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Unveiling an exoplanetary Neptunian atmosphere through multiband transit photometry

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Abstract. The "effective" radius of a planet is a function of wavelength due to scattering and/or absorption processes, and we can exploit simultaneous multiband transit photometry to probe the atmospheric scale height and composition. We present new photometric data of the recently discovered "hot Uranus" GJ3470b, gathered with the LBC camera at LBT. Light curves of unprecedented accuracy (0.0012 mag in U and 0.00028 mag in a narrow band centered at 972 nm) allowed us to measure an increasingly larger planetary radius at shorter wavelengths, which we interpret as a signature of Rayleigh scattering by a large scale height atmosphere. Further follow-up observations to confirm this result and probe the presence of specific atomic and molecular species is ongoing.

Keywords. Techniques: photometric, stars: planetary systems, stars: individual: GJ3470

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1. Introduction

Low-mass planets such as "Super-Earths" ($2 \lesssim M_\mathrm{p} \lesssim 10\ M_\oplus$) and "Neptunian" planets ($15 \lesssim M_\mathrm{p} \lesssim 50\ M_\oplus$) are puzzling theoreticians, revealing a complex diversity which cannot be easily explained by models or constrained by observations (Haghighipour 2011). These two classes were once hypothesized to be separate and well defined samples of rocky and icy planets, respectively. Now we realize that their measured densities range from $\rho_\mathrm{p} = 0.27$ to $\sim 10\ \mathrm{g\,cm^{-3}}$ (Wright *et al.* 2011), with a significant overlap between super-Earths and Neptunes. In this mass range, average densities are unable to put a firm constraint on the inner structure of the planet, and theoretical models can lead to several degenerate solutions (Adams *et al.* 2008). An emblematic case is that of GJ1214b (Charbonneau *et al.* 2009), for which allowed scenarios include a "mini-Jupiter", a Neptune-like planet, a "water world", or a rocky super-Earth (Rogers & Seager 2010).

Additional information other than ρ_p is required to break the model degeneracy, and an effective way to do it is to search for spectral signatures coming from the planetary atmosphere to probe its composition and physical state (Seager & Deming 2010). *Transmission spectroscopy* is a technique based on the observation of exoplanetary transits at different wavelengths, searching for changes of its effective radius $R_\mathrm{p}(\lambda)$ as a function of λ due to absorption and/or scattering processes undergone by stellar light after traveling through the atmospheric limb (Sing *et al.* 2011). Rayleigh scattering, due to molecules such as H_2 (Lecavelier *et al.* 2008b) or to haze from condensate particles (Fortney 2005, Lecavelier *et al.* 2008a), has a typical signature: its steep λ^{-4} dependence, which

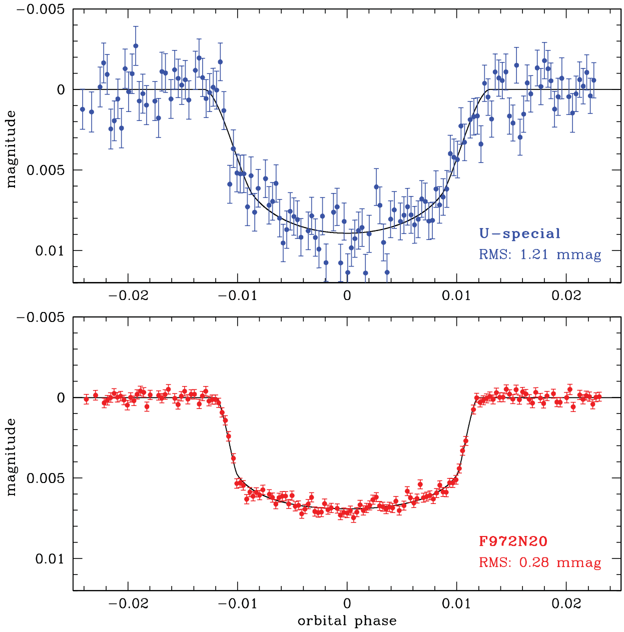

Figure 1. Light curves of GJ3470b gathered with LBC in the $U_{\rm spec}$ band (*upper panel*), and in the $F972N20$ band (*lower panel*), plotted with the original sampling cadence (the solid line is the best-fit model). The two light curves are simultaneous.

translates into a larger $R_{\rm p}$ on the blue side of the optical spectrum. Thus the scale height $H = kT_{\rm eq}/\mu g$ (and hence the mean molecular weight μ, once an equilibrium temperature $T_{\rm eq}$ and surface gravity g are assumed) can be inferred from the steepness of $R_{\rm p}(\lambda)$.

GJ3470b is a "hot Uranus" planet orbiting in about 3.3 days around its M1.5V host star, discovered by a radial velocity search and then caught transiting through ground-based photometry (Bonfils *et al.* 2012). Very recently, a follow-up analysis based on Spitzer, WIYN-3.5m and Magellan data (Demory *et al.* 2013) resulted in updated values for the mass and radius of GJ3470b: $M_{\rm p} = 13.9 \pm 1.5\ M_{\oplus}$ and $R_{\rm p} = 4.83 \pm 0.21\ R_{\oplus}$, making it one of the least dense, low-mass planets known with $\rho_{\rm p} = 0.72 \pm 0.13$ g cm^{-3}. Showing this peculiarity, having a total mass at the boundary between super-Earths and Neptunes, GJ3470b stands out as an ideal case to test the present planetary structure and evolution theories, which predict for it a significantly extended envelope of primordial H and He (Demory *et al.* 2013, Rogers & Seager 2010) and thus a large scale height.

2. Observations and data analysis

We observed a full transit of GJ3470b at the Large Binocular Telescope (LBT) on the night of 2013 Feb 16, under a photometric sky. The Large Binocular Camera (LBC) consists of two prime-focus, wide-field imagers mounted on the left and right arm of LBT, and optimized for blue and red optical wavelengths, respectively. We exploited their full power to gather two simultaneous photometric series, setting the $U_{\rm spec}$ filter on the blue channel (a Sloan u-like filter centered at $\lambda_{\rm c} = 357.5$ nm) and the $F972N20$ filter in the red channel (a narrow-band filter centered at $\lambda_{\rm c} = 963.5$ nm). This choice of passbands has been made to maximize the wavelength span of our observations while at the same time avoiding most of telluric lines in the red channel.

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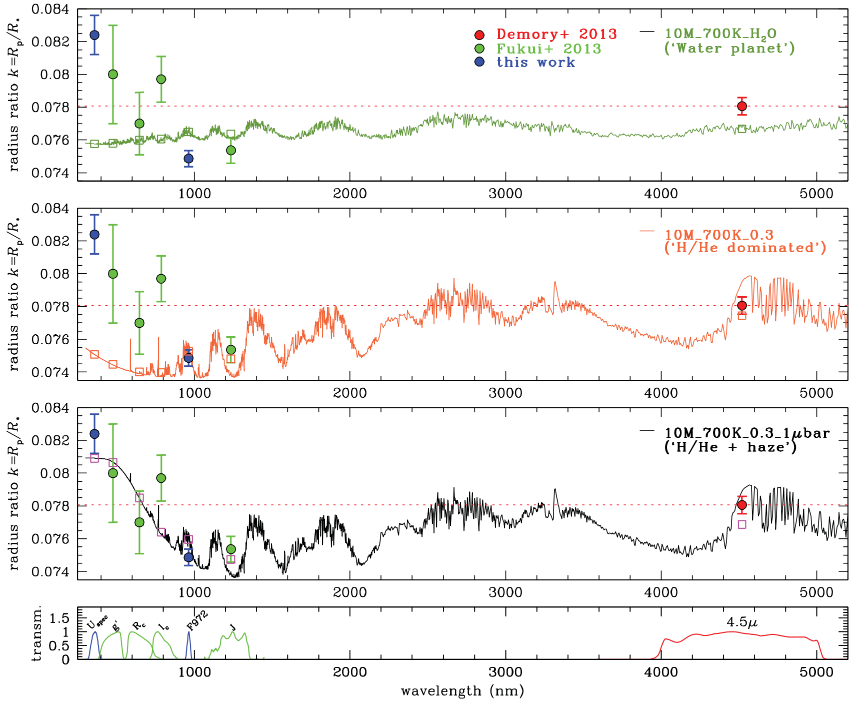

Figure 2. Reconstructed transmission spectrum of GJ3470b. The $U_{\rm spec}$ and $F972N20$ data points are extracted from our LBC light curves, the $g'R_cI_cJ$ points from Fukui *et al.* (2013), and the 4.5μm point from Demory *et al.* (2013). The model plotted with a solid line is scaled from a Howe & Burrows (2012) model computed for a 10-$M_\oplus$ cloud-free, haze-free planet with $T_{\rm eq}$ = 700 K and a pure water (H_2O) atmosphere. *Second panel:* same as above, but with a cloud-free, haze-free, metal-poor atmosphere dominated by H and He, computed by the same authors. Abundances are scaled from the solar ones ($Z = 0.3 \times Z_\odot$) *Third panel:* same as above, but adding the contribution of a scattering haze from Tholin particles at 1 μbar. *Lower panel:* Instrumental passbands employed for each data point.

Both the $U_{\rm spec}$ and $F972N20$ light curves of GJ3470 were extracted using STARSKY, a photometric pipeline optimized to perform high-precision differential aperture photometry over defocused images, originally developed for the TASTE project (Nascimbeni *et al.* 2013). The resulting light curves are plotted in Fig. 1 in their original cadence. Their overall RMS scatter is 1.19 mmag ($U_{\rm spec}$) and 0.28 mmag ($F972N20$) over a mean cadence of 95 s, only slightly larger than the theoretical values estimated by standard "white noise" formulae. It is worth noting that the $F972N20$ series is, to our knowledge, the most accurate light curve ever obtained from a ground-based facility. The JKTEBOP code version 28 (Southworth *et al.* 2004) was employed to fit a transit model over the light curves. We derived the best-fit uncertainties with a Monte Carlo bootstrap algorithm to avoid underestimation due to correlations between parameters and residual systematic noise. The output parameters include the ratio $k = R_{\rm p}/R_\star$ between the radius of the planet and the radius of the star.

3. Results

If we examine the transmission spectrum of GJ3470b as reconstructed by our LBC measurements and from those by Demory *et al.* (2013) and Fukui *et al.* (2013) (Fig. 2, large circles), it appears evident that no constant value of k could explain the data

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($\chi^2 = 67.8$ for 5 degrees of freedom, corresponding to a reduced value of $\chi^2_{\rm r} = 13.5$). The color dependence of k is then significant, with a steep increase toward the blue side of the spectrum which is usually associated with scattering processes. How can we interpret this spectrum $k(\lambda)$? We rescaled the model transmission spectra computed by Howe & Burrows (2012) taking the grid point of their simulations closer to GJ3470b ($T_{\rm eq} = 700K$, $M_{\rm p} = 10M_{\oplus}$) and investigating which class of atmospheric composition best matches the observed data points, and which ones can be excluded.

The most striking result is that the large observed variations of $k(\lambda)$ are totally incompatible with all model sets by Howe & Burrows (2012) having an atmosphere of high mean molecular weight μ, such as those made of pure H_2O (solid line in Fig. 2, upper panel) or pure methane (CH_4). All those models predict a very flat spectrum due to their tiny scale height, and are rejected by the available data at $>10\sigma$. On the other hand, we investigated the fitness of cloud-free, haze-free atmospheric models of low μ, that is largely dominated by H and He and with a large scale height H. This is the most probable atmospheric composition expected for GJ3470b following current theories on planetary interiors (Demory *et al.* 2013, Rogers & Seager 2010). A metal-poor model atmosphere (solid line in the second panel of Fig. 2) provides us with a much better fit on the red/IR passbands (F972N20, J, 4.5μm), but it fails at reproducing the steep rise observed on the blue side of the spectrum, especially for our $U_{\rm spec}$ measurement.

An additional source of scattering, other than H_2, seems to better explain the data. Fortney (2005) showed that condensate particles can be very efficient in this regard. Indeed, the Howe & Burrows (2012) class of models with a metal-poor H/He dominated atmosphere and high-altitude hazes from Tholin provide us with a satisfactory fit with $\chi^2_{\rm r} = 5.2$ (solid line in Fig. 2, third panel).

Additional high S/N observations will be required to confirm this scenario, especially in the H and K spectral region, where molecular bands such as H_2O, CO or CH_4 are expected to dominate the trasmission spectrum giving rise to strong features (Fig. 2).

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Discussion

Bonnefoy: How far do we know the transmission properties of tholins?

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NASCIMBENI: Yes, this is right. Remember that it is still an ad-hoc model. I can say that tholins are able to reproduce the optical data.

BEATTY: How much do uncertainties in the theoretical limb-darkening coefficients affect your final error bars?

NASCIMBENI: The linear LD coefficients were fitted on both light curves, while the quadratic terms along with their theoretical uncertainties were input as Gaussian priors in our bootstrap analysis, so the final result takes it into account.

TRIAUD: How did you choose your reference stars to prevent colour effects?

NASCIMBENI: It is hard to find proper reference stars. Giants were removed, other effects of colours would show as airmass-dependent effects out of transit. These are accounted for.

WIKTOROWICZ: Defocusing to keep from saturating in the red channel probably limits your precision in U band. Can you change the focus of the two channels independently?

NASCIMBENI: Yes, our U band precision is limited by the fact that the integration times have to be the same between the two channels.