Spectroscopic Inversions of the Ca II 8542 Å Line in a C-class Solar Flare

D. Kuridze, V. Henriques, M. Mathioudakis, J. Koza, T. Zaqarashvili, J. Rybak

The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 606862 (F-CHROMA)
Semi-empirical models

• Quit Sun (Gingerich et al. 1971; Vernazza et al. 1981; Fontenla et al. 1990, 1991, 1993, 2006, 2009; Rutten & Uitenbroek 2012; Ruiz Cobo & del Toro Iniesta 1992)

• Flaring photosphere and chromosphere Machado & Linsky (1975) Machado et al. (1980); Mauas 1990; Mauas et al. 1990; Mauas 1993; Gan & Mauas (1994) Falchi & Mauas (2002) Berlicki et al. (2005). Falchi & Mauas (2002))
Inversions

- Guess Atmosphere \([T(z), B(z), \rho(z)\ etc]\)
  - Simulate
  - Non-acceptable fit
  - Compare

- Synthetic Spectra
  - Observed Spectra
    - Acceptable fit

- Model atmosphere
C3.8 Flare (14/05/2016) Observed with SST/CRISP

- **Ca ii 8542 Å - 26 line positions**
- **Ranging from -1.2 Å to +1.2 with 0.1 Å steps, plus 1 position at -1.5 Å**
- **Acquisition time for Ca ii 8542 Å 7 seconds per scan**
Inversion of Ca II 8542 spectra with NICOLE

Inversion code - NICOLE (Socas-Navarro et al. 2015)

- 1D NLTE radiative transfer with a 5 levels + continuum Ca II atom
- Complete frequency redistribution
- Barklem et al. (1998) collisional broadening formalism
- Hydrostatic equilibrium
Inversion of Ca II 8542 spectra with NICOLE

Inversion code - NICOLE (Socas-Navarro et al. 2015)

- 1D NLTE radiative transfer with a 5 levels + continuum Ca II atom
- Complete frequency redistribution
- Barklem et al. (1998) collisional broadening formalism
- Hydrostatic equilibrium
- Initial guess model: FALC atmosphere

Figure 2. The top row shows the images at 11:38 UT (4 minutes after the flare peak) and the bottom row images at 11:45 UT. SST images of the flaring region in the Ca$^{+}$ line core are shown in the left panels. NICOLE outputs showing the temperature and the LOS velocity maps in the interval $\log \tau \in (-3.5, 5.5)$ are provided in the middle and right panels, respectively. Blue contours show the area analysed in this paper which has intensity levels greater than 30% of the intensity maximum. 'FL', 'FF', 'QS' mark the selected pixels at the flare loop, flare footpoint, and quiet Sun, respectively discussed in the text in more detail. The red and blue colors in the dopplerograms represent positive Doppler velocities (downflows) and negative Doppler velocities (upflows), respectively. The white dotted line indicates the location where vertical cut of the atmosphere is made for detailed analyses.

NICOLE includes a five bound level plus continuum Ca$^{+}$ model atom (Leenaarts et al. 2009) with complete frequency redistribution, which is applicable for lines such as Ca$^{+}$ (Uitenbroek 1989; Quintero Noda et al. 2016; Wedemeyer-Böhm & Carlsson 2011). The synthetic spectra were calculated for a wavelength grid of 113 datapoints in 0.025 Å steps, 4 times denser than the CRISP dataset. Stratification of the atmospheric parameters obtained by the inversions are given as a function of the logarithm of the optical depth-scale at 500 nm (hereafter log $\tau$). The response function of the Ca$^{+}$ line is expanded to Table 1.

| Physical parameter       | Cy 1     | Cy 2     | Cy 3     |
|--------------------------|----------|----------|----------|
| Temperature              | 4 nodes  | 7 nodes  | 7 nodes  |
| LOS Velocity             | 1 node   | 5 nodes  | 5 nodes  |
| Microturbulence          | 1 node   | 1 node   | 1 node   |
| Macroturbulence          | none     | none     | none     |
| Input atmosphere         | FAL-C    | model from Cy 1 | model from Cy 2 |
Inversion of Ca II 8542 spectra with NICOLE

Ca II 8542 – 1.2 Å
Ca II 8542 Å core
Ca II 8542 + 1.2 Å

Start Time (14–May–16 11:38:20)
Inversion output

Ca II 8542 Å core

Temperature [kK], log $\tau=-(3.5 - 5.5)$

LOS Velocity [km/s], log $\tau=-(3.5 - 5.5)$
Inversion output: Line profiles and temperature/velocity stratifications
Temporal evolution of the temperature stratification
Energy content

\[ e = \frac{1}{\gamma - 1} \frac{p}{\rho} \]
Energy content

\[ e = \frac{1}{\gamma - 1} \frac{p}{\rho} \]
Evolution of the ratio of internal energy
Evolution of the total energy

\[ E_{\text{tot}} [\text{erg}] \]

Start Time (14-May-16 11:38:20)
Summary

• A comparison of the temperature stratification in flaring and non-flaring areas reveals strong footpoint heating in the lower atmosphere.

• The temperature of the flaring footpoints between optical depths of $\log \tau \approx -2.5$ and $-3.5$ is $\sim 5 - 6.5$ kK, close to the flare peak, reducing gradually to $\sim 5$ kK.

• The temperature in the middle and upper chromosphere, between $\log \tau \approx -3.5$ and $-5.5$, is estimated to be $\sim 6.5 - 20$ kK, decreasing to pre-flare temperatures, $\sim 5 - 10$ kK, after approximately 15 minutes.

• The temperature stratification of the non-flaring areas is unchanged.

• The inverted velocity fields show that the flaring chromosphere is dominated by weak downflowing condensations at the Ca ii 8542 Å formation height.