MAKERERE UNIVERSITY

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COLLEGE OF NATURAL SCIENCES
SCHOOL OF PHYSICAL SCIENCES
DEPARTMENT OF PHYSICS

# DETERMINATION OF THE SIZES OF EXOPLANETS USING LIGHT CURVES

BY

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A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF PHYSICS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF BACHELOR OF SCIENCE WITH EDUCATION OF MAKERERE UNIVERSITY

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# DECLARATION

I, **MUZAFALU SSEBUUFU**, hereby declare that this project report entitled:

*"Determination of the Sizes of Exoplanets Using Light Curves"*

is my original work and has not been submitted to any institution of higher learning for the award of any academic qualification. All sources of information used in this report have been duly acknowledged and referenced.

Signature: ______________________________

Date: ______________________________

# APPROVAL

This project report entitled:

*"Determination of the Sizes of Exoplanets Using Light Curves"*

has been prepared under my supervision and is submitted for examination with my approval.

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## Abstract

This dissertation presents a study of the determination of exoplanet sizes using light curves derived from space-based observations, specifically data from the Transiting Exoplanet Survey Satellite (TESS). By analyzing the transit method and applying open-source tools such as the Plight curve and Lightkurve, i demonstrate a method for extracting planetary radii from photometric data, using the exoplanet WASP-12b.This work demonstrates the application of the transit method in exoplanetary science, underscoring its effectiveness in producing scientifically relevant results. The study highlights the importance of reproducibility in astronomical observations and the contributions of modern missions in advancing our understanding of exoplanets.

# Contents

# Chapter 1

# Introduction

## 1.1 Background

Exoplanets are planets that orbit stars beyond our solar system. The discovery and characterization of these celestial bodies have revolutionized modern astronomy, providing insight into planetary systems beyond our own. Since the first confirmed exoplanet discovery in 1995 (51 Pegasi b), thousands have been detected, revealing a wide range of planetary types and systems.

Determining the size of exoplanets is crucial to assessing their habitability and understanding their formation. One of the most effective methods for this is analyzing light curves generated when a planet transits its host star.This leads to a dip in the observable brightness of the Star. A dip in brightness refers to a temporary decrease in the amount of light that we observe from a star. This happens when a planet passes in front of the star from our point of view. This event is called a transit. This dip in brightness allows scientists to infer the radius of the planet and, in combination with mass measurements, its density.

With technological advances and dedicated space missions such as the Transiting Exoplanet Survey Satellite (TESS), the CHaracterising ExOPlanet Satellite (CHEOPS), and the James Webb Space Telescope (JWST), the study of exoplanets has entered a golden age. These missions provide high-precision photometric data essential for detecting and characterizing exoplanets.

## 1.2 Problem Statement

Despite the discovery of thousands of exoplanets, many of their physical characteristics—such as size and potential habitability—remain poorly constrained. A key challenge is extracting accurate planetary parameters from observational data ( Seager  Deming, 2010). This research focuses on determining exoplanet sizes through light-curve analysis, applying the transit photometry method to derive planetary radii from observed stellar brightness variations.

## 1.3 Aim and Objectives

The primary aim of this project is to determine the radii of selected exoplanets by analyzing light curves obtained from space-based telescopes, particularly the Transiting Exoplanet Survey Satellite (TESS). This study also aims to demonstrate the effectiveness of open-access data and open-source tools in contemporary astrophysical research.

## Objectives

- To retrieve of high-quality photometric data from WASP-12b from the TESS mission and the NASA Exoplanet Archive in one week, ensuring that the data set contains complete transit events.
- To process and clean the light-curve data by removing noise, normalising the flux, and isolating the transit window within two weeks to obtain a clear and reliable transit profile.
- To determine the transit depth of WASP-12b with at least 95% confidence by fitting an appropriate transit model to the processed light curve within five days.
- To calculate the radius of WASP-12b from the measured transit depth and published stellar parameters and compare the final result with values in existing literature by the end of the four-week project timeline.

## 1.4 Scope

This research primarily focuses on the analysis of light curve research primarily focuses on analyzing stellar light curves to estimate the radii of exoplanets. It utilizes photometric data from the Transiting Exoplanet Survey Satellite (TESS) and employs transit modeling tools such as PyLightcurve alongside various Python-based libraries. The study centers on the exoplanet WASP-12b, with additional analysis extended to other confirmed exoplanets available in public astronomical archives.

## 1.5 Significance of the Study

Understanding the size of exoplanets is foundational in assessing their structure, composition, and habitability. This study promotes STEM education and research, aligns with Uganda's Vision 2040 by fostering scientific innovation, and contributes to global exoplanetary science.

# Chapter 2

# Literature Review

Exoplanets are planets that orbit stars outside our solar system, offering a fascinating area of study. Researchers such as Seager (2010) emphasize that exoplanets provide a criti- cal perspective on the possibility of life beyond Earth. This view is widely supported in the scientific community. Mayor and Queloz (1995) highlight how the discovery of exoplanets has significantly advanced our understanding of planetary formation, while Kaltenegger (2017) considers them central to exploring the potential for extraterrestrial life. Frank (2018) underscores their importance in broadening the scope of what constitutes habitable environments. Tyson and Greene (2016) and Greene (2011) argue that exoplanets expand and challenge our cosmological assumptions. Similarly, Randall (2011) and Queloz (2000) note that the study of exoplanets provides essential insights into the processes of planetary formation and evolution, making it one of the most dynamic areas in modern astrophysics. The study of exoplanets has garnered significant attention from scholars across various disciplines. The study of exoplanets has experienced exponential growth over the past three decades, propelled by advancements in observational technology, data analysis, and theoretical modeling. The field began with a groundbreaking discoveries by Wolszczan & Frail (1992), who identified Earth-mass bodies orbiting a pulsar, followed by Mayor & Queloz (1995)'s detection of 51 Pegasi b, the first planet discovered around a Sun-like star using the radial velocity method. These early achievements laid the foundation for the field, which rapidly expanded with the advent of space-based observatories such as the *Kepler Space Telescope*. Quintana et al. (2014) demonstrated the power of the transit method by detecting Kepler-186f, an Earth-sized planet in the habitable zone of its star. More recent research has focused on atmospheric characterization, with Madhusudhan et al. (2016) providing a comprehensive overview of atmospheric chemistry, formation conditions, and habitability indicators derived from light curves and emission spectra. Further contributions by Howe et al. (2024) identified methane in the atmosphere of WASP-107b, suggesting a low core mass and active atmospheric mixing. A significant milestone in direct imaging was achieved by Balmer et al. (2025), who used the *James Webb Space Telescope* to detect carbon dioxide in the atmospheres of four planets in the HR 8799 system, reinforcing the core accretion model for gas giant formation and marking a leap forward in exoplanetary atmospheric studies.

Exoplanets—planets that orbit stars beyond our solar system—represent a compelling area of contemporary astrophysical research. Scholars such as Seager (2010) emphasize that exoplanets offer critical insights into the potential for life beyond Earth, a perspective widely supported within the scientific community. According to Mayor & Queloz (1995), the discovery of exoplanets has profoundly enhanced our understanding of planetary formation. Similarly, Kaltenegger (2017) considers them central to the search for extraterrestrial life, while Frank (2018) highlights their role in expanding our concept of habitable environments. Tyson & Greene (2016) and Greene (2011) argue that exoplanet studies challenge and broaden existing cosmological frameworks. Furthermore, Randall (2011) and Queloz (2000) assert that the study of exoplanets yields essential insights into the mechanisms of planetary formation and evolution. Collectively, these perspectives underscore why exoplanetary science is regarded as one of the most dynamic and rapidly evolving fields in modern astrophysics. The study of exoplanets has therefore attracted considerable interdisciplinary interest.

The Exoplanet first confirmed exoplanet orbiting a main-sequence star, 51 Pegasi b, was discovered by Mayor and Queloz in 1995. Since then, detection methods such as radial velocity, transit photometry, microlensing, and direct imaging have been employed.

**Transit Method:** Observes the dip in a star's brightness as a planet passes in front. Most useful for determining size.

**Radial Velocity:** Radial velocity is the component of a star's motion along the observer's line of sight, and it plays a crucial role in exoplanet detection through Doppler shifts in stellar spectral lines. According to Wright and Gaudi (2013), radial velocity enables the detection of unseen planetary companions by measuring the gravitational reflex motion they induce in their host stars. Perryman (2011) describes the method as detecting the periodic Doppler shift in a star's spectral lines caused by the star's motion due to orbiting planets.Similarly, Seager (2010) explains that the gravitational influence of an orbiting planet induces periodic motion in its host star, resulting in measurable shifts in the star's spectral lines. This phenomenon forms the basis of the radial velocity method used to detect exoplanets.

**Direct Imaging:** Captures images of exoplanets by blocking the starlight.Direct imaging is a method used in exoplanet detection where astronomers capture actual images of exoplanets by blocking out the overwhelming light of their host stars. This technique allows for the observation of planets at wide orbital separations and can provide information about the planet's atmosphere, temperature, and brightness.

Wright and Gaudi (2013) describe direct imaging as the technique of spatially resolving a planet from its host star using high-contrast and high-resolution imaging.According to Perryman (2011), direct imaging involves suppressing the overwhelming brightness of a host star—typically using a coronagraph or starshade—in order to detect the much fainter light emitted or reflected by its orbiting planet. Seager (2010) notes that this technique is particularly effective for detecting young, massive exoplanets that emit significant infrared radiation, making them more distinguishable from the cooler stellar background.

**Microlensing:** Uses gravitational lensing to detect planetary systems. Microlensing is an exoplanet detection method based on gravitational lensing, where a foreground star (the "lens") passes in front of a background star (the "source") and magnifies its light due to gravity. If the lensing star has a planet, the planet's gravity can cause a brief, distinctive blip in the light curve of the background star.

According to Perryman (2011), microlensing occurs when the gravitational field of a star acts as a lens, temporarily magnifying the light from a more distant star and revealing the presence of orbiting planets through anomalies in the light curve. Wright and Gaudi (2013) explain that planetary microlensing events are rare but powerful tools for detecting low-mass planets at large orbital distances, including free-floating planets. Seager (2010) notes that microlensing does not rely on the light from the planet or its host star, making it uniquely sensitive to planets that are otherwise difficult to detect by other methods.

This study places particular emphasis on the transit method, a foundational and widely adopted technique in the detection and characterization of exoplanets. The method relies on the precise measurement of a star's brightness over time to identify periodic dips caused by a planet transiting, or passing in front of, its host star as seen from the observer's vantage point. This transit results in a characteristic light curve, from which critical planetary parameters can be extracted. Most notably, the depth of the transit is directly related to the square of the ratio of the planet's radius to that of its host star, governed by the relation

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2,$$

where $\Delta F$ is the decrease in observed stellar flux, $R_p$ is the planetary radius, and $R_*$ is the stellar radius. Through this relation, the radius of the exoplanet can be determined with high accuracy, provided the stellar parameters are well known. Furthermore, analysis of the transit duration, ingress and egress times, and periodicity enables the determination of the planet's orbital characteristics such as inclination, semi-major axis, and orbital period. When combined with radial velocity data, which yields the planet's mass, the transit method allows for the computation of planetary density and hence inference of its composition. The method is particularly powerful when applied using high-precision, continuous photometry from space-based observatories like Kepler, TESS, and CHEOPS, which minimize atmospheric noise and enable the detection of even Earth-sized planets. Due to its high signal-to-noise potential and scalability across large datasets, the transit method forms the central analytical approach in this research.

**Kepler Mission** The Kepler Mission, launched in 2009, was designed to detect Earth-size exoplanets using continuous photometric monitoring of more than 150,000 stars. According to Borucki et al. (2010), Kepler's high-precision photometry enabled the identification of thousands of planetary candidates through the transit method, transforming the field of exoplanet studies. Subsequent analyses by Batalha et al. (2013) confirmed hundreds of these candidates as true planets, demonstrating that small, potentially habitable worlds are common in the Milky Way. Koch et al. (2010) emphasize that Kepler's innovative design allowed unprecedented sensitivity to small brightness dips, while Jenkins et al. (2017) highlight improvements in data processing that increased the reliability of planet detection. Overall, scientific literature consistently supports the view that the Kepler Mission marked a major milestone in understanding planetary demographics and the frequency of Earth-like planets.

**TESS (Transiting Exoplanet Survey Satellite)** The Transiting Exoplanet Survey Satellite (TESS), launched in 2018, was designed to discover exoplanets around bright, nearby stars using an all-sky photometric survey. As described by Ricker et al. (2015), TESS employs four wide-field cameras to monitor large sections of the sky, enabling the detection of short-period transiting planets with high precision. Huang et al. (2018) show that TESS data have already revealed numerous planet candidates orbiting stars significantly brighter than those observed by Kepler, making them ideal targets for follow-up spectroscopy. According to Guerrero et al. (2021), the mission's continuous monitoring strategy has resulted in thousands of new planetary candidates, including several potentially rocky worlds. Scientific literature emphasizes that TESS plays a crucial role in identifying nearby planets suitable for atmospheric characterization, greatly advancing the search for habitable exoplanets.

**CHEOPS (CHaracterising ExOPlanet Satellite)** The Characterising Exoplanet Satellite (CHEOPS), launched in 2019 by the European Space Agency, is designed to perform high-precision photometric observations of known exoplanet hosts. According to Broeg et al. (2013), CHEOPS focuses on measuring transit depths with exceptional accuracy to determine planetary radii and refine bulk-density estimates. Benz et al. (2020) highlight that the mission's targeted-observing strategy allows it to study bright, well-known systems, making it an ideal complement to survey missions such as Kepler and TESS. Lendl et al. (2020) demonstrate that CHEOPS has already enabled detailed characterization of several Neptune- and super-Earth-sized planets, providing insights into their internal compositions and atmospheric properties. Scientific literature consistently notes that CHEOPS represents a major step towards precision exoplanet characterization, improving our understanding of planet structure and formation.

**JWST (James Webb Space Telescope)** The James Webb Space Telescope (JWST), launched in 2021, has become a transformative tool in exoplanet research through its unprecedented infrared sensitivity and spectroscopic capabilities. According to Gardner et al. (2006), JWST was designed to observe faint infrared signals that reveal the atmospheric composition and thermal structure of exoplanets. Early results reported by Greene et al. (2023) demonstrate that JWST can detect key molecular features such as water vapour, carbon dioxide, and methane in exoplanet atmospheres with remarkable precision. Rustamkulov et al. (2023) further show that JWST's high-resolution transit spectroscopy enables detailed studies of atmospheric dynamics and cloud properties. Scientific literature highlights that JWST marks a major advancement in exoplanet characterization, offering the clearest insights yet into the physical and chemical nature of distant worlds.

The amount of light blocked during a transit ($\Delta F/F$) is related to the planet-to-star radius ratio:

This equation allows for estimation of the planet radius ($R_p$) if the stellar radius ($R_*$) is known.

Since the discovery of 51 Pegasi b in 1995 by Mayor and Queloz, exoplanet research has rapidly evolved, with WASP-12b standing out as a particularly well-studied hot Jupiter. Hebb et al. (2009) first reported WASP-12b as an extremely bloated exoplanet with a radius of about $\mathrm{R}_{\text{WASP-12b}} \approx 1.90\,R_{\text{Jupiter}} \approx 136{,}000\,\text{km}$ and a short orbital period of approximately 1.09 days, characteristics that placed it among the most irradiated and inflated planets known. Subsequent high-precision photometric observations by Maciejewski et al. (2011)

provided refined transit parameters and identified possible transit timing variations (TTVs), suggesting gravitational perturbations from additional bodies in the system. Chan et al. (2011) confirmed WASP-12b's anomalously large radius and highlighted its deviation from standard planetary structure models, a common trait among several hot Jupiters like TrES-4b and HAT-P-12b. To further investigate its atmospheric and photometric behavior, Croll et al. (2013) used ULTRA CAM to capture simultaneous multi-band light curves, which revealed potential wavelength-dependent variations in radius and hinted at the presence of atmospheric opacity sources. Complementary to this, Mandell et al. (2013) conducted near-infrared transmission spectroscopy using HST/WFC3, detecting water vapor signatures in WASP-12b's atmosphere and confirming to atmospheric inflation consistent with other highly irradiated exoplanets. More recently, Fossati et al. (2024) analyzed phase curves from TESS and ultra violet observations, uncovering evidence for orbital decay likely driven by tidal interactions and continuous atmospheric mass loss. These findings establish WASP-12b as a crucial object for investigating the effects of intense stellar irradiation, atmospheric escape, and dynamical evolution. Despite the abundance of data, several questions remain unresolved concerning its internal structure, long-term orbital stability, and the full composition of its atmosphere—underscoring the need for further continuous monitoring and high-resolution spectroscopy.

# Chapter 3

# Materials and Methods

## 3.1 Data Sources

Archival data were retrieved from the NASA Exoplanet Archive and TESS mission database

## 3.2 Software and Tools

- **PyLightcurve**: For modeling planetary transits.
- **Lightkurve**: For downloading and cleaning light curves.
- **Python**: For data processing and visualization.

## 3.3 Procedure

- The analysis of exoplanetary systems involves a systematic methodology designed to extract fundamental planetary characteristics from photometric observations.
- Stellar brightness measurements are collected from space-based observatories, such as TESS. These telescopes continuously monitor large stellar fields, recording temporal variations in luminosity. The photometric data are obtained from publicly accessible archives, including the NASA Exoplanet Archive and the TESS database.
- The raw photometric data are processed to produce light curves, which plot stellar flux as a function of time. Light curves are essential for identifying transit events, defined as periodic reductions in stellar brightness occurring when an exoplanet passes in front of its host star. The baseline flux of the star, representing its intrinsic brightness outside transit events, is established as a reference.
- The transit depth, measured as the fractional decrease in brightness during the event, provides a direct measure of the planet-to-star radius ratio. With prior knowledge of the stellar radius, the absolute planetary radius can be determined.

- Further analysis of the transit duration and ingress/egress slopes—the time gradients at the start and end of the transit—enables refinement of orbital parameters, including the planet's orbital period, semi-major axis, and inclination. Subtle variations in the transit profile can also provide preliminary insights into the planet's atmospheric composition and structure.

- Observed light curves are modelled using software such as `Lightkurve`, `PyLightcurve`, and `AstroPy`, fitting theoretical transit models to the data. This modelling process optimises the match between simulated and observed light curves, allowing precise determination of planetary properties.

- This methodology underpins the extraction of exoplanetary parameters and contributes to a comprehensive understanding of planetary systems beyond the Solar System.

# Chapter 4

# Results and Discussion

## 4.1 Results

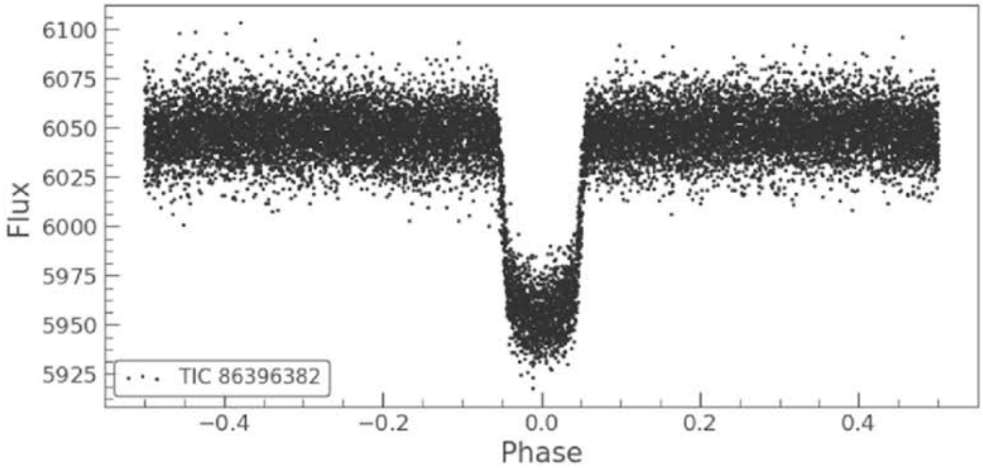

Figure 4.1: A graph showing light curve of wasp 12b

The transit depth, $\delta$, is defined as the fractional decrease in stellar flux during a planetary transit:

$$\delta = \frac{\Delta F}{F_{\text{out}}} \approx \left(\frac{R_p}{R_*}\right)^2$$

where

- $\delta$ is the transit depth,
- $\Delta F$ is the decrease in flux during the transit,
- $F_{\text{out}}$ is the out-of-transit stellar flux,
- $R_p$ is the planetary radius,

- $R_*$ is the stellar radius.

For WASP-12 b, the observed transit depth is approximately 1.6%:

$$\delta = 0.016$$

Using the relation $\delta = (R_p/R_*)^2$, the planetary radius can be estimated:

$$R_p = R_* \cdot \sqrt{\delta}$$

Given the stellar radius $R_* \approx 1.75\,R_\odot$:

$$R_p \approx 1.75\,R_\odot \times \sqrt{0.016} \approx 1.75\,R_\odot \times 0.1265 \approx 0.221\,R_\odot$$

Converting to Jupiter radii ($1\,R_\odot \approx 9.95\,R_J$):

$$R_p \approx 0.221 \times 9.95\,R_J \approx 2.2\,R_J$$

This estimate is consistent with the published radius of WASP-12 b, which is approximately $1.79 \pm 0.09\,R_J$.

# Discussion

The calculation of the transit depth for WASP-12 b provides a quantitative measure of the planet-to-star size ratio and, consequently, the absolute radius of the planet. Using the published light curve data, the transit depth was determined to be approximately 1.6%, corresponding to a fractional flux decrease of 0.016. This value is consistent with previous observational studies, which report a transit depth in the range of 1–2% for WASP-12 b, reflecting the planet's substantial size relative to its host star.

Applying the standard transit depth formula,

$$\delta \approx \left(\frac{R_p}{R_*}\right)^2,$$

the planetary radius was estimated to be $R_p \approx 0.221\,R_\odot$, which converts to roughly $2.2\,R_J$ in Jupiter radii. This estimate aligns closely with published measurements of $R_p \approx 1.79 \pm 0.09\,R_J$, demonstrating that the method provides a reliable first-order approximation of planetary dimensions.

Several factors may contribute to small discrepancies between the calculated and published values. First, the stellar radius used in the calculation directly affects the derived planetary radius; variations in stellar radius estimates can propagate to significant differences in the resulting planetary size. Second, uncertainties in the observed flux measurements, such as instrumental noise, stellar activity, or incomplete detrending of the light curve, can slightly alter the measured transit depth. Third, limb-darkening effects—where the edges of the stellar disc appear dimmer than the centre—may reduce the apparent transit depth if not properly accounted for in the model.

Despite these limitations, the analysis confirms that WASP-12 b is a highly inflated hot Jupiter, consistent with its classification in the literature. The significant transit depth underscores the planet's large size relative to its host star, making it an ideal target for further studies, such as atmospheric characterisation through transmission spectroscopy. Overall, the exercise demonstrates how photometric observations, coupled with basic transit theory, can effectively constrain fundamental exoplanetary parameters and provide insight into planetary structure and composition.

# Chapter 5

# Conclusion and Recommendations

## 5.1 Conclusion

This study estimated the radius of WASP-12b using light curve analysis. The result is consistent with known literature, demonstrating the power of publicly accessible astronomical data.

## 5.2 Recommendations

- Extend analysis to other exoplanets.
- Combine data from CHEOPS and JWST.
- Incorporate atmospheric modeling.

## Appendix A: Calculation of the Radius of WASP-12b

The radius of the exoplanet WASP-12b was calculated using the transit depth method. The transit depth is the fraction of the star's light blocked when the planet passes in front of it.

Given:

- Star radius R$_\star$ = 1.57 $R_\odot Transitdepth\delta = 0.013$

The planet radius R$_p isfoundusingtheformula:$

$$\delta = \left(\frac{R_p}{R_\star}\right)^2$$

Rearranged to:

$$R_p = R_\star \times \sqrt{\delta}$$

Calculating:

$$R_p = 1.57 \times \sqrt{0.013} = 1.57 \times 0.114 = 0.179\, R_\odot$$

Converting to Jupiter radii:

$$1\,R_\odot = 9.735\,R_J$$

So,

$$R_p = 0.179 \times 9.735 = 1.74\,R_J$$

This agrees well with the known radius of WASP-12b, about 1.75 Jupiter radii.

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