On the Role of Acoustic-Gravity Waves in the Energetics of the Solar Atmosphere

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Abstract

We revisit the dynamics and energetics of the solar atmosphere, using a combination of high-quality observations and 3D numerical simulations of the overshoot region of compressible convection into the stable photosphere. We discuss the contribution of acoustic-gravity waves to the energy balance of the photosphere and low chromosphere. We demonstrate the presence of propagating internal gravity waves at low frequencies (< 5mHz). Surprisingly, these waves are found to be the dominant phenomenon in the quiet middle/upper photosphere and to transport a significant amount of mechanical energy into the atmosphere outweighing the contribution of high-frequency (> 5mHz) acoustic waves by more than an order of magnitude. We compare the properties of high-frequency waves in the simulations with results of recent high cadence, high resolution Doppler velocity measurements obtained with SOT/SP and SOT/NFI on Hinode. Our results seem to be in conflict with the simple picture of upward propagating sound waves. We discuss the implications of our findings on the energy flux estimate at high-frequencies.

Question

How important are non-magnetic waves in supplying the energy needed to sustain the radiative losses of the Sun's chromosphere (~ 4 kW m^{-2})?

Our Tools

Observations

Energy flux: $\rho \langle v_z^2 \rangle v_{gr.}$

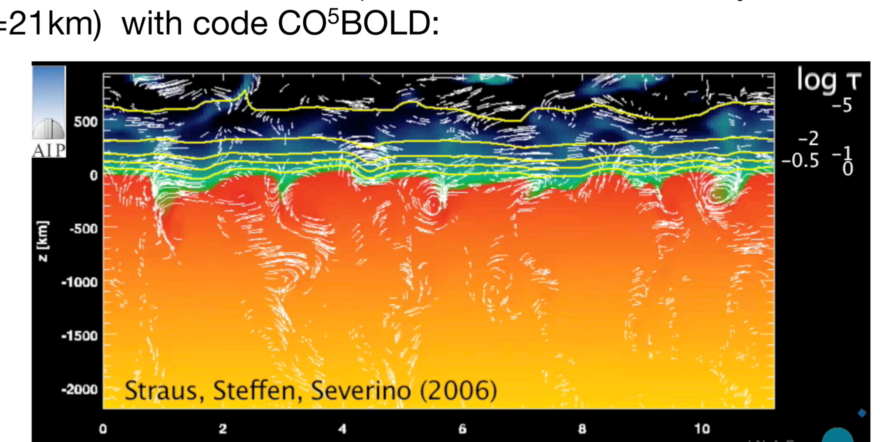
Source	DST Sac Peak			
Date	1983/08/31	1983/10/05	1988/10/06	2004/05/31
Lines	Fe 5930, Na D_1	Fe 8497, Ca 8498 & 8542	Fe 6302, Mg b_2, Ca 8542	Fe 7090
Cycle time	10 s	10 s	12 s	19 s
Duration	180 min	275 min	140 min	55 min
Spatial res.	0."611/pix	0."611/pix	0."347/pix	0."17/pix
slit length	420 pixel	420 pixel	400 pixel	**2D**

Source	SOHO/MDI		Hinode SP + FG		
Date	1997/03/06	2007/10/20	2007/08/13	2007/10/20	2008/03/19
Lines	Ni 6768	Ni 6768	Fe 6302 & 6301 FG: Fe 5576	FG: Mg b_2	Fe 6302 & 6301 FG: Mg b_2
Cycle time	60 s	60 s	16 s	40 s	16 s
Duration	15 hr	12 hr	237 min	12 hr	66 min
Spatial res.	0."61/pix	0."61/pix	0."16/pix	0."32/pix	0."32/pix
slit length	**2D**	**2D**	1024 pixel	**2D**	384 pixel

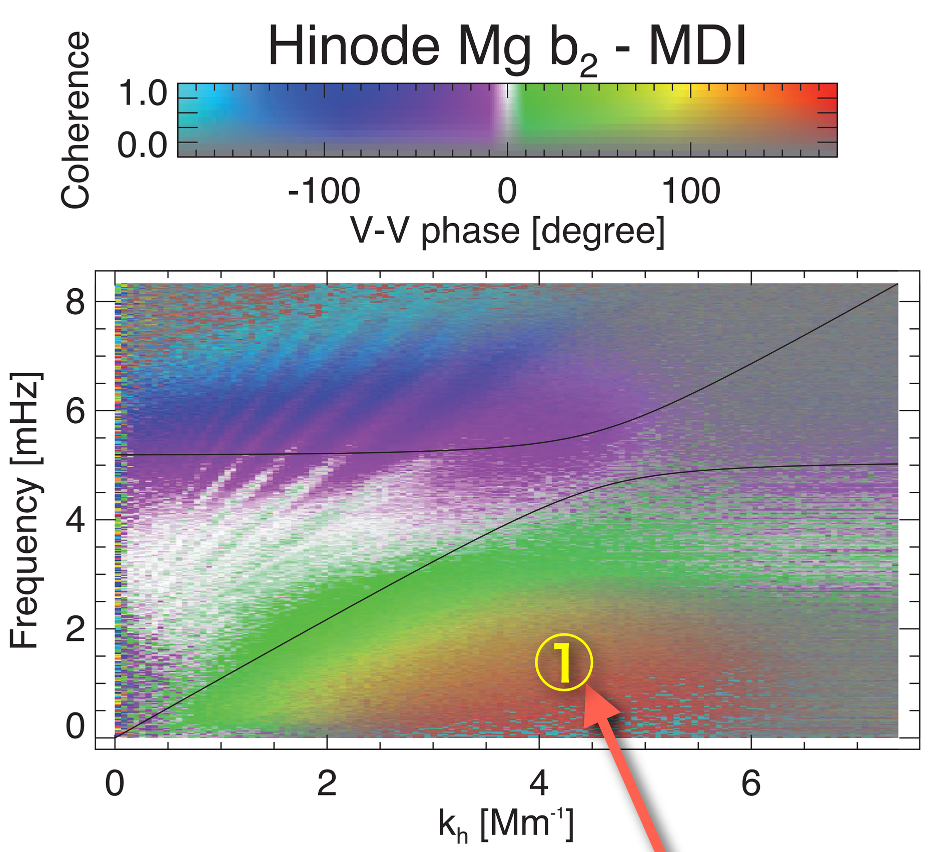
Simulations

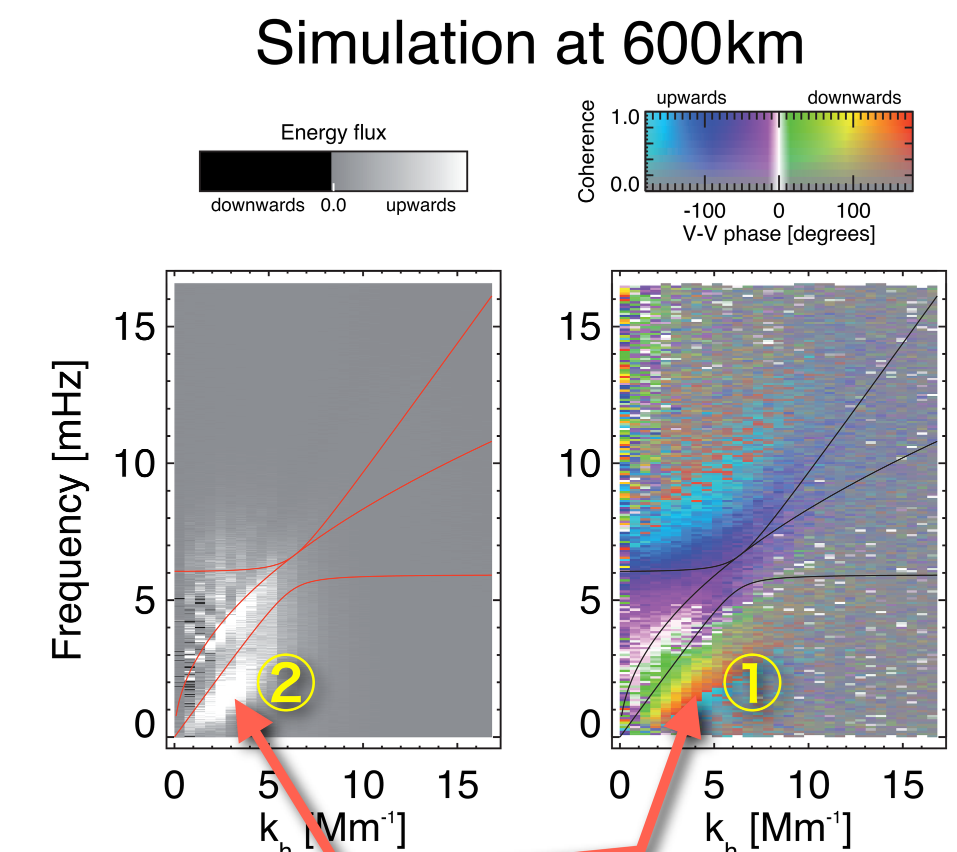
Energy flux: $\langle p \cdot v_z \rangle$

- 17 hours of a 3D time-dependent radiation-hydrodynamics simulation of a fully compressible, chemically homogeneous plasma in a constant gravity field on a fixed 3D Cartesian grid of 200×200×250 cells (11.2×11.2×5.2Mm, Δx=Δy=56km, Δz=21km) with code CO^{5}BOLD:



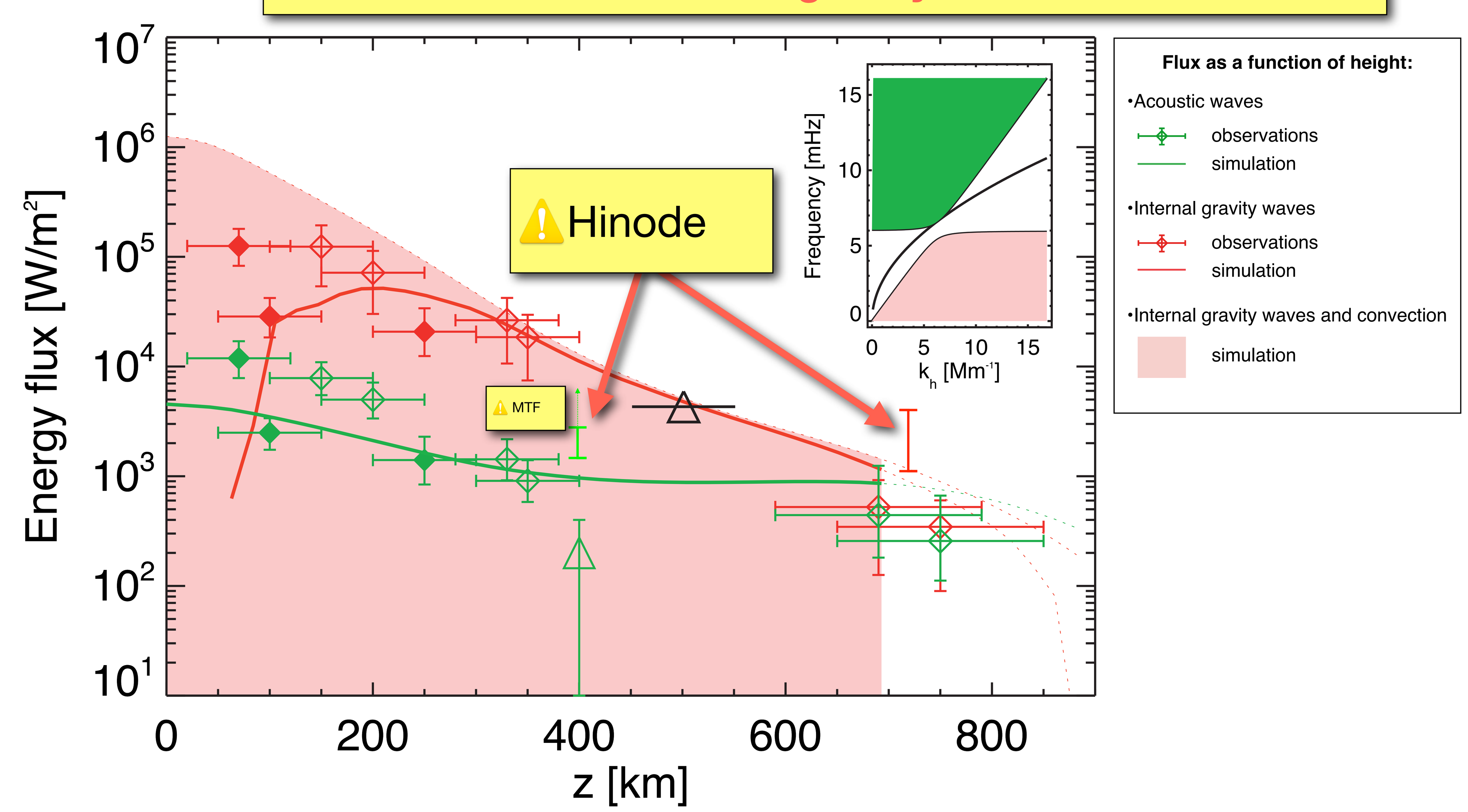
- Model of acoustic waves in a stratified atmosphere





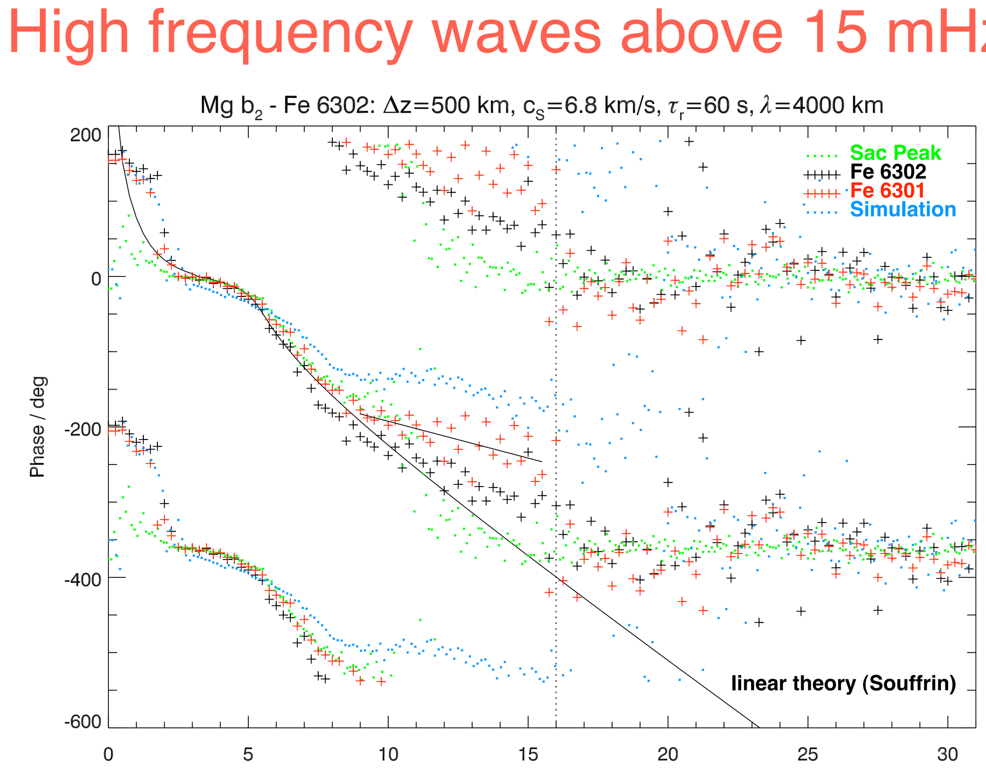
① Downward phase propagation + ② upward energy flux

⇒ **internal gravity waves**

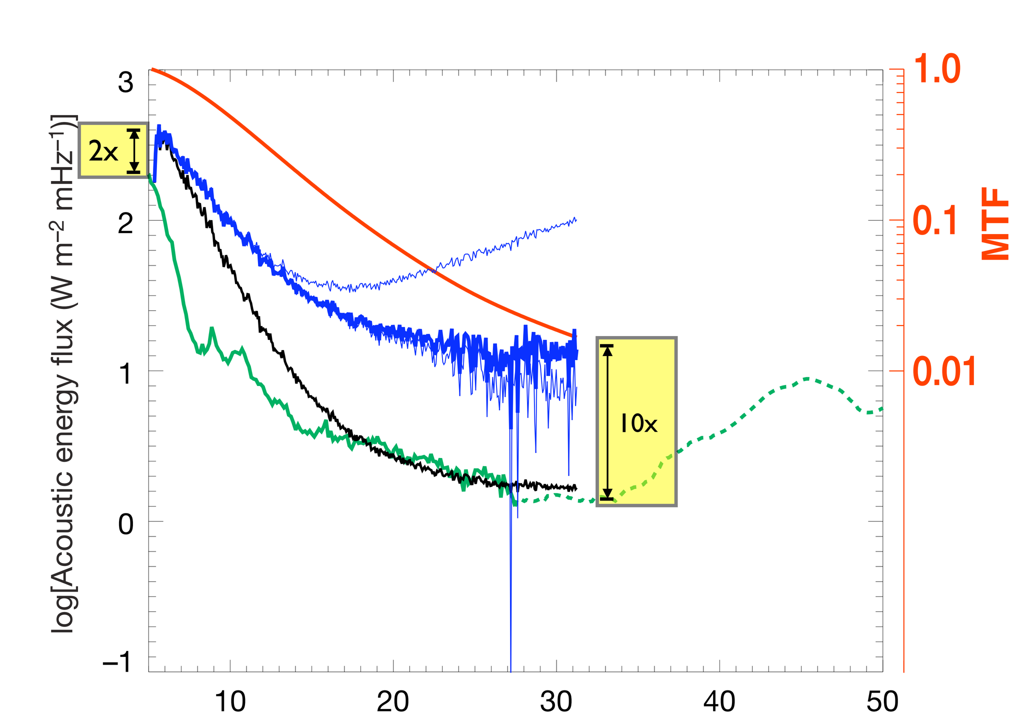


Hinode		≫	Fossum & Carlsson (TRACE)
5...31mHz	1600 W m^{-2}		5...50mHz < 438 W m^{-2}
10...31mHz	550 W m^{-2}		
>31mHz	13 W m^{-2} mHz^{-1}		

High frequency waves above 15 mHz?



Effects of the line transfer MTF



Results

- Internal gravity waves are the dominant energy transport mechanism in the quiet, middle to upper photosphere / lower chromosphere.
- Simulation suggests significant energy flux in f-mode.
- Energy flux of internal gravity waves is a factor 20 higher than acoustic flux (if not corrected for line transfer MTF effects).
- We model a spectrum of monochromatic waves in a stratified atmosphere with frequencies in the range 6-100 mHz and constant amplitude. With the synthesis of the Fe 6301 line profile the "observed" velocity power spectrum can be determined which gives the observed flux. The MTF is the ratio of the "observed" flux and the flux in the wave spectrum.
- The MTF of the Fe 6301 line (a typical photospheric line) falls off by 2 orders of magnitude in the range 5<v<30 mHz.
- Taking into account MTF effects could even lead to a turnaround of power spectra at high frequencies.
- Major difficulty: determination of noise level
- The expected linear increase of the phase delay at high frequencies is not observed above 16 mHz, neither in the observations nor in the simulation, suggesting a change of propagation behaviour (wave reflection effects?).
- The velocity signal derived from Hinode Mg b2 NFI filtergrams appears to originate from surprisingly high altitudes (~700 km).

Conclusions

It appears justified to reconsider the significance of the energy flux of **(non-M)**HD waves, for four reasons:

(1) In the past, the contribution of **internal-gravity waves** has been **underappreciated**. They turn out to carry enough energy to balance the radiative losses of the chromosphere.

(2) With Hinode data we find an **acoustic flux** 3-5 times larger than Fossum & Carlsson (2005). We believe that their estimate of the upper limit is **underestimated**.

(3) The effects of the line transfer **MTF** seem to have been **underestimated** in the past.

(4) The propagation behaviour of **high frequency acoustic waves** in the "real" solar atmosphere appears to be more **complicated** than commonly assumed.