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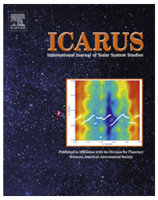

The compressional beta effect: A source of zonal winds in planets?

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ABSTRACT

Giant planets like Jupiter and Saturn feature strong zonal wind patterns on their surfaces. Although several different mechanisms that may drive these jets have been proposed over the last decades, the origin of the zonal winds is still unclear. Here, we explore the possibility that the interplay of planetary rotation with the compression and expansion of the convecting fluid can drive multiple deep zonal jets by a compressional Rhines-type mechanism, as originally proposed by Ingersoll and Pollard (Ingersoll, A.P., Pollard, D. [1982]. Icarus 52(1), 62–80). In a certain limit, this deep mechanism is shown to be mathematically analogous to the classical Rhines mechanism possibly operating at cloud level. Jets are predicted to occur on a compressional Rhines length $l_R = (2\Omega\langle H_\rho^{-1}\rangle v_{jet}^{-1})^{-1/2}$, where Ω is the angular velocity, $\langle H_\rho^{-1}\rangle$ is the mean inverse density scale height and v_{jet} is the typical jet velocity. Two-dimensional numerical simulations using the anelastic approximation reveal that this mechanism robustly generates jets of the predicted width, and that it typically dominates the dynamics in systems deeper than $O(l_R)$. Potential vorticity staircases are observed to form spontaneously and are typically accompanied by unstably stratified buoyancy staircases. The mechanism only operates at large rotation rates, exceeding those typically reached in three-dimensional simulations of deep convection in spherical shells. Applied to Jupiter and Saturn, the compressional Rhines scaling reasonably fits the available observations. Interestingly, even weak vertical density variations such as those in the Earth core can give rise to a large number of jets, leading to fundamentally different flow structures than predicted by the Boussinesq models typically used in this context.

1. Introduction

Strong zonal winds organize the colorful clouds on Jupiter's surface into banded structures. These cloud patterns have already been observed with telescopes more than 350 years ago (Rogers, 1995), and since then, scientists have studied them with ever more sophisticated observation tools. In addition to optical telescopes, the Hubble space telescope and the Pioneer, Voyager, Galileo and Cassini spacecraft missions have revealed fascinating pictures of the complex wind patterns shaping the surfaces of the gas and ice giants in our planetary system. Jupiter and Saturn exhibit strong prograde (i.e. eastward) equatorial jets, which are flanked by weaker, alternating westward and eastward winds on each hemisphere. Uranus and Neptune also exhibit pronounced zonal winds, but in contrast to Jupiter and Saturn, strong retrograde equatorial jets are observed.

It is still unknown how deep the winds extent into the interior. The Galileo probe that entered Jupiter's atmosphere down to 150 km in 1995 gave evidence for an increase of the wind speeds at larger depth (Atkinson et al., 1997), but provided little information about the deep interior. The Juno mission that will reach Jupiter in mid-2016 is expected to better constrain the radial extent of the jets by carrying out high-resolution measurements of Jupiter's gravity field (Kaspi et al., 2010).

The theoretical understanding of the zonal winds is still incomplete. The different theories proposed so far are commonly classified into two distinct groups. The first class of models suspects the key to the zonal winds in a shallow layer at cloud level, with energy being pumped into the jets by processes like moist convection, lateral variations in solar heating or other processes occurring close to the surface. In contrast, the second class of models views the zonal winds as an expression of processes occurring deep in the planetary interior, typically driven by convective instabilities. In the following, we will refer to these two classes as shallow- and deep-forcing models. They represent end-member cases of potential forcing scenarios, and it is possible that a combination of both, deep- and shallow-forcing, is needed in order to explain all observational data.

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It is instructive to reconsider the key processes driving zonal flows in the different approaches. The models following the shallow-forcing paradigm typically consider a fluid confined to a thin layer at the planetary surface, which leads to considerable simplifications of the governing equations. In the simplest cases, two-dimensional, incompressible flow is assumed, while more advanced approaches include shallow-water and multi-layer models. In all these cases, the latitudinal variation of the tangential component of the Coriolis force, the so-called *beta effect*, plays a key role, as it forces fluid parcels moved in latitudinal direction to change their vorticity. The effect becomes significant for large flow structures only, whereas the dynamics on small and intermediate scales is usually characterized by an inverse cascade of kinetic energy. This turbulent upward cascade ceases at the so-called Rhines length (Rhines, 1975) when the beta effect becomes felt by the flow. From this length scale on, the flow dynamics is dominated by Rossby waves, which leads to a strong anisotropy of the large scales and ultimately to the formation of jets. A large number of theoretical, experimental and numerical studies have confirmed the robustness of this now classical picture of zonal wind generation (see Vasavada and Showman (2005) for a review). While earlier works typically report retrograde equatorial jets, more recent simulations have also succeeded in producing prograde equatorial jets by including additional physical processes like energy dissipation by radiative relaxation or latent heating resulting from the condensation of water vapor (e.g. Cho and Polvani, 1996; Williams, 2003; Showman, 2004; Scott and Polvani, 2008; Lian and Showman, 2010).

In contrast to these shallow models, in the deep-forcing scenario, convection in a fluid confined to a deep spherical shell is considered. In case of the gas giants, the inner boundary is often assumed to be set by the transition from molecular to metallic hydrogen, where Lorentz forces become important and are thought to lead to different flow dynamics deeper within the planet. As in the shallow models, Rossby waves are believed to play a central role in driving deeply seated zonal jets as well. However, the processes of local vorticity generation that are responsible for the waves are governed by different physics. Mainly, two mechanisms have been identified as possible sources of Rossby waves in the deep interior – the so-called *topographic beta effect* and a process that we call the *compressional beta effect* in this paper. Both are reviewed in more detail below.

Apart from different wave mechanisms considered, theories on deep jet generation also differ in their mechanistic view on how these waves channel kinetic energy into zonal winds. Table 1 gives a schematic overview over several popular models, along with their underlying assumptions and key predictions. Even though this table only presents a somewhat simplified view and fails to include all aspects of the various theories, we feel that it is nevertheless useful in providing a compact overview of the similarities and differences between the various approaches. Note that these different views of the jet generation mechanics are complementary in many ways, and should not be seen as being necessarily contradicting. In the following, we give a brief review of the different models, which allows us to discuss the “Compressional beta effect” studied in this paper in a broader context.

The vast majority of studies performed so far are based on the *topographic beta effect* as the source of Rossby waves. Since the large scales in rapidly rotating flows are strongly affected by Coriolis forces, coherent columnar structures parallel to the rotation axis can be expected to exist in giant planets. Such fluid columns may extend through the entire planet touching the spherical boundaries. When moved perpendicular to the rotation axis, they undergo vertical stretching or compression due to the spherical geometry. This, through angular momentum conservation, results in a change of their vorticity, a process often called *topographic beta effect*. Since the newly generated vorticity is out of phase with the vorticity associated with the outward and inward movement of the fluid columns, azimuthally propagating Rossby waves can be generated.

As shown by Busse (1970), convection is most easily excited outside an imaginary cylinder parallel to the rotation axis enclosing the inner spherical shell, the so-called tangent cylinder. Due to the topographic beta effect, the flow takes the form of propagating

Table 1

List of popular mechanisms possibly driving zonal winds in giant planets in the deep-forcing scenario. The above mechanisms can be subdivided into two groups that consider different Rossby wave sources, i.e. the topographic- and the compressional beta effect. Within each group, different mechanistic pictures of the jet generation process exist, which are discussed in more detail in the text. Note that these mechanistic views may in many respects be complementary and do not necessarily oppose each other.

Rossby wave source	Mechanism (Reference)	Prediction	Mechanistic process
Topographic beta effect	Busse picture (review of Busse (2002) and references therein)	Jet direction (i.e. prograde equatorial jets)	• Topographic beta effect induces Rossby waves • Wave velocity depends on variation of system height • Outside the tangent cylinder the wave velocity is low near the inner boundary and increases towards the surface leading to a tilt of convective plumes • Tilt of convective plumes causes Reynolds stresses transporting prograde angular momentum to the planets surface at low latitudes. This process is reinforced by a mean flow instability
	Topographic Rhines picture (e.g. Heimpel and Aurnou, 2007)	Length scale of jets (i.e. number of jets)	• Inverse cascade of kinetic energy transports energy injected by a small scale convective forcing to larger scales • Inverse cascade ceases at topographic Rhines length • Rossby wave dynamics channels energy into alternating jets
Compressional beta effect	Evonuk/Glatzmaier picture (e.g. Glatzmaier et al., 2009)	Jet direction (depends on radial density profile)	• Compressional beta effect induces Rossby waves • Wave velocity depends on density scale height • For Jupiter/Saturn-like density profiles the wave velocity is low near the inner boundary (large density scale height) and increases towards the surface (small density scale height) leading to a prograde tilt of convective plumes • Tilt of convective plumes causes Reynolds stresses transporting prograde angular momentum to the planets surface at low latitudes. This process is reinforced by a mean flow instability • Uranus and Neptune are believed to feature radially increasing density scale heights close to the surface, which could explain their retrograde equatorial jets
	Compressional Rhines picture (e.g. Ingersoll and Pollard, 1982 and this paper)	Length scale of jets (i.e. number of jets)	• Inverse cascade of kinetic energy transports energy injected by a small scale convective forcing to larger scales • Inverse cascade ceases at compressional Rhines length • Rossby wave dynamics channels energy into alternating jets