A feature-rich transmission spectrum for WASP-127b
Cloud-free skies for the puffiest known super-Neptune?

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Received Month 00, 2017; accepted Month 00, 2017

ABSTRACT

Context. WASP-127b is one of the lowest density planets discovered to date. With a sub-Saturn mass ($M_p = 0.18 \pm 0.02 M_J$) and super-Jupiter radius ($R_p = 1.37 \pm 0.04 R_J$), it orbits a bright G5 star, which is about to leave the main-sequence.

Aims. We aim to explore WASP-127b's atmosphere in order to retrieve its main atmospheric components, and to find hints for its intriguing inflation and evolutionary history.

Methods. We used the ALFOSC spectrophotograph at the NOT telescope to observe a low resolution ($R \sim 330$, seeing limited) long-slit spectroscopic time series during a planetary transit, and present here the first transmission spectrum for WASP-127b.

Results. We find the presence of a strong Rayleigh slope at blue wavelengths and a hint of Na absorption, although the quality of the data does not allow us to claim a detection. At redder wavelengths the absorption features of TiO and VO are the best explanation to fit the data.

Conclusions. Although higher signal-to-noise ratio observations are needed to conclusively confirm the absorption features, WASP-127b seems to posses a cloud-free atmosphere and is one of the best targets to perform further characterization studies in the near future.

Key words. Planetary systems -- Planets and satellites: individual: WASP-127b -- Planets and satellites: atmospheres -- Techniques: spectroscopic

1. Introduction

The atmospheres of exoplanets are a unique window to investigate the planetary chemistry, which can help improve our understanding of planetary interior properties and provide links to planet formation and migration histories (e.g., Guillot 2005; Fortney et al. 2007; Fortney & Nettelmann 2010; Öberg et al. 2011; Mousis et al. 2012; Madhusudhan et al. 2014, 2016). Transmission spectroscopy retrieves the absorption and scattering signatures from the atmosphere at the planetary day-night terminator region. These signatures are only imprinted on the stellar light when it is transmitted through the planetary atmosphere during a transit, and they can be extracted through the differential method when compared to out-of-transit measurements. Such studies have been carried out by many ground-based large telescope and space telescope, in a wide range of spectral resolutions (e.g., Charbonneau et al. 2002; Snellen et al. 2010; Bean et al. 2010; Sing et al. 2016), resulting in robust detections of Na, K, H\textsubscript{2}O, CO, and scattering hazes (see the inventory listed in Bailey 2014 and Sing et al. 2016). A recent HST+Spitzer survey led by Sing et al. (2016) performed a comparative study on ten hot Jupiters covering 0.3 – 5\textmu m. This diverse hot Jupiter sample reveals a continuum from clear to cloudy atmospheres, and suggests clouds/hazes as the cause of weakened spectral features.

As the investigated sample increases, it is fundamental to construct a spectral sequence for exoplanets, for a global picture of population characteristics and formation/evolution scenarios, as we have achieved for stars and brown dwarfs. In the near-future the JWST will provide spectral resolutions at high SNR with a large wavelength coverage 0.6 – 28\textmu m that can distinguish among different atmospheric compositions. However, ground-based observations can also complement JWST by extending the wavelength range to $\lambda < 600$\textmu m, which is critical to examine spectral signatures arising from Rayleigh scattering, Na, or TiO/VO (Murgas et al. 2014; Nortmann et al. 2016; Chen et al. 2017a,b). The ideal starting point are low density planets, which are more likely to host extended atmospheric envelopes that can produce stronger transmission signals if cloud-free.

WASP-127b (Lam et al. 2017), with a mass of $0.18 \pm 0.02 M_J$ and a radius of $1.37 \pm 0.04 R_J$, is the puffiest, lowest density, planet discovered to date. It has an orbital period of 4.18 days, and orbits a bright parent star (V = 10.2), which makes it a very interesting object for atmospheric follow-up studies.

WASP-127b’s host star is a G5 star which is at the end of the main-sequence phase and moving to the sub-giant branch (Lam et al. 2017). Moreover, the unusually large radius (compared to its sub-Saturn mass) cannot be explained by the standard coreless model (e.g., Fortney et al. 2007), and places it into the short-period Neptune desert, a region between Jovian and super-
Earth planets with a lack of detected planets (Howard et al. 2012; Mazeh et al. 2016). Several inflation mechanisms have been proposed to explain this inflation, including tidal heating, enhanced atmospheric opacity, Ohmic heating, and/or re-inflation by host star when moving towards the RGB phase (Leconte et al. 2010; Batygin & Stevenson 2010; Batygin et al. 2011; Lammer et al. 2013; Rauscher & Menou 2013; Spiegel & Burrows 2013; Wu & Lithwick 2013; Lopez & Fortney 2016), although no concluding observations have yet been established to favour one or the other. Therefore, the formation and evolution mechanisms of WASP-127b are very intriguing, given its transition size between these two classes of planets.

Fig. 1. Example stellar spectra of WASP-127 (red) and the reference star (blue) obtained with the Grism #4 of NOT on the night of February 23, 2017. The color-shaded areas indicate the divided passbands that are used to create the spectroscopic light curves. Note how the oxygen-A band region is excluded.

2. Observations and data reduction

We observed one transit of WASP-127b on the night of February 23rd, 2017, using the Andalucia Faint Object Spectrograph and Camera (ALFOSC) mounted at the 2.5 m Nordic Optical Telescope (NOT) at ORM observatory. ALFOSC has a field of view of 6′.4×6′.4 and a 2048×2048 E2V detector with a pixel size of 0″.2. The observation was carried out in the long-slit mode using a 40″ wide slit to avoid flux losses, and placing both WASP-127 and a reference star simultaneously aligned into the slit. The reference star TYC 4916-897-1 is located 40″.5 away from WASP-127 and it is about one magnitude fainter (V = 11.2) over the observed spectral range. Grism #4 was used covering simultaneously the spectral range from 320-960 nm. Observations started at 23:45 UT and ended at 05:36 UT, resulting in a time series of 746 spectra. Exposure times were set to 20s. The transit of WASP-127b (T_{trans}) started at 00:19 UT and ended at 04:38 UT, resulting in 554 spectra taken within transit. The night was clear, with a relatively stable seeing of around 0″.5 during the full observation. The airmass changed from 1.35 to 1.19, then to 2.45.

Data reduction was carried out using the approach outlined in Chen et al. (2016, 2017a) for similar OSIRIS long-slit data taken with the GTC. The one-dimensional spectra (see Figure 1) were extracted using the optimal extraction algorithm (Horne 1986) with an aperture diameter of 13 pixels, which minimized the scatter for the white-color light curves created from various trial aperture sizes. The time stamp was centered on mid-exposure of auxiliary state vectors, including spectral and spatial position drifts (x, y), spectra’s full width at half maximum (FWHM) in the spatial direction (s_x), airmass (z), and time sequence (t).

Fig. 2. Panels from top to bottom: (1) raw flux of WASP-127 (black line) and the reference star (red line) obtained with ALFOSC at NOT; (2) relative flux between the WASP-127 and the reference star (black dots) and the best-fitting combined model (red line), (3) same as in panel 2, but detrended, (4) best-fitting light-curve residuals.

3. Light-curve analysis

The light-curve data were modeled in the approach detailed in Chen et al. (2016, 2017a). In brief, the light-curve model contains two multiplicative components. One component describes the astrophysical signal, which adopts the analytic transit model \( T(p) \) proposed by Mandel & Agol (2002). The other component describes the systematics of telluric or instrumental origins in a fully parametric form or in a semi-empirical form, which is designated as the baseline model \( B(c) \).

The transit model \( T(p) \) was parameterized as orbital period \( P \), inclination \( i \), scaled semi-major axis \( a/R_\star \), planet-to-star radius ratio \( R_p/R_\star \), mid-transit time \( T_{mid} \), and limb-darkening coefficients \( u_i \), where a circular orbit was assumed. The orbital period \( P \) was fixed to 4.178062 days as reported by Lam et al. (2017). A quadratic limb-darkening law was adopted and conservatively constrained by Gaussian priors of width \( \sigma = 0.1 \), whose central values were calculated from the ATLAS atmosphere models following Espinoza & Jordán (2015) with stellar parameters \( T_{eff} = 5750 \, K \), log \( g = 3.9 \), and [Fe/H] = −0.18.

The baseline model \( B(c) \) consisted of a selected combination of auxiliary state vectors, including spectral and spatial position drifts (x, y), spectra’s full width at half maximum (FWHM) in the spatial direction (s_x), airmass (z), and time sequence (t).
Table 1. Derived system parameters for white light curve analysis

| Parameter | Value |
|-----------|-------|
| $P$ [days] | 4.178062 (fixed) |
| $e$ | 0 (fixed) |
| $T_{\text{mid}}$ [BJD$_{\text{TDB}}$] | 2457808.60283 ± 0.00031 |
| $i$ [°] | 88.2 $^{+0.9}_{-0.3}$ |
| $a/R_\star$ | 7.95 $^{+0.19}_{-0.27}$ |
| $R_p/R_\star$ | 0.1004 $^{+0.0004}_{-0.0014}$ |
| $u_1$ | 0.365 ± 0.057 |
| $u_2$ | 0.258 $^{+0.08}_{-0.05}$ |

The Bayesian information criterion (BIC; Schwarz 1978) was used to find the baseline model that can best remove the systematics. For the white-color light-curve, the model was chosen in a semi-empirical form:

$$BIC = \Delta \sum \text{of}$$

gave the lowest BIC value. The second best model yields a value $BIC = 3.3$ higher. For the spectroscopic light-curves, the model was chosen in a semi-empirical form:

$$BIC = \Delta \sum \text{spec}(\lambda) = S_w \times (c_0 + c_1 S\lambda(\lambda) + c_2 T + c_3 \lambda^2),$$

which inherited a common-mode component $S_w$ determined from the white-color light-curve. The common-mode systematics $S_w$ were derived after dividing the white-color light-curve by the best-fitting transit model $T(p)$. The Transit Analysis Package (TAP; Gazak et al. 2012), customized for our purposes, was employed to perform the Markov chain Monte Carlo analysis. The correlated noise was taken into account by the wavelet-based likelihood function proposed by Carter & Winn (2009). The overall transit parameters were determined from the white-color light-curve, whose best-fitting values and associated uncertainties were calculated as the median and 1σ percentiles of the posterior probability distributions and listed in Table 1. For the spectroscopic light-curves, only the planet-to-star radius ratio $R_p/R_\star$, the limb-darkening coefficients $u_i$, and the baseline coefficients $c_i$ were fit, while the other transit parameters were fixed to the ones determined from the white-light-curve. The wavelength-dependent radius ratios are presented in Table A.1. The white-color and spectroscopic light-curves are shown in Fig. 2 and A.1, respectively.

4. Results and Discussion

4.1. Second order contamination

When using the grism #4 with ALFOSC, second order contamination can be present due to the overlap in the detector of different diffraction orders (Stanishev 2007). To check this issue, on March 21st 2017, we performed consecutive observations of WASP-127 with the grism #4, with and without the second order blocking filters #101 (GG475) and #102 (OG515). We find that for WASP-127, second order contamination of the stellar flux appears at 1% level at 655 nm and rises nearly monotonically reaching 10% at 900 nm. Following the approach of Stanishev (2007), we were able to directly remove the second order component of the blue light from the first order stellar spectra, and then to derive a new transmission spectrum. As shown in Fig. 3, this correction makes the transit depths slightly smaller at red wavelengths ($\lambda \geq 600$ nm), which agree with the original ones well within the error bars and still show the same relative spectral shape.

Table 2. Goodness of fit for different atmospheric models

| Model | 415–885 nm | 415–655 nm |
|-------|------------|------------|
| $\chi^2$ | $P(\chi^2)$ | $\chi^2$ | $P(\chi^2)$ |
| Pure Rayleigh Scattering (RS) | 22.11 | 0.453 | 4.89 | 0.936 |
| Flat | 18.83 | 0.656 | 8.43 | 0.645 |
| 1×solar, Na/K, 5×RS | 24.97 | 0.299 | 10.61 | 0.477 |
| 0.1×solar, Na/K, clear | 23.95 | 0.350 | 13.40 | 0.268 |
| 0.1×solar, Na, 5×RS | 23.29 | 0.386 | 5.79 | 0.887 |
| 0.1×solar, Na/K/TiO/VO, 5×RS | 13.60 | 0.915 | 5.51 | 0.904 |
| 0.1×solar, TiO/VO, 5×RS | 11.73 | 0.963 | 4.45 | 0.955 |

4.2. Transmission spectrum

To interpret the transmission spectrum of WASP-127b, a series of atmospheric models with an isothermal temperature structure were generated using the Exo-Transmit code (Kempton et al. 2016). Various metallicities, chemical compositions (with or without the presence of Na, K, TiO, VO), and weather conditions (clear, hazy, or cloudy) were considered. We also analytically calculated a pure Rayleigh scattering model following the approach of Leclavelier Des Etangs et al. (2008), and used a simple flat straight line to represent the gray absorbing clouds.

It is clear from Fig. 3 that the transmission spectrum is not flat, but on the contrary it has strong spectral features. It is not surprising that we can detect spectral features even using a relatively small aperture telescope, given that one atmospheric scale height, $H$, of WASP-127b corresponds to approximately 2500 km (equivalent to a signal of 510 ppm) assuming an H-He atmosphere, and that the amplitude of a given spectral signature can typically achieve about $5H$ (e.g., Seager 2010).

At the bluer wavelengths, the spectrum shows a decreasing slope with $\lambda$, which seems to indicate the presence of Rayleigh scattering. A hint of Na absorption is seen (although statistically insignificant), with the band centered on the Na doublet presenting a larger $R_p/R_\star$ value than the surrounding bands. Unfortunately, the analysis of narrower pass bands around Na did not provide more information but increasing noise (not shown). No K absorption is seen. Toward the red, strong absorptions from TiO and VO molecules seem to dominate the spectral shape.

Fitting the different models to the whole spectral range (415–885 nm) or the blue spectral range free of second order (415–655 nm), the one with the minimum $\chi^2$ is always precisely the model including only TiO/VO, and with an enhanced Rayleigh slope indicative of some haze in the atmosphere (see Figure 3, and Table 2 for $\chi^2$ fitting results). We find that the best fitting models are metal poor, which is interesting because the host star is also metal poor ([Fe/H] $= -0.18 \pm 0.06$).

Given the relatively cool equilibrium temperature of WASP-127b ($T_{eq} = 1400 K$; Lam et al. 2017), the tentative inference of the TiO/VO molecules is somewhat unexpected and intriguing. For planets with equilibrium temperatures lower than $\sim 1900 K$, TiO could be cold trapped in the deep atmospheric layers when the temperature-pressure profile crosses the condensation curve (Showman et al. 2009; Parmentier et al. 2013, 2016). Several other possibilities could also account for TiO/VO’s absence in the upper atmosphere (Spiegel et al. 2009). Until now only two very hot Jupiters, that is WASP-121b ($T_{eq} = 2400 K$; Evans et al. 2016).
Fig. 3. The NOT/ALFOSC transmission spectrum of WASP-127b, using bins 20 nm wide in wavelength. Error bars are ±1σ errors. The left panel shows the transmission spectra with (black) or without (blue) the second order correction in the stellar spectra. The right panel shows two 0.1σ solar atmospheric models computed using Exo-Transmit (Kempton et al. 2016, red model: with TiO/VO but without Na/K, 5× Rayleigh scattering, sky-blue model: with Na/K but without TiO/VO, clear), and a pure Rayleigh slope, together with the corrected transmission spectrum.

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Appendix A: Spectro-photometric data

Observed color light curves are shown in Figure A.1 and the derived transit depths at each spectral pass band are given here in Table A.1.

Table A.1. Transmission spectrum values obtained with NOT/ALFOSC

| # | Wavelength (nm) | $R_p/R_*$ (With 2nd order) | $R_p/R_*$ (Corrected) |
|---|----------------|-----------------------------|------------------------|
| 1 | 425            | 0.0977 ± 0.0045             | 0.0977 ± 0.0045        |
| 2 | 445            | 0.0984 ± 0.0029             | 0.0984 ± 0.0029        |
| 3 | 465            | 0.1022 ± 0.0025             | 0.1022 ± 0.0025        |
| 4 | 485            | 0.1011 ± 0.0018             | 0.1011 ± 0.0018        |
| 5 | 505            | 0.0986 ± 0.0024             | 0.0986 ± 0.0024        |
| 6 | 525            | 0.0996 ± 0.0019             | 0.0996 ± 0.0019        |
| 7 | 545            | 0.0976 ± 0.0022             | 0.0976 ± 0.0022        |
| 8 | 565            | 0.0950 ± 0.0029             | 0.0950 ± 0.0029        |
| 9 | 585            | 0.0990 ± 0.0017             | 0.0990 ± 0.0017        |
| 10| 605            | 0.0977 ± 0.0019             | 0.0971 ± 0.0019        |
| 11| 625            | 0.0959 ± 0.0025             | 0.0955 ± 0.0027        |
| 12| 645            | 0.0975 ± 0.0026             | 0.0970 ± 0.0028        |
| 13| 665            | 0.0994 ± 0.0019             | 0.0991 ± 0.0020        |
| 14| 685            | 0.1009 ± 0.0025             | 0.1006 ± 0.0026        |
| 15| 705            | 0.1009 ± 0.0024             | 0.1002 ± 0.0026        |
| 16| 725            | 0.1033 ± 0.0023             | 0.1018 ± 0.0023        |
| 17| 745            | 0.1019 ± 0.0029             | 0.1006 ± 0.0030        |
| 18| 775            | 0.0988 ± 0.0037             | 0.0973 ± 0.0043        |
| 19| 795            | 0.1019 ± 0.0020             | 0.1000 ± 0.0020        |
| 20| 815            | 0.0962 ± 0.0029             | 0.0940 ± 0.0029        |
| 21| 835            | 0.0965 ± 0.0025             | 0.0946 ± 0.0027        |
| 22| 855            | 0.0966 ± 0.0026             | 0.0948 ± 0.0030        |
| 23| 875            | 0.0981 ± 0.0040             | 0.0971 ± 0.0043        |

Fig. A.1. Spectroscopic light-curves of WASP-127 and the best-fitting models after the common-mode systematics have been removed.