An Analysis of Exoplanets WASP-33b, WASP-3b, CoRoT-8b, and HAT-P-32b Using the Transit Method

Kailly Nocera
University of Michigan, Ann Arbor

Abstract

Exoplanets are planets that orbit a star other than our Sun. The purpose of this research was to analyze the light curves of exoplanets WASP-33b, WASP-3b, CoRoT-8b, and HAT-P-32b produced by their transits comparatively with existing information. Original data was provided by Dr. Michael Zeilnhofer, who conducted observations at the Westside Observatory at Western Connecticut State University over multiple years and dates. Julian date vs delta magnitude graphs were created to analyze transit start times and geometries. Phase vs. flux graphs were input into Binary Maker 3.0 to determine additional parameters that best fit the program-generated light curve to existing data. Phase vs. flux graphs were analyzed for each date of the WASP-33 and HAT-P-32 systems by altering the parameters of Binary Maker 3.0 to match the generated light curve with the light curve based on original observations. The alteration of parameters in Binary Maker 3.0 indicated there was a star spot on WASP-33, the star that exoplanet WASP-33b orbits, on November 7th, 2011, and December 7th, 2012. This observation implies the existence of previously uncharacterized stellar phenomena. In addition, a change in the transit geometry and transit timing of the light curve of WASP-33b implies the existence of multi-star system. Differences in transit geometry in the light curves of WASP-3b and HAT-P-32b indicate gravitational pulls. Further studies with space-based telescopes rather than ground-based telescopes should be performed to ensure more accurate observations and measurements, and to support or refute the existence of gravitational pulls on these systems.

Keywords: exoplanets, transits, light curves

doi: 10.18278/sesa.5.4.24

Un análisis de los exoplanetas WASP-33b, WASP-3b,

RESUMEN

Los exoplanetas son planetas que orbitan una estrella distinta a nuestro Sol. El propósito de esta investigación fue analizar las curvas de luz de los exoplanetas WASP-33b, WASP-3b, CoRoT-8b y HAT-P-32b producidas por sus tránsitos, comparándolas con la información existente. Los datos originales fueron proporcionados por el Dr. Michael Zeilnhofer, quien realizó observaciones en el Observatorio Westside de la Universidad Estatal de Western Connecticut durante varios años y fechas. Se crearon gráficos de fecha juliana frente a magnitud delta para analizar las horas de inicio y las geometrías de los tránsitos. Los gráficos de fase frente a flujo se introdujeron en Binary Maker 3.0 para determinar parámetros adicionales que mejor ajustaran la curva de luz generada por el programa a los datos existentes. Se analizaron los gráficos de fase frente a flujo para cada fecha de los sistemas WASP-33 y HAT-P-32 modificando los parámetros de Binary Maker 3.0 para que coincidieran con la curva de luz generada en las observaciones originales. La alteración de los parámetros en Binary Maker 3.0 indicó la presencia de una mancha estelar en WASP-33, la estrella que orbita el exoplaneta WASP-33b, el 7 de noviembre de 2011 y el 7 de diciembre de 2012. Esta observación implica la existencia de fenómenos estelares no caracterizados previamente. Además, un cambio en la geometría y la sincronización de los tránsitos de la curva de luz de WASP-33b implica la existencia de un sistema multiestelar. Las diferencias en la geometría de los tránsitos en las curvas de luz de WASP-3b y HAT-P-32b indican atracción gravitatoria. Se recomienda realizar estudios adicionales con telescopios espaciales en lugar de terrestres para garantizar observaciones y mediciones más precisas, y para confirmar o refutar la existencia de atracción gravitatoria en estos sistemas.

Palabras clave: exoplanetas, tránsitos, curvas de luz

利用凌日法分析系外行星WASP-33b、WASP-3b、CoRoT-8b和HAT-P-32b

摘要

系外行星是指围绕太阳以外的恒星运行的行星。本研究旨在分析系外行星WASP-33b、WASP-3b、CoRoT-8b和HAT-P-32b的

凌日光变曲线，并将其与现有数据进行比较。原始数据由Michael Zeilnhofer博士提供，其曾在西康涅狄格州立大学西侧天文台进行了多年多日的观测。我们绘制了儒略日与星等变化图，以分析凌日起始时间和几何形状。我们将相位与光通量图输入Binary Maker 3.0软件，以确定能够使程序生成的光变曲线与现有数据最佳拟合的其他参数。我们通过调整Binary Maker 3.0的参数，对WASP-33和HAT-P-32系统的每个观测日期的相位与光通量图进行了分析，以使生成的光变曲线与基于原始观测的光变曲线相匹配。Binary Maker 3.0的参数调整表明，在2011年11月7日和2012年12月7日，WASP-33（系外行星WASP-33b的环绕恒星）上存在星斑。这一观测结果暗示了此前未被描述的恒星现象的存在。此外，WASP-33b光变曲线的凌星几何形状和凌星时间的变化表明其可能是一个多星系统。WASP-3b和HAT-P-32b光变曲线中凌星几何形状的差异表明存在引力作用。为了确保更精确的观测和测量，并验证或否定这些系统中是否存在引力作用，应使用空间望远镜而非地面望远镜进行进一步研究。

关键词：系外行星，凌星，光变曲线

Introduction

Exoplanetology is a field of planetary science that allows researchers to expand on overarching knowledge of our universe, form conclusions about exosolar system formation, and further understand our own solar system. The discovery of “Hot Jupiters,” large gaseous planets that orbit their stars extremely closely, became the base for an entire remodeling of solar system formation. The discovery of “Hot Jupiters” provided researchers the necessary knowledge to form the two most widely accepted theories of solar system formation today—the Nice model (Gomes et al., 2005) and the Grand Tack model (Morbidelli & Crida, 2007).

One method to discover and study exoplanets is to observe their transit. Every exoplanet observed in this study was discovered through the transit method (Schneider, 2022). An exoplanet transit is defined as the instance of an exoplanet’s passing in front of the star it orbits from Earth’s perspective. This decreases the visual magnitude, or brightness, of the star from Earth’s perspective, as the planet blocks some of the light emitted from the star (Street, n.d.). When formatted as a graph detailing brightness vs time, a dip in the graph can be observed during the exoplanet’s transit (Figure 1). This graph is known as a light curve.

The exoplanets observed in this study are WASP-33b, WASP-3b, CoRoT-8b, and HAT-P-32b. All observed ex-

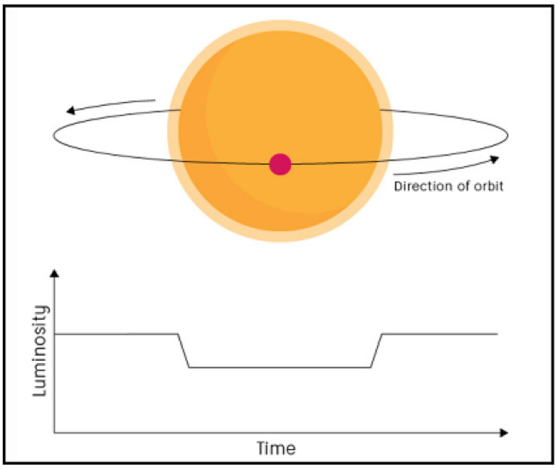

Fig. 1. **Exoplanet Transit.** Image showing a model of an exoplanet transit and the resulting light curve. This image was taken from (Street, n.d.).

oplanets are the only known planets within their respective solar systems. Each system is only known to contain one star, and none of the observed exoplanets have confirmed moons. This means that any observed evidence of a gravitational pull would be indicative of an undiscovered object's effect on the system. Evidence of a gravitational pull on an exoplanet system can be discovered through the transit method.

One way to depict the transit of exoplanets is to create a light curve (Figure 1) using delta magnitude and Julian Date. Delta magnitude is the magnitude of a comparison star subtracted from the magnitude of the observed star. The comparison star is a nearby star with a similar magnitude. Julian date is simply the time with reference to the Julian calendar. All Julian dates used in this project are heliocentric, meaning with reference to the Sun. Julian date can be converted to regular date and vice versa.

Flux and phase are also important measurements for magnitude and time, similarly to delta magnitude and Julian Date. Phase is a measurement of time and can be determined for every exoplanet. It is derived using the Julian date, epoch (the time in Julian Date when the exoplanet was first discovered), and period (the time in Julian Date that an exoplanet takes to fully orbit its star). Flux is a measurement of magnitude and can only be determined for some exoplanets. It is derived using the delta magnitude and the flux of the comparison star. Flux and phase are accepted by Binary Maker 3.0 (Bradstreet & Steelman, 2002), while Julian date and delta magnitude are not. This is important for comparing light curves generated by the program to light curves produced with collected data. Binary Maker 3.0 generates a theoretical light curve with an x-axis of phase and a y-axis of flux based on inputted parameters. The application creates a plot that overlays this generated light curve with the observational light curve.

Methods

Initial observations were acquired from Dr. Michael Zeilnhofer. These observations were conducted at the Westside Observatory at Western Connecticut State University during two separate periods of time. The first was September 2011 – December 2011, and the second was September 2012 – December 2012. The telescope used was an f/8.1 20-inch Ritchey Chréiten telescope with an SBIG ST-7e CCD camera and a Kron-Cousins filter (Zeilnhofer 2013).

The delta magnitude was derived by subtracting the magnitude of the comparison star from the magnitude of the observed star for each frame. This information was used to create a Julian date vs. delta magnitude light curve for each date of each observed exoplanet using Excel.

Each light curve was analyzed both qualitatively and quantitatively. Transit geometry is a visual method of qualitatively analyzing the shape of a light curve. Individually analyzed transit geometries, or transit geometries analyzed by looking at a specific light curve for one date, can indicate a gravitational pull on the system. If the transit dip is steeper on one side of the light curve, this may indicate a gravitational pull on the system. Transit geometry may also be analyzed over the course of multiple dates to determine a change in the shape of the transit. For example, if the transit dip of a specific planet appears steeper in one year compared to another, there may be a gravitational pull causing this difference. Transit timing is a quantitative method of analyzing the start time of the transit dip. Transit timing may only be analyzed over the course of multiple dates to discern a difference between the start time of the transit over time. Since Julian date can easily be converted back to regular date, it is simple to determine the difference between transit start times in understandable terms. A greater difference in transit start time indicates a stronger gravitational pull on the system. For example, a difference of a few seconds would indicate a moon or other small object's gravitational pull on the system, a difference of a few minutes or hours would indicate a planet or other medium sized object's gravitational pull on the system, and a difference of many hours or days would indicate a star or other large object's gravitational pull on the system.

Flux and phase were also calculated using publicly available data regarding each exoplanet system. Due to a lack of certain data, flux and phase were only able to be calculated for exoplanets WASP-33b and HAT-P-32b. Flux vs. phase diagrams were created in Excel.

These diagrams were analyzed using Binary Maker 3.0. Known, publicly available parameters for each system were input into the application. Then, observational flux vs. phase data was input into the system. The program generated a light curve based on the known parameters and overlayed this light curve with the observational light curve. Unknown parameters were tweaked until the generated light curve best fit the observational light curve, allowing for inferences regarding these unknown parameters.

When creating both Julian date vs. delta magnitude and phase vs. flux light curves, observation error was mitigated by excluding any blank original values. These values may have been caused by the blocking of the lens of the telescope and therefore could not be included in the finalized data.

Results and Conclusions

All exoplanets were analyzed qualitatively through transit geometry using the Julian date vs. delta magnitude diagrams. WASP-33b was analyzed quantitatively through transit timing using its Julian date vs. delta magnitude diagrams. WASP-33b and HAT-P-32b were analyzed through Binary Maker 3.0 using their flux vs. phase diagrams.

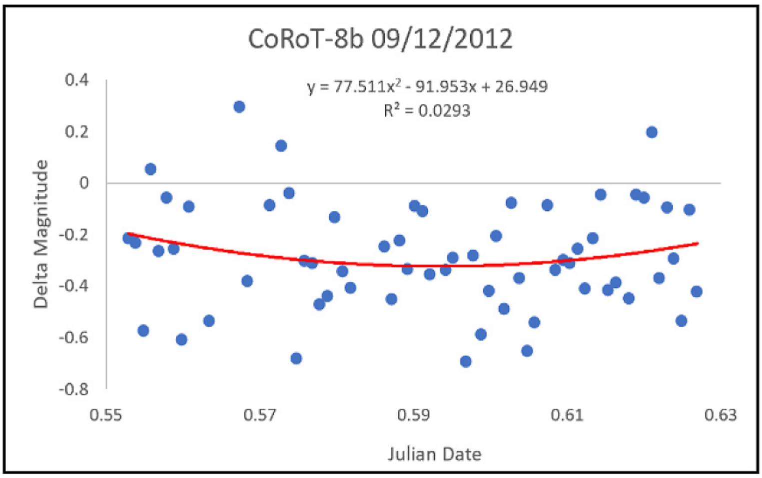

Fig. 2. **Light Curve JD/DM CoRoT-8b.** This light curve plots the transit of CoRoT-8b on September 12th, 2012. This graph depicts Julian Date vs delta magnitude. *Created using Excel.*

The light curve created for CoRoT-8b (Figure 2) is extremely scattered and inconclusive. This is consistent with many other publicly available light curves for the system. The data for this system is inconclusive, and it is not possible to determine evidence of a gravitational pull on the system through this diagram.

There was an observable transit for three out of four days during which this system was observed. Due to the relatively flat shape of the 09/13/2012 diagram, this data was not counted as an observable transit. In analyzing the Julian Date vs. delta magnitude graphs (Figure 3), there are potential gravitational pulls due to transit geometry. On 09/05/2011, the left side of the transit curve was much steeper than the left side of the curve, indicating a gravitational pull. In addition, on 09/24/2012, the right side of the transit curve was steep-

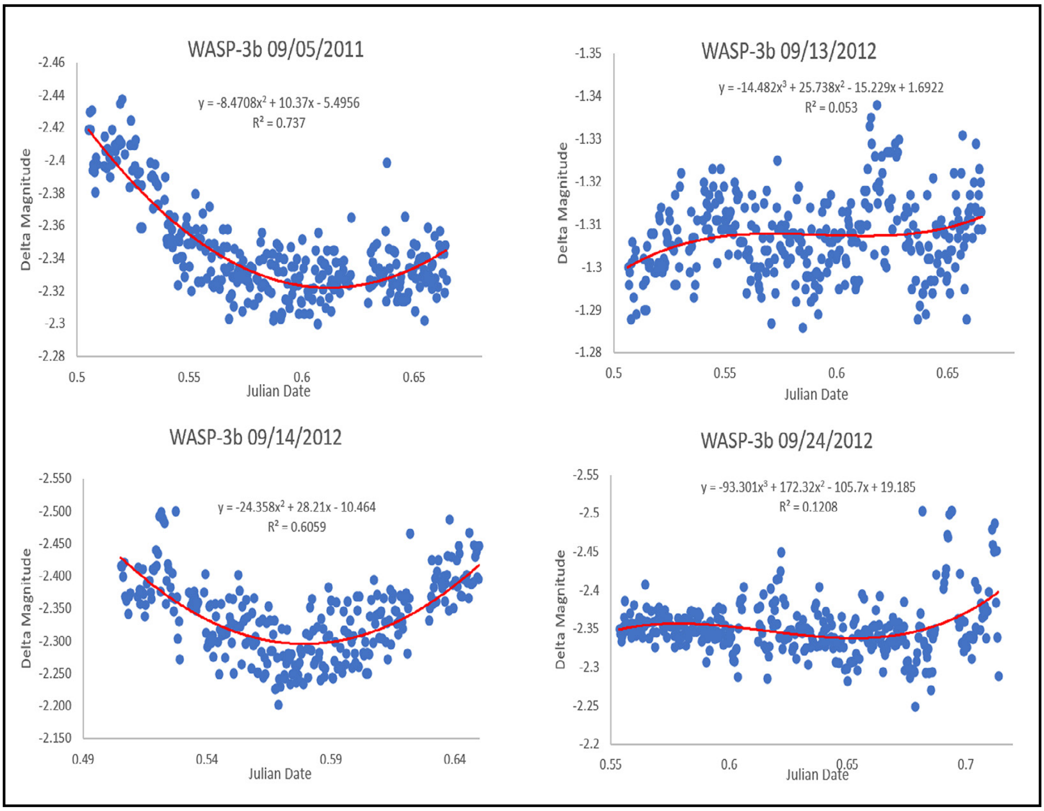

***Fig. 3.* Light Curves JD/DM WASP-3b.** These light curves plot the transit of WASP-3b on September 5th, 2011, September 13th, 2012, September 14th, 2012, and September 24th, 2012. These graphs depict Julian Date vs delta magnitude. *Created using Excel.*

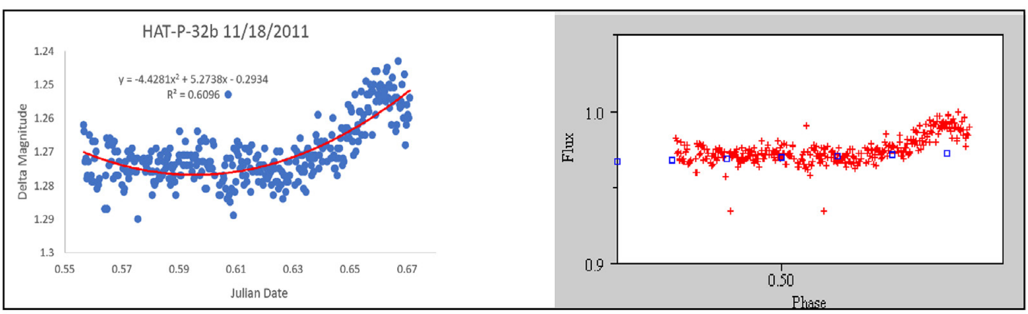

***Fig. 4.* Light Curve JD/DM and Flux/Phase HAT-P-32b.** This light curve plots the transit of HAT-P-32b on November 18th, 2011. These graphs depict Julian Date vs delta magnitude and flux vs. phase with the Binary Maker 3.0 generated light curve shown as blue squares in the right diagram. *Created using Excel and Binary Maker 3.0.*

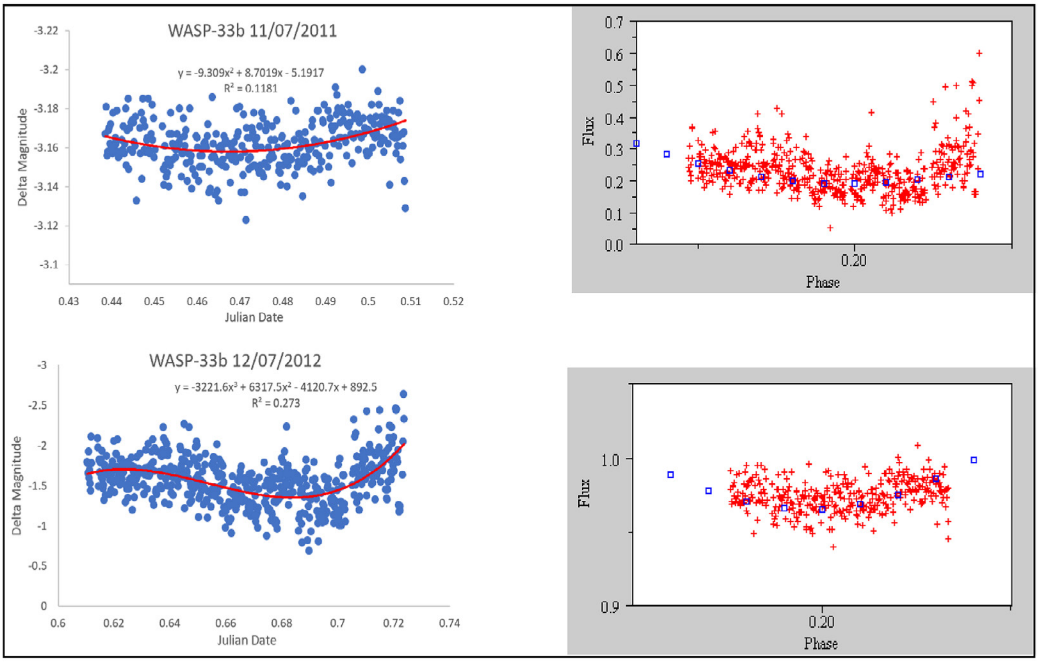

***Fig. 5.* Light Curves JD/DM and Flux/Phase WASP-33b.** These light curves plot the transit of WASP-33b on November 7th, 2011, and December 7th, 2012. These graphs depict Julian Date vs. delta magnitude and flux vs. phase with the Binary Maker 3.0 generated light curve shown as blue squares in the right diagram. *Created using Excel and Binary Maker 3.0.*

er than the left side, indicating a gravitational pull. However, on 09/14/2012, the transit curve appears to be even and symmetrical. The change in transit geometry over multiple dates is an additional indicator of a gravitational pull on the system. In addition, the quantitative analysis of transit timing further refines the nature of this system. On 09/05/2011 and 09/14/2012, the transits begin at approximately 0.5 Julian date, while on 09/24/2012, the transit begins at approximately 0.6 Julian date. This is a difference of approximately two hours, suggesting the existence of a medium-sized gravitational pull on the system, such as another planet.

There was a clear, observable transit for one out of three days which this system was observed. The right side of the transit curve on 11/18/2011 (Figure 4) is much steeper than the left side, indicating a potential gravitational pull on the system. When placed into Binary Maker 3.0, the adjusted parameters showed no abnormalities. However, the parameters could not be adjusted to account for the steepness on the right side of the graph.

There is a clear, observable transit for both days this system was observed (Figure 5). Unknown parameters were tweaked in Binary Maker 3.0 to best align the generated light curves with the observational light curves. This process revealed a potential star spot on WASP-33, the star that WASP-33b orbits, that increased in radius from 8 kilometers in 2011 to 24 kilometers in 2012. In addition, there may be another star in the WASP-33 system. Both transit timing and transit geometry are indicative of a gravitational pull on the system. With comparative observation of the transit geometries of WASP-33b on 12/07/2012 and 11/07/2011, the transits appear to be shaped very differently. The light curve of WASP-33b on 11/07/2011 is much flatter than the light curve of WASP-33b on 12/07/2012. In addition, the transits start at different times. The transit for 11/07/2011 starts at approximately 0.44 Julian date, while the transit for 12/07/2012 starts at approximately 0.64 Julian date. In analyzing the transit timing, it was found that there was a difference of approximately 19 hours between the transit start time in 2011 and 2012. This large difference in transit timing is indicative of a large gravitational pull on the system, such as another star. These findings are similar to recent discoveries which showcased evidence of WASP-33 being a trinary system, a system with three central stars rather than one (Von Essen et al., 2020).

Gravitational pull indicators were abundant, with factors suggesting a large gravitational pull on WASP-33, a medium gravitational pull on WASP-3b, and an indeterminate gravitational pull on HAT-P-32b. There is also evidence of a star spot on WASP-33. However, in using a ground-based telescope, observational error may skew the data. Factors such as cloudiness, precipitation, and lens blockage may tamper with observation. In future research, it would be ideal to obtain observations using a space-based telescope as to have more accurate measurements, leading to more accurate light curves. A space-based telescope would completely eliminate earthly weather-based observational error while also having a more powerful lens. This would allow for better analysis of exoplanets WASP-33b, WASP-3b, CoRoT-8b, and HAT-P-32b using the transit method. This will allow for additional evidence either supporting or refuting the conclusions made from the data collected by the ground-based telescope. A space-based telescope would also be ideal for observing other exoplanet systems with unconfirmed gravitational pulls.

References

Bradstreet, D. H., & Steelman, D. P. (2002). Binary Maker 3.0 – An Interactive Graphics Based Light-Curve Synthesis Program Written in Java. ResearchGate, 34. https://www.researchgate.net/publication/234526669

Gomes, R., Levison, H. F., Tsiganis, K., & Morbidelli, A. (2005). Origin of the Cataclysmic Late Heavy Bombardment Period of the Terrestrial Planets. Nature, 435, 466–469. https://doi.org/10.1038/nature03676

Morbidelli, A., & Crida, A. (2007). The Dynamics of Jupiter and Saturn in the Gaseous Proto-Planetary Disk. arXiv. https://doi.org/10.48550/arXiv.1801.06117

Schneider, J. (2022, December 27). The Extrasolar Planets Encyclopaedia. http://exoplanet.eu/

Street, R. (n.d.). Transit Method. Las Cumbres Observatory. https://lco.global/spacebook/exoplanets/transit-method/

Von Essen, C., Mallonn, M., Borre, C. C., Antoci, V., Stassun, K. G., Khalafinejad, S., & Tautvaišiene, G. (2020). TESS Unveils the Phase Curve of WASP-33b. Astronomy & Astrophysics, 639. https://doi.org/10.1051/0004-6361/202037905

Zeilnhofer, M. (2013). Light Curve Analysis of Transiting Exoplanets. ResearchGate. https://www.researchgate.net/publication/325225935