Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

Atmospheric Dynamics with EChO

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1 PREAMBLE

1.1 SCOPE

This document focuses on the dynamics of gaseous planet atmospheres. Much of the discussion is also relevant to the dynamics of terrestrial planet atmospheres. Specifically, the document addresses the following questions:

- How can EChO contribute to constrain the thermal structure and large-scale dynamics of gaseous extrasolar planets?
- Which are the observables (e.g., space-time temperature and albedo distributions, etc.)?
- What type of, and how many, planets should we observe?
- How many times, and with what cadence, should we observe the same planet?

1.2 PURPOSE

The purpose of this document is to provide readers of PRR, and to the extrasolar planet and astronomy and planetary science communities in general, a brief description of how EChO can be used to effectively characterise and study the atmospheres of extrasolar planets – particularly gaseous giant extrasolar planets.

1.3 APPLICABLE DOCUMENTS

AD #	APPLICABLE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1			
2			
3			

1.4 REFERENCE DOCUMENTS

RD #	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1			
2			
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2 INTRODUCTION

The strong thermal-gravitational-convective forcing experienced by extrasolar planets orbiting close to their host stars sets the planets apart from their solar system counterparts. The strikingly different forcing makes the atmospheres on these "close-in" planets not only interesting to study for their own sake: the knowledge gained in studying them can also help us to understand the dynamics of atmospheres in the solar system better. This is because in many ways the forcing on close-in planets – and gaseous planets, in particular – present a more idealized forcing with which to test theories and construct clear model baselines (e.g., Cho et al 2008, Thrastarson & Cho 2010, Politchchouk et al. 2013).

Sophisticated general circulation models (GCMs), employing various algorithms, have been developed to help interpret observations and to develop large-scale atmospheric dynamics theory. However, this activity is only in its beginning stages. One reason for this is because organized, *repeated* observations of individual planets do not exist thus far to help constraining atmospheric circulation models. The general strategy of EChO is then to obtain stable flux measurements with good spectral and temporal coverage. As model parameters become better constrained (e.g., phase dependence of day-night temperature gradient), the characterizations and predictions from the models will become more reliable.

Close-in gaseous giant planets have been the first type of extrasolar planets for which atmospheres have been directly detected. With plausible assumptions and accurate numerical modeling, some *broad* characterizations are possible for these planets. Generally, numerical simulations show nearly planetary-scale coherent storms (often two pairs) and up to three, broad zonal (east-west) jets – even under strong day-night thermal forcing gradient expected on tidally synchronized planets (e.g., Showman & Guillot 2002, Cho et al. 2003, Cho et al. 2008, Showman et al. 2008, Showman et al. 2009, Menou & Rauscher 2009, Thrastarson & Cho 2010, Heng et al., 2011). Moreover, high-resolution models show distinctive spatiotemporal variability in the global temperature and kinetic energy (motion) of synchronized planet atmospheres (Cho et al. 2003, 2008, Thrastarson & Cho 2010, Polichtchouk et al. 2013, Cho & Thrastarson, in prep.). An example is shown in Fig.1. EChO can directly detect these variability signatures and verify and advance theory.

2.1 CONSTRAINING THERMAL STRUCTURE AND ATMOSPHERIC DYNAMICS

EChO can help constraining planetary thermal and circulation structure – particularly if the planet is 1:1 spin-orbit synchronized. The assumption of synchronization "pins down" an extremely important parameter for the circulation and dynamics modelling: the planetary rotation rate. Broadly speaking, the rotation rate strongly controls the "zonality" (bandedness) of the flow and temperature structure, and therefore the maximum (latitudinal) size of the coherent features – such as jets and spots (storms). Related to this, the rotation rate also strongly controls the temporal variability in the flow and temperature distribution. There are several mechanisms for producing these features (e.g., inverse cascade arrest, interacting triads, etc.), and those mechanisms are well understood.

Once the rotation rate is known, simulations can be performed with plausible initial conditions to produce three-dimensional (3-D) temperature and flow structures. These structures can be directly compared with observations obtained by EChO. Theoretical understanding of atmospheric dynamics of synchronized giant extrasolar planets has been steadily advancing over the past decade. Using temperature maps and species abundances obtained by EChO over many planet orbits (phases), much of the degeneracies inherent in course-resolution spatial observations (as well as simulations) can be alleviated.

One remarkable finding that has been emerging in recent theoretical work with three-dimensional GCMs, is the degree of "barotropicity" (vertical alignment) in flow and temperature distributions over large vertical ranges (several pressure scale heights). This suggests that, if the depth from which the thermal signatures originate can be ascertained, very high-resolution (much more than with typical GCMs) two-dimensional models can be used to study temperature and species distribution in the lateral (e.g., along-isentrope) direction (e.g., Cho et al 2008). Such model "reductions" have a long history of fruitful use in Earth and Solar System studies. It is becoming clear than high resolution is required to simulate synchronized planet atmospheres, because of the regime in dynamical parameter-space (e.g., large Rossby number and deformation length) in which the planets reside (e.g., Cho et al. 2008, Thrastarson & Cho 2011, Polichtchouk et al. 2012). Sophisticated versions of such reduced models have been developed, and continue to be improved, trough further theoretical studies and observations.

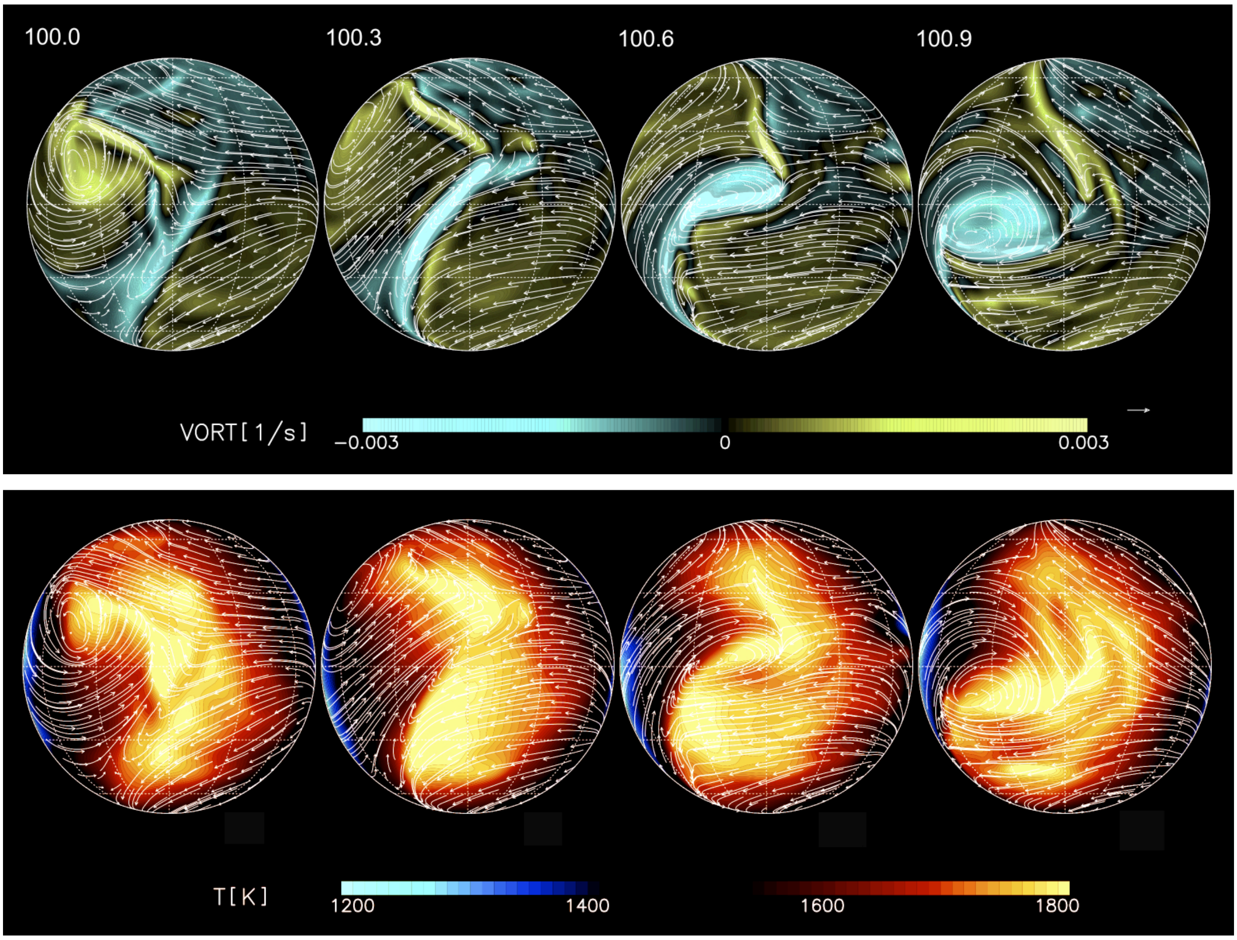

Fig 1: Nonlinear formation and evolution of coherent storms on a model hot-Jupiter. The frames are from a simulation performed with a 3-D high-resolution, state-of-the-art pseudospectral model. The time in planet days (rotations) is shown on upper left of each frame in the upper panel. Also, vorticity (color) and flow (vector) fields are shown, as is the reference flow vector for 50 m/s (lower right). In the lower panel, the temperature (color) field at the same time and height (~867 mbar level) as the frames in the upper panel are shown. Alternating storms (in the northern and southern hemispheres) form near the substellar point and move off to the nightside on a thermal relaxation timescale (approximately ½ planet day), where they dissipate. The evolution is in accordance with a fundamental in atmospheric fluid dynamics principle – conservation of potential vorticity – and leads to observable variability in thermal signatures, as can be seen in the lower panel. Note in the lower panel the complex (not simply-connected) distribution of temperature, when the dynamics is accurately represented: not only is the broad hot region shifted away from (and at times west of) the substellar point, it is highly variable in time due to its close connection with the formation of fronts (intense, narrow vorticity structures) and advection by translating storms.

2.2 OBSERVABLES

A technique that can be successfully used is eclipse mapping. This technique can be used to image the dayside of synchronized planets, in principle, but the technique has been thus far essentially beyond the capability of current instruments. However, its implementation can be practically achieved with EChO.

Signatures of large-scale atmospheric variability in measurements of primary eclipses (for the nightside) and thermal orbital phase curves can be obtained as well. Current theoretical models predict the amount of variation in eclipse depth, and the amplitudes and detailed shapes of phase curves (i.e., time series of flux over the orbits). Note that many current 3-D circulation models with simplified forcing predict high-speed winds (often supersonic jet at the equator), dynamic baroclinic (e.g., vertically slanted or twisted) storms that mix both temperature and radiatively- and chemically-active tracers. An example of such storm systems has been presented in Fig.1. Such storms are also responsible for the type of observable signatures, as shown in Fig. 2.

Fig. 2. Shows time series of disk-integrated radiative flux (σT^4, where σ is the Stefan-Boltzman constant and T is the temperature, corrected for the viewing geometrical factor). Here, disk-integrations centred at four different points – substellar (Fdss), east terminator (Fdet), west terminator (Fdwt) and antistellar (Fdas) – on a model hot-Jupiter planet are shown. Cloudless atmosphere are assumed in these simulations. In Fig. 2, two sets of series are presented (four in the upper panel and four in the lower panel) from two simulations set up identically, except the top panel is produced from a simulation started at rest and the bottom panel is produced from a simulation started with a broad, 1000 m/s westward equatorial jet. Note the relative magnitudes of the integrated fluxes, as well as the simple correlation among the four series in each panel – demonstrating the general dominance of the dayside in the integrated flux and planetary scale of the flux fluctuations in time, respectively. Note also, that the two sets of series in the upper and lower panels are distinctive, suggesting “initial condition” (more precisely a measure of eddy kinetic energy content) may be distinguishable via observation. By closely examining the flow field in time, the macro- and micro-structure of time series can be precisely connected with flow structures and their motions. In this way, it is possible to infer detailed motions and temperature variability on spatially unresolved planets.

2.3 TARGETS

As can be seen from the discussion above, gaseous giant planets that are expected to be 1:1 spin-orbit synchronized (e.g., HD209458b and HD189733b) are excellent targets for a beginning study. This is because, as already noted, the planetary rotation rate can be plausibly assumed and composition is relatively simple (compared to a terrestrial type planet). Moreover, unhampered by topography and thermal inhomogeneity (e.g., ocean/land/ice distribution) the dynamics is also expected to be simpler on gas giant planets. This class of planets, therefore, suffers least amount of modelling complexity, while offering significantly increased understanding of general circulation and atmospheric dynamics of planets in general.

2.4 OBSERVING STRATEGY

In general, the overall strategy will be to maximize the number of visits to the same targets. This is based on recent, careful study of synchronized gas giant planet like HD209458b (Cho & Thrastarson, in prep.; Thrastarson & Cho, in prep.). High-resolution simulations show that the dynamics spectrum on such planets is dense, signifying coherent oscillations of the atmosphere with many distinct periods. This is shown in Fig. 3., in which the power spectra of the disk-integrated flux at the substellar point on the planet are presented. Note, much more activity is seen in the run initialized with the resting state (E0) at early times (before ~25 days). Gradually, flow induced by the thermal forcing shows more distinctive periodicities at later times (after ~25 days). Such information can be used to plan observations over time, including cadences when continuous observations cannot be made. For example, in the figure, strong approximate periodicities of {6, 7, 9, 13, 19} days for the E0 case and {60, 90, 120, 300} days for the

W1000 case. There are some periodicities which are common in the two case – e.g., roughly speaking, {23,31} days.

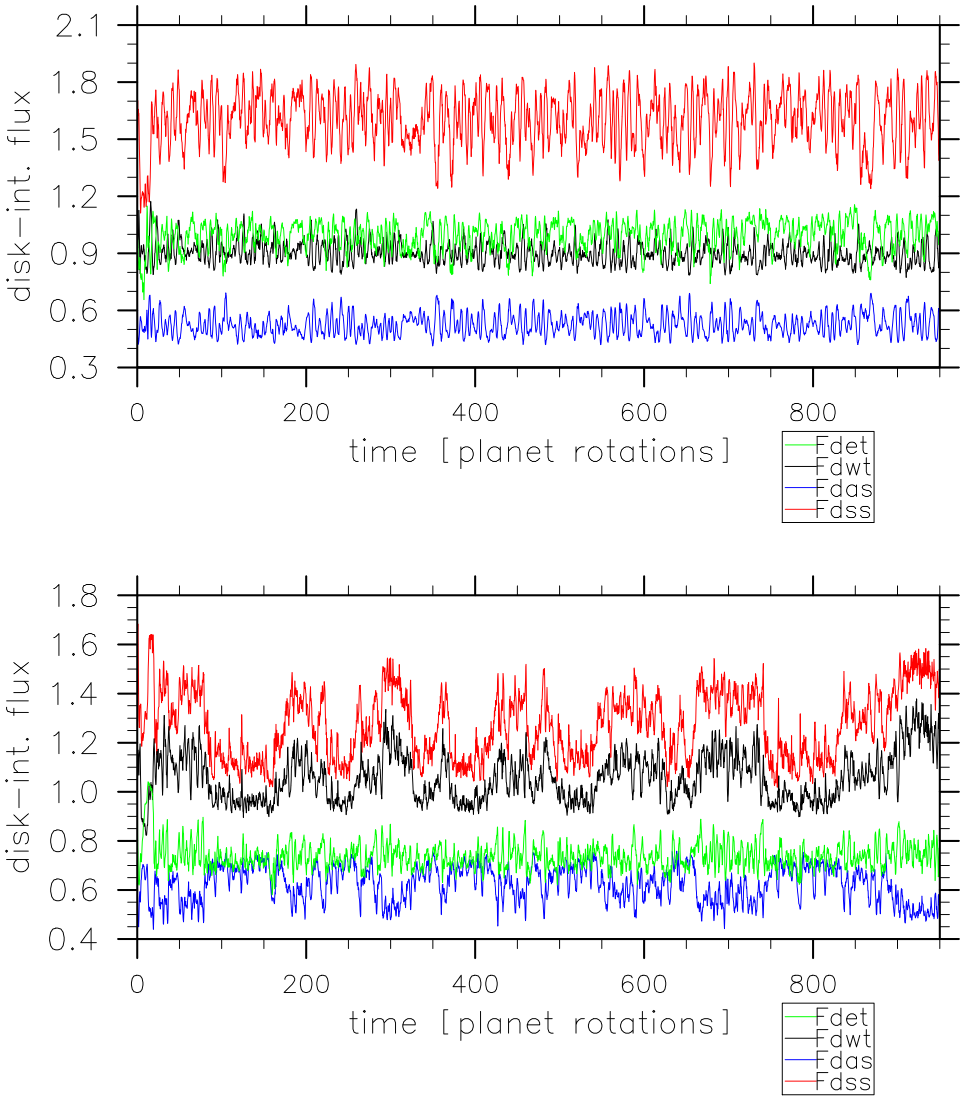

Fig. 2: Time series of disk-integrated flux (geometry-corrected σT^4). Disk-integrations centred at four different points – substellar (Fdss), east terminator (Fdet), west terminator (Fdwt) and antistellar (Fdas) – on a model hot-Jupiter planet are shown. Cloudless atmosphere are assumed in these simulations. Eight time series are presented (four in the upper panel and four in the lower panel) from two simulations set up identically, except for the initial condition. Top panel is from a simulation started at rest and the bottom panel is from a simulation started with a broad 1000 m/s westward equatorial jet. The relative magnitudes of the integrated fluxes, as well as the simple correlation among the four series in each panel, demonstrate the general dominance of the dayside in the integrated flux and planetary scale of the flux fluctuations in time. Additionally, the two sets of series in the upper and lower panels are distinctive, suggesting “initial condition” (more precisely a measure of eddy kinetic energy content) may be distinguishable through observations. The macro- and micro-structure of time series can be precisely connected with flow structures and their motions.

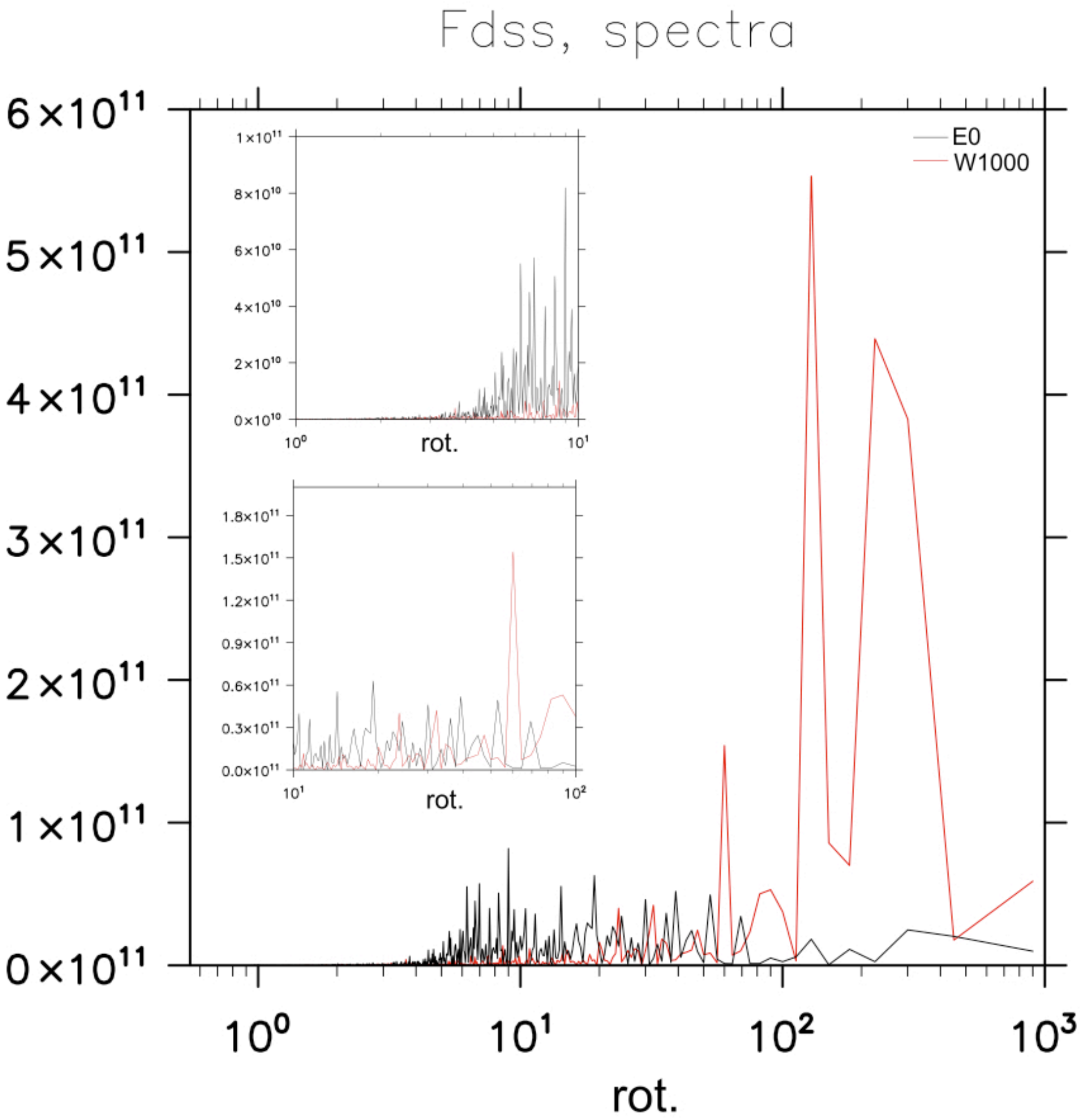

Fig. 3: Power spectra of disk-integrated flux time series (Fdss) in Fig. 2. The two insets are magnifications of two time windows, [1:10] and [10:100] rotations (or planet days). At early times (before ~25 days), much more activity is seen in the run initialized with rest state. Gradually, flow induced by the thermal forcing shows more distinctive periodicities at later times (after ~25 days). Such information can be used to plan observations over time, including cadences when continuous observations cannot be made.

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