SUPERSONIC DOWNFLOWS IN THE SOLAR CHROMOSPHERE ARE VERY COMMON

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ABSTRACT

We present an overview of a large dataset of 13 active regions obtained in the chromospheric He I 1083.0 nm triplet. Infrared spectropolarimetric observations were obtained with the Tenerife Infrared Polarimeter (TIP) at the German Vacuum Tower Telescope (VTT) of the Spanish observatory of Izaña, Tenerife. Observations in the chromospheric He I 1083.0 nm multiplet were used to create maps in the Stokes parameters I, Q, U and V. A technique to invert Stokes profiles of the He I 1083.0 nm multiplet lines was applied in order to obtain the full magnetic vector and the line-of-sight velocity. Supersonic flows with line-of-sight velocities of $30-60$ km s^{-1} (corresponding to Mach number $M_a = 2.9-5.8$) turn out to quite common and are generally found in several locations of most observed active regions. Three quiet sun regions scanned close to disk centre reveal that supersonic downflows of the order of 30 km s^{-1} are also present.

Key words: Sun: chromosphere; magnetic fields; activity.

1. OBSERVATIONS, INSTRUMENTATION AND DATA REDUCTION

Observations of 13 active and 3 quite sun regions were carried out with the Tenerife Infrared Polarimeter (TIP) at the Vacuum Tower Telescope (VTT), Izaña Observatory, Tenerife, during May 2001, October 2002 and August 2003. The spectrograph spectral resolution was 30 mÅ per pixel and the pixel size was $0.38''$ ($\sim$ 275 km). In order to increase the signal-to-noise level, all spectra were binned over three spectral pixels. The observed wavelength range, from 1082.5 to 1083.3 nm, contains two photospheric lines of Si I (at 1082.709 nm, effective Land factor $g_{\rm eff} = 1.5$) and Ca I (at 1082.93 nm), the chromospheric He I multiplet (He I at 1082.909 nm, He I at 1083.025 nm and He I at 1083.034 nm, with $g_{\rm eff} = 2.0$, 1.75 and 1.25, respectively) and a telluric blend at 1083.21 nm. Flat-field, calibration and dark current measurements were obtained before and after each scan to correct the measurements.

Table 1. Observational details together with maximum values of downflow velocities of the chromospheric He I *1083.0 nm line.*

Date	NOAA	μ	UT	Downflow (km s^{-1})
13/05/2001	9451	0.80	15:06	30
03/10/2002	10134	0.79	08:09	11
18/08/2003	10432	0.88	08:33	36
27/08/2003	10436	0.57	09:54	60
22/08/2003	10440	0.96	08:23	60
26/08/2003	10441	0.98	09:09	35
25/08/2003	10444	0.69	07:45	15
26/08/2003	10445	0.81	08:00	44
17/08/2003	E19—S3	0.93	17:52	10
18/08/2003	W5—S22	0.88	09:09	14
20/08/2003	E30—S6	0.84	10:29	37
21/08/2003	E18—S5	0.93	08:42	45
23/08/2003	W1—N6	1.00	08:03	32
26/08/2003	Quiet Sun	0.99	09:50	25
26/08/2003	Quiet Sun	0.85	10:09	28
27/08/2003	Quiet Sun	1.00	08:41	30

Table 1 reports some details of the observations presented in this work. The angle $\mu = \cos\theta$, where θ is the heliocentric angle, i.e., the angle between the line-of-sight and the normal to the solar surface. UT is the universal time at the beginning of each observation. Maximum values of downflow velocities obtained with the chromospheric He I 1083.3 nm line are listed in the last column.

The speed of sound of the chromospheric He I 1083.0 nm line, assuming a formation temperature for this line of about 10 000 K, is of the order of 10 km s^{-1}. Hence, from Table 1 we clearly see that all maximum downflow velocities measured in the chromospheric He I 1083.3 nm line of our active and quiet sun regions show supersonic values, with two possible exceptions (NOAA 10134 and E19-S3).

2. INVERSION OF THE FULL MAGNETIC VECTOR

The He I triplet (nearly optically thin, but with a complex non-LTE formation) was analysed by inverting the data using the Unno-Rachkowsky solution to describe the individual Zeeman components of each member of the triplet to the data (method described in Lagg et al. 2004). The inversion allows us to retrieve the full magnetic vector in the upper chromosphere (where the He I triplet is formed), including the strength of the magnetic field, its inclination to the solar surface normal and its direction in the horizontal plane (i.e., the azimuthal angle). Line-of-sight velocity maps are also obtained (positive values of velocity denote downflows).

3. THREE-COMPONENT ATMOSPHERE

From the analysis of the 16 regions involved in this work we can report that in the areas where fast downflows ($> 10\ \mathrm{km\ s^{-1}}$) are present the Stokes profiles, in general, clearly exhibit two coexisting atmospheric components, with the first component being almost unshifted. For some regions and at some locations, even a third magnetic component seems to be necessary, with strongly supersonic velocities of the order of $40 - 60\ \mathrm{km\ s^{-1}}$. This upper limit in the velocity is limited by the available spectral range given by our observations. At some locations line profiles are found to be shifted right to the edge of the detector's spectral range, so that this value could even be higher.

Figure 1 shows the atmospheric parameters returned by a 1-component inversion obtained in the He I doublet at $1083.0\ \mathrm{nm}$ of the active region NOAA 10436. The chromospheric maps show regions with strong downflow velocities (see bottom panel of Figure 1). At these locations the 1-component provides poor fits to the observed Stokes profiles.

Consequently, a 3-component analysis of this region was performed and the velocity maps characterising the different components are presented in Figure 2. A 3-component fit of this region (see Figure 3) clearly identifies a slow component (corresponding to the left panel of Figure 2), almost at rest, and two fast components (mid and right panels of Figure 2) showing supersonic velocities. Table 2 reports the values of the atmospheric parameters derived from the best fit shown in Figure 3.

4. MAGNETIC FIELDS IN QUIET SUN REGIONS

Figure 4 shows the atmospheric parameters retrieved from a 1-component inversion obtained in the chromospheric He I $1083.0\ \mathrm{nm}$ line of a quiet sun region, observed close to the disk centre ($\mu = 0.85$), obtained on

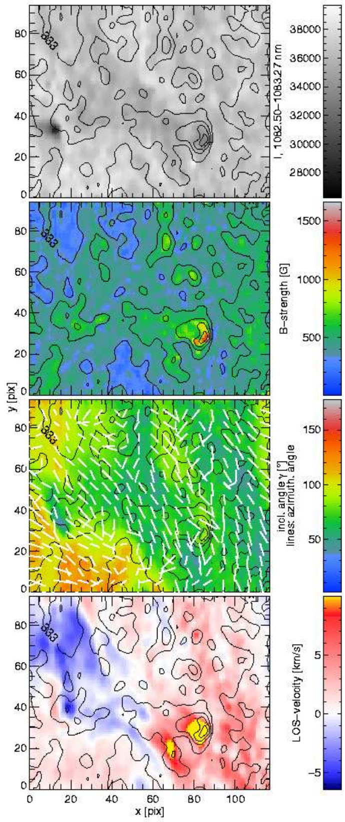

Figure 1. 1-component analysis of NOAA 10436, obtained on 27 August 2003 at 09:54 UT, of the He I doublet at $1083.0\ \mathrm{nm}$. *The black contour lines give the values for the magnetic field strength in Gauss.*

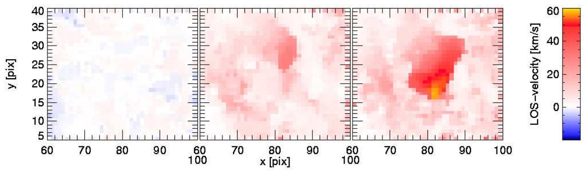

Figure 2. Velocity maps of a 3-component analysis for a region of NOAA 10436. Each panel shows the velocity of one component, ordered according to increasing maximum downflow velocity.

Table 2. Fitting parameters of a 3-component analysis of NOAA 10436 observed on 27 August 2003, for pixel (83,21).

27 August 2003	Comp 1	Comp 2	Comp 3
B–strength (G)	408	655	850
Azimuth (°)	55	-15	18
Inclination (°)	43	51	28
LOS–Vel. (km/s)	1.23	18.83	51.26

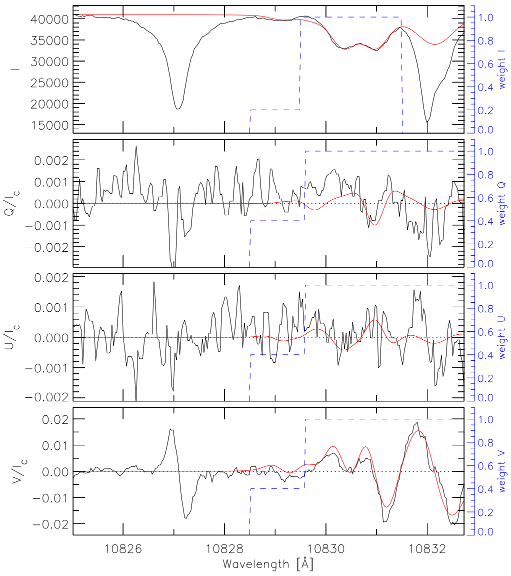

Figure 3. Stokes profiles of NOAA 10436, observed on 27 August 2003 at 09:54 UT, for pixel (83,21). The observed profile is shown in black while the fit in red represents three independent magnetic components (see results in Table 2). The dashed blue lines indicate the weighting scheme applied in the 3-component inversion.

Table 3. Best-fit parameters of a 2-component analysis of the spectrum shown in Figure 5 of a quiet sun region observed on 26 August 2003 at 10:09 UT.

26 August 2003		Comp 1	Comp 2
B–strength	(G)	564	783
Azimuth	(°)	10	49
Inclination	(°)	108	101
LOS–Vel.	(km/s)	3.02	27.12

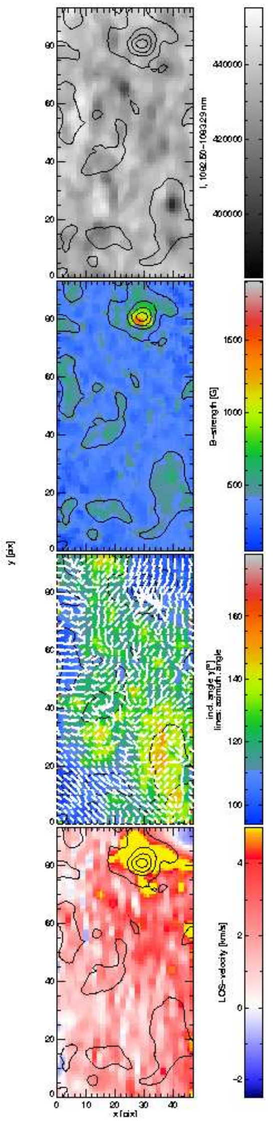

Figure 4. 1-component analysis of a quiet sun region, observed on 26 August 2003 at 10:09 UT, of the He I *doublet at* 1083.0 nm.

26 August 2003, at 10:09 UT. Magnetic field structures due to the network are clearly visible in the *B* map (see second panel of Figure 4). Black contour lines indicate the values for the magnetic field strength.

In 100% of the field of view we measured amplitudes of Stokes V above a $3\,\sigma$ threshold of 2.7×10^{-4}, while 99% of the pixels of this *"quiet sun"* observation showed amplitudes above the $5\,\sigma$ level. Thus, at the level at which the He I 1083.0 nm line is formed, the whole atmosphere is filled by a magnetic field.

A 2-component analysis of the region showing strong magnetic fields reveals the existence of two coexisting components (see Figure 5), one being at rest and a redshifted component showing supersonic velocities. Values of the best-fit parameters of the spectrum shown in Figure 5 are given in Table 3. This shows that supersonic downflows are not limited to active regions.

5. CONCLUSIONS

We have presented spectropolarimetric observations of 13 active and 3 quiet sun regions in the chromospheric He I triplet taken with the Tenerife Infrared Polarimeter (TIP). By inverting the Stokes profiles of the He I 1083.0 nm multiplet lines we have obtained the full magnetic vector and the line-of-sight velocity. We have shown that supersonic flows with line-of-sight velocities of typically $20-30$ km s^{-1} (Mach number $M_a = 2-3$) are extremely common and are found in several locations of most observed active regions. Strongly supersonic downflows up to 60 km s^{-1} (Mach number $M_a = 5.8$), where a third component is necessary to fit the chromo-

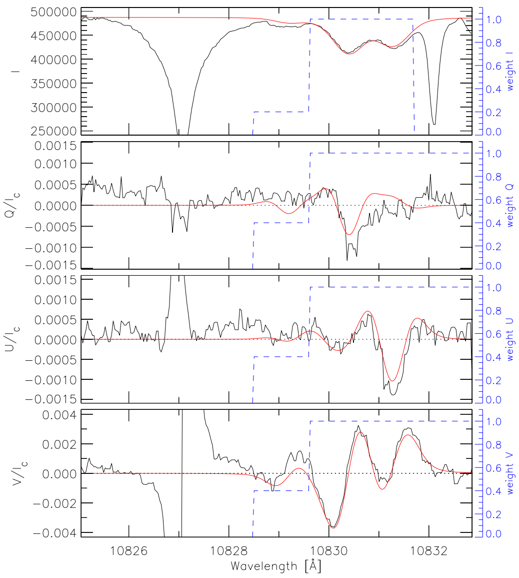

Figure 5. Stokes profiles of NOAA 10436, observed on 27 August 2003 at 09:54 UT, for the pixel (31,79). The observed profile is shown in black while the fit in red represents two independent magnetic components (see results in Table 3). The dashed blue lines indicate the weighting scheme applied in the 2-component inversion.

spheric He I $1083.0\,\mathrm{nm}$ line profiles, are observed in some cases. Although less common, supersonic downflow velocities of the order of $30\,\mathrm{km\,s^{-1}}$ are also observed in regions of quiet sun scanned close to disk centre.

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