THE THREE-DIMENSIONAL STRUCTURE OF A SUNSPOT MAGNETIC FIELD

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ABSTRACT

We report on observations of the three-dimensional structure of a sunspot magnetic field from the photosphere to the chromosphere, obtained with the new visible/infrared spectropolarimeter SPINOR. The observations, interpreted with a non-LTE modeling technique, reveal a surprisingly complex topology with areas of opposite-sign torsion, suggesting that flux ropes of opposite helicity may coexist together in the same spot.

Subject headings: line: profiles — Sun: atmosphere — Sun: chromosphere — Sun: magnetic fields

The observations that we use in this work are first-light data from the new instrument SPINOR (Spectro-Polarimeter for Infrared and Optical Regions; Socas-Navarro et al. 2005). Still under development, SPINOR can already be used for high-resolution full spectropolarimetry at virtually any combination of three spectral regions in the 400–1000 nm range. The particular data set that we report on was acquired on 2004 June 16 at 15:16 UT. We observed two photospheric Fe I lines (at 849.7 and 853.8 nm) and two chromospheric lines of the Ca ii infrared triplet (at 849.8 and 854.2 nm) in active region NOAA AR 0634 at a time of particularly good seeing. The spectrograph slit was scanned over that region to construct a three-dimensional data cube, in such a way that for each (x, y, z)-point we have the four Stokes parameters I, Q, U, and V. We made use of the new adaptive optics system (Ren et al. 2003) of the Dunn Solar Telescope. Combined with the excellent atmospheric conditions at the time of the observations, we achieved a spatial resolution as good as 0.06″ (note that this figure varies slightly in the scanning direction because of temporal changes in the seeing conditions), which is among the best attained thus far in this kind of observation.

The sunspot subject to detailed analysis is rather irregular (see Fig. 1) and exhibits two distinct umbral cores adjacent to the main umbra. One of them, above the main umbra in the figure, is surrounded by its own penumbra. The other umbral core is almost merged with the main umbra and is seen to its left, separated by a faint light bridge. The interpretation of the data was carried out using the Stokes inversion code developed by Socas-Navarro et al. (2000) for spectral lines formed in non-LTE. The code infers the depth stratification of the temperature, line-of-sight velocity, and magnetic field vector that yield the best fit to a particular set of Stokes spectra. The photospheric Fe blends in the wings of the Ca lines are also computed by the code, providing a fully connected picture of the whole atmosphere, from the low photosphere to the chromosphere.

Each spatial point in the data set is analyzed independently of the rest. In order to ensure proper convergence and minimize the risk of the algorithm’s settling in secondary minima, each inversion is repeated 10 times with randomized initializations. The best solution is picked as representative of the atmospheric conditions in the spatial location under study. The non-LTE inversions are very computing-intensive. However, this kind of analysis is necessary for accurate vector magnetometry (Lites et al. 1994; Socas-Navarro 2002) because radiative transfer and magneto-optical effects give rise to very complex dependences of the observables on the atmospheric conditions. We employed a scheme in which the non-LTE inversion code is efficiently run in parallel on several networked workstations. The hardware employed includes three dedicated and three shared (mostly off-hours) Intel P4 processors running Linux kernels. On average, we used the equivalent of five processors running at a clock speed of 2.7 GHz. The real time employed in the entire analysis was 29 days. This included a first inversion of a larger area (some 200 × 150 pixels) and a second pass at the area shown in Figure 1, of nearly 150 × 110 pixels. In the second pass, the profiles were averaged over a 3 × 3 pixel (1″ × 0.06″) box before inverting, with the aim of improving the signal-to-noise ratio. The noise level was thus reduced to approximately 1.5 × 10⁻⁴ in units of the quiet-Sun continuum intensity.

The detailed analysis outlined above produced a three-dimensional reconstruction of the full magnetic field vector in the active region. Figure 1 shows the magnetic structure in the large sunspot, after deprojecting it to disk center and with the magnetic field transformed to the solar reference frame. The 180° ambiguity in the (observer’s frame) azimuth was resolved by picking the value that resulted in a more radial field when converted to the solar coordinate frame. As a consistency test, we computed the divergence of the field across the entire map using boxes of 1.6 Mm in each dimension. It was found that the divergence is always small compared with B/l (the magnitude of the field divided by the length of the box), with an average absolute value of 1.8%. This argument, as well as the spatial coherence of the results obtained (recall that each pixel was inverted independently), strongly supports the reliability of our findings.

The east side of the sunspot (left of the figure) is reminiscent of what is typically found in numerical simulations of a simple sunspot, with field lines bending outward in the penumbra. This area is partly force-free, as can be deduced from Figure 2 (recall that the condition for a force-free field is that $\nabla \times B$ must be parallel or antiparallel to $B$), particularly in the chromosphere, but not entirely. The west side (right of the figure), on the other hand, exhibits a very different structure, and the field is mostly non–force-free. Photospheric magnetograms of the region (not shown) reveal an intricate pattern of flux near the sunspot on that side, suggesting a complex topology that would manifest itself also in the sunspot structure, perturbing the field away from the classical picture of a near-potential configuration. This
Fig. 1.—Three-dimensional structure of the magnetic field lines. Top, perspective view; bottom, view from above. The height range between 0 km and 800 km is represented in yellow, whereas the range between 800 km and 1600 km is in red. Axes are in megameters. Only field lines originating on a 5 x 5 pixel grid are shown in the bottom panel (5 x 10 in the top panel), to avoid cluttering the figure.

idea is further supported by Hα images from the same day showing considerable activity on the west side of this sunspot.2

To avoid confusion with the terminology, which is sometimes used with different meanings in the literature, we adopt the following definitions in this work: We denote by “twist” the deviation of the field from the radial direction and by “torsion” the vertical gradient of the azimuth.3 In this context, the concept of torsion is probably better defined from a mathematical point of view, because the radial direction is not well defined in cases like the present one. Furthermore, while twist and torsion (as defined here) refer essentially to the same concept in a rigid object, this is not necessarily the case in nonrigid systems such as the magnetic field lines. Imagine, for example, a magnetic field that does not vary along the flux-rope axis but whose azimuth does not follow the radial direction. This configuration would have twist but not torsion.

A detailed representation of the magnetic torsion is provided in Figure 3. This figure shows that the torsion is negative over most of the sunspot, but there are also two large areas of positive torsion. The first one corresponds roughly to the upper right quadrant. It may be associated with the direction connecting the main umbra to the umbral core located toward the northwest. The torsion in this area decreases in magnitude as we move up into the chromosphere. The other positive-torsion area is roughly the lower left quadrant and, contrarily to the first one, its magnitude increases with height.

The results presented in this Letter reveal a very complex topology of sunspot fields. The fact that most of the spot departs from the force-free regime is quite surprising and has some important implications. While the force-free approximation is a convenient way to estimate the magnetic field structure (whether by means of extrapolations or using it to make empirical twist determinations), our observations do not support its applicability in general. Empirical determinations of twist or electric currents from two-dimensional maps in complex regions seem particularly questionable. In fact, such investigations have even more caveats, because one can only obtain one of the components of the curl vector and also because the “measurement heights” at different pixels have variations as large as 500 km in a sunspot. In summary, there are no convenient shortcuts to measuring the actual three-dimensional structure of the field by means of full Stokes spectropolarimetry and proper non-LTE modeling. Finally, it is important to note that the non–force-freeness of the field provides potential energy that may become available for chromospheric or coronal heating by means of magnetic reconnection into a lower energy state. The coexistence of opposite-sign torsions is a rather surprising finding since, to the author’s best knowledge, it has not been predicted or proposed in any previous theoretical models.

The physical mechanism that twists the field is yet to be established. Three different processes have been proposed: (1) the dynamo itself generates twisted fields (Choudhuri et al. 2004); (2) Coriolis forces twist the flux tubes during their ascent (Fisher et al. 2000; Fan & Gong 2000); (3) turbulent convective buffeting twists the flux tubes during their travel through the convection zone (Longcope et al. 1998). The mixed-twist scenario of our observations seems to be difficult to explain by the first two possibilities, which should produce flux ropes with same-sign twist in a given active region. The convective buffeting scenario, on the other hand, is essentially a turbulent process and would naturally produce either sign of twist in a more or less stochastic manner. Therefore, while the three mechanisms are probably contributing with different relative importance, our data indicate that convective buffeting is probably the dominant one. However, convective buffeting cannot be the only mechanism producing twist, since the statistics of active regions clearly indicate that there is also a systematic trend in the twist (see, e.g., Pevtsov et al. 1995).

2 See, e.g., the Active Region Monitor at NASA Goddard Space Flight Center’s Solar Data Analysis Center, http://www.solarmonitor.org/20040616/0634.html.
3 The term “azimuth” here is defined as the angle between the (measured) magnetic field vector B and the solar east-west direction, measured counterclockwise from solar west.
Fig. 2.—Maps of the angle between vectors $\nabla \times \mathbf{B}$ and $\mathbf{B}$ at three different heights. The field is strictly force-free only in those pixels shown in dark blue (parallel) or light yellow (antiparallel).
Fig. 3.—Torsion maps. The color scale represents degrees measured counterclockwise from the solar west direction. The top left panel shows the photospheric azimuth. All other panels show the difference between the azimuth at the optical depth indicated by the label minus the photospheric azimuth (shown in the first panel), i.e., the magnetic torsion. The umbral and penumbral boundaries are overlaid for reference.

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