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Multi-Height Spectropolarimetry of Sunspots with FIRS and IBIS

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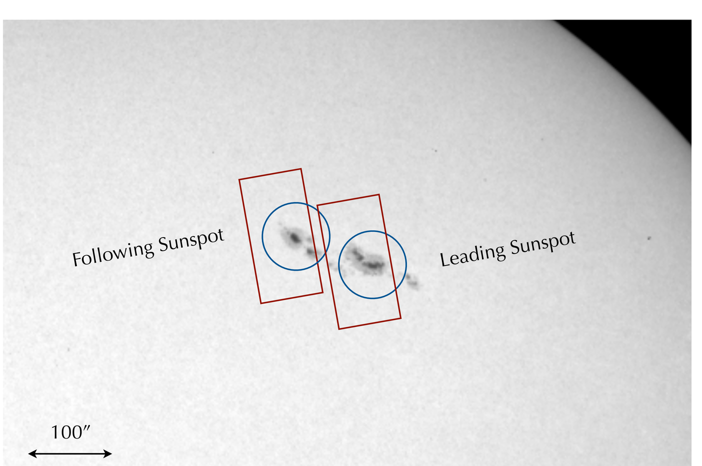
MONTANA STATE UNIVERSITY SOLAR PHYSICS

The effects of radiative transfer prevent the characterization of the magnetic field at a single geometric height in the photosphere of a sunspot. Therefore, a full 3D characterization of the magnetic field is necessary to understand many properties of sunspots, such as the true state of hydrostatic equilibrium. Many current and proposed solar spectropolarimeters are capable of taking near-simultaneous observations at multiple wavelengths. Combining these rich datasets provides a welcome problem to the community. We present joint observations of the magnetically sensitive photospheric Fe I lines at 6302 and 15650 Å taken with the Facility Infrared Spectropolarimeter (FIRS); and the chromospheric Ca II line at 8542 Å taken with the Interferometric Bidimensional Spectrometer (IBIS); both instruments operated at the Dunn Solar Telescope. These wavelengths allow us to probe the magnetic field over a broad range of heights, from the bottom of the photosphere to the chromosphere. We investigate the magnetic field topologies of two sunspots of different magnetic complexity from the same active region.

Observations

NOAA active region 11035 was a complex βγ-region that emerged rapidly on 14 Dec 2009, approximately 10° from the central meridian. Disorganized pore groups rapidly coalesced into a large leading and following polarity sunspot. The observations of the leading and following polarity sunspots were taken on 17 Dec when they were largest. After producing several C-class flares on this day at 01:02, 12:36, and 21:35 UT, the region began to decay, but the spots remained large as they traveled around the west limb on 22 Dec.

Observations of the following and leading



Sub-section of the SOHO/MDI full-disk image on 2009-12-17 showing the fields of view for FIRS (blue rectangles) and IBIS (red circles).

sunspots in NOAA 11035 began at 08:16 and 08:44 local time (15:16 and 15:44 UT respectively) and were each approximately 20 minutes in duration. Simultaneous imaging-spectropolarimetry at of the Zeeman-sensitive Fe I line pair at 6302 Å (g=1.67, 2.5), Ca II line at 8542 Å (g=1.1), and Fe I line pair at 15650 Å (g=3, 1.53) was obtained using the instruments FIRS and IBIS on the Dunn Solar Telescope (DST), a 76 cm vacuum coelostat located at the National Solar Observatory on Sacramento Peak, New Mexico. The High Order Adaptive Optics system (Rimmele, 2004) on the DST was used to achieve good image quality in the infrared, even in the mediocre seeing conditions present during the observations. The instruments and observational setup are described in more detail in the following paragraphs.

The Facility Infrared Spectropolarimeter (FIRS) is a dual-beam, dual-wavelength infrared and visible spectropolarimeter capable of increased observing cadence due to its multi-slit configuration (Jaeggli et al., 2010). Scans with FIRS are built up by stepping the image produced by the telescope across the slit unit in the spatial dimension, achieving a rectangular field of view of 150 x 75″ with 0.3″/pixel sampling in about 20 minutes. FIRS provides spectral coverage of of about 5 and 10 Å around the Zeeman-split photospheric Fe I line pairs at 6302 and 15650 Å respectively.

The Interferometric Bidimensional Spectrometer (IBIS) is a Fabry-Perot imaging-spectropolarimeter (Cavallini, 2006) which builds up spectra by stepping the narrow filter bandpass in the wavelength dimension. IBIS has an 80″ diameter field of view which is masked to 40″ in one direction when the polarimeters are in use, with 0.16″/pixel sampling. The wavelength tuning was set up to observe a 2.5 Å bandpass around the chromospheric Ca II line at 8542 Å sampled with 0.08 Å steps in scans lasting ~36 sec. IBIS was run continuously during the FIRS scans, so we have selected only the first scan for this analysis.

The FIRS slit was oriented in a direction perpendicular to the horizon so that the displacement due to atmospheric refraction was in the direction along the slit. The figure to the left shows the relative size and alignment of the FIRS and IBIS fields on the active region.

Reduction

Data reduction for FIRS data was carried out as in Jaeggli (2012). All infrared images were first corrected for the detector linearity. Darks and line-subtracted flat-fields were applied to the observations. The observed polarization states were demodulated to obtain the Stokes vector. The spectra from the four slits were geometrically corrected, and the two beams were combined to reduce spurious signals from seeing effects. Instrumental polarization cross-talk was corrected via the Kuhn Method (Kuhn, 1994) based on the expected polarization properties of the Stokes line profiles in the sunspots. The telluric lines were removed from the 6302 Å spectra.

IBIS data reduction was somewhat more complicated. Apart from the standard dark and flat-field corrections, the IBIS observations were speckle reconstructed to account for image motion due to seeing, and a polarization correction based on the telescope geometry and polarization calibration was applied to the Stokes spectra. The IBIS spectra were resampled to be linear in wavelength.

The spectropolarimetric data cubes from FIRS and IBIS were co-aligned using the continuum intensity at each wavelength, and the data cubes were cropped to contain only the overlapping areas for each wavelength region.

Analysis

Maps of the continuum intensity, the integrated, continuum-subtracted line strength, and the unsigned, integrated Stokes Q, U, and V polarization for each wavelength are shown in the maps to the right. These maps were produced using the Fe I lines with the larger splitting for FIRS (6302.5, 15648.5 Å). Intensity contours for the umbra and penumbra determined from the 8542 Å continuum are overplotted in black on all maps for easy reference. In the maps of the line strength, dark regions show where the line is weak in absorption, or in emission (in the case of Ca II), and light regions show strong absorption lines. The polarization states are relative to the line of sight, and not the local solar surface.

The 3-wavelength full-Stokes spectra from interesting positions in the umbra and penumbra of each of the sunspots are shown on the far right.

Results

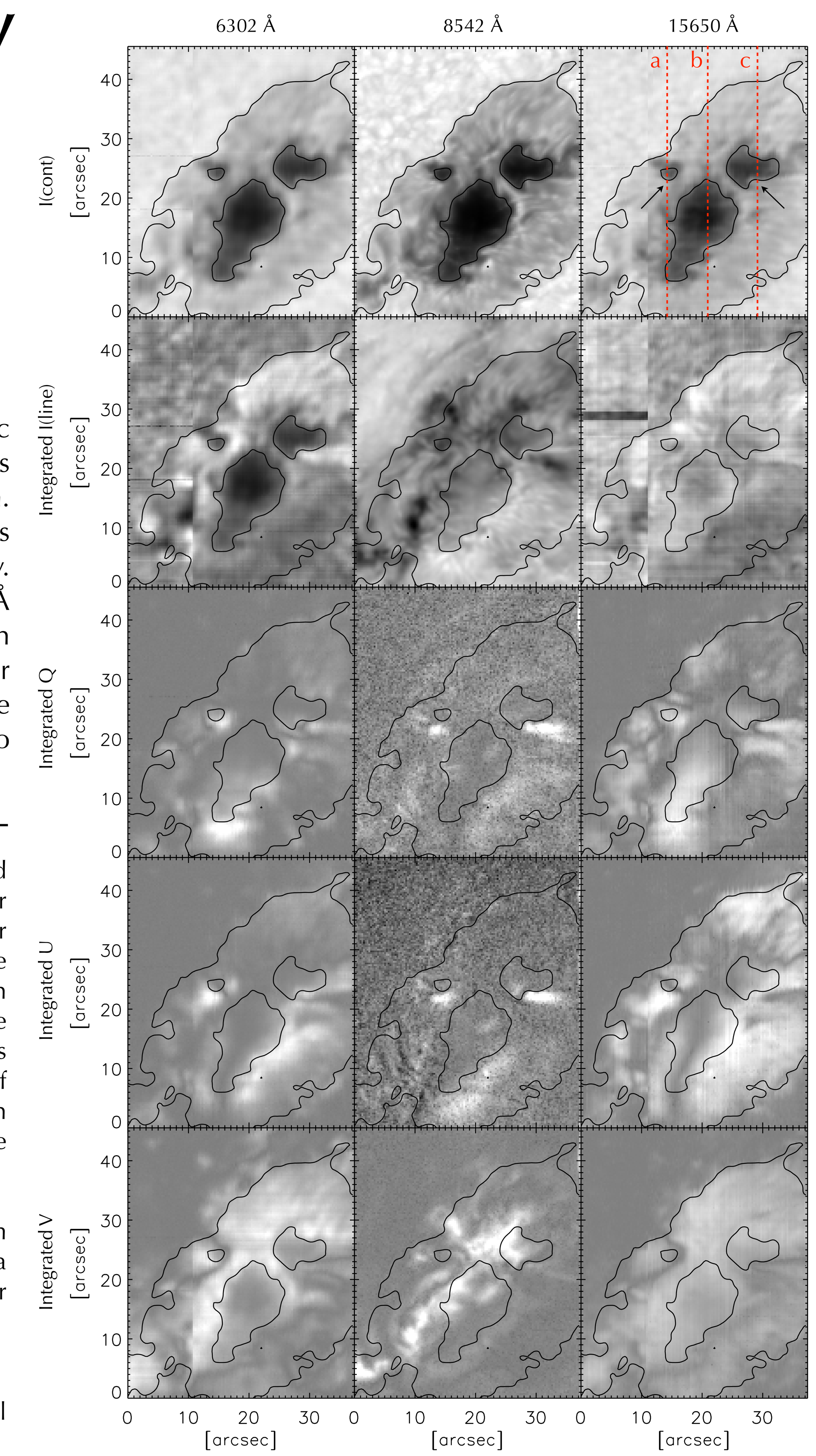
See the sections on the right for individual discussion of the sunspots.

Conclusions

In spite of being part of the same active region, the leading and following sunspot in NOAA 11035 show significantly different topologies. The leading sunspot has a more complicated umbral structure in intensity and polarization at all wavelengths. The presence of a down-flowing filamentary structure in the leading sunspot is particularly interesting, and may be related to the flare activity that occured in this region on the same day. A similar structure seen in the Ca II 8542 Å line during flare activity has been discussed recently in Kleint (2012).

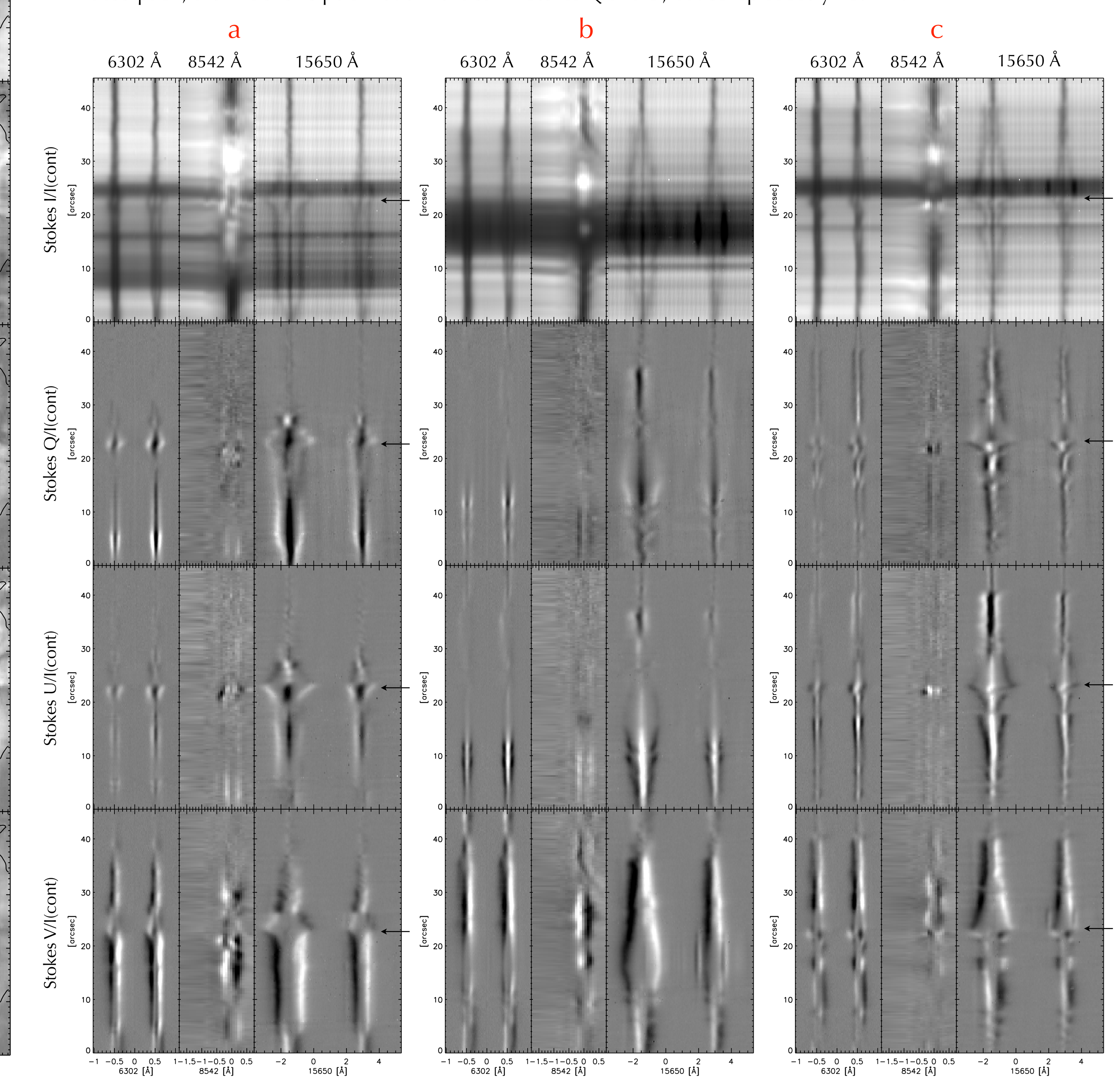
The multi-wavelength observations show a good deal of promise for further analysis. Using a spectropolarimetric inversion code such as NICOLE (Socas-Navarro et al., 2000), it would be possible to derive the magnetic atmospheric profile of the sunspots. In simple sunspots it might be possible to use a relatively simple atmospheric model for the inversion, however in regions which display complex line profiles and emission signatures in the Ca II line, a multi-component atmosphere is necessary to account for polarization reversal and multiple magnetic components along the line of sight.

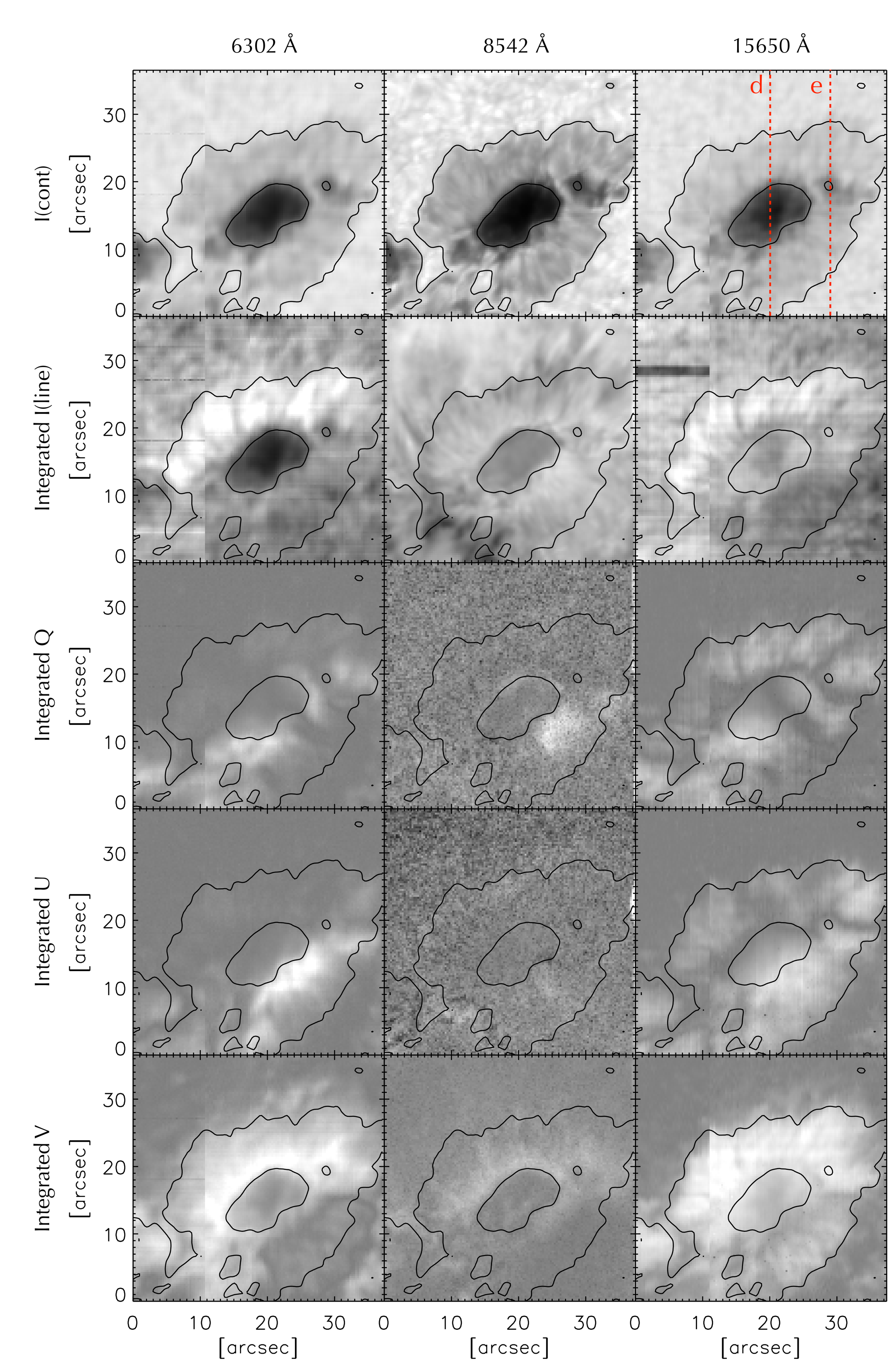
Multi-wavelength, multi-height inversions will provide a significant advantage over single-wavelength Ca II inversions. With a single chromospheric wavelength it may not be obvious when the Stokes vector polarity is reversed due to emission at the contributing height, or weather the magnetic field is simply reversed. By including Zeeman-split lines formed at photospheric heights, we can place better constraints on the model atmosphere and improve the accuracy of the resulting magnetic field model.



Results: Leading Sunspot

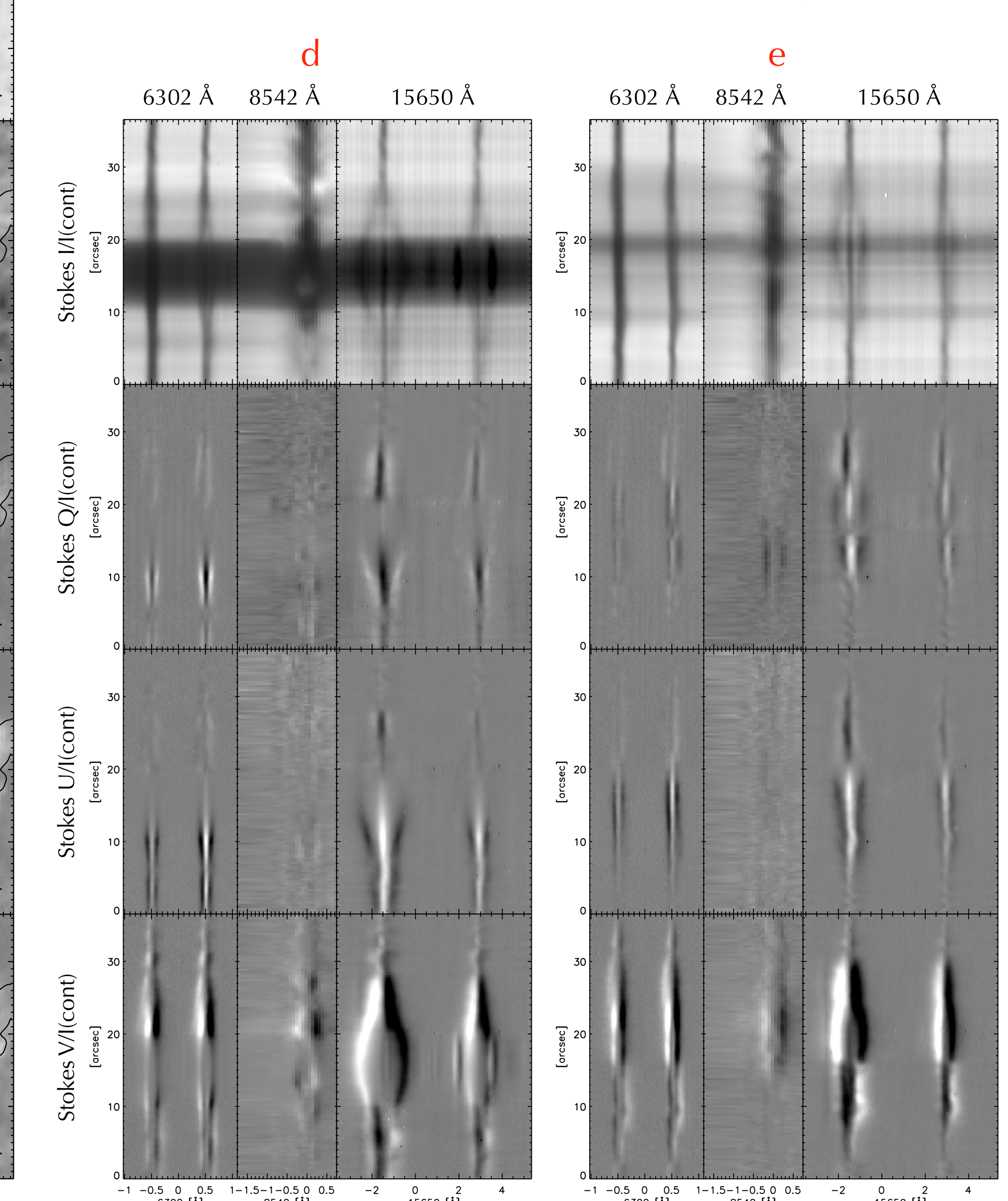
Previous analysis of the photospheric observations with a Milne-Eddington inversion technique (Jaeggli, 2012) showed this sunspot to have exceptionally high magnetic field strengths in excess of 3500 G in two small features (indicated by the arrows on the map and in a and c) located just outside the secondary umbrae of the sunspot. Strong magnetic fields and down flows in the photosphere are especially apparent in the photospheric Stokes V spectra of position c. Ca II shows strong linear polarization signatures in both of these features. Clumpy regions of Ca II emission are seen in the integrated line intensity map which correspond roughly with regions of stronger polarization, and polarization reversal of the Stokes spectra is apparent in these regions. Position b shows a "typical" slice through the main umbra and penumbra of the sunspot. Although the net behavior of the Ca II line in the penumbra shows absorption, the line shows polarization reversal in Stokes Q and U, but conspicuously not in V.





Results: Following Sunspot

In spite of the proximity to its active neighbor, the following sunspot in NOAA 11035 shows very weak polarization signatures for all lines. In addition the Ca II line rarely shows strong emission above this sunspot, as can be seen from the integrated line intensity. Positions d and e in the following sunspot show spectral slices across the umbra and penumbra of the sunspot. Polarization reversal relative to the photospheric signature is also apparent in Stokes Q, U, and V where the Ca II line goes weakly into emission in the sunspot umbra.



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