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Transit spectroscopy of a temperate Jupiter

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Abstract

In this study, we consider the expected infrared transmission spectrum of a temperate Jupiter, with an equilibrium temperature ranging between 350 and 500 K, and we analyse the best conditions for the host star to be filled in order to optimize the S/N ratio of its transmission spectrum. According to our analysis, temperate Jupiters around M stars could have an amplitude signal higher than 10^{-4} in primary transits, with revolution periods of a few tens of days and transit durations of a few hours. In order to enlarge the sampling of exoplanets to be observed with ARIEL (presently focussed on objects warmer than 500 K) [1], some of these objects could be considered as additional possible targets for the mission.

1. Introduction

Temperate Jupiters, with equilibrium temperatures ranging between 350 and 500 K, are not expected to exist according to the standard nucleation model, which requires that giant planets are formed at large distances from their host star. However, some objects of this type have been found around solar-type stars, with expected equilibrium temperatures ranging between 250 and 500 K (Table 1). If such objects are also transiting around low-mass stars, they would be suitable targets for transit spectroscopy. Future surveys with space missions like GAIA, but also CHEOPS, TESS or PLATO, are likely to provide new targets for this class of exoplanets.

Table 1
Examples of temperate giant exoplanets detected around F, G and K stars, with a mass larger than 0.5 Jovian mass and an eccentricity smaller than 0.1 (from www.exoplanets.eu). The equilibrium temperature is calculated assuming an albedo a = 0.03 and a fast-rotating planet [2].

Name	$M_P(M_J)$	P(d)	D(AU)	T_P (K)
HD 134113 b	47	202	0.64	295
HD 233604 b	6.6	192	0.747	434
HD 28185 b	5.7	383	1.03	320
HD 32518 b	3.04	157	0.59	395
HD 159243 c	1.9	248	0.8	338
HD 9446 c	1.82	193	0.654	342
HD 141399 c	1.33	202	0.69	390
HD 231701 b	1.08	142	0.53	419
Kepler-11 g	0.95	118	0.46	392
HD 92788 c	0.9	162	0.6	392
HD 37124 b	0.675	154	0.53	331
HD 45364 c	0.66	343	0.897	252
Mu Ara d	0.52	310	0.92	306

2. The infrared spectrum of a temperate Jupiter

According to thermochemical equilibrium, we expect CH_4, NH_3 and H_2O to be the main minor tropospheric species (after H_2 and He) of a temperate Jupiter. The main difference with the true Jupiter is that there is no cold trap at the tropopause, so the three molecules are expected to keep a constant mixing ratio with the altitude. We assume their relative abundances to be consistent with the cosmic abundances, i.e. $H_2O:CH_4:NH_3 = 2:1:0.1$. Their relative abundances are expected to stay unchanged even in the case of a higher metallicity (as in the case of Jupiter).

Above the tropopause, photo-dissociation products are expected: C_2H_2 and C_2H_6 (from CH_4 photo-dissociation), CO and CO_2 (from H_2O photo-dissociation. By analogy with the case of Jupiter, we assume the following abundances in the stratosphere: $CH_4:C_2H_2:C_2H_6 = 1:10^{-4}:2\ 10^{-3}$, and $H_2O:CO:CO_2 = 1:1:0.2$. Calculations show that CO and CO_2 contribute as minor absorbers in the infrared spectrum, while the contribution of hydrocarbons is negligible (Figure 1).

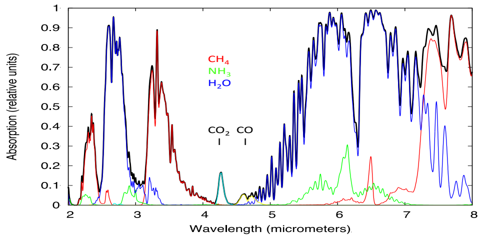

Figure 1. A typical absorption spectrum (primary transit) for a temperate giant exoplanet, including the effect of photochemistry. The contribution of hydrocarbons is negligible. The full scale is equal to the amplitude of the primary transit absorption A, as calculated in Table 2.

What could be the condensates present in a temperate Jupiter? For temperate objects colder than 500 K, there are few expected condensates, except possibly hydrated silicates; in addition, all ices are in gaseous form. We can thus expect temperate Jupiters to be relatively free of condensates [3]. As a result, the albedo of such a planet can be expected to be very low, as has been actually observed on hot Jupiters, for which typical values of 0.03 have been derived.

3. Primary transit spectroscopy of a temperate Jupiter

The amplitude of the primary transit absorption of a hydrogen-rich Jupiter-like exoplanet can be approximated as follows [1]: $A = 1.94\ 10^{-7} \times T_P/\rho R^{*2}$, where T_P is the planet's equilibrium temperature and R* is the radius of the star (in solar radii). In order to get A larger than 10^{-4}, we need to consider temperate Jupiters around low-mass stars.

Table 2
Estimated revolution period, amplitude of primary transit signal, and transit time for a Jovian-like exoplanet transiting around a star of spectral type between G2 and M8. Two cases are considered: T_P = 350 K and T_P = 500 K. The fast rotator case is favoured for G2 to M0 stars (M0 stars are actually an intermediate case); the tidally locked object case is favoured for M5 and M8 stars.

Spectral type	R (Rs)	M (Ms)	P (d)	A	Transit time (h)
G2 (T_P= 350 K)	1.0	1.0	180	$6.78\ 10^{-5}$	10.3
G2 (T_P= 500 K)			61	$9.69\ 10^{-5}$	7.1
G5 (T_P= 350 K)	0.93	0.93	159	$7.84\ 10^{-5}$	9.4
G5 (T_P= 500 K)			54	$1.12\ 10^{-4}$	6.6
K0 (T_P= 350 K)	0.85	0.78	117	$9.38\ 10^{-5}$	8.3
K0 (T_P= 500 K)			40	$1.34\ 10^{-4}$	5.8
K5 (T_P= 350 K)	0.74	0.69	94	$1.24\ 10^{-4}$	7.0
K5 (T_P= 500 K)			32	$1.77\ 10^{-4}$	4.9
M0(T_P= 350 K)	0.63	0.47	48	$1.71\ 10^{-4}$	5.4
M0(T_P= 500 K)			17	$2.44\ 10^{-4}$	3.9
M5(T_P= 350 K)	0.32	0.21	18	$6.64\ 10^{-4}$	2.6
M5(T_P= 500 K)			6	$9.50\ 10^{-4}$	1.7
M8(T_P= 350 K)	0.13	0.10	6	$3.98\ 10^{-3}$	1.0
M8(T_P= 500 K)			2	$5.70\ 10^{-3}$	0.6

4. Sensitivity estimate

As a calibrator, we use the exoplanet WASP-76 b as described in the ARIEL proposal [1]. The amplitude of its primary transit is 10^{-3} and the transit time is 3.4 hours. A summation of 25 transits (corresponding to a total integrating time of 85 hours) is needed to achieve a S/N of about 10. According to our calculations, with a total observing time of 100 hours, a S/N of 2.5, 9.5 and 57 can be reached for temperate Jupiters around M0, M5 and M8 stars, respectively. In all cases, the observing time of 100 hours could be achieved within a total time of 3 years, compatible with the expected lifetime of ARIEL.

References

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