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Diagnostics of thermal and non-thermal processes in solar flares using chromospheric lines

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Abstract. The non-thermal electrons accelerated during solar flares can produce enhanced and broadened chromospheric lines when they precipitate into the chromosphere. In this paper, we propose a method to diagnose the non-thermal processes using two chromospheric lines, Hα and Ca II 8542 Å lines. First, we perform non-LTE calculations of these two lines for various (thermal) model atmospheres and (non-thermal) electron beams. Since the two lines have different sensitivities to the non-thermal electrons, a set of line spectra can uniquely determine a model atmosphere and an electron beam. We then apply this method to a solar flare for which we have observed two-dimensional spectra of the two lines. In particular, we examine the temporal variation of thermal vs. non-thermal effects in flare bright kernels, as well as the spatial variation across flare ribbons. The results show clearly that the non-thermal effects appear most obviously at the flare maximum, and preferentially at the outer edges of flare ribbons. The results are consistent with flare theoretical models.

Keywords. line: profiles, Sun: atmosphere, Sun: flares

1. Introduction

It is believed that the high-energy electrons and the heat conduction are two of the main energy sources that can heat the lower atmosphere in solar flares. Recently, it becomes an interesting topic to quantify the non-thermal and thermal energies in flares (e.g., Saint-Hilaire & Benz 2005). Here, we propose a method based on analysis of multi-line spectra and show some preliminary results regarding the thermal and non-thermal effects in a flare.

2. The method

On the one hand, when the temperature and density of the flaring atmosphere get changed, the lines and continua that are formed there get enhanced. On the other hand, bombardment of the atmosphere by the electron beam results in non-thermal excitation and ionization of the ambient atoms. Therefore, the lines and continua, especially those formed in the chromosphere and above, can be significantly enhanced. For example, the Hα line in flares is often very strong and broad, which is thought as a signature of non-thermal electron beam heating (Fang *et al.* 1993). Since different lines have different sensitivities to thermal and non-thermal effects, we may use two or more lines to diagnose their relative importances.

Here, we use two typical lines, Hα and Ca II 8542 Å lines, to diagnose the thermal and non-thermal effects in flares. The former is more sensitive to non-thermal effects while the latter to thermal effects. We first do non-LTE calculations for atmospheric models

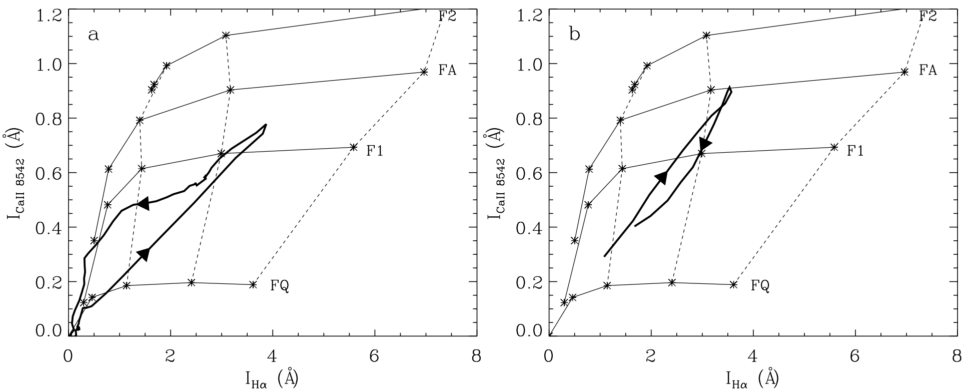

Figure 1. Ca II 8542 Å versus Hα line intensities calculated for different model atmospheres with different electron beams. The thick lines show (a) the temporal evolution of the flare kernel from observations and (b) the spatial variation across the flare ribbon from observations.

that are bombarded by electron beams. From calculations, we get the two lines in dependence of the atmospheric models and the electron beam strengths. For a quantitative comparison with observations, we use the wavelength-integrated intensities (normalized to the continuum) for the two lines. The advantage of doing so is to refrain from adopting a macro-turbulent velocity that may broaden the line profiles, while the disadvantage is to neglect the physical processes implied by the shapes of the profiles.

3. Results and Discussions

We apply the above method to a two-ribbon solar flare of 2001 October 19 (Li & Ding 2004). In particular, we check the time evolution of the flare kernel and the spatial variation across the flare ribbon. In Fig. 1, we plot the Ca II 8542 Å versus Hα intensities calculated for different model atmospheres, FQ (quiet-Sun), F1 (small flare), FA (medium flare), and F2 (large flare), which are bombarded by electron beams of various fluxes 0, 10^9, 10^{10}, 10^{11}, and 10^{12} ergs cm^{-2} s^{-1}, denoted by the 5 asterisks from left to right. Overplotted in Fig. 1a is the temporal evolution of the flare kernel from observations. We find that during the impulsive phase, the electron beam flux rises rapidly to more than 10^{11} ergs cm^{-2} s^{-1}, while the atmosphere is heated to a status slightly hotter than the F1 model. After the flare maximum, it cools gradually to the original status when the electron beam is obviously weaker than in the rise phase. In Fig. 1b, we plot the spatial variation across a flare ribbon, i.e., from the inner edge to the outer edge. The results show that the non-thermal effects in the outer part of the flare ribbon is more significant than in the inner part. This is consistent with the scenario of two-ribbon flare models that the outer part of flare ribbons maps the footpoints of newly reconnected flare loops.

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