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The Effect of Internal Gravity Waves on Cloud Evolution in Substellar Atmospheres

I. BACKGROUND

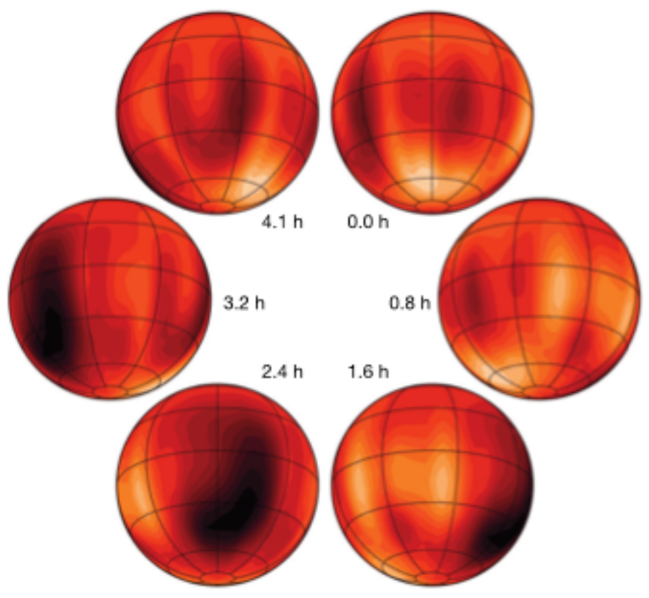

Fig. 1: The Surface map of the Luhman 16B. (Crossfield et al. 2014)

Substellar objects exhibit photometric variability, believed to be caused by processes such as magnetically-driven spots or inhomogeneous cloud coverage.

Recent models suggest that turbulent flows (Helling et al. 2001, *A&A 376, 194–212*) and atmospheric waves may play an important role in dust cloud evolution (Freytag et al. 2010, *A&A, 513, A19*).

- What is the effect of internal gravity waves on dust cloud evolution?
- Can observation of resulting cloud structures be used to recover atmosphere parameters?

II. FLUID MODEL

$$\frac{\partial \zeta}{\partial t} = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial x} \quad (1)$$

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho_0}{\partial y}\frac{\partial \psi}{\partial x} \quad (2)$$

$$\zeta = -\frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial y^2} \quad (3)$$

We use a linear vorticity ζ stream-function ψ fluid model.

-Waves driven from the domain's centre by an oscillating, gaussian perturbation of density ρ_A;

-Eqs. (1), (2) solved using leapfrog;

-Eq. (3) solved using Successive Over-Relaxation.

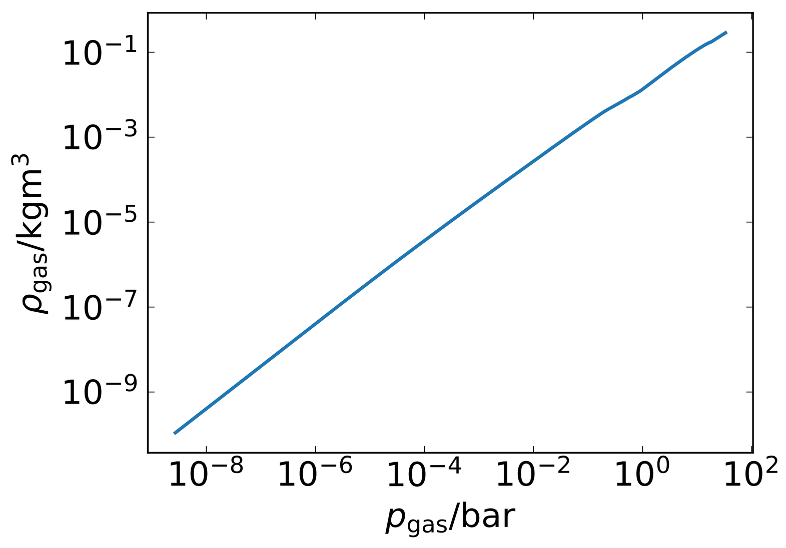

Fig. 2: Equilibrium atmospheric profile used for simulations. ($T_{\rm eff} = 1500{\rm K}, \log g = 5.0$) *brown dwarf data obtained from Drift-Phoenix atmosphere model (Hauschildt & Baron 1999; Helling et al. 2004; Helling & Woitke 2006; Witte et al. 2009, 2011) and additional data from Rodríguez-Barrera et al. (2018)*

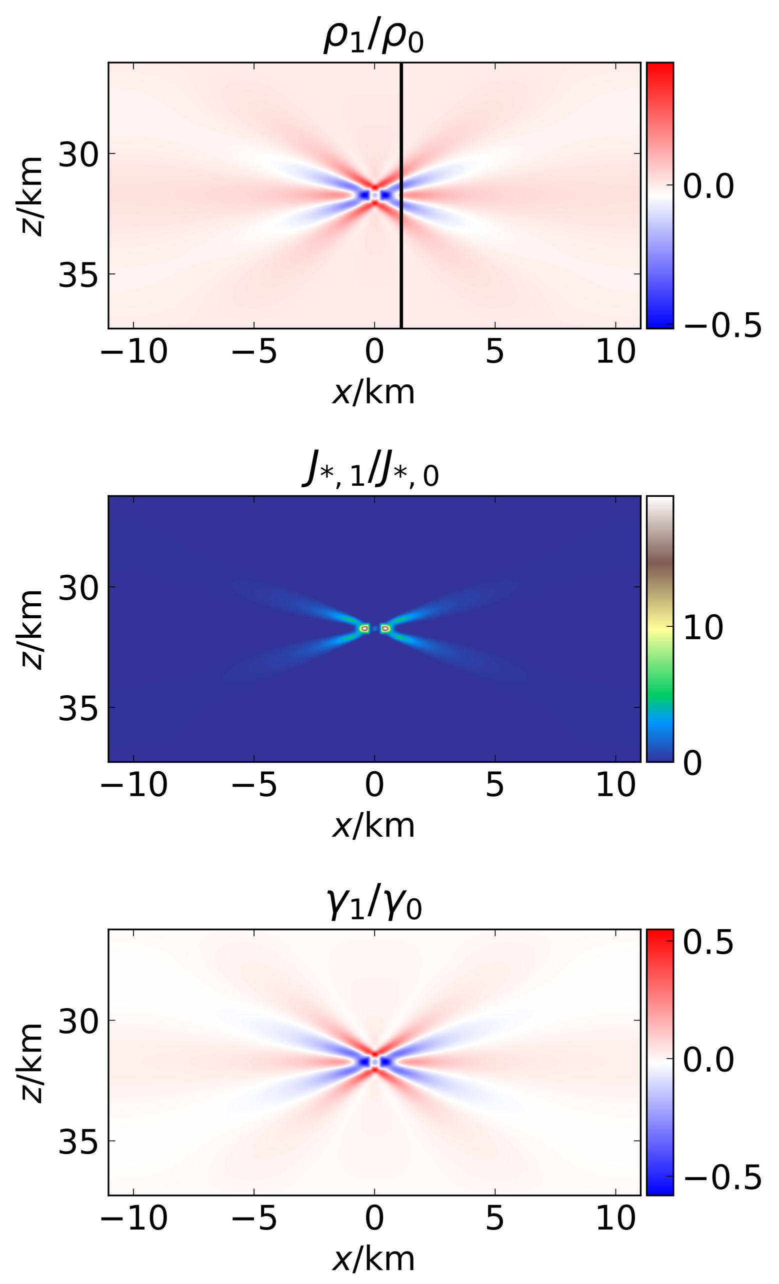

Fig. 3: vertical 2D maps of a wave's density (top), nucleation (middle) and mantle growth (bottom) perturbation. $\omega = 0.5\,N, \rho_A = 0.15\rho_0$

Core Findings

(1)
Internal Gravity Waves in brown dwarf model atmospheres propagate along an x-shaped pattern and create banded areas of perturbed density, pressure and temperature.

(2)
Lower temperatures raise the supersaturation ratio, causing a strong increase of the dust nucleation rate.

(3)
Higher densities and temperatures raise the thermal velocity of the gas, causing a weaker but non-negligible increase of the dust mantle growth rate.

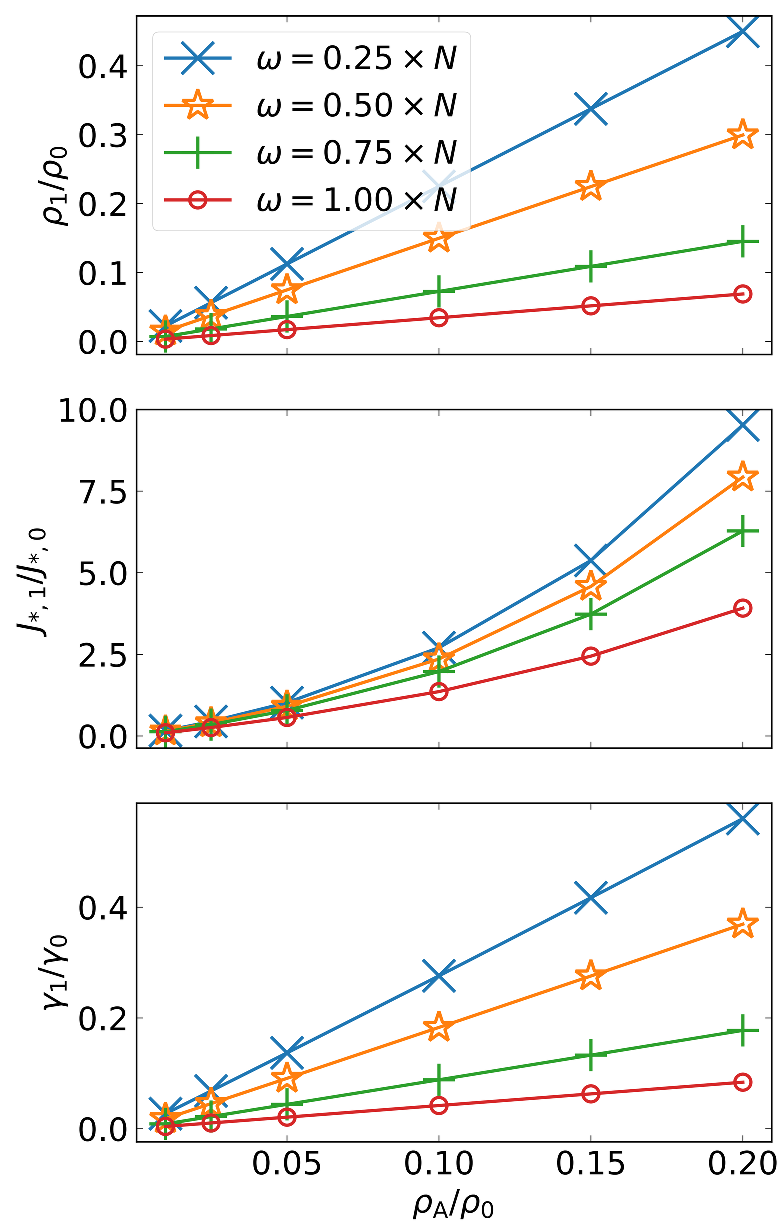

Fig. 4: plots of density (top), nucleation (middle) and mantle growth (bottom) responses to a range of perturbation frequencies and amplitudes

III. DUST MODEL

The nucleation rate J_* and mantle growth rate γ are derived from Gail et al. (1984, *A&A 133, 320*); Helling et al. (2001, *A&A 376, 194–212*); Stark et al. (2018, *A&A 611, A91*):

$$J_* = \frac{n_x}{\tau} Z \exp\left[(N_* - 1)\ln S - \left(\frac{T_\Theta}{T}\right)\frac{N_* - 1}{(N_* - 1)^{1/3}}\right]$$

$$\gamma = \frac{f_x \rho_{\rm gas} v_{{\rm rel},x}}{4\rho_{\rm dust}}$$

With:

- n_x the number density of the dust species,
- N_* the size of the critical cluster,
- τ the dust settling timescale,
- S the supersaturation ratio,
- $v_{{\rm rel},x}$ the thermal equilibrium velocity of the gas.

IV. FURTHER WORK: OBSERVATIONAL DIAGNOSTICS

We link the governing equations of internal gravity waves to observable characteristics through the waves' dispersion relation:

$$\omega^2 = -\frac{g}{\rho_0}\frac{\partial \rho_0}{\partial y}\cos^2\Theta$$

$$\rho_0 \propto f(\Delta y, \Delta m, g, \omega, J_*)$$

With Δm the difference in apparent magnitude between a wave's peaks and troughs, and Δy the wave's apparent spatial wavelength.

Next steps: establish the relationship and test it on observational data and simulation results for known bodies.

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