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# MAGNETIC FLUX CANCELLATION IN THE MOAT OF SUNSPOTS: RESULTS FROM SIMULTANEOUS VECTOR SPECTROPOLARIMETRY IN THE VISIBLE AND THE INFRARED

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## ABSTRACT

We analyze multiwavelength observations of the cancellation of a moving magnetic feature and a plage element at the outer edge of the moat of an isolated, round sunspot. The event lasted for some 35 minutes until the smaller flux concentration disappeared completely from the photosphere. The data set consists of high-resolution, full vector spectropolarimetric measurements of four visible lines and two near-infrared lines, along with speckle-reconstructed G-band and Ca II H filtergrams. The observations reveal strong chromospheric emission at the neutral line separating the two magnetic poles; it becomes visible 18 minutes *after* the cancellation has started and persists for 25 minutes. We have carried out an inversion of the observed Stokes profiles to determine the variation of the vector magnetic field, temperature, and line-of-sight velocity during the cancellation. No significant changes in field strength, field inclination, or temperature are observed in either of the two opposite-polarity patches. The decrease in magnetic flux is primarily due to a decrease in magnetic filling factor, which is accompanied by strong upflows (of at least 1.1 km $s^{-1}$) in the smaller flux concentration. These results suggest that the cancellation is due to magnetic reconnection in the photosphere.

*Subject headings:* MHD — Sun: chromosphere — Sun: magnetic fields — Sun: photosphere — sunspots

## 1. INTRODUCTION

The mutual disappearance of magnetic flux when two flux concentrations of opposite polarity collide in the solar photosphere is called magnetic flux cancellation. This process is observed to occur within active regions (Martin et al. 1985; Yurchyshyn & Wang 2001; Chae et al. 2004) and in the quiet Sun (Livi et al. 1985). Flux cancellation events are known to be associated with transient enhanced emission and flows in the chromosphere and corona. The cancellation is generally interpreted as being caused by the submergence of an Ω-shaped loop or the rise of a U-shaped loop (Zwaan 1987, his Fig. 2). These loops would be the result of magnetic reconnection of two originally unrelated magnetic poles: if reconnection occurs above the photosphere, an Ω-loop moving downward would be observed in the photosphere as a cancellation of two opposite-polarity magnetic flux patches; if reconnection occurs below the photosphere, the upward motion of a U-loop would be interpreted as a cancellation process.

Harvey et al. (1999) determined the time difference between the disappearance of quiet-Sun magnetic bipoles from the photosphere and the chromosphere, and came to the conclusion that magnetic flux is retracting below the surface for most of the cancellation events studied. These authors thus favor reconnection above the photosphere and submergence of Ω-loops. Recently, Chae et al. (2004) have presented magnetograms of two flux cancellations in the vicinity of a sunspot. They find nearly horizontal magnetic fields at the neutral line separating the two magnetic polarities. Further, they deduce significant downflows associated with the horizontal fields. These observations also support the scenario of submerging Ω-loops. However, Yurchyshyn & Wang (2001) examined the cancellation of two pores in the moat of a rapidly evolving sunspot and found upflows of about 0.6 km $s^{-1}$. They suggest that the cancellation could have been produced by reconnection in the photosphere, the upflows being the signature of strong plasma jets emanating from the reconnection site.

Photospheric reconnection has been studied from a theoretical point of view by, among others, Litvinenko (1999), Furusawa & Sakai (2000), and Ryutova et al. (2003). The latter authors considered the collision of thin and thick flux tubes of opposite polarity. Reconnection of field lines in the photosphere occurs as a result of the interaction, leading to partial flux cancellation and the formation of a U-shaped loop above the site of reconnection and an Ω-shaped loop below (Ryutova et al. 2003, Fig. 10*a*). These loops coexist with the original thick tube, which is not completely destroyed in the process. Magnetic tension causes a fast shortening and straightening of the U-loop. The shortening is accompanied by the generation of acoustic waves that may eventually become upward propagating shocks. Testing these predictions calls for a good observational characterization of photospheric reconnection processes.

In this Letter we use simultaneous high-resolution filtergrams and spectropolarimetric measurements of six lines to investigate a flux cancellation event observed in the moat of a regular spot. We determine the evolution of the vector magnetic field, temperature, and velocity in the two canceling features and show that the cancellation is consistent with the idea of magnetic reconnection in the photosphere.

## 2. OBSERVATIONS AND DATA ANALYSIS

The isolated, round sunspot NOAA AR 10425 was observed from 9:36 to 10:34 UT on 2003 August 9 with the Tenerife Infrared Polarimeter (TIP; Martínez Pillet et al. 1999) and the POlarimetric LIttrow Spectrograph (POLIS; Schmidt et al. 2003), both attached to the German Vacuum Tower Telescope (VTT) of Observatorio del Teide (Tenerife, Spain). Simultaneous observations of the same spot were taken at the Dutch Open Telescope (DOT) in Observatorio del Roque de Los Muchachos (La Palma, Spain) between 8:25 and 11:58 UT. The spot was located at an heliocentric angle of 27°.

The TIP and POLIS slits (of width 0\farcs35 and 0\farcs48, respectively) were aligned carefully in order to observe the same field of view (FOV). Maps of the limb-side part of the spot were

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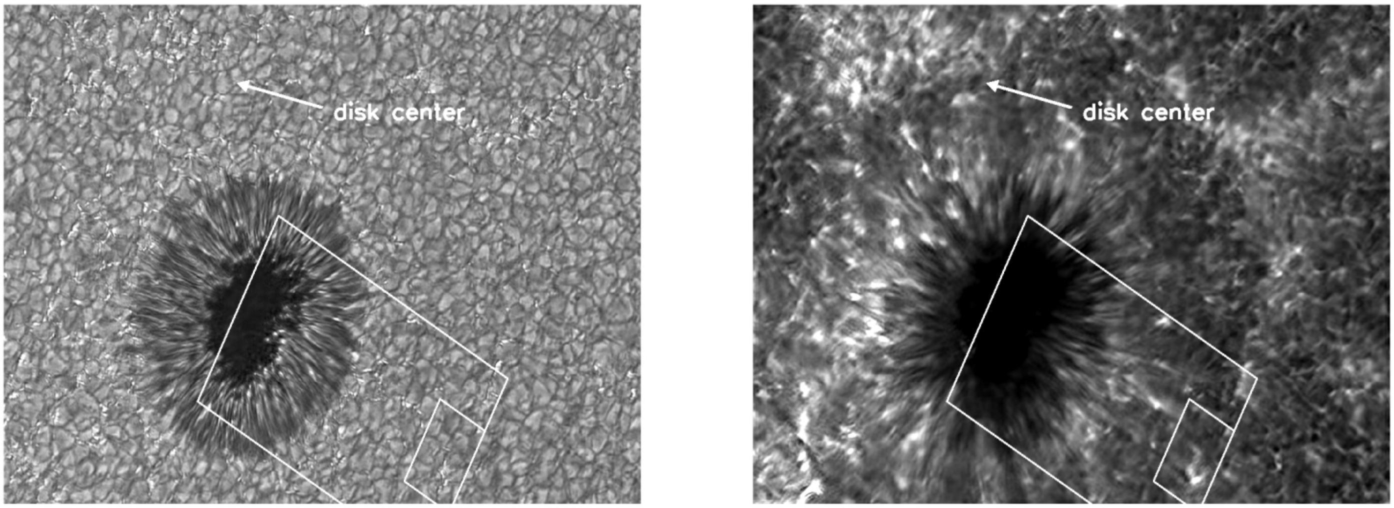


FIG. 1.—DOT G-band (*left*) and Ca II H (*right*) images of NOAA AR 10425 on 2003 August 9 at 10:14 UT. North is up and east to the left. The direction to disk center is indicated by the arrow. The large box shows the area scanned by TIP and POLIS. The small box marks the cancellation site with the FOV used in Fig. 2.

created by scanning the solar image in steps of 0″.35, for a total of 70 steps (24″.5). We repeated the scan eight times. The integration time was 6 s per slit position, leading to a total scan time of about 7 minutes. During the observations a correlation tracker was used to stabilize the solar image. The excellent seeing conditions allowed us to reach an effective spatial resolution of 0″.9–1″.0. The two instruments were operated strictly simultaneously: TIP recorded the four Stokes profiles of the Fe I lines at 1564.8 and 1565.2 nm, while POLIS measured the Stokes profiles of Fe I 630.15 nm, Fe I 630.25 nm, Fe I 630.35 nm, and Ti I 630.37 nm. All six lines are formed in the photosphere. The measurements have been corrected for instrumental polarization, and a common absolute wavelength scale has been set up carefully (see Beck et al. 2005).

The DOT observations consist of speckle-reconstructed filtergrams in the G band at 430.5 $\pm$ 0.5 nm and the core of the Ca II H line at 396.85 $\pm$ 0.06 nm, with a cadence of 1 minute, a pixel size of 0″.071, and a total FOV of 77″ $\times$ 60″ (Sütterlin et al. 2004). The spatial resolution of the processed DOT data reaches the diffraction limit of the telescope (0″.2 at 430.5 nm). The G-band filtergrams provide information about the photosphere, whereas the Ca II H line core is formed in the chromosphere.

The alignment of the various data sets has been carried out using the TIP pixel (0″.35 $\times$ 0″.35) as a reference. The procedure is explained in detail by Beck et al. (2005). Here we only mention that the maximum spatial misalignments between TIP/POLIS data and VTT/DOT data are 0″.1 and 0″.35, respectively. The maximum time difference between observations of the same spatial position is 30 s.

The Stokes profiles of the observed spectral lines have been inverted simultaneously with the SIR code (Ruiz Cobo & del Toro Iniesta 1992). We use a two-component model atmosphere to analyze each pixel: one component is magnetic and the other is field-free. The inversion returns the temperature stratifications in the two components, along with the field strength, field inclination, and field azimuth (all assumed to be constant with height) of the magnetic atmosphere. Other parameters derived from the inversion are the (height-independent) line-of-sight (LOS) velocities in the two atmospheric components, the magnetic filling factor (i.e., the fraction of the resolution element occupied by the magnetic atmosphere), and the amount of stray light contamination.

## 3. RESULTS

The DOT G-band time sequence[3] shows many small bright points moving radially outward in the moat of the sunspot. Beck et al. (2005) demonstrate that the majority of these bright points are unipolar moving magnetic features (MMFs). During the observations, one of the MMFs reached the boundary of the moat and collided with an existing plage element of opposite polarity (see Fig. 1). As a result of the collision, the two structures underwent magnetic flux cancellation.

The first three panels of Figure 2 display the temporal evolution of the magnetic flux, the G-band intensity, and the Ca II H line-core intensity at the cancellation site with a cadence of 7 minutes. The magnetic flux has been computed as $\phi = fSB \cos \gamma_{\rm LOS}$, where $f$ represents the filling factor, $S$ the area of the resolution element, $B$ the field strength, and $\gamma_{\rm LOS}$ the field inclination with respect to the LOS. The flux concentrations corresponding to the MMF (*white polarity*) and the plage element (*black polarity*) are observed to shrink with time, until the smaller one (the plage element) disappears completely. The cospatial and cotemporal G-band images show that each flux concentration consists of a number of small bright points. The Ca II H images reveal stronger chromospheric emission above these G-band bright points, but no unusual behavior is detected for the first 36 minutes of the VTT observations. Eighteen minutes after the cancellation has started, however, we observe strongly enhanced Ca II H line-core emission at the neutral line separating the two polarities. The chromospheric brightening increased steadily with time from 10:12 UT onward, reached a maximum at 10:20–10:25 UT, and persisted for a total of 25 minutes (i.e., it remained visible after the smaller flux concentration had disappeared).

The last five panels of Figure 2 show the magnetic field zenith angle ($\gamma$), the field strength ($B$), the magnetic filling factor ($f$), the LOS velocity ($v$), and the temperature ($T$) at $\tau_c = 1$ in the magnetic component resulting from the inversion.

[3] Available at http://hst33127.phys.uu.nl/DOT/Data/2003_08_09.

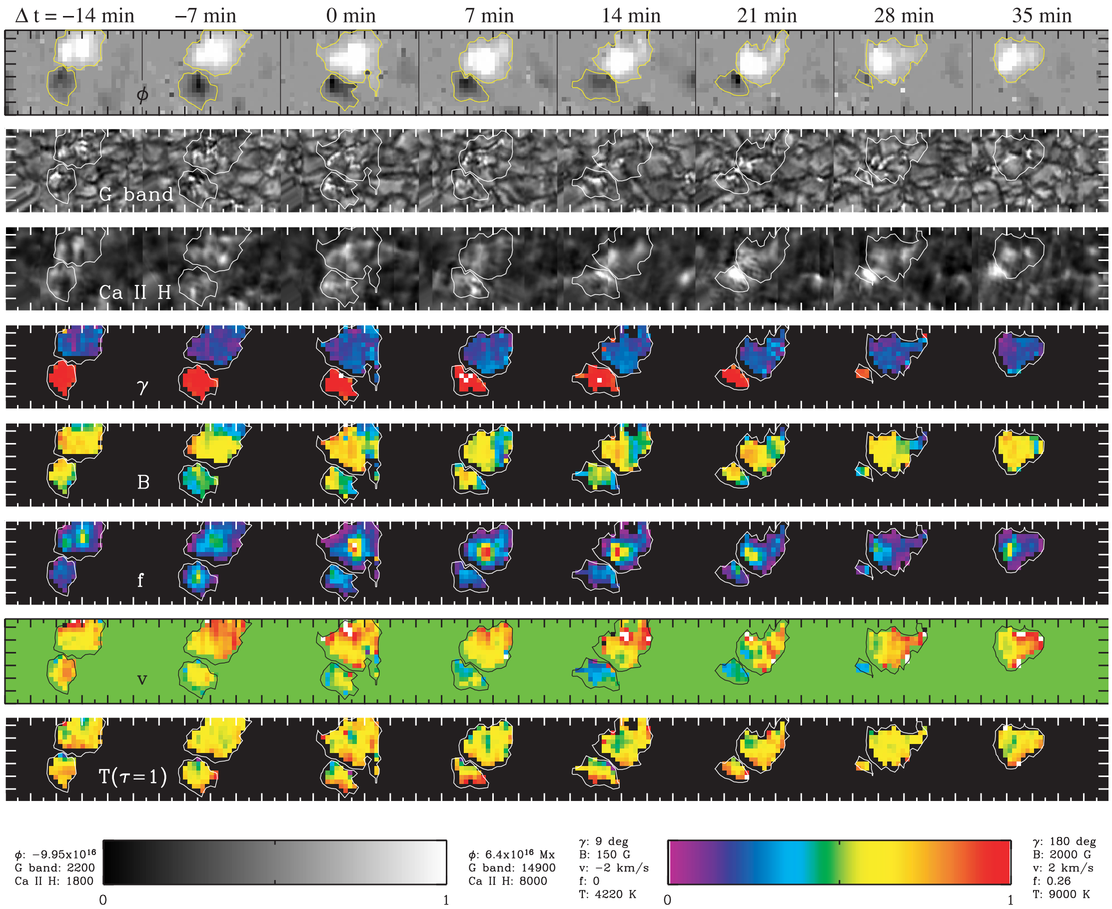


Fig. 2.—Evolution of physical quantities during the flux cancellation event. *Top to bottom*: Maps of magnetic flux ($\phi$), G-band intensity, Ca II H line-core intensity, magnetic field zenith angle in the local reference frame ($\gamma$), magnetic field strength ($B$), magnetic filling factor ($f$), LOS velocity ($v$), and temperature ($T$) at $\tau_c = 1$. Contours outline the two flux concentrations. Positive velocities indicate redshifts. Tick marks are arcseconds; $\Delta t = 0$ represents the start of the cancellation and corresponds to 9:54 UT. The time interval between snapshots is 7 minutes.

The magnetic zenith angle has been computed from the LOS field inclination by adopting the solution for the 180° azimuth ambiguity that yields the more vertically oriented vector magnetic field in the plage element. The average zenith angles in the MMF and the plage are 45° and 170°, respectively. The average field strength is very similar in the two flux concentrations: about 1.2 kG. Both the inferred zenith angles and azimuths (not shown) indicate that the two flux concentrations were unrelated; i.e., they cannot be considered as the footpoints of the same magnetic loop. Also, it is important to mention that no horizontal fields occurred near the polarity inversion line. In fact, we have been unable to find pixels with large Stokes $U$ or $Q$ profiles and small (or zero) Stokes $V$ signals, which would be indicative of horizontal fields.

In Figure 3 we plot the evolution of the physical quantities in the two patches, averaged inside the contours of Figure 2. The only magnetic parameter that changed significantly during the cancellation was the filling factor: from 8% to 5% in the MMF and from 7% to 5% in the plage. The LOS velocity panel indicates redshifts at the beginning of the observations in the MMF and the plage element. These redshifts may have resulted from (1) the location of both structures within intergranular lanes, and/or (2) the projection to the LOS of the horizontal moat outflow. The evolution of $v$ in the two canceling features, however, was different. In the MMF, the LOS velocity did not change much from its initial value of 0.7–0.8 km s$^{-1}$. In the plage, by contrast, the initial redshifts became blueshifts at the start of the cancellation ($\Delta t = 0$), reaching maximum average values of $-0.6$ km s$^{-1}$ 14 minutes later. Note that the blueshifts had to be produced by upflows, since the moat flow can only contribute redshifts to the LOS velocity in the limb-side part of the spot. The largest upflows (with LOS components of $-1.1$ km s$^{-1}$) occurred in the vicinity of the neutral line at 10:08 UT, i.e., some 4 minutes *before* the strong Ca II H line-core brightening was first detected.

The last panel of Figure 3 shows the temporal evolution of the net flux and the *unsigned* flux at the cancellation site. The unsigned flux decreased from $|\phi| = 8 \times 10^{18}$ to $4 \times 10^{18}$ Mx in 35 minutes; i.e., the flux loss rate was approximately $6.9 \times 10^{18}$ Mx hr$^{-1}$. The net magnetic flux remained more or less constant at $\phi \simeq 2.5 \times 10^{18}$ Mx, implying an almost exact balance between positive and negative flux losses. Note that through this cancellation event, the spot lost $2 \times 10^{18}$ Mx. Hence, only 50 such cancellations a day (two per hour) would be able to explain the rate at which magnetic flux disappears from decaying sunspots (∼$10^{20}$ Mx day$^{-1}$ according to Martínez Pillet 2002).

## 4. DISCUSSION AND CONCLUSIONS

The cancellation event that we have observed bears an interesting resemblance to the reconnection scenario described by Ryutova et al. (2003) and sketched in their Figure 10*a*: two independent, non-colinear flux concentrations approach each

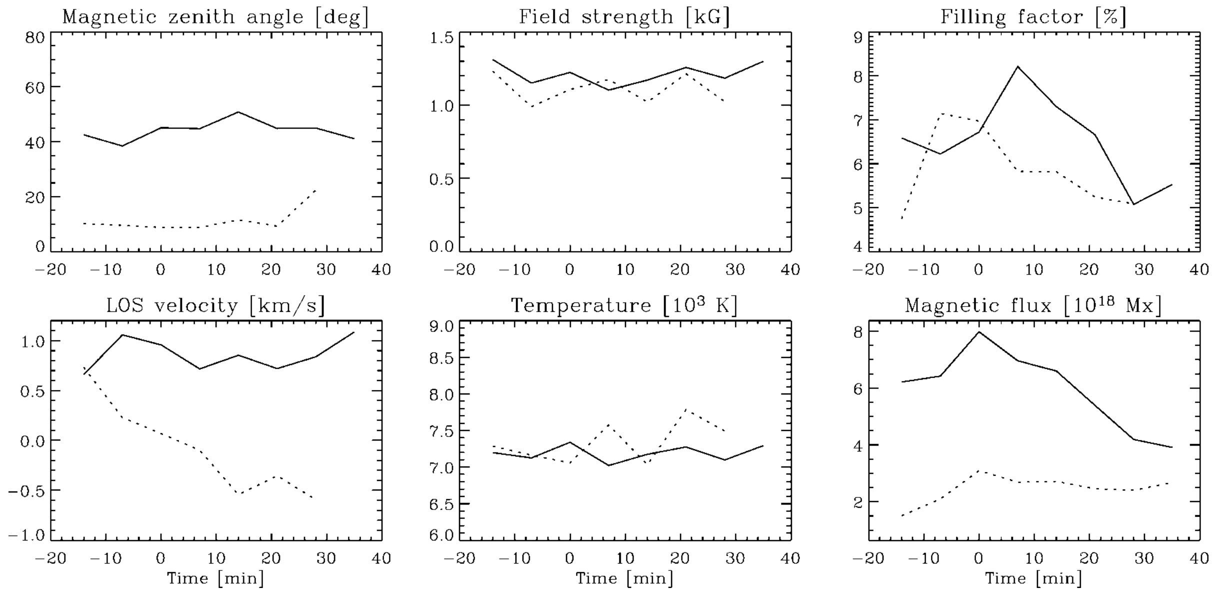


FIG. 3.—Evolution of average physical quantities in the MMF (*solid lines*) and the plage element (*dashed lines*). The zenith angle values given for the plage are $180 - \gamma$, with $\gamma$ the real zenith angle. Negative velocities indicate upflows. In the last panel, solid and dashed lines represent the unsigned and net magnetic flux in the cancellation site, respectively. Time is measured from the moment at which the magnetic flux is first seen to decrease (2003 August 9, 9:54 UT).

other and cancel until the smaller one disappears completely. The cancellation is due to magnetic reconnection in the photosphere. Ryutova et al. (2003) mention that this process is not expected to give an immediate gain in energy, and indeed we do not observe significant temperature enhancements in either of the two canceling elements. Also, we do not detect variations of the field strength and field inclination. This suggests that the reconnection takes place in a very small volume in which few field lines from the two flux concentrations merge and disappear. This would not change the average strength and inclination of the field in the two canceling patches, but would certainly decrease the magnetic filling factor (as observed) because field lines would be disappearing steadily. In summary, the cancellation seems to be consistent with a series of "elemental" reconnection events at the neutral line that do not affect the two flux concentrations as a whole.

We do not directly observe the post-reconnection Ω-loops and U-loops, probably because they are very small and our spatial resolution is not sufficient to distinguish them. However, we detect the expected consequences of the straightening of the U-loops by magnetic tension: upflows of at least 1.1 km $s^{-1}$ occur in the smaller flux concentration, especially near the neutral line. The geometry of the collision may explain why upflows are not visible in the larger flux concentration. Very interestingly, enhanced chromospheric emission is observed at the place where photospheric upflows are present, but the emission becomes visible only 18 minutes *after* the upflows develop. Thus, the chromosphere "reacts" to changes in the photosphere with a certain time delay. Presumably, this is the time needed by the upflows to reach the chromosphere, perhaps in the form of shocks capable of producing transient brightenings.

The cancellation described here is essentially different from the ones observed by Chae et al. (2004), the main difference being that no horizontal fields or enhanced downflows occurred near the polarity inversion line. This suggests that not all flux cancellations in active regions have the same origin.

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