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AN OBSERVATIONAL MANIFESTATION OF MAGNETOATMOSPHERIC WAVES IN INTERNETWORK REGIONS OF THE CHROMOSPHERE AND TRANSITION REGION

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ABSTRACT

We discuss an observational signature of magnetoatmospheric waves in the chromosphere and transition region away from network magnetic fields. We demonstrate that when the observed quantity, line or continuum emission, is formed under high-β conditions, where β is the ratio of the plasma and magnetic pressures, we see fluctuations in intensity and line-of-sight (LOS) Doppler velocity consistent with the passage of the magnetoatmospheric waves. Conversely, if the observations form under low-β conditions, the intensity fluctuation is suppressed, but we retain the LOS Doppler velocity fluctuations. We speculate that mode conversion in the $\beta \approx 1$ region is responsible for this change in the observational manifestation of the magnetoatmospheric waves.

Subject headings: Sun: atmospheric motions — Sun: chromosphere — Sun: magnetic fields — Sun: transition region — Sun: UV radiation

1. INTRODUCTION

Theoretical efforts to describe the propagation of magneto-acoustic-gravity (MAG) waves through the solar atmosphere have largely been confined to one of two fields: (1) the suppression and modification of *p*-mode oscillations due to sunspots (see references in Bogdan 2000) or (2) oscillations in prominences (see, e.g., Schutgens 1987). In both cases, the magnetic fields generally have gradual spatial variations (primarily due to the size of the magnetic structures, some 10 Mm or more) compared with those imposed on them by the typical oscillation wavelengths. These studies have brought to light the importance of regions in which the magnetic and gas pressures p_g are in approximate balance (i.e., $\beta = 8\pi p_g/B^2 \approx 1$), wherein mode mixing can take place and critical layers can form in which resonance absorption can occur. In this Letter, we extend these analyses to the internetwork regions of the quiet Sun where the spatial variations of the magnetic field are surely of a smaller scale, perhaps comparable to the characteristic MHD wavelengths. Owing to the structural complexity inherent in the quiet Sun, we shall focus on the observational data and what they have to tell us about the passage of MAG waves upward in the solar atmosphere.

Previous theoretical efforts to quantify atmospheric oscillations in the quiet Sun have generally adopted idealized magnetic topologies (see the review by Thomas 1983) or have neglected the presence of magnetic fields altogether. Of the latter set of studies, there are two separate schools of thought, one that advocates linear standing wave interactions (see, e.g., Deubner 1998) and another that champions nonlinear hydrodynamic shock interaction (see, e.g., Carlsson & Stein 1998). Recent observational studies by Wikstøl et al. (2000, hereafter WHCJ) and Judge, Tarbell, & Wilhelm (2000, hereafter JTW) have qualitatively described the observational signatures of MAG waves propagating through the atmosphere. Here we shall pursue a more quantitative description that embraces previous theoretical and observational studies. The argument advanced in the following sections is that the location of the $\beta \approx 1$ layer within the atmosphere plays a prominent role in influencing the mixing and conversion, and hence the observational signature, of MAG waves as they propagate, even in the presence of complex magnetic topologies.

2. DESCRIPTION OF THE OBSERVATIONS

We reexamine a time series data set, discussed in detail by WHCJ, taken on 1997 April 25 around the quiet disk center. WHCJ provide details about the data extraction and reduction process, and we have made use of their reduced data set. In addition to the 1997 April data set, we consider another disk center data set taken on 1999 February 26 and an off–active region data set taken on 1998 May 16; the latter data sets are described in JTW. All of these time series data sets were acquired by the SUMER (Solar Ultraviolet Measurements of Emitted Radiation) spectrograph (Wilhelm et al. 1995) on board the ESA/NASA *Solar and Heliospheric Observatory* (*SOHO*; Fleck, Domingo, & Poland 1995).

Figure 1 shows the time series of neutral carbon C I λ1043 continuum intensity for these days. With only a cursory glance, the lower panels look very similar in C I continuum intensity, but on closer inspection, they reveal some marked differences. The striking feature of Figure 1 is that the 1998 May data (*middle panel*) do not exhibit the 3″–5″ wide, ∼200 s period coherent oscillatory structures that are clearly visible in the internetwork regions of the 1997 April data (see, e.g., spatial positions 40″–80″ in the left panel). The internetwork regions of the 1999 February data appear to represent an intermediate state. Throughout, we identify an internetwork region with a dark lane in the C I continuum time series. To obtain a measure of oscillatory power present in each data set, we show, in the upper panels of Figure 1, the integrated oscillatory power in the intensity fluctuations ($\Delta I/I$) present in the 3–10 mHz frequency band (*thick solid line*), its spatial mean (*dashed line*), and the estimated noise level (*thin solid line*; integrated in the 20–27 mHz frequency band). The strong oscillatory power in the 1997 April internetwork is clear but is lacking in the 1998

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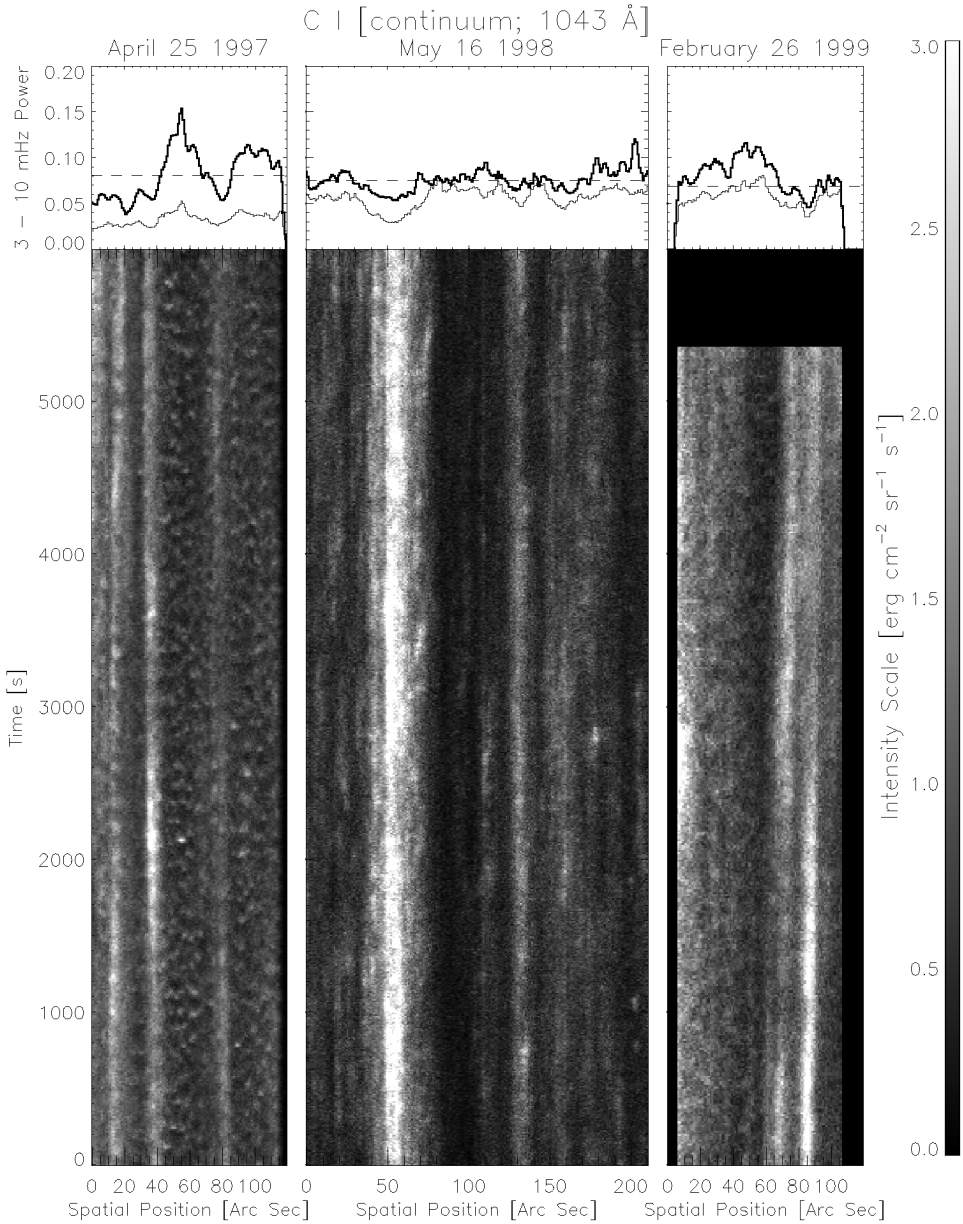

FIG. 1.—*From left to right*: *SOHO*/SUMER C I λ1043 continuum intensity time series data acquired on 1997 April 25, 1998 May 16, and 1999 February 26. All the data sets show the variation of the continuum intensity of a region of atmosphere tracked by the SUMER slit over a 6000 s interval (note the cropping in the right panel). At the top of each panel, we show the integrated power in the 3–10 mHz region of the intensity fluctuation ($\Delta I/I$) Fourier power spectrum as a function of spatial position (*thick solid line*), an estimate of the signal noise in the 20–27 mHz frequency band (*thin solid line*), and the spatial mean (*dashed line*). The enhancement of oscillatory power in the 1997 April internetwork emission is clear.

May observations. An obvious question is why do data sets of comparable quality and of similar regions present such distinct oscillatory signatures and power, especially for the 1997 April and 1998 May data sets? This question is underlined when, from Figures 4 and 6 of JTW, it is clear that internetwork oscillatory power, akin to that of 1997 April, is present in the *SOHO*/Michelson Doppler Imager (MDI; Scherrer et al. 1995) photospheric Doppler velocity and the *Transition Region and Coronal Explorer* (Handy et al. 1999) UV continua data, formed near 0.2 and 0.45 Mm, respectively, in both the 1998 May and 1999 February data sets, whereas the C I continuum is formed around 1.1 Mm (see below). Clearly, something is influencing the wave modes between these lower regions and the formation of the C I continuum.

Further supplemental evidence to assist us in addressing the question posed above is available in the 1997 April data set. WHCJ demonstrated that the 1997 April observations contain a strong correlation between the C I continuum emission in the internetwork regions and the Doppler velocity measurements from simultaneously acquired C II (upper chromosphere, $\lambda = 1037.018$ Å) and O VI (transition region, $\lambda = 1037.613$ Å) emission lines (see Fig. 7 of WHCJ), and they deduced that this was consistent with an upward-propagating MAG wave. These data also exhibited small-amplitude fluctuations in the C II and O VI line intensities that were correlated with the C I continuum emission (as noted in WHCJ). The small amplitudes of the intensity fluctuations are significant since, in the case of a nonmagnetic chromospheric internetwork, the prop-

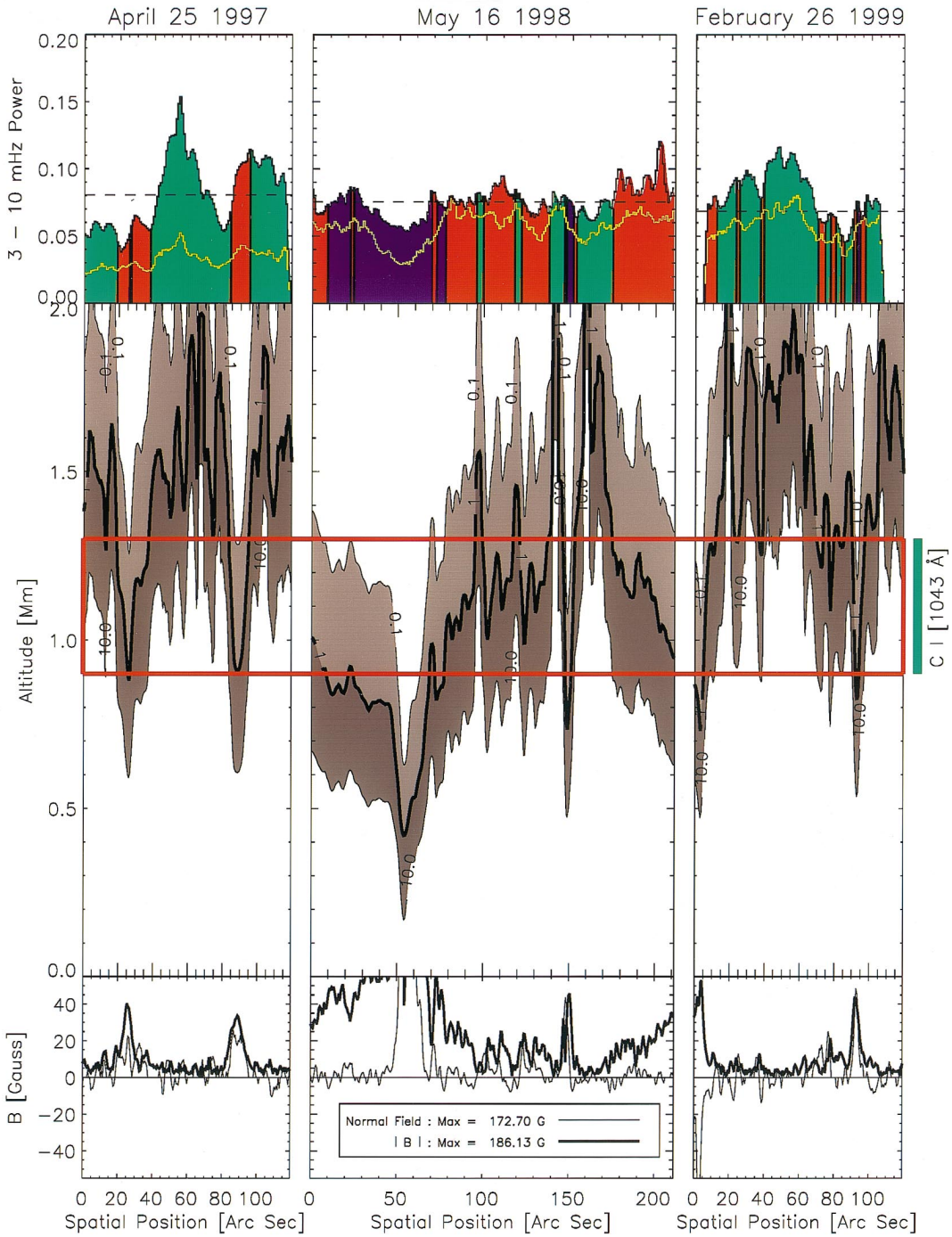

FIG. 2.—*From left to right*: Extrapolated plasma topography in the SUMER LOS slit plane during the 1997 April, 1998 May, and 1999 February observing runs shown in Fig. 1. The lower level of each panel details the underlying MDI magnetic field (normal field [*solid line*] and $|B|$ [*thick solid line*]) under the SUMER slit at the midpoint of the time series. The middle level shows features of the extrapolated plasma topology, contours of plasma β and λ1043 continuum formation layer (*rectangular box*) estimated using the VAL 3C atmosphere as a basis for the thermodynamic structure. Note the position of the $\beta = 1$ contour (*thick solid line*) relative to the continuum formation layer. In the upper tier of each panel, we again show the coaligned integrated 3–10 mHz oscillatory power, the spatial mean (*dashed line*), and the associated signal noise, in $\Delta I/I$ as a function of position.

agation of a compressive wave mode (like those observed in the C I continuum) in higher atmospheric regions should produce order-of-magnitude intensity fluctuations (see, e.g., Carlsson & Stein 1997); this is not the case in the 1997 April data set. In the following discussion, we propose that the reduced C II and O VI intensity fluctuations in the 1997 April data set arise from exactly the same effect as the apparent disappearance of C I oscillations seen in the 1998 May and 1999 February data sets.

3. PROPOSITION

We propose that the primary cause of the two observational anomalies noted above is a difference in the underlying magnetic

topology between these 3 days. The magnetic topology of the atmosphere underlying the observations can affect the nature of any upward-propagating wave in two ways: (1) through variations in the location of the region where the plasma β is of order unity and (2) the partitioning of the atmosphere into regions of open and closed magnetic fields, on a variety of spatial scales.

The careful coalignment of simultaneous SUMER and MDI data, as described in JTW, allows us to determine the normal magnetic field in a two-dimensional region surrounding the SUMER slit during the observation time period on both days. High-resolution MDI magnetograms were obtained close to the middle of the SUMER time series on the 3 days of 1997 April, 1998 May, and 1999 February (the latter magnetograms appearing as the left and right panels, respectively, of Fig. 1 in JTW; the position of the SUMER slit is indicated by a solid line). In each case, we select a rectangular region surrounding the SUMER slit (100″ on each side) that we then use as the base ($z = 0$) normal field component (B_n^0) from which we determine a unique three-dimensional Cartesian potential field extrapolation with periodic horizontal boundary conditions. The transverse components [$B_t(z)$] of the extrapolated magnetic field are computed at each height z directly from the Fourier components of $B_n(z) = B_n^0 \exp(-z/H_B)$, where the magnetic scale height H_B is set by the dimensions of the lower boundary region. We note that the potential field extrapolation serves as the simplest representation of the field topology. It is possible to construct force-free extrapolations and to add electric currents that are field-aligned (Sakurai 1989) or perpendicular to gravity (Low 1985). At this point of the investigation, there is little point in adding such complexity.

In order to produce a view of the plasma topography underlying the SUMER slit, we assume that the atmospheric stratification follows the VAL 3C model of Vernazza, Avrett, & Loeser (1981).[6] Using the VAL 3C vertical pressure profile and the extrapolated magnetic field allows us to compute the variation of β up to 2 Mm in height. From the resulting atmospheric cube, it is straightforward to extract a vertical slice that lies in the line of sight (LOS) of the SUMER slit at a time approximately halfway through the time series observations. In the middle panels of Figure 2, we show the contours of the plasma β in the SUMER LOS plane on all 3 days, 1997 April, 1998 May, and 1999 February in chronological order from left to right. The bottom panels of Figure 2 show B_n^0 (*thin solid line*) and $|B(z = 0)|$ [$= (B_n^2 + B_t^2)^{1/2}$] (*thick solid line*) under the SUMER slit position. The effect of B_t on the β-contours is evident, especially in the middle panel where the large transverse field acts to depress the β-contours neighboring the network field concentration. This could not be anticipated solely from knowledge of the normal field. This strong transverse field in the 1998 May data originates from the active region to the west of the slit, which is clearly identifiable as "plage" in the left panel of Fig. 1 in JTW. Therefore, its qualitative impact is not likely to be affected by the choice of magnetic field extrapolation.

The upper panels of Figure 2 again show the integrated 3–10 mHz Fourier power, its spatial mean (*dashed line*), and the associated 20–27 mHz noise (*thin solid line*), but they are now color-coded to indicate the position of the C I continuum formation layer[7] relative to the $\beta = 1$ contour (*thick solid line*). In the dark (*blue*) region, the $\beta = 1$ contour is completely below the continuum formation height. The light (*green*) region indicates that the $\beta = 1$ contour is completely above the continuum formation height. The remaining color (*red*) denotes intermediate conditions. On inspection of Figure 2, it is clear that regions of enhanced oscillatory power have a significant correlation with the regions where the $\beta = 1$ contour lies above the formation layer of the continuum (e.g., in the 40″–80″ internetwork region of the left panel). Conversely, regions of suppressed oscillatory power generally correspond to locations where the C I continuum forms in magnetically dominated plasmas (see, e.g., the 20″–70″ region of the middle panel).

Cally (2001) demonstrates, by considering the problem of MAG waves propagating in an isothermal plasma permeated by a uniform vertical magnetic field, that, around the $\beta = 1$ region, the fast mode generated in the photosphere will essentially change "polarization," i.e., lose its horizontal wavenumber, and become a field-aligned slow mode. We note, however, that uncertainty exists as to whether the produced slow mode would lack the compressive power in the low-β plasma that could cause the reduction in intensity fluctuations. However, the findings of Cally (2001) appear to be consistent with, and shed some light on the possible mechanism behind, the correlation of continuum intensity and Doppler velocity fluctuations noted by WHCJ.

4. CONCLUSION

The evidence is compelling that the subtleties of the extension of the surface magnetic field above the photosphere greatly affect the observation of propagating MAG waves. Whether the plasma is in a high- or low-β regime relative to the line/continuum formation height dictates, respectively, whether we observe correlated fluctuations in intensity and Doppler velocity or only in Doppler velocity. We note, however, that a physical clarification of the loss of correlated intensity fluctuations above the $\beta \approx 1$ region must wait for further theoretical calculations in the spirit of Cally (2001).

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[6] The exact choice of model atmosphere does not influence our conclusions. We have also performed the calculations with an isothermal atmosphere with no change to the results.

[7] The C I continuum formation height is again taken from the VAL 3C model. From Fig. 36 of Vernazza et al. (1981) and from verification calculations accomplished using the MULTI code of Carlsson (1986), we estimate that the C I λ1043 continuum has a source function peaked at 1.1 Mm with a width (FWHM) of ±0.2 Mm.

REFERENCES

Bogdan, T. J. 2000, Sol. Phys., 192, 373
Cally, P. S. 2001, ApJ, 548, 473
Carlsson, M. 1986, A Computer Program for Solving Multi-Level Non-LTE Radiative Transfer Problems in Moving or Static Atmospheres (Uppsala Astron. Obs. Rep. 33; Uppsala: Uppsala Astron. Obs.)
Carlsson, M., & Stein, R. F. 1997, ApJ, 481, 500
———. 1998, in IAU Symp. 185, New Eyes to See inside the Sun and Stars: Pushing the Limits of Helio- and Asteroseismology, ed. F.-L. Deubner, J. Christensen-Dalsgaard, D. W. Kurtz (Dordrecht: Kluwer), 435

Deubner, F.-L. 1998, in IAU Symp. 185, New Eyes to See inside the Sun and Stars: Pushing the Limits of Helio- and Asteroseismology, ed. F.-L. Deubner, J. Christensen-Dalsgaard, D. W. Kurtz (Dordrecht: Kluwer), 427
Fleck, B., Domingo, V., & Poland, A. I. 1995, The *SOHO* Mission (Dordrecht: Kluwer)
Handy, B. N., et al. 1999, Sol. Phys., 187, 229
Judge, P. G., Tarbell, T. D., & Wilhelm, K. 2000, ApJ, submitted (JTW)
Low, B. C. 1985, ApJ, 293, 31
Sakurai, T. 1989, Space Sci. Rev., 51, 11
Scherrer, P. H., et al. 1995, Sol. Phys., 162, 129
Schutgens, N. A. J. 1987, A&A, 323, 969
Thomas, J. H. 1983, Annu. Rev. Fluid Mech., 15, 321
Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, ApJS, 45, 635
Wikstøl, Ø., Hansteen, V. H., Carlsson, M., & Judge, P. G. 2000, ApJ, 531, 1150 (WHCJ)
Wilhelm, K., et al. 1995, Sol. Phys., 162, 189