

# LOW-FREQUENCY MAGNETO-ACOUSTIC WAVES IN 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) magneto-acoustic 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 four 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 magneto-acoustic waves provide a significant source of energy for balancing the radiative losses of the ambient solar chromosphere.

Key words: Sun: chromosphere - Sun:magnetic fields - Sun:atmospheric motions.

## 1. INTRODUCTION

One of the outstanding puzzles of stellar astronomy is why do 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 ( $\sim 10,000$  K) is higher than that at the bottom ( $\sim 4,500$  K). The two competing theories that have been advanced to explain this enigma are (a) mechanical heating by upward propagating waves [1, 25], and (b) Joule heating associated with magnetic field reconnection [20] and the resistive dissipation of electric currents [22]. Recent results have ruled out high-frequency ( $> 5$  mHz) acoustic waves [15], magnetic reconnection and electric currents [27], as being too weak to heat the solar chromosphere and have prompted speculation that magnetic waves must play the dominant role [27]. Here we argue that low-frequency

( $< 5$  mHz) propagating magneto-acoustic waves provide a significant source of the energy necessary for balancing the radiative losses of the ambient solar chromosphere ( $\sim 4.3$  kWm<sup>-2</sup>) [32]. These waves, which are normally evanescent in a non-magnetic atmosphere, are able to propagate through “magneto-acoustic portals” that are created by areas of strong (magnetic pressure  $\sim$  gas pressure), and significantly inclined ( $> 30^\circ$  with respect to the surface gravity), magnetic fields. Such conditions are ubiquitous both in active regions and at the boundaries of convection cells [5]. 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 process (b), but also functions as an essential catalyst, or conduit, for the waves in mechanism (a). The distinctions between the two competing theories are likely to be based more in semantics than on physical substance.

## 2. OBSERVATIONS

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 5890Å and 7699Å, respectively. The observations were obtained by the Magneto-Optical filter at Two Heights experiment (MOTH) [11] that was run at the geographic South Pole during the austral summer of 2002/2003. The MOTH data provide a low-resolution (3.7 Mm/pixel at disk center) view of the full solar disk at two heights in the atmosphere ( $\sim 250$  km and  $\sim 500$  km above the base of the photosphere for the 7699Å and 5890Å data, respectively).

After removing the effects of differential rotation and co-registering the two sets of velocity images, we gener-

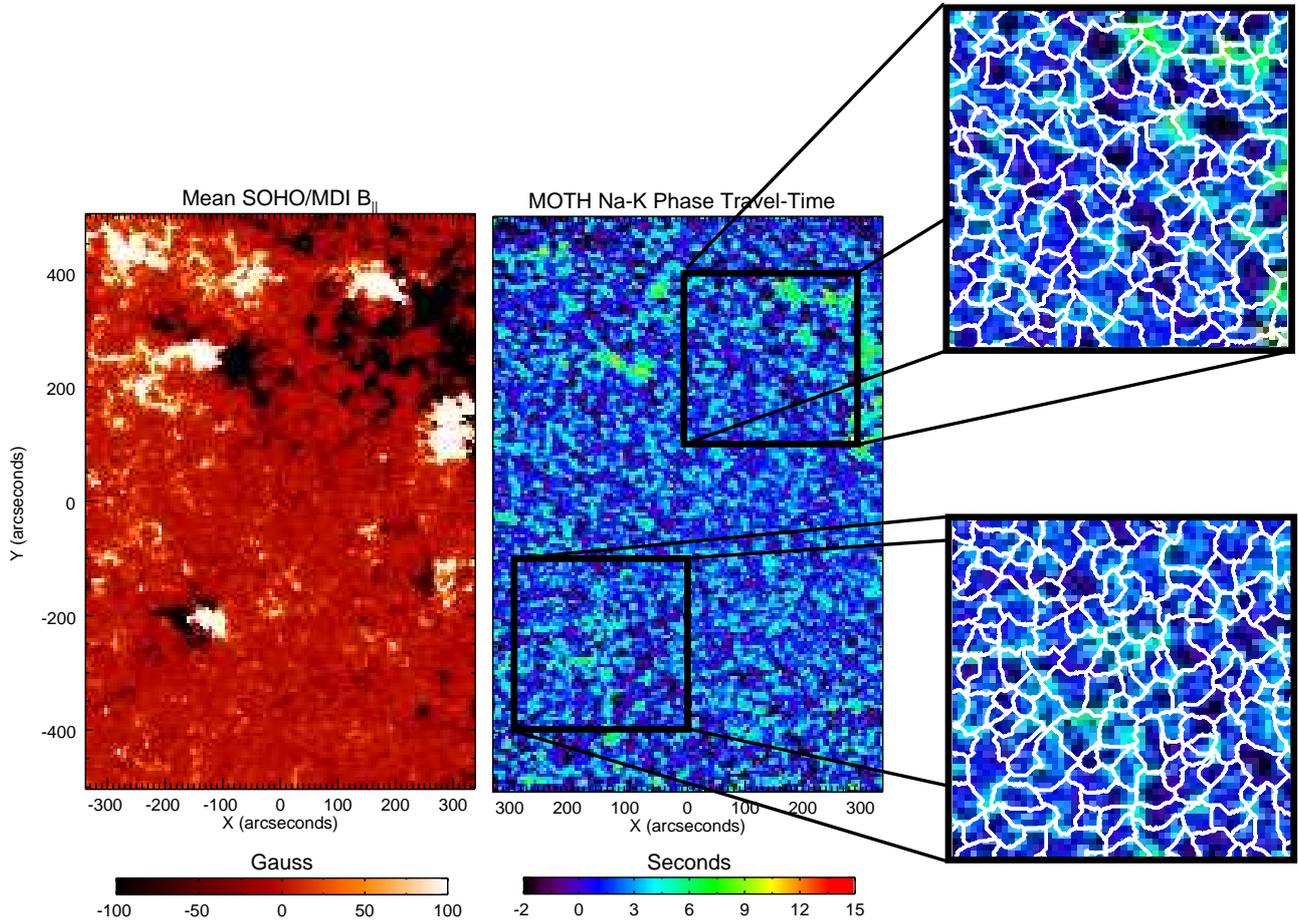


Figure 1. Left: Map of the average line-of-sight component of the magnetic field in the Sun's photosphere for the 107 hour period starting 06:59 UT on 2003 January 6 (from the Michelson Doppler Imager experiment on SOHO [23]). Middle: map of phase travel time [12] for magneto-acoustic waves with frequencies near 3 mHz based on contemporaneous, simultaneous Doppler velocity data of the full solar disk as viewed at 5890Å (Na) and 7699Å (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 [16]) as determined using an enhanced watershed segmentation [17] of the mean intensity image at 5890Å. Note that there is not significant travel time signal in all of the observed plage, 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 plage.

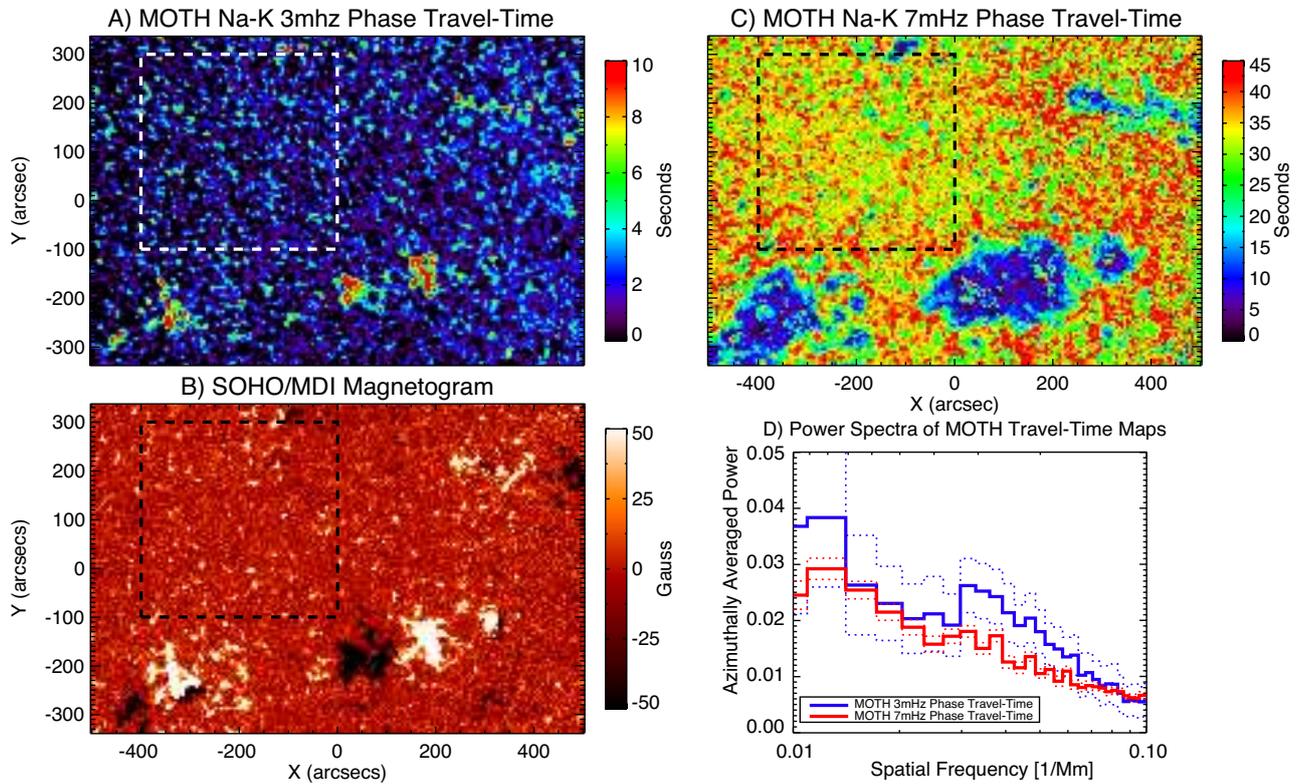


Figure 2. Top left: map of the phase travel time for magneto-acoustic waves with frequencies near 3 mHz based on 20 hours of simultaneous Doppler velocity data of the full solar disk as viewed at  $5890\text{\AA}$  (Na) and  $7699\text{\AA}$  (K), starting 23:00 UT on 2003 January 19. The dotted line 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 Michelson Doppler Imager experiment on board SOHO) corresponding to the mid point in time of the travel time observations. Bottom right: normalized, azimuthally averaged power spectra of the phase travel-time maps at 3 mHz and 7 mHz for the 400 arcsec by 400 arcsec 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 that 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 cut-off 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 [12]).

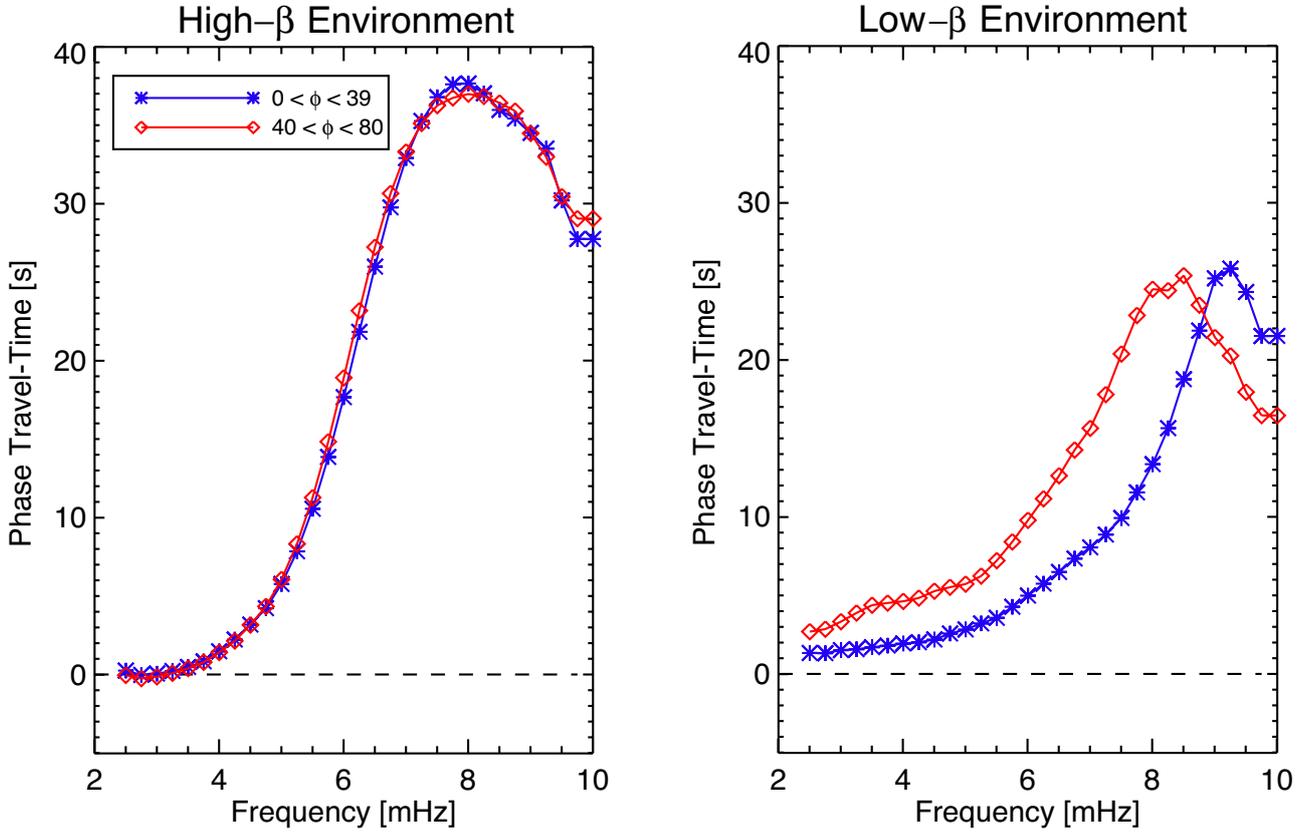


Figure 3. The phase travel times in regions of high- $\beta$  plasma ( $\beta > 1000$ ) for the quiet Sun data shown in Fig. 2, show no dependence on field inclination angle (left panel), whereas in regions of low plasma- $\beta$  ( $0.2 < \beta < 10$ ) the observed phase travel times show a dependence on the inclination of the magnetic field that is commensurate with a decrease in the cut-off 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 [26, 33]. The plasma- $\beta$  values were computed using the extrapolated magnetic field to obtain the magnetic pressure and the FAL3 models for the solar atmosphere [14]. We note that in order to observe the dependence of wave travel time on the plasma- $\beta$  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 long enough that there is sufficient signal-to-noise to be able to accurately measure the wave travel time. We found 20 hours to provide a reasonable compromise.

ate 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 co-registered images [12]. The resulting maps clearly exhibit a difference in the wave travel times between magnetic and non-magnetic regions (Figs. 1 and 2). This phenomenon is observed at all frequencies at which there is significant signal-to-noise ( $\sim 2$  to  $\sim 10$  mHz).

### 3. RESULTS & DISCUSSION

From a theoretical perspective describing the general properties of magneto-acoustic-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 [34]. This allows a local dispersion relation to be developed [19, 2, 34] where the cut-off frequency - the frequency above which the waves can propagate vertically through the atmosphere - in general depends on the local plasma- $\beta$  ( $= 8\pi p/B^2$ ), 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 cut-off frequency is independent of the magnetic field [2] and has the value  $\nu_{ac} = \gamma g / 4\pi c = 5.2$  mHz ( $\gamma = 5/3$  is the ratio of specific heats,  $g = 274$  ms $^{-2}$  is the gravitational acceleration, and  $c = 7$  km s $^{-1}$  is the sound speed). Interestingly, the MOTH Doppler velocity data (Fig. 3) and TRACE intensity data [18] (Fig. 4) provide observational support of this picture, even though the small wave approximation is clearly not applicable for the waves under consideration (wave frequencies of  $\sim 6$  mHz correspond to a wavelength of  $\sim 1$  Mm which represents several scale heights in the chromosphere [29]). Why a local dispersion description has merit for waves with frequencies  $< \sim 30$  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 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, non-zero, 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 [21, 24, 5, 28] and a concomitant lowering of the MAG cut-off frequency in regions of low- $\beta$  plasma where the magnetic field lines are significantly inclined. Since the travel times observed indicate velocities in the magnetic regions which are close to the expected local sound speed ( $\sim 7$  kms $^{-1}$ ), we infer that we are detecting

upward propagating, low- $\beta$ , slow MAG (acoustic) waves. These waves are able to propagate through “magneto-acoustic portals” that exist where the local  $\beta$  and field inclination conditions favor a lowered cut-off 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 [31].

Additional support for this concept of magneto-acoustic portals for low-frequency waves in 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 towards the boundary of the large convective cells where they interact with existing magnetic flux tubes [21]. 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 Fig. 5, and also by temporal 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 oppositely polarity pre-existing 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 co-spatial 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 [11] with the MOTH data and the 195Å intensity imagery from the Extreme ultraviolet Imaging Telescope [7] on board the Solar and Heliospheric Observatory [13].

### 4. CONCLUSION

The association of localized magneto-acoustic 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 [4],  $F(z) = P(z)\rho(z)v_g(z)$ , carried by waves of different frequencies (e.g., Fig. 5). Here  $P(z)$  and  $v_g(z)$  are the power and group velocity of

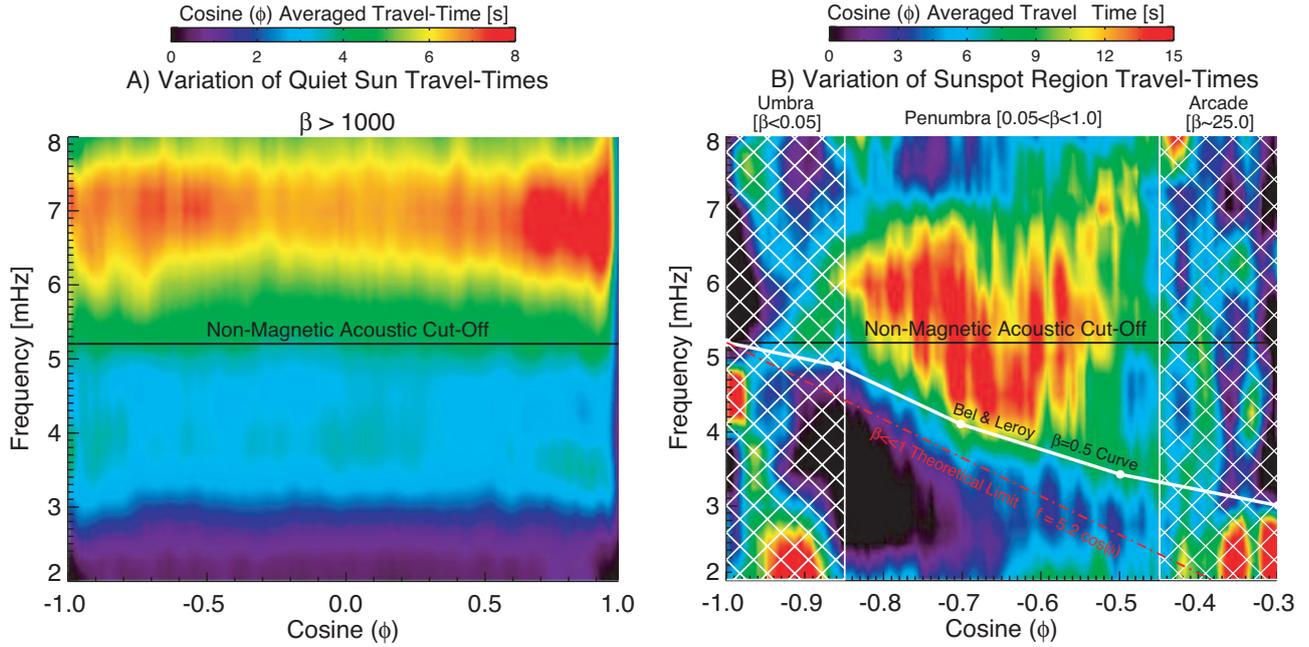


Figure 4. The cosine ( $\phi$ ) averaged TRACE 1700-1600 phase travel-times for a frequency sampling of 0.25mHz and filter width of 0.4mHz in the  $\beta > 1000$  quiet-Sun region (panel A) and a sunspot region (panel B) [18]. Here  $\phi$  is the inclination of the magnetic field with respect to the surface gravity. In both panels we show the location of the non-magnetic acoustic cut-off frequency ( $\nu_{ac} = \omega_{ac}/2\pi$ ) at 5.2mHz (thick horizontal black line). In panel B we show the theoretical limit of  $\nu_{ac}$  for a  $\beta \ll 1$  plasma [ $\nu_{ac} = 5.2 \cos \phi$  mHz] (red dot-dashed line) and the variation of  $\nu_{ac}$  at  $\beta = 0.5$  [white solid curve] that we have derived from the family of curves in Fig. 1 of Bel & Leroy (1977). The cross-hatched regions are representative of the sunspot umbra ( $\beta < 0.05$ ) and expanding spot arcade/canopy ( $\beta > 1$ ).

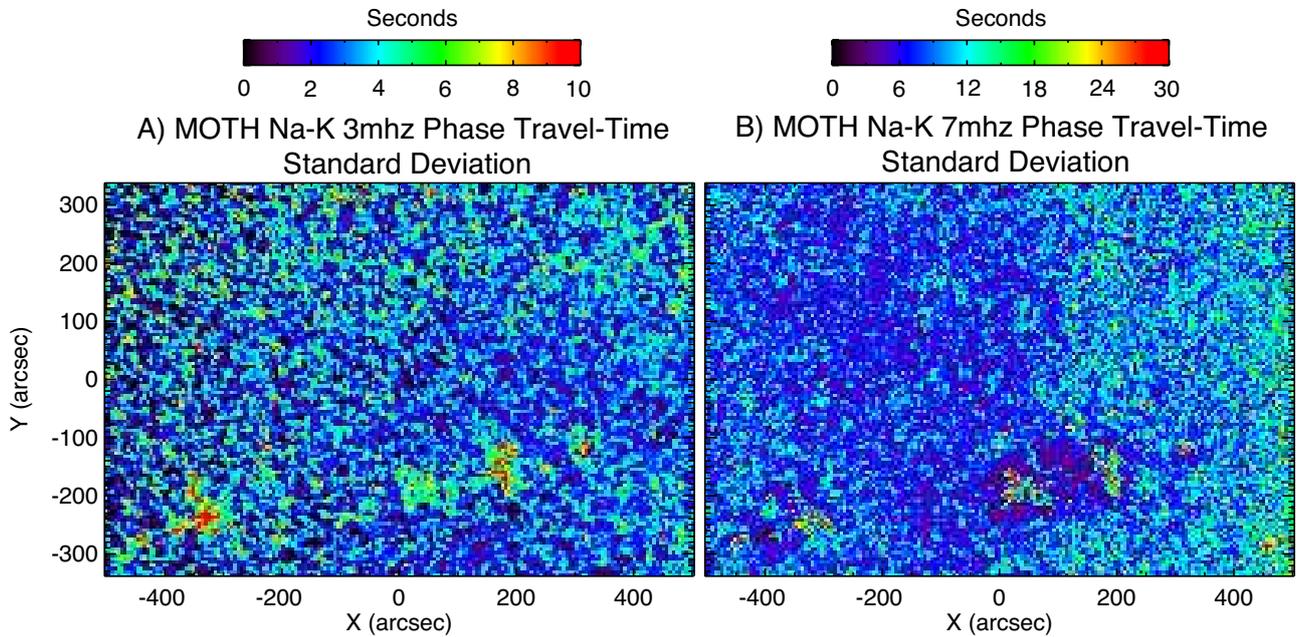


Figure 5. The variance in the phase travel times over the duration of the observations presented in Fig. 2. These maps show the locations where the largest fluctuations in phase travel time occur are closely related to where the magnetic field is concentrated. For frequencies above the non-magnetic cut-off frequency ( $\sim 5$  mHz) the largest changes are correlated with changes in the global magnetic topology, or “magnetic canopy” [12].

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  $\Delta z$  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 [29], 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 non-magnetic atmosphere the effective formation heights of the Na (5890Å) and K (7700Å) lines [29], as sampled by the MOTH filters, can be expected to range between 200 - 800km for Na and 50-450km for K. We therefore ascribe mean heights for our Na and K observations of regions of magnetically quiet Sun, of  $\sim 500$ km and  $\sim 250$ km, respectively. This gives an overall mean height for our phase travel time observations of  $\sim 400$ km. We note that the uncertainty in this value is close to a scale height ( $\sim 200$ km). This translates into an uncertainty in the density, and therefore the mechanical energy flux, of a factor of ten. 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: which, to the best of our knowledge, is the vast majority. 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 non-magnetic plasmas. With these caveats in mind, we make a qualitative estimate of the measured energy flux at  $\sim 400$ km. Interestingly, we find that the energy flux for waves with frequencies greater than  $\nu_{ac}$  is a factor of four smaller than that for waves with frequencies less than  $\nu_{ac}$  (Fig. 5). This result, which is insensitive to the details of the energy calibration, is at variance with the expectation that the high-frequency waves (high- $\beta$ , fast acoustic-gravity waves) provide the dominant source of wave heating for the chromosphere [30, 10]. The larger flux of low-frequency waves (low- $\beta$  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 reduction in the observed power due to spatial smearing caused by using 4 arcsec pixels<sup>1</sup>, we see that the flux carried by the low- $\beta$  slow waves is  $\sim 1.4 \text{ kWm}^{-2}$  which represents close to one third of the required energy budget for the chromosphere<sup>2</sup>. It is there-

<sup>1</sup>The energy flux carried by high-frequency waves (5 to 28 mHz) at  $\sim 400$ km has been shown [15], using TRACE observations (0.6 arcsec pixels) of the continua at 1600Å and 1700Å, to be  $346 \text{ Wm}^{-2}$ . Our calibration thus entailed scaling the energy spectrum such that the integral of the high-frequency component (5 to 28 mHz) was the same as that determined from the TRACE data.

<sup>2</sup>As our data is insensitive to the signal from small-scale ( $\sim 200$ km) magneto-acoustic portals that are inevitably present at the boundaries

fore 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 magneto-acoustic portals generated by the action of the magnetic carpet.

Lastly, the leakage of low-frequency acoustic waves on inclined magnetic field lines has recently been associated with both the formation of chromospheric spicules [8] and the presence of propagating magneto-acoustic waves in the corona [9]. We speculate that magneto-acoustic portals may in fact be the underlying physical mechanism behind the majority of oscillatory phenomena in the solar atmosphere, including the presence of 1-4mHz waves in network bright points [3] and polar plumes [6].

## 5. ACKNOWLEDGMENTS

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of convective cells at granular scales ( $\sim 1$ Mm), this represents a lower limit.

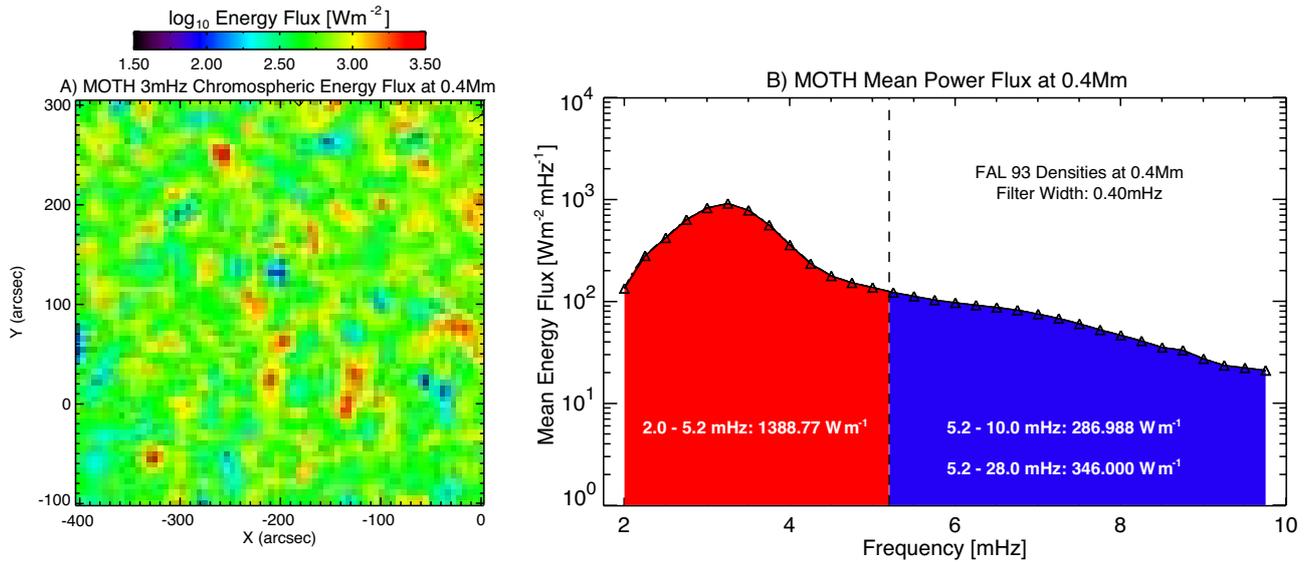


Figure 6. Left: map of mechanical energy flux at  $\sim 400$  km above the base of the photosphere for 3 mHz waves in the quiet Sun region shown in Fig. 2. The density values used to generate the map varied with magnetic field strength and were taken from the FAL3 models “C, F and P”, representing different components of the quiet Sun [14]: an average intensity area ( $B < 10$ ), a bright area of network ( $10 < B < 100$ ) and an area of medium brightness plage ( $B > 100$ ), respectively. Right: the 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 [15] for the TRACE continuum data at 1600Å and 1700Å ( $346 \text{ W m}^{-2}$ ) which are also formed at  $\sim 400$  km above the solar surface. The integral of the low-frequency component (2-5.2 mHz) is then  $\sim 1.4 \text{ kW m}^{-2}$ .

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