Ground-based transit observations of the super-Earth GJ 1214 b⋆,⋆⋆

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ABSTRACT

Context. GJ 1214 b is one of the few known transiting super-Earth-sized exoplanets with a measured mass and radius. It orbits an M-dwarf, only 14.55 pc away, making it a favorable candidate for follow-up studies. However, the composition of GJ 1214 b’s mysterious atmosphere has yet to be fully unveiled.

Aims. Our goal is to distinguish between the various proposed atmospheric models to explain the properties of GJ 1214 b: hydrogen-rich or hydrogen-He mix, or a heavy molecular weight atmosphere with reflecting high clouds, as latest studies have suggested.

Methods. Wavelength-dependent planetary radii measurements from the transit depths in the optical atmospheric windows that cover three transits. The photometric and spectrophotometric time series obtained were analyzed with MCMC simulations to measure the planetary radii as a function of wavelength. We determined radii ratios of 0.1173±0.00072 at 2.14 μm.

Results. Our measurements indicate a flat transmission spectrum, in agreement with the last atmospheric models that favor featureless spectra with clouds and high molecular weight compositions.

Key words. planetary systems – techniques: photometric – techniques: spectroscopic – planets and satellites: atmospheres – stars: individual: GJ 1214

1. Introduction

The handful of known transiting extrasolar super-Earths have been mostly found by space missions such as Kepler, CoRoT, or MOST, with the notable exception of GJ 1214 b (2.7 R⊕, 6.55 M⊕), which was discovered by the ground-based transiting survey MEarth around a bright nearby M-star (Charbonneau et al. 2009). Despite the relatively small radius of GJ 1214 b, the small stellar radius of its host star results in a ~1.5% transit depth, making it one of the super-Earths best suited for follow-up studies.

The recent theoretical predictions for the atmosphere of GJ 1214 b currently offer the most plausible models that fit the planet’s mass, radius, and irradiation level: a rocky or an icy core with a nebular hydrogen-helium envelope, that is, a mini-Neptune, a rocky planet with an outgassed hydrogen atmosphere, or a core with a heavy (up to 45% of the planet mass) hot water vapor envelope with high molecular mass (Rogers & Seager 2010; Nettelmann et al. 2011), as well as a planet with a cloudy or hazy atmosphere, with a high mean molecular mass composition (Morley et al. 2013).
source of achromatic haze. Strangely, Narita et al. (2013b) reported J- and H-band observations consistent with a flat featureless transmission spectrum, but shallower $K_S$-band transmission depth, in disagreement with the result of Croll et al. (2011). Fraine et al. (2012) also reported constant planetary atmosphere radii at $J + z$, 3.6$\mu$m, and 4.5$\mu$m. Finally, Murgas et al. (2012) found a radius of GJ 1214 b at the H$\alpha$ line higher than the radii measured at nearby continua, but the difference is not statistically significant. The latest observations reported by Teske et al. (2013), Colón & Gaidos (2013), Wilson et al. (2014), Gillon et al. (2014), de Mooij et al. (2013), and Kreidberg et al. (2014) have agreed in showing a featureless spectrum, favoring high mean molecular mass compositions. In that context, recently Kreidberg et al. (2014) ruled out the cloud-free high molecular weight atmosphere scenario for GJ 1214b with a high statistical significance.

Here we report new optical and NIR ground-based observations of GJ 1214 b transits, aiming to independently verify these results. The paper is organized as follows: Sect. 2 presents our observations, Sect. 3 describes the analysis, Sect. 4 presents a discussion of our results, and Sect. 5 is a summary of the main points of this paper.

2. Observations and data reduction

2.1. NIR photometry with OSIRIS

We observed a GJ 1214 b transit from UT 0:19 to 4:10 on the night of 09 August 2011 with the Ohio State Infrared Imager/Spectrometer (OSIRIS; Depoy et al. 1993) at the 4.1 m Southern Astrophysical Research (SOAR) Telescope at Cerro Pachón, Chile. OSIRIS only uses a $577 \times 577$ px window from a $1024 \times 1024$ px HgCdTe array, yielding $191 \times 191$ arcsec field of view (FoV) (pixel scale 0.331 arcsec px$^{-1}$). A narrow-band (1%) filter centered on 2.14 $\mu$m was used. We placed GJ 1214 and a nearby reference star (2MASS J17152424+0455041) within the FoV. They have similar apparent brightness and are separated by ~3 arcmin.

The observations were carried out in AIAI mode, that is, the stars were kept on the same positions to minimize the systematic effects associated with inaccurate flat-fielding and intra-pixel sensitivity variations. A total of 1,030 science images were collected, with exposure times ranging from 5 to 20 s, which had to be adjusted to avoid reaching the nonlinearity regime under variable seeing and airmass.

First, we subtracted the dark current by scaling one series of darks to match the different exposure times used throughout the night, and flat-fielded the images. To extract the apparent fluxes from the reduced images we carried out aperture photometry with the IRAF Digiphot package$^1$. Led by our previous experience with stare-mode NIR data, we removed the sky by measuring it in circular annuli, contiguous to the aperture centered on the object (Cáceres et al. 2009, 2011). We performed photometry for different aperture radii, ranging from 4.0 to 14.0 px, in steps of 0.5 px, and selected the combination of source and sky apertures that minimizes the root mean square (rms) of the final differential light curve: target and reference aperture radii of 2.32 arcsec, and a sky annulus with 4.9 arcsec inner radius and 3.3 arcsec width. The generated light curve is shown in Fig. 1 (top).

2.2. Optical photometry with SOI

A transit of GJ 1214 b was observed in the I-Bessel filter from UT 04:03 to 09:30 on the night of April 28, 2010 with the SOAR Optical Imager (SOI) at the SOAR telescope on Cerro Pachón. The instrument has a mosaic of two E2V 2 k CCDs, covering a ~5.5 $\times$ 5.5 arcmin FoV (pixel scale 0.077 arcsec px$^{-1}$). The binning was 2 $\times$ 2, and the readout time was 11 s.

We placed the target close to the center of the FoV, which allowed us to observe eight reference stars of similar or slightly fainter brightness to that of the target. We obtained 1730 frames, with integration times between 3 and 5 s – adjusted throughout the night to keep the core of the stellar images in the linear regime.

The basic data reduction included trimming the images, bias subtraction and flat-fielding corrections with SOI’s custom-made pipeline (Hoyer et al. 2012). Next, we performed standard aperture photometry of the target and the eight reference stars. The optimal aperture and sky-annulus radii were selected to minimize the rms of the portions of the light curve before and after the transit, best values being stellar aperture radius ~18 pix, sky annulus radius ~20 pix and 10 pix in width. Similarly, our experiments with the reference stars demonstrated that the best light curve is obtained using only one of them – the brightest 2MASS J17152424+0455041 ($K_s$ = 8.983 mag). According to our tests, adding more reference stars increased the noise. The generated light curve is shown in Fig. 2 (top).

2.3. NIR spectrophotometry with SofI

Three GJ 1214 b transits were observed with the NIR spectrograph SofI (Son of ISAAC; Moorwood et al. 1998) at the ESO New Technology Telescope (see Table 1). The instrument is equipped with a 1024 $\times$ 1024 Hawaii detector and ~4.9 arcmin long slits (pixel scale 0.292 arcsec px$^{-1}$). The red grism was used, providing a spectral coverage from $\lambda$ ~1.5 to 2.5 $\mu$m.

A comparison star (2MASS J17152424+0455041; ~3.06 arcmin separation from the target) of similar spectral type and...
brightness as GJ 1214 was placed in the slit at all times for continuous and simultaneous monitoring of the telluric absorption. The observations were performed in stare mode, that is, without nodding, to keep the objects on nearly the same pixels, minimizing effects from flat-fielding errors and intra-pixel sensitivity variations. The NDIT \times DIT combination was chosen to keep the peak count level at \sim 6000 ADU, well below the \sim 1.5% non-linearity limit of 10000 ADU.

The first steps of the basic data reduction were the usual cross-talk and flat-fielding corrections, and bad-pixel replacement. However, the stare mode made it impossible to remove the sky emission by subtracting corresponding nodding image pairs, as is normally done. Instead, we took advantage of having small field distortions and bright targets to individually trace their continuum on each frame, and to extract at each side of the objects two adjacent sky emission spectra. Then, we subtracted from each object’s one-dimensional spectrum the linearly interpolated value of the two one-dimensional sky spectra that correspond to the location of the object. Since the sky spectra also include the dark and bias contributions, we successfully removed the detector pattern from our data as well. These steps were performed with the task \texttt{apall} from the IRAF package \texttt{twodspec}.

The wavelength calibration is based on xenon lamp spectra for each object and each frame we separately extracted a one-dimensional lamp spectrum from the lamp frame using the same tracing and extraction aperture as for that object on that frame. Typically, nine Xe lines were used in the calibration, and the rms was 1–2 Å. A typical target spectrum at this stage of the processing is shown in Fig. 3.

### Table 1. Observing log for the spectroscopic SofI Observations of GJ 1214 b.

<table>
<thead>
<tr>
<th>Date</th>
<th>Observations Predicted</th>
<th>Airmass range</th>
<th>Cloud</th>
<th>Seeing</th>
<th>Slit width</th>
<th>Spectral</th>
<th>NDIT \times DIT</th>
<th>Number of frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>yyyy-mm-dd</td>
<td>UT range</td>
<td>sec z</td>
<td>conditions</td>
<td>arcsec</td>
<td>arcsec</td>
<td>resolution</td>
<td>N \times s</td>
<td>frames</td>
</tr>
<tr>
<td>2011-05-17/18</td>
<td>5:44–9:55</td>
<td>7:32–8:26</td>
<td>clear</td>
<td>0.8</td>
<td>1.0</td>
<td>600</td>
<td>3 \times 60</td>
<td>79</td>
</tr>
<tr>
<td>2011-06-13/14</td>
<td>2:36–6:53</td>
<td>4:21–5:14</td>
<td>clear</td>
<td>1.0</td>
<td>2.0</td>
<td>300</td>
<td>4 \times 45, 5 \times 36</td>
<td>79</td>
</tr>
<tr>
<td>2011-08-09/10</td>
<td>0:45–4:07</td>
<td>1:49–2:42</td>
<td>cirrus</td>
<td>&gt;0.1</td>
<td>2.0</td>
<td>300</td>
<td>3 \times 60</td>
<td>65</td>
</tr>
</tbody>
</table>

**Fig. 3.** Typical wavelength-calibrated one-dimensional spectrum of GJ 1214 b, not corrected for telluric absorption, obtained with SofI on May 17/18, 2011.

The telluric absorption was removed by dividing in the wavelength space the planet’s host spectrum by the spectrum of the reference star. This was done separately for each individual frame, ensuring that the absorption variations are accounted for, because the two spectra were obtained simultaneously and very close on the sky.

Finally, we integrated the flux in the reduced spectra within selected bandpasses – the standard SofI NIR broad-band filters, \( H (\lambda_C = 1.653 \mu m, \text{FWHM} = 0.297 \mu m) \) and \( K_S (\lambda_C = 2.162 \mu m, \text{FWHM} = 0.275 \mu m) \). We refrained from splitting the data into finer spectral bins because of the low signal-to-noise ratio of the data. The individual spectrophotometric series for GJ 1214 b and its comparison star are shown in Fig. 4, and the composed light curves are shown in Fig. 5 (top).

### 3. Data analysis

#### 3.1. OSIRIS and SOI data

Despite the intrinsic correction of systematics due to differential nature of the photometry, the OSIRIS raw light curve of GJ 1214 b shows significant structure, especially in the second half of the observations (Fig. 1, top). We found strong correlations of the out-of-transit flux measurements with both the \((x_C, y_C)\) position of the stellar centroids on the detector, and the sky flux level \(m_k\) – related to guiding errors, residual flat-field errors, and to variable weather conditions (Fig. 6).

To extract the physical parameters from the obtained light curves we fit the photometric time series with both a transit model \(\Theta(t)\), and a linear model \(\kappa(t)\) that accounts for the systematics observed in the light curve. The best combination of parameters we found to de-trend the OSIRIS light curve was

\[
\kappa_{\text{OSIRIS}}(t) = a_0 + a_1 m_k + a_2 x_C + a_3 y_C, \tag{1}
\]

where the coefficients \(a_i\) are the free parameters to be determined in the fitting procedure.
The SOI data showed a prominent linear drift in the differential light curve (Fig. 2, top), which is most likely caused by movement of the stars across the detector through the night. We modeled it as
\[ \kappa_{SOI}(t) = a_0 + a_1 x_C + a_2 y_C. \]  
(2)

The final fitted model for each data set was the product
\[ M(t) = \kappa(t) \Theta(t). \]  
(3)

To find the best-fitting model we carried out a Markov chain Monte Carlo (MCMC) simulation (Tegmark et al. 2004; Gregory 2005; Ford 2006), aimed at drawing the a posteriori probability distribution for the parameters to fit. It is widely used to determine physical parameters from observations in exo-planetary science (e.g., Ford 2005; Holman et al. 2006; Collier Cameron et al. 2007). The MCMC code uses a Metropolis-Hasting algorithm to explore the parameter space. The GJ 1214 b planetary system model included a transiting planet orbiting a star on a Keplerian orbit.

To create the transit model we made use of the quadratic limb-darkening eclipse parametrization of Mandel & Agol (2002). The free parameters in the fitting procedure, jumps in the MCMC code, are the time at the minimum flux \( T_{\text{C}} \), the planet-to-star area ratio \( p^2 = (R_p/R_s)^2 \), the impact parameter \( b \), the transit length \( T_{14} \), and the two quadratic limb-darkening coefficients \( u_1 \) and \( u_2 \). However, we replaced the two limb-darkening coefficients with their linear combinations \( c_1 = 2 \times u_1 + u_2 \), and \( c_2 = u_1 - 2 \times u_2 \) because this substitution has been proven to minimize the correlations among the parameters in the MCMC fitting (e.g. Winn et al. 2008; Gillon et al. 2010).

To determine the limb-darkening coefficients \( (u_1 \) and \( u_2) \), we assumed Gaussian priors for the fitting procedure. The starting values were interpolated from the Claret & Bloemen (2011) tables for the \( K \) and \( I \) band, and assuming the stellar parameters \( T_{\text{eff}} = 3026.0 \pm 130.0 \) K, \( \log g = 4.991 \pm 0.029 \), and \( \text{[Fe/H]} = 0.39 \pm 0.15 \) (Charbonneau et al. 2009). We calculated the errors in the limb-darkening parameters following Gillon et al. (2009). We adopted the orbital period \( P = 1.5803925 \) d from Charbonneau et al. (2009) and fixed the eccentricity to zero.

The linearity of the detrending models allowed us to calculate the fitting coefficients with linear least-squares minimization using the SDV algorithm (Press et al. 1992) on the resulting curve produced after dividing the raw light curve by the proposed transit model for each specific jump (Gillon et al. 2010), instead of perturbing the coefficients within the MCMC code.

We first ran five chains with \( 10^6 \) jumps each, where we discarded the first 20% of points of each chain to remove the burn-in phase of the simulation. Using the obtained best-fitting model of this first run, we determined the significance of the red-noise
in the photometric time series by measuring the $\beta$ parameter defined by Gillon et al. (2006) and Winn et al. (2008) as

$$\beta = \frac{\sigma_N}{\sigma_1} \left( \frac{N(M-1)}{M} \right)^{1/2},$$

where $M$ is the obtained number of bins for a specific bin width $N$, and $\sigma_N$ and $\sigma_1$ parameters represent the rms of the binned and unbinned residuals obtained after removing the best-fitting model, respectively. We selected the value that corresponds to a temporal scale similar to the ingress-egress duration, that is, ~6 min (Carter et al. 2011), which yielded values of $\beta_{\text{OSIRIS}} = 1.03$ and $\beta_{\text{SOI}} = 1.23$. We multiplied the individual photon-noise flux errors by this value to execute a new set of chains including the red-noise.

With the new set of flux errors, we ran five new MCMC chains with the same configuration as described above to obtain the final a posteriori probability distribution of the jump parameters. The final values for each of the jump parameters were the median of the distribution, and its errors correspond to the boundaries of the region enclosing the 68.3% of values around the median. A Gelman & Rubin (1992) test was applied to this MCMC run to check for a good mixing and convergence, which yielded $\omega_1 = 0.230$ and $\omega_1 = -0.011, +0.011$. A Gelman & Rubin (1992) test was applied to this MCMC run to check for a good mixing and convergence, which yielded $\omega_1 = 0.230$ and $\omega_1 = -0.011, +0.011$.

The determined parameters agree well with those reported by Bean et al. (2011) and Carter et al. (2011). We decided to decrease the number of free parameters in our MCMC fitting by fixing the values given by Bean et al. (2011), which are $i = 88.94^\circ$ and $a/R_S = 14.9749$. This selection allowed us to directly compare the measured depth values with those reported in Désert et al. (2011), Croll et al. (2011), Bean et al. (2011), de Mooij et al. (2012), Murgas et al. (2012), Narita et al. (2013a,b), Fraine et al. (2013), and Teske et al. (2013).

The final de-trended light curves, the best-fitting transit-plus-trend models, and their residuals are shown in the middle and bottom panels in Figs. 1 and 2 for the OSIRIS and SOI observations, respectively. Low time-correlated noise in the SOI data is apparent in Fig. 7 (top).

### 3.2. Analysis of SOI data

First, we studied the main sources of systematic errors. One of our concerns was to understand how stable the centering of the target and the reference sources on the slit is. We measured the drifts and the full-width at half-maximum (FWHM) variations of both objects at two different wavelengths, corresponding to the $H$ and $K$ bands. The analysis consisted of the following steps: (i) determine the pixel corresponding to the center of the band; (ii) fit the spectral profiles at these wavelengths with Gaussian profiles to determine the center and FWHM of the two spectra. These steps were repeated independently for each good-weather run. The results for these runs are plotted in Fig. 8.

![Red-noise diagram for the residuals of the best-fitting model for SOI (top) and OSIRIS (bottom). Solid lines represent the rms calculated for a given bin width. Dashed lines show the expected behavior of the residuals for a pure Poisson-noise model.](image)

Table 2. Transit parameters of GJ 1214 b derived from the OSIRIS and SOI data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>68.3% Conf. limits</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSIRIS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_C$</td>
<td>2.455 315.79475</td>
<td>$-0.00010$, $+0.0011$</td>
<td>BJD</td>
</tr>
<tr>
<td>$R_p/R_s$</td>
<td>0.11735</td>
<td>$-0.00076$, $+0.000072$</td>
<td></td>
</tr>
<tr>
<td>$u_1$</td>
<td>0.341</td>
<td>$-0.010$, $+0.011$</td>
<td></td>
</tr>
<tr>
<td>$u_2$</td>
<td>0.301</td>
<td>$-0.011$, $+0.010$</td>
<td></td>
</tr>
<tr>
<td>SOI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_C$</td>
<td>2.455 315.79475</td>
<td>$-0.00010$, $+0.0011$</td>
<td>BJD</td>
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<td>0.301</td>
<td>$-0.011$, $+0.010$</td>
<td></td>
</tr>
</tbody>
</table>

**Notes.**(1) Value fixed in the MCMC fitting (Bean et al. 2010).

- **Common parameters**
  - $P$ | 1.580404938 | $\pm 0.000000090$ |
  - $T_0$ | 2.454 934.916934 | $\pm 0.000027$ |
  - $\alpha^*$ | 14.9749 | |
  - $\beta^*$ | 88.94 | |
  - $\epsilon^*$ | 0.0 | |
  - $\omega^*$ | 0.0 | |

- **Parameter** | **Value** | **68.3% Conf. limits** | **Unit** |
- $T_C$ | 2.455 315.79475 | $-0.00010$, $+0.0011$ | BJD |
- $R_p/R_s$ | 0.11735 | $-0.00076$, $+0.000072$ | |
- $u_1$ | 0.341 | $-0.010$, $+0.011$ | |
- $u_2$ | 0.301 | $-0.011$, $+0.010$ | |

- **Notes.**(1) Value fixed in the MCMC fitting (Bean et al. 2010).
smoothly along the slit, without jumps, particularly, without dramatic jumps at the time of ingress and egress. This smooth variation is likely to occur due to color-dependent differential atmospheric refraction or smooth guider drift — mechanisms that are probably not related with the slit orientation. Therefore, we expect that the drift across the slit follows a similar smooth pattern.

The FWHM ratio (Fig. 8, bottom) also varies smoothly with time and is distinctly different from unity. The latter is related to the fixed position of the SofI collimator — for technical reasons it was not moved to adjust the focus for each setup. Instead, it was set at a position optimized for imaging observations, and the focus at spectroscopy is suboptimal, leading to a gradient across the FoV. This is the reason why the FWHM is different at the locations of the target and the reference stars. The effect of the suboptimal focus is more pronounced at the beginning of the observations at lower airmass, and weaker towards the end, when the higher airmass smears the images and makes the defocusing less important.

The resulting light curve was analyzed via two different MCMC-based routines: one as described in previous section for our photometric data sets, and another based on the code by Gillon et al. (2009, 2012). Both methods provided consistent results. For clarity we present in the following text and in Table 3 the fitting parameters obtained with the second mentioned MCMC code described in Gillon et al. (2009, 2012).

Table 3. Transit parameters of GJ 1214 b obtained from the SofI data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>68.3% Conf. limits</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SofI H+K run 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_C$</td>
<td>2455699.83386</td>
<td>−0.00093, +0.00094</td>
<td>BJD</td>
</tr>
<tr>
<td>$R_p/R_s$</td>
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<td>−0.0074, +0.0070</td>
<td>1.6$\mu$m</td>
</tr>
<tr>
<td>$R_p/R_s$</td>
<td>0.1230</td>
<td>−0.0090, +0.0084</td>
<td>2.2$\mu$m</td>
</tr>
<tr>
<td>SofI H+K run 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_C$</td>
<td>2455726.7001</td>
<td>−0.0010, +0.0010</td>
<td>BJD</td>
</tr>
<tr>
<td>$R_p/R_s$</td>
<td>0.1180</td>
<td>−0.0062, +0.0058</td>
<td>1.6$\mu$m</td>
</tr>
<tr>
<td>$R_p/R_s$</td>
<td>0.1202</td>
<td>−0.0110, +0.0100</td>
<td>2.2$\mu$m</td>
</tr>
</tbody>
</table>

The careful analysis shows that SofI is fairly stable in terms of differential flux losses, and the duty cycle was extremely high — 95–97%, that is, we lost only 3–5% of the time for detector readout, fits-file merging, and transferring. Unfortunately, the

4. Discussion

4.1. Spectrophotometric observations

The careful analysis shows that SofI is fairly stable in terms of differential flux losses, and the duty cycle was extremely high — 95–97%, that is, we lost only 3–5% of the time for detector readout, fits-file merging, and transferring. Unfortunately, the
loss of the third night because of poor weather conditions under-
maintained the analysis of our spectroscopic data, and the brightness of
the exoplanet host was marginal. We still present the data here
as a benchmark and reference for similar future observations,
to demonstrate the potential of long-slit spectrographs at 4-m
class telescopes to study extrasolar planets (e.g. Crossfield et al.
2013).

SOFI has a major advantage over other spectrographs: its
long slit length of ~5′, which facilitates finding a suitable com-
parison star, which is necessary to control the systematics (see
discussion in previous section and Fig. 9). Therefore, we con-
clude that SOFI is suitable for studying exoplanet atmospheres,
if the planets orbit brighter stars.

4.2. Photometric GJ 1214 b atmosphere

A variety of measurements of the effective planet-to-star radius
ratio at various wavelengths have provided conflicting clues on
the composition of the GJ 1214b’s atmosphere. The first detec-
tions of this planet suggested that its radius is too large to be
explained by a solid (pure rock or pure ice) composition (e.g.,
Charbonneau et al. 2009), implying the presence of a significant
gaseous atmosphere. Depending on the assumptions made for
the composition of the planet’s interior, this atmosphere could
be composed primarily of hydrogen, water, or some combina-
tion thereof, a hypothesis that cannot be probed from a single
radius measurement.

More recent detections at different wavelengths have sug-
gested a high molecular weight atmosphere with a probable
dominance of water, which would show shallow K-band depths
(e.g., Bean et al. 2010, 2011; Désert et al. 2011; Berta et al.
2012). At the same time, Croll et al. (2011) reported a deep
K3-band transit, which favors a low molecular weight atmos-
phere, with an hydrogen-rich component; this result was ac-
companied by the relatively deep K3-band transit reported by
de Mooij et al. (2012). Meanwhile, Crossfield et al. (2011)
reported that the hydrogen-rich atmosphere is not favored by
their results. As noted by Howe & Burrows (2012), the shorter
wavelength measurements reported by Bean et al. (2011) and
de Mooij et al. (2012) favor hydrogen-rich atmospheres as well.

Nettelmann et al. (2011) considered different models for
GJ 1214b’s interior, inferring metal-rich H/He atmospheres are
the most plausible models, and suggesting an H/He/H2O model
with a high water mass fraction for the atmosphere of the planet.

There is no individual theoretical model that accounts for all
the observational data, but atmospheres that either have a water-
rich composition (more than 70% by mass) or a thick layer of
clouds or hazes in the upper atmosphere are the best-suited in-
terpretations of current data (e.g., Fortney 2005; Miller-Ricci &
Fortney 2010; Nettelmann et al. 2011; Howe & Burrows 2012;
Miller-Ricci Kempton et al. 2012). The last option has been stud-
ied by Morley et al. (2013), who found that in an enhanced
metallicity atmosphere, clouds that formed either in chemical
equilibrium or nonequilibrium frameworks can reproduce cur-
rent observations. The authors also pointed out that hydrocar-
bon haze produced by photochemistry can flatten the GJ 1214 b
spectrum.

Some studies have been performed to try to solve the discrep-
cy between the models. Murgas et al. (2012) used GTC tun-
able filters to attempt the detection of the Hα signature during
transits of GJ 1214b, which yielded a nondetection, consistent with
the featureless transmission spectra presented by Bean et al.
(2011). Finally, Kreidberg et al. (2014) have provided strong evi-
dence of the presence of clouds in the atmosphere of GJ 1214 b,
based on HST transmission spectra. They reported the signifi-
cant detection of a featureless spectrum, ruling out the cloud-free
high molecular weight atmosphere hypothesis.

Figure 10 shows all current observational data that have a
wavelength-dependent radius ratio, where the models cor-
respond to updated best-fit atmosphere models proposed in
Miller-Ricci Kempton et al. (2012). Photometric data were ob-
tained from de Mooij et al. (2012, 2013), Carter et al. (2011,
Bean et al. (2011), Murgas et al. (2012), Croll et al. (2011),
Désert et al. (2011), Narita et al. (2013a,b), Teske et al. (2013),
Colón & Gaidos (2013), Wilson et al. (2014), Gillon et al.
(2014). Transmission spectroscopy measurements were obtained

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**Fig. 10.** Updated best fit atmospheric models reported in Miller-Ricci Kempton et al. (2012), including all current observational data. The models shown were smoothed for the sake of clarity. Light-gray points represent spectrophotometric measurements, and dark-gray points represent photometric measurements. The horizontal extension of the bars represents the wavelength coverage of the point, instead of an error associated with the observation. Black points represent our SOAR measurements. The dashed windows represent the zoomed-in regions displayed in Fig. 11. This figure is available in color in electronic form.
from Berta et al. (2012), Bean et al. (2011), and Kreidberg et al. (2014). Our measurement at 0.87 \( \mu m \) agrees well with current measurements at the shorter wavelengths, also suggesting the presence of the Rayleigh scattering tail argued in Howe & Burrows (2012). On the other hand, our NIR detection at 2.14\( \mu m \) shows a moderate depth that disagrees with that of Croll et al. (2011) and the \( K_S \)-band detection of Désert et al. (2011). Recently, Narita et al. (2013b) reported simultaneous \( J, H, \) and \( K_S \)-band transit depths for transits of GJ 1214.b. Of particular interest is their shallow detection at 2.16\( \mu m \), which strongly disagrees with the deeper measurements. Our 2.14\( \mu m \) detection is consistent with the detections of Narita et al. (2013b) and Bean et al. (2011) and the \( K_C \) detection of Désert et al. (2011).

For better orientation, Fig. 11, left, is a zoom-in of Fig. 10 with a focus on the optical region around our SOI measurement, while the same Fig. 11, right, shows the NIR region around our OSIRIS measurement. For both panels, relevant measurements by the above mentioned groups are presented for comparison.

Finally, we would like to point out a discrepancy between the narrow-band and broad-band photometric measurements at similar wavelengths (see Fig. 11). Our measurement at 2.14\( \mu m \) contrasts with the broad band measurements by Croll et al. (2011) and Narita et al. (2013b) and agrees well with the narrow-band measurement of de Mooij et al. (2012) at 2.27\( \mu m \).

### 4.3. Transit-timing observations

The timing information in the raw images was converted from MJD to BJD (TDB) to determine the final individual transit timing, following the prescriptions in Eastman et al. (2010). Our photometric data show no significant deviations from a constant period, which is consistent with what has been found by Carter et al. (2011) and Berta et al. (2012), and has been recently confirmed by Harpsøe et al. (2013), who used a Bayesian approach to infer that a TTV is unlikely to be present in the GJ 1214b data. We collected all available transit-timing data from the literature, which we combined with our measurements to refine the ephemeris of the GJ1214b system, with parameters \( T_0 = 2454934.917003 \pm 0.000023 \) BJD and \( P = 1.580404599 \pm 0.00000056 \). Timing data from de Mooij et al. (2012), Kündurthi et al. (2011), Carter et al. (2011), Murgas et al. (2012), Bean et al. (2011), Charbonneau et al. (2009), Berta et al. (2011, 2012), Croll et al. (2011), Désert et al. (2011), Sada et al. (2010), Narita et al. (2013b), Harpsøe et al. (2013), Teske et al. (2013), Gillon et al. (2014), Colón & Gaidos (2013), Fraine et al. (2015), and our measurements are shown in Fig. 12.

Based on the timing analysis of GJ1214b transits, we put strong constraints on the mass of an additional body in the system, especially in mean motion resonances (MMRs) with the transiting exoplanet. Using dynamical simulations with the MERCURY N-body orbital integrator (Chambers 1999), we determined the mass of an orbital perturber as a function of the distance from the star. To run the simulations we followed the same procedure as described in detail in Hoyer et al. (2011). We used the updated physical parameters of the system reported by Anglada-Escudé et al. (2013) as input for the simulations. For the perturber body, we explored a wide range of masses (0.5\( M_\oplus \)–1000\( M_\oplus \)) and orbital distances (0.0015 AU–0.055 AU), searching for the masses that produce an rms of \( \sim 30 \) s in the calculated central time of the transits of GJ1214b during the ten years of integration time we used. The results of these dynamical simulations are presented in Fig. 13 where a region of unstable orbits is marked by the gray strip. For all the other stable orbits we determined the perturber mass that would produce a TTV rms of 30 s (represented by the solid line). In the 1:2,
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5. Summary

GJ 1214 b is undoubtedly one of the most intriguing objects and the first of its class with an extensively studied atmosphere. The NIR and optical photometric measurements we present here provide additional evidence for a rather flat featureless spectrum, indicating either a metal-rich, or a cloudy or hazy atmosphere. The TTV analysis of our data combined with previous data sets by other groups have confirmed the constant value of the planetary orbital period.

All observations reported here were performed with 4m class telescopes and prove the suitability of such facilities for high-precision photometry. Furthermore, we encourage new spectroscopic measurements especially in the \( H \) and \( K_s \) bands of the spectra. Particularly suitable instruments are either multi-object spectrographs or, as presented in this paper, long-slit spectrographs. Particularly suitable instruments are either multi-object spectrographs or, as presented in this paper, long-slit spectrographs. Particularly suitable instruments are either multi-object spectrographs or, as presented in this paper, long-slit spectrographs.

Fig. 13. Upper mass limits for the system GJ 1214b based on numerical simulations. The dashed line represents the limits imposed by the radial velocity measurements.

References


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