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Atmospheric dynamics of tidally synchronized extrasolar planets

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Tidally synchronized planets present a new opportunity for enriching our understanding of atmospheric dynamics on planets. Subject to an unusual forcing arrangement (steady irradiation on the same side of the planet throughout its orbit), the dynamics on these planets may be unlike that on any of the Solar System planets. Characterizing the flow pattern and temperature distribution on the extrasolar planets is necessary for reliable interpretation of data currently being collected, as well as for guiding future observations. In this paper, several fundamental concepts from atmospheric dynamics, likely to be central for characterization, are discussed. Theoretical issues that need to be addressed in the near future are also highlighted.

Keywords: extrasolar planets; atmospheric dynamics; waves; turbulence; variability; magnetohydrodynamics

1. Background

Roughly a quarter of the nearly 300 extrasolar planets orbit very close to their host stars ($\lesssim$0.1 AU, where 1 AU is the distance the Earth is from the Sun). Owing to the likelihood of transiting their parent stars and the high temperatures on many of them, these ‘close-in’ planets are first to reveal information about their physical properties. Through them, we already have constraints on the size, composition, albedo and even the day–night temperature difference on some planets. However, to reliably interpret current and future observations and to obtain more detailed characterizations, knowledge of their atmospheric dynamics is crucial. Guided by theory, such observations of the atmospheres represent the first step towards eventually detecting signatures of life on worlds beyond our Solar System.

If the close-in planets possess very low eccentricities, they are likely to be tidally locked into a 1 : 1 spin–orbit resonance state (e.g. Goldreich & Soter 1966). These *synchronized* planets have the remarkable property that they are heated by their host star on only one side of the planet ‘in perpetuity’. This is due to the same process that forces us to always see the same face of the Moon. These new types of planets present an unprecedented opportunity to broaden—and deepen—our understanding of planetary atmospheres. In particular, the exotic

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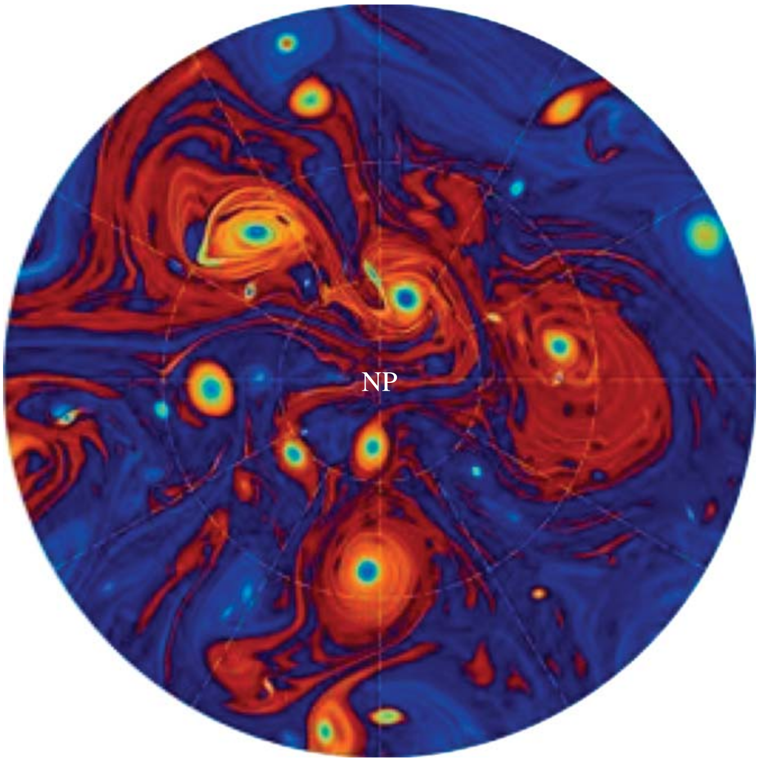

Figure 1. Potential vorticity (q) viewed from the Northern Hemisphere from a high-resolution simulation; q is a dynamically active tracer, which is materially conserved in the absence of source or dissipation. Small-scale vortices are undergoing successive mergers, expelling q filaments. Note the homogeneity of the turbulence, when jets are not present.

(and in some sense ideal) forcing configuration may produce circulation patterns and dynamics that are markedly different from those on the Solar System planets, none of which are 1 : 1 synchronized. The response of the atmosphere to the permanent day–night forcing and the atmosphere's role in the overall evolution of the planets (through the crucial boundary condition it represents for interior cooling) are just beginning to be studied systematically.

The motions of planetary atmospheres are governed by the *primitive equations*, so-called because they constitute the starting point for studying large-scale dynamics of the atmosphere (e.g. Holton 2004). By 'large scale' we mean here lengths much larger than approximately $a/10$, where a is the planetary radius. To use the primitive equations, the following physical conditions must be met: $(z/a) \ll 1$, $(N/\Omega)^2 \gg 1$ and $(\omega/N)^2 \ll 1$, where z is the vertical distance above some fiducial height (e.g. the 1 bar level or solid surface); N is the Brunt-Väisälä (buoyancy) frequency; Ω is the planetary rotation rate; and ω is the frequency (reciprocal of the time scale) of the atmospheric motion under consideration. These restrictions render vertical accelerations to be small and sound waves to be unimportant among other things. Otherwise, the equations admit the full range of motions. One of the major aims of using these equations is to study the distribution of temperature to help guide and interpret the observational data currently being collected on extrasolar planets.

Along with the close connection with observations, a good sense of 'what is robust' is much desired in theoretical work. The current state of extrasolar planetary atmospheric dynamics is very much only at the beginning stages (see Showman *et al.*

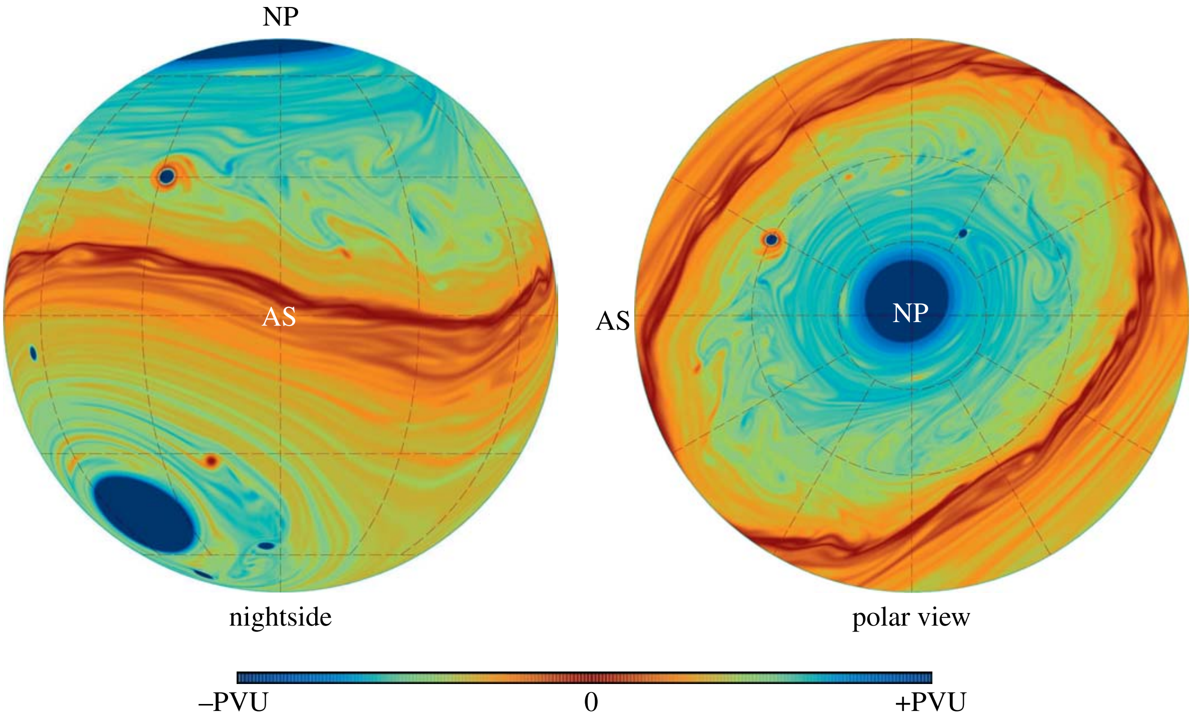

Figure 2. Maps of q viewed from (*a*) the antistellar side and (*b*) the Northern Hemisphere of a tidally synchronized giant planet (reproduced from Cho *et al.* (2003)). The flow is characterized by several broad bands, or jets (high latitudinal gradients of q), and robust off-the-pole vortices. Note the inhomogeneous turbulence, with efficient mixing—particularly at the periphery of the jets. Many small-scale vortices are present in the flow. (Note that the colour scale is different from that in figure 1.)

in press). With this in mind, this paper briefly summarizes dynamical concepts important for tidally synchronized planets, reviewing some recent works along the way (both published and not yet), and concludes with some important challenges for the future in this research area. New developments in geophysical–astrophysical fluid dynamics, relevant for synchronized planets, are emphasized.

2. Large-scale structures

(*a*) *A tale of two scales*

Work of many investigators over the past half century or so has now firmly established the importance of two fundamental length scales in atmospheric dynamics: the Rhines length $L_{\rm Rh}$ and the Rossby deformation radius $L_{\rm D}$ (e.g. Cho & Polvani 1996; Vasavada & Showman 2005 and references therein). Here, $L_{\rm Rh}=(U/\beta)^{1/2}$, where U is the characteristic flow speed and β is the latitudinal gradient of the Coriolis parameter f. Note that $f=2\Omega\sin\phi$, where ϕ is the latitude and $\beta=2\Omega\cos\phi/a$. Also, $L_{\rm D}=NH/f\lesssim(gH)^{1/2}/f$, where H is the characteristic thickness. Note also that both $L_{\rm Rh}$ and $L_{\rm D}$ vary over the planet, due to their dependence on ϕ.

Roughly speaking, $L_{\rm Rh}$ is the latitudinal spacing with which the zonal (east–west) jets form from initially isotropic turbulence by the rotation of the planet (Rhines 1975; Williams 1978). At small scales (early times), quasi-two-dimensional turbulent flows tend to be horizontally isotropic, as illustrated in figure 1. But, at length scales approaching L_{Rh} (later times), turbulent structures grow preferentially in the zonal direction. This leads to a flow exhibiting zonally elongated structures—i.e. jets and bands—at large scales.

As for L_{D}, in the present context, its significance is manifested at the small and large asymptotic régimes: $L_{\mathrm{D}}/a \to \infty$ and $L_{\mathrm{D}}/a \to 0$. When $L_{\mathrm{D}} \gg a$, the dynamics is effectively long range and flow structures can interact coherently over long distances over the planet. On the other hand, when $L_{\mathrm{D}} \ll a$, the interaction is muted. The weak interaction can lead to, among other effects, meandering jets—i.e. sideways undulations of a jet about a latitude line (see §3). Hence, one possible outcome of increased L_{D} for close-in planets, due to high temperatures (greater than or approx. 10^3 K) leading to large H, is increased straightening or sharpening of the jets that have formed by the 'Rhines effect' described above. Note that many synchronized giant planets have $L_{\mathrm{D}}/a \sim 1$ over a large area of their surfaces.

An example of the two scales at work for a synchronized planet is presented in figure 2. The simulation is initialized with small-scale turbulent (random) stirring and then allowed to evolve under an applied forcing representing an idealized day–night forcing. Both L_{Rh}/a and L_{D}/a are approximately 1 in this case. In such cases, the flows subsequently evolve to states containing revolving polar vortices, breaking Rossby waves, turbulent mixing and meandering jets of 'planetary scale' ($\gtrsim a$).

(*b*) *A question of forcing*

To date, there is no general theory for what sets the jet amplitudes in planetary atmospheres, for giant or terrestrial planets. In general, average amplitudes on giant planets exceed those on terrestrial planets in the Solar System. Presumably, this is related to the much deeper surface—or a lack of one altogether—in the giant planets, imposing much less drag on the flow. However, heating from the host star must be dominant in some general sense on a close-in, tidally synchronized planet. On the dayside, the irradiation on these planets can be several orders of magnitude greater than that of Solar System planets. However, convective and wave forcing must also be important, at least in some parts of the extrasolar planet atmospheres.

For synchronized planets, numerical simulations have been performed that are driven by a simple large-scale forcing, mostly with a prescribed diabatic heating. Typically, the 'Newtonian cooling' (Andrews *et al.* 1987) procedure is used in which the potential temperature θ (or ordinary temperature in some cases) is linearly 'dragged' to a specified equilibrium distribution: $\mathrm{D}\theta/\mathrm{D}t = -(\theta - \theta_{\mathrm{e}})/\tau_r$, where $\mathrm{D}/\mathrm{D}t$ is the material derivative; $\theta_{\mathrm{e}} = \mathcal{Z}(z)\Theta(\cos\lambda \cdot \cos\phi)$ is the equilibrium distribution, where λ is the longitude; and $\tau_r = \tau_r(z)$ is the characteristic e-folding cooling time. Such prescription of the forcing is an idealized representation of the permanent dayside 'heating' and nightside 'cooling' (Joshi *et al.* 1997; Showman *et al.* in press). Given the current lack of information on the actual equilibrium temperature and radiatively active species distributions, this is adequate.

It is worth bearing in mind, however, that the Newtonian cooling procedure applies to a situation in which the deviation of the temperature from the equilibrium is small (Andrews *et al.* 1987; Cho *et al.* 2008). Moreover, at the high temperatures expected on close-in planets, the net cooling is not expected to be a linear function of the temperature (Field 1965). Note that in addition to the nonlinear dependence on temperature, the actual cooling time can be highly variable in both space and time, and span an enormous range. Here, comparisons of simulations with currently observed light curves and spectra of hot Jupiters (e.g. Harrington *et al.* 2006; Knutsen *et al.* 2007) can provide some constraints on the dynamics modelling.

(*c*) *Inhomogeneous turbulence*

Generic dynamical processes that operate on Solar System planets, such as wave–mean flow interaction and dynamical instabilities, will also be important on synchronized planets (see §3). Many processes, such as baroclinic instability, require three dimensions. But, many others—such as the dynamics of polar vortex, Rossby wave breaking, critical layers and jet formation—are more fruitfully studied with two-dimensional and quasi-two-dimensional models (e.g. Juckes & McIntyre 1987; Polvani *et al.* 1995; Cho & Polvani 1996). This is because high resolution is required.

Similarly, two-dimensional 'one-layer' models have been used for tidally synchronized planets, to emphasize lateral dynamics at high resolution (Cho *et al.* 2003, 2008; Langton & Laughlin 2007). For example, simulations in figures 1 and 2 are one-layer calculations, which evolve 341 azimuthal and total modes each using a pseudospectral algorithm; 682 modes each have also been used in simulations of shorter durations. Such simulations are able to focus on lateral inhomogeneities and nonlinear coupling of large scales and small scales, which are at present extremely difficult to capture in three-dimensional models. In numerical simulation studies, spurious unphysical results due to numerical dissipation (or lack of resolution) and boundary conditions are often insidious and difficult to root out (e.g. Harnik & Lindzen 2001), and they remain a major concern: two-dimensional models can either alleviate or obviate some of the issues (e.g. Lindzen & Fox-Rabinovitz 1989; Cho *et al.* 2008).

In some three-dimensional simulations (e.g. Showman & Guillot 2002; Cooper & Showman 2005) extremely high-speed jets (several thousand $\mathrm{m\,s^{-1}}$) are obtained after simulation times of several hundred planetary rotations. Outside the jet, the flow field is smooth (e.g. compared with figure 2) and contains few large-scale vortices. By contrast, quasi-two-dimensional simulations with a steady day–night heating contrast *and* initialized with random stirring at small scales (Cho *et al.* 2003, 2008) lead to flows containing coherent polar and small-scale vortices, strong wave activity (particularly at jet flanks) and 'patchy' (inhomogeneous) turbulence (see figure 2). The resulting turbulent flow is highly variable in space and time, particularly if the mean flow is strong (greater than or approx. $400\,\mathrm{m\,s^{-1}}$) *or* efficiency of the layer in absorbing stellar irradiation is low (less than or approx. 4%). Figure 3 presents an example of the spatio-temporal variability in the thermal maps resulting from one of these simulations. Such feature may be detectable in observational signatures (e.g. Rauscher *et al.* 2007).

In summary, some features are common in three-dimensional and two-dimensional simulations. For example, few broad zonal jets and large vortices are seen in both. However, other features—such as Rossby waves interacting with the mean flow and leading to inhomogeneous turbulent states—appear to be observed in two-dimensional models only so far. No small-scale vortices are observed in three-dimensional flows using only Newtonian cooling to drive the flow, unlike the two-dimensional simulations initialized with stirring (see figure 2).

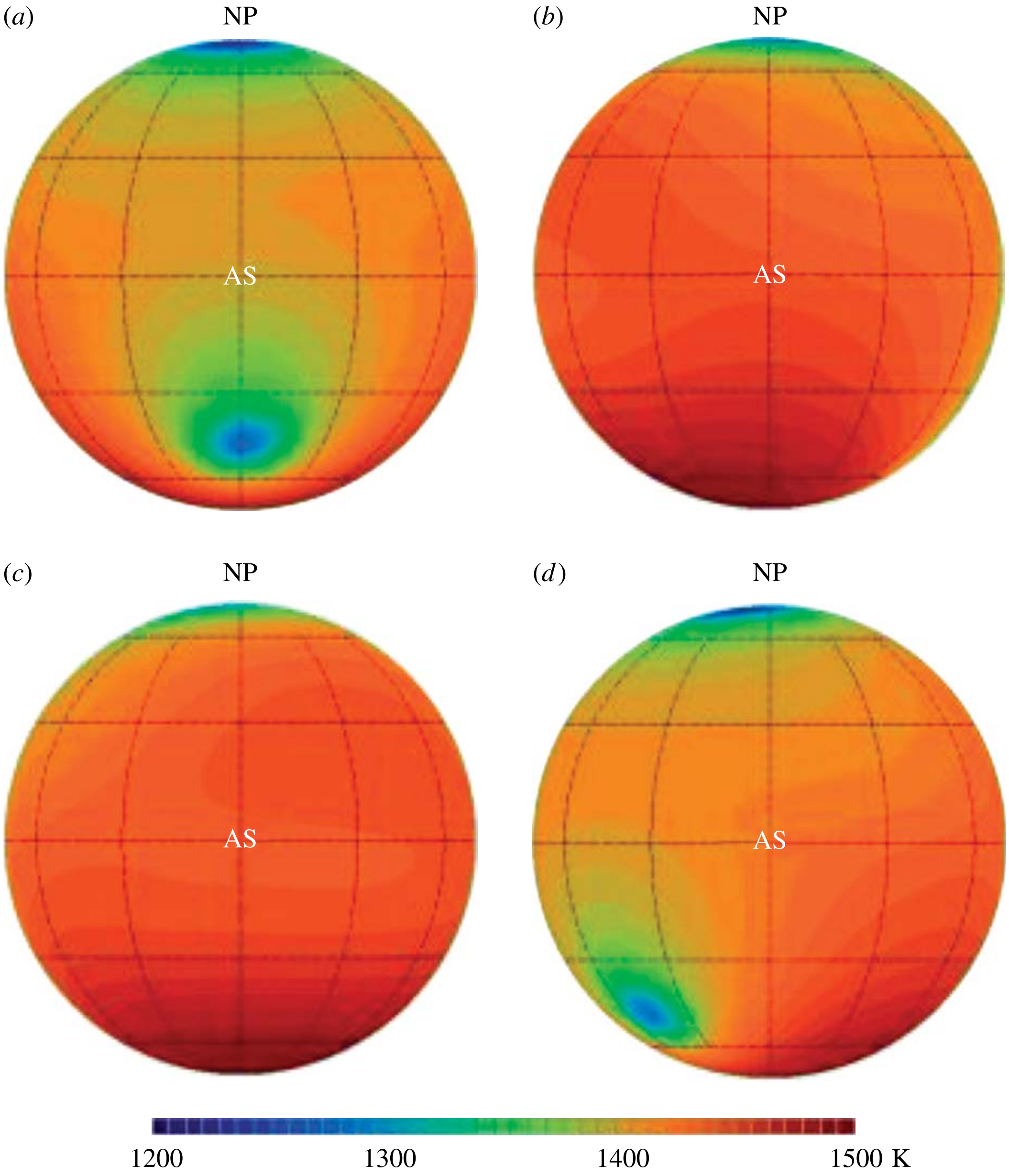

Figure 3. The nightside temperature T over 15 planetary rotations: (*a*) day 40, (*b*) day 45, (*c*) day 50 and (*d*) day 55. In this simulation, a 'thermal dipole', associated with the off-centred polar vortex (see figure 2), revolves around each pole, providing high thermal contrasts that may be detectable in observations (reproduced from Cho *et al.* (2003)). Note the high-amplitude breaking thermal waves/fronts (e.g. day 50), one mechanism that can redistribute and homogenize T.

3. Jets, waves and variability

It is remarkable that jets, straight or meandering, are so persistent and ubiquitous in planetary atmospheres. Jupiter's jets and Earth's jet stream provide well-known examples. The persistence points to the crucial role of Rossby (planetary) waves, and is also closely related to the principle of potential-vorticity (q) invertibility. Basically, q-mixing is favoured on one or both of the jet flanks, via the presence of critical layers (e.g. Bretherton 1966); but, mixing is inhibited in the jet core, where high q-gradients stiffen Rossby waves and gradients are maintained. Jets are thereby sharpened. In this scenario, one speaks of zonal q forming 'staircases' when plotted against latitude (e.g. Dritschel & McIntyre 2008). The corners (or jumps) correspond to the jet cores; and, in between the jumps (jets), q is well mixed.

As can be seen, there is an intimate relationship between jets and waves which is quite distinct from the classical picture of turbulence–wave conversion in the 'Rhines effect' sense discussed in §2. The new picture is robust and useful since jets obtained from inverting $q = q(\boldsymbol{v})$, where $\boldsymbol{v}$ is the flow, are accurate even in parameter regimes far outside those justified by formal asymptotics. For example, the inversion, $\boldsymbol{v} = \boldsymbol{v}(q)$, works even for Froude number, $Fr = U/(gH)^{1/2}$, near unity; Fr is the shallow layer analogue of the Mach number. The significance here is that $Fr \sim 1$ is a regime in parameter space appropriate for many tidally synchronized extrasolar planets. Hence, accelerated algorithms that make explicit use of the inversion can be used with great efficacy (e.g. Dritschel & Ambaum 1997).

The development of a quasi-steady super-rotating (eastward) equatorial jet appears to be a robust feature in some three-dimensional simulations (e.g. Showman & Guillot 2002; Cooper & Showman 2005). Similar behaviour has been observed in other three-dimensional model simulations, though with much weaker jet amplitudes (K. Menou *et al.* 2008, unpublished works; H. Thrastarson & J. Y.-K. Cho 2008, unpublished works). One mechanism for driving the equatorial jet must involve meridional flux of negative eddy momentum ('up-gradient eddy flux') powered by the applied day–night heating contrast. However, other mechanisms can also result in super-rotating equatorial jets (Cho *et al.* 2008 and references therein; R. K. Scott 2007, personal communication).

Waves (or eddies) constitute a major component of atmospheric general circulation, the large-scale atmospheric flow pattern on a planet. They are major transporters of momentum and heat. Waves/eddies would have to be involved in transporting heat between dayside and nightside, as well as between the tropics and the poles. Wave momentum flux acts to reduce baroclinic shears, and adjustment processes induce a simultaneous reduction of meridional temperature gradients. Similarly, wave momentum flux could also reduce zonal temperature gradients.

Rossby waves are not the only transporters of momentum and heat. Gravity waves also play a major role, particularly if the waves originate from deep down. For example, gravity waves deposit heat and cause the winter pole to be warmer than the summer pole in the Earth's mesosphere; equatorial waves also cause wind and temperature oscillations in the tropical stratosphere (e.g. Andrews *et al.* 1987; Lindzen 1990). Similar mechanism on tidally synchronized planets may cause major oscillations or significant reduction in the day–night temperature contrast, due to changes in environments in which the waves propagate.

4. Ionization

Tidally synchronized extrasolar planets experience extreme heating on the dayside. If the planets have migrated in from greater separation distances, they are subject to intense irradiation, even before reaching short enough distance to tidally interact with the host star (e.g. Koskinen *et al.* 2007). Hence, their atmospheres should be strongly ionized by the ultraviolet component of the stellar flux. The resulting ionized region probably penetrates deep into the atmospheric envelope, particularly for planets with weak intrinsic magnetic

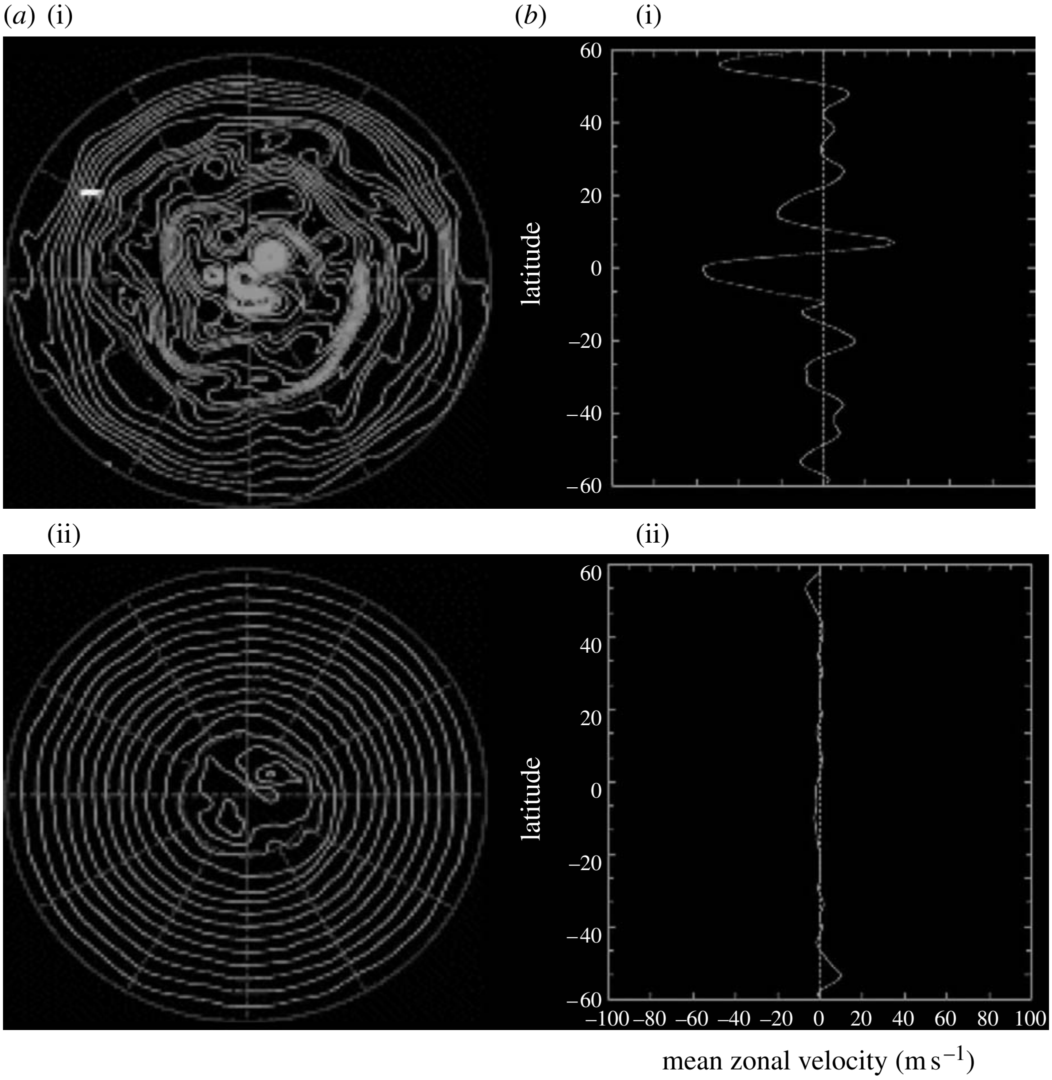

Figure 4. Maps of the q-field viewed from (a) the Northern Hemisphere ((i) $B=100$ G and (ii) $B=5500$ G), and (b(i)(ii)) their corresponding zonally averaged zonal winds as a function of the latitude from a high-resolution simulation of a magnetohydrodynamic atmosphere on a fast-rotating giant planet. The day–night heating contrast is turned off. The flow is characterized by numerous narrow jets when the magnetic field is weak (a(i),b(i)) as expected. However, when the magnetic field is not weak the zonality disappears (a(ii),b(ii)).

fields. Under these conditions, a magnetohydrodynamic (MHD) description is necessary to describe the atmosphere. More precisely, a differentially rotating, stably stratified, magnetized fluid on a sphere is needed (figures 4 and 5). Note that, in addition to the more complicated physics present, the MHD situation is exacerbated by the enormous range of space and time scales that challenges the unmagnetized studies (see §2).

Figure 4 illustrates one of the crucial differences in the resulting flow when strong magnetic fields are included (J. Y.-K. Cho & E. M. Staehling 2008, unpublished work). Owing to the differences in the quantities that are conserved, there is no inverse cascade of energy, as in the unmagnetized case. Then, the ‘Rhines effect’ is shunted and jets do not form. There will be no ‘mixing at the flanks’ and the flow field is isotropic, since jets and their associated critical layers are not present. A completely different dynamic is operative here, compared with an unmagnetized atmosphere.

Moreover, a series of numerical experiments (figure 5) show that when the magnetic field strength is weak (i.e. $\beta_\mathrm{p} \gg 1$, where β_p is the *plasma beta parameter*), the current field (curl of the magnetic field in the layer) is sheet like, acting as if 'frozen' into the MHD fluid. This is expected. However, as β_p decreases, the current sheets give way to coherent 'magnetic vortices', or current 'spikes', and the vorticity field (curl of the velocity) is dominated by the current field: it is as if the vorticity is frozen into the magnetic field.

5. Future challenges

Experience from Earth and other Solar System planet studies shows that a hierarchy of models is necessary to build a robust understanding of synchronized atmospheres (Cho *et al.* 2008; Showman *et al.* in press). Solar System planets can—and should—be used as validation, as well as a general guide. But, we must bear in mind the things not well understood for the Solar System planets and some of the glaring differences and the large variety, which make extrasolar planets so interesting to study. In this paper, we have reviewed several important concepts likely to play crucial roles in understanding extrasolar planet atmospheric dynamics, emphasizing some recent developments in turbulence and mixing.

It is not yet fully understood how heating/cooling mechanisms translate into the synchronized planet context. Often, the way the atmosphere responds to the various forcing and damping is a subtle affair. In the Solar System, Uranus and Venus starkly show us that the atmosphere can respond in a manner that is quite unexpected (and intriguing!): Uranus has zonal jets, even though it is heated at the pole, while Venus' cloud top is dominated by an equatorial jet and a polar vortex.

On synchronized planets, waves/eddies (and not just the mean flow) would likely be involved in transporting heat between dayside and nightside, as well as between the tropics and the poles. There is likely to be upwelling motion at the substellar point and downwelling motion away from this point and inside polar vortices. Wave momentum flux and adjustments could reduce shears and temperature gradients, and these mechanisms should be studied carefully.

Current simulations are in agreement about the small number of broad jets to be found on synchronized planets. However, it is not clear that the agreement stems from the same phenomenon. The situation may also change as planets are detected that orbit closer in than the current ones (with rotation periods of few days or more) and around different stars. The scales L_Rh and L_D (see Menou *et al.* 2003), as well as β_p parameter (J. Y.-K. Cho & E. M. Staehling 2008, unpublished work), are all affected. Improved numerical algorithms and models, with greater resolution and physical complexity, will be needed in these cases. Higher resolution will also be needed to resolve narrower jets that result from faster rotation rates expected for synchronized planets closer in than approximately 0.02 AU. MHD simulations will need to play a greater role as ionization becomes stronger, even at significant depths.

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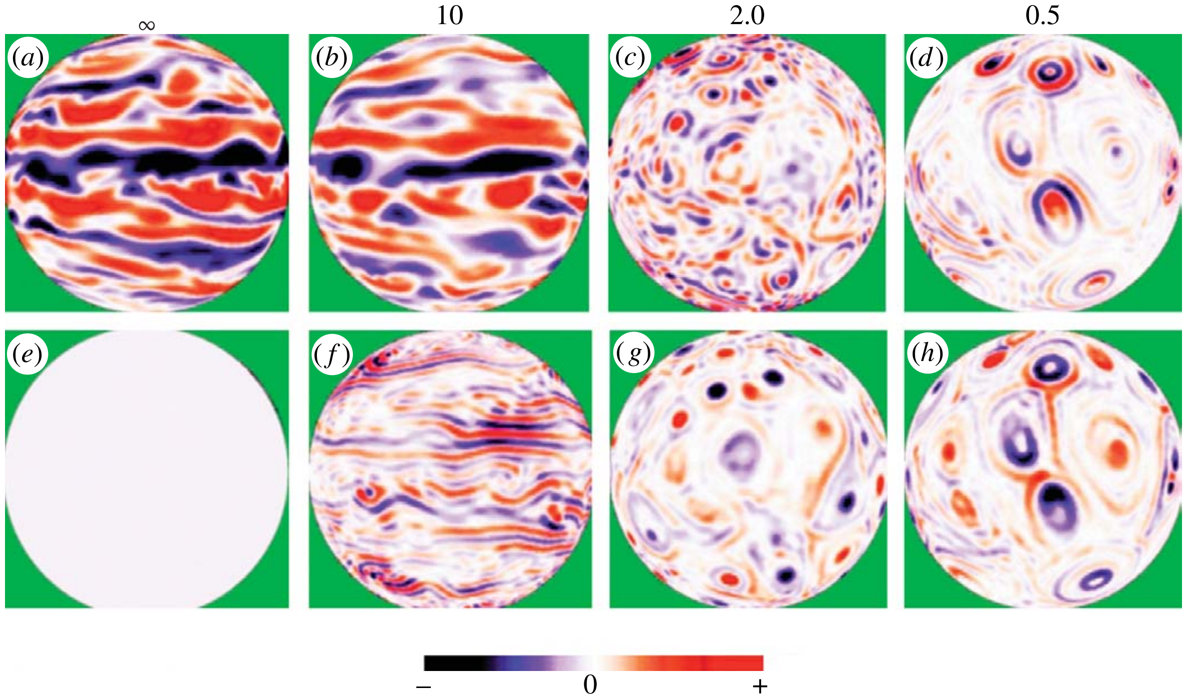

Figure 5. Maps of (*a*–*d*) *relative* vorticity and (*e*–*h*) current density at varying *plasma beta parameter* β_p (number above each column); β_p is the ratio of dynamic pressure to the magnetic pressure. Vorticity is the curl of velocity and current density is proportional to the curl of the magnetic field. When β_p is large, current ‘sheets’ track the flow (zonally elongated vortices). (*h*) However, as β_p decreases, the flow transitions to one in which current ‘spikes’ form and dominate.

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