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Solar Full-Disk Polarization Measurement with the Fe I 15648 Å Line

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Abstract. The near-infrared absorption line Fe I 15648 Å, which has a Landé g-factor of 3, shows a particularly large Zeeman splitting. We regularly take full-disk polarization maps of the Sun in the Fe I 15648 Å line (as well as the He I 10830 Å line) with an infrared spectropolarimeter installed at the Solar Flare Telescope of the National Astronomical Observatory of Japan (NAOJ). It is known that weak, mostly horizontal magnetic fields are ubiquitously distributed in the quiet regions of the Sun, while the strong magnetic fields are concentrated in active regions and network boundaries. The weak horizontal field has not been sufficiently investigated due to the difficulty of such observations. The polarization maps in Fe I 15648 Å show the magnetic field strength at each pixel, regardless of the filling factor, so we can easily isolate the weak horizontal field signals from strong magnetic field ones using the Stokes V profiles of the Fe I 15648 Å line. Here we present instrumental aspects and observational results of solar near-infrared full-disk polarimetry. We highlight the weak horizontal field inferred from Fe I 15648 Å.

Keywords. Sun: photosphere, Sun: magnetic fields, Sun: infrared, Techniques: polarimetric

1. Introduction

The magnetic field on the solar surface is mostly concentrated in active regions and supergranular network boundaries. Such magnetic field plays an essential role in solar active phenomena. However, the magnetic field in internetwork regions also plays a fundamental role. The internetwork magnetic fields used to be considered mostly horizontal and randomly oriented in azimuth (e.g. Lites *et al.* 1996, Ishikawa *et al.* 2008). However, it has also been suggested that their horizontally oriented appearance was produced by erroneous inversion of the observed polarization signals (Stenflo 2010). Recently, the distribution of its inclination has attracted attention (Ishikawa & Tsuneta 2011, Orozco Suárez & Katsukawa 2012), but its orientation is still controversial.

The internetwork magnetic field has been studied at high resolution with the aim of distinguishing individual magnetic field elements. However, there is a different approach to study the internetwork magnetic field: this is, to analyze its statistical characteristics with full-Sun data taken with moderate spatial resolution.

NAOJ operates a full-Sun spectro-polarimeter aimed at studying the long-term evolution of the solar activity (Sakurai *et al.* 2015, in preparation; see also Hanaoka & Sakurai 2014). It was installed at the Solar Flare Telescope at NAOJ/Mitaka (Sakurai *et al.* 1995), and the observable wavelengths include the Fe I 15648 Å line. This line has a Landé factor of $g = 3$; g is so big that the Zeeman splitting in the strong magnetic fields of active regions and network is considerably larger to that induced by the weak field of the internetwork (Lin 1995). Therefore, full-Sun polarimetric observations with the Fe I 15648 Å line are promising to study the internetwork magnetic field. Here we present some results from the study using the Fe I 15648 data from our polarimeter.

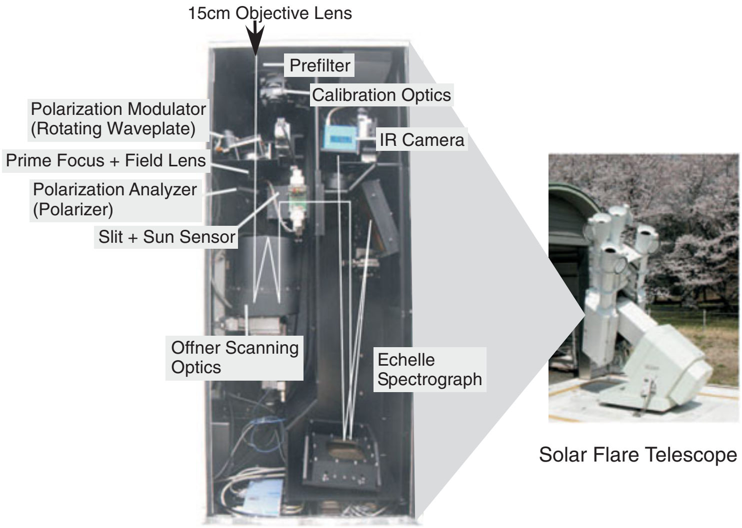

Figure 1. Main body of the spectropolarimeter (left) installed on the Solar Flare Telescope (right) at NAOJ, Mitaka. The size is about 1.6 m × 1 m. The light path is shown with white lines.

2. Instrument

The full-Sun spectro-polarimeter is one of the instruments installed at the Solar Flare Telescope (Figure 1). Its observing wavelengths are He I 10830 Å / Si I 10827 Å (chromospheric and photospheric spectral lines, respectively) and Fe I 15648 Å ($g = 3$) / 15653 Å (both photospheric lines). The outline of the instrument is shown in Figure 1. The solar light from the 15 cm objective lens enters the polarization modulator. Originally it consisted of two ferroelectric liquid crystals, but recently we replaced it with a high-speed rotating waveplate (Hanaoka 2012). The light goes through the analyzer (a polarizer), and then enters the Offner optics, which move the solar image onto the spectrograph slit. Because the telescope has other instruments which need to always point at the Sun's disk center, the spectro-polarimeter has its own image-shift device.

The infrared camera is a XENICS XEVA-CL-640 with an InGaAs 640 × 512 pixel detector. The exposure time is set to be 10 ms, and 192 images are taken at each slit position. The slit covers half of the solar diameter, and two swaths are performed to cover the full-Sun. A full-Sun scan takes about two hours. We are carrying out regular scanning observations with this instrument every day, and a couple of polarization maps per day are produced. Quick-look maps are available on the web: *http://solarwww.mtk.nao.ac.jp/en/solarobs.html* . The data used in this study are spectra of the Fe I 15648 line taken with this instrument.

3. Horizontal Magnetic Field Seen in Fe I 15648 Stokes V/I Maps

A sample spectral profile of the Fe I 15648 Å line is shown in Figure 2(a). One pixel corresponds to about 63 mÅ in wavelength, and this value corresponds to the Zeeman splitting for a magnetic field strength of 180 G. Therefore, we can produce polarization maps at every 63 mÅ or every 180 G. Figures 2(b) – (e) show full-Sun Stokes V/I maps ($(V/I_{\mathrm{blue-wing}} - V/I_{\mathrm{red-wing}})/2$) at several wavelength offsets from the center of the Fe I 15648 Å line, taken on 2013 May 5. The Stokes V/I signals are produced by the longitudinal components of the magnetic field. The wavelength offsets are 1, 3, 5, 8

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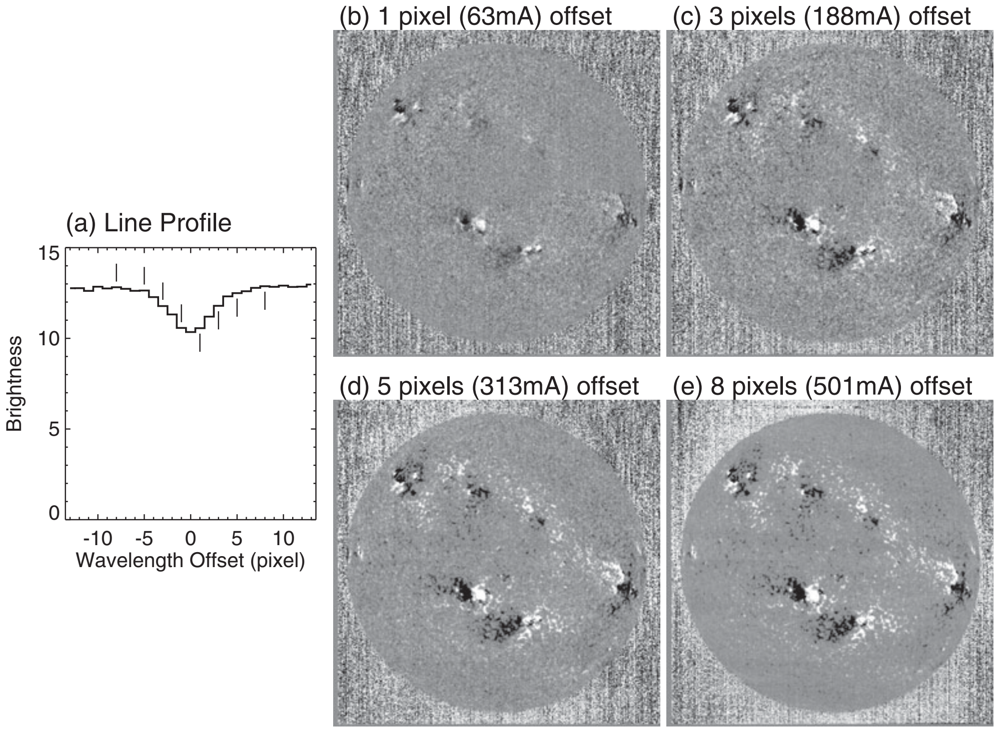

Figure 2. (a) A sample spectral profile of the Fe I 15648 Å line. Vertical bars show the wavelength positions of the Stokes maps in panels (b)–(e). (b)–(e) Full-Sun Stokes V/I maps at various wavelength offsets from the center of the Fe I 15648 Å line.

pixels (63 – 501 mÅ - which correspond to a range of field strengths between 180 G – 1.5 kG). Figure 2(e), the 8-pixel offset map, looks like a usual longitudinal magnetogram showing strong magnetic fields in active regions and the network. However, the panels with small offsets show that, in addition to the strong magnetic fields, there are weak V/I signals covering the entire disk of the Sun. This means that there are weak magnetic field elements covering the whole Sun. Furthermore, the longitudinal components of the weak magnetic field are not very remarkable around disk center, whereas they become remarkable away from it. This fact means that the weak magnetic field components seen in the small offset V/I images are, on the whole, horizontal, and that their azimuthal distribution is probably random. Therefore, our full-disk observational results using the Fe I 15648 Å line are consistent with previous studies showing that the internetwork magnetic field is mostly horizontal.

The quantitative distribution of the V/I signals in the internetwork region is shown in Figure 2. The curves in Figure 3(b) show the standard deviations of the V/I signals, as a function of the wavelength offset, encountered inside the annuli shown in Figure 3(a), which are placed at various distances from the disk center. To calculate the standard deviation, strong magnetic field regions that show conspicuous V/I signals in the maps with large wavelength offsets are excluded (black areas in Figure 3(a)) to isolate the internetwork regions. The V/I signals become maximum at the two-pixel offset (126 mÅ), and signals increase from the disk center annulus (0–5°, black curve) to the 45–50° annulus (green curve). The 126 mÅ, offset corresponds to the Zeeman splitting of magnetic field of about 360 G. Note, however, that a 126 mÅ offset from the line center corresponds to

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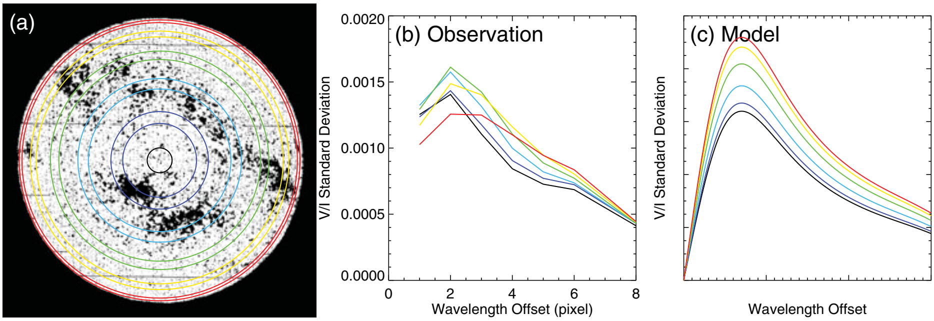

Figure 3. Standard deviations of the Stokes V/I signals at various distances from the disk center and at various wavelength offsets. Each curve in panel (b) shows the Stokes V/I signals in one of the annuli between 0–5° (black), 15–20° (blue), 30–35° (light blue), 45–50° (green), 60–65° (yellow), and 70–75° (red) from the disk center, respectively. The annuli are shown in panel (a). Regions with strong magnetic field (active regions and network) are excluded, and they are shown as black areas in panel (a). Panel (c) shows a model distribution of the Stokes V/I signals. See the on-line edition of the book for a color version of this figure.

a position in the line wing, as shown in Figure 2(a), and therefore the wavelength offset does not necessarily correspond to the magnetic field strength inferred from the Zeeman splitting. On the other hand, the distributions of the V/I signals shown in Figure 3(b) are basically identical for all the annuli from 0–5° to 45–50°. This means that the V/I signals come from magnetic fields that share the same distribution of strengths. Therefore, we can conclude that horizontal magnetic fields whose azimuths are randomly distributed at small spatial scales (but still distinguishable at the spatial resolution of the spectropolarimter, about 3″) cover the internetwork regions of the whole Sun. The distribution of the V/I signals near the limb (the 60–65° and 75–80° annuli; yellow and red curves) shows a decrease, particularly at the small wavelength offsets. This is probably due to the effective loss of spatial resolution near the limb caused by foreshortening effects. Figure 3(c) shows a model distribution of the V/I signals which approximately reproduces the observational results. The V/I signals are calculated on the basis of a model magnetic field distribution in which most of the magnetic elements have a field strength of 250 G and the rest of the elements have field strengths of up to 1.5 kG. In the model, the inclination of the magnetic field ranges between +30 and −30°, and its azimuth is randomly distributed. The effect of loss of the spatial resolution toward the limb is not taken into consideration. Therefore, the Stokes V/I signals increase monotonically toward the limb. However, the model reproduces the observed curves, except for those near the limb, and our results support the conclusion that the internetwork magnetic field is approximately horizontal and randomly distributed in azimuth. As mentioned above, the nature of the internetwork field is still controversial, but the Fe I 15648 Å Stokes maps shown here suggest that the internetwork field is basically horizontal.

Here we showed data taken on only one day near the solar maximum, but similar analyses carried out for the other epochs, including those near the solar minimum, show consistent results. The horizontal magnetic field is observed both in the active and quiet periods of the Sun.

We summarize our results as follows. The V/I signals measured around the Fe I 15648 Å line enable us to distinguish the strong magnetic field signals in active regions and the network from the weak field signals of the internetwork. Our observations support the view that the internetwork magnetic field is basically horizontal and randomly oriented in azimuth. The same characteristics were observed both at the Solar maximum and Solar minimum. Thus, polarimetry with the Fe I 15648 Å line provides us with a unique piece of information about the internetwork field that polarimetry using other lines cannot provide.

Acknowledgements

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