First discovery of variability of direct imaged exoplanet 2M1207b

Yifan Zhou,[1*] Daniel Apai,[1] Glenn Schneider[1] Mark Marley[2] Adam Showman[3]

[1]Department of Astronomy, the University of Arizona
933 N. Cherry Ave., Tucson 85721, USA
[2]NASA Ames Research Center
[3]Department of Planetary Science, the University of Arizona

[*]To whom correspondence should be addressed; E-mail: yifzhou@email.arizona.edu.

Rotational modulations in disk-integrated light of brown dwarfs have recently provided powerful constraints on the properties of ultracool atmospheres, including longitudinal and vertical cloud structures and cloud evolution. Furthermore, detection of periodic light curve variations can directly probe the rotational periods of ultracool objects. We present here, for the first time, time-resolved high-precision photometric measurements of a planetary-mass companion, 2MASS1207b, to a brown dwarf primary. Using HST/WFC3 and point spread function combination with two spacecraft roll angles we detect photometric modulations in the light curve. The amplitude is 0.9% in the F160W and 1.5% in the F125W filters; we find a consistent period and similar phase in both bands. Joint fit to the lightcurve in both bands suggest a period of $10.2^{+0.9}_{-0.8}$ h. The relative amplitudes in the two filters are very similar to that found in a recent study of a field (high-gravity) L-dwarf, suggesting that

the cloud structures that introduce the photometric modulations are similar in high- and low-gravity objects. Importantly, our study also measures, for the first time, the rotational period for directly imaged planetary-mass companion.

Introduction

ObservationWe obtained direct images of the 2M1207A+b system on UT 2014 April 11from 08:07:47 to 16:53:18 using the Hubble Space Telescope (HST) and its Wide Field Camera 3 (*?, WFC3,*)]Kimble2008 in the frame of the HST Proposal GO-13418 (PI: D. Apai). We acquired the observations in filters F125W (λ_{pivot} = 1245.9 nm, full width at half maximum (FWHM) = 301.5 nm) and F160W (λ_{pivot} 1540.52, FWHM = 287.9 nm), roughly corresponding to the J and H bands. The WFC3 pixel scale is ≈13mas. We used the 256×256 pixels sub-array mode to avoid memory dumps during the observations. In order to provide a near-continuous coverage for detecting modulations we observed the 2M1207 system in six consecutive HST orbits, obtaining data with cadence of ~ 1.5 minutes over a baseline of 8 hours and 40 minutes. The observations were interrupted by 58 minute-long Earth occultations every 94 minutes.

Data reduction Hybrid PSF photometry

One major challenge of high contrast imaging observation using WFC3/IR is significant under-sampling of the detector. 2M1207 A and b are only separated by $\sim$ 6 pixels or ∼5 FWHM of the PSF. When applying roll subtraction, notable artifact structures are generated by image interpolation and shifting. On the other hand, *Tiny Tim* PSF simulator (*1*) offers a solution by providing Nyquist or better sampled PSF, but systematic errors of *Tiny Tim* PSF for WFC3 limits its ability in high precision photometry (*2*). However, we are able to fully characterize the difference of model and observed PSFs with 6 orbits time-resolved observation data. To obtain robust *Tiny Tim* PSF photometry, we designed a 2-round PSF fitting strategy: 1. calculating correction map for *Tiny Tim*; 2. hybrid PSF photometry.

For both of 2 rounds, we used *Tiny Tim* to calculate $10\times$ over-sampled model PSFs based on the filters, the spectra (*3, 4*), the telescope's actual focus, and the telescope jitter. We used the new set of Tiny Tim parameters provided by (*2*) to improve model of the cold mask, OTA spikes, and the coma. The focus parameters were calculated using the model listed on the STScI website[1]. To register *Tiny Tim* PSF to observed PSF of 2M1207A, we moved the over-sampled PSF over a coordinate grid (gird size=0.001 pixel) using cubic interpolation and minimize the rms difference of the observed and re-binned *Tiny Tim* PSFs over a region centered on 2M1207A with a 5-pixel-radius aperture centered on 2M1207b excluded. Then we introduce another *Tiny Tim* PSF for 2M1207b and fit the position of 2M1207 b and the photometries of 2M1207 A and b simultaneously by least square optimization. From our data set, we discovered that the difference of observed PSFs and model PSFs were very stable for given PSF positions. Therefore at the end of the first round PSF fitting, we derived 8 (2 roll angles $\times$ 4 dithering positions) observationally derived correction maps for each filter:

$$\mathrm{Corr} = \mathrm{Median}(\mathrm{PSF}_{\mathrm{obs.}} - \mathrm{PSF}_{\mathrm{model}}) \tag{1}$$

where $\mathrm{PSF}_{\mathrm{model}}$ is a combination of two *Tiny Tim* PSFs for 2M1207 A and b. In the second round, we combined the correction term linearly with the two *Tiny Tim* PSFs to generate hybrid PSFs, and fitted the three components together. We found that by including the correction term, the reduced χ^2 of PSF fitting is decreased from ~ 10 to around unity. Relative photometry is acquired from the scaling parameters of the model PSFs.

PSF profiles change with exposure positions due to pixelation, especially for the case that WFC3 IR is significantly under-sampled. Also, the flat fields may potentially have large scale structures (*5*). We found a correlation of photometry with PSF positions on detector frame for both 2M1207 A and b. Correction were made by normalizing each group of exposures that have the same dithering position and roll angle individually – we took the median of the

[1] `http://www.stsci.edu/hst/observatory/focus/FocusModel`

fluxes that were measured from these exposures as normalization factors and divided them from every photometric measurement. Because the normalization factor for each group of exposures is calculated across the whole observation, this normalization step have negligible impacts on variability analysis.

Result We present the first high-contrast, high-resolution, high-cadence, and high-precision photometry of a directly imaged planet or planetary-mass companion. Our observations reveal a modulation in the light curve of the 5–7 M_J companion 2M1207b, the first detection of modulations in directly imaged ultracool objects. The best fit periods for F125W and F160W are 10.5 and 9.1 hour correspondingly. The amplitudes for the normalized light curves are 1.45% and 0.92% for F125W and F160W light curves.

The distributions for the periods demonstrate long tail shaped towards long period, with core region roughly Gaussian. With 64% confidence, we estimated the 1-σ range for the periods of F125W and F160W to be $10.5^{+1.3}_{-1.2}$ and $9.1^{+1.1}_{-1.0}$ h, respectively. The period of best fitted sine wave of F125W light curve is 1.5h longer than that of F160W that is slight larger 1-σ standard deviation. We also jointly fit the two band light curve together forcing the periods of two sine waves to be the same. We derived a modulation period of $10.2^{+0.9}_{-0.8}$ h in this circumstance.

We discovered that the variation amplitudes in the two bands were significantly different. The distributions of the amplitudes are well described by Gaussian profiles. By fitting a Gaussian function to the distribution, we determined that amplitude distribution of F125W peaks at 1.45% with a standard deviation of 0.22%, and that of F160W have mean and standard deviation of 0.92% and 0.20%, respectively. The peaks of the two histograms separated by more than 2-σ. The variation amplitude of F125W light curve is 1.58 times of that of F160W light curve.

Discussion A fundamental result of our study is the direct determination of the rotation period of a directly imaged planetary-mass object. We convert the rotation period to equatorial velocity by adopting a radius of 1 – 1.4 $R_{\rm Jup}$ for 2M1207b, and 1 $R_{\rm Jup}$ for field brown dwarfs with well defined rotation period from the study of (*6*), and compare their rotation velocities with solar system planets and β Pic b in the left panel of Figure **??**. The study by (*?,*)]Snellen2014 succeeded in measuring $v \sin i$ for β Pic b and demonstrated that it fits a trend defined by Solar System planets in which more massive planets have faster rotation rates. They suggested that this relation is linked to the accretion processes during planet formation.

Excitingly, our measurement of the rotation period demonstrates that 2M1207b, a planetary mass companion with similar age to β Pic b, has a rotation velocity that fits in the same trend, as well as majority of brown dwarfs. We note that 2M1207b is most likely formed in the same way as brown dwarfs by gravitational fragmentation, which suggests that rotation periods are not good tracers of the formation pathways and may not contribute important evidence for a formation in a disk vs. in a cloud core environment.

Furthermore, our observations allow us to compare the relative amplitudes in the J- and H-bands between the handful of brown dwarfs for which high-quality near-infrared time-resolved observations have been obtained. In the right panel of Figure **??**, we plot the relative amplitude of J- and H-bands of 2M1207b with brown dwarfs (*7–12*) that have different spectral types and J$-$H colors.

We found a strong correlation between the spectral type of the object and the J to H variation amplitude ratio. Figure **??** demonstrates that earlier spectral type objects – independent of their surface gravity – have larger variations at shorter wavelength than at longer wavelengths. Importantly, although the J$-$H color of 2M1207b is significantly redder the other L5 dwarfs, we note that its relative variation amplitude ratio is almost identical to the matching spectral type mid-L dwarf 2M1821.

SummaryIn summary from our J- and H-band high precision, high-cadence lightcurves we discovered sinusoidal modulations in the planetary mass object 2M1207b. This is the first detection of rotational modulations in a directly imaged planetary mass object. The period is

$10.2^{+0.9}_{-0.8}$, very similar to that derived from *v sin i* measurements for the direct imaged exoplanet β Pic b and significantly longer than most field brown dwarfs with known rotation periods. The relative modulation amplitude of J and H band is almost identical to one matching spectral type L5 dwarf, although they have very different J$-$H colors, and it is markedly different form later spectral type brown dwarfs.

Finally, we note that the observations presented here open an exciting new window on directly imaged exoplanets and planetary-mass objects. Our study demonstrates a successful application of high-cadence, high-precision, high-contrast photometry with planetary mass companion. We also show that these observations can be carried out simultaneously at multiple wavelengths, allowing us to prove multiple pressure levels. With observation of a larger sample and at multiple wavelengths, we will be able to explore the detailed structures of atmospheres of directly imaged exoplanets, and identify the key parameters that determine these.

References and Notes

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