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MAGNETOACOUSTIC PORTALS AND THE BASAL HEATING OF THE SOLAR CHROMOSPHERE

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ABSTRACT

We show that inclined magnetic field lines at the boundaries of large-scale convective cells (supergranules) provide "portals" through which low-frequency (<5 mHz) magnetoacoustic waves can propagate into the solar chromosphere. The energy flux carried by these waves at a height of 400 km above the solar surface is found to be a factor of 4 greater than that carried by the high-frequency (>5 mHz) acoustic waves, which are believed to provide the dominant source of wave heating of the chromosphere. This result opens up the possibility that low-frequency magnetoacoustic waves provide a significant source of energy for balancing the radiative losses of the ambient solar chromosphere.

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

One of the outstanding puzzles of stellar astronomy is why faint and tenuous stellar atmospheres and coronae have temperatures far in excess of their bright and dense underlying visible surfaces. For example, it has been known since the 1930s that the temperature at the top of the Sun's chromosphere (~10,000 K) is higher than that at the bottom (~4500 K). The two competing theories that have been advanced to explain this enigma are (1) mechanical heating by upward-propagating waves (Alfvén 1947; Schwarzschild 1948) and (2) Joule heating associated with magnetic field reconnection (Parker 1988) and the resistive dissipation of electric currents (Rabin & Moore 1984). Recent results have ruled out high-frequency (>5 mHz) acoustic waves (Fossum & Carlsson 2005), magnetic reconnection, and electric currents (Socas-Navarro 2005b) as being too weak to heat the solar chromosphere, and they have prompted speculation that magnetic waves must play the dominant role (Socas-Navarro 2005b). Here we argue that low-frequency (<5 mHz) propagating magnetoacoustic waves provide a significant source of the energy necessary for balancing the radiative losses of the ambient solar chromosphere (~4.3 kW m^{-2}; Vernazza et al. 1981). These waves, which are normally evanescent in a nonmagnetic atmosphere, are able to propagate through "magnetoacoustic portals" that are created by areas of strong (magnetic pressure approximately equal to gas pressure), and significantly inclined (>30° with respect to the surface gravity), magnetic fields. Such conditions are ubiquitous both in active regions and at the boundaries of convection cells (Cattaneo et al. 2003). The latter implies that acoustic portals are omnipresent over solar and stellar surfaces and thrive throughout the entire stellar magnetic activity cycle, essential prerequisites for any baseline heating mechanism for stellar atmospheres. It is fascinating to note that the magnetic field not only participates directly in the atmospheric heating through the second process (i.e., theory 2) but also functions as an essential catalyst, or conduit, for the waves in the first mechanism (theory 1). The distinctions between the two competing theories are likely to be based more on semantics than on physical substance.

Our argument is based on the analysis of simultaneous Doppler velocity observations made using the solar sodium (Na) and potassium (K) Fraunhofer absorption lines at 5890 and 7699 Å, respectively. The observations were obtained by the Magneto-Optical filter at Two Heights experiment (MOTH; Finsterle et al. 2004a) that was run at the geographic South Pole during the austral summer of 2002/2003. The MOTH data provide us with a low-resolution (3.7 Mm $pixel^{-1}$ at disk center) view of the full solar disk at two heights in the atmosphere (~250 and ~500 km above the base of the photosphere for the 7699 and 5890 Å data, respectively).

After removing the effects of differential rotation and coregistering the two sets of velocity images, we generate maps of the phase times taken for waves with different frequencies to travel between the two heights. This is done by modeling the observed cross-correlation of the two sets of frequency-filtered, time series data for each pixel in the coregistered images (Finsterle et al. 2004b). The resulting maps clearly exhibit a difference in the wave-travel times between magnetic and nonmagnetic regions (Fig. 1 and Fig. 2 [Plate 1]). This phenomenon is observed at all frequencies at which there is a significant signal-to-noise ratio (~2 to ~10 mHz).

From a theoretical perspective, describing the general properties of magnetoacoustic-gravity (MAG) waves in the magnetized solar atmosphere is difficult, and, in order to make progress, the wavelengths of the waves are typically assumed to be small compared to the local scale on which the atmospheric parameters determining the Alfvén and acoustic velocities vary (Zhugzhda & Dzhalilov 1984). This allows a local dispersion relation to be developed (McLellan & Winterberg 1968; Bel & Leroy 1977; Zhugzhda & Dzhalilov 1984) where the cutoff frequency—the frequency above which the waves can propagate vertically through the atmosphere—in general depends on the local plasma β ($=8\pi p/B^2$), the ratio of gas to magnetic pressure, and the inclination of the magnetic field lines with respect to the normal to the Sun's surface. However, in regions of weak magnetic field ($\beta \gg 1$), the cutoff frequency is independent of the magnetic field (Bel & Leroy 1977) and has the value $\nu_{ac} = \gamma g/4\pi c = 5.2$ mHz ($\gamma = 5/3$ is the ratio of specific heats, $g = 274$ m s^{-2} is the gravitational acceleration, and $c = 7$ km s^{-1} is the sound speed). Interestingly, the MOTH Doppler velocity data (Fig. 3) and *Transition Region*

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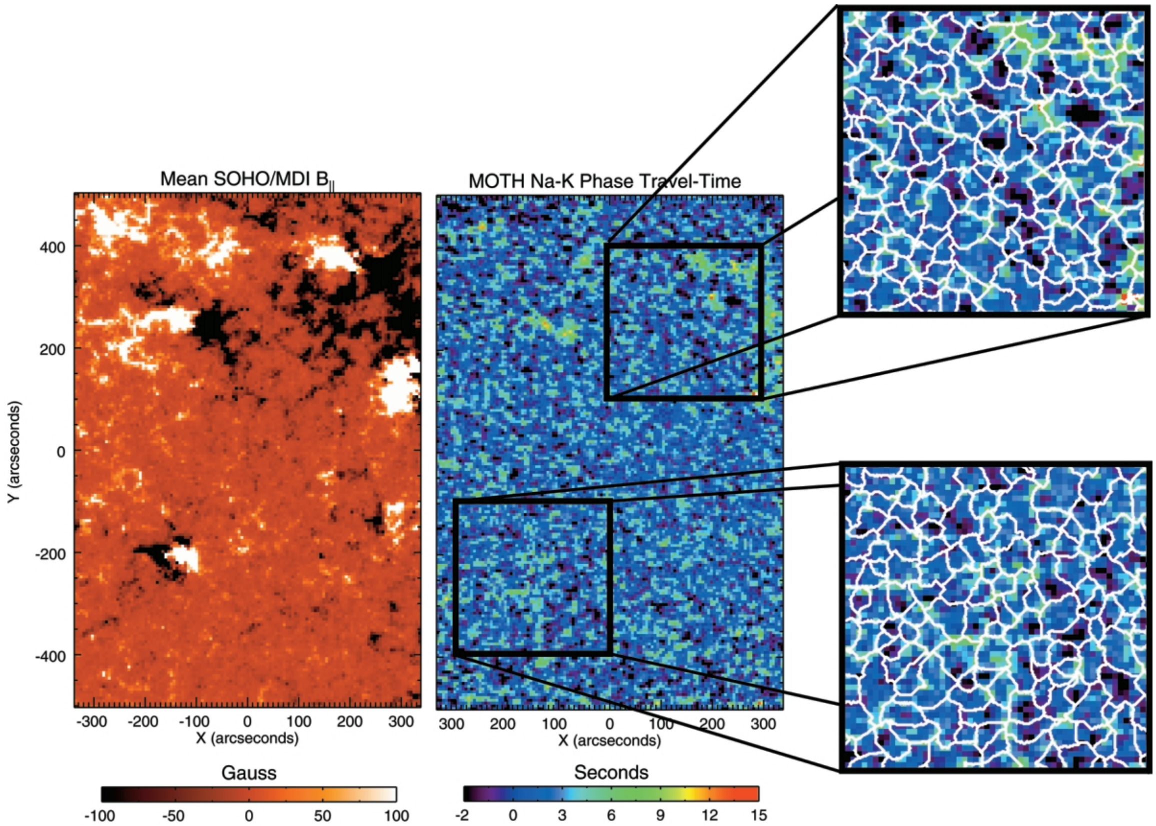

FIG. 1.—*Left*: Map of the average line-of-sight component of the magnetic field in the Sun's photosphere for the 107 hr period starting 06:59 UT on 2003 January 6 (from the Michelson Doppler Imager [MDI] experiment on *SOHO*; Scherrer et al. 1995). *Middle*: Map of phase travel time (Finsterle et al. 2004b) for magnetoacoustic waves with frequencies near 3 mHz based on contemporaneous, simultaneous Doppler velocity data of the full solar disk as viewed at 5890 Å (Na) and 7699 Å (K). *Right*: Magnified views of two regions of the phase-travel-time map overlaid with an estimate of the location of the boundaries of the supergranular-scale convective cells (typical size 13–35 Mm; Krijger et al. 2002) as determined using an enhanced watershed segmentation (Lin et al. 2003) of the mean intensity image at 5890 Å. Note that there is not a significant travel-time signal in all of the observed plages, only in regions where the field is highly inclined. This signal is noticeably larger than that in the boundaries of the supergranules. This is probably due to the larger magnetic filling factor in the plage.

and Coronal Explorer (*TRACE*) data (McIntosh & Jefferies 2006) provide us with the observational support of this picture, even though the small wave approximation is clearly not applicable for the waves under consideration (wave frequencies of ∼6 mHz correspond to a wavelength of ∼1 Mm, which represents several scale heights in the chromosphere; Uitenbroek 2006). Why a local dispersion description has merit for waves with frequencies <∼30 mHz (the approximate frequency corresponding to a wavelength equal to the scale height) is an open question. Nevertheless, since recent high-resolution observations of regions typically referred to as "quiet" Sun have shown the presence of strong localized magnetic fields at the boundaries of convective cells, one might therefore expect to witness the leakage of low-frequency waves ($\nu < \nu_{ac}$) at locations in the cell boundaries where the field lines are substantially inclined. The MOTH travel-time maps substantiate this expectation. They show patterns of significant, nonzero, travel time with dimensions that are commensurate with large-scale convective cells (Figs. 1 and 2). This behavior is consistent with strong magnetic fields being swept to the convective cell boundaries (Priest et al. 2002; Schrijver & Title 2003; Cattaneo et al. 2003; Trujillio Bueno et al. 2004) and a concomitant lowering of the MAG cutoff frequency in regions of low-β plasma where the magnetic field lines are significantly inclined. Since the travel times observed indicate velocities in the magnetic regions that are close to the expected local sound speed (∼7 km s^{-1}), we infer that we are detecting upward-propagating, low-β, slow MAG (acoustic) waves. These waves are able to propagate through "magnetoacoustic portals" that exist where the local β and field inclination conditions favor a lowered cutoff frequency. The waves are guided up into the chromosphere along the ambient magnetic field, becoming progressively steeper, until they eventually shock and dissipate their energy (Ulmschneider et al. 2005).

Additional support for this concept of magnetoacoustic portals for low-frequency waves in the quiet Sun is provided by the temporal behavior of the low-frequency wave-travel-time maps. First, the magnetic topology in the convective cell boundaries is continually changing due to both the motion of the convective cells (e.g., granular buffeting) and the ubiquitous action of the so-called magnetic carpet. The latter is where small magnetic dipoles are constantly being created in the centers of the supergranular "network" and advected toward the boundary of the large convective cells where they interact with existing magnetic flux tubes (Priest et al. 2002). We therefore expect the low-frequency wave leakage through a portal to be intermittent, being present when the magnetic topology is favorable (inclined field and sufficient strength so that $\beta <\sim 1$) and otherwise absent. This conjecture is supported by the temporal variance map shown in Figure 4, and also by temporal

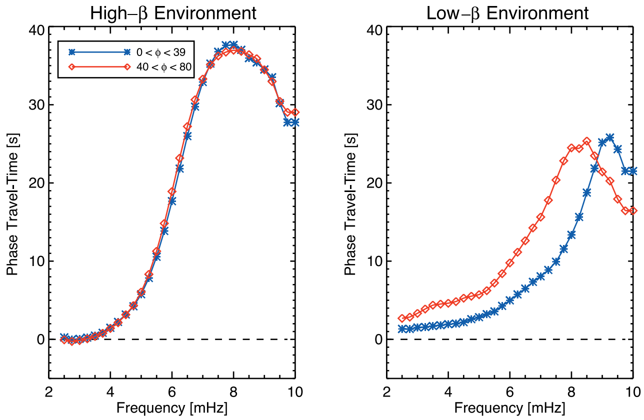

FIG. 3.—The phase travel times in regions of high-β plasma ($\beta > 1000$) for the quiet-Sun data shown in Fig. 2 show no dependence on field inclination angle (*left panel*), whereas in regions of low-β plasma ($0.2 < \beta < 10$) the observed phase travel times show a dependence on the inclination of the magnetic field that is commensurate with a decrease in the cutoff frequency (*right panel*). That is, the "switch on" of the travel time occurs at a lower frequency. The field inclination angle was qualitatively determined from a potential field extrapolation of the observed line-of-sight magnetogram shown in Fig. 2. We note that the validity of such extrapolations has recently been questioned (Socas-Navarro 2005a; Weigelmann et al. 2005). The plasma β-values were computed using the extrapolated magnetic field to obtain the magnetic pressure and the Fontenla et al. (1993) models for the solar atmosphere. We note that in order to observe the dependence of wave-travel time on the plasma β and field inclination, it is necessary to analyze data sets that are short enough in duration that field-inclination-angle information has not been lost, due to the dynamic nature of the magnetic field at the boundaries of the supergranules, but are long enough that there is a sufficient signal-to-noise ratio to be able to accurately measure the wave-travel time. We found that 20 hr provided a reasonable compromise.

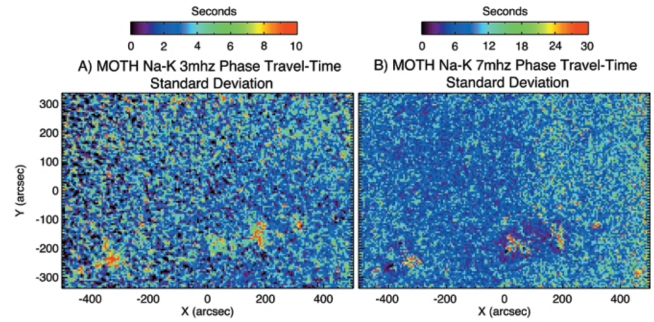

FIG. 4.—Variance in the phase travel times over the duration of the observations presented in Fig. 2. These maps show the locations where the largest fluctuations in phase travel time occur, and they are closely related to where the magnetic field is concentrated. For frequencies above the nonmagnetic cutoff frequency (∼5 mHz), the largest changes are correlated with changes in the global magnetic topology or "magnetic canopy" (Finsterle et al. 2004b).

animations of the low-frequency travel-time maps (not presented here), both of which show that the largest variations of the travel times occur in the vicinity of the boundaries of the supergranules and in and around active regions (in the animations it appears as a "twinkling"). Second, when a magnetic field line created by the magnetic carpet process finally annihilates with opposite polarity preexisting flux, there should be a simultaneous termination of wave propagation at all low frequencies ($\nu < \nu_{ac}$), due to the closing of the acoustic portal that allowed the wave propagation, and a release of the magnetic energy stored in the field. If this magnetic energy heats the atmosphere, then it should produce a local brightening in the intensity of any spectral line that is formed over the heights where the heating occurs. This brightening will be essentially cospatial with the acoustic portal and will appear as the portal closes. This sequence of events, which constitutes a direct signature of magnetic reconnection, has likely been observed (Finsterle et al. 2004a) with the MOTH data and the 195 Å intensity imagery from the Extreme ultraviolet Imaging Telescope (Delaboudiniére et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; Fleck et al. 1995).

The association of localized magnetoacoustic portals with convective cell boundaries has important implications for the transport of photospheric convective energy into the chromosphere throughout the solar activity cycle. Using the MOTH Doppler velocity data, we are able to generate maps of the spatial distribution of the net mechanical energy flux (Canfield & Musman 1973), $F(z) = P(z)\rho(z)v_g(z)$, carried by waves of different frequencies (e.g., Fig. 5). Here $P(z)$ and $v_g(z)$ are the power and group velocity of waves at height z, and $\rho(z)$ is the plasma density at that height. The group velocity is obtained via the observed phase travel time, t_p, and the relation $v_g = c^2 t_p/\Delta z$, where Δz is the height difference between the Na and K observations. Since the formation region of a spectral line varies with spatial location in a dynamic or spatially inhomogeneous atmosphere (Uitenbroek 2006), we need to turn to simulations to estimate the effective heights of the Na and K observations (the heights are needed to determine the effective density and calibrate the group velocity). Three-dimensional hydrodynamic simulations of solar convection show that for a nonmagnetic atmosphere, the effective formation heights of the Na (5890 Å) and K (7700 Å) lines (Uitenbroek 2006), as sampled by the MOTH filters, can be expected to range between 200 and 800 km for Na and 50 and 450 km for K. We therefore ascribe mean heights for our Na and K observations of regions of magnetically quiet Sun of ∼500 and ∼250 km, respectively. This gives an overall mean height for our phase-travel-time observations of ∼400 km. We note that the uncertainty in this value is close to a scale height (∼200 km). This translates into an uncertainty in the density, and therefore the mechanical energy flux, of a factor of 10. However, similar levels of uncertainty must be present in all previous estimates of the mechanical energy flux in the solar atmosphere that do not allow for the dynamic nature of the atmosphere, a condition that, to the best of our knowledge, the vast majority of estimates have. The uncertainty is further compounded by our lack of understanding of how the different plasma properties of a magnetic atmosphere affect the Na and K response functions for the line-of-sight velocity, in particular, whether there are relative shifts between them that are different in magnetic and nonmagnetic plasmas. With these caveats in mind, we make a qualitative estimate of the measured energy flux at ∼400 km. Interestingly, we find that the energy flux for waves with frequencies greater than ν_{ac} is a factor of 4 smaller than that for waves with frequencies less than ν_{ac}. This result, which is insensitive to the details of the energy calibration, is at variance with the expectation that the high-frequency waves (high-β, fast acoustic-gravity waves) provide the dominant source of wave heating for the chromosphere (Ulmschneider et al. 1996; Fawzy et al. 2002). The larger flux of low-frequency waves (low-β slow MAG waves) thus provides a paradigm shift in our understanding of which wave frequencies provide the major contribution to the wave heating of the solar chromosphere. Moreover, after calibrating our energy flux spectrum to compensate for the

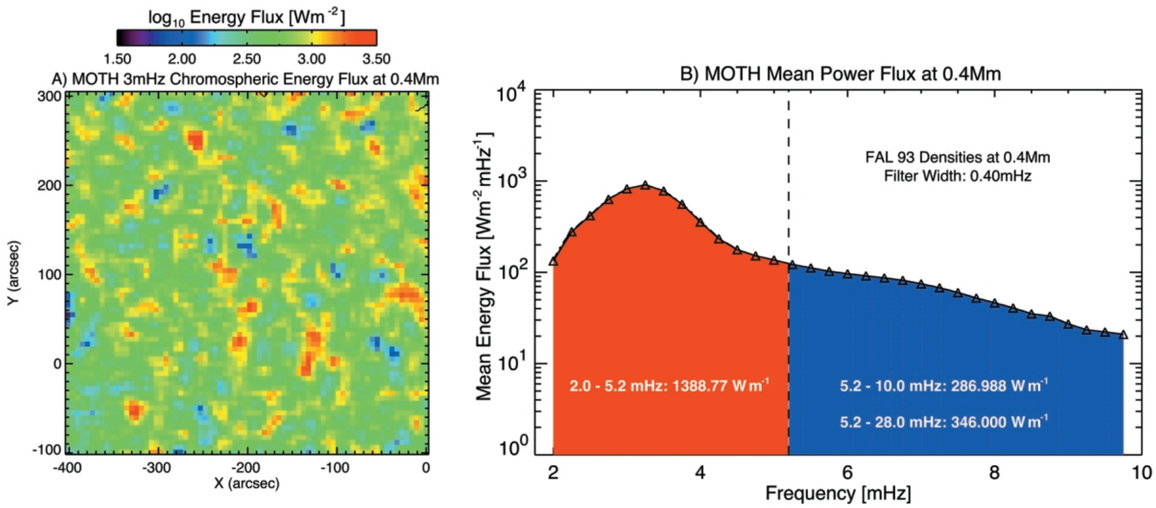

FIG. 5.—*Left*: Map of mechanical energy flux at ∼400 km above the base of the photosphere for 3 mHz waves in the quiet-Sun region shown in Fig. 2. The density values used to generate the map varied with magnetic field strength and were taken from the FAL 93 models "C, F, and P," representing different components of the quiet Sun (Fontenla et al. 1993): an average intensity area ($B < 10$), a bright area of the network ($10 < B < 100$), and an area of medium brightness plages ($B > 100$), respectively. *Right*: Variation of the mean energy flux, over the region shown in the left panel, with frequency. The integral of the high-frequency component of the flux (5.2–28 mHz) has been calibrated to match the value found by Fossum & Carlsson (2005) for the *TRACE* continuum data at 1600 and 1700 Å (346 W m^{-2}) that are also formed at ∼400 km above the solar surface. The integral of the low-frequency component (2–5.2 mHz) is then ∼1.4 kW m^{-2}.

reduction in the observed power due to spatial smearing caused by using 4″ pixels,[7] we see that the flux carried by the low-β slow waves is ∼1.4 kW m^{-2}, which represents close to one-third of the required energy budget for the chromosphere.[8] It is therefore plausible that a significant part of the basal heating of the solar chromosphere is mechanical heating by low-frequency acoustic waves that are able to propagate in the chromosphere through magnetoacoustic portals generated by the action of the magnetic carpet.

[7] The energy flux carried by high-frequency waves (5–28 mHz) at ∼400 km has been shown (Fossum & Carlsson 2005), using *TRACE* observations (0″.6 pixels) of the continua at 1600 and 1700 Å, to be 346 W m^{-2}. Our calibration thus entailed scaling the energy spectrum such that the integral of the high-frequency component (5–28 mHz) was the same as that determined from the *TRACE* data.

[8] As our data is insensitive to the signal from small-scale (∼200 km) magnetoacoustic portals that are inevitably present at the boundaries of convective cells at granular scales (∼1 Mm), this represents a lower limit.

Finally, the leakage of low-frequency acoustic waves on inclined magnetic field lines has recently been associated with both the formation of chromospheric spicules (De Pontieu et al. 2004) and the presence of propagating magnetoacoustic waves in the corona (De Pontieu et al. 2005). We speculate that magnetoacoustic portals may in fact be the underlying physical mechanism behind the majority of oscillatory phenomena in the solar atmosphere, including the presence of 1–4 mHz waves in network bright points (Bloomfield et al. 2004) and polar plumes (DeForest & Gurman 1998).

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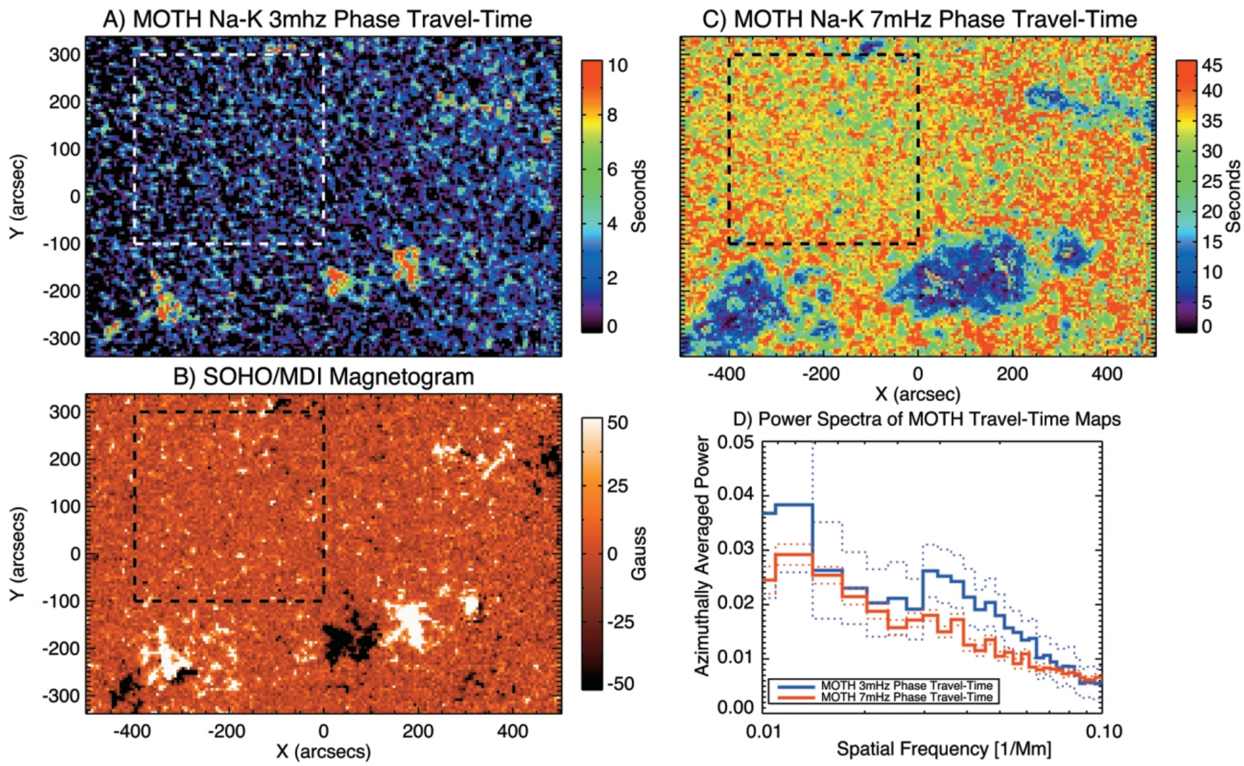

PLATE 1

FIG. 2.—*Top left*: Map of the phase travel time for magnetoacoustic waves with frequencies near 3 mHz based on 20 hr of simultaneous Doppler velocity data of the full solar disk as viewed at 5890 Å (Na) and 7699 Å (K), starting 23:00 UT on 2003 January 19. The dotted line outlines a region of magnetically "quiet" Sun. *Top right*: Phase-travel-time map for waves with frequencies near 7 mHz. *Bottom left*: Line-of-sight component of the magnetic field in the Sun's photosphere (from the MDI experiment on board *SOHO*) corresponding to the midpoint in time of the travel-time observations. *Bottom right*: Normalized, azimuthally averaged power spectra of the phase-travel-time maps at 3 and 7 mHz for the 400″ × 400″ area of quiet-Sun region outlined in the other three panels. The power spectrum of the travel-time map for 3 mHz waves exhibits a broad peak centered close to 20 Mm and is contained within the expected range of spatial frequencies for supergranulation (13–35 Mm). The power spectrum of the 7 mHz travel-time map shows no such structure. This is as expected, as waves with frequencies above the acoustic cutoff are free to propagate through the atmosphere from anywhere on the solar surface (the suppression of travel time in the active regions is due to the interaction of the high-frequency waves with the magnetic canopy; Finsterle et al. 2004b).