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First detection of exoplanet transit in Vietnam

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Abstract

In this paper, we report the results obtained from the first observations of exoplanet transit conducted with the 600 mm telescope at Quy Nhon Observatory (QNO) in Vietnam. The object of our observation is the exoplanet WASP-3b, transiting its host star WASP-3 with a period of approximately 1.8468 Earth days. Through our observations and modeling, we obtained a magnitude depth of 0.0121 ± 0.007 mag and a planet radius of 1.42 ± 0.05 $R_{\rm Jupiter}$ for WASP-3b. This result is consistent with the previous published results and it implies that QNO 600 mm telescope is capable of monitoring short-period exoplanet transits, even at the atmospheric conditions of Quy Nhon city.

Key words: WASP-3b — Exoplanets — Exoplanet transits —Techniques: photometry — Quy Nhon Observatory (QNO).

1. Introduction

Detection of exoplanets is crucial in our search for other planets with Earth-like properties. There are several methods for detecting exoplanets, including transit, radial velocity, direct imaging, and gravitational microlensing (Dai et al. 2021). Transit detection is the most commonly used method, as it can be performed with relatively small- and mid-size telescopes that have good sensitivity and seeing. This method involves measuring the flux of stars and looking for periodic dips in brightness as exoplanets pass between the stars and the observer. The first transiting exoplanets were reported by Charbonneau et al. (2000).

Most of the exoplanets that have been discovered are massive, gaseous giant planets (Nascimbeni et al. 2013). Recent studies have been focusing on less massive, small size exoplanets with masses ranging from 1 $M_{\rm Earth}$ to 10 $M_{\rm Earth}$ and radii from 1 $R_{\rm Earth}$ to 3 $R_{\rm Earth}$, aiming for detecting temperate super-Earth's (also known as Earth-sized rocky planets) around solar-type stars.

Typically, we are interested in determining the planet's radius and mass ($R_{\rm p}$, $M_{\rm p}$), i.e., the basic quantities necessary to confirm the planetary status of the transiting body.

In this article, we report the first successful transit observation of WASP-3b[1] at QNO. This is known as a typical short-period (P $\simeq$ 1.8468 Earth days)[2] "hot Jupiter" discovered by Pollacco et al. (2008). The host star of WASP-3b is an 10-mag yellow-white dwarf F-type star located in the Lyra constellation. The host star has a mass of 1.23 ± 0.03 $M_\odot$, a radius of 1.36 ± 0.02 $R_\odot$, and a density of $0.488^{+0.018}_{-0.017}$ $\rho_\odot$ (Rostron et al. 2014).

Multiple studies have conducted measurements of the transits of WASP-3b at various points in time in order to investigate potential transit timing variations, which are believed to be caused by a low-mass body in a distant orbit. Gibson et al. (2008) observed two transits of WASP-3b, but did not find a significant variance from the original timing estimated by Pollacco et al. (2008).

Our observation was designed to characterize the properties of WASP-3b such as its radius, and magnitude depth, and to verify the feasibility of transit observation in the QNO conditions. The observation was done within the context of the SAGI summer school in Observational Astronomy 2023 (Nguyen-Luong et al. 2023). SAGI is the Simons Astrophysics Group at the International Center for Interdisciplinary Science and

[1] WASP-3b ⟨http://exoplanets.org/detail/WASP-3_b⟩

[2] WASP-3b ⟨https://exoplanets.nasa.gov/exoplanet-catalog/5360/wasp-3-b/⟩

Education (ICISE) in Quy Nhon city, Viet Nam.

2. Observations and data reduction

2.1. The observatory characteristics

QNO[3] is the astronomical observatory of Explorascience[4] (table 1), located at No. 10, Science Avenue, Quy Nhon city, Binh Dinh province, Vietnam. Explorascience is the largest science science museum in Vietnam that was built to promote science and technology, both in research and education. Currently, QNO and Explorascience are managed by the Department of Science and Technology of Binh Dinh province. The observatory houses a 600 mm telescope with an alt-azimuth drive system that has been synchronized with automatic control of the dome structure. The mount has a slew speed of up to 50 degrees per second. In addition, the observatory is equipped with auxiliary equipment including cameras, smaller telescopes, solar telescopes, and a 3 m diameter radio telescope to support the dissemination of scientific knowledge and research in astronomy. The observatory will therefore play a significant role in supporting research in astronomy, international collaboration, and disseminating astronomical knowledge to the public.

2.2. Data and instruments

The observation of WASP-3b was performed with QNO telescope within the context of the 2023 SAGI Observational Astronomy School[5] (Nguyen-Luong et al. 2023). The ZWO ASI2600MM Pro camera and a Bessel V-band filter were used. The timeline and transit duration (i.e., 136.8 minutes) were obtained from the Find Exoplanet Transits[6]. We observed for total of 4.5 hours in July 18$^{\rm th}$ 2023. We observed in total 549 frames, each frame has 30 seconds exposure time. Observational parameters are shown in table 2.

2.3. Data reduction

After obtaining the required data, we checked the coordinates of WASP-3 in the photos to make sure the data obtained was correct (figure 1), we proceeded to image calibration. We removed data which has bad conditions (e.g., cloud, etc), subtracted counts caused by non-photoelectric effects (bias components and dark components), and corrected with flat-field.

Image calibration is essential for producing high fidelity images by correcting for defects in the camera sensor and optical system. Each sensor has different bias levels, dark current sensitivity to temperature, and sensitivity to light, all of which can corrupt the intensity expressed in each pixel of the image in a specific way. Calibration helps improve the signal-to-noise ratio (SNR). The three basic calibration steps are bias, dark, and flat-field.

- Bias frame: Bias is an offset that occurs when a pixel is read from the camera. Unfortunately, the bias can vary from image to image[7]. If bias is not corrected, flat-field calibration will not work correctly. Essentially, a bias frame is a zero-length exposure, or as close to zero length as possible, with the shutter closed. For the ASI2600MM Pro camera, the exposure time selected to capture the Bias image is 0.001 second. Each pixel will have a slightly different value, but aside from a small amount of noise, the value for any one pixel will be consistent from image to image. This means that the bias, being

Table 1. Information for QNO and equipments

Info.	Details
Observatory	Quy Nhon Observatory
Longitude	109.2136 East
Latitude	13.7183 North
Altitude	8 m
Location	Quy Nhon city
Opening year	2022
Country	Vietnam
Clear sky	100 days per year
Seeing	about 1.5–2 arcsec
Telescope	Planewave CDK600
Diameter	600 mm
Focal length	3974 mm
Producer	PlaneWave Instruments
Camera	ZWO ASI2600MM Pro
Maximum quantum efficiency	91 %
Pixel size	3.76 μm
Cooling temperature	35 °C below ambient

Table 2. Observational information for WASP-3b at QNO

Info.	Details
Target coordinate	$18^{\rm h}34^{\rm m}31^{\rm s}.62$ $+35°39'41''.15$
Time	21:25–2:28 (UTC+7)
Date	July 18, 2023
Temperature of camera	0 °C
Number of frames	549
Exposure time/frame	30 sec
Filter	Bessel V band
Humidity	54.2 %

3 QNO ⟨https://astro.explorascience.vn/⟩
4 Explorascience ⟨https://explorascience.vn/⟩
5 2023 SAGI Observational Astronomy School ⟨https://ifirse.icise.vn/2022/12/03/2023-sagi-observational-astronomy-school/⟩
6 Find Exoplanet Transits ⟨https://astro.swarthmore.edu/transits/⟩
7 Cyanogen Imaging ® MaxIm DL ⟨https://cdn.diffractionlimited.com/help/maximdl/MaxIm-DL.htm⟩

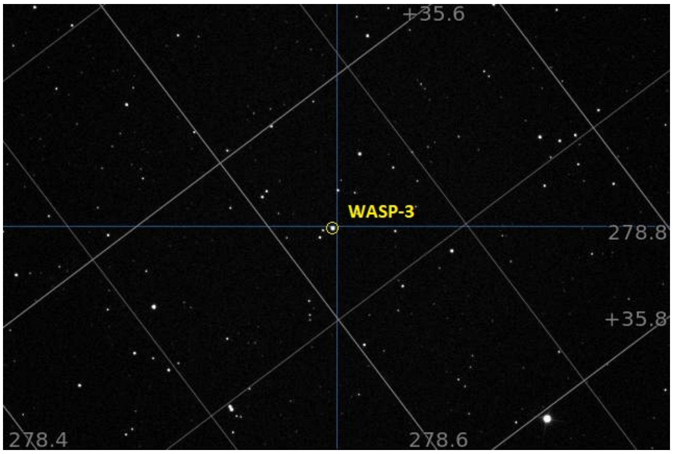

Fig. 1. Coordinate of the WASP-3. We use website Astrometry[8] to astrometric calibration and find the coordinates of the image (Astrometry is a project built by the US National Science Foundation, the US National Aeronautics and Space Administration, and the Canadian National Science and Engineering Research Council).

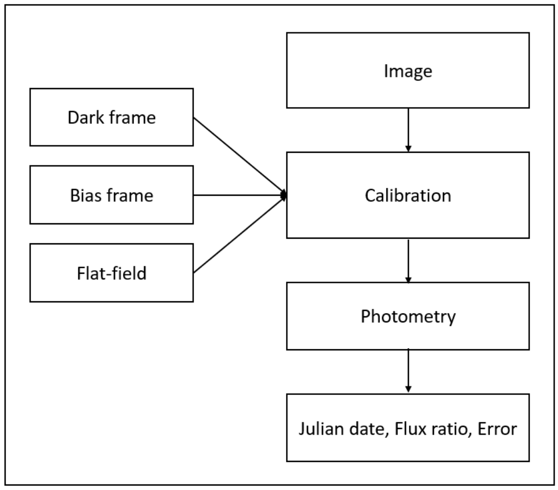

Fig. 2. The diagram of the calibration process

consistent from image to image, can be subtracted. The convenient thing about bias frames is that they can be reused on all images for many months, assuming that the bias for a particular camera remains generally constant over this period of time. Additionally, bias is also included in dark frames, meaning that it is technically possible to perform accurate calibration without using bias frames.

- Dark frame: Dark current is present in every camera sensor and accumulates in the pixels during an exposure. It is caused by heat, although high-performance cameras cool their sensors to minimize this effect. The main issue with dark current is that it accumulates at different rates in each pixel, with some pixels being "hot" and others "cold". This can result in a scattering of "hot" pixels that degrades the image quality. By subtracting the dark frame, the effects of the hot and cold pixels can be mitigated. The dark frame is taken under the same conditions as the light frame, except that no light enters the focal plane. However, while subtracting a dark frame eliminates pixel-to-pixel variation in dark current, it also adds noise to an image. To eliminate this noise, it is necessary to average multiple dark frames.

- Flat-field: Vignetting is a reduction in image brightness at the edges of the field of view. There are two possible causes, the lens/mirror design or an obstruction in the light path. Telescopes bend the light that passes through them, forming a cone of light that creates a circular image at the focus point but there is always a brighter central region in the cone leading to light fall-off towards the edges[9]. This is where flat-fielding correction comes into play. To create a flat-field frame, the optical system is illuminated by a uniform light source and an exposure is taken. A flat-field frame can eliminate the distortions caused by vignetting, and it also used for correction of pixel-to-pixel variation of quantum efficiency.

From the initial 549 image frames, we excluded data affected by clouds. We then proceeded to calibrate the remaining 455 image frames and used them for analysis. The diagram of the calibration process is shown in figure 2. The collected data will be read for Julian Date (JD), flux ratio and error parameters.

In this work, we used MaxIm DL software[10], a commercial product for the WindowsXP operating system designed for serious amateurs as well as professional astronomers. It includes an extensive suite of image acquisition, processing, and analysis tools.

3. Result & Discussion

3.1. *Photometry*

After calibrating the image, we proceeded with point source photometry to measure the brightness of WASP-3. First, we determined the full width at half maximum (FWHM) of the source diameter by fitting a Gaussian shape to the star, as shown in figure 3. The FWHM of the reference star was found to be approximately 5.3 pixels, varying depending on frames. The total number of counts calculated in the aperture was about 1.5 to 2 times the FWHM of the star's radius[11]. Therefore, we chose an aperture of 11 pixels for photometry and performed stellar flux measurements.

Because the Earth's atmosphere can affect the flux measurements of stars, we carefully select a pair of reference stars for the purpose of photometric comparison with the target. These chosen stars need to be situated in close proximity to WAPS-3 and must not be saturated. The coordinates of the first and second reference stars, denoted as R_1 (Name: TYC 2636-92-1[12])) and R_2 respectively, can be found in table 3. To minimize the impact of changing observational conditions, we calculate the flux ratio between WASP-3 and the reference stars. This ratio is then used to create a light curve, which visually depicts the fluctuations in flux ratio over time.

Following from these relations,

$$F'_{\mathrm{obj}} = T \times F_{\mathrm{obj}}, \quad (1)$$

$$F'_{\mathrm{refstar}} = T \times F_{\mathrm{refstar}}. \quad (2)$$

8 Astrometry.net ⟨https://nova.astrometry.net/⟩
9 BBC Sky at Night Magazins ⟨https://www.skyatnightmagazine.com/advice/what-is-vignetting⟩
10 Maxlm DL ⟨https://diffractionlimited.com/product/maxim-dl/⟩
11 aavso ⟨https://www.aavso.org/ccd-camera-photometry-guide⟩
12 Simbad ⟨https://simbad.cds.unistra.fr/simbad/sim-fbasic

Table 3. Reference stars information. Information of R_1 taken from SIMBAD, and information of R_2 is not available.

Star	Name	RA	Dec	V-band [mag]
R_1	TYC 2636-92-1	$18^{\mathrm{h}}34^{\mathrm{m}}43^{\mathrm{s}}.8$	$+35°42'26''.3$	11.76
R_2	-	$18^{\mathrm{h}}34^{\mathrm{m}}41^{\mathrm{s}}.6$	$+35°38'21''.2$	-

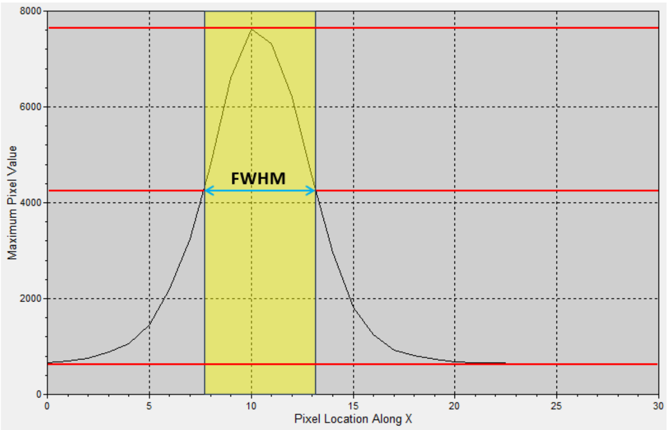

Fig. 3. The full width at half maximum (FWHM) of the reference star. From graph, we find FWHM = 5.3 pixel.

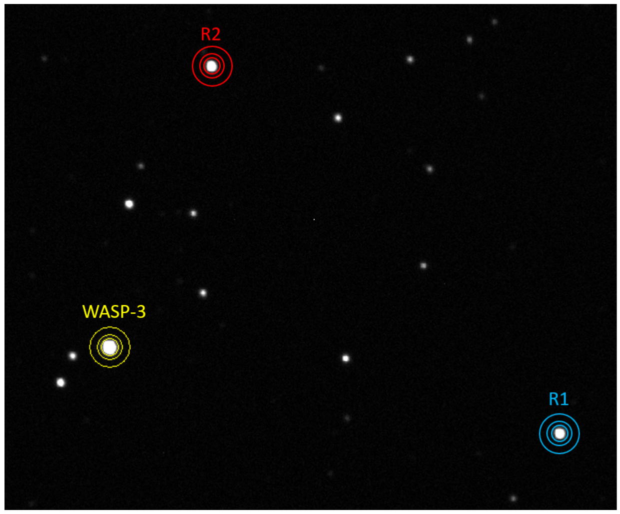

Fig. 4. A reduced frame obtained with V-band filter. Yellow circle is WASP-3, blue circle and red circle are the two references stars R_1 and R_2 (see table 3). The aperture is chosen with an inner radius of 11 pixel, the gap width = 5 pixel and the outer radius of the aperture is 26 pixel.

Therefore,

$$\frac{F'_{\mathrm{obj}}}{F'_{\mathrm{refstar}}} = \frac{F_{\mathrm{obj}}}{F_{\mathrm{refstar}}}, \quad (3)$$

where F_{obj} and F_{refstar} are object and reference star flux observed outside of the Earth, while F'_{obj} and F'_{refstar} are observed object and reference star flux observed on the Earth. T is the transparency of the Earth atmosphere.

The calculation process is performed as follows:

$$FR = \left(\frac{F'_{\mathrm{obj}}}{F'_{\mathrm{refstar1}}} + \frac{F'_{\mathrm{obj}}}{F'_{\mathrm{refstar2}}} \right) \times \frac{1}{2}, \quad (4)$$

where F'_{refstar1} and F'_{refstar2} are the observed fluxes of reference star 1 and reference star 2, and FR is the average flux ratio.

The mean FR value of 455 clean data points is 4.451 and the standard deviation is 0.052. We then derived a normalized FR by dividing it to 4.451. The new mean normalized FR is 1 and the standard deviation of the normalized FR is 0.012.

3.2. *Light curve*

From the 455 clean data points, we removed additional data points that are two times the standard deviation (2σ) from the mean of the normalized FR. These removed data points lie outside of the grey area in figure 5. These outliers were likely caused by cloudy conditions during data collection. The resulting light curve, plotted by flux ratio in figure 6, clearly shows a drop in the brightness of WASP-3.

We used the data obtained with these variables: Julian date, flux ratio, error, and successfully processed the light curve in the Exoplanet Transit Database (ETD)[13]. ETD came online in

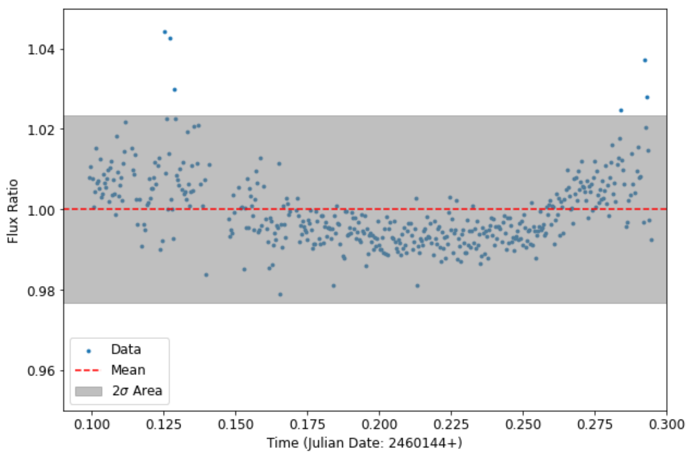

Fig. 5. The light curve of WASP-3b. The mean value of the normalized flux ratio obtained from 455 image frames is 1 ± 0.012. Red line is the mean normalized flux ratio and the grey zone is the 2std area. The beginning time of the transit process is JD time 2460144.168 and the ending time is JD time 2460144.260.

September 2008 as a project of the Variable Star and Exoplanet Section of the Czech Astronomical Society. ETD includes all known transiting planets that have published ephemerides. ETD used the formulas in the model presented in Mandel and Agol (2002) and the input data from our observations to calculate the transit depth and the transit duration.

From result of the ETD we obtain a magnitude depth

13 ETD ⟨http://var2.astro.cz/ETD/protocol.php⟩

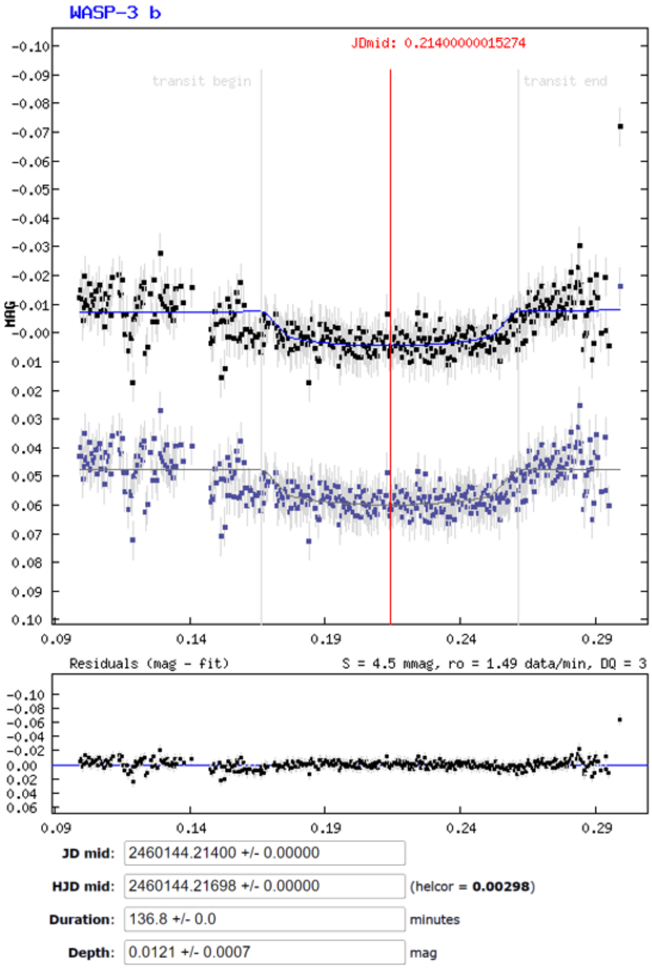

Fig. 6. The light curve of WASP-3 is provided by ETD using our data. The y-axis depicts the magnitude depth of the exoplanet transit, while the x-axis represents the Julian date. (The data must have three columns: JD time, Flux and Error, with the columns separated by either a space or a TAB).

$(\Delta m) = 0.0121 \pm 0.0007$ mag. The magnitude depth is the magnitude difference between the out-of-transit and in-transit moments, and it is clearly shown by the light curve in figure 6. The derived transit duration is 136.8 minutes.

3.3. *Exoplanet radius*

The transit flux depth (ΔF) is approximately related to the ratio of planetary and stellar area by assuming a homogeneous stellar disk and treating the planet like a black disk (Wells 2022):

$$\Delta F = \frac{F_{\text{out}} - F_{\text{in}}}{F_{\text{out}}} \approx \left(\frac{R_{\text{p}}}{R_*}\right)^2. \tag{5}$$

Therefore,

$$R_{\text{p}} = R_* \sqrt{\Delta F}, \tag{6}$$

where R_{p} is the planetary radius, R_* is the stellar radius, F_{out} is the flux observed out-of-transit, and F_{in} is the flux observed in-transit.

Additionally, the magnitude depth is calculated by:

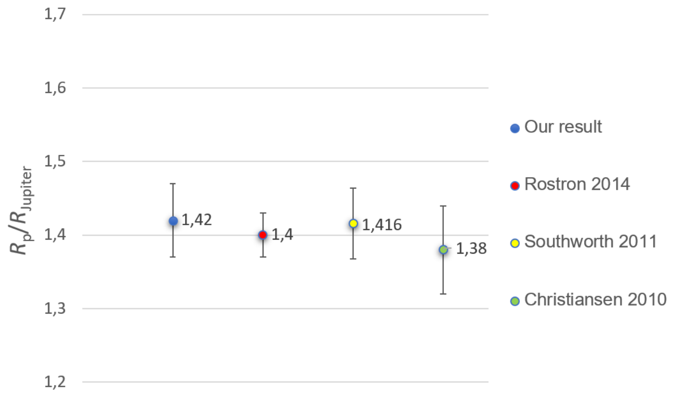

Fig. 7. Different measurements of the radius of WASP-3b. Others data are from Christiansen et al. (2010), Southworth et al. (2011), and Rostron et al. (2014).

$$\Delta m = m_{\text{in}} - m_{\text{out}} = -2.5 \log\left(\frac{F_{\text{in}}}{F_{\text{out}}}\right). \tag{7}$$

Therefore,

$$1 - 10^{\frac{-\Delta m}{2.5}} = \frac{F_{\text{out}} - F_{\text{in}}}{F_{\text{out}}} = \Delta F, \tag{8}$$

where Δm is the magnitude depth, m_{in} is the magnitude of the star calculated in-transit, and m_{out} is the magnitude of the star calculated out-of-transit.

From that, we calculate the radius of the exoplanet:

$$R_{\text{p}} = R_* \sqrt{1 - 10^{\frac{-\Delta m}{2.5}}}. \tag{9}$$

Therefore,

$$R_{\text{p}} = 0.1002 \pm 0.0033 \times 10^6 \text{ km} = 1.42 \pm 0.05 \, \text{R}_{\text{Jupiter}}, \tag{10}$$

with R_* = 1.36 ± 0.02 $R_\odot$ (Rostron et al. 2014), $R_\odot$ = 695.658 ± 0.140 × 10^3 km (Haberreiter et al. 2008), and R_{Jupiter} = 69.911 × 10^3 km [14].

3.4. *Comparison with previous published results*

Our calculated radius for the planet, R_{p} = 1.42 ± 0.05 R_{Jupiter}, aligns with the results of previous studues. For example, Rostron et al. (2014) reported R_{p} = 1.4 ± 0.03 R_{Jupiter}, Southworth et al. (2011) reported R_{p} = 1.416 ± 0.048 R_{Jupiter}, and Christiansen et al. (2010) reported R_{p} = 1.385 ± 0.06 R_{Jupiter}. This consistency is shown in table 4 and figure 7.

This time, we observed in the V band, but the radius ratios are nearly the same as the previous studies in the g, i, and z bands. In other words, the observation in the V-band alone this time did not show evidence of Rayleigh scattering. Although simultaneous observation is necessary, real conditions do not yet allow us to do.

4. Conclusion

This study presents the initial observation of an exoplanet transit with the 600 mm telescope at QNO. This is the first

[14] Jupiter Fact Sheet ⟨https://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html⟩

Table 4. $R_\mathrm{p}/R_\mathrm{Jupiter}$ between the WASP-3b with Jupiter. Others data are from Rostron et al. (2014), Southworth et al. (2011), Christiansen et al. (2010).

	This work	Rostron et al.	Southworth et al.	Christiansen et al.
Year	2023	2014	2011	2010
Telescope	600 mm at QNO	Spitzer Space Telescope[15]	CoRoT and Kepler satellites	The High Resolution Instrument on Deep Impact flyby satellite[16]
Diameter (mm)	600	850	270 and 950	300
Country	Vietnam	Space	Space	USA
Photometric band	V band	infrared band	g, i, and z band	0.65 μm
Radius (R_Jupiter)	1.42	1.4	1.416	1.385
Error	$\pm$0.05	$\pm$0.03	$\pm$0.048	$\pm$0.06

detection in Vietnam to our knowledge. From our data, we derive fundamental properties of the exoplanet, including magnitude depth of the transit (Δm = 0.0121 $\pm$ 0.0007 mag), the planet's radius (R_p = 1.42 $\pm$ 0.05 R_Jupiter), and the duration of the transit (136.8 minutes). We found that our results are consistent with results from previous studies.

Our results demonstrate that the 600 mm telescope at QNO is capable of detecting the transit of exoplanets and providing quality data for studies of exoplanet transits. Our plan is to follow up on the observations of WASP-3b and extend our sample to more targets in the future.

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16 https://deepimpact.astro.umd.edu/tech/hri.html
17 http://metaspace.co.kr/wp/?lang=en