SUPERCSONIC DOWNFLOWS IN A SUNSPOT LIGHT BRIDGE

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Received 2009 June 18; accepted 2009 August 24; published 2009 September 24

ABSTRACT

We report the discovery of supersonic downflows in a sunspot light bridge using measurements taken with the spectropolarimeter onboard the Hinode satellite. The downflows occur in small patches close to regions where the vector magnetic field changes orientation rapidly, and are associated with anomalous circular polarization profiles. An inversion of the observed Stokes spectra reveals velocities of up to 10 km s⁻¹, making them the strongest photospheric flows ever measured in light bridges. Some (but not all) of the downflowing patches are cospatial and cotemporal with brightness enhancements in the upper chromosphere/lower chromosphere, which suggest that these flows are due to magnetic reconnection in the upper photosphere/lower chromosphere, although other mechanisms cannot be ruled out.

Key words: Sun: magnetic fields – sunspots – techniques: polarimetric

1. INTRODUCTION

Light bridges (LBs) are bright structures in the otherwise dark umbra that often exhibit a granular-like morphology (Muller 1979; Sobotka et al. 1994; Hirzberger et al. 2002; Rimmele 2008). They represent a discontinuity or interruption in the regular umbral field (García de La Rosa 1987). LBs are known to harbor weak and inclined fields (Ruedi et al. 1995; Leka 1997; Jurčák et al. 2006; Katsukawa et al. 2007), but their origin and magnetic nature is still a matter of debate (Parker 1979; Choudhury 1986; Spruit & Scharmer 2006; Rimmele 1997, 2004).

One of the reasons that make LBs interesting is their chromospheric activity, seen as surges in Hα (Asai et al. 2001), localized brightenings in Ca ii H filtergrams (Louis et al. 2008; Shimizu et al. 2009), and brightness enhancements in the upper chromosphere and transition region (Berger & Berdyugina 2003). The stressed magnetic configuration associated with LBs is perceived to be responsible for this activity, but the precise relationship, if any, is yet to be established. Unfortunately, there is a lack of simultaneous vector magnetic field measurements in the photosphere to diagnose these events.

Here we analyze Hinode spectropolarimetric observations and Ca ii H filtergrams of a sunspot LB in an attempt to relate its chromospheric activity to the photospheric magnetic field. We discover patches of supersonic downflows in the photospheric layers of the LB and show that some of them are associated with strong Ca ii H brightness enhancements. Interestingly, the supersonic flows produce spectral signatures never seen before in LBs.

2. OBSERVATIONS

On 2007 May 1, the leading spot of NOAA Active Region 10953 was observed with Hinode (Kosugi et al. 2007) at a heliocentric angle of 8° (μ = 0.99). Between 10:46 and 12:25 UT, the Hinode spectropolarimeter (Lites et al. 2001; Ichimoto et al. 2008; Tsuneta et al. 2007) recorded the four Stokes profiles of the iron lines at 630 nm with a spectral sampling of 21.55 mÅ, a pixel size of 0′′.16, and an exposure time of 4.8 s per slit position (normal map mode). The observations were corrected for dark current, flat field, thermal flexures, and instrumental polarization using routines included in the Solar-Soft package. Simultaneously, the Broadband Filter Imager of Hinode took Ca ii H filtergrams with a cadence of 1 minute to monitor the chromosphere of the LB. The effective pixel size of the Ca images is 0′′.11.

3. RESULTS

3.1. Downflowing Patches and Chromospheric Activity

The left panel of Figure 1 shows a continuum map of the spot and the LB. We have inverted the observed Stokes profiles using the SIR code (Stokes Inversion based on Response Functions; Ruiz Cobo & del Toro Iniesta 1992). SIR computes perturbations in the physical quantities at specific locations across the optical depth grid called nodes, and then carries out an interpolation to yield values at all grid points. To determine the global structure of the LB and the surroundings, we performed a one-component inversion setting the magnetic and dynamic parameters to be constant with depth. The temperature stratification was perturbed with two nodes. A total of nine parameters were retrieved from the observed profiles, including height-independent micro- and macro-turbulent velocities and a stray-light factor.

The three components of the vector magnetic field (strength, inclination, and azimuth) deduced from the inversion are shown in the second and third columns of Figure 1. All the angles are expressed in the local reference frame after a manual disambiguation of the line-of-sight (LOS) azimuths. As can be seen, the LB is characterized by weaker and more inclined fields than the umbra. This confirms earlier results by, e.g., Leka (1997) and Jurčák et al. (2006). In the upper half of the LB, the magnetic field is parallel to the axis of the bridge. Both photometrically and magnetically, the LB looks like an extension of the penumbra protruding into the umbra. Louis et al. (2008) detected a horizontal flow along the LB that starts in the adjacent penumbra, demonstrating that the two structures are also connected dynamically. At the lower end of the LB, where the LB fields pointing south encounter sunspot fields oriented toward the north, one observes an isolated region with relatively weak magnetic fields. In addition, there is a discontinuity in the field azimuth running parallel to the west edge of the LB.

The LOS velocity map displayed in the third column of Figure 1 reveals the existence of strong, localized downflows in the LB with velocities of up to 4 km s⁻¹. Interestingly, the downflows occur close to the weak-field region and the
azimuth discontinuity described above, i.e., at positions where
the magnetic field changes orientation very rapidly (fourth
column of Figure 1). Some of the downflowing patches coincide
with chromospheric Ca II H brightness enhancements, as can
be seen in Figure 2. The filtergram displayed there was taken
during the polarimetric scan of the LB and shows a strong Ca II H
line-core brightening at the position and time of the largest
photospheric velocities. NOAA AR 10953 produced many
other long-lasting chromospheric plasma ejections on April 29
and 30 (Shimizu et al. 2009).

The Stokes V profiles associated with the downflows have
two peaks in the red lobe, i.e., they exhibit a total of three peaks.
Hereafter they will be labeled as Type 1. In the LB one also
finds anomalous linear polarization profiles with normal Stokes
V signals which are designated as Type 2. Type 3 profiles are
essentially a combination of the other two classes. Examples of
these profiles are given in Figure 3, together with their spatial
distribution.

3.2. Anomalous Stokes V Profiles

Milne–Eddington-like atmospheres such as the ones used to
determine the global structure of the LB cannot reproduce the
complex shapes of Type 1 profiles. For this reason, the velocities
given in Section 3.1 are only approximate. Here we obtain more
reliable values with the help of two-component inversions.

We start with a simple two-component model in which the
magnetic field and the LOS velocity do not vary with height.
The results of this inversion are presented in Figure 4. As can
be seen, one of the components has supersonic velocities of
$\sim 10$ km s$^{-1}$ and the other is essentially at rest. The model
explains the observed profiles in a very satisfactory way, but the
assumption of two magnetic components separated horizontally
in the resolution element may not be realistic because of

The other two patches do not exhibit significant brightness enhancements. However, they are located near the end of thread-like chromospheric structures
that reach into the umbra U1 (see the white lines in Figure 2). These structures
show brightenings, but not as intense as those associated with the strongest
downflows.
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Figure 3. Left: anomalous Stokes spectra observed in the LB. Type I, II, and III profiles are shown in orange, green, and yellow, respectively. Right: spatial distribution of the anomalous profiles. Blue contours mark velocities larger than 2.5 and 4 km s\(^{-1}\).

Figure 4. First and second columns: observed (solid) and best-fit (dashed) Stokes profiles using a simple two-component atmosphere. Third and fourth columns: atmospheric stratifications for the two components (solid and dashed lines, respectively). The filling factor of the fast component is 43%.

preparation). The results show that the fast component always has velocities exceeding 10 km s\(^{-1}\). As an example, Figure 5 displays the stratifications of one such model with the downflows occurring in the lower half of the photosphere.

While the two-component models used in this section differ in complexity, all of them indicate supersonic velocities and magnetic fields of the same polarity. In fact, the existence of supersonic flows is obvious from the shapes of the observed Stokes V profiles, which are similar to those emerging from the outer part of the penumbra where the Evershed flow exceeds the sound speed. The inclined red wings of Stokes I also demonstrate the occurrence of strong velocities. All these spectral signatures are well reproduced by the two-component inversions. To the best of our knowledge, this is the first time that supersonic downflows have been reported by Rüedi et al. (1995), Schleicher et al. (2003), and Bharti et al. (2007).

3.3. Anomalous Linear Polarization Profiles

In regions where the magnetic field is relatively horizontal, the supersonic flows are associated with Type 3 profiles. They have similar Stokes I and V spectra as Type 1 profiles, but also complex linear polarization signals which cannot be seen when the field is more vertical. We observe anomalous Stokes Q profiles with up to five peaks and signatures of strong redshifts (Figure 3, left). The multiple peaks indicate that different magnetic components coexist in the resolution element at the position of the downflows.

Type 3 profiles are common near the azimuth discontinuity on the west side of the LB, where the LB fields meet the umbral fields (Figure 3, right). Thus, it is likely that these are the magnetic components giving rise to the complex Stokes Q signals. They may lie horizontally next to each other in the resolution element, or could be stacked one on top of the other.
In both cases, the large variations of field azimuth that occur on very small spatial scales should facilitate the reconnection of magnetic field lines from the LB and the adjacent umbra, even if they have the same polarity (Ryutova et al. 2003). The interaction is expected to produce bidirectional jets, and we speculate that the supersonic downflows observed near the azimuth discontinuity and the weak-field region are the signatures of reconnection jets directed toward the photosphere. This would agree with Shimizu et al. (2009), who believe that the LB is essentially a horizontal, twisted flux tube that reconnects with the umbral field at a low altitude. However, our measurements cannot confirm the reconnection scenario unambiguously because the upward jet components are not always visible in the Ca II H images. Indeed, another possibility is that the supersonic downflows are produced by a mechanism similar to that driving the Evershed flow at the outer end of penumbral filaments.

4. SUMMARY AND CONCLUSIONS

We have determined the global magnetic and dynamic properties of a sunspot light bridge from the inversion of Stokes profiles observed by Hinode. A one-component model atmosphere with height-independent parameters (except for the temperature) has been used to that end. Our analysis reveals patches of strong downflows exceeding 4 km s\(^{-1}\) in the LB, associated with complex Stokes V spectra having double red lobes. Two-component inversions of the profiles indicate supersonic velocities of 10 km s\(^{-1}\) or more. A Milne–Eddington inversion by Shimizu et al. (2009) of the same LB on the previous day shows only a small downflow patch with velocities of 0.7 km s\(^{-1}\).

The supersonic downflows occur in regions where the magnetic field of the LB meets sunspot fields with rather different orientations. In those locations one observes anomalous linear polarization signals, but only when the field is relatively horizontal. Moreover, the supersonic downflows are sometimes associated with transient chromospheric brightenings. The interaction of the LB field and the sunspot fields may create current sheets, leading to magnetic reconnection in the upper photosphere/lower chromosphere. The strong photospheric flows could represent the downward directed jets generated in this process. However, such an explanation remains speculative because the associated upward jets are not always seen as chromospheric brightenings.

The discovery of supersonic downflows in LBs has been possible due to the high spatial resolution and stability of Hinode, but their interpretation is still unclear. Additional observations should be performed to investigate the chromosphere and photosphere of LBs simultaneously, in an attempt to detect small brightness enhancements that would confirm the reconnection scenario or favor alternative explanations.

We sincerely thank the Hinode team for providing the data used in this Letter, and the referee for valuable suggestions. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). We acknowledge support by the Spanish MICINN through projects ESP2006-13030-C06-02 and PCI2006-A7-0624, and by Junta de Andalucía through project P07-TEP-2687.

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