MULTI-COLOR TRANSIT PHOTOGRAPHY OF GJ 1214b THROUGH $BJHK_s$ BANDS AND A LONG-TERM MONITORING OF THE STELLAR VARIABILITY OF GJ 1214

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ABSTRACT

We present five new transit light curves of GJ 1214b taken in the $BJHK_s$ bands. Two transits were observed in the $B$ band using the Subaru Prime Focus Camera (Suprime-Cam) and the Faint Object Camera and Spectrograph (FOCAS) instruments on board the Subaru 8.2 m telescope, and one transit was done in the $JHK_s$ bands simultaneously with the Simultaneous Infrared Imager for Unbiased Survey (SIRIUS) camera on the Infrared Survey Facility (IRSF) 1.4 m telescope. Markov Chain Monte Carlo analyses show that the planet-to-star radius ratios are $R_p/R_\star = 0.11651 \pm 0.00065$ ($B$ band, Subaru/Suprime-Cam), $R_p/R_\star = 0.11601 \pm 0.00117$ ($B$ band, Subaru/FOCAS), $R_p/R_\star = 0.11654 \pm 0.00080$ ($J$ band, IRSF/SIRIUS), $R_p/R_\star = 0.11550^{+0.00142}_{-0.00153}$ ($H$ band, IRSF/SIRIUS), and $R_p/R_\star = 0.11547 \pm 0.00127$ ($K_s$ band, IRSF/SIRIUS). The Subaru Suprime-Cam transit photometry shows a possible spot-crossing feature. Comparisons of the new transit depths and those from previous studies with the theoretical models by Howe & Burrows suggest that the high molecular weight atmosphere (e.g., 1% H$_2$O + 99% N$_2$) models are most likely, however, the low molecular weight (hydrogen-dominated) atmospheres with extensive clouds are still not excluded. We also report a long-term monitoring of the stellar brightness variability of GJ 1214 observed with the MITSuME 50 cm telescope in the $g'$, $r_c$, and $I_c$ bands simultaneously. The monitoring was conducted for 32 nights spanning 78 nights in 2012, and we find a periodic brightness variation with a period of $P = 44.3 \pm 1.2$ days and semi-amplitudes of 2.1% $\pm$ 0.4% in the $g'$ band, 0.56% $\pm$ 0.08% in the $r_c$ band, and 0.32% $\pm$ 0.04% in the $I_c$ band.

Key words: planetary systems – planets and satellites: atmospheres – planets and satellites: individual (GJ1214b) – stars: individual (GJ1214) – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Super-Earths are an emerging population of extrasolar planets whose masses and radii lie between those of the Earth and Uranus/Neptune. The nature of super-Earths, such as internal structure and atmospheric compositions, remains almost unknown since there is no super-Earth in our solar system. Transiting super-Earths are thus invaluable targets for observations to understand the nature of super-Earths in details.

The GJ 1214b discovered by Charbonneau et al. (2009) is the first-ever transiting super-Earth around an M dwarf that enables us to study its atmosphere through so-called transmission spectroscopy, due to the small host star’s size ($\sim$0.2 $R_\odot$). For the purpose, a number of observers have measured transit depths of GJ 1214b in various wavelength regions (e.g., Bean et al. 2010, 2011; Croll et al. 2011; Désert et al. 2011a; Carter et al. 2011; Berta et al. 2011, 2012; de Mooij et al. 2012; Narita et al. 2013; Fraine et al. 2013; Teske et al. 2013), and have narrowed down possible atmospheric models proposed by theorists (e.g., Miller-Ricci & Fortney 2010; Howe & Burrows 2012; Benneke & Seager 2012).

Among recent publications, Howe & Burrows (2012) reported various atmospheric models and compared them with the previous observations. They concluded that a hydrogen-rich atmosphere with a haze of small ($\sim$0.1 $\mu$m) particles is the most likely model for GJ 1214b, however, they also noted that this is only valid if the Rayleigh scattering feature (a rise of transit depths in short optical wavelength) claimed by de Mooij et al. (2012) in the optical $g$ band is true. Howe & Burrows (2012) also reported that if the short-wavelength result is inaccurate, then alternative likely models are (1) an N$_2$ and water-dominated atmosphere; (2) a solar-abundance (hydrogen-dominated) atmosphere with thick clouds at or above the 1 mbar level; or (3) a solar-abundance atmosphere with a haze of $\geqslant 1 \mu$m particles. In those alternative cases, however, deeper $K_s$-band transits claimed by Croll et al. (2011) and de Mooij et al. (2012) are incompatible with the models. Thus, the discussions of likely atmospheric models largely depend on
the reliability of the results by Croll et al. (2011) and de Mooij et al. (2012).

Motivated by this fact, we previously tried simultaneous $JHK_s$-transit photometry of GJ 1214b using the Simultaneous Infrared Imager for Unbiased Survey (SIRIUS) camera on the Infrared Survey Facility (IRSF) 1.4 m telescope in 2011 (Narita et al. 2013). Consequently, we did not find a deeper transit in the $K_s$ band; namely our result was inconsistent with the results by Croll et al. (2011) and de Mooij et al. (2012), and instead support a shallower transit reported by Bean et al. (2011). This result has raised the possibility of the alternative models by Howe & Burrows (2012).

Moreover, Teske et al. (2013) recently presented new $g$- and $V$-band transits, which were shallower than the $g$-band transit by de Mooij et al. (2012). Their results were still consistent with de Mooij et al. (2012), but also consistent with the no Rayleigh scattering (water-dominated atmosphere) model due to large uncertainty in $R_p/R_*$. Although the $g$-band result by de Mooij et al. (2012) could not be explained without the Rayleigh scattering, the new results by Teske et al. (2013) raised fundamental questions as to whether or not the Rayleigh scattering feature is actually present. Thus, the argument of the presence of the Rayleigh scattering in the atmosphere of GJ 1214b is still unsolved.

More recently, Fraine et al. (2013) presented new Spitzer photometry and also conducted comparisons of various atmospheric models with all of the previous observations. They found that the best-fit model was one of the alternative models in Howe & Burrows (2012), which contains 1% H$_2$O + 99% N$_2$ with a thick tholin haze of 0.5 mm particles. They also mentioned that a pure water model and a flat line (no atmosphere) model are still acceptable at the time of their publication.

Based on the previous discussions, we consider that the remaining important keys for distinguishing atmosphere models of GJ 1214b are (1) confirmation of a rise of transit depths in the optical blue region due to the Rayleigh scattering, and (2) further confirmation of $K_s$-band transit depths compared to the $J$-band ones. To address the above problems, we conducted $B$-band (bluer than the $g$ and $g'$ bands) transit observations with the Subaru 8.2 m telescope to confirm or constrain the Rayleigh scattering feature, and also conducted follow-up transit observations in the $JHK_s$ bands with the IRSF 1.4 m telescope in South Africa to check the transit depths in those bands once again.

Meanwhile, it is also important to learn and estimate the systematic effects due to the stellar variability for implications of transit depths. Previously, Berta et al. (2011) reported ~3.5 mmag stellar brightness variability in MEarth band (similar to the $i + z$ band) with a period of ~53 days and ~7 mmag variability in the $V$ band with a period of ~41 days. However, no independent confirmation of the stellar variability was reported. For this reason, we additionally monitored long-term stellar brightness variability with the MITSuME 50 cm telescope at Okayama Astrophysical Observatory (OAO) in the $g'$, $R_s$, and $I_s$ bands spanning 78 nights to examine any systematic effect due to the stellar variability of GJ 1214. All the listed observations were conducted in 2012.

In this paper, we report the results of the above new observations and present discussions on atmosphere models of GJ 1214b. The rest of the paper is organized as follows. We summarize our observations and methods of data reductions in Section 2. We describe analyses of transit light curves and stellar variability in Section 3. We present the results of our analyses and discuss the implications of the results in Section 4. Finally, we summarize this paper in Section 5.

## 2. OBSERVATIONS AND DATA REDUCTIONS

### 2.1. Subaru 8.2 m Telescope

We observed two transits of GJ 1214b with the Subaru 8.2 m telescope on Mauna Kea, Hawaii, USA. We used the Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) on 2012 August 12 UT and the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) on 2012 October 8 UT. Both transits were observed through the Johnson–Cousins $B$-band filter (0.440 μm ± 0.054 μm).

The Suprime-Cam11 equips a mosaic of 10 fully depleted-type 2K × 4K CCDs manufactured by Hamamatsu Photonics K.K., which covers a 34′ × 27′ field of view (FOV) in total with a pixel scale of 0.′20 pixel$^{-1}$ (each CCD has an FOV of 6′.8 × 13.6). GJ 1214 was observed with the Suprime-Cam during 06:20–10:10 of 2012 August 12 UT. The condition was photometric through the observations. The exposure time was set to 40 s and the dead time (including the CCD readout time of 18 s and other setup times) was about 29 s (duty cycle of 58%). We took 185 frames in total with the Suprime-Cam. GJ 1214 was located in the fifth CCD chip, named “satsuki.” We defocused the telescope so that stars have doughnut-like point-spread function (PSF) to achieve higher photometric precision. The typical size of the PSF was ~15 pixels (~3′′) in radius. Primary data reduction, including bias subtraction and flat fielding, and aperture photometry were carried out with a customized pipeline by Fukui et al. (2011), with a constant aperture-size mode where a same aperture size is applied for all images.

The FOCAS12 is installed at the Cassegrain focus of the Subaru telescope. The camera has a circular FOV of 6′ in diameter, covered by two fully depleted-type 2K × 4K CCDs by Hamamatsu Photonics K.K. Each CCD has four readout channels and each channel has 512 × 4176 active pixels. The pixel scale is 0′.104 pixel$^{-1}$. Note that the CCDs of the Suprime-Cam and the FOCAS are different. We observed GJ 1214 with the FOCAS during 04:46–07:08 of 2012 October 8 UT. The weather on that night was clear, but the observation began just after dusk and the first half of the transit occurred during twilight. The exposure time was 40 s and the dead time was about 22 s (duty cycle of 65%). We obtained 130 frames in total with the FOCAS. We again defocused the telescope and the typical size of the PSF was ~17 pixels (~1′.8) in radius. Primary reduction for bias subtraction using overscan region was processed with a dedicated tool called FOCASRED. Subsequent procedures, such as flat fielding and aperture photometry, were conducted with the same customized pipeline (Fukui et al. 2011) as the case for the Suprime-Cam.

### 2.2. IRSF 1.4 m Telescope

We observed a full transit of GJ 1214b with the IRSF 1.4 m telescope located in Sutherland, South Africa.13 The transit was observed during 1926–21:40 of 2012 June 14 UT. We used the SIRUS (Nagayama et al. 2003) camera for the observation, which is the same instrument we used in Narita et al. (2013).

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11 http://www.subarutelescope.org/Observing/Instruments/SCam/index.html
12 http://www.subarutelescope.org/Observing/Instruments/FOCAS/index.html
13 The IRSF was constructed and has been operated by Nagoya University, South African Astronomical Observatory (SAAO), and National Astronomical Observatory of Japan (NAOJ).
The SIRIUS camera is equipped with two dichroic mirrors and three 1K × 1K HgCdTe detectors, which can observe the J (1.250 μm ± 0.085 μm), H (1.63 μm ± 0.15 μm), and Ks (2.14 μm ± 0.16 μm) bands simultaneously. The FOV of the SIRIUS camera is a square of 7′′ on a side and the pixel scale is 0′.45 pixel−1. The exposure times were set to 40 s and the dead time of the SIRIUS is about 8 s (duty cycle of 83%). We obtained 163 frames on the night.

During observations, we used a position locking software introduced in Narita et al. (2013). Due to this software, the positions of GJ 1214's centroid on the three detectors were kept within an rms of about 2 pixels in both the X- and Y-directions. We note that the stellar images were widely defocused so that the PSF was spread to ~16 pixels (~7′′) in radius.

Data reduction for the IRSF data is carried out with a dedicated pipeline for SIRIUS,14 including a correction for nonlinearity, dark subtraction, and flat fielding. The nonlinearity correction enables us to work up to ~25,000 ADU with <1% linearity, which is sufficient for the current observations (Narita et al. 2013). Subsequent aperture photometry was done with the pipeline by Fukui et al. (2011).

2.3. MITSuME 50 cm Telescope

We monitored the brightness of GJ 1214 for 32 nights spanning from 2012 August 15 to 2012 November 1 (spanning 78 nights in total) with the MITSuME 50 cm telescope located in OAO, Okayama, Japan. The purpose of those observations is not for planetary transits but for stellar variability monitoring. The MITSuME telescope is equipped with three 1K × 1K CCD cameras, which can obtain g′-, R′-, and I′-band images simultaneously (Kotani et al. 2005; Yanagisawa et al. 2010). The each CCD has the pixel scale of 1.5 pixel−1 and the FOV is 26′ × 26′. We obtained about 10–80 frames per clear night. The exposure time was 60 s and the dead time was 3 s for all bands. We slightly defocused the MITSuME telescope so that the target did not saturate in the Ic band. The PSF extends about 2–4 pixels or 3″–6″ in radius. We note that the contamination from objects surrounding the target and reference stars are negligible, because there is no bright object around the stars based on the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003), and we have checked that the PSFs of the stars do not show significant contamination. Data reduction and aperture photometry for the MITSuME data are carried out with the pipeline by Fukui et al. (2011) as with the case for the Suprime-Cam.

3. ANALYSES

3.1. Transit Light Curves

First, we create dozens of trial light curves using different aperture sizes (Ar) and combinations of comparison stars for each observation. For the comparison stars, we use such stars that are not saturated, nor variable stars, and in the same CCD chip with GJ 1214. On this occasion we convert the time system, which is recorded in the FITS headers in units of Modified Julian Day based on Coordinated Universal Time, to Barycentric Julian Day (BJD) based on Barycentric Dynamical Time (TDB) using the algorithm by Eastman et al. (2010). Note that the time for each datum is assigned as the mid-time of each exposure. We find that all the trial light curves, Fobs, exhibit trends at out-of-transit (OOT) phase. The trends could be caused by the slow variability in the brightness of GJ1214 itself or comparison stars, changing airmass, position changes of the stars on the detectors, or high sky background, and so on. We then check the all trial light curves by eye and eliminate the obviously poor-quality ones.

Second, in order to select the most appropriate light curve for each observation and its baseline correction model for the OOT phase, we adopt the Bayesian Information Criteria (BIC; Schwarz 1978) for our analyses. The BIC value is given by

\[ \text{BIC} = \ln N - k \ln N, \]

where \( k \) is the number of free parameters, and \( N \) is the number of data points. We fit the trial light curves with an analytic transit light curve model and various baseline models simultaneously.

For the transit light curve model, we employ a customized code (Narita et al. 2007) which uses the analytic formula by Ohta et al. (2009), which is equivalent to Mandel & Agol (2002) when using the quadratic limb-darkening law. The quadratic limb-darkening law is expressed as

\[ I(\mu) = 1 - u_1(1 - \mu) - u_2(1 - \mu)^2, \]

where \( I \) is the intensity and \( \mu \) is the cosine of the angle between the line of sight and the line from the position of the stellar surface to the stellar center. For the transit model, we fix the orbital period of GJ 1214b to \( P = 1.58040481 \) days and the origin of the transit center to \( T_{\text{c,0}} = 2454966.525123 \) BJD_TDB determined by Bean et al. (2011). We note that this assumption is justified by the fact that there is no evidence of significant transit timing variations (e.g., Carter et al. 2011; Fraine et al. 2013). We also fix the orbital inclination \( i \) to 88′.94 and the orbital distance in units of the stellar radius \( a/R_\star \) to 14.9749, which were determined by Bean et al. (2010) and widely adopted in previous studies (Bean et al. 2011; Croll et al. 2011; de Mooij et al. 2012; Berta et al. 2012; Narita et al. 2013; Fraine et al. 2013; Teske et al. 2013). This assumption is necessary to directly compare transit depths with previous ones. Empirical quadratic limb-darkening coefficients for the BJHK_s bands are adopted from Claret & Bloemen (2011); specifically, \( u_{1,B} = 0.6366, u_{2,B} = 0.2737, u_{1,H} = 0.0875, u_{2,H} = 0.4043, u_{1,K_s} = 0.0756, u_{2,K_s} = 0.4070, u_{1,K_s} = 0.0475, u_{2,K_s} = 0.3502 \), assuming the stellar effective temperature \( T_{\text{eff}} = 3000 \) K and the log of the stellar surface gravity \( \log g = 5.0 \), assuming the stellar effective temperature \( T_{\text{eff}} = 3000 \) K and the log of the stellar surface

### Table 1

| Parameter | Value       | Source          |
|-----------|-------------|-----------------|
| \( P \) (days) | 1.58040481 | Bean et al. (2011) |
| \( T_{\text{c,0}} \) (BJD_TDB) | 2454966.525123 | Bean et al. (2011) |
| \( i \) (°) | 88′.94 | Bean et al. (2010) |
| \( a/R_\star \) | 14.9749 | Bean et al. (2010) |
| \( u_{1,B} \) | 0.6366 | Claret & Bloemen (2011) |
| \( u_{2,B} \) | 0.2737 | Claret & Bloemen (2011) |
| \( u_{1,H} \) | 0.0875 | Claret & Bloemen (2011) |
| \( u_{2,H} \) | 0.4070 | Claret & Bloemen (2011) |
| \( u_{1,K_s} \) | 0.0475 | Claret & Bloemen (2011) |
| \( u_{2,K_s} \) | 0.3502 | Claret & Bloemen (2011) |

\[ T_{\text{eff}}(K) = 3000 \]

\[ \log g = 5.0 \]

\[ \text{Table 1} \]

Assumed Parameters and their Sources

14 http://irsf-software.appspot.com/ias/nakajima/sirius.html
For the baseline model functions $F_{\text{rot}}$, we assume the following expression (Fukui et al. 2013):

$$F_{\text{rot}} = k_0 \times 10^{-0.4 \Delta m_{\text{rot}}} ,$$

$$\Delta m_{\text{rot}} = \sum k_j X_j ,$$

where $k_0$ is the normalization factor, $F_{\text{rot}}$ is the baseline flux, $\{X\}$ are observed variables, and $\{k\}$ are coefficients. For the variables $\{X\}$, we test various combinations of $t, z, d_x, d_y,$ and $s$, where $z$ is airmass, $s$ is time, $d_x$ and $d_y$ are the relative centroid positions in $x$ and $y$ directions, and $s$ is sky background counts, respectively.

For each trial light curve (using various aperture sizes and combinations of comparison stars) and each combination of variables, we optimize free parameters using the AMOEBA algorithm (Press et al. 1992) and evaluate a BIC value. We then select a light curve which gives the minimum BIC value for each observation. After this process, we rescale the photometric errors of the data so that reduced $\chi_r^2$ for each observation becomes unity. We also estimate an effect of time-correlated noise (so-called red noise; Pont et al. 2006) following the methodology by Winn et al. (2008), and find the effect is not significant for the current data sets. For this reason, we do not further inflate the errors of the data.

Finally, we fit each selected light curve with the transit light curve model and the baseline correction function model simultaneously. This is to include systematic uncertainties due to the baseline model in the planet-to-star radius ratio $R_p/R_s$. Free parameters for the fitting are thus $R_p/R_s$, $k_0$, and selected $\{k\}$. We present all the free parameters for the selected light curves as well as the aperture sizes used for aperture photometry in Table 2.

To evaluate uncertainties of free parameters, we use the Markov Chain Monte Carlo (MCMC) method, following the analysis in Narita et al. (2013). We create three different chains of 5,000,000 points, and trim the first 500,000 points from each chain as burn-in. We set acceptance ratios of jumping for the chains to about 25%. We check the convergence of free parameters by the Gelman & Rubin (1992) test (the Gelman–Rubin convergence diagnostic is less than 1.05). We define 1$\sigma$ uncertainties by the range of parameters between 15.87% and 84.13% of the merged posterior distributions. The results are described in Section 4.1.

3.2. Stellar Variability Monitoring

For the MITSuME data, first we eliminate data that were taken in high airmass (over 2) and during predicted transit times. We then select one comparison star for each band that meets the following conditions: (1) not a variable star (confirmed by other comparison stars), (2) brighter than the target but not saturated ($\sim$100 stars for the $g'$ band, $\sim$ 50 stars for the $R_c$ band, and $\sim$20 stars for the $I_c$ band), and (3) gives a light curve with the smallest rms. The reason why we choose only one comparison star and do not use combinations of stars is one brighter comparison star is sufficient to achieve a good precision ($\sim$1%) for our purpose (namely, any combination of comparison stars do not give significantly higher precision). We note that we also confirm that our result presented in the subsequent section (the periodicity and amplitudes of GJ 1214’s variability) is robust to several choices of a single comparison star. In this process, we also remove outliers that separate beyond 3$\sigma$ from mean brightness of each night. Consequently, we use 2646 data in total.

We model the stellar variability of GJ 1214 with a sine curve following Berta et al. (2011). We assume the following expression for the stellar variability:

$$F = k_{0,j} \times 10^{-0.4 k_j z} + A_j \times \sin(2\pi (t - t_0)/P_s),$$

where $k_{0,j}$ are the normalization factors for each band ($j = g', R_c, I_c$), $k_j$ are the coefficients for the airmass, $A_j$ are the semi-amplitudes of the stellar variability, $t_0$ is the time of zero phase, and $P_s$ is the period of the stellar variability. The free parameters are $k_{0,j}, k_j, A_j, t_0,$ and $P_s$ (11 parameters in total). We search best-fit parameters giving the lowest $\chi^2$ and largest $\Delta\chi^2$ compared to a null hypothesis by minimizing $\chi^2$ using the AMOEBA algorithm. Note that we set a prior constraint on the time of zero phase as 6150 < $t_0$ < 6200 to make the fitting convergent. To estimate uncertainties, after the best-fit parameters are determined, we rescale the photometric errors of the data so that reduced $\chi^2$ for the fitting becomes unity. We note that the error rescaling factors are 1.37, 1.27, 1.13 for the $I_c$, $R_c$, $g'$ bands, respectively. The uncertainties are estimated by a criterion of $\Delta\chi^2 = 1.0$. In addition, we also conduct periodogram analyses to show that we get a unique period in the observing span. The fitting and periodogram results are shown in Section 4.2.
4. RESULTS AND DISCUSSIONS

4.1. Planet-to-star Radius Ratios

Table 2 summarizes the best-fit parameters and their uncertainties for each observation based on the MCMC analyses. As a result, we obtain the following planet-to-star radius ratios: $R_p/R_s = 0.11651 \pm 0.00065$ (B band, Subaru/Suprime-Cam), $R_p/R_s = 0.11601 \pm 0.00017$ (B band, Subaru/FOCAS), $R_p/R_s = 0.11654 \pm 0.00080$ (J band, IRSF/SIRIUS), $R_p/R_s = 0.11550^{+0.00142}_{-0.00153}$ (H band, IRSF/SIRIUS), and $R_p/R_s = 0.11547 \pm 0.00017$ (Ks band, IRSF/SIRIUS). The observed light curves with the best-fit models for the Subaru and IRSF data are plotted in Figures 1–5. We also plot OOT-normalized light curves in Figures 1–5 for reference, although we fit the transit model and the baseline model simultaneously.

Overall, our observations indicate a flat transmission spectrum through the $BJHK_s$ bands. The transit depths do not appear...
significantly deeper in the $B$ and $K_s$ bands than in the $J$ or $H$ bands. The current IRSF/SIRIUS results are consistent with our previous ones with the same instrument (Narita et al. 2013), again refuting the deeper transit in the $K_s$ band. Our two $B$-band observations with the Subaru Suprime-Cam and FOCAS are well consistent each other, however, we should note the following. In the residuals of Figure 1 ($B$ band, Subaru/Suprime-Cam), we see a small bump in the early half of the transit. The feature could be caused by a spot-crossing event. If the feature is truly a spot-crossing event, we can learn what effect the spot would have on $R_p/R_s$ by eliminating the spot region from the data. For this purpose, we repeat the MCMC analysis using such data (specifically, data during 2456151.8194–2456151.8277 BJD$_{TDB}$ are removed). Consequently, we get $R_p/R_s = 0.11882 \pm 0.00070$ for this case. Although the feature is well consistent with a crossing over a small spot (a bump height of $\sim 0.1\%$ and a timescale of $\sim 8$ minutes; Carter et al. 2011; Berta et al. 2011), we cannot refute that it is a product of systematic effects. In addition, we should consider a possibility for a possible “hot-spot” (plage) occultation. Such a event may occur in stars with strong spot activity such as GJ 1214 (see, e.g., Mohler-Fischer et al. 2013; Colon & Gaidos 2013). For the current case, we removed only a possible spot-crossing region (with upward residuals), but there is a more subtle dip (downward residuals) just after the possible spot-crossing feature. As plages are typically located around dark spots, the slight dip may be caused by a plage crossing. If this is true, the above radius ratio $(R_p/R_s = 0.11882 \pm 0.00070)$ should be considered as an upper limit. As we cannot decisively diagnose whether those features are real or not, the result with the Subaru Suprime-Cam should be treated with caution.

4.2. Stellar Variability

Figure 6 plots the observed MITSuME data and the best-fit sinusoidal models. Figure 7 presents periodograms for the MITSuME data. Table 3 presents the best-fit values and their uncertainties for the free parameters. We obtain the lowest $\chi^2$ at the period of $P_s = 44.3$ days with an uncertainty of $\pm 1.2$ days. The periodicity is a unique one (no other significant $\Delta \chi^2$ peak) in the observing span as we can see in Figure 7. The estimated semi-amplitudes of the brightness variability are $0.32\% \pm 0.04\%$ in the $I_c$ band, $0.56\% \pm 0.08\%$ in the $R_c$ band, and $2.1\% \pm 0.4\%$ in the $g'$ band. As we can see, the quality of the $g'$-band data are relatively low (compared to the other bands) due to the faintness of the target. We thus note that the semi-amplitude of the $g'$-band variability may be still inaccurate.

![Figure 6](https://example.com/figure6.png)  
Figure 6. Long-term light curves of GJ 1214 obtained with the MITSuME 50 cm telescope at the Okayama Astrophysical Observatory in 2012. The data were taken in three ($I_c$: top; $R_c$: middle; $g'$: bottom) bands simultaneously. Observed data are plotted as dots. Data with error bars indicate mean values and rms divided by $\sqrt{N}$ values, where $N$ is the number of data points, of the observed data for each night for reference. Sinusoidal curves are the best-fit models based on the AMOEBA analysis described in Section 3.2. (A color version of this figure is available in the online journal.)

Those results are very similar to the previous results by Berta et al. (2011), who reported 3.5 mmag brightness variability in the $i+z$ band with a period of $\sim 53$ days and 7 mmag variability in the $V$ band at a period of $\sim 41$ days.

To assess the significance of the variability, we calculate $\chi^2$ and BIC values for both the best-fit case and the null hypothesis case ($P$ and $i_0$ are removed from the model, and $A_{I_c}$, $A_{R_c}$, and $A_{g'}$ are fixed to zero). We find $\Delta \chi^2 = 161.4$ and $\Delta \text{BIC} = 122.0$ ($\Delta k = 5$ and $N = 2646$). Thus the brightness variability is significantly detected, and our MITSuME monitoring independently confirms the stellar variability of GJ 1214. We caution, however, as Berta et al. (2011) mentioned, that the true rotation period of GJ 1214 could instead be a positive integer multiple of the quoted period. Since our monitoring covers only 78 nights, we cannot exclude a possibility of a longer stellar rotation period.

Even though the true stellar rotation period cannot be determined, the apparent stellar variability derived by our monitoring is useful to estimate and constrain systematic effects due to the stellar variability in the transit depths observed in 2012. In Figure 6, we show the observing dates of the transits, i.e., 2012 June 14 for the IRSF SIRIUS, 2012 August 12 for the Subaru Suprime-Cam, and 2012 October 8 for the Subaru FOCAS, with vertical lines. Since the MITSuME monitoring started after the Subaru Suprime-Cam observation, the phases for the IRSF SIRIUS observation and the Subaru Suprime-Cam observation are extrapolated by the period of $P_s = 44.3$ days. According

| Parameter | Value | Uncertainty |
|-----------|-------|-------------|
| $P_s$ (days) | 44.3 | $\pm 1.2$ |
| $i_0$ (JD−2,450,000) | 6174.22 | $\pm 0.77$ |
| $A_{I_c}$ | 0.00319 | $\pm 0.00038$ |
| $A_{R_c}$ | 0.00558 | $\pm 0.00078$ |
| $k_{0, I_c}$ | 0.0213 | $\pm 0.0042$ |
| $k_{0, R_c}$ | 0.9958 | $\pm 0.0015$ |
| $k_{0, g'}$ | 0.9729 | $\pm 0.0031$ |
| $k_{c, I_c}$ | 1.0405 | $\pm 0.0155$ |
| $k_{c, R_c}$ | $-0.0028$ | $\pm 0.0011$ |
| $k_{c, g'}$ | $-0.0210$ | $\pm 0.0023$ |
| $k_{s, I_c}$ | 0.0262 | $\pm 0.0010$ |
to the figure, the brightness of GJ 1214 is nearly peak at the IRSF SIRIUS observation, middle at the Subaru Suprime-Cam observation, and bottom at the Subaru FOCAS observation.

4.3. Possible Impacts of Adopted Assumptions on Radius Ratios

We have adopted some assumptions in our analyses as shown in Table 1. Since any large systematic effects would affect discussions on atmospheric models of GJ 1214b, we should check the robustness of our results against the assumptions. In the previous study, we have already confirmed the robustness of the radius ratios against the assumption of the horizontal axis (other parameters are free). The optimal case \( \chi^2 \) is indicated by the vertical line in the bottom panel.

For case (1), we find \( u_2 = 0.20 \pm 0.06 \) and \( R_p/R_s = 0.11728 \pm 0.00088 \) for the Subaru/Suprime-Cam data, while \( u_2 = 0.30 \pm 0.06 \) and \( R_p/R_s = 0.11564^{+0.0155}_{-0.0157} \) for the Subaru/FOCAS data. The derived \( u_2 \) values are almost consistent with the empirical value of \( u_2 = 0.2737 \) (Claret & Bloemen 2011), and the derived radius ratios are also consistent with the values reported in Table 2 within 1\( \sigma \). We additionally test an MCMC analysis with letting both \( u_1 \) and \( u_2 \) free, and find \( R_p/R_s = 0.11720 \pm 0.00085 \) for the Subaru/Suprime-Cam data, and \( R_p/R_s = 0.11548^{+0.0155}_{-0.0164} \) for the Subaru/FOCAS data. Those values are almost the same with the case (1), showing that letting one limb-darkening parameter free is sufficient for this kind of tests. Based on this test, we estimate that the possible systematic effect due to the limb-darkening parameters is smaller than \( \Delta(R_p/R_s) \sim 0.001 \), and we conclude that our results for radius ratios in the \( B \) band are robust. We also note that the above radius ratio values with free limb-darkening parameters do not change our conclusion in Section 4.5.

From cases (2) and (3), we find an interesting trend between the radius ratio and the assumed effective temperature of GJ 1214. The derived radius ratios are \( R_p/R_s = 0.11803 \pm 0.00065 \) (case 2, Subaru/Suprime-Cam), \( R_p/R_s = 0.11838 \pm 0.00123 \) (case 2, Subaru/FOCAS), \( R_p/R_s = 0.11441 \pm 0.00070 \) (case 3, Subaru/Suprime-Cam), \( R_p/R_s = 0.11264 \pm 0.00116 \) (case 3, Subaru/FOCAS). Namely, an assumption of a hotter effective temperature gives a larger radius ratio, and vice versa. Among the assumed effective temperatures, the case for \( T_{\text{eff}} = 3000 \) K seems to be the most consistent with the test case (1), thus we do not change our main results. Although identifying a reason for this trend is beyond the scope of this paper, this kind of test for the systematic effect due to the limb-darkening parameters would be necessary in future studies, especially in bluer wavelength regions.

4.4. Possible Impacts of Unocculted Starspots on Radius Ratios

Unocculted starspots are known to cause a systematic effect on an apparent radius ratio (see, e.g., Carter et al. 2011; Désert et al. 2011b; Sing et al. 2011). The systematic difference of the radius ratio \( \Delta(R_p/R_s) \) caused by the stellar variability due to starspots can be written as

\[
\Delta(R_p/R_s) \simeq 0.5 \Delta f(\lambda) (R_p/R_s),
\]

where \( \Delta f(\lambda) \) is stellar brightness variability at wavelength \( \lambda \) (Sing et al. 2011; Narita et al. 2011).

The brightness of GJ 1214 in the \( g' \) band on the two observing nights of the Subaru Suprime-Cam and the Subaru FOCAS is different by \( \sim 2\% \) based on the MITSuME monitoring, and given that the semi-amplitude of the stellar variability in the \( B \) band is similar to that in the \( g' \) band, a systematic difference between the Subaru Suprime-Cam and the Subaru FOCAS observations is \( \Delta(R_p/R_s) \sim 0.0012 \). However, this value may be too conservative, since the semi-amplitude of the \( g' \) band variability may be inaccurate due to poor signal-to-noise ratio, as we have cautioned in the previous section, and since it appears to be much larger than the semi-amplitude in the \( V \) band (\( \sim 7 \) mmag) reported by Berta et al. (2011). For this reason, we also try an independent simple estimate for the effect of unocculted spots in the \( B \) band as follows. First, we assume the temperatures of the (normal) stellar surface and the spot region to be \( T_{\text{star}} = 3000 \) K and \( T_{\text{spot}} = 2700 \) K. Assuming the blackbody profile for the emission from those regions, we search for an optimal spot coverage that can explain the semi-amplitude of \( R_c \) and

![Figure 7. Periodograms for the MITSuME data. Results for the \( I_c, R_c, g' \) bands, and a combined case are shown from top to bottom. The vertical axis indicates \( \Delta \chi^2 \) between the models for no variation (\( A_i = 0 \)) and for a fixed period at the horizontal axis (other parameters are free). The optimal case (\( P_f = 44.3 \text{ days} \)) is indicated by the vertical line in the bottom panel.](image-url)
$I_c$-band variability. We find that a spot coverage of 0.73% gives the best fit for those two bands. Using this value, the semi-amplitude of the stellar variability in the $B$ band is estimated as 0.88% and the possible systematic difference in the radius ratio is $\Delta(R_p/R_*) \sim 0.00053$ at most. In either case, we estimate a possible systematic effect on the radius ratio in the $B$ band is as small as or smaller than $\Delta(R_p/R_*) \sim 0.001$.

We note that the more unocculted spots exist, the deeper transits would be observed (Carter et al. 2011). Namely, the transit at the time of the FOCAS observation is expected to be the deepest. Our results shown in Table 2, however, appear to be inverse, but this is not significant when considering the uncertainties in $R_p/R_*$ for the Suprime-Cam and the FOCAS observations.

For the near-infrared region, if we suppose that the semi-amplitude of the stellar variability in the near-infrared region is similar or smaller than the variability in the $I_c$ band from the MITSuME monitoring, then the difference of the stellar brightness in the $JHK_s$ bands is less than $\sim 0.6\%$. Based on this assumption, we estimate that the maximum systematic differences of radius ratios in the $JHK_s$ bands are $\Delta(R_p/R_*) \leq 0.0004$, which is well smaller than the observational uncertainties. On the other hand, if we again adopt the same estimation method used for the $B$ band, we derive the semi-amplitudes of the stellar variability in the $JHK_s$ bands as 0.20%, 0.15%, and 0.12%, respectively. Those values are consistent with the above assumption. Based on the values, we estimate possible systematic effects on the radius ratio as $\Delta(R_p/R_*) \sim 0.00012(J)$, 0.00009($H$), and 0.00007($K_s$), respectively. Thus, we conclude that we can neglect systematic effects due to unocculted spots in the near-infrared region within the current observational errors.

### 4.5. Atmospheric Models

Measured radius ratios of GJ 1214b published so far are plotted with respect to the wavelength in Figure 8, which also shows the five best-fit spectra from the Figure 21 of Howe & Burrows (2012). As described in Section 1, Narita et al. (2013) raised a possibility of a high molecular weight (high-$\mu$), vapor-rich atmosphere which predicts a flat spectrum, by showing that a $K_s$-band transit was shallower than those from Croll et al. (2011) and de Mooij et al. (2012). The new $K_s$-band transit depth from the IRSF SIRIUS observation is consistent with the previous values of ours and Bean et al. (2011). This does not mean, however, that another possibility of a low-$\mu$, hydrogen-dominated atmosphere is excluded when considering extensive clouds. This is because both theoretical spectra of the high-$\mu$ and low-$\mu$ atmospheres yield similar transit depths at the $K_s$-band wavelength, as seen in Figure 8(a).

The $B$-band transit that we have observed with the Subaru FOCAS is significantly shallower than the $g$-band transit reported by de Mooij et al. (2012). As discussed in Howe & Burrows (2012), the deep $g$-band transit needs a Rayleigh-scattering-like feature (the Rayleigh slope) in the visible to near-infrared wavelength region, which appears in the theoretical spectrum of a hydrogen-rich atmosphere with tholin haze (see Figure 8(a)). In contrast, the shallow $B$-band transit is consistent with the model spectra for high-$\mu$ atmospheres without the Rayleigh slope (see Figure 8(b)). Among the five best-fit models proposed by Howe & Burrows (2012), the model spectra for the 1% $H_2O + 99\% N_2$ atmosphere (with and without tholin haze) appear most likely. While the solar-composition (low-$\mu$) atmosphere with opaque clouds may also account for the FOCAS $B$-band transit as well as the IRSF $JHK_s$-band transits. In contrast, the low-$\mu$ atmosphere with 0.1 $\mu$m tholin haze is inconsistent with the FOCAS $B$-band transit, and the similar atmosphere with 1 $\mu$m tholin haze is also inconsistent with the IRSF $HK_s$-band transits.

Unfortunately, the result from the Suprime-Cam is inconclusive due to the possible spot-crossing event, as discussed in the Section 4.1. Given that the spot-crossing is real, the difference of the transit depths between the two observations ($R_p/R_*$ (Suprime-Cam) $= 0.11882 \pm 0.00070$ and $R_p/R_*$ (FOCAS) $= 0.11601 \pm 0.00117$) is about $2\sigma$ ($1\sigma$ here is a square root of sum of squares of both uncertainties). Although the significance of the difference is marginal, the two transit depths appear to be inconsistent. One possibility to explain the difference is that the stellar activity might cause a temporal change in the amount of haze in the atmosphere. In the case of Titan’s atmosphere, it is known that the solar UV flux and Saturn’s magnetospheric electrons and protons contribute to synthesize tholin haze (Khare et al. 1984). When a close-in planet like GJ 1214b passes through a stellar-spot magnetosphere, the production rate of tholin haze might be affected. A time variation in the amount of tholin haze might lead to the change of the $B$-band transit depths. In this case, some amount...
of a low-$\mu$ component should be present in the atmosphere of GJ 1214b. Although it is highly speculative, this possibility is worth exploring by repeated future observations.

Whether or not the atmosphere contains a significant amount of water affects our understanding of the origin of GJ 1214b. The deep photometric transit originally presented by Charbonneau et al. (2009) suggests that GJ 1214b contains some low-$\mu$ components. If the planet is completely differentiated, it must be enveloped with a low-$\mu$ atmosphere. Within the context of the core-accretion model, a hydrogen-rich atmosphere of nebular origin is the most likely possibility (Ikoma & Hori 2012). Detailed modeling of the internal structure of GJ 1214b (Nettelmann et al. 2011; Valencia et al. 2013) predicts that the hydrogen-rich atmosphere constitutes several percent of the planet mass to reproduce the mass–radius relationship for this planet. It should be also noted that Morley et al. (2013) recently suggested that cloud and hydrocarbon haze formation in the atmosphere of GJ 1214b by (non-)equilibrium chemistry favored atmospheric models with enhanced metallicity.

The atmosphere of GJ 1214b may have been subject to photoevaporative mass loss due to stellar XUV irradiation. Although the current irradiation level would be so low that the atmosphere will undergo no significant mass loss today and in the future, several studies advocated that a GJ 1214b-like planet had experienced a significant removal of the atmosphere in the past (e.g., Owen & Wu 2013). The mass loss history is, however, not well constrained, because we do not know the current intrinsic luminosity of GJ 1214b, which affects the speed of the thermal evolution significantly. Thus, we cannot deny the presence of such a hydrogen-rich atmosphere theoretically from the viewpoint of the internal structure and evolution.

On the other hand, absence of low-$\mu$ components in the atmosphere would give some important constraints on the structure and origin of this planet. To reconcile with the planet’s low density, one possibility would be that low-$\mu$ components should be incorporated in the interior; for example, the envelope in the mixed state with water and H/He. Giant collisions between super-Earths or heavy secondary bombardments of volatile-rich planetesimals would be needed for such mixing to occur. Such processes triggered in a planetary system would lead to the formation of multiple planets. Provided that this picture holds true for GJ 1214b, we predict that additional planets should exist in the GJ 1214 system. Thus, search for outer planets helps us to learn the formation history of GJ 1214b.

4.6. Suggestions for Future Observations

Although our results have suggested that GJ 1214b has a fairly flat transmission spectrum through the $BJHK_s$ bands, it is still difficult to determine one decisive atmosphere model. Experiences have shown that broadband single-color transit photometry is not efficient to constrain an atmosphere model in the presence of starspots and the stellar variability. More effective ways to characterize atmospheres of transiting planets would be (1) simultaneous multi-band transit photometry using small-medium ground-based telescopes (e.g., Croll et al. 2011; de Mooij et al. 2012; Narita et al. 2013; Fukui et al. 2013), (2) multi-object spectrophotometry using large ground-based telescopes (e.g., Bean et al. 2010, 2011), and (3) spectrophotometry using space telescopes (e.g., Berta et al. 2012). It would be important to observe the wavelength region where the difference of transit depths between the low-$\mu$ and the high-$\mu$ atmospheres is significant, especially the Rayleigh slope (optical) region and around the $K$-band region. In addition, repeated transit observations are highly desirable to improve the significance and to check possible time variations. As the ongoing ground-based transit surveys (e.g., MEarth) and the future space-based survey like TESS (Ricker et al. 2010) will discover more transiting super-Earths around nearby cool host stars, the current experiences for GJ 1214b would become a good practice for the future.

5. SUMMARY

We have presented two $B$-band transits observed with the Suprime-Cam and FOCAS on the Subaru 8.2 m telescope and one simultaneous $JHK_s$-band transit taken with the SIRIUS camera on the IRSF 1.4 m telescope. Our measurements of transit depths suggest a fairly flat transmission spectrum through the $BJHK_s$ bands. Comparisons of our new results and previous observations with theoretical atmospheric models from Howe & Burrows (2012) indicate that the high-$\mu$ (water-rich) atmosphere models are most likely, although the low-$\mu$ (hydrogen-dominated) atmosphere with thick clouds may still account for the observations. As noted in Section 4.1, our Subaru Suprime-Cam data show a possible spot-crossing event. Suppose that the spot-crossing is real and the data from the event are removed, our two $B$-band results are marginally inconsistent. It is slightly puzzling, but it may be simply due to unknown systematic effects, or it may be explained by temporal changes of transit depths due to the stellar activity and thereby time variations of haze amount. To further constrain the atmosphere model of GJ 1214b and to check a possibility of the presence of time variations in transit depths or the Rayleigh slope, additional repeated observations described in the previous subsection (Section 4.6.) would be desirable in the future.

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