Optical observations of the transiting exoplanet GJ 1214b

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ABSTRACT

We observed nine primary transits of the super-Earth exoplanet GJ 1214b in several optical photometric bands from 2012 March to August, with the goal of constraining the short-wavelength slope of the spectrum of GJ 1214b. Our observations were conducted on the Kuiper 1.55 m telescope in Arizona and the STELLA-I robotic 1.2 m telescope in Tenerife, Spain. From the derived light curves we extracted transit depths in R′ (0.65 µm), V (0.55 µm) and g′ (0.475 µm) bands. Most previous observations of this exoplanet suggest a flat spectrum varying little with wavelength from the near-infrared to the optical, corresponding to a low-scale height, high-molecular-weight atmosphere. However, a handful of observations around Ks band (−2.15 µm) and g band (−0.46 µm) are inconsistent with this scenario and suggest a variation on a hydrogen- or water-dominated atmosphere that also contains a haze layer of small particles. In particular, the g-band observations of de Mooij et al., consistent with Rayleigh scattering, limit the potential atmosphere compositions of GJ 1214b due to the increasing slope at optical wavelengths. We find that our results overlap within errors the short-wavelength observations of de Mooij et al., but are also consistent with a spectral slope of zero in GJ 1214b in the optical wavelength region. Our observations thus allow for a larger suite of possible atmosphere compositions, including those with a high molecular weight and/or hazes.

Key words: techniques: photometric – planets and satellites: atmospheres – planets and satellites: individual: GJ 1214b.

1 INTRODUCTION

Since the detection of the ‘super-Earth’ transiting extrasolar planet GJ 1214b (Charbonneau et al. 2009), its composition has been a topic of interest and debate. Discovered by the MEarth programme, GJ 1214b has a radius (2.85 ± 0.20 R⊙; Harpsøe et al. 2013) and mass (6.26 ± 0.86 M⊙; Harpsøe et al. 2013) only slightly larger than that of the Earth, and transits a nearby (13 pc) M star (0.216 ± 0.012 R⊙; Harpsøe et al. 2013) with an orbital period of 1.5804 d and a semimajor axis of 0.0197 au (Harpsøe et al. 2013). This causes a planet-to-star flux ratio comparable to that of a Jupiter-sized planet orbiting the Sun, and makes it one of only a handful of ‘super-Earth’ atmospheres that currently can be investigated with transit spectroscopy (Charbonneau et al. 2009). GJ 1214b represents a unique opportunity to study a planetary object unlike those in our Solar system, yet potentially similar to a large fraction of currently detected exoplanets, many of which are smaller than Jupiter sized (Borucki et al. 2010, 2012; Howard et al. 2010; Muirhead et al. 2012).

The mass and radius of GJ 1214b imply a low density of 1.87 ± 0.40 g cm−3 (∼0.35 ρEarth; Rogers & Seager 2010) and suggest that GJ 1214b cannot be composed of rock and water ice alone, but likely has a significant gaseous atmosphere (Bean, Miller-Ricci Kempton & Homeier 2010; Miller-Ricci & Fortney 2010; Kundurthy et al. 2011). Models of its interior structure indicate that GJ 1214b’s composition is most likely either (i) a mini-Neptune made of mainly solid rock and ice with a significant hydrogen-dominated atmosphere accreted from its protoplanetary nebula, (ii) a world composed mainly of water ice with a secondary water vapour envelope formed by sublimation or (iii) an object composed of purely rocky material with a hydrogen-dominated atmosphere formed by outgassing (Rogers & Seager 2010). A determination of the current composition of GJ 1214b will shed light on this planet’s formation history, and thus potentially that of other super-Earth planets. If GJ 1214b’s atmosphere is largely hydrogen, it is likely formed from the accretion of protosolar nebular gas or from the outgassing of significant amounts of hydrogen during the planet’s cooling and solidification (Miller-Ricci Kempton, Zahnle & Fortney 2012). However, if instead the atmosphere is water rich, then GJ 1214b could have formed from ice-rich material farther out in the protoplanetary disc before migrating inwards towards the star. Alternatively or in addition, the planet could have accreted less
hydrogen-dominated nebular gas in the first place, or lost by atmospheric escape any hydrogen-rich gas that it did accrete (Rogers & Seager 2010).

Transmission photometry and spectroscopy indicate the bulk composition of GJ 1214b by measuring the attenuation of stellar light as it passes through the limb of the exoplanet’s atmosphere. The modulation in the spectrum with wavelength increases with the atmosphere’s scale height, which is inversely proportional to the atmosphere’s molecular weight. The modulation in GJ 1214b’s spectrum thus distinguishes between its possible compositions, since models (i) and (iii) (listed above) will have a large scale height and show prominent spectral features from absorption by molecular hydrogen, whereas model (ii) will have relatively small spectral features and scale height.

Several studies using transmission observations to determine GJ 1214b’s atmospheric scale height and composition have been published. From the optical (∼0.6 μm) through the near-infrared (4.5 μm), most measurements indicate no significant spectral modulation with wavelength in the atmosphere of GJ 1214b (Bean et al. 2010, 2011; Crossfield, Barman & Hansen 2011; Désert et al. 2011; Berta et al. 2012; Narita et al. 2012). Taken together, these observations suggest that GJ 1214b has a small scale height, and favours model (ii) above, in which the exoplanet’s atmosphere is dominated by water rather than hydrogen. However, there are hints of deviation (albeit with less statistical significance) from the flat-spectrum model in K, band (2.15 μm; Croll et al. 2011; de Mooij et al. 2012), g band (0.46 μm; de Mooij et al. 2012) and R band (0.65 μm; Murgas et al. 2012). Including these latter observations requires modification of the water-world explanation. Collectively, the observations may alternatively be explained by a hydrogen-dominated atmosphere with an opacity source causing the muted spectral features (Howe & Burrows 2012; Miller-Ricci Kempston et al. 2012).

The increase in the radius ratio observed at short wavelengths is roughly consistent with Rayleigh scattering in an atmosphere with a relatively high scale height.

The goal of this paper is to constrain the transmission spectrum of GJ 1214b in the optical wavelength bands (≤0.70 μm) in order to study the short-wavelength slope and the scattering regime in GJ 1214b’s atmosphere. If the short-wavelength data are indicative of a Rayleigh scattering power law, this indicates a relatively high-scale height atmosphere, and scattering particles that are much smaller than the wavelength of light. A shallower slope in the short-wavelength data would indicate a particle size closer to the Mie scattering regime, ∼1 μm, or a small scale height atmosphere.

In Section 2, we give an overview of our observations and data reduction procedures. We discuss our transit light-curve analysis in Section 3 and the implications of our results in Section 4.

## 2 OBSERVATIONS AND DATA REDUCTION

Our R- and V-band observations of the transit of GJ 1214b were conducted between 2012 March and June at the Steward Observatory 1.55 m Kuiper Telescope on Mt. Bigelow near Tucson, Arizona using the Mont4k CCD. The Mont4k CCD contains a 4096× pixel sensor with a field of view (FOV) of 9.7 arcmin × 9.7 arcmin. We used 3 × 3 binning to achieve a resolution of 0.43 arcsec pixel−1, and a 3072 × 1024 pixel subframe with a FOV of 7.28 arcmin × 2.43 arcmin to shorten read-out time to roughly 10 s. Our observations were taken with the Harris V [473–686 nm; full width at half-maximum (FWHM) 88 nm] and Harris R (550–900 nm; FWHM 138 nm) photometric band filters, and we did not defocus the telescope (GJ 1214A is not bright enough to saturate the detector with our short integration times). To ensure accurate timekeeping, an onboard clock was automatically synchronized with a global positioning system (GPS) every few seconds throughout the observational period. Due to excellent autoguiding, there was no more than a 4.4 pixels (∼1.9 arcsec) drift in the x position and 2.1 pixels (∼0.9 arcsec) in the y position of GJ 1214A in all our data sets for the Kuiper 1.55 m telescope (with averages of 0.03 arcsec in the x position and 0.06 arcsec in the y position). Our Kuiper 1.55 m observations are summarized in Table 1.

All g′-band (401–550 nm; FWHM 153 nm) transit observations were taken between 2012 May and August with STELLA-I, a fully robotic 1.2 m telescope in Tenerife, Spain (Strassmeier et al. 2010). Its Wide Field STELLAR Imaging Photometer (WiFISP) hosts a 40962×15 μm pixel back-illuminated CCD. It images an FOV of 22 arcmin × 22 arcmin with a scale of 0.322 arcsec pixel−1. Because of a sufficiently high density of suitable comparison stars in the field of GJ 1214A, we applied a CCD window of 20002 pixels, reducing the FOV to about 11 arcmin × 11 arcmin. We did not defocus the telescope because there was no danger of saturation of GJ 1214A due to its faintness at blue wavelengths. Each transit observation lasted ∼3 h covering a sufficient amount of out-of-transit baseline before and after the rather short transit of ∼53 min. The robotic telescope took 98 exposures per run with 90 s exposure time and 20 s overhead resulting in a cadence of about 110 s. Our STELLA-I 1.2 m observations are summarized in Table 1.

Using standard IRAF1 reduction procedures, each of our Kuiper 1.55 m images were bias-subtracted and flat-fielded. Turner et al.

### Notes

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
(2013) determined that using different numbers of flat-field images (flats) in the reduction of Kuiper telescope/Monk4k data did not significantly reduce the noise in the resulting images. Thus, to save time, we used 10 flats in all sequential observations and reductions, as well as 10 bias frames taken during each observing run.

To produce the light curves from the Kuiper 1.55 m data, we performed the light aperture photometry (using the task PHOT in the IRAF DAOPHOT package) by measuring the flux from our target star as well as the flux from several (usually between 5 and 10) companion stars within an aperture radius that varied based on the star and the observing night conditions. For the analysis of each night’s observations, we used a constant sky annulus (with a width of 20 pixels), which was chosen to always start at a radius greater (by at least 7 pixels) than the target aperture; no stray light from the star was included. Considering several different combinations of reference stars and aperture radii, we picked the combination that produced the lowest rms in the out-of-transit data points. To check that our derived transit depth from the Kuiper 1.55 m data was not dependent on the chosen aperture radius, we also tested several different aperture radii and found that the resulting change in transit depth was not significant based on our derived errors, which are a factor of \( \sim 2 \) larger. A synthetic light curve was produced by averaging the light curves from our reference stars, and the final light curves of GJ 1214b were normalized by dividing by this synthetic light curve. The light curves for all of our data are shown in Fig. 1 with 1σ errors on each point converted from magnitude errors provided by the IRAF reduction. The out-of-transit baseline in all transits achieved a photometric rms between 2 and 4 mmag (~2.5 times the photon noise limit), which is typical for the Mont4k on the 1.55 m Kuiper telescope for high-S/N transit photometry (Dittmann et al. 2009a,b, 2010, 2012; Scuderi et al. 2010; Turner et al. 2013).

For the STELLA-I 1.2 m WiFSIP data, we developed a photometry data reduction pipeline that is based on ESO MIDAS routines to subtract a bias using the overscan regions and a 2 d bias structure using a master bias. The robotic system cycles through all filters of WiFSIP to take twilight flat-fields resulting in a time difference between science data and appropriate flat-field observations of less than 3 d. One master flat-field based on ~20 flat-field exposures was used for flat-field correction. We performed aperture photometry using the publicly available software SExtractor\(^2\) (Bertin & Arnouts 1996), which supplies several options for aperture photometry; we tested the estimation of fixed aperture magnitudes and automatic aperture magnitudes in our pipeline. For both options several aperture widths were tested to minimize the scatter of the out-of-transit data, and we consistently find an automatic aperture to yield the lowest rms value. Again, to check that our derived transit depth from the STELLA-I 1.2 m WiFSIP data was not dependent on the chosen aperture radius, we also tested several different aperture radii and found that the resulting change in transit depth was not significant based on our derived errors. It should be mentioned that this option does not use a constant aperture shape over the FOV, nor the same aperture shape and width throughout the exposure time series. It computes an elliptical aperture for every exposure and object using a master bias. The robotic system cycles through all filters of WiFSIP to take twilight flat-fields resulting in a time difference between science data and appropriate flat-field observations of less than 3 d. One master flat-field based on ~20 flat-field exposures was used for flat-field correction. We performed aperture photometry using the publicly available software SExtractor\(^2\) (Bertin & Arnouts 1996), which supplies several options for aperture photometry; we tested the estimation of fixed aperture magnitudes and automatic aperture magnitudes in our pipeline. For both options several aperture widths were tested to minimize the scatter of the out-of-transit data, and we consistently find an automatic aperture to yield the lowest rms value. Again, to check that our derived transit depth from the STELLA-I 1.2 m WiFSIP data was not dependent on the chosen aperture radius, we also tested several different aperture radii and found that the resulting change in transit depth was not significant based on our derived errors. It should be mentioned that this option does not use a constant aperture shape over the FOV, nor the same aperture shape and width throughout the exposure time series. It computes an elliptical aperture for every exposure and object by second-order moments of its light distribution (see also Matute et al. 2012; Polishook et al. 2012; Law et al. 2013). Several widths of the ‘rectangular annulus’ used for local background estimation by SExtractor were tested in order to minimize the out-of-transit scatter. The same criterion was also used in the pipeline to search automatically for the best combination of comparison stars. We allways started with the 25 brightest stars in the field and found four to seven calibration stars to give the optimal solution. The light curves for all of our data are shown in Fig. 1 with 1σ errors on each point converted from magnitude errors provided by the SExtractor reduction. The rms value of the out-of-transit STELLA-I data is in most cases ~1.2 times higher than the theoretical limit estimated from the photon noise of object and background and the read-out noise.

### 3 LIGHT-CURVE ANALYSIS

The light-curve depth is a measurement of the effective area of light from the primary star that is blocked by the occulting planet \((\frac{R_p}{D_p})^2\). The effective size of the planet depends on the opacity of the atmosphere, and thus the atmosphere’s spectral features and composition. To derive the light-curve depths, we used two different publicly available modelling software packages – the Transit Analysis Package\(^3\) (TAP; Gazak et al. 2012) and JKTEBOP\(^4\) (Southworth, Maxted & Smalley 2004a,b; Southworth 2008) – that simulate the shape of the light curves, considering the planet’s orbit and the limb darkening of the star. TAP utilizes Bayesian probability distributions with Markov Chain Monte Carlo (MCMC) techniques and a Gibbs sampler to fit transit light curves using the Mandel & Agol (2002) model and uses a wavelet likelihood function to more robustly estimate parameter uncertainties (Carter & Winn 2009). JKTEBOP was originally developed from the EBOP program written for eclipsing binary star systems (Etzel 1981; Popper & Etzel 1981) and uses the Levenberg–Marquardt Monte Carlo (LMMC) technique to compute errors, although there are additional error computation options (Southworth et al. 2004a,b; Southworth 2010; Hoyer et al. 2011).

We modelled each transit individually with TAP, after normalizing the out-of-transit data to one, using five MCMC chains with lengths of 100 000 links each. (We note that TAP does not take into account the 1σ individual-point errors as input.) The Gelman–Rubin statistic (Gelman & Rubin 1992) was used to ensure chain convergence, as outlined in Ford 2006. We also combined the data from the same bands into one simultaneous TAP analysis for each band in order to increase our sampling and precision; all of our TAP results are listed in Table 3. During the analysis, the inclination (\(i\)), scaled semimajor axis \((\frac{a}{D_p})\), eccentricity (\(e\)), argument of periastron (\(\omega\)), quadratic limb-darkening coefficients (\(\mu_1\) and \(\mu_2\)) and the orbital period \((P_b)\) of the planet were fixed to the values listed in Table 2. The time of mid-transit \((T_c)\) and planet-to-star radius ratio \((\frac{R_p}{D_p})\) were left as free parameters. In addition, white and red noise were left as free parameters, as were the airmass fitting parameters (slope and y-intercept). The linear \((\mu_1)\) and quadratic \((\mu_2)\) limb-darkening coefficients in each respective band were taken from Claret (1998) using approximations of the stellar parameters of GJ 1214 \((T_{eff} = 3000, \log g = 5.0)\). See Table 2 for the limb-darkening coefficients used for each band.

We also performed a similar analysis of our data with JKTEBOP in order to check our TAP results against a different TAP. We obtained results consistent with those from TAP, although with slightly smaller errors (~1.5–3 times smaller). Both JKTEBOP and TAP have been shown to produce similar results in the study of another transiting exoplanet, WASP-5b (Hoyer, Rojo & López-Morales 2012). Hoyer et al. (2012) found that, in its default mode, JKTEBOP can underestimate the errors in the fitted parameters because it lacks

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\(^2\) http://www.astromatic.net/software/sextractor

\(^3\) http://ifa.hawaii.edu/users/zgazak/IfA/TAP.html

\(^4\) http://www.astro.keele.ac.uk/jkt/codes/jktebop.html
Figure 1. Individual light curves of GJ 1214b for each date of observed transit (UTC), shown in chronological order (L-R; top-bottom). The data have all been normalized to one, and the linear trend derived from the TAP analysis removed. Overplotted with a red dashed line are the TAP analysis fits to the data. The residuals from the TAP analyses are shown in the lower panels of each plot. The 1σ error bars plotted on each point are based on the IRAF or SExtractor reduction and were not included in the TAP analysis fits.

multiparameter uncertainty estimation and does not account for red noise. By including the wavelet decomposition likelihood function (see Carter & Winn 2009), TAP allows parameters that measure photometric scatter (uncorrelated white noise and time-correlated red noise) to evolve as free parameters in the transit fitting; the TAP method will recover the traditional χ² fitting statistic in the case of no red noise and the white noise fixed to the characteristic measurement error (Johnson et al. 2011). Hoyer et al. (2011) also found that if the parameter space does not have local minima, the LMMC (JKTEBOP) and MCMC (TAP) algorithms are equivalent, but that LMMC minimization can get trapped in such minima, and that the LMMC results can be biased towards their initial input values.
Table 2. Fixed model values for TAP.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>1.580 404 81</td>
<td>Bean et al. (2011)</td>
</tr>
<tr>
<td>Inclination</td>
<td>88.94</td>
<td>Bean et al. (2011)</td>
</tr>
<tr>
<td>a/R$_{S}$</td>
<td>14.9749</td>
<td>Bean et al. (2011)</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Omega</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Harris V limb-darkening coefficients</td>
<td>0.6406, 0.2955</td>
<td>Claret (1998)</td>
</tr>
<tr>
<td>Harris R limb-darkening coefficients</td>
<td>0.5392, 0.3485</td>
<td>Claret (1998)</td>
</tr>
<tr>
<td>Sloan g’ limb-darkening coefficients</td>
<td>0.6528, 0.2978</td>
<td>Claret (2004)</td>
</tr>
</tbody>
</table>

We find similar results as Hoyer et al. (2012) in that the errors derived from our TAP analysis are slightly greater than the errors derived from our JKTEBOP analysis. We choose to use our TAP results throughout the rest of the paper due to their more conservative errors.

In the June 18 light curve, there appears to be a feature in the middle of the transit that could affect the TAP analysis and our measurement of R$_{p}$/R$_{S}$. We tested how the model would change by just excluding these potentially anomalous data points and performing our light-curve fitting without them. We do indeed find slightly larger R$_{p}$/R$_{S}$ values for the transit of June 18, which in turn slightly increases our combined-night a/R$_{S}$ value in g’ band (by ~0.0014). However, within errors, these values are consistent with the values we derive using all of the data points; to avoid any bias due to attempts to fit out these points, we report here the values derived using all of the data.

Our TAP analysis results are summarized in Table 3, and a comparison of our results and R$_{p}$/R$_{S}$ values from the literature is shown in Figs 2 and 3.

4 DISCUSSION AND CONCLUSIONS

Our derived R$_{p}$/R$_{S}$ values match those in the literature (see Fig. 2). Our analysis adopts the same values for the period, inclination (i), a/R$_{S}$, eccentricity and omega (see Table 2) used by Bean et al. (2010, 2011), making our results directly comparable to theirs. These values were also used by de Mooij et al. (2012), except for the period, for which de Mooij et al. (2012) used 1.580 404 8346 d rather than Bean et al. (2011)’s 1.580 404 81 d. Bean et al. (2011) allowed the limb-darkening coefficients to be free parameters in their fitting analysis, using as priors the theoretical values that they computed based on the PHOENIX models of GJ 1214A with stellar parameters T$_{eff}$ = 3026 K, [M/H] = 0.0 and log g = 5.0. Neither the theoretical priors nor the resulting fitted values for the limb-darkening coefficients are discussed in Bean et al. (2011), so we cannot compare our limb-darkening coefficients directly. We did use the limb-darkening coefficient values from various Claret sources (see Table 2) corresponding to stellar parameters very similar to Bean et al. (2011): T$_{eff}$ = 3000 K, [M/H] = 0.0 and log g = 5.0.
De Mooij et al. (2012) used a four-parameter limb-darkening law, so their coefficients are also not directly comparable, although de Mooij et al. (2012) do use the same stellar parameter values ($T_{\text{eff}} = 3026$ K, $[\text{M/H}] = 0.0$ and log $g = 5.0$) and Claret (2000, 2004) as sources for their non-linear limb-darkening coefficients.

**GJ 1214A** is known to have star-spot-induced variability (Charbonneau et al. 2009; Berta et al. 2011), and stellar activity can have an observable effect on the transmission spectrum of a transiting planet from star spots that are occulted or not occulted by the planet (Pont et al. 2008; Agol et al. 2010; Sing et al. 2011). If a planet passes in front of a star spot, fully or partially masking it on the stellar surface, the observed flux will increase in proportion to the dimming effect of the star spot on the total flux of the star, causing one to underestimate the true size of the planet, and decreasing $R_p/R_S$. If the star spot is not occulted by the planet, the transit depth will appear greater, since the planet will pass over a region that is on average brighter than the entire star; this will reduce the effective stellar radius and increase $R_p/R_S$ (these effects are parametrized in Singh et al. 2011). De Mooij et al. (2012) found from their out-of-transit monitoring observations of GJ 1214A that the corrections in their $R_p/R_S$ observations in $r$ band and $K_S$ band due to the possibility of occulted star spots were 0.0011 and 0.0003, respectively. These authors also calculated the influence of different base levels of unocculted spots on the transmission spectrum observations of GJ 1214b, and found that for a spot-covering fraction of 10 per cent, the change in their $R_p/R_S$ values was $-0.0007$ in $g$ band and $-0.00065$ in $r$ band (the authors shifted their values such that the $i$-band radius ratio remained the unaltered baseline value, to compare to non-corrected results more easily). Due to the errors in our derived $R_p/R_S$ values, the level of star-spot-induced variations calculated by de Mooij et al. (2012) is not distinguishable with our data.

We also performed our own check calculations for possible star-spot corrections, using our $g'$ band out-of-transit data, i.e., data taken on the same nights as (and acting as the baseline for) the transit data. This check allows us to directly probe the host star variability in $g'$ band, our ‘bluest’ band and thus the one most affected by spots. We took the out-of-transit data from each night, calibrated using the same comparison stars, found the mean relative out-of-transit flux, and normalized it to the brightest epoch (August 6; see Fig. 4), which we assume to be the epoch with the lowest spot coverage. Between the dimmest (June 10) and brightest (August 6) epochs, there was a change of $\sim 3$ per cent in the flux of the star, translating to a transit depth that is deeper by 1.097, or $\sim 1.0$, due to star spots.

To ensure that the observed change in flux of GJ 1214A was not due to systematic error, we performed the same analysis on three of the closest (in angular separation) reference stars and found that their flux varied by $< 1$ per cent over the time period of our $g'$-band observations. Thus, we assume that the $\sim 3$ per cent variability of GJ 1214A's flux is real, and that this change in host star flux is due to dark spots; we do not consider bright plage or faculae regions. Note that a dark region that is occulted will make the transit appear deeper than it really is. Applying this star-spot correction to the June 10 transit results in a transit depth correction of $0.0196^2 \times 0.03 = 0.00043$, or an $R_p/R_S$ correction of 0.0018 (using our TAP-analysis values for June 10; see Table 3). According to our data, this is the greatest magnitude of correction that could affect our $R_p/R_S$ values, and it is markedly less than our TAP-based $R_p/R_S$ errors on June 10 of $0.0064$. Since June 10 was the dimmest epoch, on the other $g'$-band nights the potential star-spot corrections are even smaller, and for $V$ and $R$ bands we can assume a lower flux variation due to the lower $T_{\text{eff}}$. We also performed our own check calculations for possible star-spot corrections.

### Table 3. TAP model fitting results.

<table>
<thead>
<tr>
<th>Transit date (UTC)</th>
<th>Filter</th>
<th>Mid-transit time (BJD)</th>
<th>$R_p/R_S$</th>
<th>Airmass slope</th>
<th>Airmass y-intercept</th>
<th>Red noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 29</td>
<td>Harris R</td>
<td>245 6015.914 53</td>
<td>$+0.0037$</td>
<td>$0.1203$</td>
<td>$0.0098$</td>
<td>0.0005</td>
</tr>
<tr>
<td>April 9</td>
<td>Harris R</td>
<td>245 6026.974 65</td>
<td>$+0.0050$</td>
<td>$0.1192$</td>
<td>$-0.0340$</td>
<td>0.0012</td>
</tr>
<tr>
<td>May 6</td>
<td>Harris V</td>
<td>245 6053.842 03</td>
<td>$+0.0063$</td>
<td>$0.1180$</td>
<td>$-0.0240$</td>
<td>0.0018</td>
</tr>
<tr>
<td>May 30</td>
<td>Sloan $g'$</td>
<td>245 6077.549 70</td>
<td>$0.0011$</td>
<td>$0.1210$</td>
<td>$0.0000$</td>
<td>0.0019</td>
</tr>
<tr>
<td>June 5</td>
<td>Harris V</td>
<td>245 6083.870 44</td>
<td>$0.0058$</td>
<td>$0.1093$</td>
<td>$-0.0660$</td>
<td>0.0051</td>
</tr>
<tr>
<td>June 10</td>
<td>Sloan $g'$</td>
<td>245 6088.511 19</td>
<td>$0.0093$</td>
<td>$0.1197$</td>
<td>$0.0040$</td>
<td>0.0019</td>
</tr>
<tr>
<td>June 18</td>
<td>Sloan $g'$</td>
<td>245 6096.501 20</td>
<td>$0.0114$</td>
<td>$0.1058$</td>
<td>$-0.0310$</td>
<td>0.0025</td>
</tr>
<tr>
<td>July 25</td>
<td>Sloan $g'$</td>
<td>245 6134.443 20</td>
<td>$0.0111$</td>
<td>$0.1077$</td>
<td>$-0.0032$</td>
<td>0.0020</td>
</tr>
<tr>
<td>August 6</td>
<td>Sloan $g'$</td>
<td>245 6145.505 90</td>
<td>$0.0012$</td>
<td>$0.1250$</td>
<td>$-0.018$</td>
<td>0.0038</td>
</tr>
<tr>
<td>Two nights</td>
<td>Harris R</td>
<td>–</td>
<td>–</td>
<td>0.1192</td>
<td>$0.0026$</td>
<td>0.0000</td>
</tr>
<tr>
<td>Two nights</td>
<td>Harris V</td>
<td>–</td>
<td>–</td>
<td>0.1108</td>
<td>$0.0027$</td>
<td>0.0021</td>
</tr>
<tr>
<td>Five nights</td>
<td>Sloan $g'$</td>
<td>–</td>
<td>–</td>
<td>0.1169</td>
<td>$0.0043$</td>
<td>0.030</td>
</tr>
</tbody>
</table>
Figure 2. The results of our combined-night analyses (the last three rows in Table 3), as compared to other published transit measurements of GJ 1214b. Our results are bolded in red; the band-pass error bars on our measurements represent the FWHM of each filter. We overplot two examples of end-member models that are consistent with different selections of the existing data: a hydrogen-based and hazy atmosphere with a solar abundance of water (green) and a water-based atmosphere (blue). The former displays a greater modulation in the spectral features as a result of the higher scale height of the H₂-based atmosphere.

Figure 3. The same as Fig. 2, but now including data covering a greater range in wavelength. See the caption of Fig. 3 for details.

et al. 2012; Narita et al. 2012), the measurements of Croll et al. (2011) (in K_s band), de Mooij et al. (2012) (g band and K_s band) and Murgas et al. (2012) (around R band) indicate potential variation in transit depth with wavelength. Yet there are a few constraints that persist, considering the two end-member models, one that is hydrogen based and another that is water (or heavy gas) based, that have been proposed to explain the structure of GJ 1214b’s atmosphere. The observed spectral features of GJ 1214b are
Figure 4. The variability in the out-of-transit (OoT) \(g^\prime\)-band data from our observations. The x-axis represents the normalized epoch at which the data were observed, with the first \(g^\prime\)-band epoch set to one. The OoT data from each night were calibrated using the same set of comparison stars; then we found the mean OoT flux level of each night and normalized all the data by dividing through the highest mean value, corresponding to the time at which the stellar surface was least spotted. The greatest difference is between epochs 8 (June 10) and 44 (August 6), \(\sim 3\) per cent. The error bars represent the standard deviation of the OoT flux for each night.

sufficiently muted such that, if it did have an \(H_2\) rich atmosphere, the prominent spectral features of water would need to be reduced by adding large-sized (>1 \(\mu m\)) particulates (Bean et al. 2010; Croll et al. 2011; Berta et al. 2012; Howe & Burrows 2012) and/or reducing the water abundance to one lower than that expected in a solar elemental abundance atmosphere (de Mooij et al. 2012; Howe & Burrows 2012). Alternatively, the variations on a water-rich atmosphere proposed for GJ 1214b have muted features as a result of the atmosphere’s larger mean molecular mass and thus smaller scale height. These models match most of the spectra except the high absorption measured in \(K\) band (Croll et al. 2011; de Mooij et al. 2012) and arguably in \(g\) band (de Mooij et al. 2012).

Here, we investigate one of the largest differences between the \(H_2O\)-based and \(H_2\)-based atmospheres – their spectral signatures at optical wavelengths. To illustrate the disparity in the spectra predicted for these two end-member atmospheric structures, we calculate spectra of an \(H_2\) and an \(H_2O\) atmosphere, consistent with prior studies. Transit depths \((\Delta\alpha/\alpha)^2\) were calculated with a numerical model that sums the contributions of the primary star’s transmission through the limb of the extrasolar planet. The absorption of light is derived along tangent lines at pressures that extend from \(10^{-7}\) to 10 bar. Since there is no evidence so far of the presence of methane or ammonia, as would be expected in a thermochemical equilibrium atmosphere at the temperatures in GJ 1214b’s atmosphere (Miller-Ricci Kempton et al. 2012), we include the spectroscopic absorption due to water only, which is calculated using the absorption coefficients of Freedman, Marley & Lodders (2008), and assuming a constant mixing ratio, as expected for the pressure levels we are probing (below the \(10^{-5}\) bar level) (Miller-Ricci Kempton et al. 2012). The \(H_2\)-based model shown in Figs 2 and 3 assumes a water abundance of \(3.5 \times 10^{-5}\) and a cloud of brightly scattering particles (with real and imaginary indices of refraction of 1.65 and \(10^{-4}\)) below 1 m bar, which represents one solution that mutes the water features. This particular model, one of many degenerate solutions, is compared to that of a non-cloudy water atmosphere to illustrate the different slopes between 0.3 and 0.9 \(\mu m\) that result primarily from the different atmospheric scale heights. The \(H_2\)-based atmosphere has a spectrum that demonstrates the increase in opacity due to Rayleigh scattering, which is suggested by the observations of de Mooij et al. (2012). The \(H_2O\)-based atmosphere is excluded by the observations of de Mooij et al. (2012), because the small scale height of the model depresses the 0.46 \(\mu m\) radius below that measured.

Our measurements are consistent with prior studies; we measure a \(g^\prime\)-band radius that agrees with de Mooij et al. (2012), but allows for a greater number of solutions that include an \(H_2O\)-based atmosphere. We have recorded the first \(V\)-band observations of GJ 1214b (centred at 0.55 \(\mu m\)). These data point to a lower absorption more consistent with an \(H_2O\)-rich atmosphere or a mixture of \(H_2\) and water, that is, an intermediate atmospheric structure. Such an atmosphere might be expected because any \(H_2O\)-rich atmosphere would necessarily produce hydrogen through photochemistry. We measure an \(R\)-band radius that is also consistent with either an \(H_2\) or an intermediate water and \(H_2\)-based atmosphere. Taken together, our observations can be best interpreted with an atmosphere that is partly \(H_2\) and partly water based. However, additional observations are needed from ground-based and space-based platforms to establish the optical continuum of GJ 1214b.
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NOTE. In the process of resubmission of this work, another paper concerning GJ 1214b was submitted (Fraine et al. 2013). The conclusions of this work are unaffected by the new submission.

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