ECHO's view on gas giant exoplanets atmospheres

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The diversity of targets EChO will observe

Most of EChO targets – and the ones for which the best observations will be available – orbit close enough to their host star such that tidal interaction should force them toward a tidally locked state (Lubow et al. 1997; Guillot & Showman 2002) where their rotation period becomes the same as their revolution period (see Fig. 1). Hundreds of close-in transiting planets with very different orbital period are already known and more will be discovered and confirmed before the launch of the mission. Although, for a given star, the irradiation is sole function of the distance to the star, the large diversity in exoplanets stellar hosts ensure a good coverage of the orbital period / irradiation temperature parameter space, the equilibrium temperature varying by a factor of 4 for planets with a given rotation period as can be seen in Fig. 2. Thus, the sample of planets EChO will observe cover a large area in equilibrium temperature/rotation period plane, the two main parameters shaping the atmospheric circulation.

A whole range of atmospheric constraints is obtainable for close-in, tidally locked planets because *we know which hemisphere is facing us at any orbital phase*, knowing perfectly the geometry of the system. Thus, monitoring permanently the star-planet system during its whole orbit, one can obtain longitudinal information on the planet brightness distribution (Knutson et al. 2008). During the ingress and egress of the secondary eclipse, the technique of eclipse mapping (Majeau et al. 2012; de Wit et al. 2012) constrains latitudinally the brightness distribution of the planet's dayside. Finally, the frequency dependance of the observed flux, as EChO will provide with an exquisite quality (Barstow et al. 2013), allow a determination of the vertical distribution of temperature. Using the combination of those techniques, EChO will provide a three dimensional vision of numerous close-in planets atmospheres, extending the study of climate to extrasolar planets.

Nowadays, a significant number of atmospheric measurements has been acquired on a dozen of exoplanets. None of those measurements were done with a dedicated instrument. Thus, they suffer from large error bars due to the instrument systematics, they are averaged over large bins of frequency, and measurements at different wavelength are usually made at different time, making the construction of a full spectrum a difficult task. EChO will observe hundreds of exoplanets atmospheres with a high spectral resolution and an exquisite photometric precision. EChO will get a full exoplanet spectrum in one observation and will be able to observe periodically a given target, thus we will be able to extract the planet intrinsic variability from the background noise. Hereafter we list several key scientific questions concerning gas giant atmospheres that EChO observations will allow to solve.

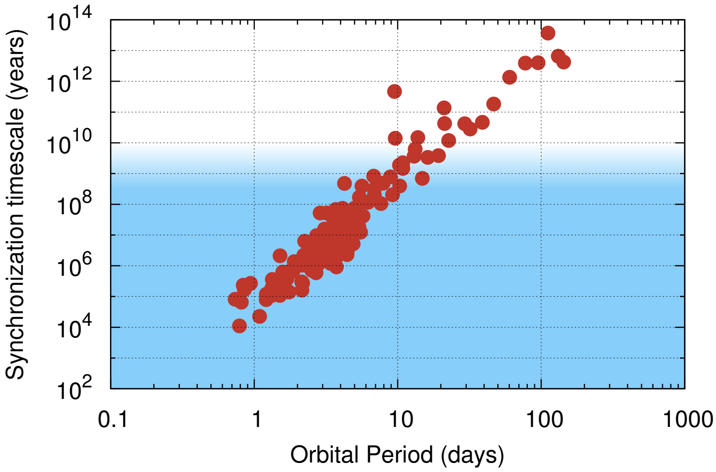

Fig. 1. Tidal synchronization timescale for all known exoplanets with a mass and radius measured in function of their orbital period for a dissipation factor $Q = 10^6$. Planets in the shaded area should be tidally locked.

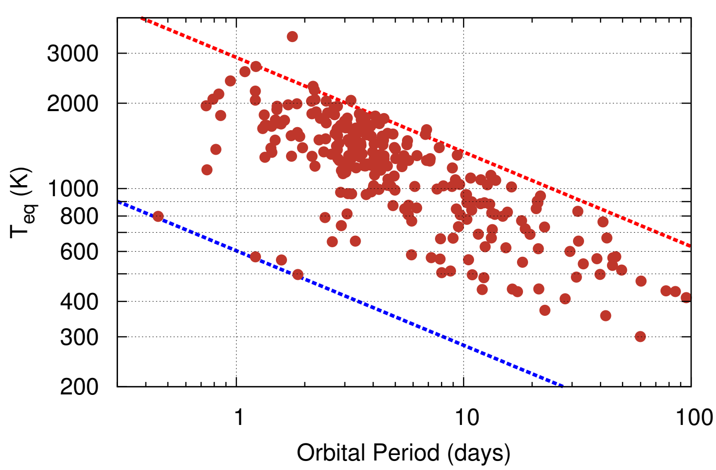

Fig. 2. Equilibrium temperature assuming zero albedo of all known exoplanets with a mass and radius measured. The blue (red) line is the equilibrium temperature for a planet around a M5 (A5) type star.

Key questions in atmospheric structure and dynamics to be addressed by EChO

1. How common are stratospheres, and what determines their distribution and properties? More generally, what is the vertical temperature profile on the dayside, nightside, and terminator?

Existing Spitzer secondary-eclipse photometry and spectra of hot Jupiters typically suggest the existence of atmospheric absorption bands due to water, CO, and CH_4, among other species in the dayside of hot Jupiters (e.g., Charbonneau et al. 2008; Grillmair et al. 2008; Swain et al. 2008). Hot Jupiters with such behavior exhibit a temperature profile that decreases with altitude in the pressure region characteristic of IR photospheres (~0.01–1 bar). Nevertheless, a variety of hot Jupiters seem to exhibit dayside *emission* features which indicate a temperature that *increases* with altitude—i.e., a stratosphere (e.g. Knutson et al. 2008; Burrows et al. 2008). Theoretical calculations show that stratospheres are naturally produced when the atmosphere efficiently absorbs incident stellar light such that the visible opacity exceeds the infrared opacity (e.g., Thomas & Stamnes 2002; Pierrehumbert 2010; Guillot 2010). In the case of Earth, absorption of stellar ultraviolet by O_3 plays this role. For hot Jupiters, the necessary absorber is unknown. It was originally suggested that TiO could cause the necessary absorption Hubeny et al. (2003); Fortney et al. (2006, 2008). This hypothesis lead to a prediction that atmospheres sufficiently hot to prevent condensation of TiO would exhibit stratospheres, whereas cooler planets—for which TiO would condense in the deep atmosphere—would not (Fortney et al. 2008). Subsequently, however, several challenges to the prediction have emerged. A number of cooler planets with stratospheres and warmer planets without stratospheres have been discovered, in contradiction to the expectations of this mechanism (Knutson et al. 2010; Madhusudhan 2012). Moreover, recent HST STIS observations of several hot planets exhibit an apparent lack of TiO, at least at the terminator (Huitson et al. 2013; Sing et al. 2013). It is possible the absorber results from some photochemically produced species (e.g., Zahnle et al. 2009), but it has yet to be identified.

Because EChO will retrieve the temperature/pressure profile of close-in planets with accuracy (Barstow et al. 2013, and the *spectral* retrieval technical note) EChO will perform a broad census of which hot Jupiters exhibit stratospheres and which do not, and will determine the extent to which the presence of stratospheres correlate with incident stellar flux, stellar activity, atmospheric composition, and other parameters. Because EChO will obtain full IR spectra from which absorption/emission features can be well identified, the determination of whether a planet exhibits a stratosphere—and the pressure range of any stratosphere—will be much more robust than possible with existing Spitzer and groundbased data. Moreover, spectral features seen in transit and secondary eclipse will provide strong constraints on the specific chemical absorber that allows for the existence of stratospheres.

2. What is the longitudinal structure of the temperature in hot Jupiter atmospheres, and how does it depend on depth?

High-quality lightcurves—as obtainable from EChO for a wide range of hot Jupiters—will allow longitudinal maps of brightness temperature to be derived. This will allow the longitudinal locations of hot and cold spots, among other features, to be identified; observations at many wavelengths will allow the depth-dependence to be determined in the range ~0.001–10 bar. Spitzer observations of several hot Jupiters, including HD 189733b (Knutson et al. 2007, 2009, 2012) and Ups And b (Crossfield et al. 2010) indicate that the hottest regions are displaced eastward of the substellar point by tens of degrees of longitude or more (see Figs. 3 and 4). This phenomenon was predicted and has now been reproduced in a wide range of three-dimensional circulation models under conditions appropriate to benchmark hot Jupiters such as HD 189733b and HD 209458b (Showman & Guillot 2002; Cooper & Showman 2005; Showman et al. 2008, 2009; Menou & Rauscher 2009; Dobbs-Dixon & Lin 2008; Dobbs-Dixon et al. 2010; Rauscher & Menou 2010, 2012a; Heng et al. 2011a,b; Perna et al. 2012). In these models, the eastward displacement results from advection by an eastward "superrotating" jet stream at the equator. Theory shows that, on tidally locked planets, such superrotation is the natural result of the day-night heating pattern, which leads to planetary-scale waves that pump angular momentum to low latitudes (Showman & Polvani 2011). Nevertheless, current predictions—yet to be tested—suggest that the longitudinal offset of the hotspot should scale inversely with incident stellar flux (Showman & Polvani 2011; Perna et al. 2012; Showman et al. 2013). The extent to which such longitudinal offsets are prevalent on hot Jupiters—and their dependence on incident stellar flux, planetary rotation rate, atmospheric composition, and other factors—remains unknown. EChO can address this question with a broad census and map the depth dependence of these features.

3. What sets the day-night temperature contrast? How does it vary with depth (wavelength) and among different planets? What is the mechanism that controls the day-night temperature contrast on tidally locked planets?

Current lightcurve observations have allowed the day-night brightness temperature contrast to be determined for over a dozen hot Jupiters. These observations suggest a trend wherein cooler planets exhibit modest fractional day-night temperature contrasts whereas hotter planets exhibit near-unity fractional day-night temperature variations (Cowan & Agol 2011; Perna et al. 2012; Perez-Becker & Showman 2013). The details of this trend place strong contraints on the mechanisms that maintain the day-night temperature differences on hot Jupiters (e.g., on the relative roles of dynamical timescales associated with horizontal advection, vertical advection, and wave propagation), the extent to which frictional and ohmic drag becomes important for the hottest planets (Rauscher & Menou 2012b, 2013), and other aspects of the circulation. Current observations exist at only a few broadband wavelengths, and full spectral information as obtainable from EChO would provide significant information on how the transition from small to large fractional day-night flux difference depends on wavelength, and in turn how this transition depends on depth in the atmosphere.

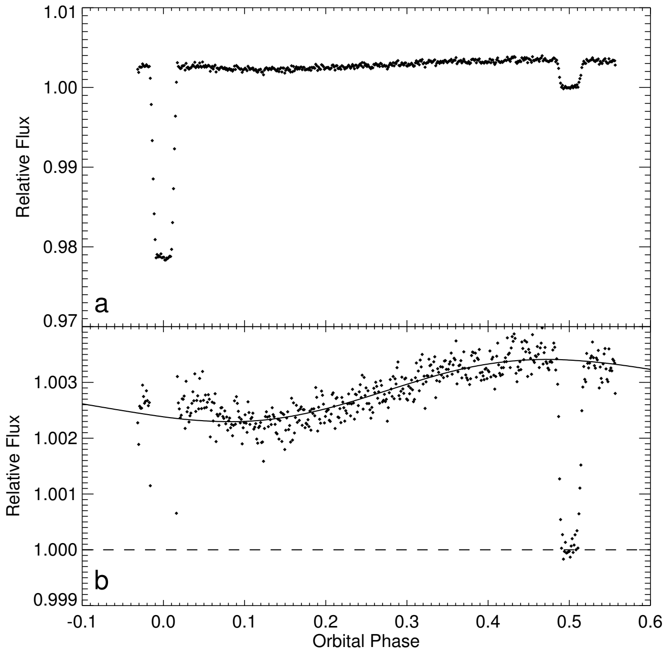

Fig. 3. Thermal phase curve of HD189733 observed by the IRAC instrument on the Spitzer Space Telescope at 8 microns by Knutson et al. (2007). In the top panel, the transit (orbital phase 0) and secondary eclipse of the planet orbital phase 0.5) are visible. In the bottom panel, the increase of flux between the transit and the secondary eclipse is due to the planet phase: before and after the transit the planet shows its cold and thus dark nightside whereas before and after the secondary eclipse is shows its warm, and thus luminous, dayside.

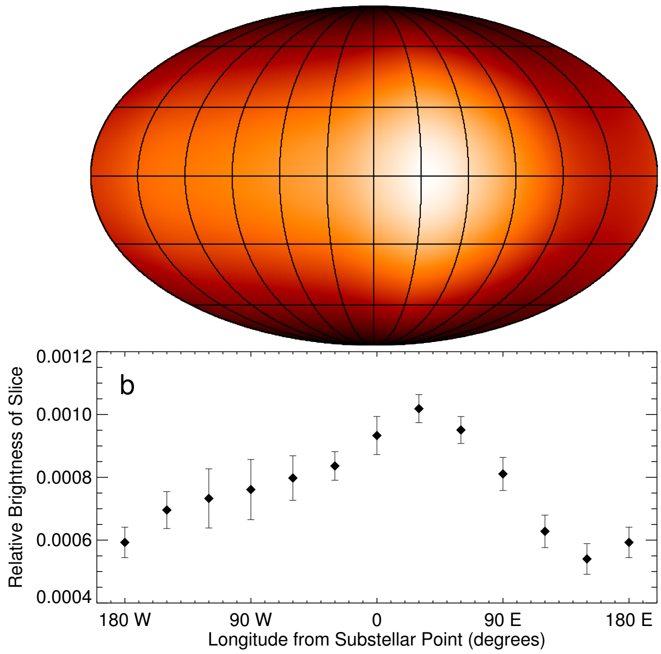

Fig. 4. Longitudinal temperature map of the planet HD189733b retrieved from the phase curve observation depicted in the previous figure (Knutson et al. 2007). The shift of the hottest point of the planet east of the substellar point is attributed to fast eastward equatorial winds (Showman et al. 2009).

4. What is the latitudinal structure of the temperature in hot Jupiter atmospheres?

The high and low latitudes of a planet differ by the amount of irradiation they receive and by the strength of the Coriolis forces. As a result, in hot Jupiters atmospheric models, the circulation patterns change from a deep super-rotating jet at the equator to a day-to-night circulation at the poles (Showman et al. 2013). Chemical composition and cloud coverage could follow this trend and be significantly different between the poles and the equator (Parmentier et al. 2013). The secondary eclipse of an exoplanet yields latitudinal information about the temperature structure of its atmosphere. During a secondary eclipse, the planet disappears behind its host star. For non-zero impact parameter, the disappearance and appearance of the planet happen by slices that are tilted with respect to the north/south direction. The ingress and egress of an exoplanet's secondary eclipse can thus allow the construction of full two-dimensional maps of the dayside hemisphere (Majeau et al. 2012; de Wit et al. 2012), in opposition to phase curves that lead to longitudinal maps only. Furthermore, as each wavelength probes different optical depth of the dayside atmosphere, multi-wavelength observations, as the ones EChO will provide, can allow tri-dimensional maps of the atmosphere. As an example, the eclipse mapping of HD 189733b using Spitzer 8 microns data constrains its hot spot to low latitudes and provides independent confirmation of its eastward shift relative to the substellar point (Majeau et al. 2012; de Wit et al. 2012).

Based on the technique developed by de Wit et al. (2012) we present in Fig. 5 the map retrieval of a synthetic version of the hot Jupiter HD 189733 b with an hypothetical hot spot with a temperature contrast of $\Delta T/T \approx 30\%$ located on the northern hemisphere (similar to the 5µm Jupiter's hot spots). Such a hot spot in a given spectral bin could be formed by the presence of patchy clouds (see Fig. 6) or chemical differences between the poles and the equator. With one secondary eclipse, EChO will detect the presence of latitudinal asymmetry in the planet's brightness distribution, with ≈ 10 (resp. ≈ 100) secondary eclipses, the temperature contrast will be measured with a precision of 300 K (resp. 100 K) and the latitudinal location of the hot-spot will be known with a precision of 10° (resp. 3.5°). This observations will be available in different spectral intervals, with a spectral resolution of ≈ 20, for the most favorable targets.

5. How common are clouds, what are they made of, and what is their spatial distribution?

The atmospheres of many hot and warm Jupiters have temperatures that cross the condensation curves for various refractory materials, suggesting that cloud formation may be an important process on some of those planets. Transmission spectra indicate that HD 189733b and perhaps HD 209458b exhibit haze-dominated atmospheres (Pont et al. 2013; Deming et al. 2013). This may also be true for the super-Earth GJ 1214b (e.g. Bean et al. 2011; Berta et al. 2012; Morley et al. 2013) and GJ 3470b (Crossfield et al. 2013; Nascimbeni et al. 2013). Given the cold conditions on the nightsides of typical hot Jupiters, many chemical species should condense on the nightside. Three-dimensional circulation models including condensable tracers (Parmentier et al. 2013) indicate

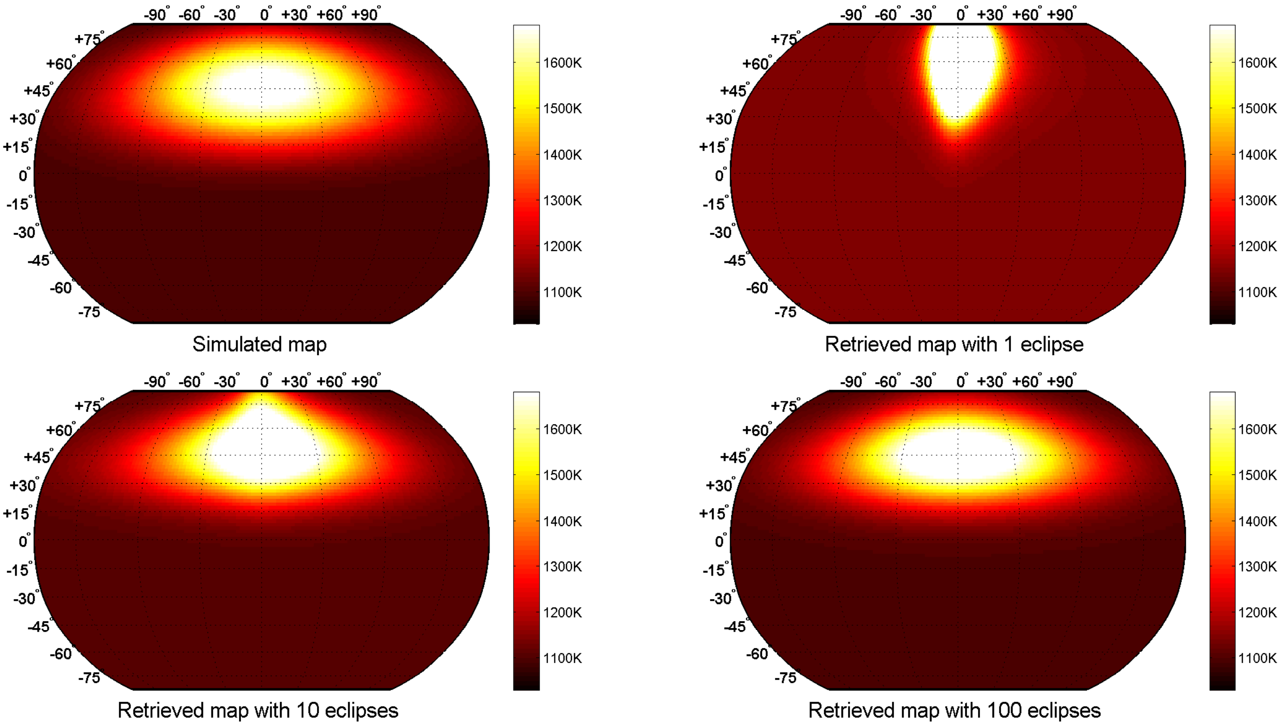

Fig. 5. Dayside brightness temperature as a function of latitude and longitude at a given wavelength for the hot Jupiter HD189733b. Simulated map and retrieved map with, 1, 10 and 100 secondary eclipse observed by EChO in a single spectral bin.

that complex spatial distributions of clouds—on both the dayside and nightside—can result from such nightside condensation (see Fig. 6).

Multi-wavelength lightcurves obtained by EChO will provide major constraints not only on the chemical composition and thermal structure but on the existence and properties of clouds in gas giant's atmospheres. Phase curves in the visible frequency range will provide insight on the longitudinal variation in albedo along the planet, which could be a strong signature of inhomogeneous cloud coverage on the planet atmosphere (Demory et al. 2013). By monitoring planets with widely different equilibrium temperatures, EChO is expected to characterize the transition from cloudy to cloudless atmospheres and the change in the dominant condensable species with equilibrium temperature, from silicate clouds at high temperatures to water clouds in temperate planets.

6. What are the main dynamical regimes and what determines the shift from one to another?

Hot Neptunes and Jupiters span an enormous range of incident stellar fluxes, orbital parameters, masses, surface gravities, and rotation rates, among other parameters. Not surprisingly, then, theory and numerical simulations suggest that such planets exhibit several fundamentally different circulation regimes depending on these parameters. Most circulation models to date have emphasized the benchmark hot Jupiters HD 189733b and HD 209458b (Showman & Guillot 2002; Cooper & Showman 2005; Showman et al. 2008, 2009; Menou & Rauscher 2009; Dobbs-Dixon & Lin 2008; Dobbs-Dixon et al. 2010; Thrastarson & Cho 2010, 2011; Rauscher & Menou 2010, 2012a; Lewis et al. 2010; Heng et al. 2011b,a; Perna et al. 2012; Miller-Ricci Kempton & Rauscher 2012; Parmentier et al. 2013). These models tend to produce several broad zonal (east-west) jets including a fast superrotating equatorial jet, and day-night temperature differences of hundreds of K at photospheric levels. Nevertheless, recent theoretical explorations of wider parameter spaces suggest that at extremely large stellar fluxes, the fractional day-night temperature differences increase and the longitudinal offset of hot spots decrease (Perna et al. 2012; Perez-Becker & Showman 2013). This shift is also accompanied by a shift from a circulation dominated by zonal (east-west) jets at moderate stellar flux to a circulation dominated by day-to-night flow at extreme stellar flux (Showman et al. 2013). At orbital separations beyond those typically identified with hot Jupiters (> 0.1 AU), models suggest that the eastward equatorial jet will give way to a circulation exhibiting one or more eastward jets in the midlatitudes of each hemisphere generated by baroclinic instability—a pattern more reminiscent of Earth or Jupiter (Showman et al. 2012). Detailed spectra and lightcurves from EChO for hot Jupiters spanning a wide range of conditions can help test these hypotheses and identify the actual circulation regimes that preside on these planets.

7. What is the role of magnetic coupling in the circulation of hot exoplanets?

Several authors have suggested that, at the extreme temperatures achieved on the most highly irradiated hot Jupiters, thermal ionization may allow a coupling of the atmosphere to the planet's magnetic field, causing the Lorentz force to become dynamically important (Perna et al. 2010a,b; Rauscher & Menou 2013). This could lead to qualitative changes in the day-night temperature difference and the geometry and speed of the global wind pattern relative to an otherwise similar planet without such coupling.

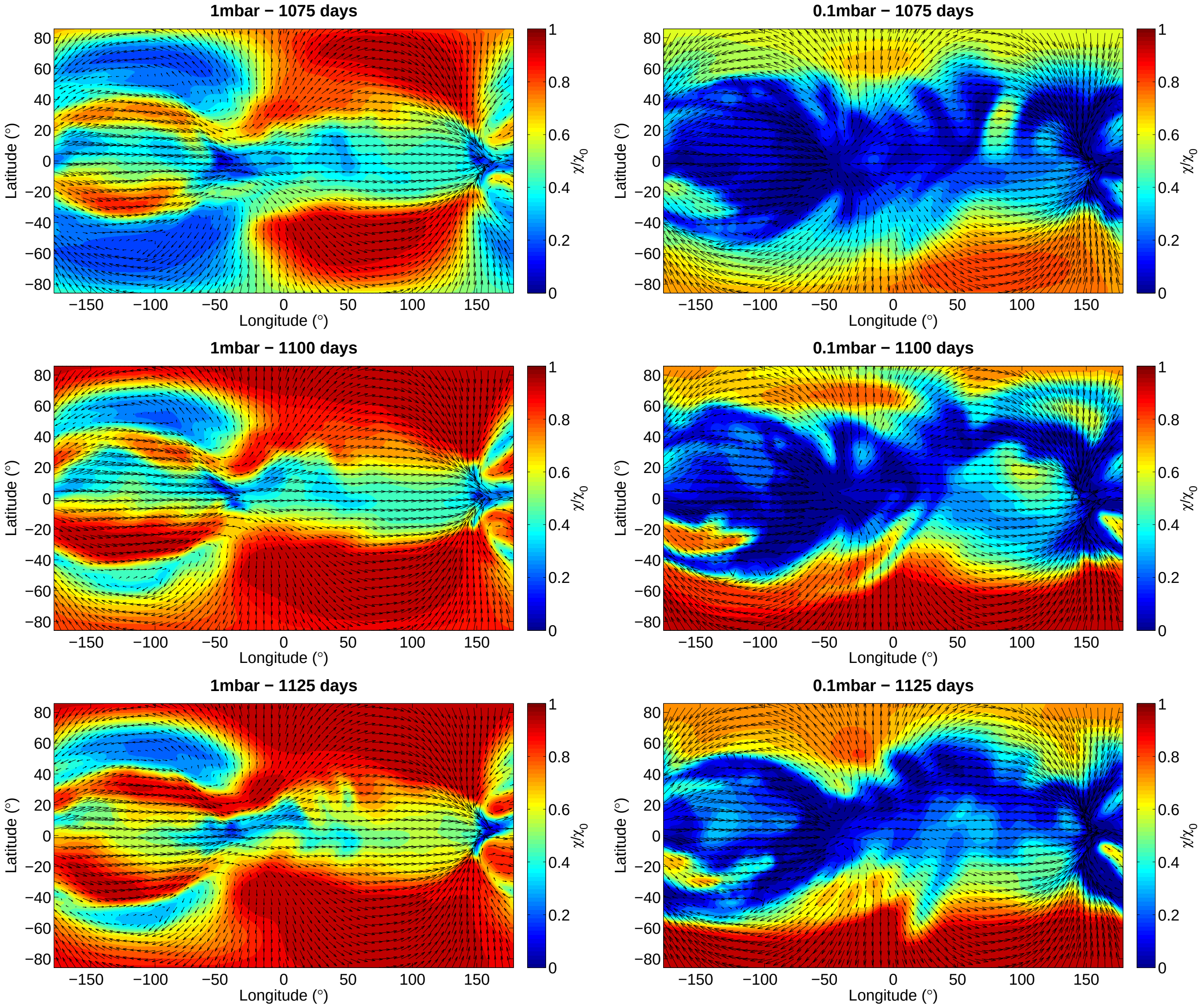

Fig. 6. Spatio-temporal variability of clouds in a hot-Jupiter model of Parmentier et al. (2013). Arrows represent the winds.

Dynamical coupling to the magnetic field could in principle even allow feedbacks that influence the existence and amplitude of a dayside stratosphere (Menou 2012). Moreover, such coupling could lead to Ohmic dissipation, with possible implications for the planet's long-term evolution (Batygin & Stevenson 2010; Perna et al. 2010b; Huang & Cumming 2012; Wu & Lithwick 2013). The sensitivity of the magnetic effects to the ionisation rate – given by the composition and the temperature profile – and the wind speed will allow EChO to identify their role in the hottest planets.

8. Are hot Jupiters temporally variable, and if so, what is the nature and distribution of the variability?

Atmospheres of planets in the solar system are turbulent, leading to temporal fluctuations on a wide range of space and time scales. This question is also a crucial one for hot Jupiters, especially because the temporal behavior of any variability contains telltale clues about the atmospheric state that would be hard to obtain using other techniques. A variety of searches for variability have taken place over the years, so far without any firm detections of variability. Using Spitzer observations of eight transits of HD 189733b, Agol et al. (2010) demonstrated an upper limit of 2.7% of the variability of the secondary-eclipse depth at 8 μm. Most 3D circulation models of typical hot Jupiters exhibit relatively steady circulation patterns; for example, circulation models coupled to radiative transfer predict variability in the secondary-eclipse depth of ~1% in the Spitzer IRAC bandpasses (Showman et al. 2009). Nevertheless, some circulation models predict high-amplitude variability of up to 10% or more at global scales (Cho et al. 2003, 2008; Rauscher et al. 2007). The amplitude and temporal spectrum of variability have much to tell about the basic atmospheric structure. Periods of variability are likely to be linked to the periods for dynamical instabilities in the atmosphere. In turn, these fundamental periods are influenced by the structure of the circulation's basic state including the stratification (e.g., the Brunt-Vaisala frequency), the vertical shear of the horizontal wind, and other parameters. As a dedicated mission, EChO will be able to observe systematically *all* transits and secondary eclipses of a given planet for a given amount of time and shed light on the different timescale and on the amplitude of the variability of a handfull of hot Jupiters. This way, EChO will allow insights into the dynamics not obtainable in any other way.

9. Why are some hot Jupiters inflated?

Transit observations show that many hot Jupiters have radii larger than can be expected from standard evolution models (see the review by Guillot 2005). The best way of explaining these radii is that some hot Jupiters experience an interior heat source (not accounted for in "classical" evolution models) that maintains a large interior entropy and thereby planetary radius. Several explanations have been put forward for this missing energy source, including tidal dissipation (e.g. Bodenheimer et al. 2001), mechanical energy transported downward into the interior by the atmosphere (Guillot & Showman 2002), suppression of convective heat loss in the interior as a result of compositional layering ((Chabrier & Baraffe 2007; Leconte & Chabrier 2012), and Ohmic dissipation associated with ionized atmospheric winds (Batygin & Stevenson 2010; Perna et al. 2010a; Huang & Cumming 2012; Wu & Lithwick 2013). However, the amount of extra-heating needed to keep hot-Jupiters inflated is strongly affected by the ability of the atmosphere to transport the energy from the deep interior to the outer space (Guillot & Havel 2011). By constraining the chemical composition and thermal profiles of those planets, EChO will provide a deeper constrain on the amount of extra-heat needed to be transported in the interior.

10. What are the conditions in the deep, usually unobservable atmosphere ?

EChO observations can be used to detect and infer the atmospheric abundances of major molecules potentially including H_2O, CO, CH_4, CO_2, and various other trace and/or disequilibrium species (see Barstow et al. 2013). To these extent that these species exhibit chemical interactions with short timescales, they may exhibit spatially variable three-dimensional distributions (e.g., differing dayside and nightside abundances). Any detected spatial variations in such chemical species across the planet would thus provide important constraints on the dynamics.

Several species, including CO and CH_4, are predicted to have long interconversion timescales, implying that they will be chemically "quenched" in the observable atmosphere at constant abundances that should vary little from one side of the planet to the other (Cooper & Showman 2006; Moses et al. 2011). The quench level—above which the abundances are in disequilibrium and below which they are approximately in equilibrium–is predicted to be at $\sim$1–10 bars pressure on typical hot Jupiters (Cooper & Showman 2006) and even deeper for cooler planets. Interestingly, this is deeper than can be directly probed by thermal emission measurements (which sense pressures less than $\sim$10 bar). Because the quenched abundances depend on the atmospheric vertical mixing rate, this implies that precise measurements of the CO and CH_4 abundances will place constraints on the dynamical mixing rates at pressures deeper than can be directly sensed. These insights on the dynamics via chemistry will thus be highly complementary to insights obtained on the dynamics from light curves and ingress/egress mapping. Moreover, they will give constrains on the deep atmosphere, a fundamental zone for understanding the interior and evolution of gas giant planets (Guillot & Showman 2002). On cooler planets, quenching in the N_2/NH_3 system can provide analogous insights.

11. How does the circulation respond to seasonal and extreme forcing?

Several transiting hot Jupiters, including HD 80606b, HAT-P-2b, and HD 17156 have orbital eccentricities exceeding 0.5, which imply that these planets receive an order of magnitude or more stellar flux at apoapse than at periapse. This extreme time-variable heating may have significant effects on the atmospheric circulation (Kataria et al. 2013). As the planet goes back and forth between apoapse and periapse, EChO will provide a unique opportunity to see the atmosphere heating up and cooling down at different wavelength, measuring its global thermal inertia (Lewis 2012) and how it varies with depth. Then, those heating and cooling rates can be used to better understand the atmospheric dynamics of planets on a circular orbits, where this measurement is not possible.

Conclusion

EChO will be a dedicated instrument to observe exoplanets atmospheres. Its exquisite photometric precision and high spectroscopic resolution over a wide spectral range will provide ground-breaking information on exoplanets atmospheres. It will perform a broad survey of their atmospheres, exploring a large range of stellar irradiations and rotation periods, two parameters that determine the main dynamical regime of an atmosphere. It will also allow a deeper understanding of some benchmark planets, characterizing their full three-dimensional thermal structure, chemical composition, cloud coverage and composition, and spatio-temporal variability, opening the field of climate study to exoplanets.

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