

## Measuring the Magnetic Vector with the He I 10830 Å Line: A Rich New World

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**Abstract.** The triplet of the He I transitions around 10830 Å not only shows a rich variety of Stokes profiles, but also allows the full magnetic vector in the upper chromosphere to be probed, thus revealing the magnetic structure of loops, current sheets, finely structured supersonic downflows, the chromospheric layers of sunspots (supporting the presence of uncombed fields in the penumbra), flares, and the quiet Sun. A very brief overview of some of the observations and results obtained so far is given.

### 1. Introduction

Whereas the magnetic field in faculae and the network is nearly vertical in the photospheric layers, in the chromosphere and corona the magnetic vector is often inclined to the vertical, as canopies and loops take over from flux tubes. Thus the need to measure the full magnetic vector is larger in the chromosphere and corona than in the photosphere. Unfortunately, however, almost all such measurements are restricted to the photosphere.

Here we present an overview of some measurements and results obtained with the He I 10830 Å triplet, formed in the upper chromosphere, near the base of the corona. Only a glimpse can be given into the rich variety of observed He I 10830 Å Stokes profiles and the magnetic and dynamic structures deduced therewith.

The He I triplet is composed of three lines at  $\lambda 10829.911$  Å,  $\lambda 10830.250$  Å, and  $\lambda 10830.339$  Å ( $g_{\text{eff}} = 2.0, 1.75, \text{ and } 1.25$ , respectively). It has the great advantage that under normal circumstances it is nearly optically thin, so that the magnetic vector and the line-of-sight (LOS) velocity can be extracted relatively easily, without having to go into details of line formation. It should be noted, however, that it is not straightforward to determine the height to which the measurements refer, which can vary by a far larger amount than the heights of formation of typical photospheric lines.

The first measurements of the LOS magnetic field with the He I triplet were carried out by Harvey & Hall (1971). We have regularly observed the full Stokes vector since 2001 with the Tenerife Infrared Polarimeter (TIP) and its recent upgrade to a  $1024 \times 1024$  pixel detector, the MPS-IAC TIP II. An example Stokes

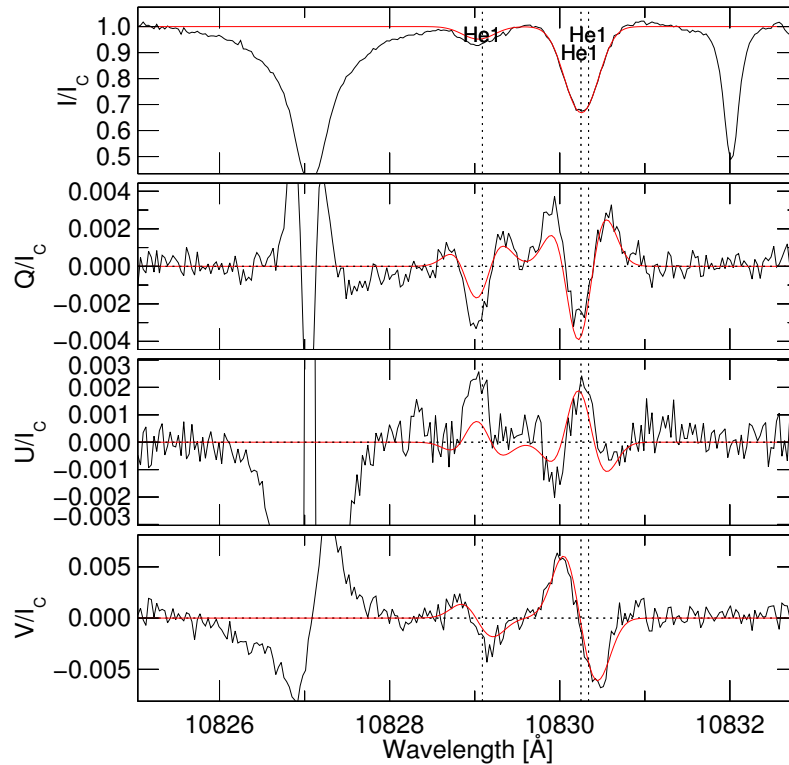


Figure 1. Stokes  $I, Q, U, V$  spectra recorded with the Tenerife Infrared Polarimeter (TIP) (black curves), showing from left to right the Si I 10827 Å photospheric line, the chromospheric He I triplet (central wavelengths of the three transitions are marked by the vertical dotted lines), and a telluric line. The red curves denote fits to the He I triplet using the code described by Lagg et al. (2004).

spectrum is shown in Fig. 1, together with the best-fit profile obtained by applying an inversion code (Lagg et al. 2004) that takes into account line saturation using a Milne-Eddington atmosphere, and the Paschen-Back effect according to Socas-Navarro, Trujillo Bueno, & Landi Degl’Innocenti (2005) (cf. Sasso, Lagg, & Solanki 2005). The code further employs a simple description of the Hanle effect and searches for global  $\chi^2$  minima with the help of a genetic algorithm.

## 2. Sample Results

A variety of results have been achieved. The best studied dataset so far has been of an emerging flux region. Because the freshly emerged loops are still filled with relatively cool gas the He I triplet is formed throughout these loops. Consequently, observations of these lines have allowed the magnetic field to be reconstructed along a whole arcade of loops (Solanki et al. 2003, see also Fig. 2a) This observation provides a unique possibility to test different approximations of magnetic field extrapolations. Wiegelman et al. (2005) computed the potential field and the linear and non-linear force-free field starting from the photospheric

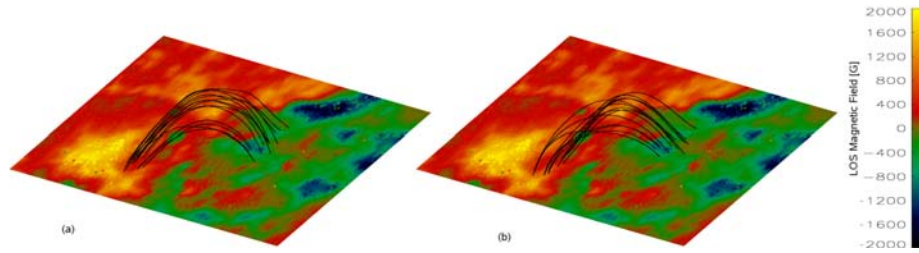


Figure 2. a) Magnetic loops in an emerging flux region reconstructed from He I data. Plotted are sample magnetic field lines overlying a photospheric magnetogram. b) The same view of loops computed using a non-linear force-free extrapolation starting from the measured photospheric vector field.

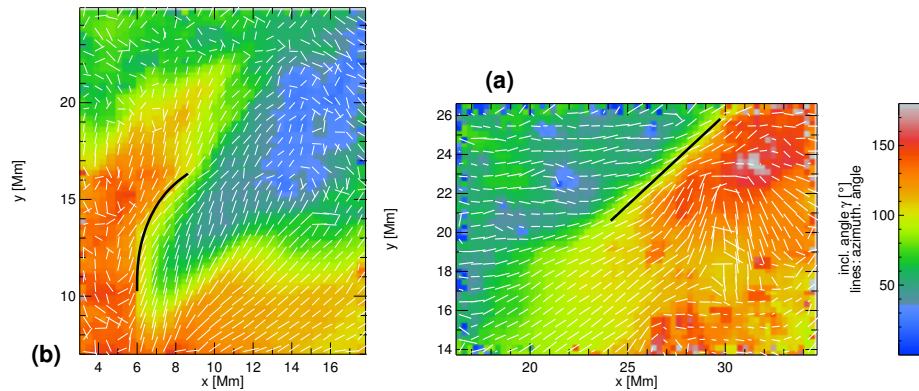


Figure 3. a) Direction of the chromospheric magnetic field around an electric current sheet located at the border of an emerging flux region. Colours represent the inclination of the field to the vertical, the white dashes the azimuthal direction. b) The same for a current sheet in another active region.

magnetic vector deduced from the simultaneously measured Si I 10827 Å line. They found that the non-linear force-free field (see Fig. 2b) displayed the best correspondence to the observations. This implies that the magnetic arcade was already strongly sheared at emergence.

The same region also showed a vertical current sheet located at the boundary between emerging flux and preexisting flux (Solanki et al. 2003). The inclination angle of the field to the LOS is shown in Fig. 3a. The current sheet passes diagonally from lower left to upper right. Also indicated is the magnetic azimuth, by the white dashes, which lie parallel to the current sheet. Another example is shown in Fig. 3b, where the sharp polarity inversion line is curved (polarity changes within a spatial resolution element, given by seeing).

A surprisingly common feature are the supersonic downflows, found in almost every scanned solar region, irrespective of whether it is an active region or the quiet Sun. Multiple velocity and magnetic field components can often be distinguished, two being most common, but three and even four being seen in some cases. More rarely supersonic upflows are also seen. One example of a supersonic downflow is discussed in detail by Lagg et al. (2006) and a more general

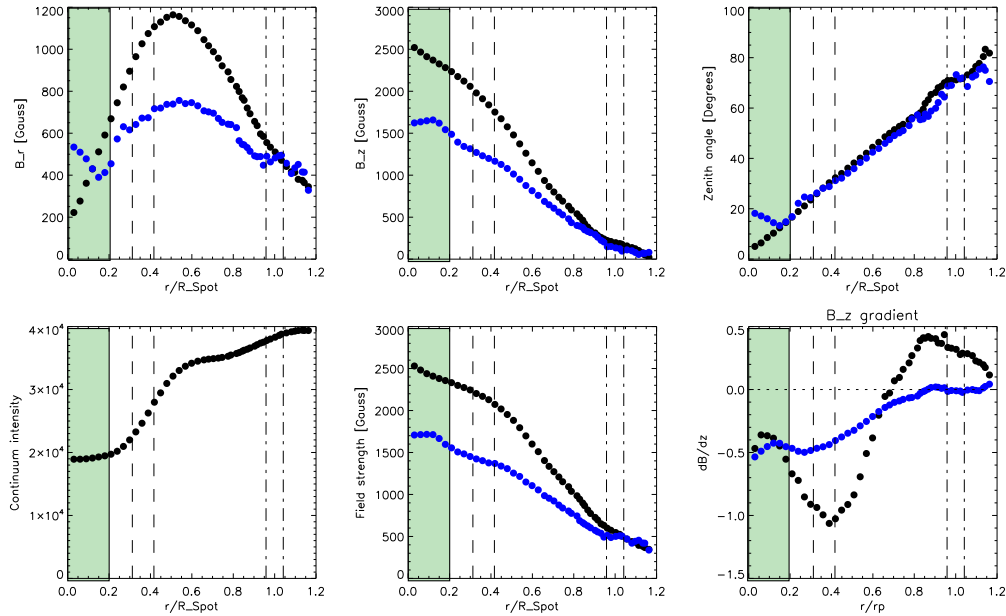


Figure 4. Azimuthal averages of magnetic and thermodynamic parameters in sunspots at the photospheric (black dots) and chromospheric levels (blue dots) vs. radial distance from the centre of the spot. The shaded area indicates where the chromospheric values are of lower accuracy due to oscillations.

overview is given by Aznar Cuadrado, Solanki, & Lagg (2005), so that we refrain from going into further details here.

Sunspots also turn out to be interesting objects to study with the He I triplet (cf. Penn & Kuhn 1995; Rüedi, Solanki, & Livingston 1995), in particular in conjunction with simultaneous measurements of the photospheric field using the Si I line. In Fig. 4 azimuthal averages of various parameters are plotted vs.  $r/r_p$ , where  $r$  is the distance from the center of the spot and  $r_p$  is the outer penumbral radius. High-amplitude oscillations present in the chromospheric layers of the inner umbra are the limiting factor determining the accuracy of the deduced physical parameters (shaded area in the figures). These results allow the vertical gradient of the magnetic vector to be determined. More details are given by Orozco Suárez et al. (2006). Figure 5 demonstrates the presence of net circular polarization not just in the Si I line, but also in the He I triplet (very close to the neutral line). Since a single-lobe profile, as plotted there, in general requires strong gradients of the magnetic vector and the velocity along the LOS, the measurement suggests that such gradients (as present along the boundary of a flux tube embedded in the surrounding field) are present not just in the photosphere, but right up into the upper chromosphere (Rüedi et al. 1995).

The most puzzling and unexpected Stokes profiles have been observed in flares, however. There the line can become extremely deep and broad, increasing its equivalent width by over an order of magnitude relative to its average over an active region. Even more exciting is the signal in Stokes  $V$ , which can show many lobes or components. An example of such a gigantic  $I$  profile and the corresponding complex  $V$  profile observed with TIP II is plotted in Fig. 6. Note

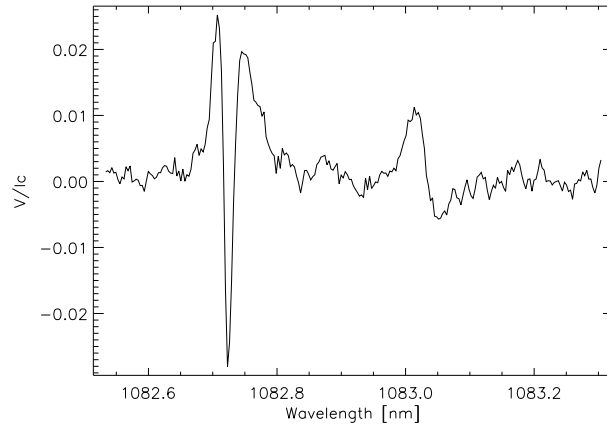


Figure 5. Stokes- $V$  spectrum obtained very close to the polarity inversion line in a sunspot penumbra. Note the asymmetric  $V$  profile of He I.

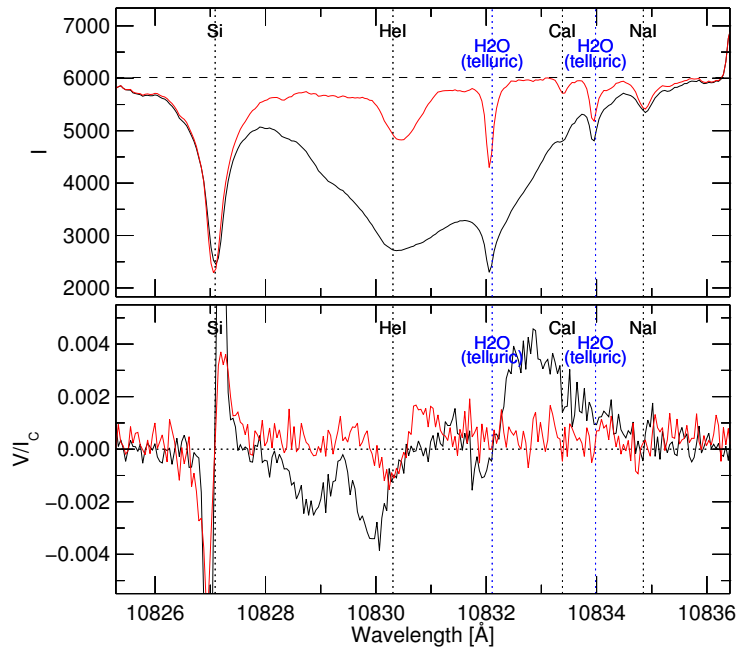


Figure 6. Stokes- $I$  and  $V$  profiles recorded with TIP II in a flaring region (black line). The central wavelengths of four photospheric and two telluric lines are indicated by vertical dotted lines. The red profile shows a typical, quiet-Sun profile outside the flaring region.

that some of the Stokes- $V$  components appear to be composed of single lobes, suggestive of strong gradients of the magnetic vector along the LOS. At other locations in the same flaring site (or at other sites) the He I triplet is seen to go into emission. At still other locations a strong absorption is found without an associated measurable Stokes- $V$  signal. This is unusual, since the upper chromosphere otherwise rarely shows any signs of field-free gas.

In addition to the work mentioned here, considerable spectro-polarimetric work has been done with the He I triplet on prominences (Trujillo Bueno et al. 2002; Merenda et al. 2005, see also Martínez Pillet's presentation in this conference), spicules (Trujillo Bueno et al. 2005), and on oscillations in sunspots and plages (Centeno Elliot, Collado, & Trujillo Bueno 2006).

### 3. Conclusions

From the examples shown above it is clear that the spectro-polarimetry of the He I 10830 Å triplet provides access to a rich array of phenomena, and exhibits profiles covering an unusually wide variety of shapes. This is partly due to the fact that the He I lines are in general optically thin, so that they are rather sensitive to dynamic phenomena. Another advantage is that they are unadulterated by a photospheric contribution, which can drown some of the chromospheric effects. It has become clear from these studies that the physical structure of the upper chromosphere, including its magnetic field, is very different from the photosphere, the layer best studied by spectro-polarimetric means. In that sense the He I 10830 Å triplet has indeed opened up a rich new world.

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