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FIRS: a new instrument for photospheric and chromospheric studies at the DST

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Abstract. The simultaneous observation of select spectral lines at optical and infrared wavelengths allows for the determination of the magnetic field at several photospheric and chromospheric heights and thus the 3D magnetic field gradient in the solar atmosphere. The Facility Infrared Spectropolarimeter (FIRS) is a newly completed, multi-slit, dual-beam spectropolarimeter installed at the Dunn Solar Telescope (DST) at Sacramento Peak (NSO/SP). Separate optics and polarimeters simultaneously observe two band-passes at visible and infrared wavelengths with a choice of two modes: the Fe I 6302 Å and 15648 Å lines in the photosphere; or the Fe I 6302 Å and He I 10830 Å line in the photosphere and high chromosphere, respectively. FIRS can also operate simultaneously with a white light camera, G-band imager, and the Interferometric Bi-dimensional Spectrometer (IBIS) observing the mid-chromospheric Ca II 8542 Å line. The instrument uses four parallel slits to sample four slices of the solar surface simultaneously to achieve fast, diffraction-limited precision imaging spectropolarimetry, enabling the study of MHD phenomena with short dynamic time scales.

Key words. Polarization – Instrumentation: polarimeters – Techniques: polarimetric – Sun: chromosphere – Sun: magnetic fields – Sun: photosphere

1. Introduction

Magnetic fields run heedlessly from the solar interior through the photosphere, chromosphere, and corona, no matter what we decide to call them or how they are divided up. The magnetic field is mysterious and it is still not well understood how it helps transport energy from the solar interior into the corona, or how the intervening layers can remain so cool. Solar phenomena like sunspots and their active regions, filaments and prominences, spicules and the network owe their existence to the presence of magnetic fields which form, maintain, and cause them to evolve.

It is a great challenge to observe the 3D magnetic fields of these solar structures. Table 1 lists some of the most promising lines for photospheric and chromospheric studies. The photospheric Fe I lines in the visible and infrared are well known

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Table 1. Some Photo- and Chromospheric Magnetic Field Diagnostics

ID	[Å]	Landé $g_{\rm eff}$	Region
Fe I	6302	1.7, 2.5	High Photos.
Ca II	8542	1.1	Low Chromos.
Si I	10827	1.5	Photos.
He I	10830	2.0, 1.8, 1.3	Chromos. (?)
Fe I	15648	3, 1.5	Low Photos.

for their magnetic sensitivity, and multi-wavelength inversion methods have already been used for photospheric lines in sunspots (Cabrera Solana et al. 2006) and in the internetwork (Martínez González et al. 2008). In the chromosphere, Ca II 8542 Å and He I 10830 Å have been used more recently to diagnose the magnetic fields of filaments (Lin et al. 1998) and spicules (Trujillo Bueno et al. 2005), and chromospheric inversion codes such as HaZeL (Asensio Ramos et al. 2008) and HeLix (Lagg et al. 2004) can extract the magnetic field parameters from these more complicated non-LTE lines. Because these spectral lines form within finite and discontinuous height ranges, multi-wavelength observations and simultaneous inversions will provide the most reliable diagnostics of the 3D magnetic field structure of the solar atmosphere.

2. Description of the instrument

The Dunn Solar Telescope Facility Infrared Spectropolarimeter (DST/FIRS) is a new dual-beam spectropolarimeter built collaboratively by the Institute for Astronomy, University of Hawai'i (P.I. Haosheng Lin) and the National Solar Observatory, funded by the National Science Foundation Major Research Instrumentation program (NSF/MRI).

In every new spectropolarimeter it is important to push the bounds to achieve the best spatial resolution to resolve the smallest solar scales; the highest cadence to capture the evolution of dynamic solar structures; the highest spectral resolution so the physics hidden in the spectral lines can be studied; and provide coverage of the largest number of wavelengths and diagnostics. FIRS incorporates several unique design elements to fulfill these goals.

The high-order adaptive optics system (AO, Rimmele et al. 2004) provides FIRS with diffraction limited image quality during or under good seeing conditions. Interchangeable optics upstream from the FIRS slit unit re-image the corrected telescope beam for a low resolution f/36 ($174'' \times 75''$) and a high resolution f/108 ($58'' \times 25''$) field of view. The standard 40 micron slit provides $0\farcs30$ sampling at f/36 and $0\farcs10$ sampling at f/108.

In order to increase the observational cadence of the instrument, FIRS has a slit unit with four parallel slits so that large areas may be scanned more quickly. We use dense wavelength division multiplexing (DWDM) filters adapted from optical communications, basically narrow band filters, and order-sorting filters to allow us to efficiently make use of modern large-format detectors. The filters isolate the lines of interest and prevent overlap of the spectra from the separate slits at the spectrograph focus. In f/36 mode a signal to noise ratio of 1 000 can be achieved with scan steps of 7.5 sec, so 145 step scans take only 18 min to complete.

High spectral resolution is achieved using a large Echelle grating in a Littrow configuration, where an off-axis parabolic mirror acts as both collimator and camera optics. The sampling resolution is $\sim$ 300 000 for the infrared and $\sim$ 600 000 for the visible. The spectrograph FWHM was measured to be 3 pm (corresponding to a spectral resolution of 200,000) using a HeNe laser.

FIRS makes simultaneous dual-wavelength observations of visible and infrared magnetic diagnostics. The spectrograph has been optimized to observe 6302 Å in the visible and 10830 or 15648 Å in the infrared. Pick-off mirrors select the wavelengths from their proper orders and direct the light down separate optical paths, each with its own pair of liquid crystal variable retarders (LCVRs), narrow-band filter, Wollaston prism analyzer, and detector. The DWDM filters have roughly square profiles and provide FIRS with wavelength coverage of 6302 ± 2 Å, 10832 ± 5 Å, and 15651 ± 8 Å. The visible detector is a

Table 2. Properties of the FIRS Standard Configuration

Property	FIRS f/36	FIRS f/108	Hinode SOT/SP Normal Map
Telescope	76.2 cm Solar Tower	...	50 cm Aplanatic Gregorian
$\theta_{\rm Rayleigh}$(6302 Å)	0.″21	...	0.″32
$\theta_{\rm Rayleigh}$(10830 Å)	0.″36	...	...
$\theta_{\rm Rayleigh}$(15648 Å)	0.″52	...	...
Field	174″× 75″	58″× 25″	160″× 151″
Spatial Sampling (Visible)	0.″30 × 0.″08 pix^{-1}	0.″10 × 0.″03 pix^{-1}	0.″15 × 0.″16 pix^{-1}
Spatial Sampling (Infrared)	0.″30 × 0.″15 pix^{-1}	0.″10 × 0.″05 pix^{-1}	...
Scan Time	18 min	25 min	83 min
Resolution (Sampling) 6302	0.01 (0.01) Å	...	0.03 (0.02) Å
Resolution (Sampling) 10830	0.03 (0.04) Å	...	...
Resolution (Sampling) 15648	0.06 (0.05) Å	...	...

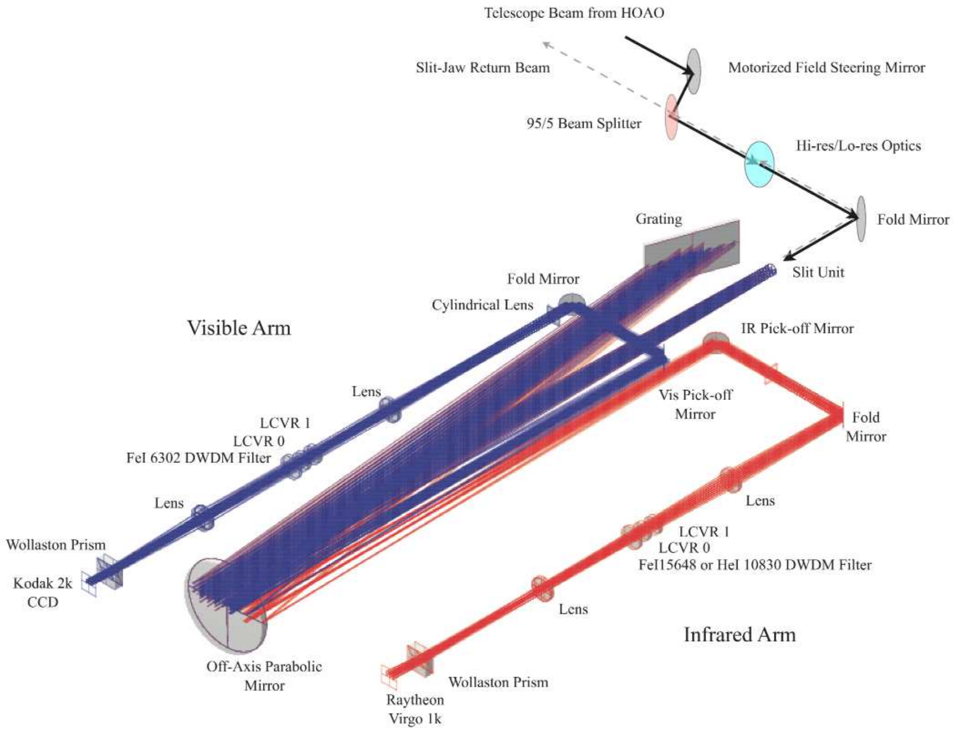

Fig. 1. Diagram of the FIRS optical path. We recommend viewing the colored online version for better visibility.

Kodak 2k × 2k CCD and the infrared detector is a Raytheon Virgo 1k × 1k HgCdTe array. The infrared arm can be easily converted from 10830 Å to 15648 Å modes simply by swapping the filters and LCVRs, and changing the position of the final lens between two

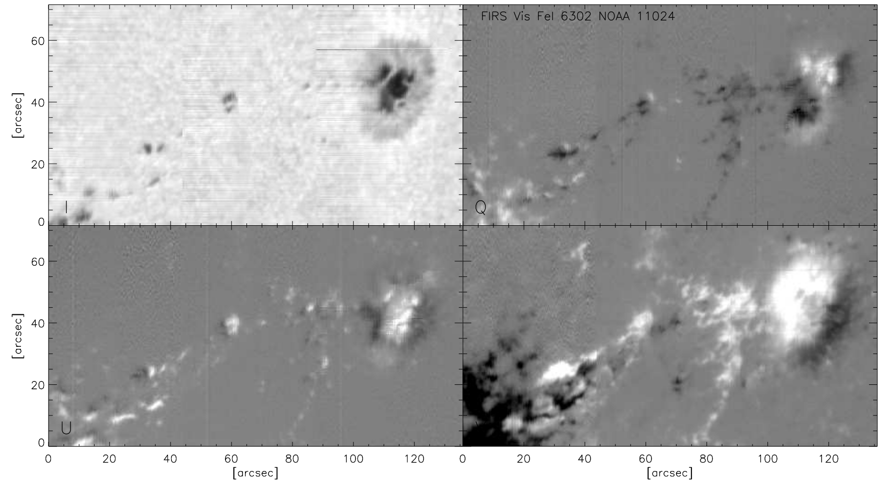

Fig. 2. FIRS 6302 Å Stokes component maps taken at 14:31 UT on 2009 July 7.

preset positions. To extend the chromospheric and photospheric wavelength coverage and increase the compatibility of the instruments on the DST, FIRS can operate simultaneously with G-Band and whitelight cameras, and the Interferometric Bidimensional Spectrometer (IBIS, Cavallini 2006). A dichroic beamsplitter that transmits the Ca II 8542 Å bandpass and reflects the 6302 Å, 10830 Å and 15650 Å wavelength regions extends the coverage to the chromospheric Ca II 8542 Å line using IBIS.

A diagram of the instruments optical path is shown in Fig. 1. The instrument properties are listed in Table 2, and for comparison we include the parameters of Hinode's SOT/SP.

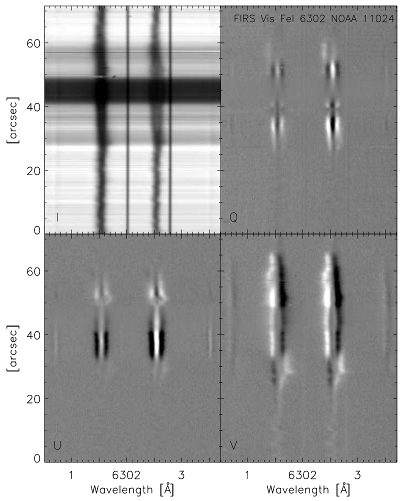

Fig. 3. FIRS 6302 Å Stokes spectra from the 115 arcsec position.

3. FIRS data

First light with FIRS was achieved on 2007 April 30. In Figs. 2 through 6 we show scans from our most recent dataset, taken on 2009 July 7 of NOAA 11024. The active region, located about half-way between disk center and the west limb, produced a fully developed spot with a penumbra. Simultaneous 6302 Å and 15648 Å scans were started at 14:31 UT and were followed by 6302 Å and 10830 Å scans started at 18:28 UT. The high-order AO system was used under conditions of fair seeing.

The data has been reduced with FIRS reduction scripts written in IDL. During the data reduction the raw data is dark subtracted and flat-fielded, the Stokes vector is reconstructed, then the spectrum from each slit is extracted from the image and shifted to remove spectrograph curvature. The Stokes Q, U, and V spectra are de-streaked and normalized relative to the continuum, the Stokes I spectrum is nor-

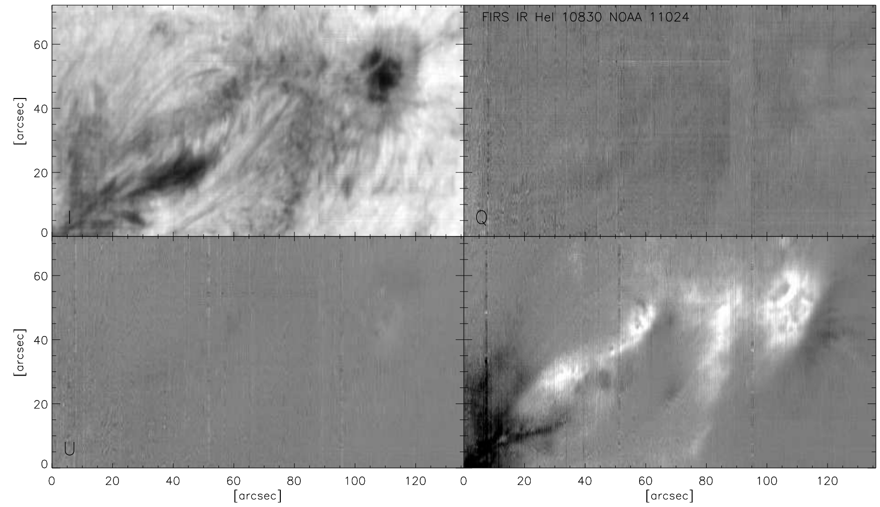

Fig. 4. FIRS 10830 Å Stokes component maps taken at 18:28 UT on 2009 July 7.

malized to the median quiet Sun intensity at each slit position. Polarization crosstalk is calculated and corrected according to the method in Kuhn et al. (1994). The Stokes components are stacked into a data cube together with the observing parameters and scan maps are reconstructed from the reduced spectra.

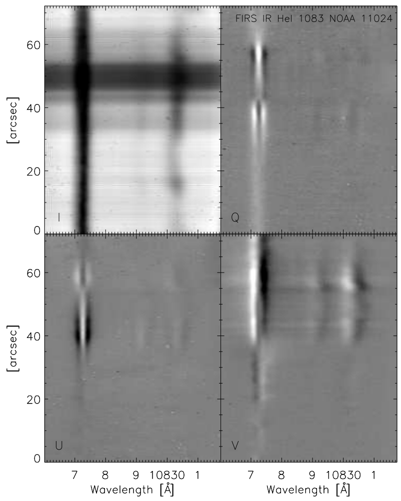

Fig. 5. FIRS 10830 Å Stokes spectra from the 115 arcsec position.

Figures 2, 4, and 6 show the resulting maps for each observed wavelength regime, 6302, 10830, and 15648 Å respectively. The 6302 and 15648 Å maps are from the first simultaneous scan, the 6302 Å map from the simultaneous 6302/10830 Å scan is not shown due to its similarity. Each set of maps shows data from 3 of the 4 slits (the first slit contains no features) that have been constructed from the I, Q, U, and V Stokes vector components. The Stokes spectra shown are from the 115″ position and include the umbra and penumbra of the leading spot. Obvious and intriguing differences in the visible and infrared Fe I Stokes Q and U maps indicate there is a change in the magnetic field with height.

4. Current status and future upgrades

FIRS was completed in July 2009 and observer training is in progress. FIRS will be available the first quarter of 2010 for general use. The plan for future upgrades includes the acquisition of additional DWDM filters and cameras to facilitate simultaneous four wavelength coverage (6302, 8542, 10830, and 15648 Å), and

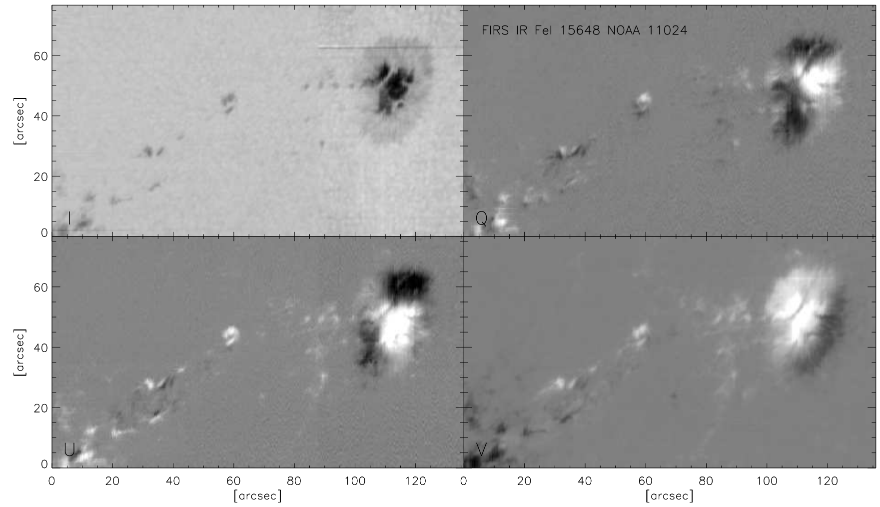

Fig. 6. FIRS 15648 Å Stokes component maps taken at 14:31 UT on 2009 July 7.

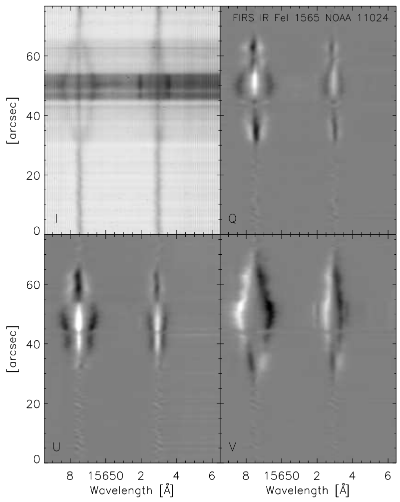

Fig. 7. FIRS 15648 Å Stokes spectra from the 115 arcsec position.

new Wollaston prisms for a larger field of view and increased efficiency.

For additional information please refer to our website: *http://kopiko.ifa.hawaii.edu/firs*

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