太阳二维光谱观测研究的进展和展望

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摘 要

论述了太阳二维光谱观测和研究的重大意义，综述了二维光谱观测技术和仪器的进展，特别介绍了应用 CCD 的成像光谱仪的最近发展。文中还介绍了近年来二维光谱观测研究所取得的一些新结果，展望了未来观测技术和课题研究的发展前景。

关键词 仪器：光谱仪 — 太阳：耀斑 — 太阳：日珥 — 太阳：米粒组织 — 太阳：基本参数

The Observational Study of Solar Bidimensional Spectra: Its Present and Future

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Abstract

This paper discusses the significance of solar bidimensional (2D) spectral observational study. It reviews the progress in the observational techniques and instruments of 2D spectroscopy, especially the recent progress in CCD imaging spectrographs. Some new results of solar 2D spectral observations and researches are presented. The prospects of the future observational techniques and researches are also discussed.

Key words Instrumentation: spectrographs—Sun: flares—Sun: prominences—Sun: granulations—Sun: fundamental parameters

1 Significance of solar 2D spectral observational study

Spectral observation is one of the main methods to obtain quantitatively various

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solar physical parameters, such as temperature, pressure, magnetic field, velocity etc. Compared with monochromatic observation (through filters), the main advantages of spectral observations are as follows: (a) It is the only method to determine the temperature, the density and the pressure etc.; (b) It is an effective method to measure precisely the velocity field, especially the velocity with a large value, which overpasses the variable range of the passband of filters; (c) It allows us to obtain the whole Stokes profiles, making the precise measurements of the magnetic structures and the depth-dependent variations of magnetic field possible. However, previous spectral observations are mainly one dimensional at fixed points and can hardly be used for 2D analysis. The use of spectra-spectroheliograph (S^2HG) provides one way to the 2D spectral analysis. However, its temporal resolution is very low, due to the use of photographic method. The data reduction is also time-consuming. So the problem still remains open.

In recent years 2D CCD technique has been greatly developed. It has been widely used in many field of astronomical measurements. The application of 2D CCD technique to the solar spectral observations gave birth to the so-called imaging spectrograph and imaging spectroscopy [1]. By use of the technique of the computer-controlled scan of solar images with the CCD high-speed data acquisition, the spectra at every point in a solar local region can be obtained in a relatively short period (say, 10–20s). This technique makes the spectral study be developed into a new stage, and provides a powerful tool for solar research.

The 2D spectral observation gives four dimensional (3D spatial and 1D temporal) information with a certain resolution. It is of great significance in the study of solar physics in two aspects:

(a) To make the "stereoscopy" become a reality. That is to say that a realistic possibility has been provided for the study of the 3D structures and spatial movements of various solar phenomena, so the situation of previous study confined mainly in one-dimensional spatial distribution (by fixed-point spectral observations) or in two-dimensional planar distribution (by monochromatic image data) has been completely changed, and the field of study has been greatly broadened.

(b) To provide a realistic possibility for the quantitative study of the fast evolution ($\sim$ 10s) of various solar phenomena. It allows us to follow the spatial evolution of different phenomena (e.g. filamemt eruption), not only showing the variations of their morphologic structures, but also giving quantitatively the evolution of the process of their physical parameters (velocity, temperature etc.). It is of essential significance for the study of the dynamic process of the phenomena. Thus, it is expected that the imaging spetroscopy will certainly become a powerful tool for the study of solar physics and open a new page for it.

2 Progress in the instruments for 2D spectral observation

In 1970's people began to use S^2HG to make 2D solar spectral observation [2]. Let solar disk scan over the slit of spectrograph and take frames of photograph one by one at the exit of spectra, one can obtain the 2D spectral data of a region on the solar disk. A series of S^2HG data, mainly in Hα waveband, were obtained in 1980's at Yunnan Observatory, and the distribution of 2D physical parameters of some loop prominences and active regions are studied (e.g. [3], [4]). A similar technique is also used with the solar tower of Nanjing University, and the 2D structures of some loop prominences and prominences are analysed [5,6]. By the end of 1970's, an important progress is the development of MSDP spectragraph at Meudon Observatory, France [7]. It can be used to obtain a 2D monochromatic image at nine points of the wavelength of Hα line within a relatively short time interval (~ 3s). That is, the 2D Hα spectra of a solar local region can be obtained, but there is only 9 points in each Hα line profile. Recently a new MSDP system has been put into operation [8], by which two lines (Hα and NaI D lines) can be observed simultaneously. By use of the 2D spectral data from MSDP, much work on the prominences, filaments, two-ribbon flares, loop prominences and the chromospheric structures has been done and fruitful results have been obtained (e.g. [9], [10]).

Some other methods of 2D spectral observation have also been developed. For example: By use of monochromatic images at different wavelengths obtained with universal birefringent filter, 2D spectra can be reconstructed [11]; The multi-slit spectrograph at Lockheed Solar Observatory in United States [12]; With an image slicer, the image around the slit can be moved to different heights along the slit and then the spectra of this region can be obtained simultaneously [13]; A method of obtaining 2D spectra by using optical fibers to guide the light from different regions onto the slit has been tested [13]. However, due to a series of difficulties, such as the correction of the profile of the filter passband etc., and the disadvantages (low spatial or spectral resolution, too small observed region etc.), all these methods were not developed and widely used.

Since 1980's, CCD has been widely used in solar observations. It was firstly used to do 2D spectral observations at Sac Peak Observatory of NSO in United States [14]. Later on, the rapid development of computer and the improvement of CCD performances provide the basic conditions for the reform of the 2D spectral observation technique. In recent years more and more observatories have constructed imaging spectrograph and put them into operation. The situation and the characteristics of various instruments are listed in Table 1. Though film is still used in the MSDP at Meudon Observatory, it is also listed in the table as a kind of important and still useful system to make 2D spectral observations.

It should be mentioned that, due to the use of computer and corresponding software,

Table 1 The main imaging spectrographs in the world

observatory or station	instrument	spectral lines	spectral resolution	spatial resolution	temporal resolution	dedicated year	ref.
Sac Peak USA	1.1m solar tower, echelon spectrograph universal filter	single waveband (Hα)	0.1Å	2″.6	10s 100×100 pixels 1″.8/pixel	1982	[14]
Mees Univ. of Hawaii USA	25cm coronagraph	single waveband (Hα±5Å)	0.2Å	2″.5	9s 50×60 pixel 3″/pixels	1990	[1]
Norikura NAO of Japan	25cm coronagraph	single waveband	0.1Å	2″	15s 120×100 pixels 2″/pixel	1989	[21]
Univ. of Bern Switzland	14cm telescope	single waveband (Hα±3.5Å)	0.5Å	3″	5s 15×48 pixels	1987	[40]
Meudon Observatory France*	60cm vacuum telescope	2 wavebands (Hα, NaI D)	≥0.06Å	2″	38s 150″ × 240″ (by film)	1990	[8]
Nanjing Univ. China	60cm solar tower	2 wavebands (Hα,CaII K)	0.05Å	3″	10s 2×60 × 200 pixels 2″/pixel	1991	[41]
Purple Mountain Obs. China	40cm ceolostat	single waveband (10830Å)	0.18Å	3″	~ 60s 512×512 pixels	1991	[42]

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the observation of imaging spectragraph is rather "flexible". It can not only chose regions with different areas and range of wavebands , but also select different spatial and spectral sampling intervals. It can thus well meet the requirements of different research work. In Table 1 only some typical characteristics of various imaging spectrographs under general conditions are listed.

3 Some new results of 2D spectral observations

Due to the low temporal resolution and time-consuming analysis, previous 2D spectral observations were mainly made for some slow-varying solar phenomena, such as loop prominences, quiet prominences and active regions. In recent 2D spectral observations, especially due to the appearance of imaging spectrograph, the temporal resolution has been greatly improved, so that the field of study has been enlarged to many aspects.

This paper gives only a brief description on some work in the recent years.

3.1 Study of flare physics

Imaging spectral observations provide a good approach to the study of the 3D structure and the evolution of flares. By use of a CCD camera, more than ten flares in the active region AR. 5395 of 1989 March, including a X4.6/3B two-ribbon flare of March 10, were observed at Sac Peak Observatory. The analysis by Wülser and Canfield [15] showed that the width of the Hα line at the flare kernel is the biggest one and increases with the hard X-ray flux. The emission profile is broader at outer edge than at the inner edge of the ribbon, indicating that the heating by non-thermal electron beam is larger at the outer edge. According to the theoretical result, which shows that the Hα line profile under non-thermal electron heating should fairly broad and has a central reversal [15a,15b], Canfield et al. [16,17] found that in a flare the electron beam bombarded point was located on the magnetic neutral line, not coincident with the position of the maximum of current. By measuring the number of pixels where the red wing of Hα lines has strong emission, Zarro et al. [18] found that in a X1.2/2B flare of 1989 March 11, the size of electron bombarded area was $(2.2\pm0.7)\times 10^{17}$ cm^2. They also pointed out that within the temporal resolution of the observation ($\sim$ 16s), the red-shift of Hα line and the blue-shift of CaXIX line as well as the impulsive increase of hard X-ray are well coincident. Using the results obtained by an imaging spectrograph with high temporal resolution in Switzland, Graeter [19] studied a X1.6/3N flare occurred on 20 June, 1989. He pointed out that at one flare kernel the maximum of the Hα intensity is coincident with the maximum of hard X-ray and microwave burst within several seconds, but at another kernel this relationship does not exist. This implies that the former kernel is probably related to non-thermal electron beam bombardment. Similar result has been obtained by Wülser and Marti[20] in the study of a M1/1B flare of 1987 May 24. Using the coronagraph at Norikura station of NAO in Japan, Fang et al. [21] made 2D spectral observation of CaII K line for the flare of 1991 Oct.18. Besides the verification of the existence of red-asymmetry in the line profile, a mass ejection along the flare loop was detected. Moreover, by use of the MSDP data, Schmieder et al. [22] studied the 2D spectra in the gradual phase of several flares and found that there is a blue asymmetry in Hα lines. They suggested a continual evaporation of chromospheric material during the gradual phase to explain this phenomenon.

It is worth pointing out that the imaging spectral observation is a very important tool to study the precursors of flares, because it can provide the information of 3D atmospheric structures and physical parameters before the flares, and then allow us to find some clues about the energy storage and release in flares. Some results of previous observations about the flare precursors, such as the upward movement and the activation of filaments [23,24] and the red-shift regions on the Hβ velocity pattern [25] etc., can be quantitatively analysed in detail by use of the imaging spectral observations. These will be the important topics to be studied in the future.

3.2 Study of prominences

Previously, the 2D spectra of prominences were obtained by the methods of scanning solar disk or S^2HG. By use of these data the distribution of the physical parameters of loop prominences (e.g. [4, 26, 27, 28]), the 2D distribution of the physical parameters in a quiet prominence[29], and the atmospheric models at different heights of prominences etc.[30] have been studied. Using the 2D spectral data of MSDP, the group at Meudon Observatory developed a so-called "differential cloud model"[31] and made a series of studies on the distribution of physical parameters, such as velocity etc., of prominences. They obtained some interesting results. For instance, the study of the physical parameters of some loop prominences showed [32,33] that the mass downflow velocity in the loop prominences is much lower than the free falling velocity, and it can not be explained even by introducing a gradient of pressure. Moreover, they found that the electron density in some loop prominences is only $\sim 3\times 10^{10}$ cm^{-3} and the pressure is only $(0.18–0.3)\times10^{-5}$ cm^{-2} etc. By use of the MSDP data and a non-LTE code, Wiik et al.[10] analysed the 2D distribution of physical parameters in a quiet prominence. Besides obtaining the electron density being $(1–5)\times10^{10}$ cm^{-3}, they found that the prominence is highly inhomogeneous, having sheared or twisted fine structures.

The formation, movement and evolution of filaments have also been studied by use of 2D spectral observations. It is well known that the filaments are formed near the magnetic neutral lines. Some filaments move upward slowly with a velocity of about several kilometers per second. Some filaments have rotational and oscillatory movements (see review in [34]). Recently a series of studies on the fine structure of filaments have been made in detail (see review in [35]). In this aspect, the 2D spectral data with high spatial resolution ($\sim 0''.5$) obtained by the MSDPs installed at Pic du Midi and Spanish Canary are especialy useful. For example, Schmieder et al.[36] found that the plasma at the feet of filaments moves upward and downward with a velocity of as high as ±15 km·s^{-1}. It was also found that the horizontal threads in filaments often move slowly upward, disappear and reform at the original place several minutes later.

By the method of reconstruction of line profiles, Mein and Mein [37] concluded that along the line-of-sight filaments on an average consist of several threads with a standard deviation of velocities being 6–7 km·s^{-1}.

3.3 Study in other aspects

Besides the study of flares and filaments, 2D spectral observations also provide a possibility for the study of other active phenomena and the atmospheric structure of the quiet Sun. However, at present the study in this aspect is not so much and should be developed further.

Mein et al.[38] proposed a non-linear profile inverse method, based on Fourier analysis, with which four physical parameters including the velocity, the temperature and their gradient can be obtained. They used it to analyse a series of high-resolution spectra at CaII 3968Åand found that the line profiles with an enhanced blue peak can be explained by a downward velocity gradient and a relative high temperature. Using the MSDP data, Roudier et al.[39] studied the dynamic process of granule. The result indicated that the material in the granule moves indeed upward and the velocity fluctuation can go through to a higher latitude than that for the intensity fluctuation. Especially, they found that the big granules with a size about 3″ are the main carriers of convective energy.

4 Prospects for the future

The application of CCD 2D spectroscopy has already opened up a new way to the research of solar physics and achieved much important progress. However, both the observational technique and the research work remain to be improved and developed further.

In the aspect of the observational technique, the main insufficiency of the imaging spectrograph using CCD and solar scan system is the low temporal resolution (~10s). The spatial resolution also changes during the scan of solar disk. Along with the increase of the speed of data gathering and storage by computers, these deficiency will be improved. The MSDP system developed in France has relatively high temporal resolution (~2–3s) and spatial resolution, but the spectral resolution is largely limited and difficult to improve greatly. In addition, by use of a series of filters working at different wavelengths in line profiles, the multi-channel 2D spectrograph is as a new way worth being developed. The main problems that need to be solved are the reduction of light scattering, the collection of huge numerical data and the precise reconstruction of the line profiles.

Generally speaking, the direction of developing the imaging spectroscopy are as follows:

(a) Increase of temporal resolution, say, to the order of magnitude of one second. The key problem is to increase the speed of data storage.

(b) Improvement of spatial resolution. For instance, by use of adaptive optics, correlation guiding system and the technique of reconstruction etc., the atmospheric perturbation may be "fixed" as far as possible, so that the 2D spectra with high quality can be obtained.

(c) To obtain 2D multi-line spectra simultaneously, so that the uncertainty in theoretical analyses can be reduced to a minimum.

In the aspect of the research work, an important task at present is to develope a series of techniques for line profile inversion and corresponding softwares. so that the 2D spectral data can be analysed in large quantities to obtain desired physical parameters. It is expected that along with the solution of these problems, the study of 2D spectral data will make essential contributions at least on the study of the following subjects:

(a) Flare precursors, including the preheating of flares, the emergence of magnetic flux, the movement of sunspots, the activity and the activation of filaments and the velocity field before flares etc.

(b) The structure and the dynamics of flare loops, such as to determine the position and the size of flare footpoints, studying the movement and the evoluton of flare atmospheres, analysing the formation and the structure of post-flare loops, studying the chromospheric evaporation during flares and to explore the energy transport mechanism in flares etc.

(c) The structure and the movement of prominences, including the 3D distribution of physical parameters, the mass motions, the radiative transfer and the energy balance, as well as the fine structures in prominences etc.

(d) The 3D structure and the evolution of active regions.

(e) The 3D structure and the evolution of other solar active phenomena, such as sunspots, facula, flocculi, surges and spicules etc., as well as the turbulence and the heating of the atmosphere of the quiet Sun.

We just list in brief the above subjects, though there are still others left out. In summary, it can be seen that as a powerful tool, 2D spectral technique provides a condition never had before and opens up a wide field of research on solar physics.

No doubt, 2D spectral observations and studies must be flouishing and give fruitful results in the near future.

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