Waves in sunspots and starspots: The critical role of mode mixing and interference

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Abstract. Time-dependent numerical simulations of of nonlinear wave propagation in a two-dimensional (slab) magnetic field geometry show wave mixing and interference to be important aspects of oscillatory phenomena in starspots and sunspots. Discrete sources located within the umbra generate both fast and slow MHD waves. The latter are compressive acoustic waves which are guided along the magnetic field lines and steepen with increasing height in the spot atmosphere. The former are less compressive, and accelerate rapidly upward through the overlying low-β portion of the umbral photosphere and chromosphere ($\beta \equiv 8\pi p/B^2$). As the fast wave fronts impinge upon the $\beta \approx 1$ penumbral "magnetic canopy" from above, they interfere with the outward-propagating field-guided slow waves, and they also mode convert to (non-magnetic) acoustic-gravity waves as they penetrate into the weak magnetic field region which lies between the penumbral canopy and the base of the surrounding photosphere. In a three-dimensional situation, one expects additional generation, mixing and interference with the torsional Alfvén waves.

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1. Introduction

Motivated by recent numerical simulations of waves in spot magnetic field configurations carried out by the group based at the Institute for Theoretical Astrophysics at the University of Oslo, we propose here a novel conceptual framework for interpreting sunspot and starspot oscillations as an interference phenomenon between the three distinct varieties of magneto-atmospheric waves: fast, slow and Alfvénic. The critical advance embodied in these simulations is the abandonment of the traditional one-dimensional or thin fluxtube approaches to modeling sunspot oscillations. While these simpler treatments have permitted a highly-detailed and particularly useful study of the mode-conversion process, they invariably exhibit various facets of resonant phenomena as a direct consequence of their low dimensionality and high degree of symmetry. The accumulating observational evidence simply does not support the view that resonant cavities are present in sunspots (Brynildsen et al. 2002).

Multi-dimensional configurations, (1) break many of these implicit symmetries, (2) allow for localized wave sources in space and time, (3) permit the magnetic field to thread the $\beta \approx 1$-layers with various orientation, and (4) provide the opportunity for complex patterns of wave ducting and interaction that are highly variable in both time and location. Unlike their highly symmetrical predecessors, the multi-dimensional configurations are not amenable to analytic treat-

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ment. A versatile numerical code to handle such problems is currently under development, and some preliminary results applicable to a simple two-dimensional spot (slab) magnetic field geometry are described here. They do not take advantage of the full capabilities of the code to operate in three spatial dimensions and to account for the transfer of radiation based on multi-group methods and incorporating non-LTE level populations. These details are of course crucial for making predictions and comparisons with observations. Thus in this contribution, we must be content to draw more general conclusions about oscillatory phenomena in spots, while leaving their critical testing and evaluation for a future publication.

2. Numerical simulations

The basic numerical simulations are a rather straight-forward extension of those introduced by Rosenthal et al (2002). The region encompassed by the simulation represents a portion of the solar atmosphere 1.26 Mm high by 7.90 Mm wide, with translational invariance enforced along the remaining lateral dimension. The base of this computational domain is taken to coincide roughly with the solar surface: it has an initial density and pressure of 2.60 $\times 10^{-7}$ gm cm^{-3}, and 1.13 $\times 10^{5}$ gm cm^{-1} s^{-2}. The overlying atmosphere is isothermal with an effective temperature of 5785 K, a scale-height of 158 km, and a sound speed of 8.49 km s^{-1}. The imposed uniform gravitational acceleration is set at 2.74 $\times 10^{4}$ cm s^{-2}, and the ratio of specific heats is 5/3. The Brunt-Väisälä and acoustic futoff frequencies are 4.19 mHz and 4.29 mHz, respectively. These atmospheric parameters are identical to those employed in Rosenthal et al (2002).

The imposed magnetic field is potential. There is a strong unipolar magnetic flux concentration located around the 4 Mm mark on the horizontal coordinate scale, with a slight amount of reverse polarity field situated about 1 Mm distant on either side. The corresponding magnetic lines of force and the contours of constant plasma-β are shown in Fig 1. Along the bottom boundary the peak positive and negative vertical magnetic field strengths are 2750 G and -1500 G, while along the upper boundary, the maximum (positive) magnetic field strength is 750 G, and the minimum is 145 G. The computational domain consists of 294 equally-spaced zones in the vertical, and 500 in the horizontal direction. Periodic boundary conditions are enforced on the side walls, a wave-transmitting boundary condition is applied on the upper boundary, and at the lower boundary the normal component of the velocity is specified throughout the simulation. For the examples shown here, u_z is fixed at zero everywhere except between 3.55 Mm and 3.95 Mm where it oscillates sinusoidally with a period of 23.8 s and a peak amplitude of 400 m s^{-1}.

Computational costs and exigencies are the primary motivations which lead us to adopt this particular magneto-atmospheric configuration as a representative scaled-down ($\approx$ 10:1) version of a two-dimensional sunspot. In so far as it is reasonably faithful to the basic morphology of a moderate-sized magnetic flux concentration on a late-type star, the results of this simulation ought to be applicable in a qualitative sense to the behavior of oscillatory disturbances in these structures. A more serious drawback of this simulation than the 10:1 spatio-temporal scaling is the assumption that the fluid motions are isentropic. The negative impact of this restriction is particularly profound for the compressive slow acoustic waves. A careful consideration of the issues again suggests, at worst, quantitative errors are entailed by this stipulation.

3. Results

Figures 1-6 illustrate the key features of the numerical simulation. In these figures we show density fluctuations (Figs 1-3) and the transverse (to the instantaneous magnetic field) fluid motions (Figs 4-6) after one (t = 24.7 s), three (t = 71.5 s), and five (t = 118.3 s) oscillations of the driving piston. In each figure we also overplot the contours of the plasma-β, and selected magnetic field lines. The $\beta = 1$ contour is thickened relative to the other contours. It separates the low-β plasma of the spot interior from the surrounding high-β regions in the lower left and right corners of the domain. The localized piston source resides entirely within the low-β region.

As it oscillates, the piston generates slow and fast magneto-atmospheric waves. The slow waves are essentially acoustic waves that are guided along the prevailing magnetic field. They are most easily discerned by their relative density fluctuations $\Delta\rho/\rho$ shown in Figs 1-3, but they would also be readily visible in parallel (to the instantaneous magnetic field) fluid motions. The fast magneto-atmospheric waves, in contrast, are produced rather inefficiently by the oscillating piston, which makes them difficult to identify from Figs 1-3. Instead, they are better detected by the fluid motions they induce transverse to the magnetic lines of force, as in Figs 4-6, since these motions are largely absent from the slow waves. The slow waves are readily identified in the transverse velocity plots only in the vicinity of the steepened N-wave shock fronts. These appear as thin, slightly curved, striations of red and dark violet in the central light violet region of Figs 5 and 6. Figures 1-3 and 4-6 are therefore complementary in providing a comprehensive visual picture of both the dominant and recessive wave motions present in the simulation.

The slow magneto-atmospheric wave has its fluid motions aligned with the magnetic field and is compressive. As it moves upward along the magnetic field into regions of lower ambient density its sinusoidal waveform gradually becomes distorted into an N-wave bounded by acoustic shock fronts. The first N-wave is visible in Fig 2 as the leading edge of the slow wave train. The pronounced compression behind the leading edge shocks is reflected in the jagged excursions the iso-β contours make in traversing Figs 2 and 3. They are also distorted, but to a lesser degree, by the rarefaction zones situated in front of the shocks. Since there are negligible magnetic field variations associated with the slow wave, these excursions are entirely due to the pressure variations across the N-wave. It is clear by looking carefully at the sequence

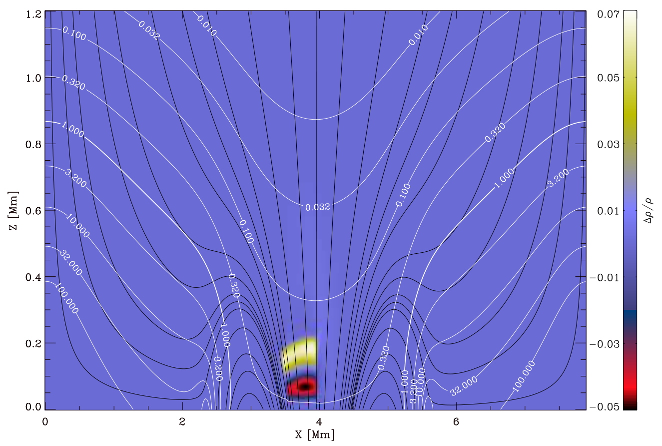

Fig. 1. Density fluctuations, $\Delta\rho/\rho$ at an elapsed time of 24.7 s. Clearly evident is the first sinusoidal compression and rarefaction of the slow magnetic field guided acoustic wave. Selected instantaneous magnetic field lines (black lines) and contours of the plasma-β (white lines) are overplotted. See Fig 4 for the transverse velocity at the same elapsed time.

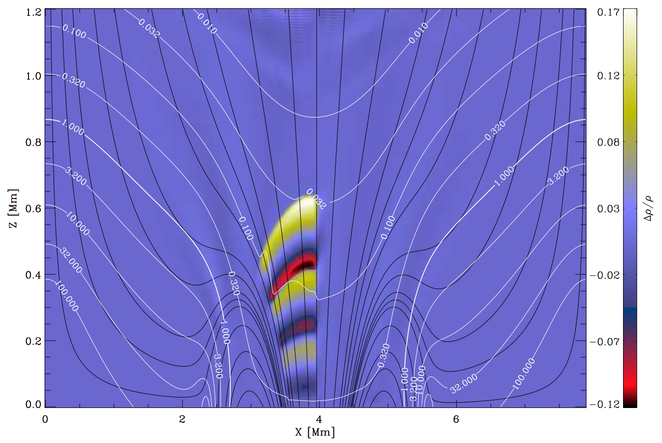

Fig. 2. Density fluctuations at an elapsed time of 71.5 s. Three sinusoidal compressions and rarefactions are now displayed. Notice the increase in the magnitude of the density fluctuations relative to those displayed in Fig 1, and also the gradual steepening of the slow waves with altitude. See Fig 5 for the transverse velocity at the same elapsed time.

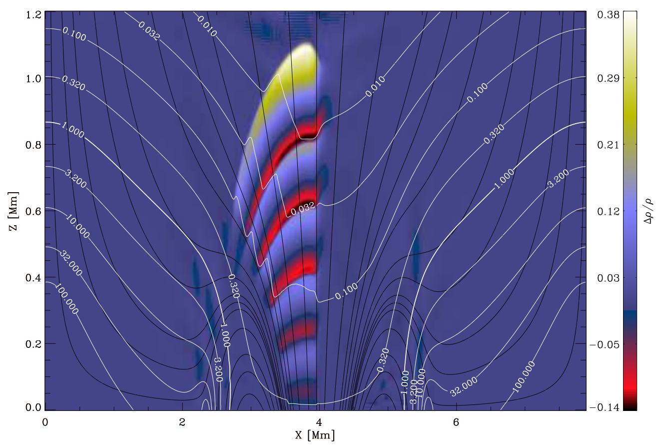

Fig. 3. Density fluctuations at an elapsed time of 118.3 s. Five sinusoidal compressions and rarefactions are now visible. The uppermost disturbances have now fully steepened into N-waves. See Fig 6 for the transverse velocity at the same elapsed time.

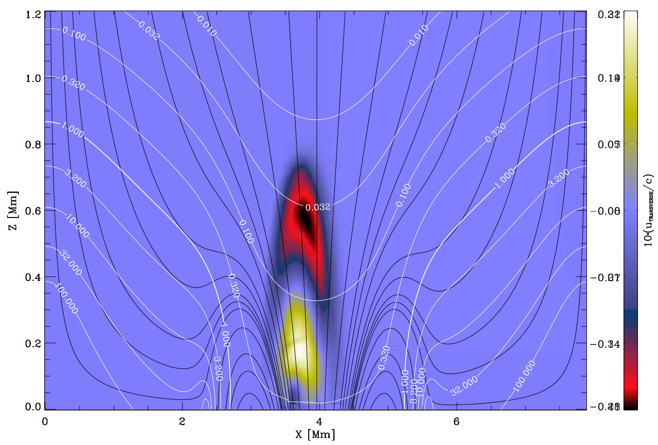

Fig. 4. Velocity component transverse to the magnetic field in units of the sound speed (8.49 km s^{-1}) at an elapsed time of 24.7 s, corresponding to the density fluctuations displayed in Fig 1. This plot principally shows the fast MHD wave. The structure shown here has little correspondence with the slow MHD wave compressions and rarefactions present in Fig 1.

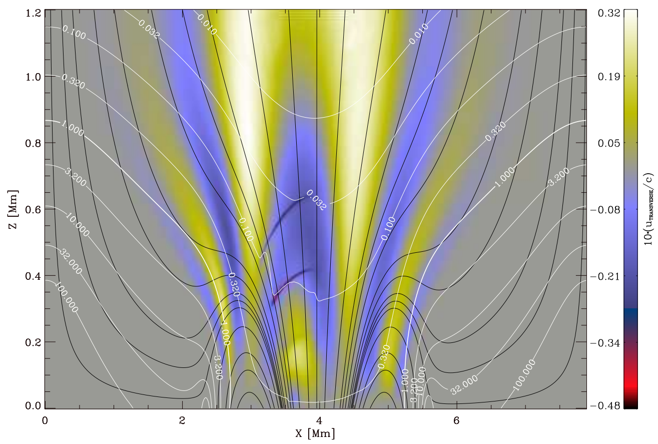

Fig. 5. Velocity component transverse to the magnetic field in units of the sound speed at an elapsed time of 71.5 s (cf. Fig 2). Three oscillatory cycles are visible with the orientation of violet hues leading yellow. Notice that the outermost violet wave fronts are quite weak. The steepened N-waves of Fig 2 can now be detected as thin striations of red within the central violet region.

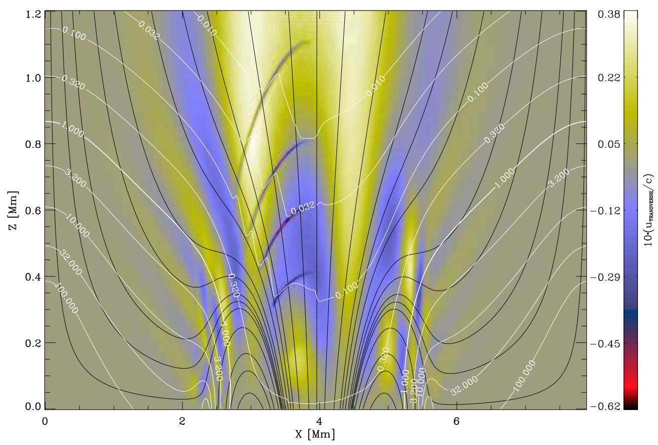

Fig. 6. Velocity component transverse to the magnetic field in units of the sound speed (8.49 km s^{-1} at an elapsed time of 118.3 s (cf. Fig 3). The steady lateral outward propagation of the fast waves is readily apparent, as are the striations associated with the acoustic shocks.

of snapshots from Fig 1 to 3 that the slow wave is not entirely contained within the field lines connected to the localized source piston. There is a gradual lateral expansion of the slow wave front to neighboring field lines, although the amplitude of the density fluctuations drop by about one order of magnitude in crossing the last field line connected to the source region. This is seen most clearly in the extension of the uppermost slow wave present in Fig 3.

The fast magneto-atmospheric wave produces somewhat less density perturbation for a given fluid velocity than the slow wave. Density fluctuations associated with the fast waves are present in Figs 1-3, but are swamped by those associated with the slow wave. The choice of the motions transverse to the magnetic field effectively filters out the dominant slow wave and provides an excellent rendering of the recessive fast wave in Figs 4-6. The fast wave also produces motions parallel to the magnetic field, but at a somewhat reduced level relative to those perpendicular to the field. Therefore snapshots of the magnetic field aligned velocity will look very similar to the density snapshots.

The iso-β contours also serve as contours of constant Alfvén speed because the atmosphere is isothermal. The fast wave fronts therefore accelerate rapidly upward along the center of the magnetic flux concentration along the prevailing Alfvén speed gradient. The lateral flanks of the wave front decelerate rather gradually as they spread sideways into the regions of lower Alfvén speed which surround the spot. As indicated in Figs 5 and 6, this causes the flanks of the fast wave fronts to become convex: the upper portion of the front has traversed a larger lateral distance than has the lower portion. A novel consequence of this configuration is that the high-β regions surrounding the spot see the fast waves propagating *downward* as they pass across the magnetic canopy.

As noted elsewhere, the $\beta \approx 1$ magnetic canopy is the principal site of wave mixing and conversion. Fig 5 indicates that significant portions of the fast wave fronts arrive at the canopy almost simultaneously. Proceeding to Fig 6, one sees that they pass seamlessly across this transition layer converted smoothly to the high-β fast wave. The high-β fast magneto-atmospheric wave is essentially an acoustic-gravity wave which is unaffected by the (weak) magnetic field. In an isothermal atmosphere the frequency (ω), horizontal ($k_\perp$), and vertical ($k_\parallel$) wavenumbers satisfy the familiar dispersion relation

$$k_\parallel^2 = \frac{\omega^2 - \Omega^2}{c^2} + k_\perp^2 \left(\frac{N^2}{\omega^2} - 1 \right) , \qquad (1)$$

where Ω and N are the acoustic cutoff and Brunt-Väisälä (buoyancy) frequencies, and c is the sound speed. For our piston driving frequency of $\omega/2\pi = 42$ mHz, Eqn (1) is essentially acoustic,

$$k_\parallel^2 \approx \frac{\omega^2}{c^2} - k_\perp^2 . \qquad (2)$$

There is no obvious evidence present in Fig 6 of conversion to the high-β slow magneto-atmospheric wave. This object is nearly indistinguishable from an Alfvén wave in character, and would of course be propagated strictly along the magnetic lines of force. The optimal location for seeking fast-to-slow wave conversion is therefore between the altitudes of

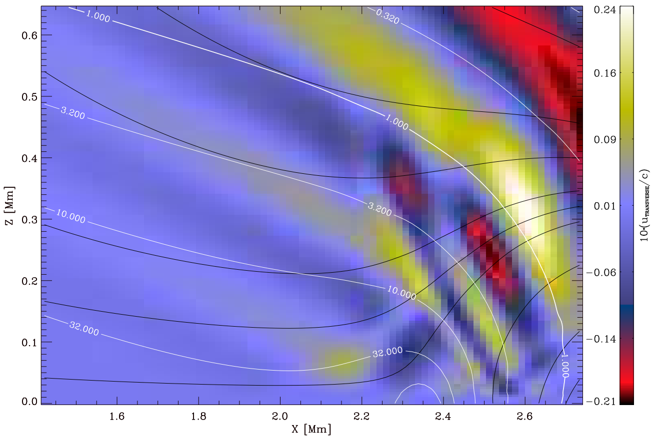

Fig. 7. Detail from Fig 6 showing the region surrounding the $\beta = 1$ canopy surface, and the motions perpendicular to the magnetic lines of force. The low-β fast waves impinge on the canopy from above, and are now seen to generate *both* slow and fast high-β waves. The slow Alfvén-like waves are represented by the two thin slightly inclined yellow-violet fronts between the $\beta = 3.2$ and the $\beta = 10$ contours. The fast acoustic-like waves are the very broad and more highly inclined undulations seen to the left of $x = 2.2$.

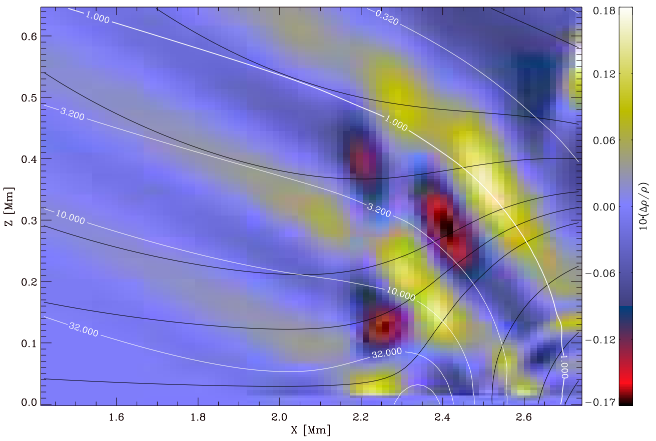

Fig. 8. Detail from Fig 3 showing 10 ($\Delta\rho/\rho$). Note the absence of any structure associated with the slow Alfvén-like waves seen in Fig 7. The fast acoustic-like waves are again obvious to the left of $x = 2.2$.

200 km and 400 km, where the magnetic field lines are both perpendicular to, and subsequently diverge away from, the $\beta = 1$ surface.

Figs 7 and 8 show detail from Figs 6 and 3, respectively, in the vicinity of this optimal location for fast-to-slow mode conversion. Above the canopy surface one sees the impinging low-β fast waves clearly in the transverse velocity (Fig 7), and between the $\beta = 3.2$ and $\beta = 10$ contours are the first emergent slow Alfvén-like waves. As the Alfvén speed decreases outward along the magnetic field lines, the wavelength of these slow waves also decreases and they are rapidly lost to the numerical viscosity and resistivity of the finite computational grid. For solar dissipation levels, they would instead dissipate by phase-mixing. A comparison of Fig 7 with Fig 8 confirms our identification of these objects as incompressible, transverse, fluctuations. Such a comparison likewise helps identify the high-β fast waves as the more

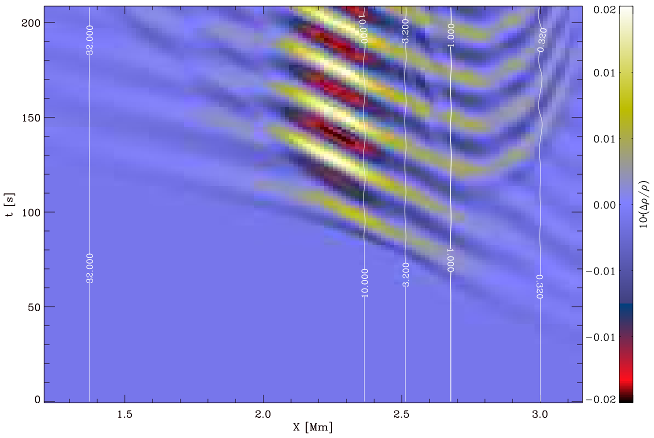

Fig. 9. Density fluctuations $\Delta\rho/\rho$ obtained at a fixed altitude of 150 km, as a function of elapsed time. The lateral location of the contours of constant plasma-β are indicated by the dark lines. See Fig 10 for the corresponding vertical velocity.

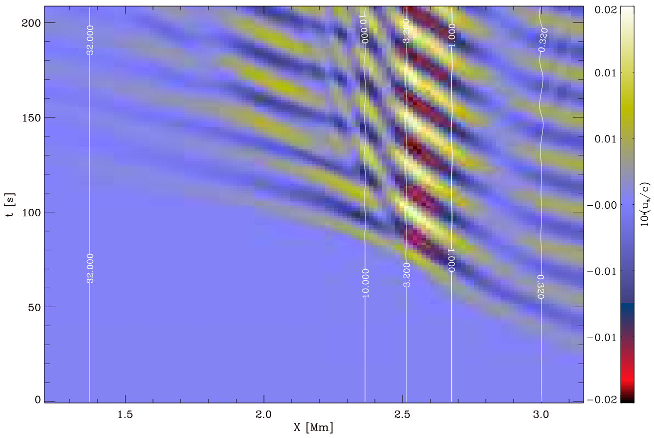

Fig. 10. Vertical component of the velocity obtained at a fixed altitude of 150 km, as a function of elapsed time. The lateral location of the contours of constant plasma-β are indicated by the dark lines. See Fig 9 for the corresponding density fluctuations.

highly-inclined relatively weak gradual undulations present in the left halves of these two figures. The first fast-wave front to emerge from the canopy is seen to intersect the lower boundary of the computational domain in the vicinity of $x = 2.0$. To the right of this point, one may just discern the upward continuation of this wave front which has already reflected off the lower boundary. It is difficult to follow the extension of this front, or reflections associated with subsequent fronts, much higher in the atmosphere owing to their interference with the later portions of the emitted wave train. In a similar vein, one may notice that the region surrounding the $\beta = 1$ canopy exhibits complicated structures which are not obviously categorized as being compressible or incompressible, nor polarized parallel or perpendicular to the magnetic field. This reflects the confusion the incoming fast waves experience when the acoustic and Alfvén speeds are difficult to distinguish.

In Fig 8 it is also just possible to discern the outer edge of the second low-β slow N-wave front. The front starts just below the upper right corner of the plot and extends down to the point $x = 2.6$ Mm and $z = 0.3$ Mm, where it gets lost in the canopy region.

It is thus quite clear that the region displayed in Figs 7 and 8 is subject to a fair amount of interference between various wave trains. Above the $\beta = 1$ canopy there is interference between the piston-generated slow and fast wave trains. The former propagate from right to left upward *along* the magnetic field lines; the latter move from right to left downward *across* the field. Below the canopy, the situation is even more complicated. We have both the mode-converted fast and slow wave trains emerging from the canopy, at distinct locations and propagating in different directions, and the fast waves reflected from the lower boundary. It therefore comes as no surprise that it would be a monumental undertaking to infer the behavior of the waves emitted from the source piston based simply on limited knowledge of the oscillations at a specified altitude in the atmosphere.

The point is illustrated by Figs 9 and 10, which display fluctuations present at a fixed altitude of 150 km, which spans the two-dimensional region shown in Figs 7 and 8. In Fig 9, we show the density fluctuation, $\Delta\rho/\rho$, and in Fig 10 we show the vertical velocity u_z in units of the sound speed, both enhanced by a factor of 10 to bring out the color bar scale. In a naive sense, the former are representative of hypothetical intensity fluctuation ($\sim \Delta I/I$) time series, while the latter mimic Doppler velocities from a vantage point looking down on the simulation from above. Notice that the images of the full computational domain displayed in Figs 1-6 correspond to the three epochs $t = 24.7$ s, 71.5 s, and 118.3 s.

Figs 9 and 10 show some expected similarities and some remarkable differences. The principal distinction concerns the absence of the high-β slow waves from the density fluctuation time series. These waves have motions transverse to the magnetic field, which have a component parallel to the z-direction, and thus they appear between $x = 2.1$ Mm and 2.5 Mm in Fig 10. One observes that at $t = 118.3$ s, one complete wavelength plus the beginning of a second are present at $z =$ 150 km, which is consistent with the detailed view provided by Fig 7. Fig 10 very nicely illustrates the mode conversion process of low-β fast waves impinging upon the $\beta = 1$ magnetic canopy from the right, and splitting as they emerge into the high-β plasma as decelerating slow waves, and constant phase speed fast waves. The interference between these two emitted wave trains is evident in the Doppler velocity time series, but does not occur for the intensity fluctuations.

A careful examination of the left halves of Figs 9 and 10 reveals the presence of *two* compressive high-β fast wave trains: one with a fast lateral phase speed (small slope) and the other significantly slower (larger slope). The high phase speed fronts are the mode-converted fast waves which emerge from the inclined portions of the canopy, i.e., from altitudes greater than $z = 300$ km, say. These waves fronts pass obliquely downward through the $z = 150$ km level and produce a large apparent lateral phase speed in the fluctuation time series. Below $z = 250$ km, the $\beta = 1$ canopy is nearly vertical, and so the converted fast waves which emanate from this portion of the mode-mixing layer propagate more-or-less horizontally away from the flux concentration. The extension of their wave fronts along the $z = 150$ km level produce the slow phase speed fast waves. Indeed a rough estimate of the phase speed of this second slower fast-wave train form Figs 9 and 10 gives 8.5 km s^{-1}, consistent with the sound speed of the isothermal atmosphere. Notice, in particular, how the constructive and destructive interference of these wave trains can give rise to fluctuations in the apparent lateral phase speed from position to position.

A second remarkable distinction between the two time series occurs to the right of the $\beta = 1$ canopy. After an elapsed time of approximately 110 s, a compressive inward propagating wave train appears to reflect from the canopy, and decelerates very rapidly as it moves into the low-β, closed-field, region. From Fig 10, we observe that the motions associated with this wave must be predominantly in the x-direction. This would offhand suggest identification with a Lamb wave, however, the apparent deceleration is not consistent with such an explanation. Analysis of additional data not presented here instead reveals that these are slow field-aligned acoustic waves which are yet a third byproduct of the mode-conversion of the impinging fast wave near the $\beta = 1$ surface (the other two being the transmitted fast and slow waves discussed earlier in this section). The fluid motions are aligned with the magnetic field, but just to the right of the canopy surface at $z = 150$ km, the field is predominantly horizontal, and so these waves are absent in Fig 10 until the field develops a sensible vertical component to the right of $x = 3$ Mm. In retrospect, one finds that these reflected slow waves are in fact just visible in Fig 8 as the two small nearly concentric arcs which appear to emanate from the bottom right corner of the plot. They are not as prominent in the analogous portion in Fig 7 because they have reduced fluid motion perpendicular to the magnetic field. The reduction is not as dramatic in this figure as elsewhere, because modest values of β are in force. In a continuation of this plot further into the low-β region, these arcs rapidly fade away in the transverse velocity.

4. Summary

Our brief discussion of Figs 1-10 has brought out a number of important points concerning the general nature of wave propagation in two-dimensional magneto-atmospheres. Despite several idealizations present in these simulations, our findings are broadly relevant for studies of oscillatory phenomena in starspots, sunspots, and generic stellar surface magnetic flux concentrations.

We have seen very clearly the critical role played by the "magnetic canopy surface", defined here as where the Alfvén and sound speeds are comparable, or equivalently, where the plasma-β is of order unity. This surface separates regions of high- and low-β plasma. Within these distinct regions the fast- and slow magneto-atmospheric waves are readily distinguished one from the other, but such an unambiguous identification does not extend *across* the canopy, where the waves of each side are mixed and lose their respective identities. The canopy is therefore the quintessential site for conversion between the different waves.

This fact was of course well-appreciated by very many one-dimensional treatments of sunspot oscillations (see references in Bogdan 2000). What is new here is the novel facets introduced by the curvature of this surface and the spatial variations of the angle between the normal to the surface and the local magnetic field. This can both inhibit or promote the conversion to a particular variety of wave, while at the same time allowing wave trains emanating from different portions of the canopy to overlap and interfere at various privileged locations in the surrounding high- and low-β plasmas. A visual inspection of Figs 9 and 10 is sufficient to appreciate the profound impact carried by this last point. Not only do canopy surfaces create additional wave varieties, but localized sources do the same. The vertical motion of the driving piston was selected to produce slow high-β acoustic waves, but we have seen that high-β fast waves are also created, which then subsequently convert to other waves upon encountering the canopy. This fascinating interplay between mode mixing and interference therefore emerges from our discussion as the essential aspect of wave propagation in sunspots and starspots.

Those who acquire and interpret observations can capitalize upon the critical role played by the "magnetic canopy surface" in orchestrating this complicated interplay (e.g., McIntosh et al. 2001). One gains a first advantage by knowing whether the relevant observations obtain on the high- or low-β side of this surface. A second advantage follows if one can further determine the general shape and relation to the prevailing magnetic field of the canopy extensions which pass nearest to site of the observations.

For example, consider the phenomenon of running penumbral waves (RPWs). The well-known difficulty of detecting these objects at photospheric levels may well be explained by supposing, merely for the sake of argument, that these waves are related in some fashion to the low-β slow wave train shown in Fig 3. The lack of any appreciable extension of these waves into lower atmospheric layers is prohibited by the intervening $\beta = 1$ canopy. This is a fairly trivial observation, but the analysis presented in this contribution clearly indicates many other more sophisticated, and potentially powerful, lines of reasoning which may help in sorting out the bewildering array of properties of oscillations in and around magnetic flux concentrations. Lack of space prohibits us from taking this discussion further, the interested reader should consult a forthcoming paper by Bogdan et al. (2002).

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