Gravity Wave Dynamics in Hot Extrasolar Planet Atmospheres

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1. Introduction

Stably-stratified atmospheres can support internal gravity waves, which arise from the buoyancy of the fluid. The waves are readily excited by heating and flow over topography and are a ubiquitous feature of the terrestrial atmosphere. They have been intensely studied over the past several decades. They transport momentum and heat within a fluid and the effects they have on the mean flow are routinely parameterized in GCMs of the Earth’s atmosphere.

There are over 400 known extrasolar planets. Their orbits and masses vary far more than for the planets in the Solar System, as shown in Fig. 1. Many planets are very close to their parent star: nearly 70% of extrasolar planets have orbits of four days or less, they are assumed to be spin-orbit synchronised. They are exposed to a very large energy flux. There is much interest in modelling the atmospheric circulations in these extreme conditions (e.g., Cho, 2008; Showman et al., 2009). We consider the effects gravity waves have on these planets by studying their behaviour in an atmosphere based on the hot-Jupiter planet HD 209458 b.

2. Gravity Waves

Internal gravity waves have large scale effects in the terrestrial atmosphere - for example, the Quasi-Biennial Oscillation (Baldwin et al., 2001). They have also been observed in many Solar Systems atmospheres beyond the Earth (e.g., Young et al., 1997). The atmospheres of extrasolar planets are expected to be stably stratified; as gravity waves are important for modelling their dynamics.

3. The Taylor-Goldstein Equation

The behaviour of a linear gravity wave is described by the Taylor-Goldstein equation which describes how the vertical velocity $w$ varies with altitude:

$$ \frac{\partial w}{\partial t} + [\pi^2/k^2 + (\gamma-1)/\gamma \pi^2/k^2] w = \frac{\partial}{\partial z} \left[ \frac{Q}{\gamma \rho \Omega^2 g} w \right] $$

Here $\gamma$ is the horizontal phase speed and $k$ is the horizontal wavenumber. The mean flow is $\bar{w}$, primes are definitions with $\gamma$, and $Q$ is the heating. In the square brackets is the index of refraction. The equation is solved numerically using Gaussian elimination with 3000 to 10000 equally spaced levels. As the equation is linear the wave can grow without bounds. To counter this a scheme is used to introduce saturation when the wave becomes convectively unstable.

4. HD 209458 b

The extrasolar planet HD 209458 b is a hot-Jupiter planet that orbits its star at just 0.04 AU with a period of 3.52 days. It is expected to be tidally locked to its star. It has a radius of 1.32 R$_J$.

5. Effect on the Background

As can be seen in Fig. 3 the wave propagates in a sheared environment. So, $c - u_0 = 0$ is possible in some layer known as a critical layer. A wave encountering a critical layer is shown in Fig. 4. The wave is attenuated by the encounter and the momentum it transports is deposited, causing the flow speed to change. In this case the acceleration, $\sim 250$ m s$^{-1}$ per rotation, is enough to double the flow speed at this layer in about 2 planetary rotations. In reality a spectrum of waves will encounter critical layers over a range of altitudes, causing accelerations over the range. Thus the critical layers filter out waves, preventing them from propagating to high altitudes.

6. Horizontal Transport

For shorter waves it is possible for $k^2$ to dominate the index of refraction, which becomes imaginary (indicating that the wave is evanescent). A wave is reflected at a layer where it becomes evanescent, as can be seen in Fig. 6; the vertical group velocity vanishes at around the 10 $H_p$ level, where $w_0 \propto z$. Where there are layers that support propagation between evanescent layers, the wave is ducted and energy is transported horizontally. The wave in Fig. 6 is an example of this. Waves are often ducted in jets and the energy is transported at roughly the speed of the jet.

7. Conclusions

The effect of gravity waves on the dynamics of extrasolar planet atmospheres is significant. However, their inclusion in general circulation models is computationally prohibitive due to the high resolution required. Accurate parameterizations of their effects need to be developed to mitigate this. Currently, such parameterisations for the Earth’s atmosphere are in the vertical only. But, as we have shown, horizontal transport is also important on tidally locked planets. Therefore, parameterizations for modelling the circulation of such planets need to include the horizontal as well as the vertical transport of momentum and heat.

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9. References