- seeing ~2"

UT 23:59:02  T= 242 s

Si IV 1403A  C II 1335A  Mg II 2803A
Ca II K 3934A  Ca II 8542A  Hα 6563A
Measurements of Intensity, Velocity, & Widths

Original profiles are used for IRIS lines.

✓ Peak intensity
- Blue wing at 30% intensity $\equiv V_B$
- Red wing at 30% intensity $\equiv V_R$

$\rightarrow$ Doppler velocity $\equiv (V_R + V_B)/2$
Line width $\equiv (V_R - V_B)/2$

Subtracted profiles are used for DST lines.
Time-distance Maps of Intensity, Velocity, & Widths

IRIS

- Si IV 1403A
- C II 1335A
- Mg II 2803A

DST

- Ca II K 3934A
- Ca II 8542A
- Hα 6563A

**Flare footpoints moved northward.**

**Redshifts with broad widths.**

**Blueshifts only in Mg II h.**
**Evolution of Mg II h at a Location**

- **Small peak intensity**
  - Weak blue-wing enhancement (Blueshift)

- **Large peak intensity**
  - Large red-wing enhancement (Redshift)
The Mg II h Line Profile with Blueshifts

- Blueshift > 5 km/s
- Local max blueshift

Local max blueshift: -10 km/s  Duration: 30 s

Blue wing enhancement
Blue-side peak < Red-side peak
Scenario of Cool Upflow

An upflow of cool plasma is lifted up by expanding hot plasma owing to the deep penetration of high-energy electrons into the chromosphere.

Fig. 13.— Schematic diagram of the one-dimensional scenario of the chromospheric evaporation and condensation with cool upflow that we propose in this study.

Canfield+90

Implied in 1D HD simulation of flaring loops by thick-target heating (Nagai & Emslie 84; Allred+05; Kennedy+15; Rubio da Costa+15b)
Cloud Modeling of the Cool Upflow Scenario

\[ I(\Delta \lambda) = I_0(\Delta \lambda) e^{-\tau(\Delta \lambda)} + S \left[ 1 - e^{-\tau(\Delta \lambda)} \right] \]

\[ \tau(\Delta \lambda) = \tau_0 \exp \left[ -\left( \frac{\Delta \lambda - \Delta \lambda_{LOS}}{\Delta \lambda_D} \right)^2 \right] \]

\[ \Delta \lambda_D = \frac{\lambda_0}{c} \sqrt{\frac{2kBT}{m_{Mg}} + V_{turb}^2} \]

The observed line profile is successfully reproduced with:

\[ V_{LOS} = -40\text{km/s}, \quad V_{turb} = 40\text{km/s}, \quad \tau_0 = 0.5, \quad \text{and} \quad S/I_0(0) = 0.6 \]

**Attenuation** of the background intensity by cool upflow

→ **Blue-side peak < Red-side peak**

**Emission** of cool upflow → **Blue wing enhancement**
Why was No Blueshift Observed in Other Lines?

IRIS

<table>
<thead>
<tr>
<th>Line</th>
<th>Peak Intensity</th>
<th>Velocity [km/s]</th>
<th>Line Width [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV 1403Å</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C II 1335Å</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg II 2803Å</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DST

<table>
<thead>
<tr>
<th>Line</th>
<th>Peak Intensity</th>
<th>Velocity [km/s]</th>
<th>Line Width [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca II K 3934Å</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca II 8542Å</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hα 6563Å</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

t = 242s.

The lighter color shows the brighter value. Intensities that physical parameters cannot be derived from. We also show color bars for the velocity of 37 km s\(^{-1}\) and the panels to compare among different panels and each slope corresponds to the apparent...
Why was No Blueshift Observed in Other Lines?

- Si IV → forms at higher (TR) temperature. (De Pontieu+14)
- Ca II K, Ca II IR, and Hα → have smaller opacities than Mg II h. (Leenaarts+13)
- C II 1335 Å → has the similar opacity to Mg II h. (Rathore+15)
  - The blue peak is smaller than the red peak ← the same as the Mg II
  - But no blue wing enhancement ← possibly a small source function

Only Mg II h could catch the cool upflow.
Summary of Observations

• We investigated flare footpoints apparently moving along the IRIS slit in the C5.4 flare on Nov 10, 2014.

• **Blue wing enhancements preceded the strong emission and strong red wing enhancements in the Mg II h line.**

• The Mg II h line profile with blueshifts had a good agreement with the cloud modeling of the cool upflow scenario.

• It’s possible that only the Mg II h line catches the cool upflow among the investigated 6 lines (Si IV, C II, Mg II h, Ca II K, Ca II 8542A, Hα).

• **We propose that the chromospheric-temperature (cool) plasma was lifted up by the evaporated (hot) plasma owing to the penetration of non-thermal electrons into the deep chromosphere.**
Another Observation of Blue-wing Enhancement

Contours: intensity maxima

IRIS 1330A (LogT~4.3)
Another Observation of Blue-wing Enhancement

Huang+ 19

Contours: intensity maxima
Is Blue-wing Enhancement Rare?

Panos 18 “Identifying Typical Mg II Flare Spectra Using Machine Learning”

Profiles at the leading edge of fast-moving flare ribbons
Modeling of Flare Atmosphere using
*Flarix*: Non-LTE Radiation Hydrodynamic (RHD) Code

- Flarix (Varady+ 10; Heinzel+ 16; Kasparova+ 19)
- Agreement with RADYN (Kasparova+ 19)
- 1D atmosphere in a semi-circular loop
- Heating by non-thermal electron beams propagating from the apex in the corona to the lower atmosphere.

1D RHD equations

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s} (\rho v_s) = 0 \\
\frac{\partial (\rho v_s)}{\partial t} + \frac{\partial}{\partial s} (\rho v_s^2) = -\frac{\partial P}{\partial s} + \rho g_s
\]

\[
\frac{\partial E}{\partial t} + \frac{\partial}{\partial s} ((E + P)v_s) = \rho g_s v_s + H + Q - R - \frac{\partial}{\partial s} F_c
\]

- Flarix (Varady+ 10; Heinzel+ 16; Kasparova+ 19)
- Agreement with RADYN (Kasparova+ 19)
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- heating by non-thermal electron beams propagating from the apex in the corona to the lower atmosphere.

1D RHD equations

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s} (\rho v_s) = 0
\]

\[
\frac{\partial (\rho v_s)}{\partial t} + \frac{\partial}{\partial s} \left( \rho v_s^2 \right) = -\frac{\partial P}{\partial s} + \rho g_s
\]

\[
\frac{\partial E}{\partial t} + \frac{\partial}{\partial s} ( (E + P)v_s) = \rho g_s v_s + H + Q - \frac{\partial}{\partial s} F_c
\]

Gravity

- Heating to assure stability of the initial atmosphere
Result of Modeling (Flarix)

\[ E_c = 20 \text{ keV}, \delta = 3, \]
\[ F_{\text{max}} = 6 \times 10^9 \text{ erg/cm}^2/\text{s} \]
(increase till 10s then decrease towards 40s)
\[ \rightarrow F_{\text{total}} \sim 8 \times 10^{10} \text{ erg/cm}^2 \]
(in 20s)
\[ \rightarrow F_{\text{ave}} \sim 4 \times 10^9 \text{ erg/cm}^2/\text{s} \] (in 20s)
**Result of Modeling (Flarix)**

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Snapshot at Time = 10.0 sec

Increase of T and P by heating (at Z \sim 1.3 \text{ Mm})

Chromospheric plasma above the heated layer
Result of Modeling (*Flarix*)

\[ E_c = 20 \text{ keV}, \delta = 3, \]
\[ F_{\text{max}} = 6 \times 10^9 \text{ erg/cm}^2/\text{s} \]
(increase till 10s then decrease towards 40s)
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Snapshot at Time = 18.0 sec

Cool (\( \log_{10} T \sim 4.2 \) [K]),
dense (\( \log_{10} N \sim 13 \) [/cm\(^3\)]), and
upward moving (V \( \sim 10 \) [km/s]) plasma
Modeling of the Mg II h Line using *MALI*: Radiative Transfer Code (1D)

- 1D MALI: plane-parallel radiative transfer *(Heinzel+ 14)*
- Mg II lines are synthesized for each snapshot of the Flarix atmosphere.

- Mg II model: 5 levels + cont., 6 transitions
- Complete frequency re-distribution (CRD)
- Assume turbulent velocity
result of modeling (Flarix+MALI)

\[
I_v = \int_{z_0}^{z_1} S_v \tau_v e^{-\tau_v} \frac{\chi_v}{\tau_v} \, dz
\]
Result of Modeling *(Flarix+MALI)*

Cool ($\log_{10}T \sim 4.2$ [K]), dense ($\log_{10}N \sim 13$ [/cm$^3$]), and upward moving ($V \sim 10$ [km/s]) plasma.

The surface of the cool upflow contributes to the intensity around the line center and its blue-side.
Mg II h line

Result of Modeling (Flarix+MALI)

\[ S_v = \frac{\eta_v}{\chi_v} \]
\[ C_v = \eta_v \exp(-\tau_v) \]

\[ I = \](erg/s/cm^2/sr)

\[ -50 \]
\[ 0 \]
\[ +50 \]

Wavelength [km/s]

Cool (log_{10}T ~ 4.2 [K]), dense (log_{10}N ~ 13 [/cm^3]), and upward moving (V ~ 10 [km/s]) plasma

The surface of the cool upflow contributes to the intensity around the line center and its blue-side.

Blue wing enhancement, Blueshift of h3 dip
Blue peak < Red-peak
→ qualitatively similar to the observations

← Snapshot at Time = 18.0 sec
Quantitative comparison

One order difference in the peak intensities.
Less enhanced wing in the modeling.
A tiny blue wing enhancement (t ~ 5.3-6.4 s) contributed by additional emission due to the opacity increase related to an upward propagating cool upflow (~ $4 \times 10^4$ K) with a speed of ~ 36 km/s.

- Wing is less extended unless assuming large broadening.

\[ F_{\text{max}} = 5 \times 10^{11} \text{ erg/cm}^2/\text{s} \]

(increase in 20s and decrease in 20s)
Summary & Prospectives

- Blue asymmetry in the Mg II lines was observed at the foot points of a flare.
  - Cool dense upflow scenario?

- Modeling of the flare atmosphere and the Mg II h line (Flarix + MALI)
  - The scenario is qualitatively ok!

- What are needed to do:
  - Investigate more flare observations in the Mg II lines.
  - Get more quantitative agreement.
  - Synthesize the other lines.