Multi-Wavelength Two-Dimensional Spectroscopy of Solar Flares

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Preface

Posted before my desk is a portrait of Einstein, under which stands the framed photograph of my girl friend. This scenario reveals the dream of a young man in the community of scientific research. However, I am always embarrassed by the turnup moustache of Einstein when I present my idea or research work that I consider original.

Looking back, I realize that it was a little daring when I planned to graduate one year ahead. It is owing to my advisors, Profs. Ding Mingde and Fang Cheng, who offer me a remarkable insight and an essential virtue that a scientific researcher should have. Thanks are also given to Prof. Tang Yuhua, Mr. Zhou Qinglin, Dr. Chen Pengfei, Mr. Lei Shijun, Mr. Cheng Lianqing, Mr. Wang Yonghua, Mr. Chen Yuxi, Mr. Zhang Ming, Mr. Li Min, Mr. Yeh C.-T., etc. Above all, I would like to express my special acknowledgements to my family and my girl friend, who selflessly give me unending support.

Although this thesis is so trivial in contribution to knowledge, I view it as my first step towards my dream. This dream, combined with sincere encouragement from other people, prompts me to proceed in scientific research.
Abstract

In this thesis, we aim to investigate the dynamic behaviors of solar flares at different locations of the active region and at different depths of the atmosphere. For this purpose, three typical flaring events are studied in great detail. On the basis of the 2D spectra of Hα and Ca II λ8542 observed by the solar tower of Nanjing University, we incorporate the soft X-ray emission from GOES, the hard X-ray flux from Yohkoh and the radio flux observed by the Broadband Radio Spectrometer of Beijing Astronomical Observatory. The observational results offer some important clues for the flare mechanisms, in particular the heating process in the solar lower atmosphere. Besides, non-LTE computations are employed to quantitatively explain or recover the observations. The contents of this thesis are divided into the following paragraphs.

Chapter 1 gives a brief introduction to solar flares, which contains the morphology, the classification and the mechanisms of flares.

Chapter 2 presents a new method of spectral analysis. Applying this method to the 2D spectra of Hα and Ca II λ8542 in a flare of 1999 December 22, we deduce the 2D physical parameters of the flare. These parameters give an insight into the origin of line asymmetries, and enable us to investigate the dynamic behaviors of flares in different sites of the flaring area.

Chapter 3 describes in detail the derivation of physical conditions in a limb flare of 1998 November 11. We extract the macro-turbulent velocity field along the line-of-sight in the flaring loop, and show that it may be the main cause of the line broadening in this limb flare. We further deduce the temperature and density in the loop through non-LTE calculations. The results support the above point. The physical parameters obtained here provide a constraint on the flare models, and are thereby of special interest.

Chapter 4 quantitatively reports the continuum enhancement and decrease at the infrared wavelength in a white-light flare on 2001 March 10, based on the 2D spectral observations. It also presents a good example for the heating of a sunspot atmosphere. We demonstrate that energetic electrons followed by radiative backwarming is responsible for the continuum behavior.
We further quantitatively check this mechanism through non-LTE calculations, and find that the electron beam derived from the hard X-ray emission is able to power the heating of the atmosphere. These discoveries are of great importance in the investigation of the energy transport mechanisms in flares.

Chapter 5 summarizes the main results of the thesis.

Appendix A briefly describes my software for processing and visualizing the spectral data observed by the solar tower of Nanjing University. This software is written in IDL, and now becomes a useful tool for my colleagues.
Publications


[4] Liu, Y., & Ding, M.D., Physical Parameters of a Flare Derived from Multiline 2D Spectroscopy, 2001, ChJAA, 1, 460


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Chapter 1

Introduction

Solar flares are eruptive manifestation of energy release in the solar atmosphere. In a time scale of $10^2 - 10^3$ s, the total energy released in a flaring event amounts to $10^{28} - 10^{33}$ ergs. The enhanced spectral emission ranges from $\gamma$-ray to radio wavelengths. Consequently, this huge energy appreciably disturbs the whole solar atmosphere and even the interplanetary space. High-energy photons, energetic particles, shock waves and coronal mass ejections associated with the flaring phenomenon significantly influence the Earth and its immediate environment. Flare investigations and forecasting are thus of great importance.

The first flaring event ever recorded was detected in white light independently by R.C. Carrington and R. Hodgson on 1859 September 1. This flare is a relatively rare event — a white-light flare that is visible at the optical continuum. This spectacular phenomenon greatly shocked astronomers, which started the exciting research on solar flares. With the advent of the new century and the launching of the spacecraft of SOHO, Yohkoh, TRACE, and RHESSI, the research on solar flares has attained a new altitude and is becoming more attractive.

1.1 Morphology of Flares

Ground-based observations indicate that flares can be divided into two types, i.e., small compact flares and large two-ribbon ones. The first case is usually confined to a small area, while the latter appears as two ribbons. The two-ribbon flare is always associated with an erupting prominence or filament; strong emission occurring at the two sides of the filament forms the two ribbons. From the intrinsic factor, there is no essential distinction between these two types of flares, which will be seen later. On the other hand, observations at solar limb reveal the loop configuration of solar flares. The loop system roots
in the photosphere and extends to the corona. This point is confirmed by spacecraft observations of high spatial resolution.

1.2 Classification of Flares

Table 1.1: Classification by soft X-ray flux

<table>
<thead>
<tr>
<th>Class</th>
<th>intensity (erg cm(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>M</td>
<td>(10^{-2})</td>
</tr>
<tr>
<td>X</td>
<td>(10^{-1})</td>
</tr>
</tbody>
</table>

Table 1.2: Classification by H\(\alpha\) emission area

<table>
<thead>
<tr>
<th>Class</th>
<th>Area (square degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sf</td>
<td>(\leq 2.0)</td>
</tr>
<tr>
<td>1f</td>
<td>2.1 – 5.1</td>
</tr>
<tr>
<td>2f</td>
<td>5.2 – 12.4</td>
</tr>
<tr>
<td>3f</td>
<td>12.5 – 24.7</td>
</tr>
<tr>
<td>4f</td>
<td>(\geq 24.7)</td>
</tr>
</tbody>
</table>

As widely accepted, solar flares are classified based on the global output of soft X-ray emission at 1 – 8 Å monitored by GOES. Depending on the magnitude of this flux, flares are categorized as C, M, or X as given in Table 1.1. The letters represent the order of magnitude of the soft X-ray flux, while a subsequent numerical value gives the flux value for each order (e.g., M2 means the flux of \(2 \times 10^{-2}\) erg cm\(^{-2}\) s\(^{-1}\)). On the other hand, flares are also usually ranked in importance by H\(\alpha\) emission area. This area refers to the time of the flare maximum brightness, and should be measured in square degrees with projection corrected. Besides, a suffix, f (faint), n (normal), or b (brilliant) is added as a complement according to the flare brightness. This classification is given in Table 1.2.
Flares are believed to occur through magnetic reconnection. MHD simulations usually demonstrate the Y type reconnection as displayed in Figure 1.1. The energy released in the reconnection site, in the form of either high energy particles or a heat conduction front, can be transported downward along the newly formed loops to heat the chromosphere, which as a result accounts for the brightening of the two kernels. This energy drives a chromospheric condensation and makes it downward; on the other hand, chromospheric material can be evaporated into the corona, filling the soft X-ray loop. The soft X-ray loop cools through radiation to finally an Hα loop, in a time which is dependent on the loop density. The spatial and temporal correlation between soft X-ray...
Chapter 1. Introduction

and Hα loops has been extensively studied by Schmieder et al. (1995, 1996), Wiik et al. (1996), and van Driel-Gesztelyi et al. (1997).

Recently, Chen et al. (1999) demonstrated through numerical simulations that the altitude of reconnection site has an impact on the flare types. To say, if the reconnection occurs in a relatively high place, the kinetic evolution of the flaring loops are qualitatively consistent to that predicted by a two-ribbon flare model (Kopp & Pneuman 1976); while if the reconnection occurs in a relatively low place, the flare appears more likely to be a confined flare. It can be expected that the flaring loop in the latter case usually lies lower and contains a higher mass density than in the former case.

Spacecraft observations seem to confirm this model of flare eruption. Masuda et al. (1994) found a hard X-ray source above the loop top and proposed that it is generated from the place where a fast shock, emanating from the reconnection site, collides with the closed loop. Ranns et al. (2000) found for a flare that the non-thermal broadening of soft X-ray lines is located in and above soft X-ray loops. They suggested that it is due to either evaporating chromospheric plasma or plasma above the loop that is associated with the flare energy release.

The above facts highlight the significance of multi-wavelength observations and 2D spectroscopy of solar flares that can reveal the dynamic behaviors of flares at different locations and at different depths. In solar cycle 23, we have made systematic observations of solar flares at two wavelength bands around the Hα and Ca II λ8542 lines, using the imaging spectrograph in the solar tower of Nanjing University (Huang et al. 1995). These observations, complemented by data from other instruments, such as Yohkoh, GOES and the Broadband Radio Spectrometer of Beijing Astronomical Observatory, enable us to make a comprehensive study of flare dynamic properties in this thesis.
Bibliography

Chapter 2
A Modified Cloud Method and Its Application to a Flare

Analysis of contrast profiles is a useful way for the determination of physical parameters in solar chromospheric structures. The method most frequently used, known as the classical cloud model, was proposed by Beckers (1964), which allows a simultaneous determination of four parameters: the line source function, the optical thickness at line center, the line-of-sight velocity and the Doppler width. This method succeeds in inverting line profiles in chromospheric structures (Alissandrakis, Tsiropoula, & Mein 1990; Tsiropoula, Alissandrakis, & Schmieder 1993; Tsiropoula & Schmieder 1997). However, it is only effective for dark features at the disk, such as dark mottles of a chromospheric rosette region (e.g., Tsiropoula, Alissandrakis, & Schmieder 1993; Tsiropoula & Schmieder 1997; Tsiropoula, Madi, & Schmieder 1999), superpenumbral fibrils and arch filament systems (e.g., Alissandrakis, Tsiropoula, & Mein 1990; Mein et al. 1996). The heights of these structures above the chromospheric base play a decisive role in shaping the observed profiles. The method of differential cloud models was proposed by Mein & Mein (1988), which takes into account the fluctuations of the chromospheric background in active regions and velocity shears inside the cloud, but it can only be applied to dark clouds in order to avoid singularities and eliminate spurious solutions. The method of multi-cloud model has been used to analyze the spectra of limb features, such as post-flare loops (e.g., Gu et al. 1997); however, this method may lead to meaningless solutions for flare ribbons at disk. In cases of bright features, the radiative and collisional damping effect may play an important role in the formation of the Hα line. Hence, the Voigt profile is more realistic than a gaussian profile in the cloud model. Tsiropoula, Madi & Schmieder (1999) approximated the Voigt profile by the sum of a Doppler
core and Lorentzian damping wings and considered the variation of the source function with optical thickness. In this method, the theoretical profile has a singularity in Lorentzian damping wings (where the denominator equals to zero) which causes a poor fit if assuming a constant source function. Some authors have investigated the variations of the source function with the opacity of the structures (Mein et al. 1996; Paletou 1997), and the cloud model is extended to cases of non-constant source functions (Zhang et al. 1987; Mein et al. 1996; Tsiropoula, Madi, & Schmieder 1999). However, the adoption of a non-constant source function yields only little improvement in the case of a low opacity. Note also that the Hα source function is sensitive to larger macroscopic velocities of the order of a few tens of km s\(^{-1}\), but this effect is less important for high electron densities where the collisional excitation plays a significant role (Heinzel, Mein, & Mein 1999). Here we still use a constant source function to analyze the line spectra. In this sense, the value of the source function that we obtain reflects a mean value averaged over a specific region.

Concerning solar flares, the most obvious signature of line profiles is the red asymmetry, which has been interpreted as a consequence of downflows related to the chromospheric condensation (e.g., Ichimoto & Kurokawa 1984; Canfield et al. 1987; Gan & Fang 1990; Ding, Fang, & Huang 1995; Cauzzi et al. 1996). In this chapter we pay special attention to the origin of the line asymmetry and present a new method to analyze the 2D spectra in a flaring region. This method avoids using a background profile that is usually hard to determine. Two-dimensional parameters are deduced, based on the 2D spectra of the flaring region. The results are useful for a better understanding of the flare dynamics.

### 2.1 Method of Spectral Analysis

The classical cloud model adopts a mean profile over the quiet chromosphere as the background profile. However, for flares it is not feasible because of the large fluctuations in the active-region background. Here we present a technique avoiding the use of a background profile. In the cloud model, the line intensity is given by

\[
I(\Delta \lambda) = I_0(\Delta \lambda)e^{-\tau(\Delta \lambda)} + S_0[1 - e^{-\tau(\Delta \lambda)}],
\]

(2.1)

where the source function \(S_0\) is assumed to be constant and frequency independent, \(I_0(\Delta \lambda)\) is the background intensity. The optical thickness is expressed as

\[
\tau(\Delta \lambda) = \tau_0 H(a, x),
\]

(2.2)
where $H(a, x)$ is the Voigt profile, given by

$$H(a, x) = \frac{a}{\pi} \int_{-\infty}^{+\infty} e^{-y^2/a^2} \frac{e^{-(x-y)^2}}{a^2 + (x-y)^2} dy,$$

(2.3)

where

$$x = \frac{\Delta \lambda - \Delta \lambda_I}{\Delta \lambda_D},$$

(2.4)

$$a = \frac{\Gamma \lambda_0^2}{4\pi c \Delta \lambda_D}.$$  

(2.5)

In the above equations, $\Gamma$ is the damping constant (This parameter has no essential impact on the other parameters to be fitted; thus in the computations $\Gamma$ is fixed to be $5 \times 10^9$ s$^{-1}$ for H$\alpha$ and $1.5 \times 10^8$ s$^{-1}$ for CaII $\lambda$8542, considering both the radiative damping and the collisional broadening). The four unknown parameters are the source function, $S_0$, the optical thickness at line center, $\tau_0$, the Doppler shift, $\Delta \lambda_I$ and the Doppler width, $\Delta \lambda_D$, which are all assumed to be constant throughout the perturbed layer.

Below the perturbed layer, the H$\alpha$ line profile is assumed to be symmetric, namely,

$$I_0(\Delta \lambda) = I_0(-\Delta \lambda).$$

(2.6)

Hence, we define an asymmetry profile as

$$A(\Delta \lambda) \equiv I(\Delta \lambda) - I(-\Delta \lambda) = [I(\Delta \lambda) - S_0][1 - e^{\tau(\Delta \lambda)} - e^{-\tau(-\Delta \lambda)}].$$

(2.7)

Using the above formulation, we adopt an iterative least square procedure using the Levenberg-Marquardt method to fit the observed asymmetry profile $A(\Delta \lambda)$, instead of the original profile $I(\Delta \lambda)$. Doing so avoids using the profile $I_0(\Delta \lambda)$, which is not known as a pre-requisite. The computations yield the four unknown parameters $S_0$, $\tau_0$, $\Delta \lambda_I$, and $\Delta \lambda_D$ mentioned above. To check the validity of this method, we have constructed theoretical asymmetry profiles by choosing different sets of the four parameters, which can in most cases be recovered using this method. It should be emphasized that the computation converges rapidly and varying the initial values has almost no influence on the finally converged data.

2.2 Application to the 1999 December 22 Flare

2.2.1 Observations and Data Reduction

The flare to be analyzed occurred in the active region NOAA 8807 located at N10 E30 on 1999 December 22. The flare began at 01:50 UT, and ended at
02:32 UT, peaking at 02:16 UT. According to the Solar Geophysical Data, it is an event with an Hα importance 2B and soft X-ray class M1.8.

We have obtained a time series of 2D spectra of the Hα and Ca II λ8542 lines with a CCD imaging spectrograph in the solar tower of Nanjing University using a scanning technique (Huang et al. 1995; Ding et al. 1995). During the flare, we repeated 20 scans over the flaring region from 02:10:00 UT to 02:37:13 UT. Each scan recorded the 2D spectra of the two lines simultaneously. There are 150 pixels with a pixel spacing 0.′′85 along the slit, and 50 pixels with a spacing 2′′ in the scan direction. The spectrum contains 200 wavelength points with a spectral resolution of 0.05 and 0.118 Å pix⁻¹ for the Hα and Ca II λ8542 lines respectively.

The data reduction includes dark current subtraction and flat field correction for the CCD cameras. The drift of images at different times is also corrected using a cross-correlation procedure. The centers of the Hα and Ca II λ8542 lines are determined from their mean undisturbed profiles near the flaring region by adopting a technique of gaussian fitting.

Figure 2.1: Monochromatic images of the flare at the Hα line center (left panel), and at the Ca II λ8542 line center (right panel) reproduced from the 2D spectra at 02:09:53 UT. The two small boxes, marked as A and B in the left panel, cover an area of 1.′′7 × 2′′ respectively.

Figure 2.1 shows the monochromatic images at line centers of Hα and Ca II λ8542, respectively, reconstructed from the 2D spectra. The morphology of the flare in Ca II λ8542 is similar to that in Hα, which was also mentioned by Mein et al. (1997). However, the flare appears more diffusive in the case of Ca II λ8542. In computations, we concentrate on the spectra within the two kernels displayed in Figure 2.1, which show conspicuous asymmetries in each line.
2.2.2 The H\(\alpha\) Case

![Figure 2.2: Left panel: A typical H\(\alpha\) line profile with red asymmetry in the flaring region; Right panel: Comparison between the asymmetry profile observed (solid line) and the fitted one (dotted line). The intensity is normalized to the continuum near the H\(\alpha\) line.](image)

We apply the method described above to the 2D H\(\alpha\) line profiles observed. The profiles in the flare ribbon show conspicuous red asymmetries, while the line center is nearly not shifted. Figure 2.2 plots a typical line profile with red asymmetry, along with the asymmetry profile defined by Equation 2.7. We select a wavelength window with a reasonable range to eliminate the influence of other spectral lines. The asymmetry profiles from observations can be well fitted based on our method. When the asymmetry diminishes with time, the method should be used with caution, because the asymmetry profile could become very flat, namely, \(A(\Delta \lambda)\) approaches 0, which will induce poor convergence and meaningless solutions. In our work, we pick up 6 frames of 2D spectra to investigate the evolution of the parameters. The time corresponding to each frame is 02:09:53, 02:11:11, 02:14:03, 02:15:47, 02:17:04 and 02:19:23 UT. The four parameters of the flare at 02:09:53 UT are displayed as contour maps in Figure 2.3. Generally speaking, the behavior of the four parameters is similar, namely, the values are smaller at the edges of the flare ribbons, while enhanced gradually towards the kernels. This result is reasonable. Figure 2.3(c) illustrates a downward motion with a mean velocity of about 47 km s\(^{-1}\), which is in good agreement with the result of Ichimoto & Kurokawa (1984). A change of the velocity over the flaring region is distinguishable but not very conspicuous. This may in part be due to a relatively low spatial resolution in observations.

The temporal evolution of the four parameters averaged over the ten brightest pixels in each kernel are shown in Figure 2.4. Note that in the present time series of observations, the flare arrived at its maximum at 02:15:47 UT (354
Figure 2.3: Contours of the four parameters in the flaring region at 02:09:53 UT derived with our method: (a) source function with levels of (0.4, 0.6, 0.8, 1.0) × \( I_{\text{continuum}} \); (b) optical thickness with levels of (0.15, 0.25, 0.35, 0.45); (c) downward velocity with levels of (25, 35, 45, 55) km s\(^{-1}\); (d) Doppler width with levels of (0.25, 0.35, 0.45, 0.55) Å.

Figure 2.4 after 02:09:53 UT. Examining Figure 2.4, we can obtain the following results: (1) The downward motion abruptly increases at the onset of the flare, and peaks before the maximum of the flare, then it decreases gradually and remains fairly large in the later phase, which is in agreement with the result of Ichimoto & Kurokawa (1984); (2) The variations of the four parameters are roughly similar in the two kernels, though there is a quantitative difference, implying that the two kernels may be heated by a same mechanism; (3) There is a similar evolution trend for the source function and the Doppler width. At the onset of the flare the source function and the Doppler width attain their maximum, then they decrease with time. The result is reasonable, since at the onset of the flare a strong electron beam impinges on the flare atmosphere and enhances the source function and the Doppler width; the values of these two parameters should be reduced when the electron beam weakens or diminishes. Many authors have pointed out that the source function and the Doppler width should depend on each other (Durrant 1975; Steinitz, Gebbie,


& Bar 1977; Cram 1986). Our results do support such a conclusion.

Figure 2.4: Temporal variation of the four parameters averaged over the ten brightest pixels in each fixed box, A (plus signs) and B (diamonds) after 02:09:53 UT: (a) source function (in units of $I_{\text{continuum}}$); (b) optical thickness; (c) downward velocity; (d) Doppler width.

Figure 2.4(a) and 4(b) illustrate a rough proportional relation between the source function and the optical thickness at line center, which was also mentioned by other authors (e.g., Heinzel, Mein, & Mein 1999). This is also reflected from Figure 2.3(a) and 3(b), namely the source function increases with the optical thickness. Many authors have pointed out an anticorrelation between the optical thickness at line center and the Doppler width for solar features other than flares (Alissandrakis, Tsiropoula, & Mein 1990; Tsiropoula & Schmieder 1997). From the intrinsic factor, the absorption coefficient is

$$a(\Delta \lambda) = \frac{\pi^\frac{3}{2} e^2 \lambda^2 f H(a, x)}{m_e c^2 \Delta \lambda_D} n_2,$$

(2.8)

where $f = 0.641$ is the oscillator strength for Hα. Thus the optical depth at
line center is given by
\[
\tau_0 = a(0)d \sim \frac{n_2d}{\Delta \lambda_D},
\]
(2.9)
where \(n_2\) is the number density in the second level of hydrogen and \(d\) is the geometrical thickness of the structure along the line of sight. If the value of \(n_2d\) does not vary appreciably, there should exist an anticorrelation between \(\tau_0\) and \(\Delta \lambda_D\). However, in the case of solar flares, the value of \(n_2\) is greatly enhanced because of the non-thermal excitation of the hydrogen atoms caused by precipitating high-energy electrons. The value of \(d\) could also suffer a pronounced change, because the condensation is confined in a narrow layer when it is initially formed (e.g., Fisher, Canfield, & McClymont 1985), but dissipates gradually during its downward propagation. Therefore, it is conceivable that the optical thickness is proportional to the Doppler width in the case of solar flares.

### 2.2.3 The Ca\(\text{ii}\) \(\lambda8542\) Case

![Figure 2.5](image)

Figure 2.5: Left panel: A typical Ca\(\text{ii}\) \(\lambda8542\) line profile with red asymmetry in the flare kernels; Right panel: Comparison between the observed asymmetry profile (solid line) and the fitted one (dotted line). The quantities are normalized to the continuum at 8542 Å.

A typical Ca\(\text{ii}\) \(\lambda8542\) line profile with red asymmetry is plotted in Figure 2.5, along with the asymmetry profile defined by Equation 2.7. A wavelength window with a reasonable range is selected to exclude the influence of other blended lines. The asymmetry profiles from observations can be well reproduced based on the method.

The four parameters within the kernels are displayed in Figure 2.6 as contour maps overlaid on the monochromatic image (the right panel in Figure 2.1). Over the flare kernels, the properties of the four parameters deduced
Figure 2.6: Contours of the four parameters within the flare kernels at 02:09:53 UT derived from the Ca\textsc{ii} λ8542 profile: (a) source function with levels of (0.5, 0.7, 0.9, 1.1) $\times I_c$; (b) optical thickness with levels of (0.15, 0.25, 0.35, 0.45); (c) downward velocity with levels of (6, 8, 10, 12) km s$^{-1}$; (d) Doppler width with levels of (0.25, 0.35, 0.45, 0.55) Å.

from Ca\textsc{ii} λ8542 are qualitatively similar to the results from H$\alpha$. Namely, the values are smaller at the edges of the kernels, while enhanced gradually inward. Figure 2.6(c) illustrates a downward velocity with a mean value of about 10 km s$^{-1}$, smaller than that deduced from H$\alpha$. Since the forming height of the Ca\textsc{ii} λ8542 line is much lower than that of the H$\alpha$ line, we can infer that the velocity in the layer contributing to the Ca\textsc{ii} λ8542 line emission should be certainly smaller, in the framework that we ascribe the red asymmetry in the present observations as due to the downward propagation of a chromospheric condensation.

Figure 2.7 displays the temporal evolutions of the four parameters averaged over the ten brightest pixels within the kernels. From Figure 2.7, we can find a quantitative difference between the parameters derived from the two lines, which may be due to their different forming processes as mentioned above. The temporal evolutions of the parameters, however, are generally similar for the two lines. Such similarities confirm that the two lines should be perturbed
Figure 2.7: Temporal variations of the four parameters averaged over the ten brightest pixels within the flare kernels derived from Hα (plus signs) and Ca II λ8542 (diamonds) after 02:09:53 UT: (a) source function (in units of \( I_c \) near each line); (b) optical thickness; (c) downward velocity; (d) Doppler width. Note that the velocity deduced from Ca II λ8542 is multiplied by a factor of 4.

by the same heating mechanism and dynamic process, even though they are formed in different circumstances. Figure 2.7 also shows that the velocity abruptly increased at the flare onset, and peaked before the Hα maximum. Another interesting feature is that the four parameters derived from Ca II λ8542 also show a roughly similar evolution, i.e., they attain their maximum at the onset of the flare and then decrease, just as the Hα case.

2.3 Line Asymmetry in Solar Flares

The most obvious feature of line profiles for solar flares is the red asymmetry, which has been interpreted as a consequence of downflows related to the chromospheric condensation (e.g., Ichimoto & Kurokawa 1984; Canfield et al. 1987; Canfield & Galey 1987; Fisher 1987; Gan & Fang 1990; Ding et al. 1995;
Cauzzi et al. 1996). However, different lines show different asymmetries during a flaring event. For the Hα line, the asymmetry only occurs at the line wings and there is nearly no shift at the line center, which has been frequently argued (e.g., Fang et al. 1992; Ding, Fang, & Huang, 1995). We have got the same feature of the asymmetry in our observations (Figure 2.2, left panel), which produces zero-values of the asymmetry profile at the central part (Figure 2.2, right panel). The Ca ii λ8542 case lacks this feature (see Figure 2.5).

![Figure 2.8: Comparison of the mean undisturbed profile near the flaring region (solid line), the typical observed profile with red asymmetry (dashed line), and the intensity profile irradiating the perturbed layer from below (dotted line). Left panel for Hα and right panel for Ca ii λ8542. The quantities are normalized to the intensity of the adjacent continuum.](image)

To investigate the impact of the condensation on the line profiles, we plot in Figure 2.8 the mean undisturbed profile near the flaring region, a typical observed profile with red asymmetry, and the intensity profile irradiating the perturbed layer from below, $I_0(\Delta \lambda)$, for Hα and Ca ii λ8542 respectively. The last one is constructed from Equation 2.1 adopting the four parameters derived with the modified cloud method. Note that when fitting the asymmetry profile, $A(\Delta \lambda)$, we select a wavelength window to exclude the influence of other spectral lines in the wing; while the profile of $I_0(\Delta \lambda)$ is recovered using an extended wavelength window as plotted in Figure 2.8. The profile of $I_0(\Delta \lambda)$ is symmetric just as assumed in Equation 2.6, and already indicates a fairly large extent of emission compared with the undisturbed profile. This means that the atmosphere below the condensation may also be heated consequentially through diverse ways, which is in agreement with the flare dynamic models (Fisher et al. 1985; Gan & Mauas 1994). However, we note some distinction between Hα and Ca ii λ8542, i.e., $I_0(\Delta \lambda)$ reveals a central emission peak in the case of Ca ii λ8542. The result is reasonable. The chromosphere, where
Chapter 2. A Modified Cloud Method and Its Application to a Flare

the core of the Ca II λ8542 line is formed, is heated and condensed during the flaring process, and it induces an enhanced source function in this layer, thus generating the central emission in the absorption line of Ca II λ8542.

Another consequence of the condensation is that it is a significant factor in shaping the asymmetry of the observed profile. In the case of Hα, the observed line profile seems to consist of two components: one static and one displaced. The core of the observed profile is generally the center of the static component and has nearly no shift; while the shifted one makes the profile red asymmetric. For the Hα line, the Doppler shift in the downward moving region is much larger than the Doppler width, hence the two parts may become radiatively disconnected. Thus only the red wing of the observed profile exhibits an excess emission while other parts are almost identical to $I_0(\Delta \lambda)$ (Figure 2.8, left panel). Contrary to the Hα case, the Ca II λ8542 line shows an obvious excess emission in the central part (Figure 2.8, right panel). In this case, the Doppler shift is smaller than the Doppler width.

It has been found that both the blue and red asymmetries can be caused by downward motions when the condensation is constrained to different heights of the chromosphere (e.g., Gan et al. 1993; Ding & Fang 1996, 1997). It has also been demonstrated that the downflows, driven by the electron beam heating with return current, can produce a blue asymmetry in the Hα line (Heinzel et al. 1994). From the radiation transfer equation, if the source function in the condensation is greater than the underlying intensity irradiating it, the observed profile will exhibit a red asymmetry; otherwise, it displays a blue asymmetry. Actually, the source function we obtained is greater than $I_0(\Delta \lambda)$ in the wavelength window shown in Figure 2.8 for both the cases of Hα and Ca II λ8542, which is consistent with the fact that the observed profiles are red asymmetric.

2.4 Discussion and Conclusions

Numerical simulations of flare dynamics show that the chromospheric downflows, either caused by heat conduction (e.g., Pallavicini et al. 1983; Cheng et al. 1983; Karpen & DeVore 1987; Gan et al. 1991), or by precipitation of non-thermal electrons (e.g., Livshits et al. 1981; Nagai & Emslie 1984), have similar properties: (1) The chromospheric condensation is geometrically dense and thin, and the velocity is basically constant within it and decreases with time; (2) Velocities ahead of the front of the condensation are zero or negligibly small. These properties validate the adoption of constant parameters throughout the condensation, and confirm the assumption of symmetric
background profiles. Based on the precondition, our results are qualitatively consistent with the general framework of flare dynamics.

There is a discrepancy, however, between the observations and the numerical simulations concerning the lifetime of the condensation. Numerical simulations (either thermal or thick-target) predict that the lifetime of the condensation is of the order of 1 min, while from Figure 2.7(c) we can find that velocities derived from Hα remain fairly large even in the later phase. This discrepancy also appeared in previous observations (e.g., Ichimoto & Kurokawa 1984; Ding et al. 1995) which has been interpreted as a consequence of the superposition of several condensations within an unresolved region (Fisher 1989). Recent observations with high time and spatial resolution have discovered that emissions in the wings of Hα could also exhibit high frequency fluctuations (Wang et al. 2000), which are interpreted as a signature of fine structures related to flare elementary bursts. Ding et al. (2001) have made further explorations through numerical calculations, and found that such fluctuations are probably produced in the chromosphere, which is successively perturbed by short-lived and small-scale injection of high energy electrons. In this scenario, the observed line profile is a convolution of many such spatially unresolved small bursts which are initiated at different times; thus, the net line emission (line integrated intensity with the preflare value subtracted) and the velocity derived from the line could both remain fairly large in the later phase.

![Figure 2.9: Temporal variation of the downward velocity (diamonds) averaged over the pixels in the small boxes A (left panel) and B (right panel) after 02:09:53 UT. Plus signs indicate the variation of the net line emission of Hα (in arbitrary units) integrated over the line profile.](image)

To understand the above point more clearly, we choose two small boxes corresponding to an area of 1.′′7 × 2′′ respectively (see Figure 2.1, left panel),
and plot in Figure 2.9 the temporal variation of the downward velocity averaged over each small box, as well as the variation of the net line emission of H$\alpha$ integrated over the line profile. We can find that, for the box B, the net line emission gets some rise in the later phase, and the velocity correspondingly increases; for the box A, the net line emission almost remain constant in the later phase, which is also accompanied by a fairly large velocity.

In summary, we have presented a new method to derive the physical parameters of the chromospheric flare and applied it to the spectral data of a flare observed on 1999 December 22 with the CCD imaging spectrograph installed in the solar tower of Nanjing University. This method can also be applied to other chromospheric structures as long as the profiles are asymmetric. The main results are as follows:

1. The physical parameters derived from each line show similar behaviors in spatial distribution and temporal evolution, which indicates a different property of solar flares from other solar features.

2. The spatial properties of the physical parameters derived from Ca\textsc{ii} $\lambda$8542 over the flare kernels are generally similar to those derived from H$\alpha$, and so do the temporal properties. These facts imply that the two lines may be perturbed by a same heating mechanism and dynamic process.

3. There is an obvious heating effect on the material below the condensation, which is consistent with the flare dynamic model (Fisher et al. 1985; Gan & Mauas 1994).

4. It is interpreted and demonstrated in various ways that the red asymmetry of line profiles is caused by the chromospheric downflows of several tens of km s$^{-1}$. The velocity in the layer contributing to the Ca\textsc{ii} $\lambda$8542 line emission is about 10 km s$^{-1}$, much smaller than that deduced from H$\alpha$.

5. The downward velocity peaks before the H$\alpha$ maximum of the flare, and then decays gradually. It remains fairly large even in the later phase, which is interpreted as the consequence of successive flare elementary bursts, i.e., heating by short-lived, small-scale and high-energy electrons.

The results derived from multi-line 2D spectra, based on our method, are consistent with the general picture predicted by the flare dynamic models. As pointed out by some authors (e.g., Gan et al. 1991), it will be worthwhile investigating the relation between the H$\alpha$ line profile and the chromospheric condensation, whereby to provide a theoretical base for the diagnostics of the hydrodynamic process in solar flares from spectral observations. Certainly, a really sophisticated method should be able to match multi-line 2D observations. In this work, we have presented a new fitting method with which relevant results can be obtained. Therefore, it may provide a useful tool to diagnose the hydrodynamic process of solar flares.
Bibliography

Bibliography


Chapter 3

Physical Conditions in a Flaring Loop

Unusual line broadening during solar flaring events has been observed in different lines, such as lines in soft X-ray spectra (e.g., Antonucci et al. 1982; Bentley et al. 1986), the He I λ10830 line (You et al. 1998), and the Hα line (e.g., Graeter & Kucera 1992; Ding et al. 1999). All these events exhibit a common feature: the line width significantly exceeds the thermal Doppler width, which cannot be explained by a Doppler broadening mechanism or a pure Stark effect (You & Oertel 1992).

This unusual line broadening implies some physical processes that are important to the understanding of flaring phenomena. Ding et al. (1999) showed that the line opacity effect cannot fully account for the observed line width of Hα in a limb flare of 1998 November 11. Fang et al. (2000) examined the effect of non-thermal excitation and ionization by an electron beam in this limb flare, and found that the Hα line can become very broad at an altitude where the source function reaches its radial maximum. However, this may not be the main broadening mechanism, since the unusual broadening in this event extended into the later phase when the non-thermal effect does not take a leading role in the formation of lines. Li & You (2001) proposed that an expanding atmosphere can explain the unusually broad profile of the He I λ10830 line in another limb flare of 1989 August 16. They obtained an empirical velocity distribution which represents one of the possibilities that could occur.

In solar flares, various mass motions can occur as due to untwisting, squeezing of magnetic structures, or due to the gas dynamics in the flaring loop. Recent observations have indeed reported large scale radial or horizontal motions (e.g., Malherbe et al. 1997; You et al. 1998), the velocity of which can reach more than 160 km s⁻¹. Emslie & Alexander (1987) showed that all of
the excess line broadening observed in solar disk could be explained by the superposition of many hydrodynamic motions within flaring loops. Gu et al. (1984) proposed that the plasma within a helical structure of the magnetic field would spiral downward under certain conditions; some authors (e.g., Heinzel et al. 1992) pointed out that large line broadening of unknown origin could be ascribed to such rotational motions. Raju (1998) further demonstrated that mass motions within coronal loops can lead to line broadening observed at the limb. It is thus natural to relate the unusual broadening of line profiles in the limb flare of 1998 November 11 to such large inhomogeneous mass motions.

On the other hand, the physical conditions along the loop is of special interest since they might provide a constraint on the flare models. The 2D spectra of both Hα and Ca II λ8542 for the limb flare of 1998 November 11, observed by the solar tower of Nanjing University (Huang et al. 1995), provide an opportunity to study the physical condition along the flaring loop and its temporal variation. In this chapter, we derive the temperature and density values in the loop of this limb flare based on non-LTE calculations for simple slab models, extract the probability distribution of the velocity field along the line of sight in the flaring loop, and then make a systematic discussion of the
3.1 The Observational Data

The flare occurred at the northwest limb (N25 W86) on 1998 November 11. It started at 02:10 UT, peaked at 02:15 UT, and ended at 02:18 UT. Its Hα/soft X-ray importance is SF/C3.2. We used the imaging spectrograph at the solar tower of Nanjing University to scan over the flaring region. Observations yielded 2D spectra of the Hα and Ca II λ8542 lines. A detailed description of the observations and data reduction can be found in Ding et al. (1999).

![Figure 3.2: Line profiles of Hα (solid lines) and Ca II λ8542 (dotted lines) at 02:14:38 UT corresponding to the three points in Figure 3.1.](image)

We select 12 scans, covering the rise and decay phases of the Hα flaring loop, for study in this work. The images at different times are co-aligned carefully using the sunspot and limb features near the flare. The accuracy of image co-alignment is estimated to be 2″–3″. In the flaring loop, we select 3 points, which lie at the loop top and in the two legs, respectively, to check the spatial variation. Figure 3.1 shows a monochromatic image of the flaring loop at Hα line center at 02:14:38 UT and three points, denoted by A, B and C in the loop. Figure 3.2 displays the typical line profiles of Hα and Ca II λ8542 at 02:14:38 UT at the three points. From this figure, we can see that the line profiles are extraordinarily broadened, and the Hα profile is the broadest near the top of the flaring loop. This broadening lasted a rather long time and extended into the later phase of the flare.
3.2 Temperature and Density in the Loop

Solar features that extend over the limb can be simply modeled as vertical slabs of finite width. This method has been used to study the formation of spectral lines in prominences or post-flare loops under non-LTE conditions (e.g., Heinzel, Schmieder, & Mein 1992; Gouttebroze, Heinzel, & Vial 1993). For the case studied here, we take a slab width of 3000 km, which is comparable to the diameter of the flaring loop. The temperature and mass density can be treated as constant along the loop width (the line of sight). For simplicity, we do not include a detailed transition region between the loop structure and the corona, as was done by Schmieder et al. (1999) when analyzing the Lyman lines in a quiescent prominence, but instead consider an incident radiation field to both surfaces of the slab. The irradiation intensity is taken to be half the mean intensity from the solar surface.

We first make non-LTE calculations for the slab model and obtain the line profiles of H$_\alpha$ and Ca II $\lambda$8542 under different conditions by varying the slab temperature ($T$) and hydrogen number density ($n_H$). We then integrate the line intensities with respect to wavelength to get the integrated intensities as a two-dimensional function of $T$ and $n_H$. By comparing the observed and computed integrated intensities, we then search for a solution of $T$ and $n_H$ which can serve as a mean physical condition in the loop where the observed

![Figure 3.3: Temperature and hydrogen number density at the three points in the loop deduced through the method here. We have assumed an uncertainty of ±10% in the calibration of absolute intensities of both lines.](image)

We first make non-LTE calculations for the slab model and obtain the line profiles of H$_\alpha$ and Ca II $\lambda$8542 under different conditions by varying the slab temperature ($T$) and hydrogen number density ($n_H$). We then integrate the line intensities with respect to wavelength to get the integrated intensities as a two-dimensional function of $T$ and $n_H$. By comparing the observed and computed integrated intensities, we then search for a solution of $T$ and $n_H$ which can serve as a mean physical condition in the loop where the observed
lines are formed. Our searching box covers a range of $6000 < T < 16000$ K and $10^{11} < n_{\text{H}} < 10^{13}$ cm$^{-3}$. In most cases, this searching yields a unique solution. The results are displayed in Figure 3.3.

The deduced temperature in the loop lies in the range of 10000–12500 K, which is like a typical temperature in post-flare loops. The hydrogen number density varies in the range of $(1.0–3.5) \times 10^{12}$ cm$^{-3}$. This relatively high density implies a short cooling time of the loop from soft X-ray to H\textalpha emitting temperatures. The loop top, during the flare maximum time, seems to contain a temperature and a density that both are slightly higher than the values in the legs of the loop. A favorable scenario to produce this result is that magnetic reconnection occurs above the loop, and the reconnection outflow may heat and condense the plasma near the loop top.

### 3.3 Macro-turbulent Velocity in the Line Broadening

#### 3.3.1 Method of Computation

Mass motions in flaring loops represent a significant factor, as mentioned above, in understanding the line broadening. It is thus indispensable to determine the velocity distribution. Newton et al. (1995) presented a continuous Gaussian fitting to derive the velocity distribution from soft X-ray spectra. Following their idea, we develop a method to treat the H\textalpha and Ca\textsc{ii} \textlambda 8542 lines. We propose that many macro-turbulent elements (i.e., fine structures) are confined in a spatially unresolved region, and these elements can be regarded as radiatively disconnected; every element moves with a different velocity along the line of sight. Assuming that the emission from all the turbulent elements has the same profile except for different Doppler shifts, the observed line profile can be expressed as

$$I(\Delta \lambda) = \int i(\Delta \lambda - \frac{v\lambda_0}{c})P(v)dv,$$

where $P(v)$ is the velocity probability distribution, $\lambda_0$ is the line center wavelength, and $i(\Delta \lambda - \frac{v\lambda_0}{c})$ is the line intensity from a turbulent element with velocity of $v$. For a homogeneous element $i(\Delta \lambda)$ is given by

$$i(\Delta \lambda) = S[1 - e^{-\tau(\Delta \lambda)}],$$

where the source function $S$ is assumed to be constant and wavelength independent. The optical thickness is given by

$$\tau(\Delta \lambda) = \tau_0 H(a, x),$$
where \( \tau_0 \) is the optical thickness at line center, and \( H(a, x) \) is the Voigt profile, defined as

\[
H(a, x) = \frac{a}{\pi} \int_{-\infty}^{+\infty} \frac{e^{-y^2}}{a^2 + (x - y)^2} dy ,
\]

where

\[
x = \frac{\Delta \lambda}{\Delta \lambda_D},
\]

\[
a = \frac{\Gamma \lambda_0^2}{4\pi c \Delta \lambda_D} .
\]

In the above equations, \( \Gamma \) is the damping constant and \( \Delta \lambda_D \) is the Doppler width. We adopt \( \Gamma = 5.8 \times 10^8 \) s\(^{-1}\) for H\(\alpha\) and \(1.5 \times 10^8 \) s\(^{-1}\) for Ca\(\text{II} \lambda 8542\) respectively, which are mainly from the radiative damping.

Using an inversion technique, we can derive the velocity probability distribution, \( P(v) \); then, through the normalization of \( P(v) \), the source function, \( S \), can be obtained. This inversion technique will be described in the next section. In computations, we adopt \( \Delta \lambda_D = 0.356 \) Å for H\(\alpha\) and 0.291 Å for Ca\(\text{II} \lambda 8542\), which correspond to the case of a plasma temperature \( T = 10^4 \) K and a micro-turbulent velocity \( v_t = 10 \) km s\(^{-1}\); \( \tau_0 = 300 \) for H\(\alpha\) and 1 for Ca\(\text{II} \lambda 8542\), which are obtained through non-LTE computations for typical slab models corresponding to this limb event.

### 3.3.2 Scheme of Inversion

Equation 3.1 is also known as the Fredholm integral equation of the first kind, which can be rewritten as

\[
g = A \cdot f ,
\]

where \( g \) represents the data vector of \( I(\Delta \lambda) \) after proper discretization, \( A \) is the product of the discretized responsive function \( i(\Delta \lambda - \frac{\nu \lambda_0}{c}) \) and integral weight \( \Delta v \), and \( f \) is the function \( P(v) \) to be determined. Evidently it is an ill-posed problem. We here employ a linear regularization method (Tikhonov & Arsenin 1977; Press et al. 1995) to treat this problem. In application, the inversion technique is to minimize the sum of two functionals, which can be expressed as

\[
| A \cdot f - g |^2 + \mu | K \cdot f |^2 = \text{minimum} ,
\]

where the first term represents the residual, \( \chi^2 \), and the second is a measure of smoothness. \( K \) is a matrix dependent on the specific smoothing method. This technique thus involves a trade-off between two optimizations: agreement between data and solution (i.e., to minimize \( \chi^2 \)) and smoothness or stability of solution.
Equation 3.8 can be easily reduced to a set of linear equations

\[(A^T \cdot A + \mu H) \cdot f = A^T \cdot g ,\]  

(3.9)

where \(H = K^T K\). We suppose that a piecewise quadratic function for \(f\) is a good approximation. Then \((K \cdot f)\) can be represented by the central difference of the third derivative of \(f\) (Newton et al. 1995):

\[(K \cdot f)_m = f'''(v_m) = \frac{-f(v_{m-\frac{3}{2}}) + 3f(v_{m-\frac{1}{2}}) - 3f(v_{m+\frac{1}{2}}) + f(v_{m+\frac{3}{2}})}{(\Delta v)^3}.\]  

(3.10)

From Equation 3.10, we obtain the matrix \(K\) that is then substituted into Equation 3.9, which can be hereby solved by the \(LU\) decomposition method. The ill-conditioning is thus cured through the introduction of the \(\mu\) term. Application of this method can be found in some literatures (e.g., Jeffrey & Rosner 1986; Newton et al. 1995). However, how to precisely define the smoothness (i.e., the value of \(\mu\)) may be crucial to the solutions. To determine the value of \(\mu\), we synthesize the methods proposed by Tikhonov & Arsenin (1977), Titterington (1985), and Metcalf et al. (1990). We impose a random perturbation on the observed profile \(g\) to get a new one, \(g_\delta\). The error, \(\delta = |g_\delta - g|\), is a known value. We then take a finite geometric progression \(\mu = \mu_0 q^k\) \((q > 0)\), for \(k = 0, 1, 2, ..., n\); we select a \(\mu\) that yields a solution of \(f_\mu\) within the required accuracy, i.e., \(|A \cdot f_\mu - g_\delta| \leq \delta\).

To test the validity of the inversion technique, we construct artificial line spectra using different velocity distributions, and then conduct the inversion. The velocity field can be reproduced in most cases based on this method.

### 3.3.3 Results

We apply the method described above to actual computations. Figure 3.4 plots the underlying function \(P(v)\) after deconvolution. Also shown are the mean velocity that is obtained by

\[\bar{v} = \int vP(v)dv ,\]  

(3.11)

and the width of the velocity distribution defined as the range within which \(P(v)\) lies above \(e^{-1}\) of its maximum. From Figure 3.4, we can see that the half width reaches more than 150 km s\(^{-1}\) at the top of the loop for H\(\alpha\), while only about 40 km s\(^{-1}\) for Ca\textsc{ii} \(\lambda 8542\). The mean velocity, however, is relatively smaller: it is no more than 35 km s\(^{-1}\) for H\(\alpha\) and no more than 20 km s\(^{-1}\) for Ca\textsc{ii} \(\lambda 8542\). Therefore, there is an apparent difference in the velocity
Figure 3.4: The velocity probability distribution deduced from $\text{H}_\alpha$ (upper panel) and $\text{Ca\,II\,}\lambda8542$ (lower panel) for the three points at 02:14:38 UT. The center of the horizontal bar in each panel represents the mean velocity; the length of it refers to the width of the velocity profile.

distributions derived from $\text{H}_\alpha$ and $\text{Ca\,II\,}\lambda8542$. This point will be explained below. The two lines, however, can share the same type of line asymmetry, which can be seen from Figure 3.4 in which the average velocities determined from $\text{H}_\alpha$ and $\text{Ca\,II\,}\lambda8542$ possess the same sign. This argument can also be visually checked from the original line profiles.

From Figure 3.5, we can see that the observed line profiles are well recovered; besides, when we adopt other values for $\mu$ that depart from the optimal one, the velocity profiles do not change remarkably. We therefore attain a good agreement between original data and stable solutions. One interesting thing is that, as illustrated in Figure 3.5 (left panel), we can extend the recovered profile to a wavelength window broader than that in observations. This will compensate for the disadvantage of observations in $\text{H}_\alpha$ that are confined to a too narrow wavelength band. We are thus able to calculate the intensity integrated over the whole $\text{H}_\alpha$ line profile. As is commonly known, in the case of line broadening caused by macro-turbulence, only the line profile is broadened, while the equivalent width remains unchanged. By comparing the line integrated intensity of $i(\Delta\lambda)$ with that of the recovered profile $I(\Delta\lambda)$, we just attain an equality as expected.

Having acquired the velocity distribution, we then investigate the temporal
Chapter 3. Physical Conditions in a Flaring Loop

Figure 3.5: Comparison between the observed line profiles (solid lines) and the recovered ones (dotted lines) based on our method.

variation of the half width and the source function. The results are plotted in Figure 3.6. It clearly shows that the width of the velocity distribution and the source function derived from Hα are rather larger than those from Ca II λ8542. Just as stated by some authors (Heinzel & Rompolt 1987; Heinzel et al. 1992), strong turbulent broadening can significantly increase the source function of the Hα line. This point is also supported by the fact that, in the case of Hα, the width of the velocity distribution shows an evolution behavior generally similar to that of the source function. Such a similarity does not exist in the case of Ca II λ8542, which may indicate that the line source function of Ca II λ8542 is less affected by macro-turbulence.

Also note that around the flare maximum (02:15 UT), the width of the velocity distribution and the source function derived from Hα are larger at the top of the loop than in the legs, whereas it is not exactly true for Ca II λ8542. These facts show again the different behaviors of the physical parameters derived from the two lines. Through non-LTE computations, Ding et al. (1999) have demonstrated that the emission of Hα peaks at a higher temperature than that of Ca II λ8542 (see their Figure 3). In the present temperature range (10000 – 12500 K), the emission of Ca II λ8542 is rather weak and decreases with temperature, contrary to the emission of Hα. We find that the source function of Hα deduced here bears an evolution trend very similar to that of the temperature (see Figure 3.3), but this similarity does not hold for Ca II λ8542. This result supports the above points. As the flaring loop contains a large macro-velocity, the two lines may suffer different Doppler brightening or dimming effects as stated above, which can also change the velocity dependence of the line emission. Therefore, we propose that the main cause of the different velocities derived from Hα and Ca II λ8542 is that the emissions of
the two lines depend in different ways on temperature and velocity.

From Figure 3.6, we can also find that the width of the velocity distribution keeps large even in the later phase. This large scale motion can explain the excessive line broadening persisting in the later phase without invoking the non-thermal effect.

### 3.4 Discussion

After showing the feasibility of line broadening caused by large scale mass motions, we now discuss the possible origin of the motions. However, this key problem is rather controversial. In the present observations, the loop top is the brightest region, and the Hα line is most broadened there. Hence, any possible origin of the large scale motions should be consistent with this specific scenario. Uchida & Shibata (1988) have presented an MHD model for the heating of loop flares. In their model, enormous mass is driven dynamically along twisted magnetic tubes into the top of the loop through pinch effect, and
then the material collides at the top. The longitudinal motion is destroyed at
the collision, whereas the rotational motion is strengthened and remains to
exist even after the crash. Due to macroscopic fiction, the rotational motion
may be damped and would develop into a macro-turbulence over an extended
time of tens of minutes. On the other hand, if flares occur through magnetic
reconnection, as generally believed, materials will be driven as outflows from
the magnetic neutral point because huge energy is released there. We can
hence postulate that, if the neutral point is located above the flaring loop, the
outflows will impinge on the loop top and make it significantly condensed. The
macro-turbulence can also be readily induced there. The existence of such a
process is verified by hard X-ray observations (Masuda et al. 1994).

![Figure 3.7: Comparison of the cooling of the loop with a semi-length $L = 2 \times 10^4$ km for different electron densities. Solid lines indicate the cooling including radiative loss and thermal conduction while dotted lines are for the case including radiative loss only.](image)

It is generally believed that cool loops visible in H$_\alpha$ evolve from the cooling of hot X-ray loops (e.g., van Driel-Gesztelyi et al. 1997). It is thereby possible
that the macro-turbulence may remain in the H$_\alpha$ loop provided that the cooling
time of the flaring loop is short enough. We here check this point further.
We have obtained that the mass density in the flaring loop reaches about
$(1 - 3.5) \times 10^{12}$ cm$^{-3}$. We are then able to estimate the cooling time from hot
X-ray loops to cool H$_\alpha$ loops ($T < 2 \times 10^4$ K). We invoke the same method
presented by Schmieder et al. (1995, 1996, and references therein) to compute
the cooling time with an initial temperature $T_0 = 10^7$ K and a semi-length
$L = 2 \times 10^4$ km for the limb flare, taking into account radiative loss and thermal
conduction. The plasma is assumed to be fully ionized, which is approximately
valid above temperatures around $2 \times 10^4$ K. In order to make a comparison, we vary the electron density for several cases: $n_e = 10^{11}, 3 \times 10^{11}, 10^{12}$ and $3 \times 10^{12}$ cm$^{-3}$, respectively. The results are plotted in Figure 3.7.

Examining Figure 3.7, we can see that the cooling time for different electron densities is generally consistent with the results of Gan & Fang (1990, see their Table 3), Švestka et al. (1987, see their Sect. 3), and Schmieder et al. (1995, see their Fig. 10). The cooling time is rather short for electron densities above $10^{12}$ cm$^{-3}$, i.e., no more than 30 s for $n_e = 3 \times 10^{12}$ cm$^{-3}$ and about 1 min for $n_e = 10^{12}$ cm$^{-3}$. Since the loop geometry may exhibit a twisted structure, the path of thermal conduction may be greatly extended and the conductive cooling may consequently become less effective. However, we can see from Figure 3.7 that, in the case of a high electron density, the heat conduction is negligible; the radiative loss plays the leading role in the cooling that is not much affected by the loop geometry.

![Figure 3.8](image)

Figure 3.8: Time profiles of the soft X-ray flux at $1 - 8$ Å (dotted line) and $0.5 - 4$ Å (solid line). Also plotted is the evolution of the source function of Hα (diamonds) at the point B. The arrow indicates the time of the Hα maximum. The units are arbitrary.

Figure 3.8 displays the time profiles of the soft X-ray flux at $1 - 8$ Å and $0.5 - 4$ Å for this flare observed by GOES, as well as the temporal evolution of the source function of Hα at the point B. We can see that, within the time resolution, the flux at the two wavelength bands and the source function peak roughly simultaneously around the Hα maximum. This near simultaneity confirms the quick cooling of the flaring loop. It is thus reasonable to suppose that the macro-turbulence may persist at the top of the Hα loop. In this context, the Hα line at the top of the limb flare will inevitably suffer a great
broadening; the loop top is hotter, condensed, and accordingly has a greater source function than elsewhere.

3.5 Conclusions

We develop a simple method to deduce the temperature and density in a limb flare of 1998 November 11 from the spectral observations at two lines, Hα and Ca II λ8542. We build a grid of homogeneous slab models with various temperature and density values and compute the emergent line intensities using a non-LTE code. The problem is thus to find the relevant model that can match the observed intensities of the two lines. We deduce the values of temperature and hydrogen number density at different spatial points in the flaring loop, as well as their temporal variations. It is found that the loop contains a relatively high density. In addition, the loop top seems slightly hotter and more condensed than the legs of the loop at the flare maximum time.

We propose that the present unusual line broadening is mainly due to large scale mass motions or macro-turbulence, and use an inversion technique to deduce the velocity distribution along the line of sight. The line-of-sight velocity derived from Hα can exceed 150 km s⁻¹, whereas that from Ca II λ8542 is only about 40 km s⁻¹, which may result from the fact that the emissions of the two lines have different dependence on temperature and velocity. This point is also evidenced by different spatial distributions and temporal evolutions of physical parameters derived from Hα and Ca II λ8542 (Figure 3.6).

We suggest two possible origins for the large scale motions that are invoked to account for the observed line width. The flaring loop in this event bears a high mass density and accordingly a very short cooling time (several tens of seconds); therefore, the large motions or macro-turbulence produced in the energy release process (in hot loops) can persist in the cool loops of Hα. The loop top is thus the hottest and most condensed, and it is also most turbulent there.

One may question why only limb flares possess such large inhomogeneous motions. We believe that in disk flares, similar macro-turbulence should also exist. Just because the emission from the flaring loop is superimposed on the background emission, it is not easy to recover the velocity field properly. Usually, the velocity deduced in disk flares is smaller than in limb flares.
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Chapter 4

On the Infrared Continuum in a White-light Flare

Solar white-light flares (WLFs) are among the most energetic flaring events and have attracted much attention in astrophysics. They can produce strong emissions in a broad spectral range, from $\gamma$-ray to radio wavelengths. During the occurrence of a WLF, the solar atmosphere and even the interplanetary space may be disturbed. The study of WLFs is thus of special interest in understanding the mechanism of flares and flare-like phenomena in the universe.

It is proposed that there exist two types of WLFs (Machado et al. 1986). Fang & Ding (1995) studied the different characteristics between them from the aspect of observations and atmospheric models. In the case of type I WLFs, there exists a good time correlation between the peak of hard X-rays or microwave radio burst and the maximum of continuum emission; there is a strong Balmer jump in the spectra; the Balmer lines, in particular the H\textalpha line, are strong and broad, and usually exhibit a pronounced central reversal. However, type II WLFs do not show the above features. This distinction indicates different energy sources and transport processes in these two types of WLFs. In the case of type I WLFs, the enhanced continuum is closely associated with non-thermal electrons released from the upper atmosphere (e.g., Neidig & Kane 1993; Neidig et al. 1993; Mauas 1993; Fang et al. 1995); while for type II WLFs, it may originate from a heating source located in the lower atmosphere (e.g., Mauas, Machado, & Avrett 1990; Ding et al. 1994). Further investigations are required to clarify this point.

However, WLFs are rare events. The occurrence rate of WLFs depends on the heliocentric angle of the flaring region and whether WLFs can be detected relies on the observing wavelength (Hénoux et al. 1990; Neidig, Wiborg, & Gilliam 1993; Ding & Fang 1996). In most cases, enhanced continuum emis-
sions are detected at the Balmer and Paschen continuum. Continuum emission at far-infrared wavelengths (1 µ to 1 mm) produced by synchrotron radiation or non-thermal bremsstrahlung is proposed to exist in solar flares (Ohki & Hudson 1975); Hudson (1975) further suggested some observational techniques to verify it. However, very few observations were carried out later. Spectra at near-infrared wavelengths are relatively easier to observe. Continuum emission in such spectra still originates from the recombination of hydrogen atoms and the emission of negative hydrogen ions (H\(^-\)).

The continuum emission requires an appreciable heating in solar lower atmosphere. In solar flare research, the heating of the lower atmosphere remains an interesting topic since it poses a constraint on the flare energetics and is related to the enhancement of line and continuum emission. In past decades, various energy transport mechanisms have been proposed to deposit energy and heat the layers in the temperature minimum region (TMR) and the upper photosphere. Those include heating by a non-thermal electron beam (e.g., Aboudarham & Hénoux 1986) or a proton beam (Machado et al. 1978), soft X-ray irradiation (e.g., Hénoux & Nakagawa 1977), EUV irradiation (e.g., Machado et al. 1978), dissipation of Alfvén waves (Emslie & Sturrock 1982), and chromospheric radiative backwarming (Machado et al. 1989; Metcalf et al. 1990). However, most heating mechanisms, if working alone, are shown to be insufficient in producing the heating extent to explain observations (e.g., Machado et al. 1978; Emslie & Machado 1979).

On the other hand, observations indicated that flares on stars, for example, those on dMe stars, may in some cases be preceded by a continuum dip (e.g., Hawley et al. 1995). Such a dip is most plausibly explained by the absorption of photospheric radiation by an enhanced H\(^-\) opacity (Grinin 1983), which could be related to the non-thermal ionization by an electron beam (Hénoux et al. 1990; Ding & Fang 2000). Hénoux et al. (1990) further suggested that this phenomenon, called “black-light flares” (BLFs), may also occur on the Sun and presented an observation of a solar flare which shows evidence of a negative contrast of up to ~ 5% at \(\lambda = 5500\) Å. Later on, van Driel-Gesztelyi et al. (1994) searched for BLFs in Yohkoh observed flares but found no unambiguous example.

Using the imaging spectrograph in the solar tower of Nanjing University (Huang et al. 1995), we detected an enhanced emission at the continuum near the Ca\(\text{II}\) \(\lambda 8542\) line in the flare of 2001 March 10. Continuum emission in such an infrared spectral region was firstly reported by Neidig & Wiborg (1984). However, it has been largely neglected in later flare observations. Besides, this flare shows evidence for continuum dip in the early phase, and thus can be regarded as a candidate of BLFs. In this chapter, we present a detailed
analysis of the spectral data and discuss the possible cause of the continuum dip and enhancement.

4.1 Observations and Data Reduction

The flare of 2001 March 10 is located in the active region NOAA 9368 (N27W42, \( \mu = 0.63 \)). According to the Solar Geophysical Data, it is an event with soft X-ray/H\( \alpha \) importance M6.7/1B. The flare began at 04:00 UT and ended at 04:07 UT, peaking at 04:05 UT.

![Figure 4.1: Monochromatic images of H\( \alpha \) (upper panels) and Ca II \( \lambda 8542 \) (lower panels) reconstructed from the 2D spectra at 04:03:36 UT. From left to right, upper panels correspond to images at \( \Delta \lambda = -4, 0, 4 \) Å from the center of the H\( \alpha \) line, while lower panels to those at \( \Delta \lambda = -10.9, 0, 10.9 \) Å from the center of the Ca II \( \lambda 8542 \) line. The field of view is 80" \( \times \) 80". The two bars marked in the lower-left image are used to show the spatial variation in Figure 4.2. The arrows show the orientation in terrestrial coordinates.](image)

Using a scanning technique (Huang et al. 1995), we have obtained a time series of 2D spectra of H\( \alpha \) and Ca II \( \lambda 8542 \). We repeated 28 scans over the flaring region from 03:23:27 UT to 04:12:08 UT. The time interval between two successive scans is about 15 s. Each scan yielded the spectral data of the two lines simultaneously. There exist 160 pixels with a pixel size 0.85" along the slit, and 50 pixels with a spacing 2" in the scan direction. The field of view for each scan is thus 136" \( \times \) 100". The spectrum spans 200 wavelength points with a spectral resolution of 0.05 and 0.118 Å per pixel for the H\( \alpha \) and Ca II \( \lambda 8542 \) lines, respectively. The wavelength window for the Ca II \( \lambda 8542 \)
line extends to the nearby continuum (about ±11.5 Å), while it is not the case for Hα. Therefore, we could identify this flare as a WLF using the continuum emission near the Ca ii λ8542 line as a proxy of optical emission.

Figure 4.2: Variations of the continuum contrast near the Ca ii λ8542 line along the horizontal bar (solid line) and along the vertical bar (dotted line). The two bars are shown in Figure 4.1. The dashed line indicates the location of the cross center of the two bars.

In data reduction, the dark current is subtracted and the flat field is corrected for the CCD cameras. The drift of images at different times is also corrected by coaligning the sunspot locations in those images. The absolute intensity of the spectral data is carefully calibrated by using the method described in Fang et al. (1995). Figure 4.1 displays the monochromatic images of Hα and Ca ii λ8542 reproduced from the 2D spectra. In far wings of the two lines, the flare is still visible. To our surprise, there exists a bright kernel in the image at the continuum near the Ca ii λ8542 line (Δλ = ±10.9 Å). The line emission of Ca ii λ8542 is also enhanced in this flare.
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4.2 Enhanced Emission at the Infrared Continuum

WLFs are characterized as the flaring events with enhanced emission at visible continua. Apparently, it is much more difficult to produce an enhanced emission at the infrared continuum. Based on the above observational results, we propose that this flare might be a WLF. To make a further confirmation, we delineate a cross in Figure 4.1 to investigate the spatial variations of the continuum emission along the two bars. The results are displayed in Figure 4.2. The contrast is defined as $C = (I_c - I^0_c)/I^0_c$, where $I_c$ is the continuum intensity at $\Delta \lambda = -10.9$ Å from the line center of Ca II $\lambda 8542$ for the spatial points along the two bars, and $I^0_c$ is the continuum intensity averaged over the four ends of the bars, which are located in the quiet region. $I^0_c$ is thus regarded as a background continuum intensity. From Figures 4.1 and 4.2, we can see that the contrast is depressed in the sunspot region and rises in the flaring area. As $\mu = 0.63$, the limb darkening effect (Pierce & Slaughter 1977a, 1977b) between different spatial points in the window should be considered. This effect is noticed by checking the different contrasts at the two ends of the horizontal bar. However, the contrast at the flare kernel (the center of the cross) exceeds obviously the values at the four ends. The flare can thus be confirmed as a WLF. The highest contrast is estimated to be (3-5)% taking into account calibration uncertainties.

On the other hand, the H$\alpha$ line within the active region is very strong and broad, showing a pronounced central reversal. The Ca II $\lambda 8542$ line also shows an extremely strong emission in its core. This phenomenon is interesting, which implies an appreciable heating in the chromosphere preferentially by energetic electrons (Canfield, Gunkler, & Ricchiazzi 1984).

We have further analyzed the line profiles at the flare kernel and studied the temporal evolution of some characteristic parameters. Figure 4.3 shows the time profile of the radio burst flux at 7.58 GHz observed by the Broadband Radio Spectrometer of Beijing Astronomical Observatory (Fu et al. 2000). Also displayed are time variations of the intensities at line centers, the full widths at half-maximum of the net emission profiles (with the quiet component subtracted), the line-of-sight velocities (positive values for downward mass motion and negative ones for upward motion), and the continuum contrast near the Ca II $\lambda 8542$ line. All of these parameters are obtained through averaging nine adjacent points within a specific area in the flare kernel. We extract the line-of-sight velocity by using a line-wing bisector method (Ichimoto & Kurokawa 1984; Ding, Fang, & Huang 1995), based on the asymmetries of the two lines.
Figure 4.3: Temporal variations of the radio burst flux at 7.58 GHz, the intensities at line centers, the full widths at half maximum of the net emission profile, the line-of-sight velocities, and the continuum contrasts. The radio flux and line intensities are in arbitrary units. The dashed line indicates the peak time of the radio burst.

From Figure 4.3, we find that the peak of the radio flux temporally coincides with the first peak of the line-center intensities and with the maximum of other parameters; the enhanced continuum emission mainly appeared in the impulsive phase and lasted about 30 s in the present time resolution; the net emission profile of Hα is very broad, with its full width at half maximum more than 7 Å. Such a profile is hence substantially wider than the theoretical profiles computed for some electron-beam-heated model atmospheres (Canfield & Gayley 1987). As the broadening of line wings is mainly due to the Stark effect, this excessive width needs a rather higher ambient electron density, which can probably result from the non-thermal ionization of hydrogen atoms due to the precipitating electron beam. This point is confirmed by the coincidence of
the line width and the radio flux. The electron density should be well above $10^{13}$ cm$^{-3}$, as judged from the non-LTE computations for the Hα line (Fang, Hénoux, & Gan 1993). (We cannot give a more accurate value for lack of high-series Balmer lines.) The result also implies that the continuum emission is related to non-thermal electron bombardment. In addition, the line-of-sight velocity of downward mass motion attains a considerable value, i.e., about 30 km s$^{-1}$ for Hα and about 20 km s$^{-1}$ for Ca II λ8542. This may correspond to the dynamic evolution of a chromospheric condensation.

Figure 4.3 also indicates that there are two peaks in the time profile of the Hα line-center intensity with a time interval of about 1 min. The first peak is relatively weak and may be related to the non-thermal electron precipitation in the impulsive phase, while the second may be caused by thermal effects including heat conduction and irradiation by EUV and soft X-rays in the later phase. It is seen that the downward velocity peaks in the impulsive phase, which is also a typical feature of ordinary flares (e.g., Ichimoto & Kurokawa 1984; Liu & Ding 2001). This dynamic feature may be associated with the explosive heating in the chromosphere by non-thermal electrons (Fisher, Canfield, & McClymont 1985; Neidig et al. 1993).

### 4.3 Continuum Dip in the Early Phase

![Figure 4.4: Line profiles of Ca II 8542 Å at four different times, showing the temporal variation of the line core emission and the nearby continuum. The profiles are normalized to the continuum intensity in the quiescent status.](image)

In addition, this flare can be regarded as a potential candidate of BLFs since its light curve at the near infrared continuum shows a slight dip in the early phase of the flare. To show this clearly, we plot in Figure 4.4 the line profiles of Ca II 8542 Å at the point with maximum continuum dip for four
different times, the first one of which corresponds to the preflare phase, the second one to the early impulsive phase, while the later two to the impulsive phase. This point is located near the edge of the flare kernel. One notices that with the development of the flare, the line core shows a gradually increased net emission; the nearby continuum intensity (the intensity at far wings), however, is first reduced to some extent (04:03:04 UT), and then is enhanced (04:03:36 UT) relative to the quiescent value. The maximum amplitude of the continuum dip measured in this single pixel is $\sim 1\% - 2\%$ compared with the preflare status.

4.4 Interpretation of the Continuum Behavior

Based on the above results, the flare might be categorized as a type I WLF, and non-thermal electron bombardment is a probable energy source for the continuum emission. To check the latter point, we perform non-LTE computations with various input parameters of electron beams. The results, however, show that a non-thermal electron beam cannot produce the expected continuum emission directly. The reason is that the continuum emission near the Ca II $\lambda 8542$ line is formed mainly in the photosphere where the electrons cannot penetrate. Hénoux et al. (1990) have checked the role of non-thermal ionization in WLFs. They found that the contrast is negative for almost all wavelengths longward of the Paschen discontinuity. Non-thermal ionization of hydrogen by electron precipitation results in an increase of the electron density, which yields two consequences: an enhanced hydrogen recombination rate and an enhanced $H^-$ opacity (Aboudarham & Hénoux 1987). From the radiative transfer equation, the emergent continuum intensity depends on which consequence dominates. At the Brackett continuum, the effect of the enhanced $H^-$ opacity seems more dominant, which reduces the continuum intensity to some extent.

To fully account for the increased continuum emission, there should be a temperature rise in the lower atmosphere (the photosphere and the TMR). Therefore, there must exist a heating mechanism responsible for it. We think that the most probable mechanism is radiative backwarming (e.g., Machado, Emslie, & Avrett 1989). An electron beam precipitates into the chromosphere in the impulsive phase, producing an enhanced emission through non-thermal excitation and ionization; the photosphere and the TMR absorb the radiation from the chromosphere, which then induces a temperature rise there. The latter process needs a timescale of 15-25 s (Hénoux et al. 1990), which is comparable to the time resolution of the observations. So the near-simultaneity of the peak of the continuum emission and that of the radio flux shown in
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Figure 4.3 does not exclude this possibility.

To evaluate quantitatively how the lower atmosphere can be radiatively heated in the presence of an electron beam, we adopt a similar method to that proposed by Aboudarham & Hénoux (1987). We consider two cases: a background atmosphere with a precipitating electron beam and a heated atmosphere with an electron beam. Here, the heated atmosphere refers to the one with energy balance obtained. These two cases can be roughly regarded as the early impulsive phase (the onset of beam heating) and the flare maximum phase, respectively. Figure 4.5 plots the continuum contrast at $\lambda = 8500 \text{ Å}$ against the energy flux of the beam in the two cases.

Figure 4.5: Continuum contrast at $\lambda = 8500 \text{ Å}$ varying with the energy flux of the electron beam ($\delta = 4$ and $E_1 = 20 \text{ keV}$). The data are computed in two cases: a background atmosphere with a precipitating electron beam (solid line) and a heated atmosphere with an electron beam (dashed line).

Although this event cannot fully be confirmed to be a BLF since the amplitude of dip is not large enough to exclude the possible effect of measurement error, it is nevertheless consistent with the picture in Figure 4.5 that in the early phase, an electron beam bombards an unheated atmosphere and causes
a continuum dimming. This dimming disappears soon after the atmosphere is heated both collisionally and radiatively. Observations also show that the continuum contrast increases to its maximum of about 4% in about 20 s from the onset of electron beam heating (judged from Figure 4.3). This time period is roughly enough for the lower atmosphere to get fully heated by the radiation from the chromosphere. From Figure 4.5, we see that a beam with a flux of $F_1 = 10^{10}$ ergs cm$^{-2}$ s$^{-1}$ can produce a continuum contrast of $\sim 7\%$, already above the observed value. However, we note that the observed contrast represents a lower limit of the real contrast because of the limit of the spatial resolution.

4.5 Heating of a Sunspot Atmosphere

It is well known that there is a close relationship between sunspots and solar flares. Sunspots represent the most fundamental phenomenon of solar activity. Up to now, the physical conditions and energy dissipation mechanism in the sunspot atmosphere still remain unclear. Solar flares are the explosive processes of energy release in solar atmosphere, whose understanding also needs further investigations. During the eruption of a flare, in particular a WLF, the atmospheric structure of the whole active region may be considerably disturbed. Therefore, observations of WLFs, both spectral signatures and morphology, will offer important clues for the exploration of the above problems.

4.5.1 Theoretical Picture

As is shown in spectral observations and atmospheric modelling (e.g., Mauas, Machado, & Avrett 1990; Ding et al. 1994; Fang et al. 1995), the photosphere and the TMR can be heated to some extent during any type of WLFs. In some situations, such a heating process may extend to the sunspot atmosphere. As a consequence, the size of the sunspot may dwindle or finally be eliminated in the photographic image. This should be a gradual process because of the existence of strong magnetic fields in the sunspot atmosphere. On the other hand, if there exists non-thermal ionization by energetic electrons, i.e., in the case of type I WLFs, the visible continuum may appear dimming with a detectable level in the preflare phase (Aboudarham et al. 1990; Hénoux et al. 1990). Owing to this continuum darkening (the so-called BLF), the sunspot region may accordingly expand.

If the change of the sunspot morphology during a WLF, as predicted above, is captured in observations, it will be of special importance for the diagnostics
of the flare energy transport mechanism and provide a useful tool to explore the physical conditions in sunspots.

### 4.5.2 Observational Scenario

![Figure 4.6](image-url)

Figure 4.6: Contour maps of the Ca II λ8542 continuum contrast at different times overlaid on their gray-scale images. The contour levels are (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5)%, with negative contours drawn in dotted lines and positive ones in solid lines. The four points marked as A, B, C and D are extracted to show the evolution behavior of some characteristic regions. The terrestrial orientation is the same as that in Figure 4.1.

The present observations also show some evidence for the above theoretical picture. Figure 4.6 displays the contour maps of the Ca II λ8542 continuum contrast at different times. It clearly shows the spatial configuration of the
active region: different kernels visible at the Ca\textsc{ii} λ8542 continuum successively emerge nearby three sunspots during the development of the WLF. One phenomenon of special interest is that the sunspot around the point D suffers a pronounced change in morphology with the flare development. Its size is progressively squeezed, and finally it is removed from the continuum image. This process is relatively gradual, with the time scale about 3 min in the present observations. To account for this phenomenon, there should be an appreciable heating in the lower atmosphere, under the constraint of pressure balance between the sunspot and the ambient photosphere. Figure 4.7 illustrates the typical behaviors of the Ca\textsc{ii} 8542 Å line in the sunspot during the heating process. The continuum emission reaches the quiet Sun level at 04:06:00 UT, with an enhancement of 4%-6% compared with the preflare status. Besides, there is an increased emission in the line core, which indicates that the upper atmosphere also undergoes a noticed heating during this process. Later on, the sunspot recovers to its preflare state when the atmosphere cools down.

![Figure 4.7: Line profiles of Ca\textsc{ii} λ8542 at the point D for three times, normalized to the quiet Sun continuum intensity.](image)

In order to obtain a clear picture of the heating process, we select four characteristic sites (shown in Figure 4.6) to study their evolution properties. Figure 4.8 displays the time profiles of the hard X-ray flux in the first two energy channels (14-23 and 23-33 keV) observed by \textit{Yohkoh}. The flux in the higher energy channels (33-53 and 53-93 keV) is not shown, as it bears an evolution similar to that in the 23-33 keV channel. Also plotted are the time variation of the full width at half-maximum of the Hα net emission profile (with the preflare component subtracted) and that of the Ca\textsc{ii} λ8542 continuum contrast. We obtain these two parameters by averaging nine adjacent pixels at these sites. The point A is studied in Section 4. 2, with its parameters well correlated with the radio flux at 7.58 GHz and the hard X-ray flux in the
Figure 4.8: Time profiles of the HXR flux in the first two energy channels observed by *Yohkoh*, the full width at half-maximum of the Hα net emission profile and the Ca ii λ8542 continuum contrast.

higher energy channels; while the parameters at the points B and C seem more correlated with the flux in the lowest energy channel.

In addition, Figure 4.8 indicates that the continuum contrast at the point D gradually approaches zero in about 3 min, consistent with the situation displayed in Figure 4.6. The point B is studied in Section 4.3, whose continuum contrast shows a slight dip about 20 s before the impulsive phase. Because of the low spatial resolution, the sunspot does not accordingly show a detectable morphology change at that time.

Nevertheless, the whole picture of the sunspot during this type I WLF is generally consistent with the theoretical predictions.
4.5.3 Heating Mechanism

Since the width of the H\(\alpha\) line is a good indicator for electron beam bombardment (Fang, Hénoux, & Gan 1993; Fang, Hénoux, & Ding 2000), its correlation with the hard X-ray flux shown in Figure 4.8 implies that energetic electrons may be the main energy input for the sunspot heating. As shown above, radiative backwarming can effectively heat the TMR and the upper photosphere. We hence suggest that electron beam bombardment, followed by radiative backwarming, may be the main mechanism for the sunspot heating.

![Contour diagram of the contrast (in percentage) at 04:03:36 UT subtracted by that at 04:02:34 UT overlaid on the Ca\(\text{II}\) \(\lambda8542\) continuum image at 04:02:34 UT.](image)

Figure 4.9: Contour diagram of the contrast (in percentage) at 04:03:36 UT subtracted by that at 04:02:34 UT overlaid on the Ca\(\text{II}\) \(\lambda8542\) continuum image at 04:02:34 UT.

To fully heat the sunspot, an indispensable condition is that the WLF footpoint is located in or close to the sunspot area. The contour diagram of the contrast at 04:03:36 UT subtracted by that at 04:02:34 UT is displayed in Figure 4.9, overlaid on the Ca\(\text{II}\) \(\lambda8542\) continuum image at the flare onset. It manifests that the footpoint collocation can satisfy that prerequisite. Due to
the strong magnetic fields in the sunspot region, a relatively long time scale is needed to redistribute the input energy. As a consequence, the sunspot should be gradually heated, just as shown in the present event.

4.5.4 Energy Requirement

![Figure 4.10: Wavelength dependence of the contrast at μ = 0.63 obtained through non-LTE calculations for different temperature adjustment in the lower atmosphere of the VALC model.](image)

Figure 4.10: Wavelength dependence of the contrast at μ = 0.63 obtained through non-LTE calculations for different temperature adjustment in the lower atmosphere of the VALC model.

The continuum enhancement in the sunspot region, as described above, needs a temperature increase in the TMR and the upper photosphere. To estimate the temperature rise, we perform non-LTE calculations for atmospheric models with modified temperature structures. Based on the VALC model atmosphere (Vernazza, Avrett, & Loeser 1981), we simply lower the temperature in the TMR and the photosphere by 100, 150 and 200 K respectively, as representing the preflare sunspot atmosphere. Figure 4.10 displays the contrast at different wavelengths in response to the above temperature adjustment. From this figure, we find that the continuum contrast at the Hα wavelength band is
most affected by the temperature changes; while the contrast at wavelengths shortward and longward of that band suffers less influence. As the observing wavelength window for the Hα line does not contain the nearby continuum, this result cannot be tested in our observations. Judged from Figure 4.10, a temperature increase of about 150 K is required to raise the sunspot near-infrared continuum by 4%-6% to reach the quiet Sun level.

Because of the lack of broad band spectra, it is rather difficult to quantitatively evaluate the energy required to fully heat the sunspot. As revealed in Section 4.4, electron bombardment followed by radiative backwarming seems to be the main heating mechanism. Therefore, the total electron energy supplied to the atmosphere can be roughly estimated as

$$\Delta E = F_1 s \Delta t,$$

where \(s\) is the area of the heated sunspot, amounting to \(6 \times 10^{17} \text{ cm}^2\) in our measurement (see Figure 4.6), \(\Delta t\) is the heating time of the sunspot atmosphere that equals to about 3 min as mentioned above, and \(F_1\) is the energy flux of the electron beam. According to the computations in Section 4.4, the present temperature increase requires an energy flux of \(F_1 \sim 5 \times 10^9 \text{ ergs cm}^{-2} \text{s}^{-1}\) with a cut-off energy of 20 keV and a spectral index of 4 for the electron beam. From the above equation, the required energy is computed to be about \(5 \times 10^{29}\) ergs, smaller than that of a typical WLF (Neidig 1989). In the present event, this energy comprises only a small part of the total energy released in the whole flare since many areas besides the sunspot are also heated. Hence, this is a good example showing that, during a WLF, the released energy is sufficient to heat a sunspot and to make it disappear in photospheric images.

### 4.6 Observational Constraint

Based on the hard X-ray flux observed by Yohkoh, we use a similar method to that in Fang et al. (1998) to get the flux spectrum of the electron beam that produces the hard X-ray emission. To avoid the contamination of thermal bremsstrahlung, we use the 23–33 and 33–53 keV flux curves to derive the power index and the energy flux of the beam. In this method, the key parameter is the total area with electron beam heating, which is difficult to determine. Since one of the most significant effects of a non-thermal electron beam is to broaden the Hα line (e.g., Fang et al. 1993), we arbitrarily attribute the profiles with a full width at half maximum of the net emission exceeding 3 Å as caused by non-thermal effects. The total area thus amounts to \(1.13 \times 10^{18}\) cm².
Figure 4.11: Deduced energy flux and power index of the non-thermal electron beam based on the hard X-ray flux observed by Yohkoh.

The deduced power index, $\delta$, and the energy flux of the beam, $F_1$, are shown in Figure 4.11. One finds that during the impulsive phase ($\sim 04:03–04:04$ UT), $\delta$ varies in the range of 3–6. In deriving the energy flux, we have adopted two values for the low-energy cut-off, $E_1 = 20$ keV as usually assumed, and 50 keV as implied by a recent investigation by Gan et al. (2001) that the cut-off energy may be higher. In the first case, $F_1$ reaches a maximum of $\geq 10^{11}$ ergs cm$^{-2}$ s$^{-1}$ while it is about one order of magnitude lower in the second case. However, we note that in both cases, the energy flux is large enough to explain the observed enhancement of continuum emission.

### 4.7 Conclusions

We have presented a detailed analysis of multi-line 2D spectra for a flare of 2001 March 10. During the flare, we have detected an enhanced continuum emission near the Ca II λ8542 line that lasted about half a minute. The highest contrast is estimated to be 3%-5%. On the other hand, it also shows evidence
of continuum dimming in an early phase, i.e., at the beginning of flare eruption. Therefore, this flare is among very few candidates of the BLFs that are supposed to exist on the Sun (Hénoux et al. 1990). The continuum emission shows a good time correlation with the radio flux at 7.58 GHz and the hard X-ray flux. This fact suggests that the flare may be classified as a type I WLF.

We quantitatively explain the origin of the continuum feature for this flare in terms of an electron-beam-heated flare model. In the early phase, an electron beam is accelerated to bombard an unheated atmosphere; the non-thermal ionization by the beam results in an increased H\(^-\) opacity which then reduces the emergent intensity. With the flare development, the atmosphere is gradually heated. In this period, radiative backwarming is the chief heating agent in the TMR and upper photosphere. These results are consistent with the observed picture.

Besides, we have detected obvious morphology changes of a sunspot during this WLF. With the flare development, the continuum emission near the Ca\(\text{II}\) 8542 Å line in the sunspot region reaches the quiet Sun value within 3 min, showing an increase of 4%-6% relative to the preflare status. This progressive continuum enhancement makes the sunspot finally removed from the continuum image. It recovers from heated to original state only when the atmosphere cools down. We suggest that energetic electrons coupled with the radiative backwarming effect plays the main role in the heating of the sunspot atmosphere. The spatial configuration of the active region seems to support this point. We further estimate the temperature rise in the sunspot lower atmosphere and the energy input to account for such a heating. The outcome indicates that it does not challenge the energy requirement for a typical WLF.

Based on the hard X-ray emission observed by Yohkoh, we deduce the energy flux of the non-thermal electron beam in the impulsive phase, which is shown to be large enough to account for the present continuum enhancement.
Bibliography


Chapter 5

Summary

In Chapter 1, I present a brief introduction to solar flares. As described in that part, solar flares greatly affect the solar-terrestrial environment, and thus have been at the focus in solar physics. Although flares have been studied for many years, some fundamental problems, such as the energy transport mechanism in flares, still remain unsolved. There hence brings about the significance of 2D multi-spectral observations. In the following chapters, I describe our initial attempts to investigate the distribution of physical parameters in the flaring region, the line broadening mechanism and the flare energy transport process, based on three typical flaring events with good 2D spectral data. The main results and their significance are summarized as follows.

1. A modified cloud method and its application to a flare
Time series of 2D spectra of Hα and Ca II λ8542 for a flare of 1999 December 22 are obtained and analyzed with a new fitting technique, termed as the modified cloud method. The method we propose can simultaneously obtain the four parameters: the line source function, the optical thickness at line center, the line-of-sight velocity and the Doppler width. We present the spatial distributions of the physical parameters and their temporal evolutions determined from the 2D spectra. Based on the parameters obtained above, we present an interpretation of the property of the line asymmetries in the flaring region. Our results are consistent with the general picture predicted by the flare dynamic models, and are useful for a better understanding of the flare dynamics.

2. Physical conditions in a flaring loop
The line profiles of Hα in a limb flare of 1998 November 11 appear to be unusually broadened. It is considered that macro-turbulent (or macroscopic mass motions) may be one of the main causes. We employ an inversion technique
to extract the probability distribution of the line-of-sight velocity in that limb flare. There exists some difference between the velocity distribution deduced from Hα and that from Ca II λ8542, which may reflect a distinct dependence on temperature and velocity of emission for these two lines. We also develop a simple method to deduce the temperature and density in the loop of the limb flare by using non-LTE computations, from the spectral observations of Hα and Ca II λ8542. We first build a grid of homogeneous slab models with various temperature and density values and compute the emergent line intensities, and then find the relevant model that can match the observed intensities. We obtain the values of temperature and hydrogen number density at different spatial points in the flaring loop, as well as their temporal variations. The loop contains a relatively high density and possibly, the loop top is slightly hotter and more condensed than the legs of the loop at the flare maximum time. Since the loop density is high, we obtain a rather short cooling time (several tens of seconds) from hot X-ray loops to cool loops visible in Hα. Possible scenarios to produce these results are further discussed. The line broadening mechanism and physical conditions obtained along the loop are of special interest since they might provide a constraint on the flare models.

3. On the infrared continuum in a white-light flare
We have obtained a time series of two-dimensional spectra of Hα and Ca II λ8542 for a flare on 2001 March 10. This flare shows an enhanced emission at the continuum near the Ca II λ8542 line. The continuum contrast is estimated to be 3%-5%. This emission lasts about half a minute, showing a good time correlation with the microwave radio flux at 7.58 GHz and the hard X-ray flux observed by Yohkoh. The flare can be classified as a type I white-light flare. This flare also shows a negative continuum contrast in the early phase with the maximum amplitude of 1%-2%, and therefore can be regarded as a candidate of black-light flares. We quantitatively explain the origin of the continuum behavior in terms of a flare model heated by an electron beam. By making non-LTE model calculations, we find that in the early phase, when the electron beam bombards an unheated atmosphere, the non-thermal ionization by the beam results in an increased H− opacity which then reduces the emergent intensity. With the flare development, the atmosphere is gradually heated. In particular, radiative backwarming plays the chief role in the heating of the temperature minimum region and upper photosphere. In addition, the atmosphere of a nearby sunspot is gradually heated during this flare. The infrared continuum contrast in the sunspot region approaches zero in about 3 min, with an increase of 4%-6% in the present case. Judging from the spatial collocation of the active region and the time correlation of the continuum emission with the
hard X-ray flux, we propose that electron precipitation followed by radiative backwarming plays the main role in the sunspot heating. The temperature rise in the lower atmosphere and the corresponding energy requirement are further estimated. The results show that the energy released in a typical white-light flare is sufficient to power the present sunspot heating. We further find that the energy flux of the electron beam deduced from the hard X-ray emission is large enough to account for the continuum enhancement. These findings are of special importance for the diagnostics of the energy transport mechanism in flares and provide a useful tool to explore the physical conditions in sunspots.
Appendix A

SolarTower 2.0

This is a data-processing and visualization software for the solar tower of Nanjing University. It is characterized by graphical user interfaces, platform independence and fool-proof operation. I develop this software mainly for my colleagues who can save much effort from the tiring work of data processing with its assistance. This software may be used, copied, or redistributed as long as it is not sold, and it is provided as is without any express or implied warranties. The copyright is reserved to Liu Ying, poPup Studio. Explanation of this software is listed below.

Purpose
Do quick look at images or contour diagrams reconstructed from different wavelengths, dark-current subtraction, flat-field correction, wavelength and intensity calibration, output of PS and GIF files, spectra examination, etc.

Note
• The file named “*.a” means the data file of Hα, while the file named “*.b” is the data file of CaII λ8542.
• If an error occurs in reading a file, please check the value of N_SCAN in routines READFILE and READFD.
• If an error occurs in dark-current and flat-field correction, please check whether the files the user has input are the corresponding ones for the dark-current and flat-field.
• According to the output line center after calibration and the corresponding spectral resolution, the user can change wavelength in pixels to in Å. The spectral resolution is 0.05 Å pix\(^{-1}\) for Hα and 0.118 Å pix\(^{-1}\) for CaII λ8542, respectively.
• After conducting wavelength and intensity calibration, please do not hesitate
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to save the spectral data coupled with the PS file at a specific point that the user is interested in.

- Knowing the variables in the common block, the user can readily conduct data processing more detailedly by clicking the menu item of “Execute...” and inputing the procedure of one’s own. On the other hand, the user can adopt the procedures in the software for one’s own purpose.

Common Block

- data, the raw data, in form of data(n_wave, n_slit, n_scan).
- header, the header of the CCD file.
- sname, the selected data file.
- open, a switch argument, if a solartower file is opened, open=1; or open=0.
- x_size, the actual image size in the horizontal direction with a magnification factor of 3.
- y_size, the actual image size in the vertical direction with a magnification factor of 3.
- n_wave, the pixel number of data along the wavelength.
- n_slit, the pixel number of data along the slit.
- n_scan, the scan number of data along the scan direction.
- imdata, the image at a specific wavelength, in form of imdata(x_size, y_size).
- imgcntr, a switch argument, imgcntr=1 with an image displayed; imgcntr=2 with a contour diagram displayed.
- wave, the wave point the user input.
- icon, the relative continuum intensity used for intensity calibration.
- res, the spectral resolution.
- cen, the line center determined with gaussian fitting.
- dark0, the raw data of the dark-current, in form of dark0(n_waved, n_slitd, n_scand).
- n_waved, the pixel number of dark0 along the wavelength.
- n_slitd, the pixel number of dark0 along the slit.
- n_scand, the scan number of dark0 along the scan direction.
- opend, a switch argument, if a dark-current file is opened, opend=1; or opend=0.
- flat0, the raw data of the flat-field, in form of flat0(n_wavef, n_slitf, n_scanf).
- n_wavef, the pixel number of flat0 along the wavelength.
- n_slitf, the pixel number of flat0 along the slit.
- n_scanf, the scan number of flat0 along the scan direction.
- openf, a switch argument, if a flat-field file is opened, openf=1; or openf=0.
- dfc, a switch argument, if the dark-current is subtracted and the flat-field is corrected, dfc=1; or dfc=0.
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- lastc, the last character of the input data file.
- rencali, a switch argument, if relative intensity calibration is conducted, rencali=1; or rencali=0.
- abscali, a switch argument, if absolute intensity calibration is conducted, abscali=1; or abscali=0.
- abscon, the absolute continuum intensity used for intensity calibration.

Modification History
2001.3, SolarTower 1.0, developed by Liu Ying;
2001.4, SolarTower 2.0, updated by Liu Ying;
2002.1, new functions added by Liu Ying.

Future Development
The user can easily make a further development of this software in the present frame. Doing so, the user should firstly produce a new widget in the procedure of WID_BASE_0, then add the name of the widget event to the procedure of WID_BASE_0_event, and finally realize the function of the new widget. The user can imitate the present way in the software, which will make the update easy. Another way of update is to use the GUIBuilder provided by IDL.