Optical and Near-Infrared Transit Observations and Study on Weather of Exoplanets

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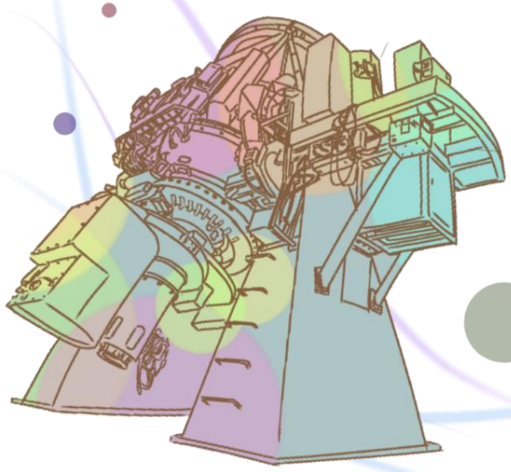

Before Starting


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Research field
・Observational Astronomy ・Exoplanet

Today's slides
(google drive)

I'm also uploading it to WhatsApp.

The superior translator

○Generally, the speaking points are written on the slides.
○I usually only speak Japanese, so I'm not very good at English.
○However, **I will do my best** to speak today!
○If you have any difficult questions,
please catch me afterwards and let's talk in detail.

History of Exoplanet Discoveries

1995：The first Exoplanet, **51 Pegasi b** was discovered by Mayor and Queloz using the radial velocity method.

1999：The first **transit**, where a planet passes in front of its host stars, was observed for HD209458. (Charbonneau et al. 2000, Henry et al. 2000)

2001：The transit observations of HD 209458 b detected an **atmosphere** of an **exoplanet**. (Vidal-Madjar et al. 2003)

2009：The Kepler Space Telescope started operations. (discovered approximately 2500 exoplanets)

2018：The Transiting Exoplanet Survey Satellite (TESS) started operations.

2019：Mayor and Queloz were awarded the Nobel Prize in Physics.

2022：The James Webb Space Telescope started operations.

A total of **5,445 exoplanets** have been confirmed (06/14/2023).

Hot Jupiter

51 Pegasi b is classified as a **Hot Jupiter.**

Hot Jupiter

- It is a giant gas planet that orbits its host star in close proximity with a short period.
- It has a mass comparable to that of Jupiter.
- It has a high-temperature surface by heating from its host star.

51 Pegasi b

- Radius: 1.9 Jupiter radius
- Mass: 0.5 Jupiter mass
- Orbital radius: 0.05 AU (Mercury: 0.38 AU)
- Orbital period: 4 days (Jupiter: 12 years)
- Temperature: 1200 K (Jupiter: 130 K)

Fig 1. Illustration of a hot Jupiter © ESA

Transit method

Transit method is a technique for detecting exoplanets. Dimming of a star is observed when a planet passes in front of the star.

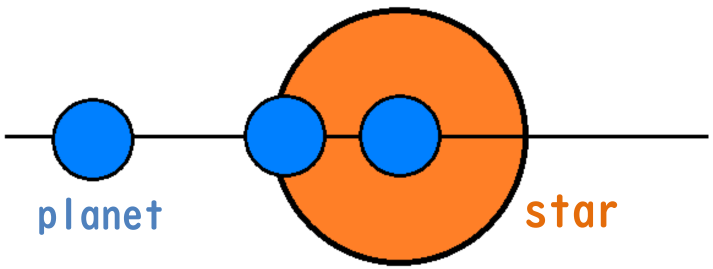


Fig 2. Illustration of a Transit Event

Fraction of dimmming
- Hot Jupiter ～ 1%
- Earth-like planets ～ 0.01%

An exoplanet was first discovered using the **transit method** by Charbonneau et al. (2000) and Henry et al. (2000).

$$\Delta F/F = (R_2/R_1)^2$$

ΔF : change in flux R_1: star radius

F : star flux R_2: planet radius

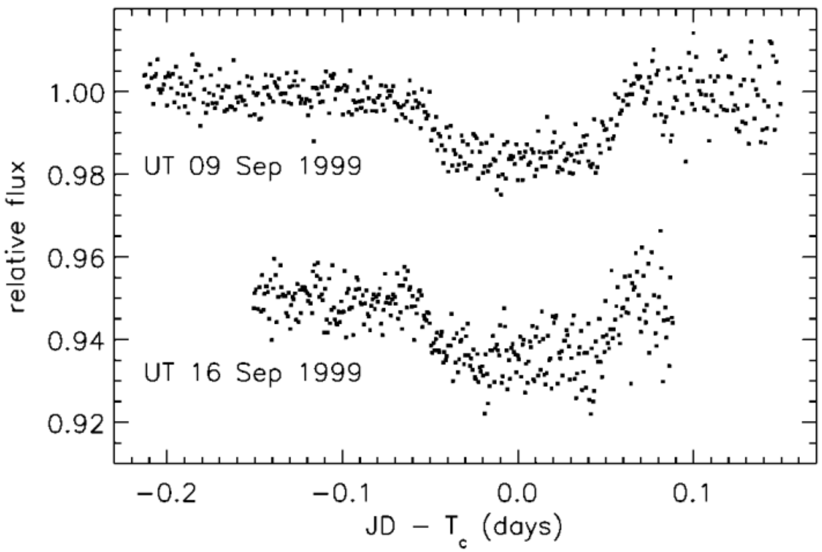


Fig 3. Transit observations of HD209458 b in the optical R band (0.66 μm) (Charbonneau et al. 2000).

Multi-wavelength transit observations

If a planet has an atmosphere, specific wavelengths of light are absorbed by the atmosphere.

By investigating the wavelength dependence of the transit depth of exoplanets, we can estimate the atmospheric composition of the planets.

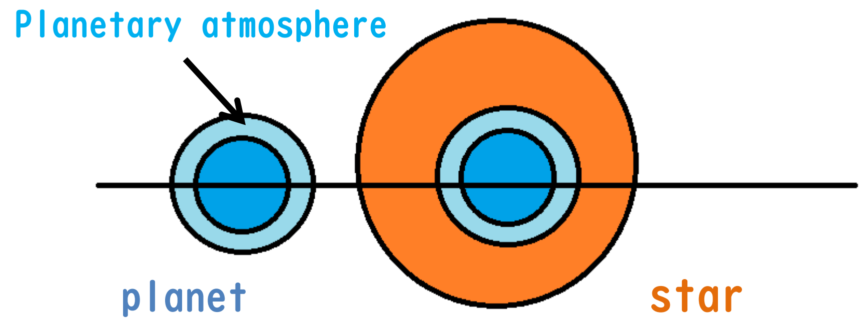


Fig 4. Illustration of a Transit Event with atmosphere.

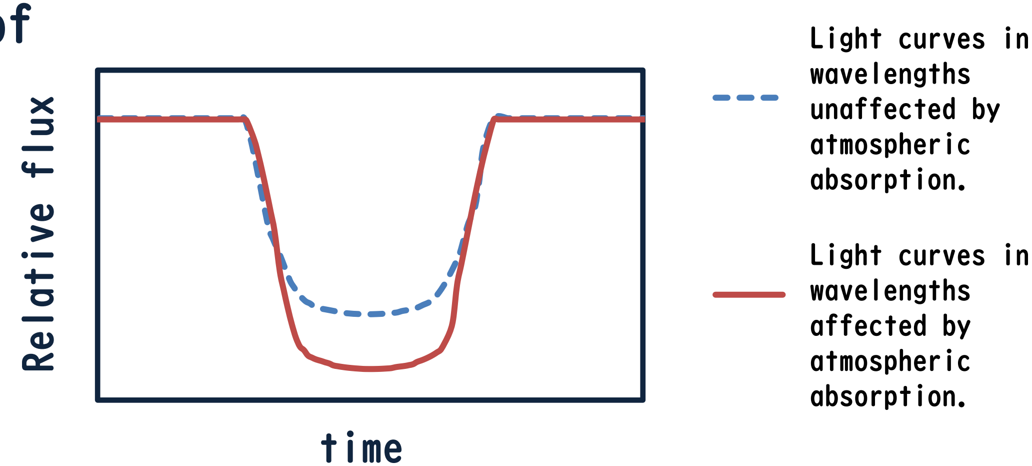


Fig 5. Transit depths at the wavelengths with no atmospheric absorption and at the wavelengths with atmospheric absorption.

Multi-wavelength transit observations

Hot Jupiters have an atmosphere **primarily composed of H_2**.

Molecules such as H_2O, CH_4, CO_2, and CO have been detected.

These molecules absorb a significant portion of near-infrared light by the vibrational transitions.

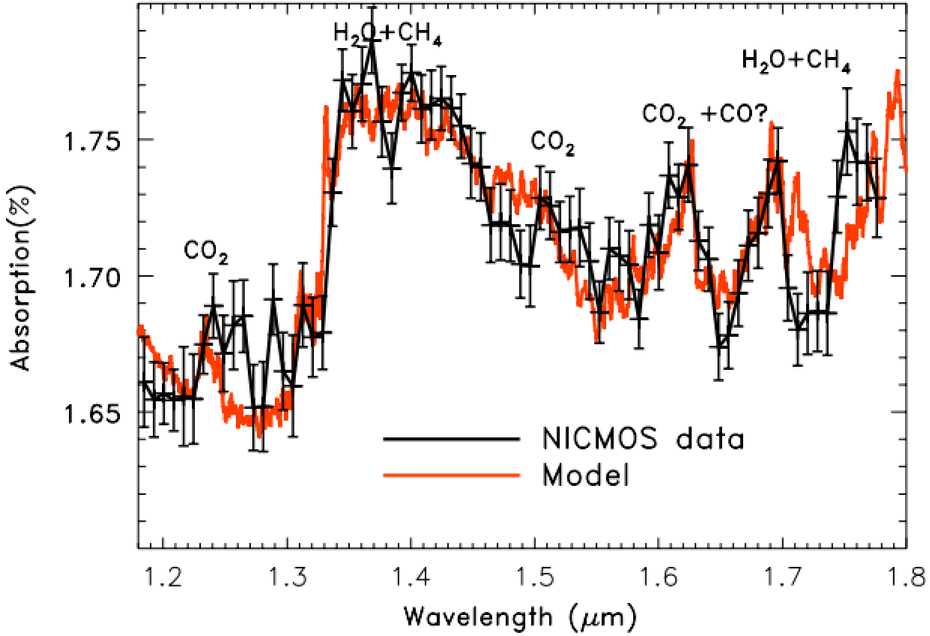
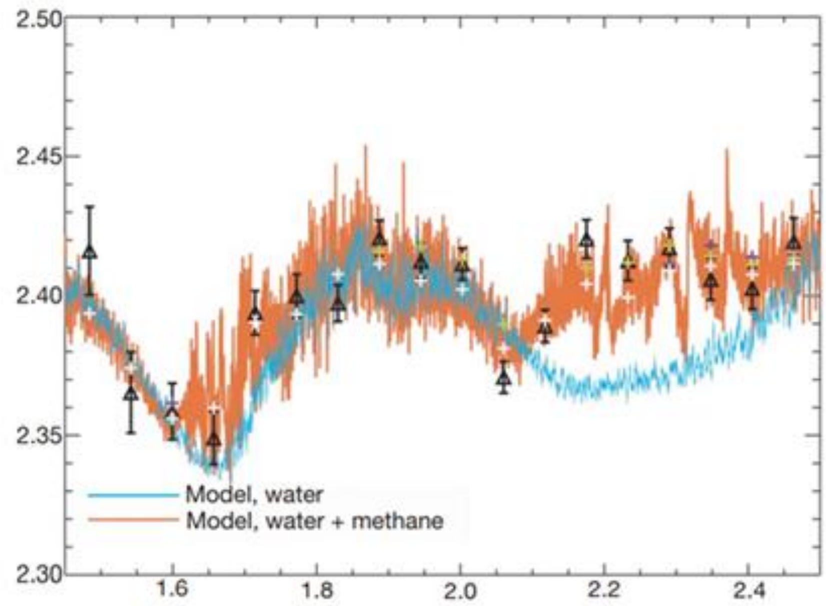


Fig 6. The atmospheric spectrum of XO-1 b observed with the Hubble Space Telescope's NICMOS and atmospheric models including H2O, CH4, CO2, and CO2 (Tinetti et al 2010).

Previous studies on planetary atmosphere

Swain et al. (2008) observed the near-infrared transit of HD189733 b using the Hubble Space Telescope.



They developed an atmospheric model consisting of H_2 (≧99%), H_2O (0.05%), and CH_4 (0.005%).

Fig 7. Observed transit depths of HD189733 b and atmospheric spectral models of the planet atmosphere.

Black dots : Observed transit depths
Blue : H2O-inclusive atmospheric model
Orange : H2O and CH4-inclusive atmospheric model
(Swain et al. 2008)

They suggested the presence of methane (CH4) in the atmosphere.

Near-infrared transit observations of Qatar-1b

Hirano observed the near-infrared transit of **Qatar-1 b** using the Nishiharima Infrared Camera (NIC) on the Nayuta Telescope (Master's thesis 2022).

Based on near-infrared observations, Qatar-1 b's atmosphere is best fitted by a 99% H_2 and 1% CO_2 model, suggesting a clear atmosphere with CO_2.

The atmospheric model was constructed using the Planetary Spectrum Generator.

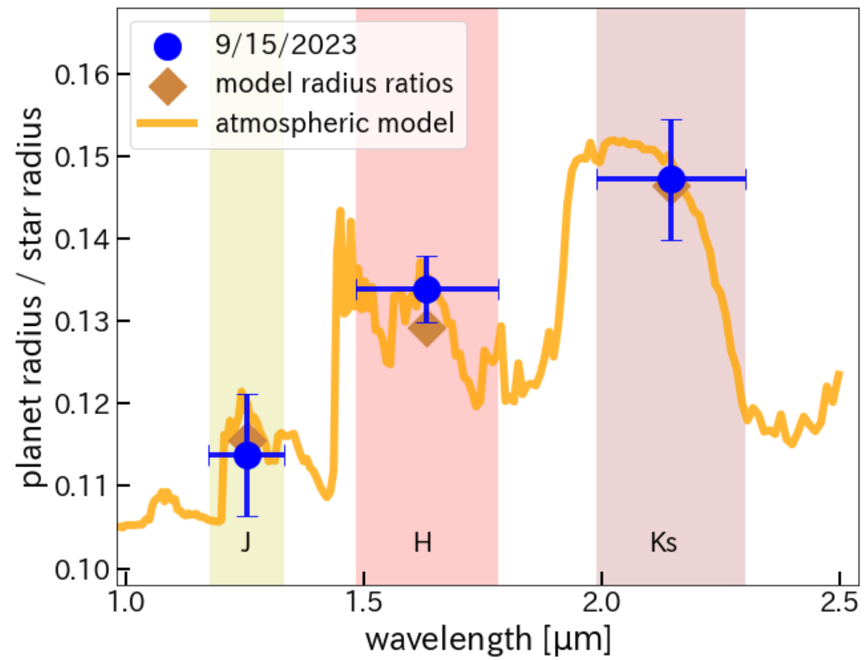


Fig 8. The measured radius ratios of the host star and the planet for Qatar-1b and its atmospheric model (H2: 99%, CO2: 1%).

Discrepancy mismatch optical and NIR

Qatar-1 b's near-infrared transit observations suggested the presence of a clear atmosphere with CO_2.

However, Covino et al. (2013) observed Qatar-1 b in the optical R-band and found a planet radius **30%** larger than that predicted by the atmospheric model from near-infrared observations.

One possible explanation is that the discrepancies between visible and near-infrared observations are due to the annual changes in clouds and haze particles.

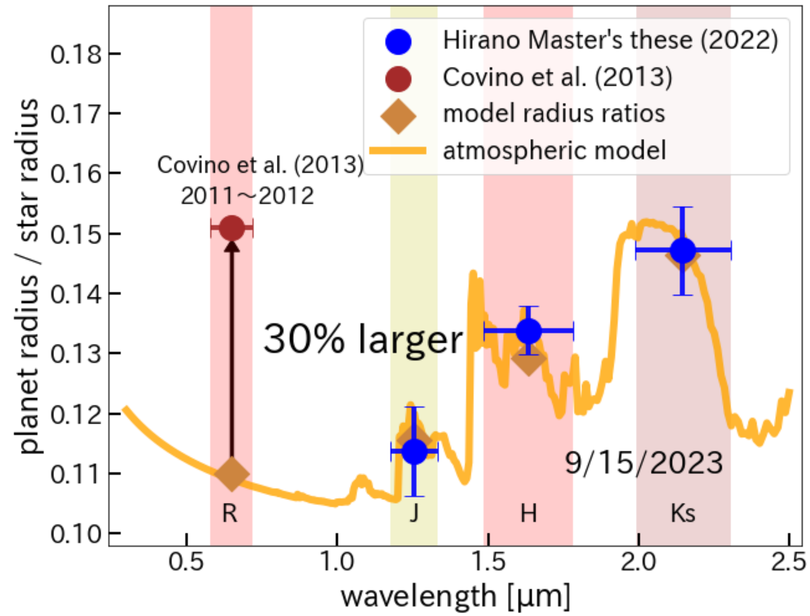


Fig 9. Discrepancy mismatch optical and NIR

Rayleigh and Mie scattering

When tiny particles are present in the atmosphere, light is scattered by those particles.

$$a = \frac{\pi d}{\lambda}$$

a : size parameter
d : particle's radius
λ : wavelength

$a \ll 1$ Rayleigh scattering

$a \approx 1$ Mie scattering

Rayleigh scattering occurs when light is scattered by small particles.

Shorter wavelengths are scattered more, leading to larger observed planet radius in the short wavelength range.

Mie scattering occurs when light is scattered by particles of similar size to the wavelength of light.

It results in uniform scattering independent of wavelength, leading to a constant planet radius regardless of wavelength.

Scattering by clouds and haze particles

Haze particles can cause Rayleigh scattering.

The presence of clouds and haze particles in planetary atmospheres can hide the characteristics of molecular absorption due to light scattering.

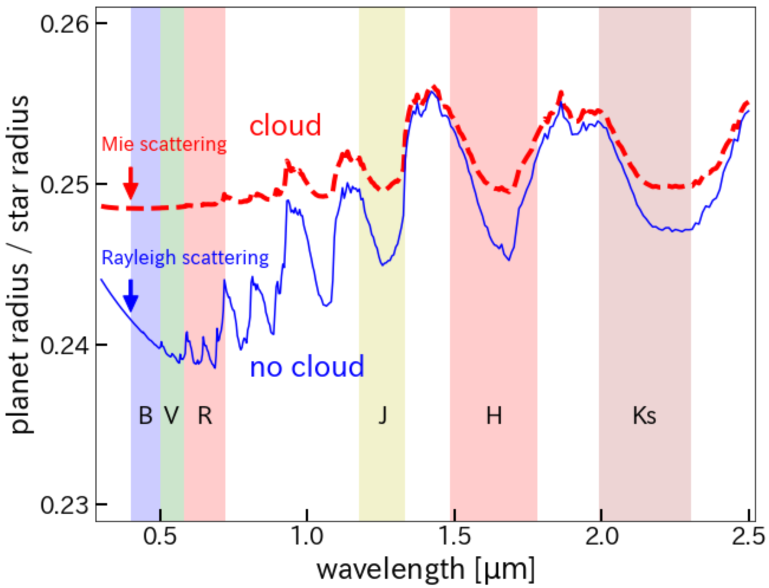


Fig 10. Cloud impact on atmospheric spectrum

Research objective

Long-term observations could allow us to study the planet’s weather by change of planet’s radius in terms of several hours to several months.

Using the Nayuta telescope and the 60 cm telescope at the Nishi-Harima Astronomical Observatory, we can observe an exoplanet in the **optical** and **near-infrared** regions over a **long period** and with a **multi-epoch**.
We observe changes of the planet’s radius caused by particles and clouds.

This study enables us to estimate a new feature of exoplanets weather.

Observations

Object：Qatar-1 b (Qatar-1)
Period：9/15/2021 – 5/10/2023 (19 times)

Instrument： Nishiharima Infrared Camera (J,H,K-band)
on the Nayuta Telescope (200 cm)

SBIG STL-1001 (V-band)
on the 60 cm Telescope

Exposure time：30 – 120 s

We observed for a total of 3.4 hours, including a 1.4 hour transit period and 1 hour before and after the transit.

We observed in the optical V-band and the near-infrared J, H, and K bands at the same time.

Fig 11. Nayuta Telescope and NIC

Fig 12. 60 cm Telescope and STL-1001

Qatar-1 b

Qatar1 is a star located 600 light years away.
Qatar1 b was discovered in 2011 by the Qatar Exoplanet Survey at the New Mexico Skies Observatory using optical light.

Qatar-1 (Star)

- effective temperature 4860±130 K
- 0.82±0.03 solar radius
- 0.85±0.03 solar mass

Qatar-1 b (Exoplanet)

- 1.16±0.05 jupiter radius
- 1.09±0.08 jupiter mass
- surface gravity 20 m/s^2
- period 1.42 days

(Alsubai et al. 2011)

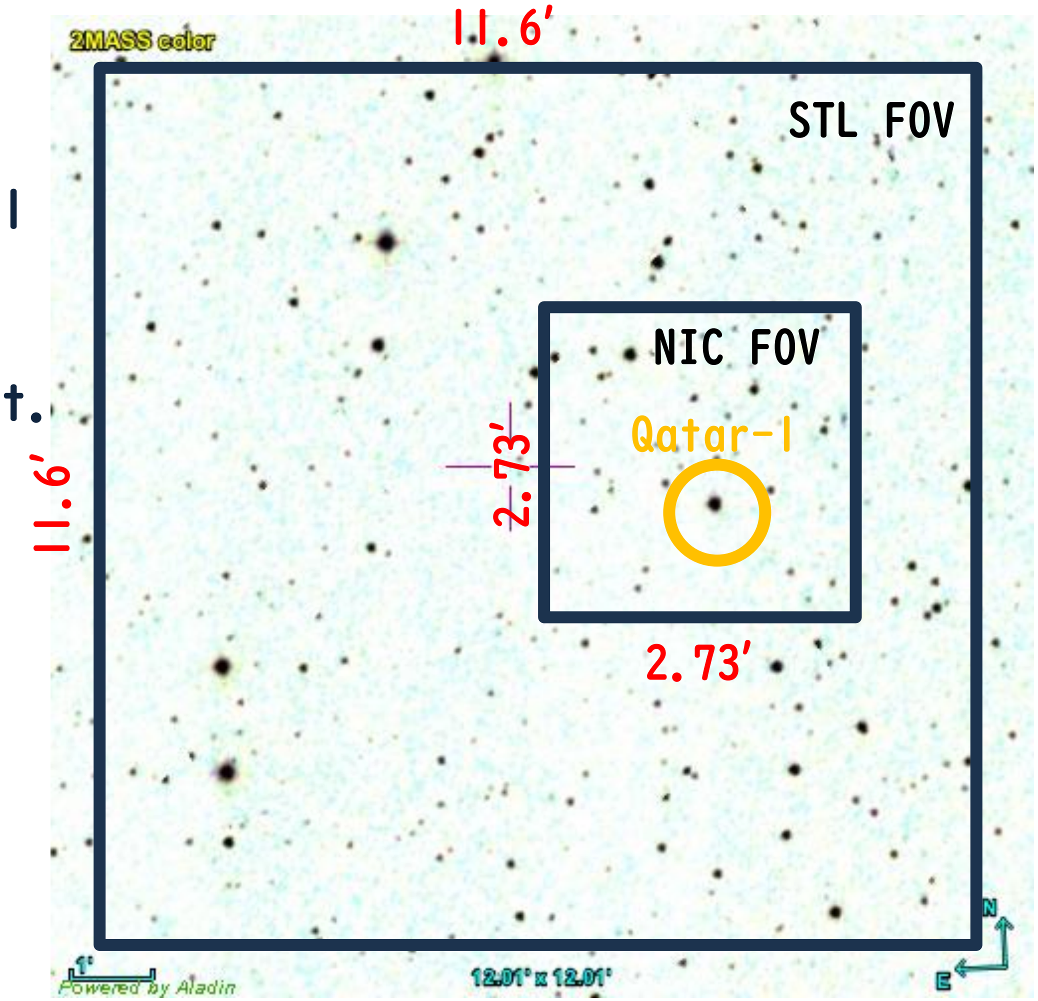


Fig 13. Qatar-1 star chart

Data Reduction

Data reduction was conducted as follows.

①Dark subtraction
②Flatfielding
③Mask the bad pixels

④Sky subtraction
⑤Stripe-pattern subtraction
only NIC

⑥cosmic ray removal

We obtained the sky pattern by stacking 10 images acquired with NIC and subtracted the sky.
We created a vertical stripe pattern from the region without stars and removed the stripes.

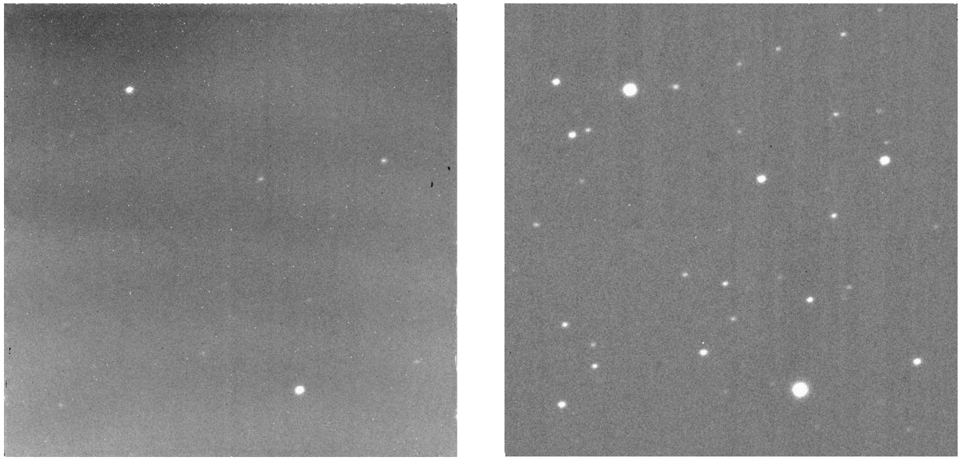


Fig 14. Raw image and final image(NIC)

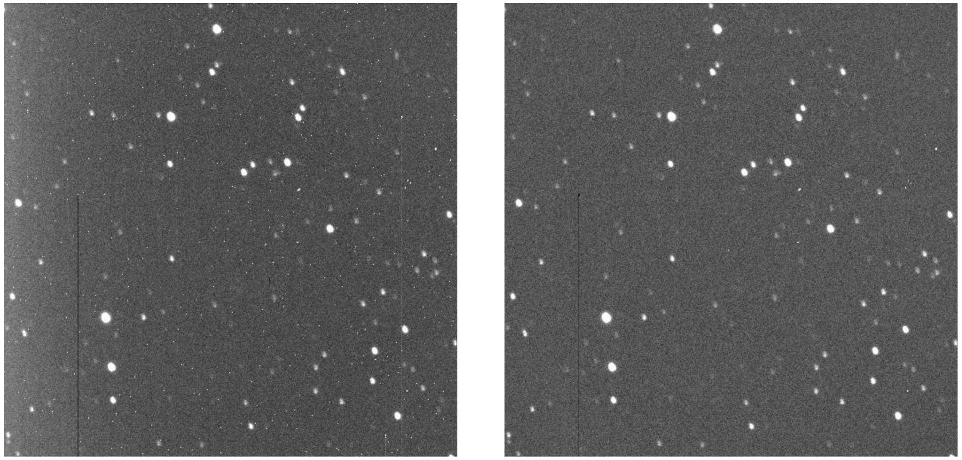


Fig 15. Raw image and final image(STL)

Photometry ①

Aperture photometry was used.
The flux (count of photons) of the target star was divided by the flux of the standard star, resulting in relative flux.

A regression line was obtained using the relative fluxes outside of transit. The value of the regression line was normalized to 1.

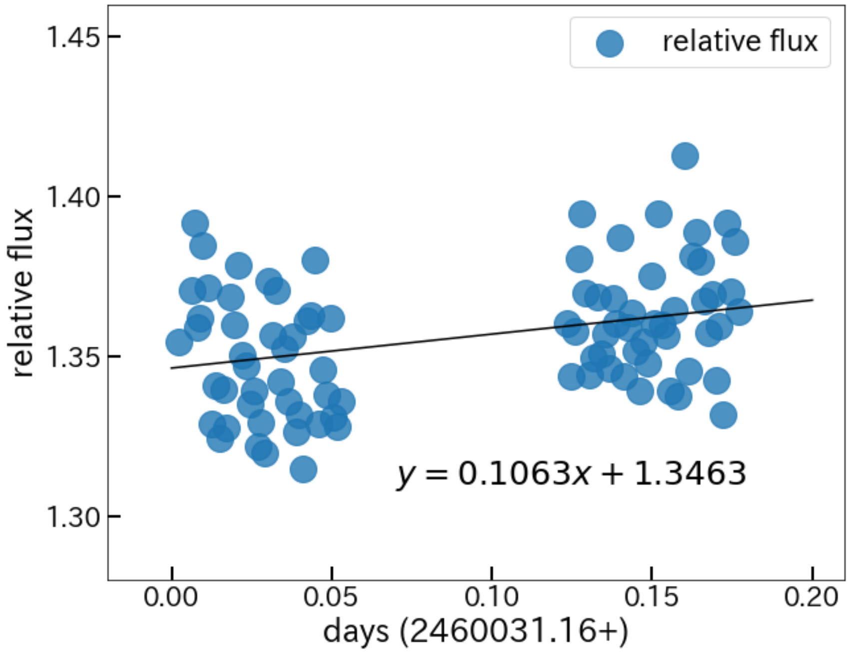


Fig 16. Normalization by regression line.

Photometry ②

Tabata discovered through dithering observations that systematic errors were observed at different positions (Master's thesis 2017).

The relative fluxes outside of transit were averaged for each dithering position, and the relative fluxes at the same positions were divided by the average value.

We removed data points that were 2σ or more.

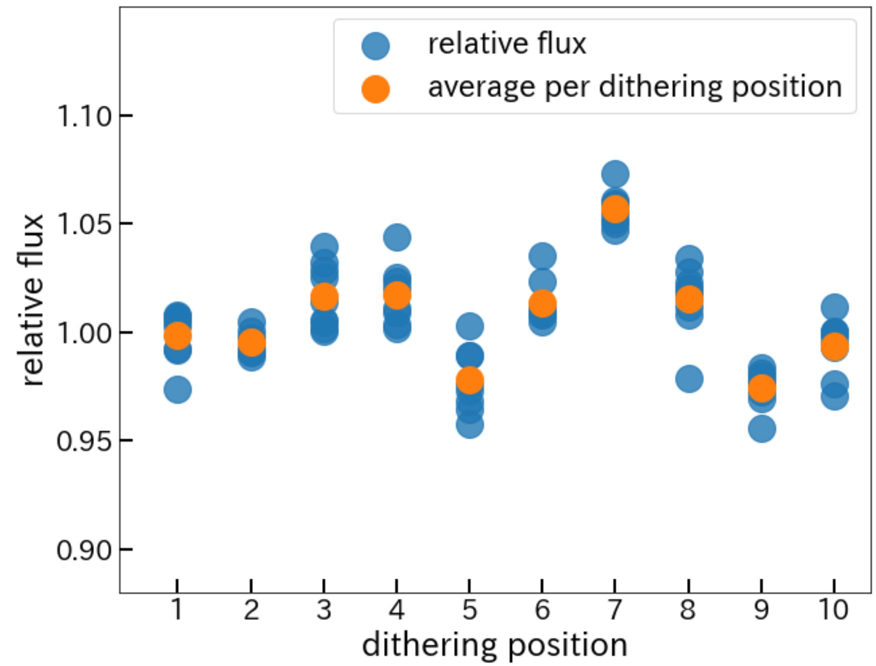


Fig 17. Relative flux for each dithering position.

result(light curve)

We observed
between September 2021 and May 2023.
- V, J, H, K-band 10 times
- V-band 7 times
- J, H, K-band 2 times

We used ETD - Exoplanet Transit Database (var2.astro.cz)to create the light curve. ETD is a tool used to calculate light curves and transit depths.

Input parameter
- relative flux
- time
- standard deviation of light curve
- transit mid-time
- transit duration

10 transit events were detected.

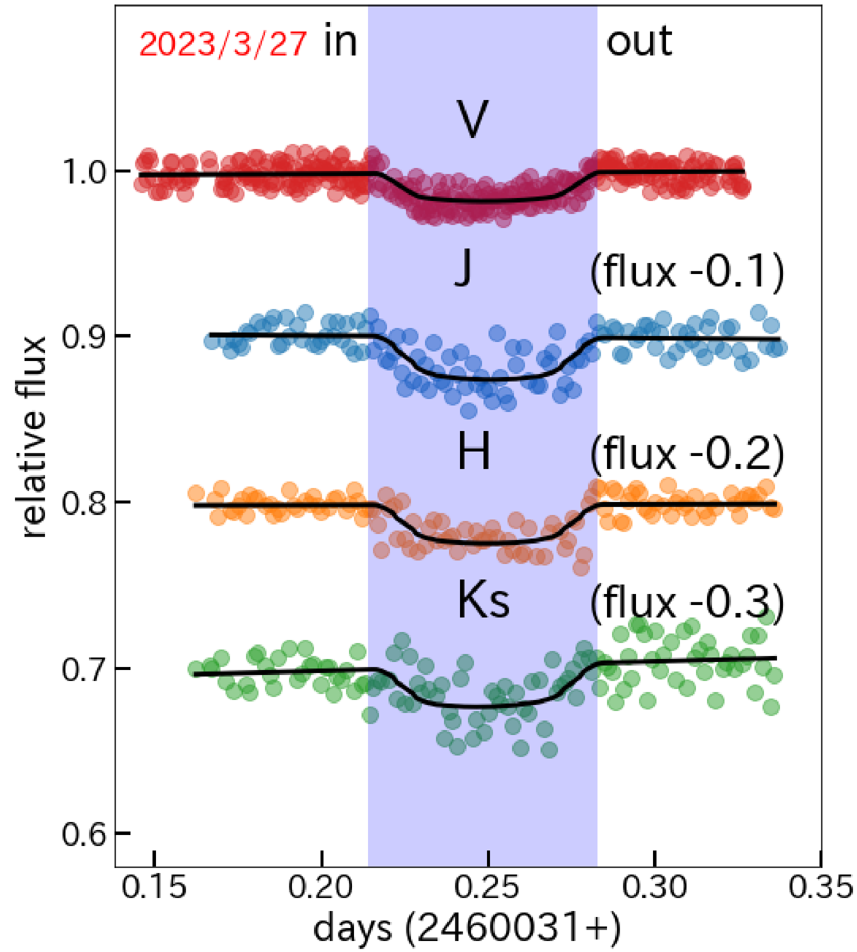


Fig 18. The relative fluxes in V, J, H, and K -bands and the light curve (3/27/2023).

result(radius ratio)

Hirano estimated based on the upward trend observed in the J, H, and K -bands on 9/15/2021 , that the exoplanet has a clear CO_2 atmosphere (Master's thesis 2022).

However, the recent observations in the near-infrared region did not show the upward trend in the radius ratio that was previously observed.

The V, J -bands radius ratio showed significant variability compared to H and Ks bands.

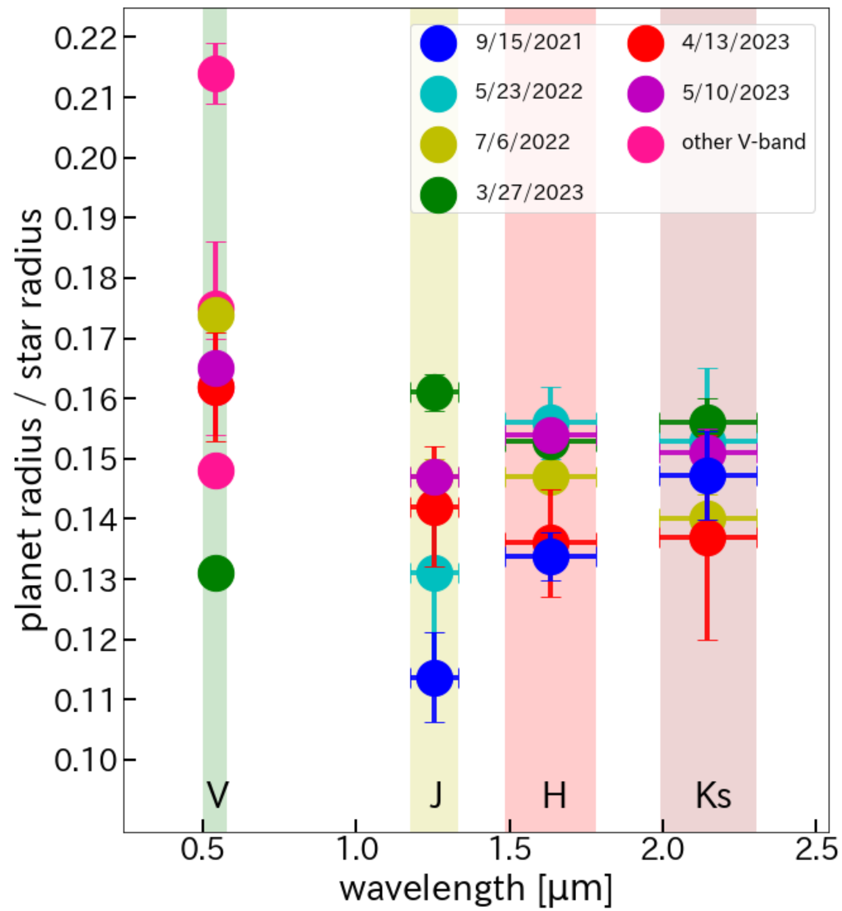


Fig 19. Planet radius observed for each band from September 2021 to May 2023.

results and previous studies

We compared the observed radius ratios with these in previous studies.

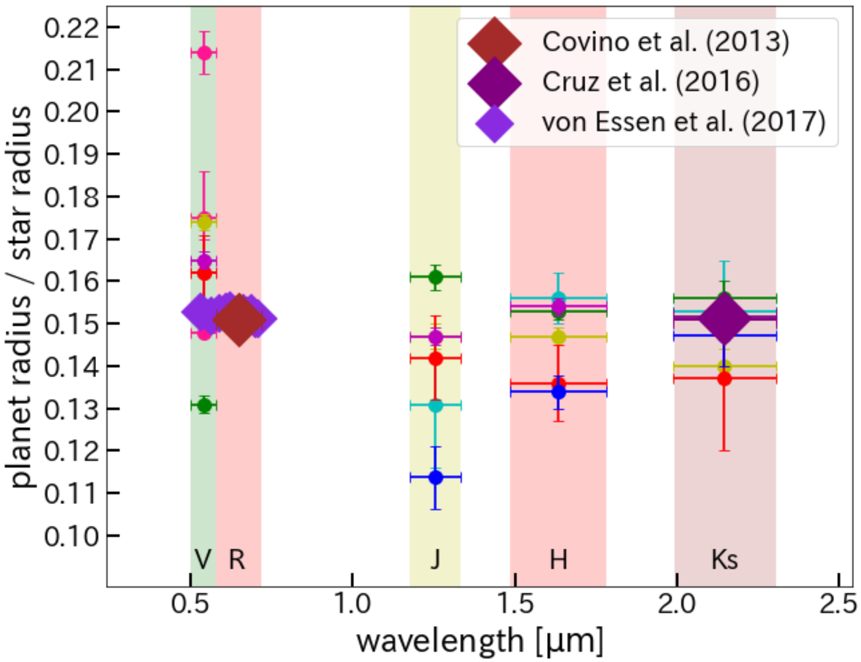


Fig 20. The radius ratios of Qatar-1 b in previous studies.

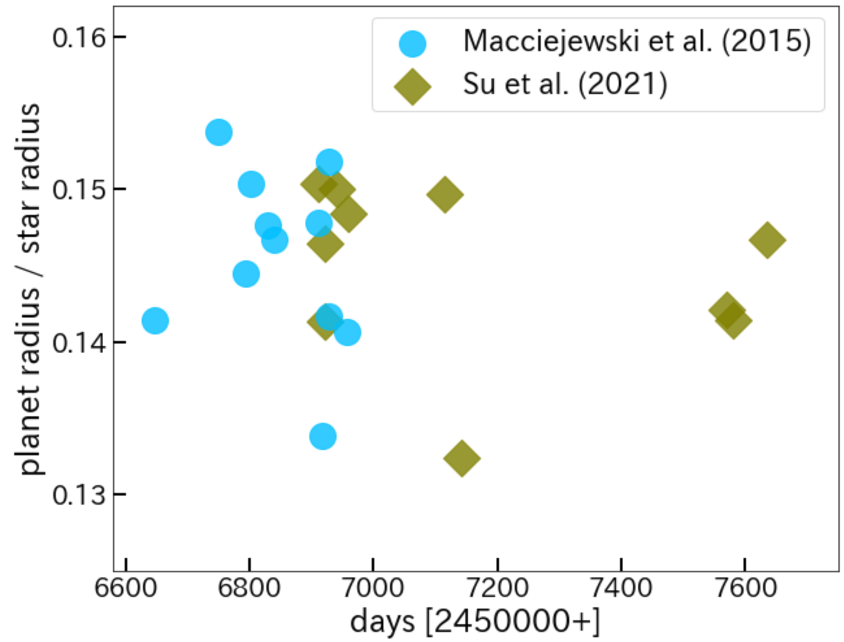


Fig 21. The radius ratio in the optical R band.

Fig 20, the radius ratios from previous studies are around 0.15 for all wavelength bands. However, Fig 21, there was a larger variability in the R band, ranging from 0.13 to 0.16.

Variations in radius ratios in four bands

We observed planet radius measurements in four wavelength bands (optical V -band, and near-infrared J, H, Ks -bands).
On 3/27/2023, the V band had a significantly smaller radius ratio (over 20% less) compared to the other days, while the near-infrared range exhibited a larger radius ratio.

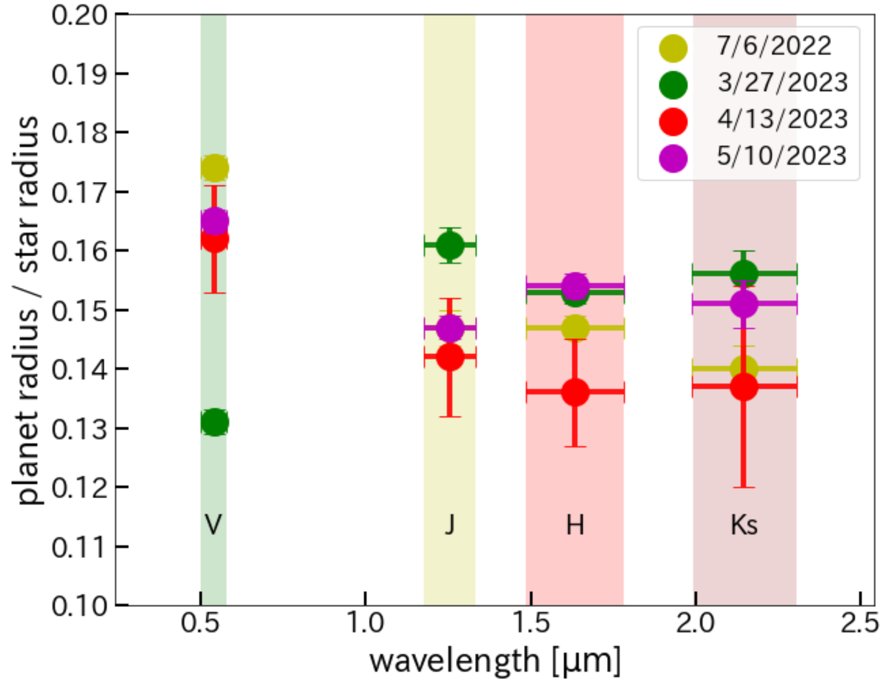


Fig 22. Radius ratios observed at the same time in four bands

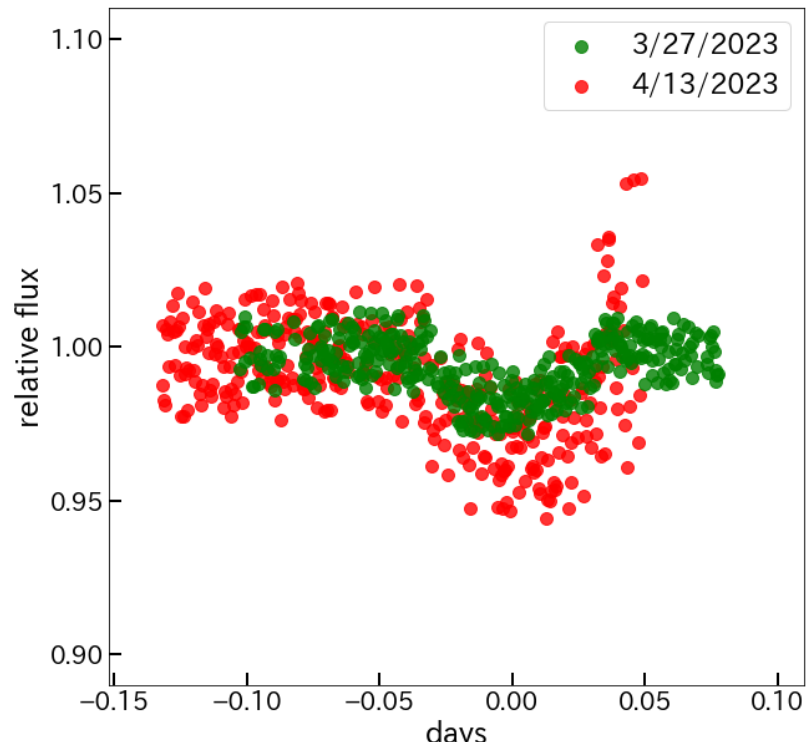


Fig 23. Difference in transit depths in the V band

Creation of the haze model

We investigated the variations in planet radius on 3/27/2023, and 4/13/2023, using a haze model.
We used PSG to create the haze model.

- suface gravity 2.0 m/s^2 (20.0 m/s^2)
- planet radius 73,500 km (81,500 km)
- Haze particle diameter 0.1 μm
- H_2 99% CH_4 1%

○suface prresure 10^{-5} – 1 bar
○haze particle abandance 0.001% – 1%
Created the model.

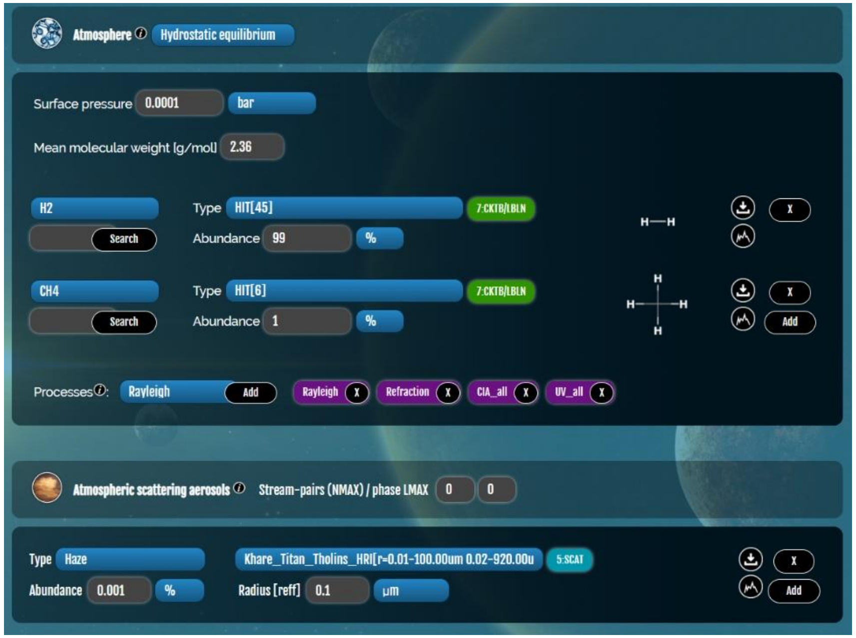


Fig 24. Parameter input screen of PSG

haze model and observational data

Using a haze model with a surface pressure of 10^{-5} bar and a haze abundance of 0.1%, and a haze-free model with a surface pressure of 10^{-3} bar, we observed a reversal in the radius ratio.

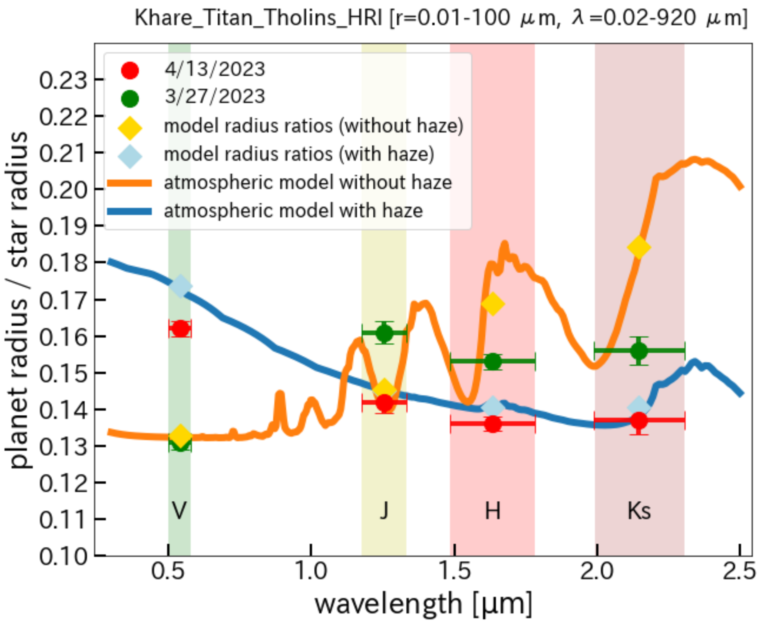


Fig 25. Haze-inclusive planetary atmospheric model

We observed variations in the planet's radius during our transit observations from September 2021 to May 2023, possibly due to haze particles in the atmosphere.

Summary

・We observed the transit of Qatar-1 b in the visible and near-infrared bands using the NIC on the Nayuta Telescope and the STL on the 60 cm telescope from September 2021 to May 2023.

・10 transit events were detected and observed significant variations in the radius ratio between the V band and J band.

・On 3/27/2022, the radius ratio in the V band was more than 20% smaller compared to the ratios on 7/6/2022, 4/13/2023, and 5/10/2023. However, in the near-infrared region, we observed larger radius ratios, indicating a reversal in the radius ratio trend between the visible and near-infrared bands.

・In the future, we plan to expand our observations to other wavelengths and observe TrES-3 b, WASP-12 b, and WASP-43 b. We aim to verify whether similar variations in planet radius occur in these exoplanets as well.