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How to turn gravity waves into Alfvén waves and other such tricks

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Abstract. Recent observations of travelling gravity waves at the base of the chromosphere suggest an interplay between gravity wave propagation and magnetic field. Our aims are: to explain the observation that gravity wave flux is suppressed in magnetic regions; to understand why we see travelling waves instead of standing waves; and to see if gravity waves can undergo mode conversion and couple to Alfvén waves in regions where the plasma beta is of order unity. We model gravity waves in a VAL C atmosphere, subject to a uniform magnetic field of various orientations, considering both adiabatic and radiatively damped propagation. Results indicate that in the presence of a magnetic field, the gravity wave can propagate as a travelling wave, with the magnetic field orientation playing a crucial role in determining the wave character. For the majority of magnetic field orientations, the gravity wave is reflected at low heights as a slow magneto-acoustic wave, explaining the observation of reduced flux in magnetic regions. In a highly inclined magnetic field, the gravity wave undergoes mode conversion to either field guided acoustic waves or Alfvén waves. The primary effect of incorporating radiative damping is a reduction in acoustic and magnetic fluxes measured at the top of the integration region. By demonstrating the mode conversion of gravity waves to Alfvén waves, this work identifies a possible pathway for energy transport from the solar surface to the upper atmosphere.

1. Introduction

Gravity waves, presumably excited by granulation, have recently been observed at multiple heights near the base of the quiet-Sun chromosphere, displaying the signature of upward (group) propagation [1]. Standard atmospheric models (*e.g.*, VAL C) suggest that these waves are confined to a gravity wave cavity in the absence of magnetic field, roughly $0 < z < 1.2$ Mm at the relevant frequencies (about 1 mHz). The observations indicate significant associated wave energy fluxes, perhaps an order of magnitude larger than co-spatial acoustic waves. However, the gravity waves appear to be substantially suppressed by magnetic fields.

These observations raise several interesting questions that we set out to answer theoretically:

(i) Why do the gravity waves avoid magnetic regions?

(ii) Why do we see them as travelling waves and not standing waves?

(iii) What happens to gravity waves as they propagate higher and inevitably encounter regions where the plasma beta is of order unity?

(iv) Can (as informally postulated in [1]) the gravity waves couple into Alfvén waves and so escape the “gravity cavity”?

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Using a combination of dispersion diagrams, ray calculations, and direct numerical solution of the wave equations, [2] find some very elegant and surprising answers to these questions, which suggest that highly inclined magnetic field may form a crucial link in the chain between the solar surface and the upper atmosphere. We summarize these results here, but then extend them to briefly explore the effects of radiative loss on atmospheric gravity waves.

2. Method

In this paper we consider waves with frequency of 1 mHz and horizontal wave numbers of 2 Mm^{-1}, subject to a uniform magnetic field. The field orientation is described by its inclination from the vertical (θ) and its azimuthal angle from the plane of wave propagation (ϕ). The atmospheric quantities were given by the VAL C model up to a height of 1.6 Mm, with an isothermal layer appended above.

We refer the reader to [2] for the form of the dispersion relation, the governing equations of motion, and details of the method of their numerical solution, in the limit of adiabatic wave propagation. The equations used to describe radiatively damped wave propagation will be described in a forthcoming paper.

3. Results

3.1. In the absence of a magnetic field

Figure 1 shows the dispersion diagram relating the vertical component of the wave number k_z to the height z for the 1 mHz, $k_x = 2\ \mathrm{Mm}^{-1}$ gravity wave in the absence of magnetic field. The closed curve indicates that it is trapped as a standing wave in a "gravity cavity", travelling upwards to a height of about 1.2 Mm before being reflected back downwards. Note that the lower branch of the curve represents the up-going gravity wave.

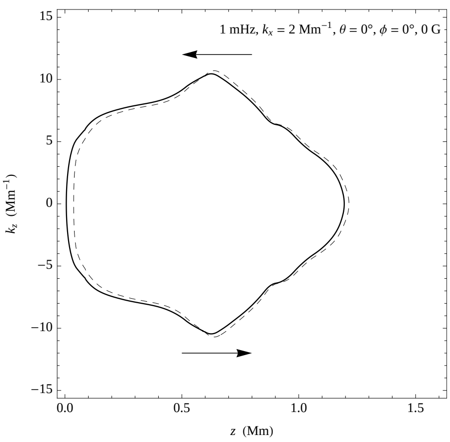

Figure 1. The dispersion diagram for the gravity wave in the absence of magnetic field. Arrows indicate the direction of energy transport. The heights at which waves reflect are evident. The full and dashed curves correspond to two different forms of the acoustic cutoff frequency: the isothermal and Deubner-Gough forms respectively (see [2] for full details). Since there is little difference, the isothermal form $\omega_c = c/2H$ will be used throughout here, where c is the sound speed and H the density scale height.

3.2. Low to moderate field inclination

Application of a magnetic field allows the gravity wave to escape the gravity wave cavity and propagate as a travelling wave. For vertical or moderately inclined field the gravity wave reflects as a down-going slow MHD wave. This explains the observations that gravity waves appear to avoid magnetic regions. Figure 2 demonstrates this behaviour with a ray diagram for the scenario of a gravity wave propagating in a 10 G vertical field.

3.3. Highly inclined field

When the magnetic field is highly inclined to the vertical (large θ values), the ramp effect, which reduces the acoustic cutoff frequency by a factor $\cos\theta$, enables the wave to penetrate

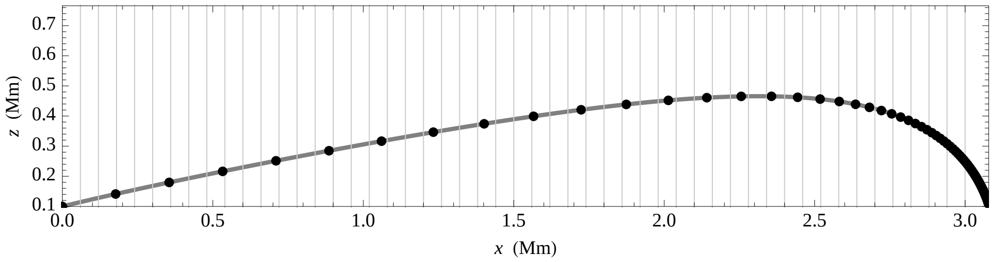

Figure 2. Ray diagram for the scenario of a gravity wave propagation in a 10 G vertical field (field lines are shown in grey). This represents the path of the wave packet in the x-z plane. The dots represent the wave packet location at one minute intervals. Note that after the reflection at a height ~ 0.4 Mm, the 1 minute dots are more closely spaced, showing that the wave has converted to a slow wave.

the equipartition level (where the Alfvén and sound speeds are equal) and mode conversion to either field-aligned acoustic waves or Aflvén waves can occur. The dispersion diagram in Figure 3 illustrates a high field inclination scenario where conversion to the Alfvén wave occurs.

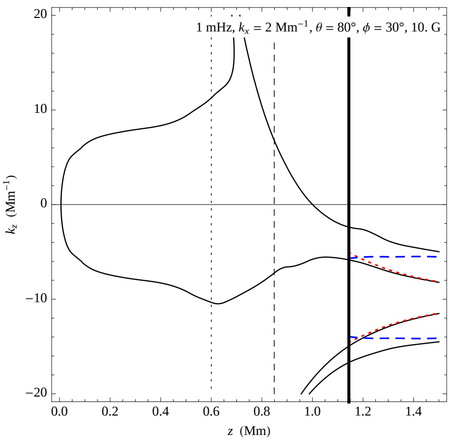

Figure 3. Dispersion diagram for a wave in a highly inclined field that penetrates the equipartition level (the vertical solid black line). Asymptotic solutions of the dispersion relation are shown – the blue dashed line is the field-aligned acoustic solution and the red dotted line is the Alfvén solution. The up-going gravity wave (bottom branch) converts to an Alfvén wave near the equipartition level.

The character of the converted wave (acoustic or magnetic) depends on the azimuthal orientation (ϕ) of the field. In cases where ϕ=0, coupling to the Alfvén wave is not possible and the gravity wave converts to a field guided acoustic wave. When ϕ is non-zero, conversion to both Alfvén and acoustic waves can occur. The orientation of the field determines the connectivity in the dispersion diagram to the field-aligned acoustic wave or the Alfén wave.

For some field orientations, (high inclination, moderate azimuthal angles) the Alfvén and field-aligned acoustic solutions are only separated by a narrow gap in the dispersion diagram. In that case, conversion to both types of wave is possible, as the energy can tunnel across the gap.

Numerical solution of the wave equation was used to measure the acoustic and magnetic fluxes at the top of the integration region. Figure 4 shows the behaviour of the fluxes as a function of the field inclination for a moderate azimuthal angle (ϕ = 30°). The dot-dashed (magnetic) and dashed (acoustic) curves represent the result of solving the adiabatic equations. Numerical solution reveals that the connectivity implied by the dispersion diagrams usually represents the dominant behaviour, even when tunnelling occurs.

3.4. Effect of radiative damping

The assumption of adiabatic wave propagation is invalid in the photosphere and low chromosphere. We attempted to incorporate the effects of radiative damping in our simulations by including a Newton cooling term in the energy equation. Our preliminary work employs a constant value for the radiative relaxation time (τ_R) up to 1.0 Mm. We have considered τ_R values from 200 s to 1 ks. Figure 4 shows the acoustic and magnetic fluxes (full and dashed curves respectively) as a function of field inclination when a 1 ks τ_R has been included in the equations. Comparison with the adiabatic results suggests that the primary effect of including Newton cooling is a reduction of flux magnitude – the smaller the damping time, the larger the flux reduction. Dispersion diagrams for damped wave propagation suggest that the effect of damping is largest in the photosphere and that the mode conversion pathways are preserved (Figure 5).

4. Conclusion

Gravity waves can couple to Alfvén waves and propagate up into the atmosphere when the magnetic field is very highly inclined. Preliminary results suggest that this coupling still occurs in the presence of radiative damping, though this is being explored further.

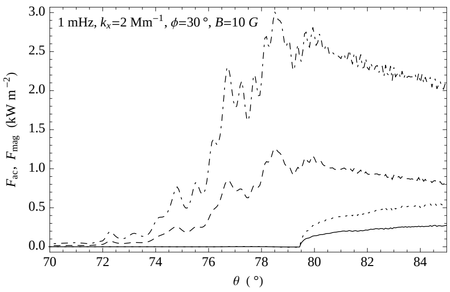

Figure 4. Magnetic and acoustic fluxes measured at the top of the model atmosphere. The dot-dashed and dashed curves represent the magnetic fluxes in the adiabatic and damped simulations respectively. The dotted and full curves are the acoustic fluxes in the adiabatic and damped simulations. The damped results shown were obtained using $\tau_R = 1$ ks.

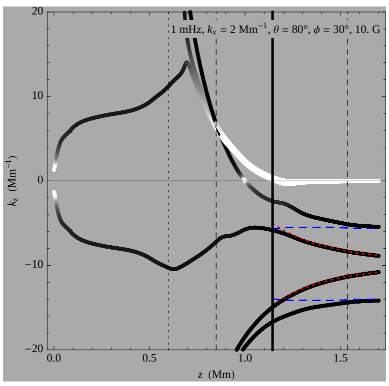

Figure 5. Dispersion diagram for the same scenario as in Figure 3, except with the gravity wave subject to weak radiative damping. The colour of the curves indicates the relative size of the imaginary part of k_z, with white sections showing where the wave is most heavily damped ($\mathrm{Im}\, k_z \geq \mathrm{Re}\, k_z$). The up-going gravity wave is most heavily damped in the photosphere. The damping does not alter the connectivity of the up-going wave to the Alfvén solution in the chromosphere.

References

[1] Straus T, Fleck B, Jefferies S M, Cauzzi G, McIntosh S W, Reardon K, Severino G, Steffen M, 2008 *ApJL* **681** L125

[2] Newington M E and Cally P S 2010 *MNRAS* **402** 386