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Solar Spectroscopy using 50 Meters of Fiber Optic Cable and CCD Camera

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ABSTRACT

Measurements of the variation of the Ca II K line profile using very modest equipment is discussed. The equipment used included a Spex 0.75 meter spectrometer, a Santa Barbara Instrument Group 16 bit ST-6 Charge Coupled Device (CCD) camera, fiber optic cable, and a 10-inch Cassegrain telescope. Observations were made in both regions of little or no solar activity as well as in regions of high solar activity (sunspots). A roughly 8% increase in Ca II K emission was observed over a sunspot. The combination of the unique observing apparatus and the intensity resolution of the CCD camera was essential for the success of the experiment.

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I. INTRODUCTION

It has long been known that the Ca II K line of the Sun and other stars exhibits a self-reversal (this phenomena will be discussed more fully below), in the one angstrom core of the line, which varies with time and solar activity.[1] Since the measurements of Wilson and Bappu, there has been a considerable amount of research conducted on the K line. It has been seen that the K line emission intensity does in fact vary with the solar activity cycle.[2,3] It has also been seen that there is a local variability of the K line, which has been attributed to local areas of activity, i.e., sunspots.[2,3] The focus of the experiment is to attempt to detect the variability of the self-reversed core using the Santa Barbara Instrument Group (SBIG) ST-6 CCD camera and other very modest equipment.

For our study, we obtained four major pieces of apparatus, a 0.75 meter spectrometer, a spool of fiber optic cable, a 10-inch telescope, and the ST-6 CCD camera with all necessary hardware. In addition, the mount to attach the CCD camera to the spectrometer and the mount to hold the fiber optic cable to the telescope were designed and built in the Physics Department. We also designed a lens system to more effectively couple the output light from the fiber optic cable to the spectrometer. A complete listing of all the equipment used can be found on page 6.

Once the entire apparatus was assembled, we began our survey of the solar spectrum in the vicinity of the Ca II K line approximately 3934 Å. After competing with the typical cloudy Missouri winter and spring, we finally observed sunspots on the solar disk and were able to observe the K line emission. The intensity of the K line emission was found to vary over the several sunspots that were observed. The largest increase in the emission intensity was found to be approximately 8%.

II. EQUIPMENT LIST

ITEM	COMPANY	MODEL #
Fiber Optic Cable	Beiden	220001
Cassegrain 10-inch telescope	Celestron	217
Double convex lens 70 X 35 mm EFL	Edmund Scientific	32879
Telescope-fiber optic mount	Physics machine shop	---
CCD spectrometer mount	Physics machine shop	---
Aspheric lens 12 X 8.5 mm EFL	Rolyn Optics	17.1015
CCD camera	Santa Barbara Instruments Group	ST-6 OPTO-HD
3/4 meter spectrometer	Spex	1500
IBM 286 compatible computer	Zenith	---

III. BACKGROUND

Before beginning the discussion of the Ca II K line variation, a clarification on the notation used in this discussion is appropriate. The K designation of the Ca II line arose when Fraunhofer first studied solar spectra. Fraunhofer designated several of the absorption lines of the solar spectra, in the order in which they appeared, by letters of the alphabet. [The K notation should not be confused with the K electron subshell of an atom. It is merely an old spectroscopic notation and nothing more.]

A. Description of the Solar Chromosphere[4,5,6]

The solar chromosphere is the inner most layer of the solar atmosphere directly above the photosphere and is only a few thousand kilometers high. The photosphere is the "surface" of the sun, or more appropriately, the region of the sun which is seen with the naked eye. Sunspots reside on, and solar flares, prominences, etc. erupt from, the photosphere. From this point of view, the chromosphere could be said to be analogous to the earth's atmosphere. Since the chromosphere is directly above the photosphere, chromospheric effects are very difficult to detect in normal daylight. However, the chromosphere has emission lines, unique to it, in the blue and ultraviolet wavelengths. With the unique lines, we can make direct observations of the chromosphere during the day.

The spectrum of the chromosphere shows strong hydrogen Balmer lines (transitions from the $n=2$ state) and also from Fe II, Chr II, Si II, and others. All of these lines are seen as emission lines because they are observed as an optically thin layer of hot gas against a background of cooler interstellar matter. The spectral lines attributed to the chromosphere are lines which are formed in layer with a T_{eff} up to about 15,000 K. This raises an interesting question: How can the photosphere, with a T_{eff} of about 6,000 K, heat the chromosphere to temperatures far greater? Unfortunately, there is not an all encompassing theory of how the chromosphere is heated to these temperatures. However, the strength of the K line emission is an indicator of the amount of extra energy which is being transferred to the chromosphere. A few of the theories which describe where this extra energy comes from will be reviewed, but, due to their length, will not be covered in depth.

One way of heating the chromosphere is Joule heating. This arises from changing magnetic fields causing electric current to flow through the chromosphere. Since the chromosphere is composed of ions, there are a sufficient number of electrons to develop a current. As we well know from basic physics, if a current flows through a medium with a certain resistivity, the medium will be heated due to collisions between the electrons and the molecules of the medium. However, the chromosphere is a rather low density medium, thus there are relatively few collisions. This fact allows us to conclude that Joule heating alone will not contribute significantly to chromospheric heating.

A second heating method to consider is by heat conduction In this process, particles from higher layers of the atmosphere, with their correspondingly higher velocities might migrate into the lower cooler layers and, through collisions, transfer their kinetic energy to the lower layer. The converse of this also occurs for particles from the lower layers. A third form of heating is by acoustic or magnetohydrodynamic waves. These waves are formed by the large turbulent velocities in the solar granulation of the photosphere. As these waves travel upwards from the photosphere, they steepen into shock waves upon entering the chromosphere. These shock waves are then damped and their energy transferred as heat into the surrounding material.

It is not known which method is actually heating the chromosphere.

B. What is Self-Reversal?

To begin, we need to consider how an absorption line is formed. In our case we have a large amount of ground state calcium in the lower regions of the chromosphere capable of absorbing any radiation with a wavelength of 3914 Å. So, the Ca II K line from the lower regions of the chromosphere will appear as a dark, although not devoid of light, band in the spectra profile. In order to get the emission line of the self-reversed K line we must have calcium which has been excited to its first excited state. This excited calcium is known to be in regions of the chromosphere known as plages (analogous to clouds in the earth's atmosphere) which form above regions of high solar activity. So, what we expect our spectra of a self-reversed absorption line to appear as an absorption line with a small emission peak in the core of the line.

The conditions which are necessary for the self-reversal of an absorption line show why the phenomena can be used as a measure of non-radiative heat transfer processes within the solar chromosphere. Since the lower chromosphere absorbs the radiation needed to excite the high layers, there must be another mechanism at work. One of the reasons this phenomena is very prominent around areas of high solar activity is that there is an increased amount of non-radiative heat transfer processes associated with the increased activity, e.g., the increase in magnetic flux into a sunspot or the motion of ionized matter during a solar eruption. Since the sunspots have a longer lifetime and are far easier to detect in normal daylight we have chosen to concentrate on sunspots.

IV. EQUIPMENT

The research which served as our model was performed at Sacramento Peak National Observatory. The most notable pieces of equipment used in the research was the heliostat used to track the sun as well as the 13.8 meter spectrometer available in the solar observatory. Lacking these components a new system was developed and assembled here on the University of Missouri - Rolla campus. The final design for the apparatus, seen schematically in Figure 1 below, was a modified version described by Ratcliff *et al*[7]. What follows is a detailed description of the equipment used along with the reasons for choosing these various components.

1. Celestron Telescope

The telescope used was a 10-inch Cassegrain with a 135 inch focal length. The telescope served dual purposes, first, it served as our solar tracking system. We did not have ready access to a heliostat and the time necessary for construction of one was impracticle. The telescope also served as our light collection and focusing device. The image projected by the telescope had a diameter of approximately two inches, making the images of sunspots approximately 225 μm. The telescope was located in the back yard (south side) of the Physics Building.

2. Fiber Optic Cable

In order to transmit the light collected by the telescope to the second floor of the Physics Building, where the spectrometer was located, we used approximately 50 m of fiber optic cable donated to us by Dr. Watkins of the Electrical Engineering Department. The fiber was a standard glass, multi-mode fiber. This fiber was chosen on the basis of its availability as well as its throughput. We found the output of the 50 m length was on the order of approximately 200 mW, a sufficient amount to expose the CCD camera.

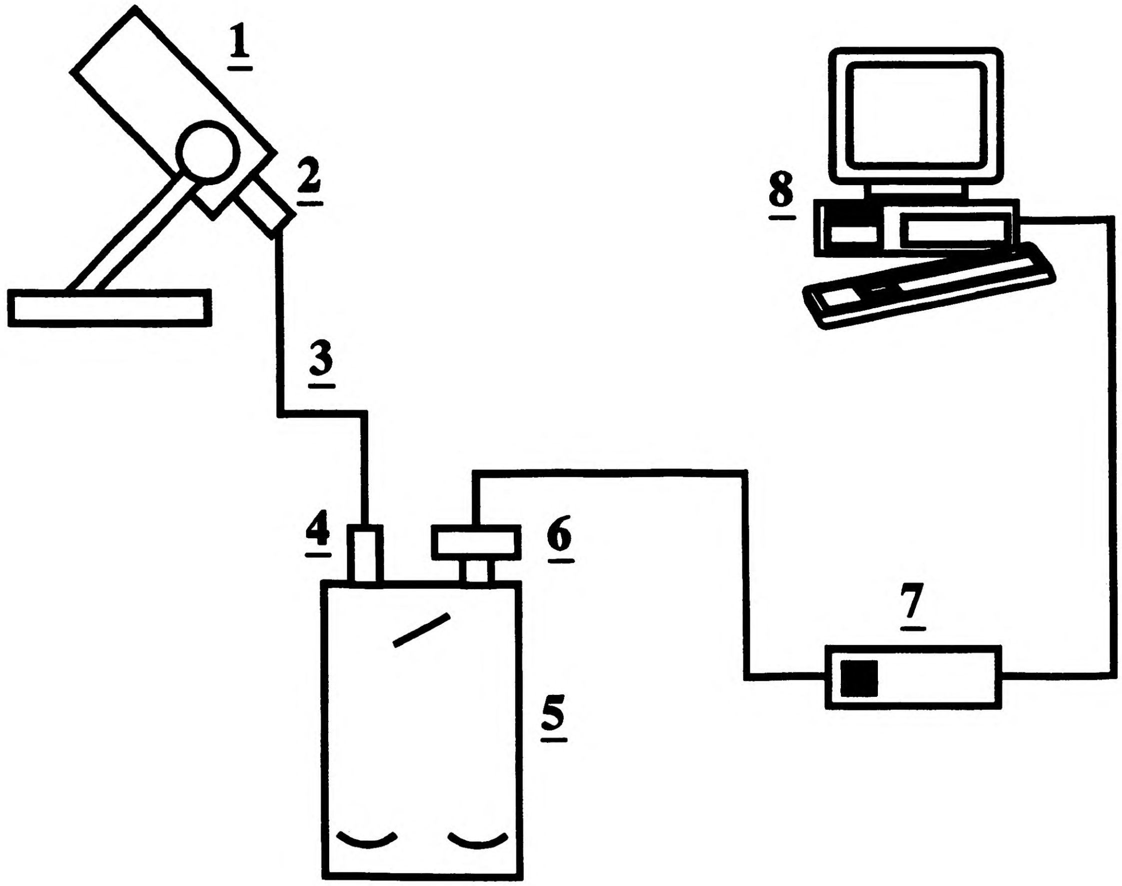

Figure 1. Schematic of apparatus setup; (1) 10 inch-telescope in south yard of Physics Building (ground level); (2) Telescope - fiber optic cable mount; (3) 50 meters of fiber optic cable; (4) Fiber optic cable to spectrometer lens coupling system; (5) Spex 3/4 meter spectrometer (second floor Physics Building); (6) SBIG ST-6 CCD camera as detection device; (7) CCD - IBM compatible computer interpreter; (8) IBM 286 compatible computer.

3. Spex 0.75 m Spectrometer

This spectrometer, owned by the Advanced Physics Laboratory, was also chosen on the basis of its availability. The spectrometer employs a diffraction grating with a ruling of 1200 lines/mm with a variable entrance slit with a width span from 5 to 1500 μm. Its position remained fixed on the second floor of the Physics Building in the Fuller Reading Room throughout the experiment. In order to more efficiently couple the output of the fiber optic cable to the spectrometer a lens system was designed and constructed. By using the lens system the amount of scattered light within the spectrometer itself was reduced while at the same time decreasing the exposure time necessary to capture an image on the CCD.

Calibration of the spectrometer was straight forward. We had available a mercury discharge lamp which provided a reliable source of spectral lines. By referencing the CRC Handbook of Chemistry and Physics we used five different emission lines characteristic of Hg which ranged from 4000 Å up to 9000 Å to insure that the spectrometer was accurate at most wavelengths. We found that the spectrometer was at most off by 2 Å from the accepted value of the Hg lines.

4. Santa Barbara Instruments Group (SBIG) ST-6 CCD camera

The Department of Physics purchased the SBIG ST-6 CCD camera during the summer of 1992. Prior to this experiment the camera was used primarily for astronomical observations. There were several factors which led to the use of the CCD camera as the detection device for this experiment. Foremost was the intensity resolution attainable by the camera. The ST-6 model is a 16-bit camera, which means it is capable of detecting 2^{16} distinct intensities. This large number of distinct intensities gives the CCD an intensity resolution of approximately

0.002%. Since the self-reversal in the K line is a relatively small deviation we felt the excellent intensity resolution of the CCD would improve the chances of detecting the phenomena. Another factor was the linearity of response the camera offered. The response of the camera is virtually constant at about 0.5 from 3800 Å up to 9000 Å.

The camera replaced the exit slit of the spectrometer. In our configuration the spectrometer was used as a monochromator rather than as a scanning spectrometer. The reason for this is that the CCD is capable of capturing roughly ± 47 Å from the spectrometer setting.

The physical dimensions of the CCD are 242 by 375 "pixels" each measuring 23 by 27 μm, which gives an overall array size of 6.5 by 8.6 mm. The CCD is connected to an IBM compatible 286 computer by an interpreter. The interpreter is used to store multiple images used in conjunction with astronomical photometry, not used in this experiment. The computer is used to control the temperature of the CCD chip and for general control of the camera. Images from the camera are downloaded to the computer and stored on disk in a standard format. By capturing an image of the K line we found we also saw the Ca II H line on the same image. From the known separation of these two lines we were able to determine that each pixel on the array corresponded to approximately 0.25 Å in the spectra.

5. LinePro Image Reduction Software

Unfortunately, there is no software available on the market which will upload an image created by the ST-6 and turn the image into a line profile. This was circumvented by the development and writing of software by the author to create the desired line profiles. The profiles of the spectra are created by taking the arithmetic average of the pixel intensity for each column of pixels. The final profile is then exported in a number of formats as ASCII data to be read into various other data analysis programs. The disadvantage of simply taking the arithmetic average intensity is that the camera must be precisely aligned such that each column of pixels is parallel with the spectral lines. This was mainly accomplished by taking an image of the standard Hg source a adjusting the camera until the emission line was as vertical as possible.

V. OBSERVATIONS

Once the apparatus assembly was completed, spectra images were taken for regions of the quiet sun and for regions of solar plages (indicated by regions of sunspot activity). Images were taken on 22 April and 27 April 1993. The data included images of the quiet sun and one sunspot. Data was only taken on this day due to constraints imposed by time and weather. As it was necessary to see the image of the solar disk in order to target sunspots for imaging it was possible to collect data only on days in which direct sunlight as well as sunspots on the solar disk was available. 22 April and 27 April 1993 were the only days on which acceptable conditions occurred following the completion of the observing apparatus.

Data were collected in the following manner: The telescope was directed at the sun and focused to provide an image. The end of the fiber optic cable was moved to a central part of the solar disk image. The spectrometer was set for the wavelength of the Ca II K line, 3934 Å. The spectrometer entrance slit was set at 23 μm, the setting for the maximum spectral resolution. The CCD camera software program was started and the camera was cooled to -25 C below ambient room temperature to reduce noise. The exposure time was set and an image was taken. Image exposure times for the data presented here were in the one-half to two second range.

The ST-6 CCD camera software next processed the image and stored it as a binary file.

This file consists of a two kilobyte (2048 bytes) header followed by the pixel reading stored sequentially by rows. The resulting byte file was further processed by the program LinePro. The image file was read in (by rows) one pixel at a time. An arithmetic average of pixel intensity was computed for each column. This was to provide an intensity profile for the spectra recorded by the camera. A sample of a spectra image and the profile calculated from the image can be seen in Figures 2 (a) and 2 (b) respectively. Observations were made on the two occasions noted above, and the results are summarized below in Table 1. The observations made consist of spectra images made of a quiet area of the sun and a plage area, indicated by the existence of a sunspot. All of the images were taken with the spectrometer set on the wavelength of the Ca II K line. The Ca II K absorption line is the large white band in the central region of the image (the image is printed as a negative for clarity). The large whit band to the right is the Ca II H line, which we are not concerned with-the focus of the project was on the K line. The identity of these two lines is certain, as testing indicated that the spectrometer used in this experiment was reasonably well calibrated, and it is known that these two absorption lines are far larger than any other absorption lines in this region of the solar spectra, enabling their easy identification.

Table I. K line intensity relative to continuum.

Observation	Area Type	Continuum Int.	K-line Int.	Relative Int.
4_27_93.2	Sunspot #1	86.66	75.65	0.87
4_27_93.7	Sunspot #2	84.16	73.23	0.87
4_27_93.9	Quiet Sun	95.94	71.42	0.74
4_22_93.6	Quiet Sun	278.90	104.92	0.37
4_22_93.4	Sunspot	217.07	112.91	0.52

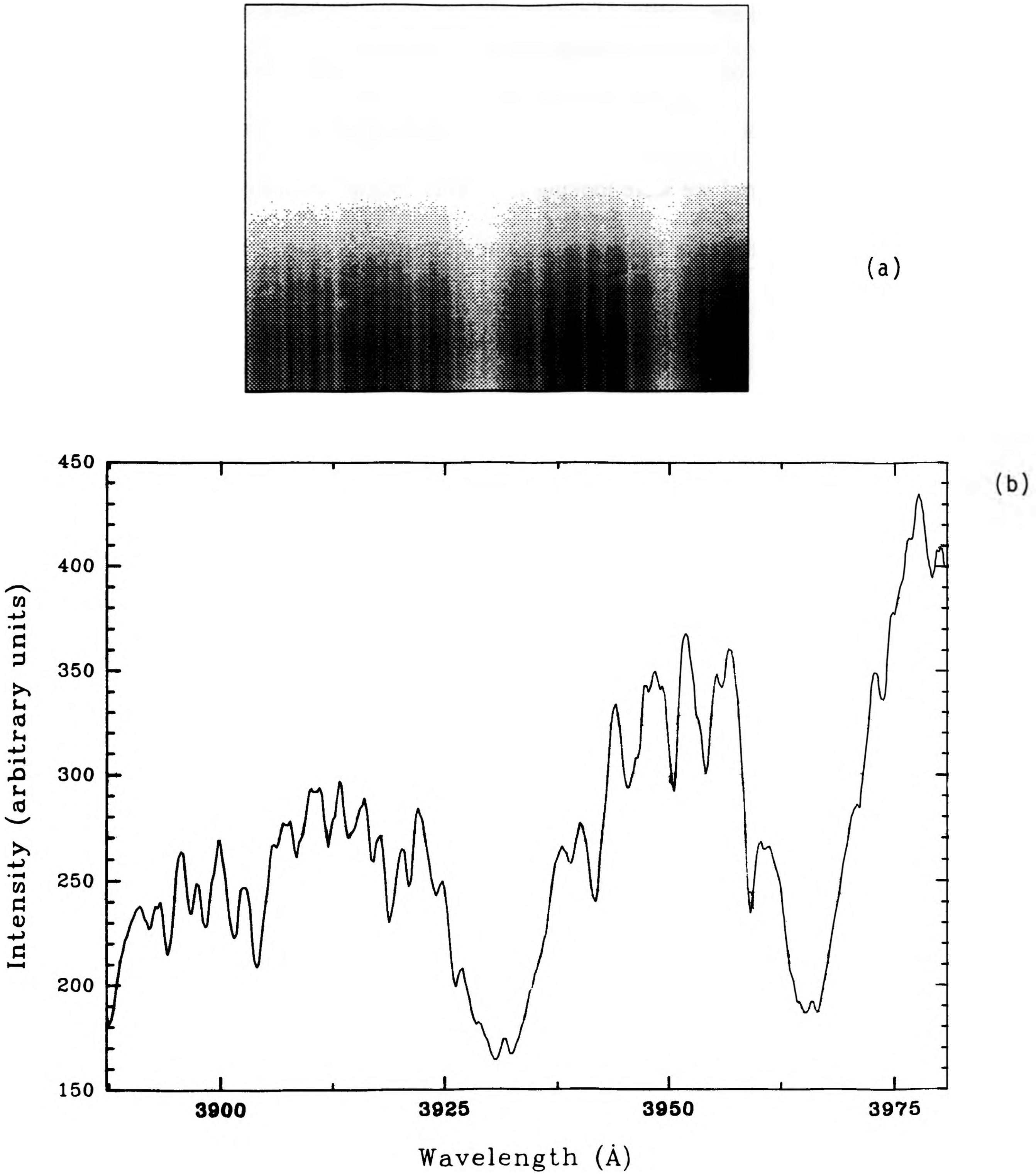

Figure 2. (a) (Top) CCD recorded image spectra of run 4_22_93.4 (sunspot). (b) (Bottom) Line profile generated from (a).

Figures 3 and 4 are profiles of a quiet sun region and a plage region. The plainly evident "bump" in the bottom of the absorption line of the plage spectra, being absent from the quiet sun spectra, clearly shows a difference in the K line in quiet and plage regions of the sun an indicates the self-reversal we were looking for. This "bump" indicates that the absorption line has reversed itself at the core to become an emission line. Figure 5 is a profile with the self-reversed K line with a line drawn to estimate the continuum. This is only a rough guess, as the determination of the actual continuum is very difficult. This rough estimate of the local continuum was arrived at by assuming the two most prominent peaks to lie on the continuum. The position for these two peaks (column number) was established for each spectra, and a line calculated for the two peaks. This line was then used to establish a "best guess" for the position of the continuum above the center of the K line. These are the values recorded for spectra in the third column of Table I. The minimum intensity value of the profile or the local maximum at the center of the K line are recorded in column four, according to whether the spectra was taken over the quiet sun or over a plage. The K line intensity is divided by the continuum intensity to give the relative intensity, the K line fraction of the continuum. In order to give some estimate of the percent intensity of the continuum of the quiet sun and plage regions, a continuum baseline is needed for the calculations. The baseline was also arrived at by a crude approximation, taking the quite sun K line intensity to be approximately five percent continuum[3]. When this is used to provide an estimate of the baseline, the percent of the continuum of the plage and quiet sun intensity can be calculated, and this is summarized in Table II below.

Table II. K line as percent of continuum.

Observation	Base (est.)	Continuum	K line Intensity	% Continuum
4_27_93.2	63	87	76	54
4_27_93.7	61	84	73	52
4_27_93.9	70	96	71	5
4_22_93.6	96	279	105	5
4_22_93.4	75	217	113	27

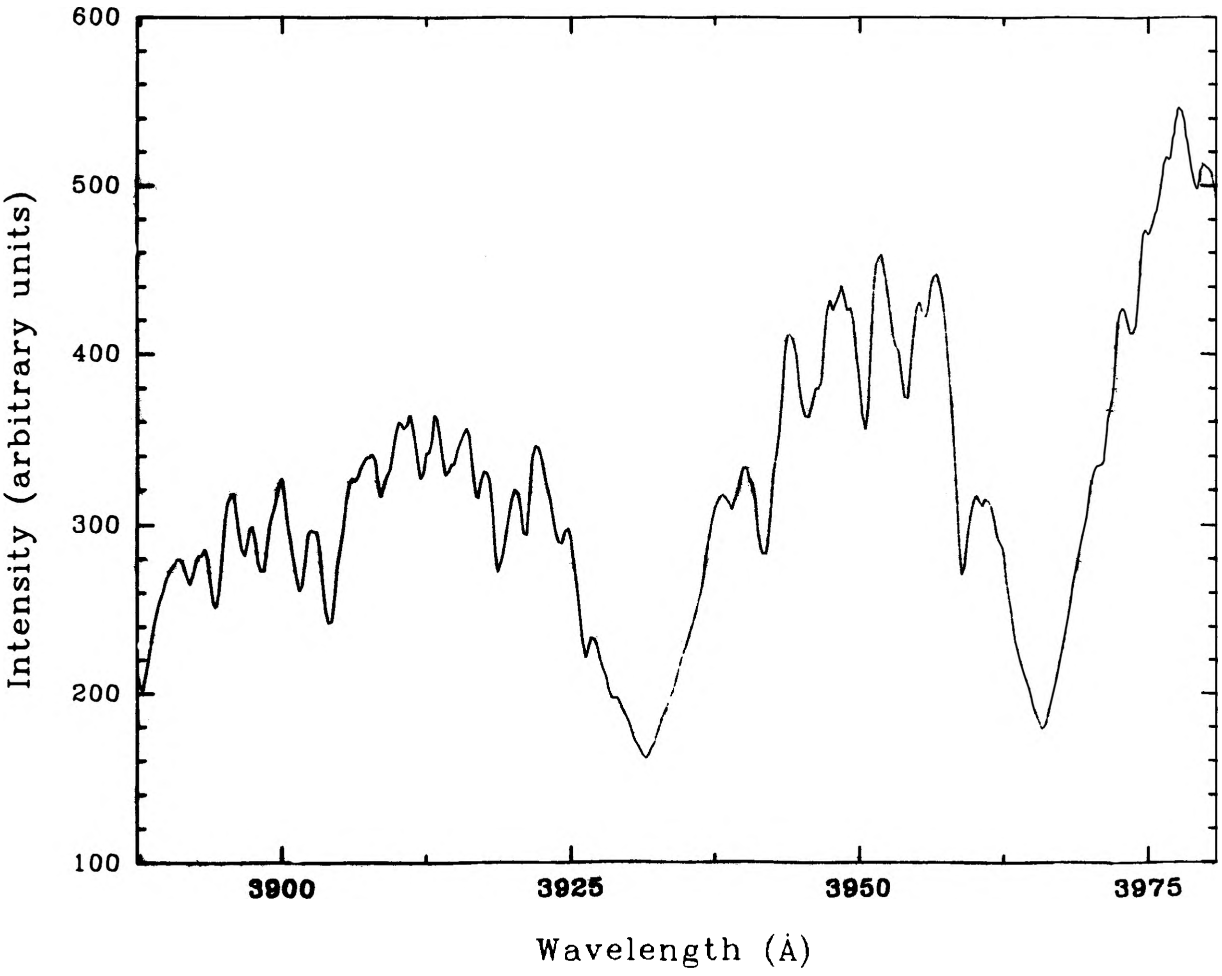

Figure 3. Line profile of recorded spectra from run 4_22_93.6 (quiet region).

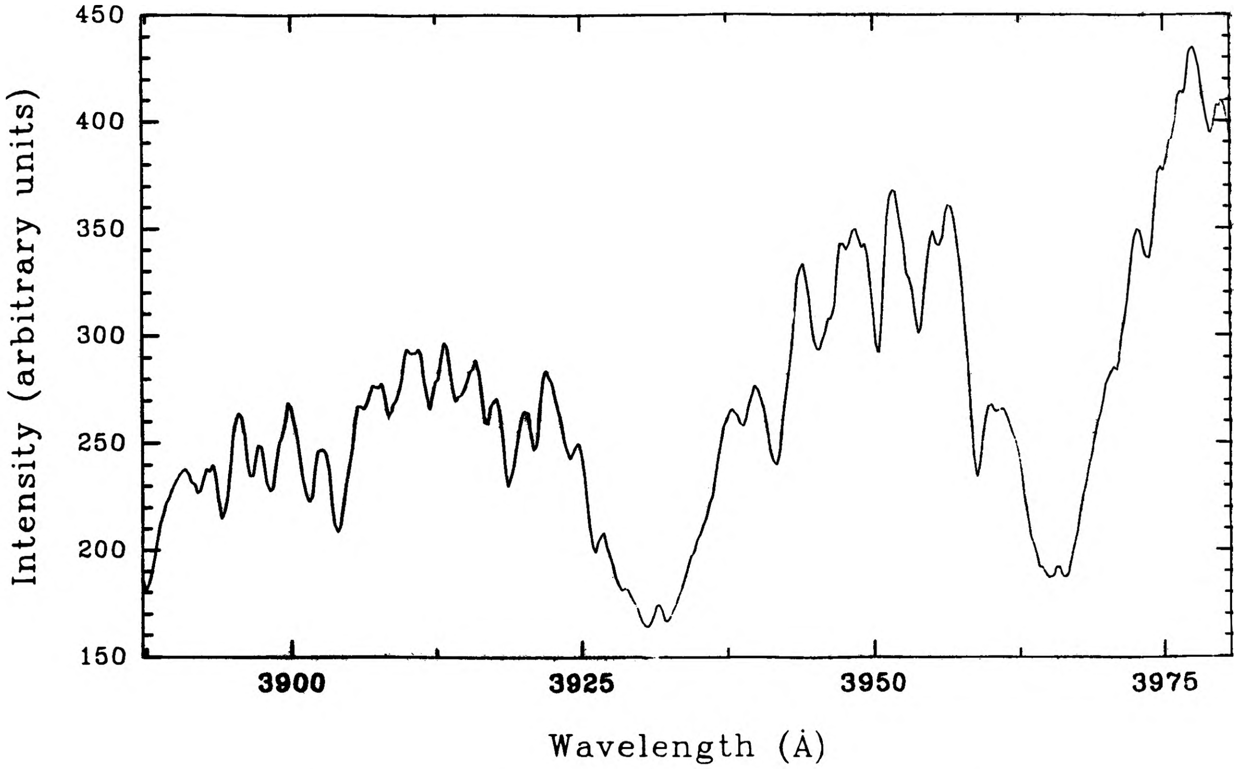

Figure 4. Line profile of recorded spectra from run 4_22_93.4 (sunspot).

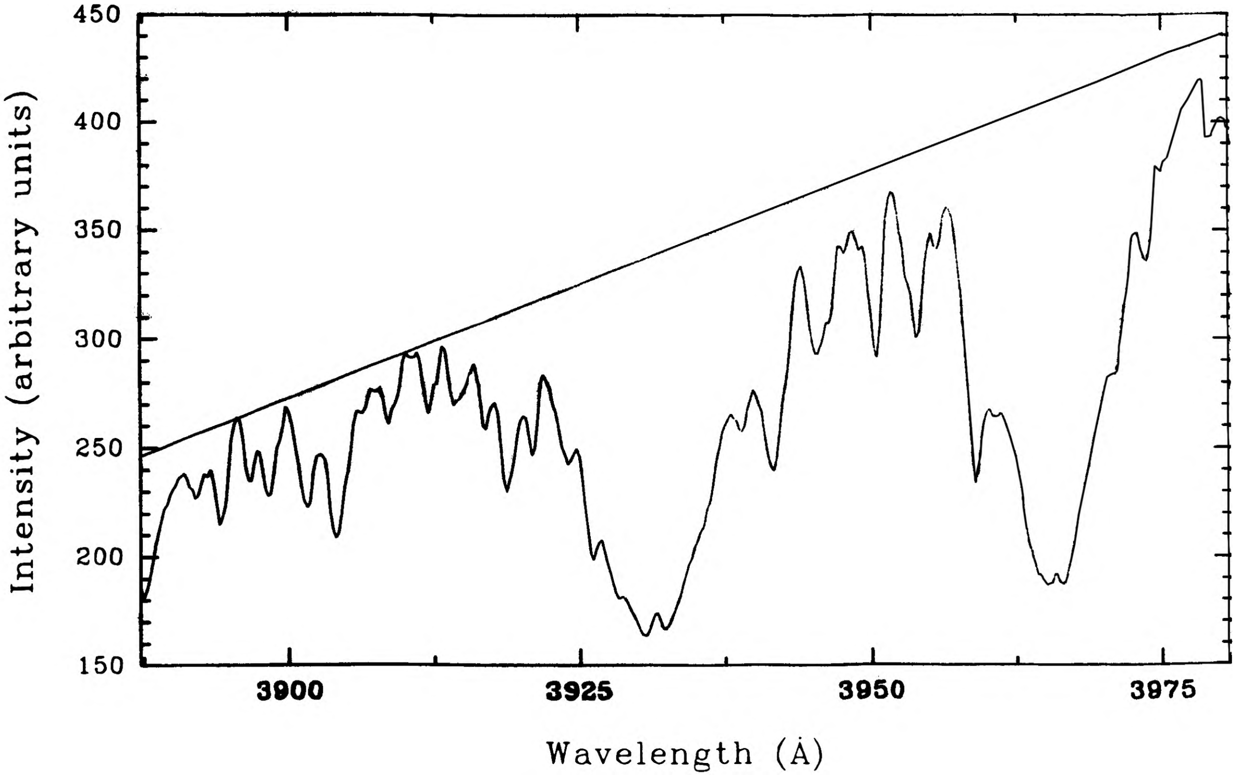

Figure 5. Line profile of recorded spectra with estimated continuum line drawn in.

VI. CONCLUSIONS

This project has demonstrated the feasibility of using the CCD camera, the 10-inch telescope, and the Advance Physics Laboratory's spectrometer together as a system for performing spectral analysis on objects accessible to the telescope. The results obtained clearly indicate that the Ca II K line intensity varies with the region on the sun's surface. The observations show that the K absorption line is only an absorption line in areas of the sun's surface not occupied by solar activity in the form of solar plages. With these plage regions, however, it is clear that the absorption line reverses itself at the core and becomes an emission line.

VII. ACKNOWLEDGEMENTS

I would like to thank the following people: Steven N. Jefferson and Eric Tavenner as my research associates in this project; Dr. John L. Schmitt without whose guidance and assistance this experiment would not have been possible; Dr. Edward B. Hale for his help in finding a suitable location in which to store our apparatus; Dr. Timothy J. Gay for letting us borrow the 0.75 meter spectrometer; Dr. W. Livingston for supplying information regarding spectroheliograms; Dr. Steve Watkins for supplying us with the fiber optic cable; Ed Stevens for his help in designing the optical system for use with the fiver optic cable and all the help he provided throughout the semester; Joel Brand for his help with the spectrometer and in the interpretations of the mercury lines used for resolution tests; Jon Fox and David Thilker for their help with the CCD camera and with program code; Dr. Don M. Sparlin for his support and encouragement through some rough times just prior to the Harold Q Fuller competition and the Missouri Academy of Science competition.

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