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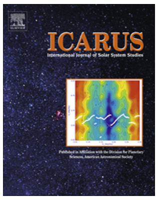

The transit spectra of Earth and Jupiter

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ABSTRACT

In recent years, an increasing number of observations have been made of the transits of ‘Hot Jupiters’, such as HD 189733b, about their parent stars from the visible through to mid-infrared wavelengths, which have been modelled to derive the likely atmospheric structure and composition of these planets. As measurement techniques improve, the measured transit spectra of ‘Super-Earths’ such as GJ 1214b are becoming better constrained, allowing model atmospheric states to be fitted for this class of planet also. While it is not yet possible to constrain the atmospheric states of small planets such as the Earth or cold planets like Jupiter, it is hoped that this might become practical in the coming decades and if so, it is of interest to determine what we might infer from such measurements. In this work we have constructed atmospheric models of the Solar System planets from 0.4 to 15.5 μm that are consistent with ground-based and satellite observations and from these calculate the primary transit and secondary eclipse spectra (with respect to the Sun and typical M-dwarfs) that would be observed by a ‘remote observer’, many light years away. From these spectra we test what current retrieval models might infer about their atmospheric states and compare these with the ‘ground truths’ in order to assess: (a) the inherent uncertainties in transit spectra observations; (b) the relative merits of primary transit and secondary eclipse spectra; and (c) the advantages of acquiring directly imaged spectra of these planets. We find that observing secondary eclipses of the Solar System would not give sufficient information for determining atmospheric properties with 10 m-diameter telescopes from a distance of 10 light years, but that primary transits give much better information. We find that a single transit of Jupiter in front of the Sun could potentially be used to determine temperature and stratospheric composition, but for the Earth the mean atmospheric composition could only be determined if it were orbiting a much smaller M-dwarf. For both Jupiter and Earth we note that direct imaging with sufficient nulling of the light from the parent star theoretically provides the best method of determining the atmospheric properties of such planets.

1. Introduction

The field of exoplanetary transit spectroscopy has advanced dramatically in recent years with the observed spectra of ‘Hot Jupiter’ planets such as HD 189733b and HD 209458b becoming increasingly better constrained. These spectra can be fitted with retrieval models to determine atmospheric states (Line et al., 2013; Lee et al., 2012) and reveal atmospheres that are very different from anything seen in our Solar System. As the measurement techniques improve, the spectra of smaller, cooler ‘Super-Earths’ such as GJ 1214b (Barstow et al., 2013b; Benneke and Seager, 2013; Kreidberg et al., 2014) are becoming measurable and ultimately planetary scientists will want to search the local galactic region for planets more similar to what we see in our Solar System and one day, perhaps, identify another Earth-like planet.

Should such a situation ever arise, it is of great interest to determine what we might actually deduce from the measured transit spectrum of a Solar System planet and a number of studies have been performed to investigate this. For example, Tinetti et al. (2006) modelled the disc-averaged spectrum of the Earth from 0.5 to 25 μm, looking at the effect of various factors such as different surfaces and clouds, and more recently Rugheimer et al. (2013) have studied the disc-averaged spectra of Earth-like planets about F, G and K stars from 0.4 to 20 μm, looking at the visibility of detectable gaseous features. von Paris et al. (2013) looked to see how well potentially habitable planets could be characterised from secondary eclipse observations from proposed exoplanet missions such as the Exoplanet Characterisation Observatory (EChO, Tinetti et al., 2012), and also early direct imaging mission proposals such

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as Darwin (Léger et al., 1996; Cockell et al., 2009a,b). von Paris et al. (2013) found that using secondary eclipses or direct imaging the atmospheric composition would not be well determined, but that the surface temperatures of small rocky planets could be recovered reasonably well. For primary transits, Kaltenegger and Traub (2009) modelled the primary transit spectra of Earth-like planets about different stars from 0.3 to 20 μm looking at the detectability of different features and Bétrémieux and Kaltenegger (2013) examined the effect of atmospheric refraction and Rayleigh scattering in the UV to near-IR range.

In this work we construct simple atmospheric models of the Solar System planets Jupiter and Earth based on ground-based and satellite observations. From these models we compute their primary transit, secondary eclipse and directly-imaged spectra as seen from an observer ten light years away with a 10-m diameter space telescope, for the planets orbiting the Sun or an M-dwarf. We then examine what might be recoverable from these spectra by a 'remote observer' and compare the retrieved results with the actual atmospheric states of these planets.

2. Construction and validation of synthetic spectra

For this study, synthetic spectra were calculated with the NEMESIS radiative transfer and retrieval model (Irwin et al., 2008). NEMESIS takes a model atmosphere, which defines the temperature profile as a function of pressure, together with the volume mixing ratio profiles of the constituent gases and the abundance profiles of clouds and aerosols and calculates the spectrum that one would expect to observe using, as a default, a correlated-k radiative transfer scheme. This modelled spectrum is then compared to that measured and the model parameters adjusted, using the technique of optimal estimation (Rodgers, 2000), to minimise the difference between the modelled and measured spectra. In this study we wish to simulate both thermal emission and reflected sunlight spectra of Earth and Jupiter and so we used a multiple scattering/thermal emission model, which is dealt with in NEMESIS using the matrix operator formalism of Plass et al. (1973); a five point Gauss-Lobatto quadrature scheme was chosen for the zenith angle integration, while the azimuthal integration was performed with Fourier decomposition, using N Fourier components, where N is set adaptively from the viewing zenith angle, θ, as $N = \mathrm{int}(\theta/3)$. To run this model, *k*-tables had first to be computed, which pretabulate the *k*-distributions of the absorption of different gases (e.g. Goody et al., 1989; Lacis and Oinas, 1991) at a set range of pressures and temperatures, for an assumed spectral resolution. In this study we chose to calculate these *k*-tables at a spectral resolution of 0.025 μm, to cover the range 0.4–15.5 μm. This resolution was chosen to be the same as the Galileo Near Infrared Mapping Spectrometer (NIMS) observations of Jupiter that we compare our model with (as described below) and is reasonably consistent with the spectral resolving power of the other observed spectra we used. The *k*-tables were calculated with 20 temperatures in the range 70–400 K and 20 pressures equally spaced in log pressure between 3.1×10^{-7} and 20.3 bar. Where available, the *k*-tables were calculated from HITRAN 2008 line data base (Rothman et al., 2008). However, for methane the band data of Karkoschka and Tomasko (2010) were used at near-IR wavelengths where the HITRAN 2008 data become insufficient. Similarly the NH_3 *k*-table was based on the band data of Bowles et al. (2008), combined with HITRAN 2004 and HITRAN 1996 linedata as described by Sromovsky and Fry (2010).

To construct the expected transit spectra of Earth and Jupiter, synthetic atmospheres first needed to be set up, with representative temperature, pressure, volume mixing ratio and cloud opacity profiles. These profiles were used to simulate the observations of Earth-observing and Jupiter-observing satellites to ensure consistency before moving on to simulate the transit spectra of these planets.

2.1. Jupiter

For Jupiter, the initial temperature/pressure/volume-mixing-ratio (vmr) profile was chosen to be consistent with the observations of the Composite Infrared Spectrometer (CIRS, Flasar et al., 2004) instrument on the NASA Cassini spacecraft, which covers the spectral range 7–1000 μm. A representative nadir co-added observed spectrum was used for this process and the atmospheric profiles fitted as described by Irwin et al. (2004) and Fletcher et al. (2009). To fit the cloud opacity needed to simulate the near-infrared and visible parts of the spectra, we made a simple approximation of assuming the particles to be composed of spherical droplets with a complex refractive index of 1.4 + 0i, and a standard Gamma size-distribution of mean-size 1 μm and variance 0.05. The extinction cross-section spectra and phase function spectra were then calculated with Mie Theory and the phase function approximated with combined Henyey–Greenstein functions for computational simplicity, where the phase function, $p(\theta)$, is modelled as

$$p(\theta) = \frac{1}{4\pi}\left[f\frac{1-g_1^2}{(1+g_1^2-2g_1\cos\theta)^{3/2}} + (1-f)\frac{1-g_2^2}{(1+g_2^2-2g_2\cos\theta)^{3/2}}\right] \quad (1)$$

This function has three parameters, f, g_1 and g_2, where g_1 is the asymmetry of the forward scattering function, g_2 is the asymmetry of the backward scattering function and f determines the relative contribution of each. Since the assumed particles have no absorption, the single-scattering albedo was calculated to be unity at all wavelengths. The scattering particles spectral properties were calculated with a step size of 0.1 μm, with linear interpolation between calculated points. Clouds and hazes in Jupiter's atmosphere were approximated with a single haze layer with variable base pressure and parameterised total nadir optical depth at 1.6 μm. The fractional scale height of this layer was set to 0.5, in accordance with NIMS near-infrared studies (Irwin et al., 2001). The synthetic model was compared with a set of four Galileo/NIMS spectra, previously analysed by Irwin et al. (1998), the so-called 'Real-time' spectra. Here we chose the fourth spectrum of this set, which has the highest 5-μm emission and thus the lowest opacity of the deeper cloud allowing radiation from the 5–8 bar level to escape to space, and adjusted the haze layer base pressure and optical depth to achieve reasonable agreement at near-IR wavelengths, eventually placing the haze at a base pressure of 0.56 bar, with a nadir optical depth at 1.6 μm of 5.25. The comparison between the synthetic spectra and the Galileo/NIMS and Cassini/CIRS spectra is shown in Figs. 1 and 2, in terms of radiance and reflectivity respectively. Since the Galileo/NIMS and Cassini/CIRS spectra do not cover the complete spectral range of these simulations we also compared the calculations with the measured ISO/SWS (T. Encrenaz, T. Fouchet, private communication) spectrum (which is close to a disc-average) and with a reference visible ground-based albedo spectrum of Jupiter described by Karkoschka (1994). In the first panel of Figs. 1 and 2, the synthetic spectrum is calculated at the Galileo/NIMS geometry of 42° solar incident angle and 0° emission angle (which is also consistent with the Cassini/CIRS observations), while the latter two panels are calculated at 45° solar incidence angle, 45° emission/reflected angle and 180° azimuth angle, i.e. in the back-scattering direction, which is more consistent with the geometry of the ISO/SWS and ground-based visible albedo observations (as discussed in Section 3). It can