Observational Evidence for Magnetic Flux Submergence in Flux Cancellation Sites

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ABSTRACT

Using high-resolution vector magnetograms of active region NOAA 10043, observed on July 26, 2002 with the Advanced Stokes Polarimeter and low-order adaptive optics system, we studied the magnetic field topology and line-of-sight velocities in two flux cancellation sites. We found that the magnetic field is near horizontal at the place, where two opposite polarities cancel each other. In addition, we observed significant downflows of about 1 km/sec near polarity reversal line, where the field is horizontal. We interpret these observations as the direct evidence of the magnetic flux submergence of concave-down (Ω-shaped) magnetic loop at the flux cancellation sites.

Subject headings: Sun: magnetic fields — Sun: atmospheric motions — Sun: photosphere

1. Introduction

The cancellation of photospheric magnetic flux elements is a well observed phenomenon. It is presumably evidence for magnetic reconnection but it is not clear whether the reconnection occurs below or above the photosphere. In this paper we present observations that can help clarify this issue. Retraction as possible explanation for disappearance of photospheric magnetic field has been discussed by Wallenhorst & Topka (1982), Martin, Livi & Wang (1985), Rabin, Moore & Hagyard (1984) and Zirin (1985). However, all these previous studies offer only weak indirect support for flux submergence.

Magnetic flux concentrations in the photosphere often disappear by colliding with opposite polarity poles, the process called the "flux cancellation" (Livi et al. 1985; Martin et al.

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1985). The magnetic field in flux cancellation events may have two different configurations (Zwaan 1987). Two poles may be connected with each other above or below the photosphere, thus forming either an Ω-shaped or U-shaped loop. The connection between two independent poles usually develops via magnetic reconnection in course of flux cancellation (e.g. Martin 1990; Wang & Shi 1993). If the reconnection occurs above the photosphere, flux cancellation event will be consistent with submerging Ω-loop; if the reconnection takes place below the photosphere, it will be consistent with rising U-loop scenario (Priest 1987). Using simultaneous measurements of the magnetic fields in the photosphere and chromosphere, Harvey et al. (1999) found that in majority of cases cancelling bipoles either disappear near simultaneously from the photosphere and chromosphere or their chromospheric disappearance precedes the photospheric one. They explained this evolution as submergence of Ω-shaped loop under the surface. The estimated vertical velocity of magnetic flux descent ranged from about 0.3 to 1 km s^{-1}. On the other hand, Yurchyshyn & Wang (2001) studied reconnection between two pores using SOHO/MDI data and found an upflow of about 0.6 km s^{-1} at a cancellation site.

In the preset Letter we provide direct observational evidence that magnetic flux retracts below the surface during two flux cancellation events.

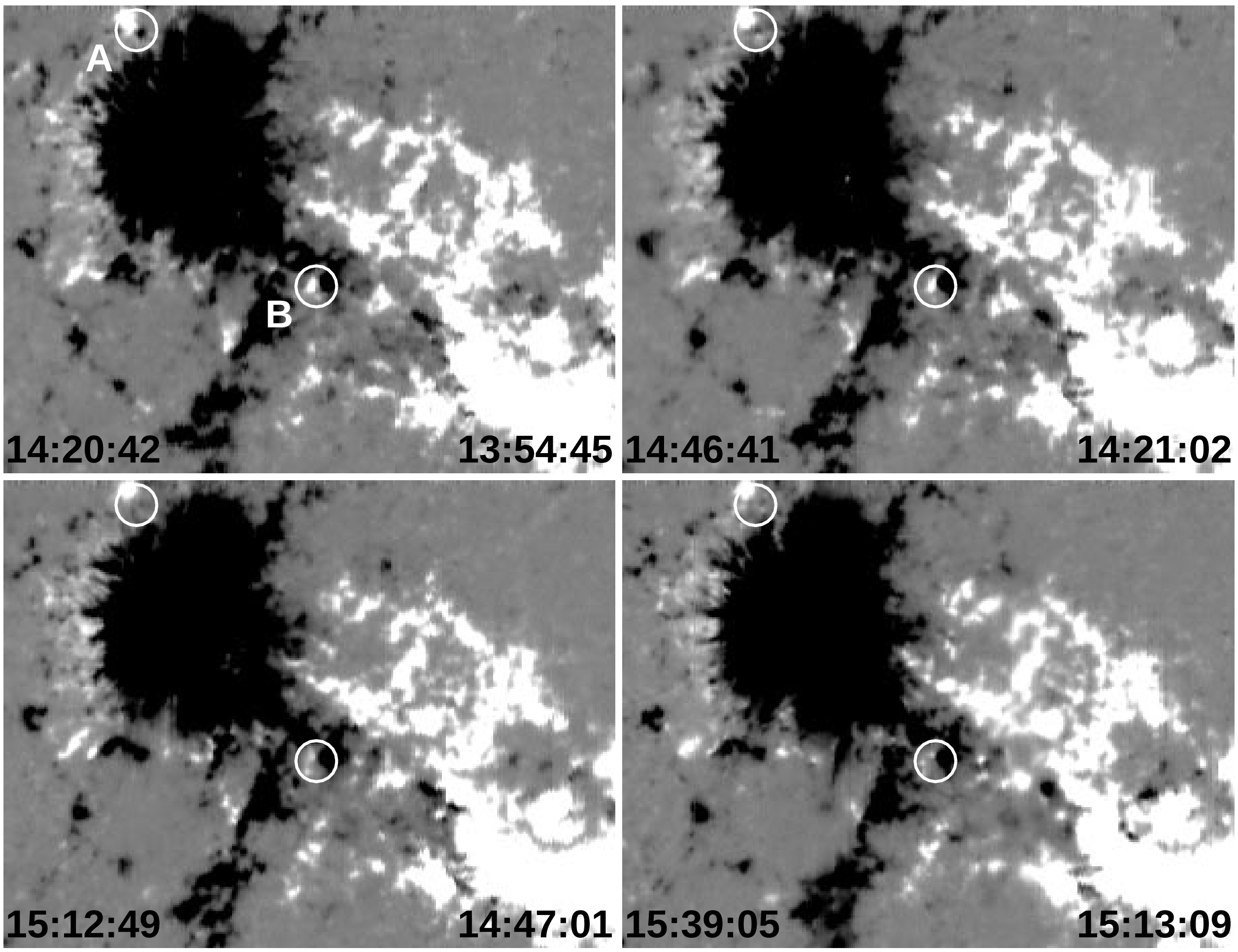

Fig. 1.— The time sequence of line-of-sight magnetograms constructed from the four raster scans of ASP observations. Note that each scan is directed from west to east, and the start and end times are specified in each image.

2. Observation

We observed active region NOAA 10043 (N12°, E22°) with the Advanced Stokes Polarimeter (ASP; Elmore et al. 1992) at the National Solar Observatory at Sacramento Peak (NSO/SP). The observations were taken from 13:54 to 15:40 UT on July 26, 2003. On the day of observations, the atmospheric seeing was excellent. In addition, we used the low-order adaptive optics (AO) system to maintain high image quality throughout the data set.

To build each magnetogram, we used the $0.''6$ spectrograph slit and scanned the solar image from west to east with 300 steps with $0.''375$ step size. For each step, ASP registered full I, Q, U and V Stokes profiles at each point along the spectrograph slit. Here, I corresponds to non-polarized light; V is circular polarization and Q and U are linear polarization in two orthogonal directions. The height of the slit was about $90''$, and the pixel size along the spectrograph slit was $0.''375$. It took about 26 minutes to complete each magnetogram. The magnetograms were taken in continuous sequence (ASP movie mode), i.e., after the last step, the spectrograph slit was repositioned to the beginning and the next magnetogram was started. Telescope tracking was used to compensate for average solar rotation of the active region.

The data reduction was done following standard ASP data reduction procedure (Skumanich et al. 1997) and the magnetic field was derived from the Stokes profiles of two spectral lines Fe I 6301.5, 6302.5 Å, using the Skumanich & Lites (1987) profile-fitting routine.

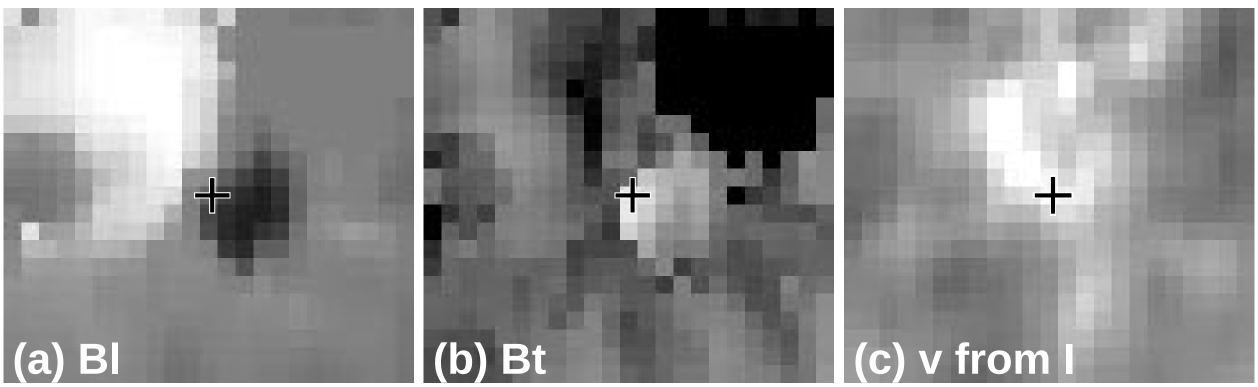

Fig. 2.— The enlarged maps of CMF A. Left: line-of-sight field map constructed from the fitting of Stoke profiles, scaled between -1500 G and 1500 G, respectively. Middle: transverse field strength map constructed from the Stokes profile fitting, scaled between 0 G and 1500 G. Right: the Doppler map constructed from the fitting of Stokes I profile only. Black and white refer to the blueshift and the redshift of 2 km s^{-1}, respectively. The plus symbol locates the pixel that display Stokes profiles shown in Figure 3.

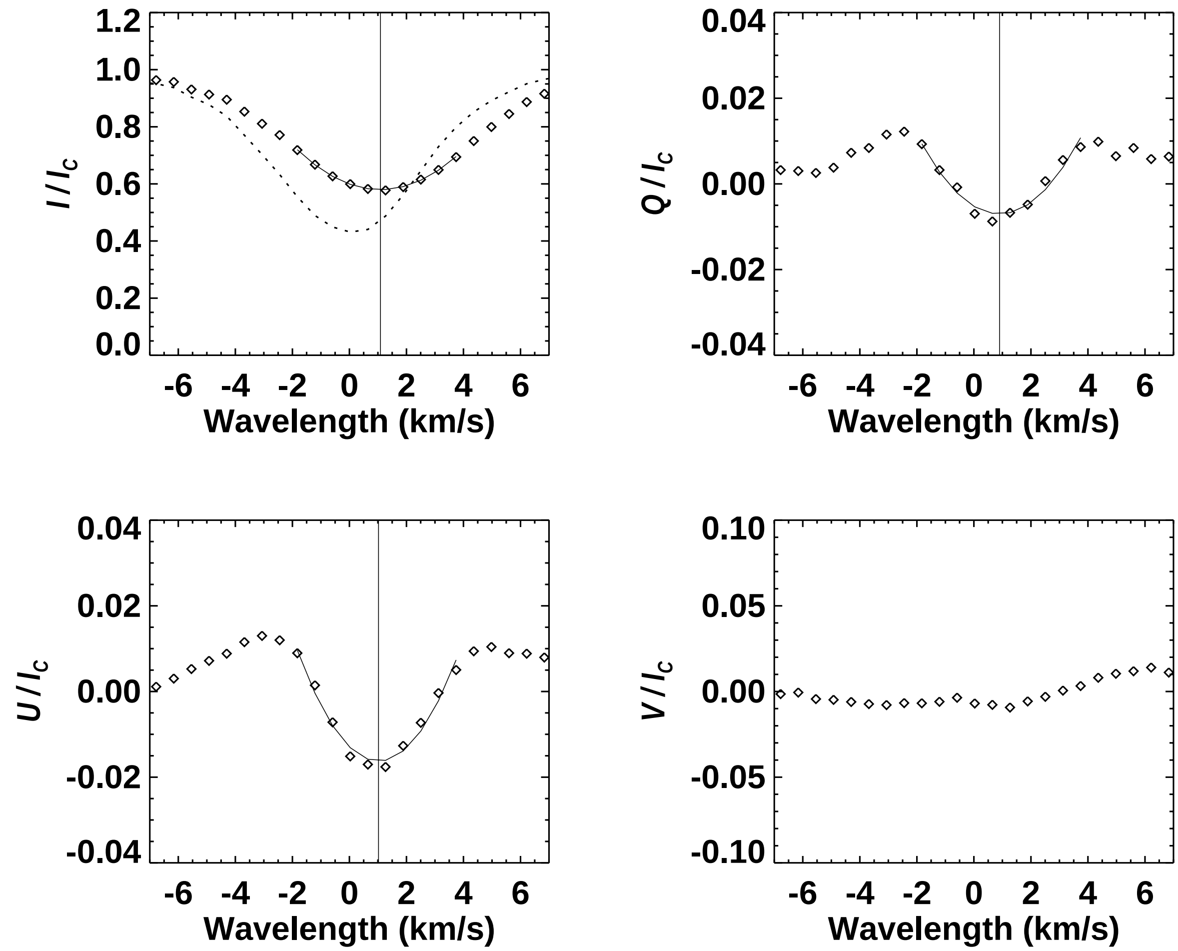

Fig. 3.— The Stokes profiles at the point in the polarity inversion line of CMF A. The wavelengths for all profiles are expressed in the units of velocity relative to the nearby quiet Sun. Negative velocity corresponds to blueshift or upward (in respect to image plane) motions. The dotted curve in the upper left panel shows Stokes I profile from the quiet Sun area near the CMF. The vertical solid line indicates the center of the corresponding Stokes profile.

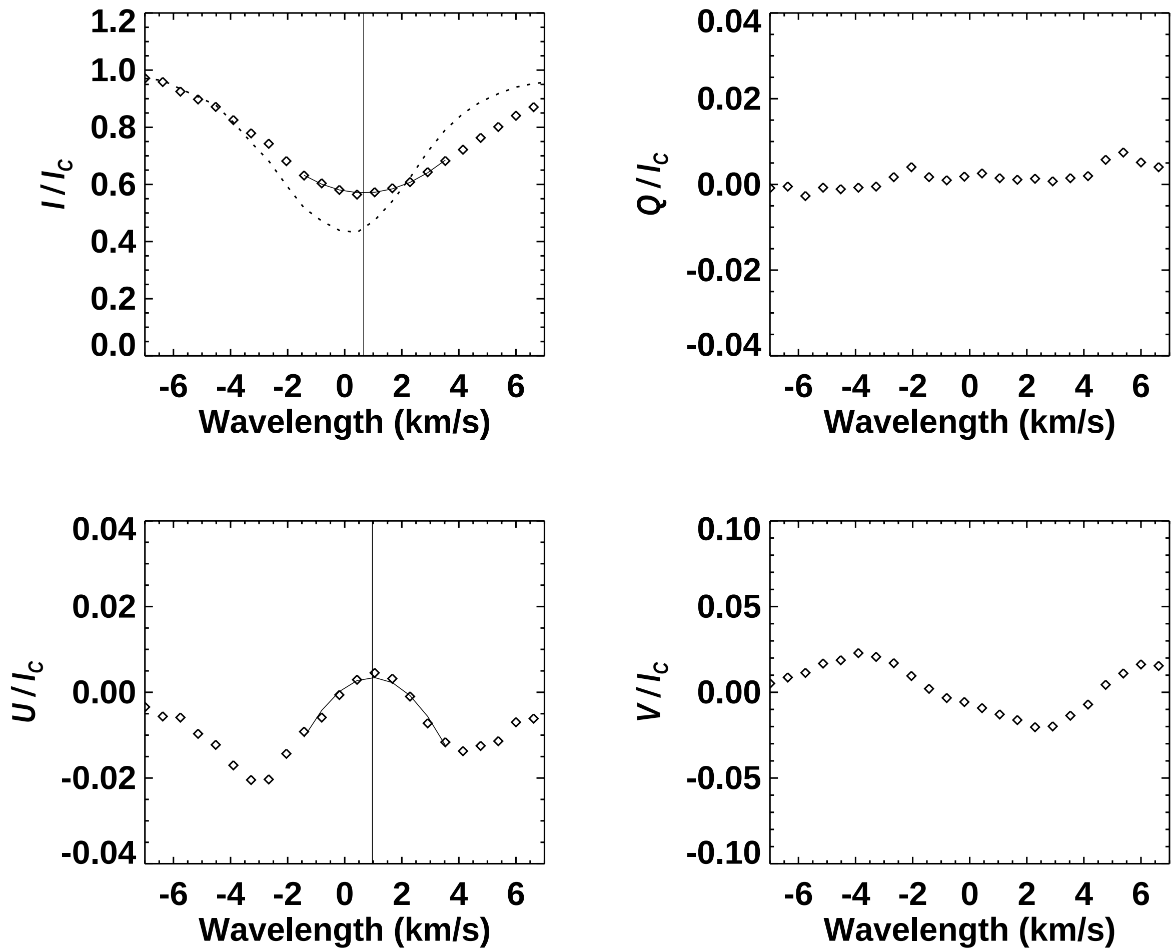

Fig. 4.— The Stokes profiles at a point in the polarity inversion line of CMF B.

3. Results

Figure 1 shows the line-of-sight magnetograms, or the maps of the degree of circular polarization $\int V_\lambda d\lambda / \int I_\lambda d\lambda$, where the integrations were taken over the spectral range [-180 mÅ, -50 mÅ] or [-8.6 km s^{-1}, -2.4 km s^{-1}] from the center of the 6302.5 Å line. We concentrate our attention on two canceling magnetic features (CMF) A and B as indicated in the first map. Comparison of the maps shows that for each CMF most of magnetic flux of smaller pole has disappeared within an hour as a result of flux cancellation. By integrating the longitudinal flux density (field strength times filling factor) over a small area surrounding each CMF, we found that in feature A the negative flux had decreased by -6.5×10^{18} Mx in an hour, and in feature B the positive flux had dropped by 3.6×10^{18} Mx in half an hour. Therefore, the approximate flux cancellation rates are -6.5×10^{18} Mx h^{-1} in A and 7.2×10^{18} Mx h^{-1} in B. These flux cancellation rates are typical for active region CMFs (e.g., Chae et al. 2000).

Figure 2 gives the spatial distributions of magnetic field and line-of-sight velocity in the CMF A area. The blank pixels (gray color in the B_l map, and the black color in the B_t map) represent the regions where the degree of polarization is less than 0.4 %, and hence the fitting was not applied. The velocity map does not have blank pixels because it has been constructed from the center of the Stokes I profile which is well defined even in weak field regions. Comparing Figure 2a and b one can see that at the polarity inversion line between two poles (near the plus symbol) the transverse field is horizontal or near horizontal. The field orientation suggests that the two poles are connected with each other across polarity inversion line, forming either an Ω-shaped magnetic loop or U-shaped magnetic loop of small size. Figure 2c shows that significant downward Doppler flows at the place where the field is near horizontal, which suggests that the magnetic field is moving downward.

Figure 3 presents the I, Q, U and V profiles at the pixel marked by the plus symbol on Figure 2. The Stokes V signal is very weak. This abnormally-shaped V profile is most likely an artifact due to the polarized stray light originating from the surrounding pixels of strong V signal. On the other hand, the Q and U signals are much stronger, which further indicates that the magnetic field is almost horizontal near this pixel. The full inversion of Stokes profiles for this pixel gives the transverse field of 800 G, and the filling factor of 0.55. The longitudinal field at this pixel was not fitted because the V signal was below a threshold. Thus, the images on Figure 2, the profiles on Figure 3 and the full Stokes inversion, all indicate that the field is nearly horizontal at the site of flux cancellation (event A). The Stokes I, Q and U profiles are clearly shifted with respect to the quiet Sun I profile (see dotted line-profile on Figure 3). Using the parabolic fittings of the central part of the Stokes I, Q, and U profiles, we determined the displacement of these profiles relative to the quiet Sun. We found that I, Q and U profiles exhibit a systematic redshift corresponding to the downward velocities of 1.1 km s^{-1}, 0.9 km s^{-1} and 1.0 km s^{-1}, respectively. For comparison the velocity determined from the standard fitting of the I, Q, and U (but not V) profiles is found to be 0.94 km s^{-1}, which does not deviate much from the values above. The fact that we see significant downflows at the place where the field is almost horizontal suggests that the field itself is moving downward.

Both magnetized and non-magnetized plasma contribute to the I profile. On the other hand, Q and U profiles represent magnetized plasma only. Thus, it is somewhat unexpected that all three Stokes profiles yields comparable Doppler shifts. The filling factor of 0.55 rules out a possibility that I is formed by the magnetized plasma only. One possible explanation may be that the adjacent non-magnetized plasma is moving downwards with the same speed as the magnetized plasma, probably through the dynamical coupling between the two.

Figure 4 shows the Stokes profiles at a pixel near the polarity inversion line of CMF B. Similar to CMF A, the Stokes U signal is redshifted by about 1 km s^{-1}. The Stokes I signal is also redshifted, but by a less value of about 0.6 km s^{-1}. The smaller velocity in I profile may be due to a contribution of stationary, non-magnetized plasma to I signal.

4. Discussion

We have examined two CMFs events, and in both cases, we found the presence of strong transverse magnetic fields and downward motions at the polarity inversion line separating two canceling poles. In combination with the previous findings (e.g., Chae et al. 2002) that two poles in a CMF converge toward each other, the present result indicates strongly that the disappearance of magnetic flux in the CMFs is due to submergence of Ω-shaped magnetic loops under the visible surface. This is the first direct observational evidence for the flux retraction in cancelling magnetic features.

It would be interesting to examine whether the observed downward velocity is consistent with the observed rate of flux cancellation. From the frozen-in condition, it is possible to infer the rate of downward flux transport vB_tL from the observed values v = 1 km s^{-1}, B_t = 800 G if an appropriate value of the contact length L is given. Figure 2 shows that the strongest horizontal field is confined to a small region of one or two pixels. If we choose two pixels ($2 \times 0.''375 = 550$ km) for the contact length L, the rate of the downward flux transport is estimated to be 1.6×10^{19} Mx h^{-1}. This value is compatible with the observed rate of flux loss 7×10^{18} Mx h^{-1} within a factor of two, especially considering the determined filling factor of 0.55.

If the flux retraction is a result of magnetic reconnection, and represents reconnection submergence (Priest 1987) our results suggest that the reconnection occurs above the level where the Fe I 6302.5 line is formed ($h = 200$ km, Bruls et al. 1991). However, the question is what is approximate height of the reconnection site? The amplitude of the downward velocity (1 km s^{-1}) is much smaller than the local Alfvén speed 10 km s^{-1}, obtained by using a field strength of 800 G we measured, and a density of 5×10^{-8} g cm^{-3} at the line formation level taken from Vernazza et al. (1981). Therefore, it is likely that the reconnection takes place much higher than the level of Fe I line formation. Harvey et al. (1999) study suggests that the reconnection level may be even above the formation level ($h = 1200$ km) of the chromospheric line Ca II 8542. Interestingly our value of 1 km s^{-1} is consistent with the range of 0.3 to 1 km s^{-1} provided by Harvey et al. (1999).

Our study is limited to only two cancelling magnetic features. Therefore, it would be premature to extend our findings to all CMFs. Although, in both cases our observations support the flux submergence, we can not exclude the possibility that some of CMFs are formed by emerging U-shaped magnetic loops, as implied by Yurchyshyn & Wang's finding (2001). A further work based on more samples will be required in the future to establish a preference of one scenario over the other.

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REFERENCES

Bruls, J. H. M., Lites, B. W., & Murphy, G. A. 1991, In NSO/SP Summer Workshop Ser. 11, Solar Polarimetry, ed L. J. November (Sunspot: NSO), 444

Chae, J., Denker, C., Spirock, T. J., Wang, H., & Goode, P. R. 2000, Sol. Phys., 195, 333

Chae, J., Moon, Y.-J., Wang, H., & Yun, H. S. 2002, Sol. Phys., 207, 73

Elmore, D. F. et al. 1992, Proc. SPIE, 1746, 22

Harvey, K. L., Jones, H. P., Schrijver, C. J., & Penn, M. J. 1999, Sol. Phys., 190, 35

Litvinenko, Y. 1999, ApJ, 515, 435

Litvinenko, Y.,& Martin, S. F. 1999, Sol. Phys., 190, 45

Livi, S. H. B., Wang, J., & Ai, G. 1985, Australian J. Phys., 38, 855

Priest, E. 1987, In Proceedings of the Inaugural workshop and round table discussion, The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere, ed. Schröter, M. Vazquez, and A.A. Wyller., Cambridge University Press, 297

Martin, S. F., Livi, S. H. B., & Wang, J. 1985, Australian J. Phys., 38, 929

Rabin, D., Moore, R., & Hagyard, M.J. 1984, ApJ, 287, 404

Skumanich, A. & Lites, B. W. 1987, ApJ, 322, 473

Skumanich, A., Lites, B. W., Martínez Pillet, V., & Seagraves, P. 1997, ApJS, 110, 357

Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, ApJS, 45, 635

Wallenhorst, S. G. & Topka, K.P. 1982, Sol. Phys., 81, 33

Wang, J. & Shi, Z. 1993, Sol. Phys., 143, 119

Yurchyshyn, V., & Wang, H. 2001, Sol. Phys., 202, 309

Zirin, H. 1985, ApJ, 291, 858

Zwaan, C. 1987, ARA&A, 25, 83
