Gravity Waves on the Planetary Atmospheres

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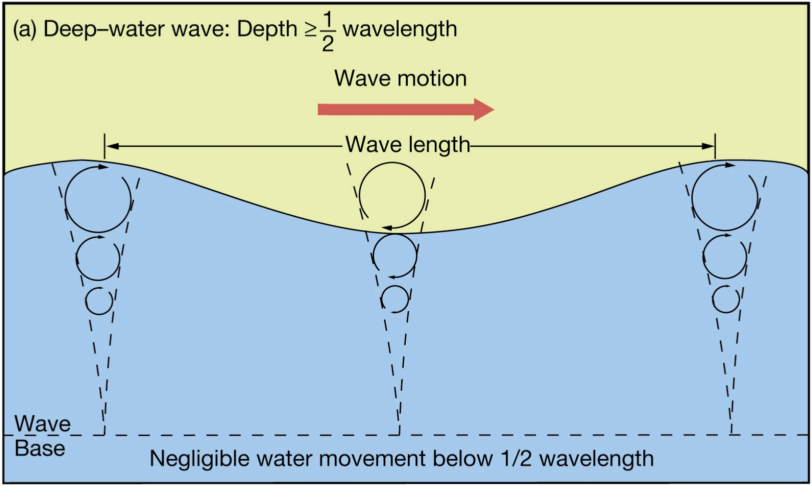
Contents

Examples of Water Waves

- Waves are ubiquitous in both the atmosphere and the ocean;
- The most familiar are sea waves:

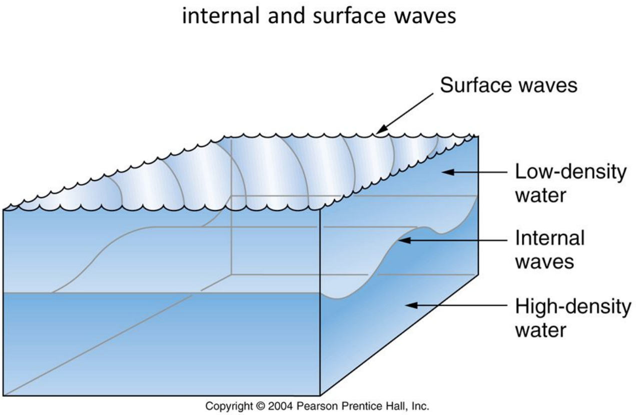
Sea Wave

Examples of Water Waves



Wave Characteristics

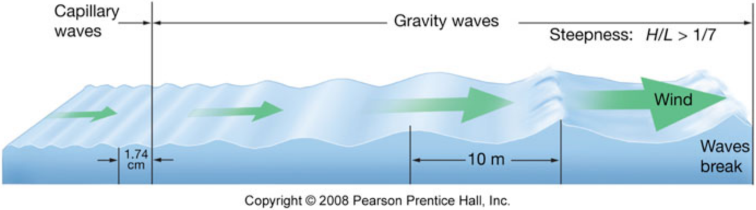
Surface and Internal Water Waves



- Internal Wave can propagate both vertically and horizontally.

Surface Water Waves

- Surface Wave:

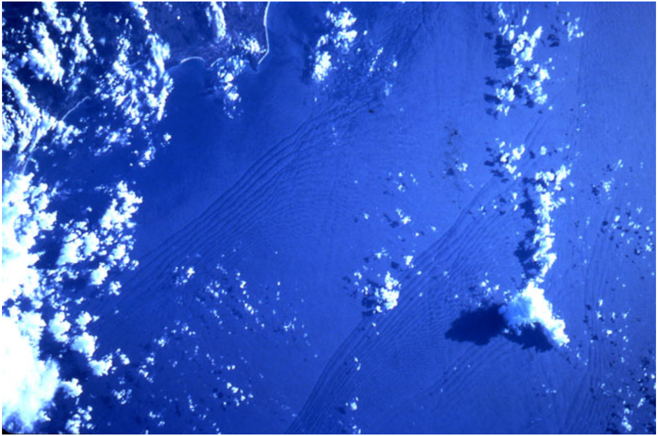


Wind-generated Waves

- Capillary Waves: capillarity acts as the restoring force, $[\lambda] \sim \mathrm{cm}$;
- Gravity Waves: gravity acts as the restoring force, $[\lambda] \sim \mathrm{m/km}$.

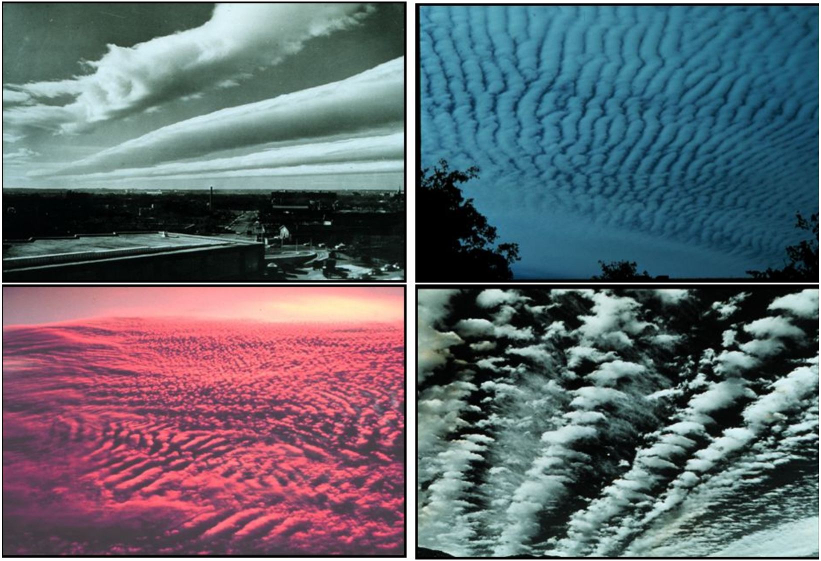
Internal Water Waves

- The motion of internal wave can be seen or tracked by satellite:



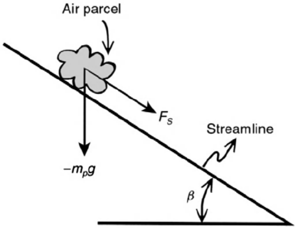
South China Sea Internal Waves as seen by NASA's Shuttle-1983.6

Examples of Atmospheric Waves

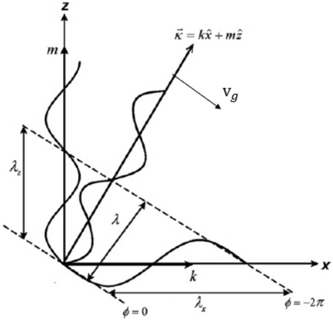


Atmospheric Waves on Earth

- Gravity waves: $[\mathrm{T}] \sim 10\mathrm{min}\&\mathrm{h}$, $[\lambda] \sim 10 - 10^2\mathrm{km}$;
- External gravity wave on Earth: $\mathrm{v} \sim 280\mathrm{m/s}(\mathrm{c_s} \sim 340\mathrm{m/s})$;
- Internal gravity wave on Earth: $\mathrm{v} \sim 22\mathrm{m/s}$;



Air parcel displaced

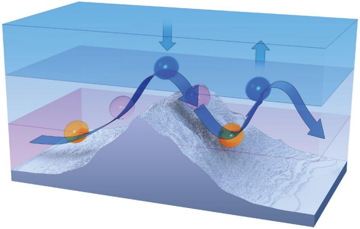


- $\frac{\mathrm{d}^2\delta \mathrm{s}}{\mathrm{dt}^2} + \mathrm{N}^2 \sin^2 \beta\delta\mathrm{s} = 0$;
- Brunt–Väisälä frequency:
  $\mathrm{N} = \sqrt{\frac{\mathrm{g}}{\theta}\frac{\partial\theta}{\partial \mathrm{z}}} \sim 10^{-2}\mathrm{s}^{-1}$.

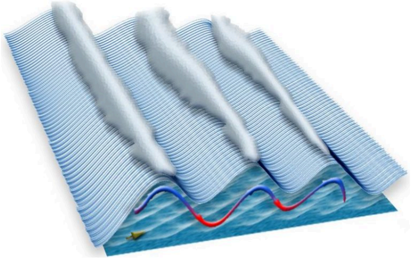
$$\frac{1}{\lambda^2} = \frac{1}{\lambda_x^2} + \frac{1}{\lambda_z^2}$$

Atmospheric Gravity Wave

- Sources: tsunamis, hurricanes, earthquakes, volcano eruptions:



A diagram to show the orographic generation of atmospheric gravity waves

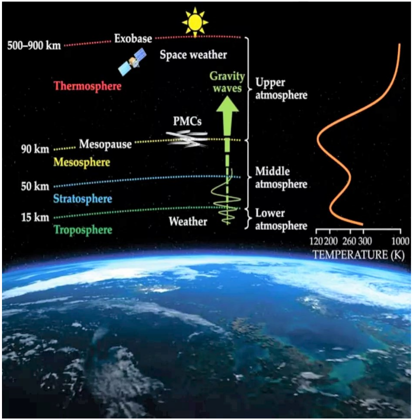


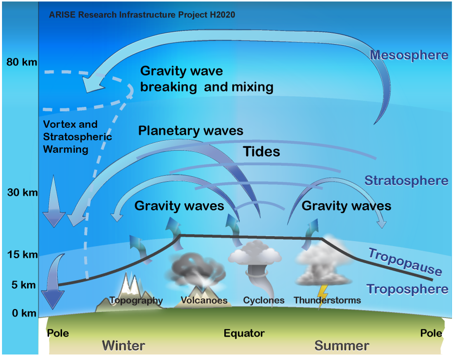
"Gravity Wave" cloud structure

- Main source: weather: convection, atmospheric fronts, cyclonic activity, and instability in wind systems.

Why Study Gravity Wave?

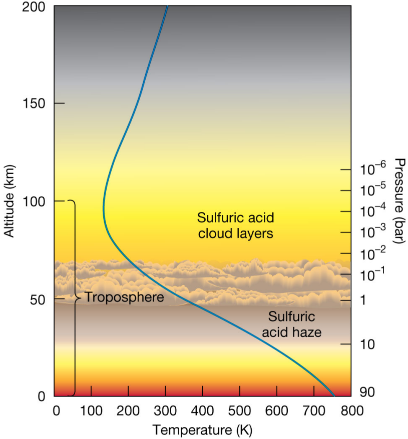
- Gravity wave carry both energy and momentum;



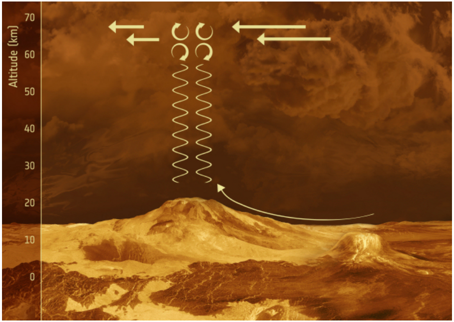


- It changes the motion of the middle/upper atmospheres.

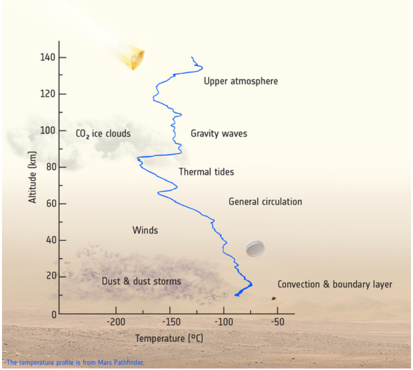
Gravity Waves on Venus



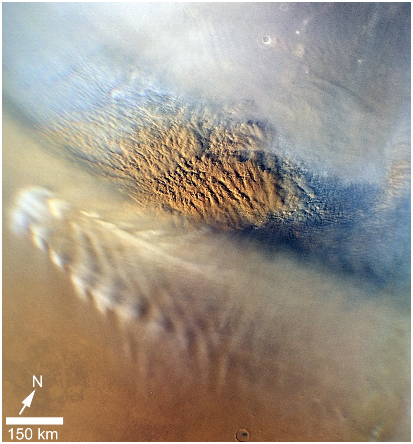
The temperature profile of Venus



Schematic illustration of gravity waves on Venus
Venus Express/18 July 2016

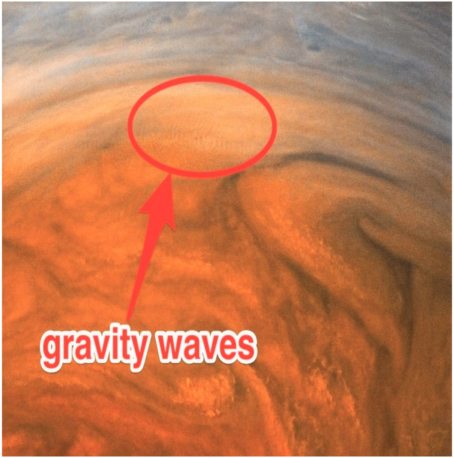


The temperature profile of Mars. Schiaparelli/11 October 2016

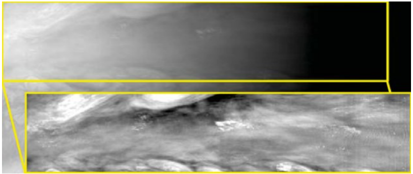


Gravity-wave signatures are imprinted in the water ice clouds around Mie Crater in the bottom right of the image.

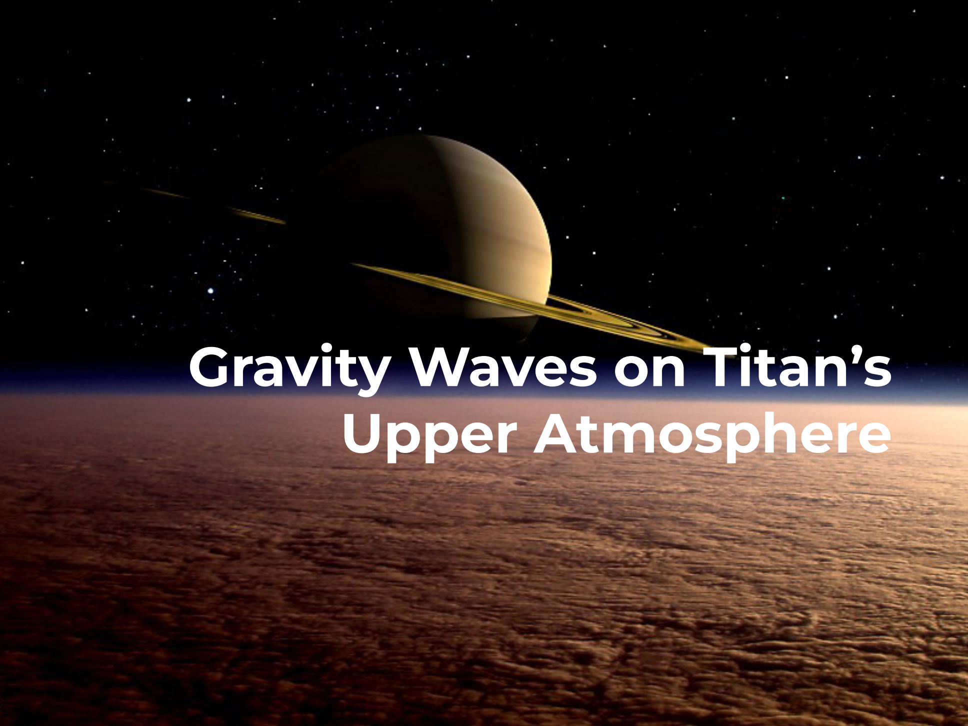
Gravity Waves on Jupiter



Winds climb up the outer wall of the Great Red Spot/Juno

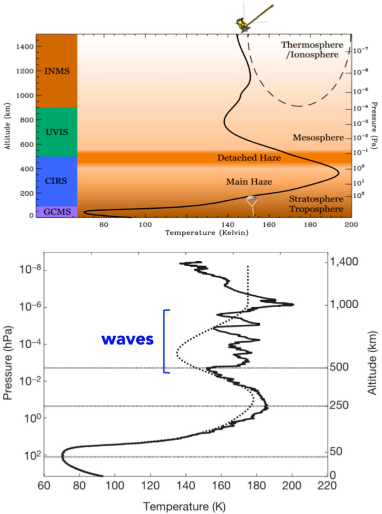


GRAVITY WAVES in Jupiter's equatorial atmosphere/New Horizons spacecraft


Gravity Waves on Titan’s
Upper Atmosphere

Saturn's Largest Moon: Titan

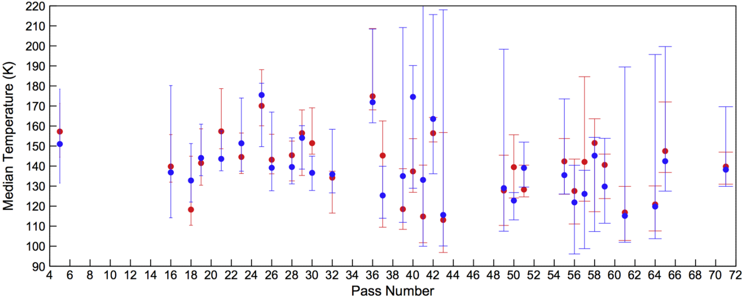
Entry, descent, and landing of Huygens (Jan. 14, 2005)



Fulchignoni et al. 2005

Temperature Variability

- Temperature variability over the range of 112-175K among 32 flybys;

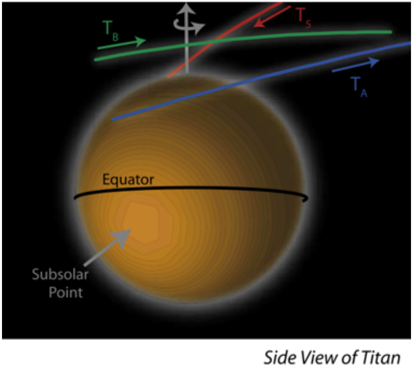


Snowden et al. 2013

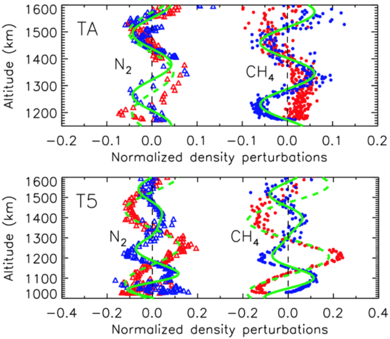
- Solar EUV radiation, charged particle precipitation, Joule Heating, HCN rotational line emission, wave dissipation.

Wave Disspation

- Flybys: TA(Oct.26,2004),T5(Apr.16,2005) ;



de La Haye et al. 2007



Müller-Wodarg et al. 2006

- Typical density perturbations of 10 % ;
- They are upward propagating gravity waves: $\lambda \sim 700\mathrm{km}$, $\mathrm{T} \sim 80\mathrm{min} - 10\mathrm{h}$(Cui, Lian, and Müller-Wodarg 2013).

Wave Model:

$$\nabla\cdot\vec{V}' - \frac{w'}{H_\rho}=0$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]u' = -\frac{1}{\rho_0}\frac{\partial p'}{\partial x}$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]v' = -\frac{1}{\rho_0}\frac{\partial p'}{\partial y}$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]w' = -\frac{1}{\rho_0}\frac{\partial p'}{\partial z}-\frac{\rho'}{\rho_0}g$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\frac{\nu}{Pr}\nabla^2\right]T' - \frac{1}{c_p\rho_0}\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}\right]p' = -\Gamma w'$$

$$\frac{p'}{p_0}=\frac{\rho'}{\rho_0}+\frac{T'}{T_0}$$

WKB solutions:

$$w' = \Delta W(z_0)\left(\frac{k_{zr}(z_0)}{k_{zr}(z)}\right)^{\frac{1}{2}} exp\left[i\left(k_x x + k_y y - \omega_0 t\right) + \int_{z_0}^{z}\left(ik_z + \frac{1}{2H_\rho}\right)dz\right]$$

$$u' = -\frac{ik_x}{k_h^2}\left(-ik_z+\frac{1}{2H_\rho}\right)w'$$

$$T' = -\frac{i}{\hat{\omega}+i\beta}\left[\Gamma + \frac{\widetilde{\omega}_0\hat{\omega}}{c_p k_h^2}\left(-ik_z+\frac{1}{2H_\rho}\right)\right]w'$$

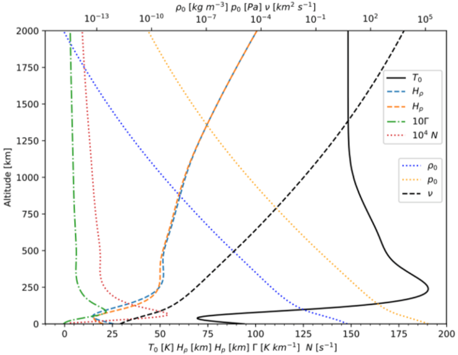
$$p' = -\frac{i\rho_0\hat{\omega}}{k_h^2}\left(-ik_z+\frac{1}{2H_\rho}\right)w'$$

$$\frac{\rho'}{\rho_0} = \mathrm{i}\left\{\frac{\Gamma}{T_0(\hat{\omega}+i\beta)} - \frac{\hat{\omega}}{k_h^2}\left[\frac{1}{RT_0} - \frac{\widetilde{\omega}_0}{T_0 c_p(\hat{\omega}+i\beta)}\right]\left(-ik_z+\frac{1}{2H_\rho}\right)\right\}w'$$

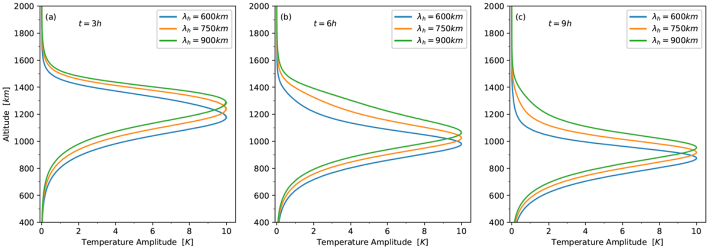
Dispersion relationship:

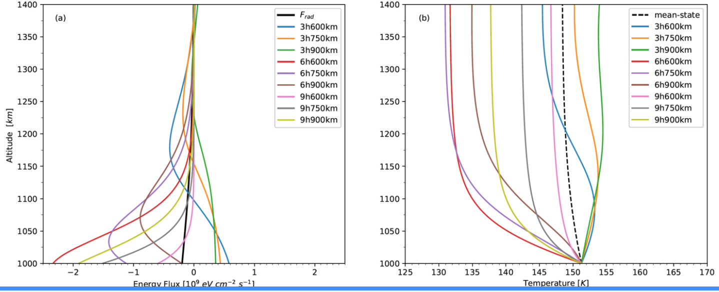
$$k_z^2 = \frac{k_h^2 N^2}{\hat{\omega}\left(\hat{\omega}+i\beta\right)} - \frac{1}{4H_\rho^2}\left(1-2\frac{dH_\rho}{dz}\right) - k_h^2$$

Profile of background parameters:

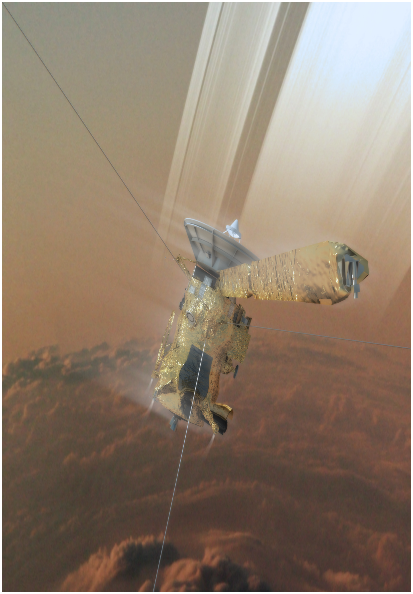


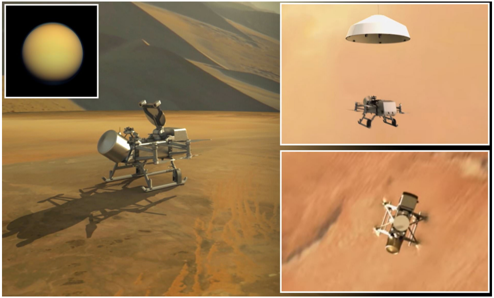
Wave Heating





Further Research





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Thanks!