Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

Characterizing planetary interiors with EChO

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Prepared by:	Tristan Guillot, Lars Sixtrude	Date:	27 sept. 2013
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DISTRIBUTION LIST

EChO Payload Consortium				External	
Co-PIs / Science Team Coordinators		**Study Engineering Team Working Group Leads**		**European Space Agency**	
✓	Giovanna Tinetti	✓	Paul Eccleston		Luigi Colangeli
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	Enzo Pascale		Marc Ollivier		
	Gillian Wright		Gonzalo Ramos Zapata		
	Graziella Branduardi-Raymont		Neil Bowles		
	Marc Ollivier	**Other Engineering Team**			
	Pierre-Olivier Lagage		*As necessary for doc*		
	Vince Coudé du Foresto				
	Athena Coustenis				
	Emanuele Pace				
	Giuseppe Piccioini				
	Giuseppe Malaguti				
	Alessando Sozzetti				
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	L Fletcher				
	D Pinfield				
	J Cho				
	F Forget				
	I Waldmann				
	P Deroo				
	I Mueller-Wodarg				
	F Selsis				
	O Grasset				
	L Stixrude				
	T Guillot				
	Others…				

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1 PREAMBLE

1.1 SCOPE

This document presents the science case of EChO in terms of characterizing the global compositions and interior structure of exoplanets.

1.2 PURPOSE

The reason for this document to exist is to show how the science of planetary interiors would benefit from EChO measurements.

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			
3			

2 INTRODUCTION

Except for the Earth and the Moon, there is no direct measurement of the deep structure of the planets. This investigation requires a network of seismometers for terrestrial planets, or techniques similar to the asterosismology for gaseous giants. Nonetheless, the internal structure of planetary bodies in the solar system is, even if not very precise, relatively well understood. Planetary bodies can be split into three main families (figure 1) which are: i) the terrestrial planets (or solid planets), ii) the giant planets (or gaseous), and iii) the intermediate planets which are in between the two extreme cases. In this section, it will be demonstrated that EChO will provide the necessary constraints for having the same “first-order” understanding of the internal structure of extrasolar planets.

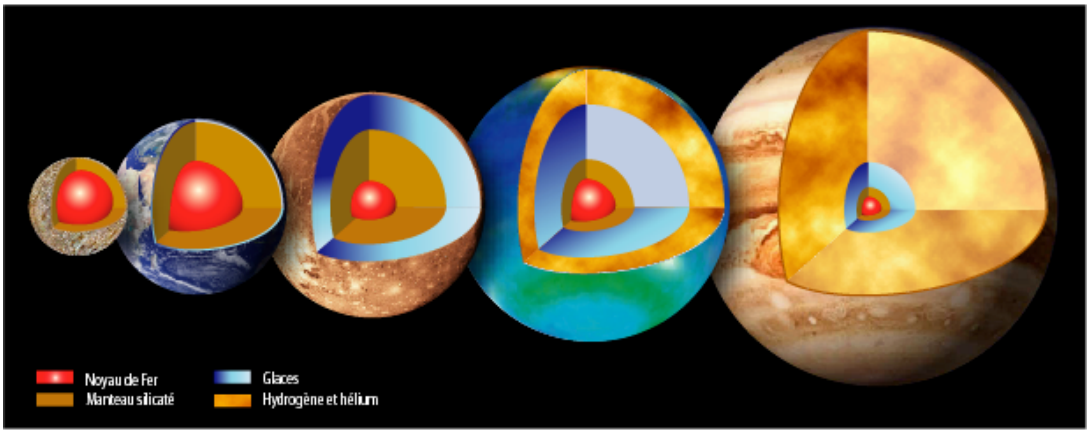

Figure 1: Internal structures of planets (not at scale). The three sub-families on the left are part of the terrestrial family (see text for detail). Giant planets (Jupiter-like) are on the right. Neptune – like planets, are on the fourth position from the left.

Although EChO will by definition measure the characteristics of planetary atmospheres it will be also crucial in improving our knowledge of planetary interiors. EChO will of course be able to measure with exquisite accuracy the depth of the primary transit and thus the planetary size. But the major improvements for interior models will come from the ability to fully characterize the atmosphere in its composition, dynamics and structure. This will be achieved by a combination of observations of primary and secondary transits and of observation of the planetary lightcurve during a full orbital cycle.

The questions to be answered will depend on the bodies that are considered, whether they are terrestrial (Earth-like), gaseous giant planets or intermediate planets between these two extreme cases.

2.1 EARTH-LIKE PLANETS

Three different sub-families of planets can be considered from left to right in figure 1: Mercury-like planets mostly composed of an iron core and a thin layer of silicates, Super-Earth made of an iron core and a thick silicate mantle (such as Venus, Mars and the Earth) and Ocean-planets made of iron, silicates, and water (similar to icy moons of Jupiter and Saturn). Super-Earths are composed of an internal iron-rich core and a thick silicate mantle (lower mantle) covered by a thin layer of low-pressure silicates similar to the upper mantle on Earth, and a very thin liquid layer (like Earth-oceans). Ocean-planets are composed of an iron core, a silicate mantle, and a thick icy layer surrounded by a thin ocean or icy crust at the surface.

For a given mass, one must expect for Ocean-like planets a smaller metallic core and silicate mantles, but also a larger radius than for Earth-like planets because icy materials are lighter than silicates. As a contrary, the radius of a Mercury-like planets, much denser, is about 80 % that of an Earth-like planets (Valencia et al., 2007; Grasset et al., 2009). In fact, it could be possible to characterize Super-Earths composition (Mercury-like, Earth-like, water-rich) from Mass - Radius measurements. Nonetheless, solutions are not unique. As an example, it must be noted that a silicate-rich planet surrounded by a very thick atmosphere could provide the same mass and radius than an ice-rich planet without atmosphere (Adams et al., 2008).

EChO will unravel the ambiguity in some cases by making the difference in lightcurve between airless planets and planets with an atmosphere (Selsis et al. 2011, Maurin et al. 2012). In the former case, or when the atmosphere is determined to be thin, theoretical works on mass-radius relations provided by many authors in the last decade (Léger et al., 2004; Valencia et al., 2007; Sotin et al., 2007; Seager et al, 2007; Adams et al., 2008; Grasset et al., 2009) can be fully exploited in order to characterize the inner structure of the new planet.

To go from the internal structure to the dynamics of the planet is much more difficult. Relationships between atmospheres and internal dynamics of planets are not clearly understood even for the Earth. Atmospheric composition depends on 1) the intensity of volcanic and tectonic activities, 2) the oxidization degree of the silicate mantle which will constrain both nature and quantity of gas that are expelled, and 3) the age of the planet. EChO, by providing the main composition of the atmospheres, will add new data to the existing constraints from solar system bodies. Such data are fundamental for understanding more thoroughly what can be the relationships in a planet between internal activity and atmospheric composition.

EChO will most certainly have the possibility to look at relatively exotic targets such as KIC 12557548, an evaporating Moon-mass planet (Rappaport et al. 2010, Brogi et al. 2012, Perez-Becker & Chiang 2013). The possibility to look spectrally of the tail of material ejected from the planet is extremely interesting and opens the possibility to probe *directly* the interior of planets. In this case, silicates are probably directly evaporated. The interpretation of the result would benefit from numerical simulations of the liquid-vapor transitions of rocks of various compositions (Sixtrude & Karki 2005, Mookherjee et al. 2008). Importantly, to first order, the extent of the exosphere does not depend on planetary size: detection would be possible even for very low-mass objects.

2.2 GIANT PLANETS

Giant planets are mostly made of hydrogen and helium and are expected to always be in gaseous form (Guillot 2005). Because they play a tremendous role in shaping planetary systems (e.g. Tsiganis et al. 2005) determining precisely their internal structure and composition is essential to understand how planets form. Contrary to solid planets, they are relatively compressible and the progressive loss of heat acquired during their formation is accompanied with a global contraction. Inferring their internal composition thus amounts to understanding how they cool. Fortunately, the dominance of hydrogen and helium implies that the degeneracy in composition (i.e. uncertainty on the mixture of ices/rocks/iron) is much less pronounced than for solid planets, so that the relevant question concerns the amounts and all elements other than hydrogen and helium, i.e. heavy elements, that are present.

The determination of sizes from primary transit measurements and masses from radial measurements have yielded in some cases a constraint on the mass of heavy elements present in the interior that is relatively independent of model hypotheses (e.g. Sato et al. 2005, Ikoma et al. 2006, Deeg et al. 2009) and otherwise global tendencies showing that this mass is correlated with the metallicity of the parent star (Guillot et al. 2006, Burrows et al. 2007, Miller & Fortney 2011). However, several problems arise. First a large fraction of the known transiting planets are larger than expected, even when considering that they could be coreless hydrogen-helium planets (e.g. Guillot & Showman 2002, Baraffe et al. 2003, Guillot et al. 2006, Burrows et al. 2007). There is thus a missing physics that is to be identified. Second, we do not know whether these heavy elements are kept inside a central core or distributed inside the planet. This influences how they cool (Guillot 2005, Baraffe et al. 2008) and is crucial in the context of formation scenarios (e.g. Lissauer & Stevenson 2007). Third, the complex dynamics of the atmosphere of heavily irradiated planets that constitutes the outer boundary condition of evolution models is poorly understood. This has direct consequences for our ability to accurately predict the evolution of these planets.

EChO will directly contribute to improve our understanding of the interiors of giant exoplanets with the following measurements:

- Measurements on short time scales (a few hours of continuous observations) of the primary or secondary transit will reveal the abundances of important chemical species globally on the terminator or on the day side. The comparison of these measurements with the characteristics of the star and of the planet, in particular the stellar metallicity and the mass of heavy elements required to fit the planetary size will be key in the determination of whether the heavy elements are mixed all the way to the atmosphere or mostly present in the form of a central core.
- Measurements on long time scales (a half or a full planetary orbit, i.e. days to weeks of continuous observations) will lead to a very accurate description of the atmospheric dynamics (wind speed, vertical mixing from disequilibrium species), atmospheric structure (vertical and longitudinal temperature field, presence of clouds) and variability. This will be extremely important to estimate the depth at which the atmosphere becomes well mixed and therefore the heat that is allowed to escape.
- Observations of a planet system locked in a fixed-point eccentricity system: the measurement of a secondary transit allows the determination of the eccentricity and a constraint on the planetary Love number. This in turn can be used to constrain the distribution of density in the interior as has been done in the case of HAT-P-13b (Batygin et al. 2009, Mardling 2010).

It is important to realize that a statistically significant number of observations must be made in order to fully test models and understand which are the relevant physical parameters. This requires observations of a large sample of objects, generally on long timescales, which is most efficiently done with a dedicated instrument such as EChO, rather than with a multi-purpose telescope such as JWST or the extremely large telescopes. Another significant aspect of the search relates to the possibility to discover unexpected "Rosetta Stone" objects, i.e. objects that definitively confirm or infirm theories: this requires wide searches that are possible only through dedicated instruments.

2.3 ICE GIANTS

Planets in between the gas giants and the small solid terrestrial planets may well prove to be the most important keys to understand the formation of planetary systems. The existence of these intermediate planets close to their star as found by radial velocity and transit surveys (e.g. Howard et al. 2010, 2012) is already crucial to highlight the shortcomings of theoretical models (Ida & Lin 2010, Mordasini et al. 2009). With the possibility of examining their atmospheric compositions, EChO measurements will prove to be invaluable in several respects: (i) Standard planet formation scenarios predict that embyos of sufficient mass (typically above 5 Earth masses) should retain some of the primordial hydrogen and helium from the protoplanetary disc (e.g. Ikoma et al. 2001). With EChO measurements, we will probe which planets indeed possess a hydrogen helium atmosphere and directly test the conditions of planet formation. (ii) The two only intermediate planets that we can characterize, Uranus and Neptune, are significantly enriched in heavy elements, in the form of methane (e.g. Guillot 2005, Nettelmann et al. 2013). The reason for this enrichment is unclear: is it due to upward mixing, early or late delivery of planetesimals? EChO will allow these measurements in many planets thereby providing observations that are key to constrain these models. (iii) We do not know where to put the limits between solid, liquid and fluid (gaseous) planets. While EChO will not directly measure the phase of a planet as a whole, the determination of its size and of the composition of its atmosphere will be key to determine whether its interior is solid, partially liquid or gaseous.

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