

T.C.
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INSTITUTE OF GRADUATE STUDIES
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**TESTING ATMOSPHERIC ESCAPE VIA
PHOTOEVAPORATION USING EXOPLANETS**

MASTER OF SCIENCE, PHYSICS

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PREFACE

"The cosmos is within us. We are made of star stuff. We are a way for the universe to know itself."

-Carl Sagan

ABSTRACT

TESTING ATMOSPHERIC ESCAPE VIA PHOTOEVAPORATION USING EXOPLANETS

**MASTER THESIS
GÖZDE DOĞRU**

**BOLU ABANT İZZET BAYSAL ÜNİVERSİTESİ
INSTITUTE OF GRADUATE STUDIES
DEPARTMENT OF PHYSICS**

**(SUPERVISOR: PROF. DR. ABDULKADİR ŞENOL)
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**BOLU, 30 MAY 2025
XV + 90**

This study aims to test the compatibility of the escape in the atmospheres of exoplanets, which are planets outside the Solar System, with the photoevaporation hypothesis. The existence of systems that are not compatible with this hypothesis indicates the existence of new atmospheric loss models and may also reveal the existence of interesting systems. In the study, three different radius and density scenarios and sub-target lists belonging to these scenarios were tested by using parameters such as radius, mass, distance to the star, and XUV radiation of exoplanet systems in the NASA Exoplanet Archive database, considering different situations. The analysis was associated with the Markov Chain Monte Carlo (MCMC) method and processed with Python. The basic findings obtained are that the vast majority of the exoplanet systems in the NEA database are compatible with the photoevaporation hypothesis. On the other hand, there are also interesting systems that can be classified as atmospheric escape processes that are predicted to occur with different mechanisms. In conclusion, it is clear that the photoevaporation hypothesis is sufficient in the process of solving the demographic structure and atmospheric escape of exoplanetary systems, but it offers important contributions to literature regarding the need to understand the different mechanisms that occur in interesting systems and to be able to solve the atmospheric escape that occurs on the surfaces of these planets.

KEYWORDS: Exoplanet systems, Photoevaporation hypothesis, Atmospheric escape, Core mass of exoplanets, NASA exoplanet archive

ÖZET

ÖTEGEZEĞENLERİ KULLANARAK FOTOBUHARLAŞMA YOLUYLA ATMOSFERİK KAÇIŞIN TEST EDİLMESİ

YÜKSEK LİSANS TEZİ
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Bu çalışmada Güneş Sistemi dışındaki gezegenler olan ötegezegenlerin atmosferlerinde gerçekleşen kaçışın fotobuharlaşma hipotezi ile uyumluluğunun test edilmesi amaçlanmıştır. Bu hipotezle uyumlu olmayan sistemlerin varlığı, yeni atmosfer kaybı modellerinin varlığını işaret etmekle beraber ilginç sistemlerin de varlığını ortaya koyabilmektedir. Çalışmada, NASA Exoplanet Archive veri tabanında bulunan ötegezegen sistemlerinin yarıçap, kütle, yıldızına olan uzaklık ve XUV radyasyonu gibi parametreleri kullanılarak üç farklı yarıçap ve yoğunluk senaryoları ile bu senaryolara ait alt hedef listeleri farklı durumlar göz önünde bulundurularak test edilmiştir. Yapılan analizler Markov Chain Monte Carlo (MCMC) metodu ilişkilendirilmiş ve Python ile işlenmiştir. Elde edilen temel bulgular, NEA veri tabanında yer alan ötegezegen sistemlerinin büyük bir çoğunluğunun fotobuharlaşma hipotezi ile uyumlu olduğu yönündedir. Buna karşın atmosferik kaçış sürecinin farklı mekanizmalar ile gerçekleşebileceğinin öngörüldüğü ilginç olarak sınıflandırılacak sistemlerin varlığı da mevcuttur. Sonuç olarak, fotobuharlaşma hipotezinin ötegezegen sistemlerinin demografik yapısını ve atmosfer kaçışını çözümleme sürecinde yeterli bir hipotez olduğu açıktır ancak ilginç sistemlerde gerçekleşen farklı mekanizmaların anlaşılması ve bu gezegenlerin yüzeylerinde gerçekleşen atmosfer kaçışının çözümlenebilmesinin gerektiğine dair literatüre önemli katkılar sunmaktadır.

ANAHTAR KELİMELER: Ötegezegen sistemleri, Fotobuharlaşma hipotezi, Atmosferik kaçış, Ötegezegenlerin çekirdek kütlesi, NASA exoplanet archive

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LIST OF ABBREVIATIONS AND SYMBOLS

B.C.	: Before Christ
TESS	: Transiting Exoplanet Survey Satellite
JWS	: James Webb Space Telescope
NEA	: NASA Exoplanet Archive
HST	: Hubble Space Telescope
SST	: Spitzer Space Telescope
CoRoT	: Convection, Rotation and planetary Transits
KST	: Kepler Space Telescope
Gaia	: Global Astrometric Interferometer for Astrophysics
CHEOPS	: CHaracterising ExOPlanet Satellite
Roman	: Nancy Grace Roman Space Telescope
PLATO	: PLANetary Transits and Oscillations of stars
Ariel	: Atmospheric Remote-sensing Infrared Exoplanet Large-survey
PS	: Planetary Systems
PSCD	: Planetary Systems Composite Data
P	: Period
a	: Semi-Major Axis
R_p, r_p	: Planet Radius
M_p, m_p	: Planet Mass
ρ_p	: Planet Density
F	: Insolation Flux
T_s	: Star Temperature
R_s	: Star Radius
M_s	: Star Mass
G	: Gravitational Constant
F_c	: Centripetal Force
v	: Orbital Speed
σ	: Stefan-Boltzmann Constant
L	: Luminosity
A	: Surface Area
η	: Mass Loss Efficiency
v_{esc}	: Escape Velocity
MCMC	: Markov Chain Monte Carlo
CL	: Confidence Level
ΔM	: Residual Mass
S/N	: Signal-to-Noise Ratio

$M_{\oplus}$: Earth Mass
 $R_{\oplus}$: Earth Radius
XUV : XUV Radiation
EUV : Extreme Ultraviolet Radiation
FUV : Far Ultraviolet Radiation



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1. INTRODUCTION

Since the beginning of the Universe, people have tried to understand the environment they live in. They have questioned what the Earth they live on is like, the structure of the Universe, the Solar System, and the planets. When looking at Antiquity, it is known that some important foundations were laid during this period. It is known that in the 4th century BC, one of the most important theories about the structure of the Universe was presented by Aristotle with his *geocentric* (Earth-centered) theory of the Universe. This theory suggested that the Earth was at the center of the Universe and that all celestial bodies revolved around it (Sagan, 1980).

Unlike this theory, Epicurus and Democritus proposed the theory of multiple universes. However, Aristotle was highly critical of this theory because of his belief that no celestial body other than the Earth could be at the center of the Universe (Timmermans, 2024). In the following years, the transformation of scientific thought progressed, especially with the Renaissance, and led to radical changes in astronomy. With the end of the Middle Ages, new questions about the functioning of the Universe emerged, and scientists seeking answers to these questions began to lay the foundations of modern science with observational data and mathematical models.

1.1 Antiquity and Post-Medieval

The year 1543 marked the beginning of a new paradigm in astronomy, as Nicolaus Copernicus introduced the *heliocentric* (Sun-centered) model of the universe in his work *De revolutionibus orbium coelestium*, following the end of Antiquity and the Middle Ages (Sagan, 1980; Timmermans, 2024). According to the theory, the Sun, including the Earth, is the center of the Universe. In 1609, Galileo Galilei made the discovery that would confirm the heliocentric theory put forward by Nicolas Copernicus. This discovery was the ability to observe the four largest known moons of Jupiter (Timmermans, 2024).

In the same year, Johannes Kepler put forward three mathematical laws explaining the motion of the planets in the Solar System, and in the following years, Isaac Newton's *Philosophiæ Naturalis Principia Mathematica*, based on Kepler's

work, combined the laws of physics describing the motion of celestial bodies and the motion of the Earth and put forward the Universal Theory of Gravitation, which laid the foundations of modern physics (Sagan, 1980; Timmermans, 2024).

In the years when the heliocentric theory of the universe began to gain acceptance, scientists began to seek answers to other fundamental questions. One of these was: Was our Solar System unique and original? In 1584, Giordano Bruno, in his book *De l'infinito universo et mundi*, building on Nicolaus Copernicus's theory, embraced Hermetism (a mystical and esoteric worldview intertwined with science and philosophy) and proposed that stars were distant suns surrounded by their own planets (exoplanets) (Sagan, 1980; Timmermans, 2024). In the 19th century and beyond, studies aiming to answer the question 'Are we unique?' began to gain momentum.

1.2 19th and 20th Century Concept and Discovery of Exoplanets

In the 19th century, William Herschel (Sagan, 1980) and other astronomers attempted to explore the outer Solar System and Deep Space through earth-based observations, as shown in Figure 1.1, but due to the technological inadequacies at the beginning of that period, the concept of exoplanets that had been proposed up to that date could not be confirmed (Timmermans, 2024). But human logic has always known that exoplanets must exist, even if they could not be confirmed. Considering the size of the Universe, it was unlikely that our star would be the only one to accumulate planets around it and form a new system.

By the end of the 19th century, when everything was progressing faster as science and studies were constantly adding to and developing previous studies, the Austrian mathematician Christian Doppler (The Doppler Effect, 2025) began to determine the speed of the stars with the discovery of the Doppler effect and formed the basis of the radial velocity method that would later emerge. This effect was based on the principle that the frequency of waves from a moving source varies according to the observer.

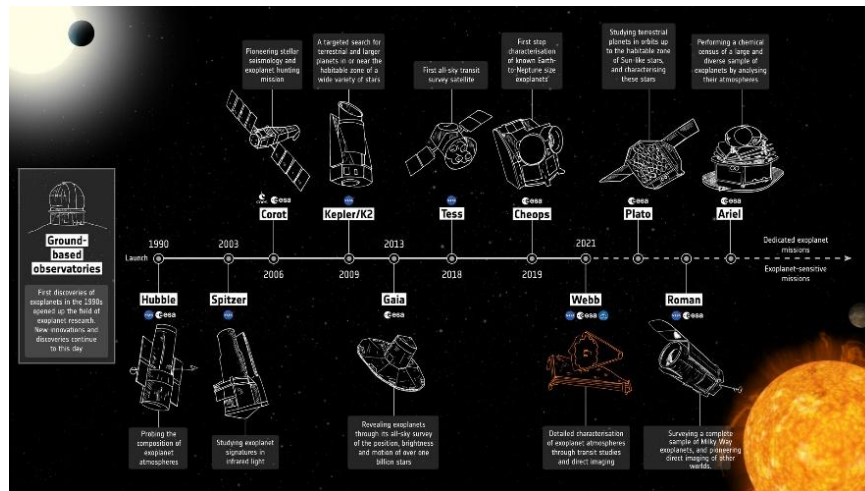


Figure 1.1. The evolution of the exoplanet discovery process, which started with ground-based observations in the 1990s, with the contribution of 11 different space telescopes (Source: ESA, 11.08.2022).

In the 20th century, the discovery of an exoplanet orbiting a star outside the Solar System was made for the first time about 35 years ago by Aleksander Wolszczan and Dale Frail in 1992 using the pulsar timing method (Estrada, 2024; Timmermans, 2024; Wolszczan & Frail, 1992). When this discovery was made, planets c and d of the system PSR 1257+12 (later renamed PSR B1257+12) were orbiting the pulsar (neutron star). This system was located 1,957 light years from Earth. Two years later, in 1994, the system's third planet, PSR 1257+12 b, was discovered.

Even though the first discovery was made after Antiquity, scientists were cautious to confirm the discovery and its continuity. This was soon followed three years later by a second discovery made in 1995 with the 51 Pegasi system (Estrada, 2024; Timmermans, 2024). The discovery was made by astronomers Michel Mayor and Didier Queloz (Mayor & Queloz, 1995). This system was located about 50 light-years from our Earth (51 Pegasi b, 2025) and orbits a main-sequence star (hydrogen fusion) that burns hydrogen into helium, just like our Sun. In other words, the first exoplanet orbiting a Sun-like star was discovered. This system contained only one planet, 51 Pegasi b. Moreover, this discovery, which had a significant impact at the time, led Michel Mayor and Didier Queloz to receive the Nobel Prize in Physics in 2019 (Timmermans, 2024). Thus, based on the radial

velocity technique, one of the most commonly used methods in exoplanet discoveries today, the first example of the exoplanet class was found.

Radial velocity (5 Ways to Find a Planet, 2025; Radial Velocity, 2025) is a method discovered by Doppler in 1842 that detects planets orbiting a star by measuring Doppler shifts in the star's spectrum. After the discovery of these two exoplanets, thousands more exoplanets were discovered. Today, thanks to the Transiting Exoplanet Survey Satellite (TESS) and James Webb Space Telescope (JWST) missions, the number of exoplanets discovered is still increasing (James Webb Space Telescope, 2025; Kepler/K2, TESS Space Telescopes, 2025).

1.3 Exoplanets and Modern Detection Techniques

Since the above-mentioned times, more than 5800 exoplanets have been discovered and confirmed¹. As shown in Figure 1.2, in the early years of discovery, radial velocity (green) was the dominant method, while in later years the transit (purple) method overtook radial velocity measurements. Both are still among the most widely used methods today. Other less commonly used methods are shown in different colors in Figure 1.2.

Radial velocity and transit methods are indirect methods that complement each other. In the radial velocity method, a planet orbiting its star causes a shift in the star due to the effect of gravity. This shift is known as the Doppler (The Doppler Effect, 2025) shift and, as presented in Figure 1.4, the color shifts experienced by a system with a known orbit as it moves away from and closer to its star are examined. The redshift (as the planet moves away from the observer) and the blueshift (as the planet moves closer to the observer) were shown in the panels. By observing these shifts, information about the existence of the planet, its mass, and orbit is determined.

¹ Data from NASA Exoplanet Archive, <https://exoplanetarchive.ipac.caltech.edu>, accessed on March 6, 2025

This method is more suitable for detecting large-mass planets due to effects such as stellar noise and instrument stability (Timmermans, 2024). In the top panel of Figure 1.3, since the radial velocity method is more consistent in estimating mass measurements, the graph is plotted as mass (in units of Jupiter mass) versus orbital period. In addition, since the planets discovered by this method are usually mass-estimated, they are shown in green squares on the graph.

In the transit method, an eclipse is observed. The decrease in light at the time of this eclipse is shown in Figure 1.5. When a planet passes in front of its star (transit) while orbiting, decreases in brightness are observed in the light of the star. The upper panels of the figure show the orbital motion of the planet, and the brightness change before the eclipse, while the lower panels show the decrease in brightness in the light curve during the transit and the increase again afterwards. Since this method is based on the proportionality between the planet's surface area and that of the star (Timmermans, 2024), the decrease in light allows for an easy determination of the planet's radius.

In addition, as seen in the bottom panel of Figure 1.3, since the transit method can obtain more probable results in the detection of planets with small radius (in the unit of Earth radius), the purple circles in the graph are given with the orbital period versus the radius because if the transit occurs at regular intervals, the orbital information of the planet can also be obtained. The transit method can easily find even small-mass planets. Therefore, mass and radius—two of the most important parameters in exoplanet detection—can be measured using these two methods, and their ratio allows for the calculation of planetary density.

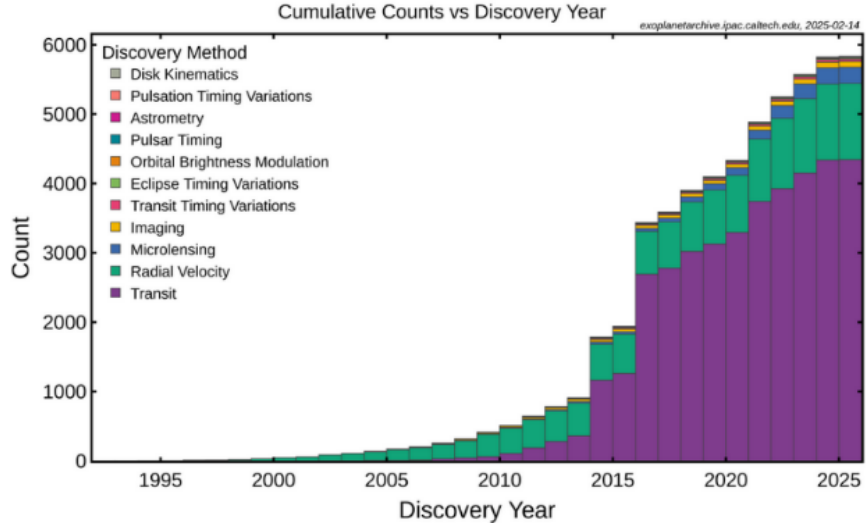


Figure 1.2. Cumulative distribution of exoplanets discovered since 1995, and the discovery methods used (Exoplanet Plots, 2025).

As a result, after obtaining the density information, it can be understood whether the planet is rocky (with a solid surface, similar to Earth) or a gas giant (with a thick gas atmosphere, similar to Neptune) by considering its radius. In line with the methods used and the accelerating studies, scientists' efforts to understand the universe have led them to work in a more categorical manner.

There are different radius assumptions used to classify a planet in current scientific studies (Borucki et al., 2011; Lopez & Fortney, 2013). As one of these assumptions, the right panel of Figure 1.8 shows the distribution between the radius of the planets and their orbital periods (Fulton et al., 2017; Fulton & Petigura, 2018).

The left panel of the same figure shows the average number of planets with orbital periods shorter than 100 days per star and their distribution according to the planetary radius (Fulton et al., 2017). The black histogram represents observational data, and the red curve represents modeling. The light blue and pink regions indicate two different populations in planet formation. The region between these two populations is called the “radius valley” in the literature (Fulton et al., 2017; Owen & Estrada, 2020; Owen & Wu, 2013, 2017). The radius valley is an observed gap in the radius distribution of planets. In the study conducted by Fulton, Petigura and colleagues in 2017 and 2018, $R_p = 1.0 - 1.7R_{\oplus}$ was used for the radius measurements of super-Earth class planets, while $R_p = 1.7 - 4.0R_{\oplus}$ was used for

the radius measurements of mini-Neptune class planets (Fulton et al., 2017; Fulton & Petigura, 2018).

The $\sin i$ scale in the right panel of Figure 1.8 shows the relative formation frequency and radius valley of the planets, while the white circles represent the planets obtained from Kepler data.

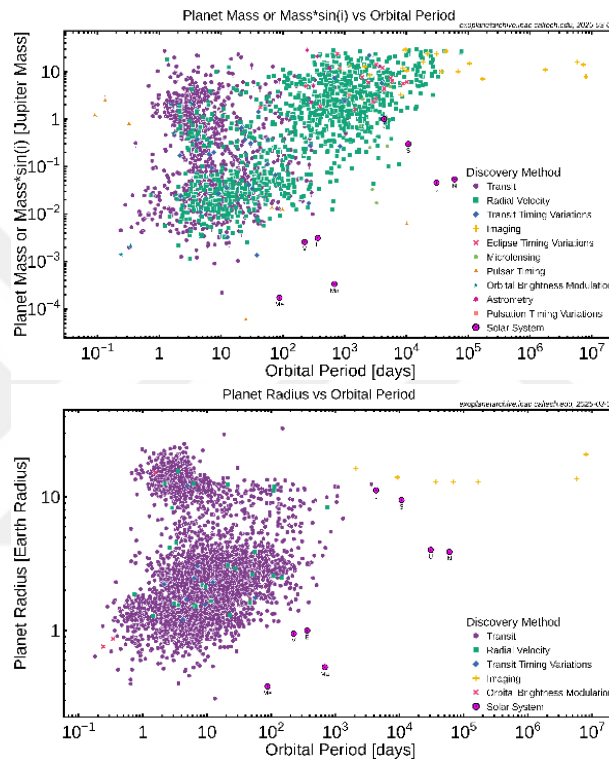


Figure 1.3. Distribution of exoplanets among their masses, radius, and orbital periods (Exoplanet Plots, 2025).

Scientists have begun to group exoplanet discoveries by classifying and categorizing different types of planets, making both research and the understanding of exoplanet types more accessible and straightforward.

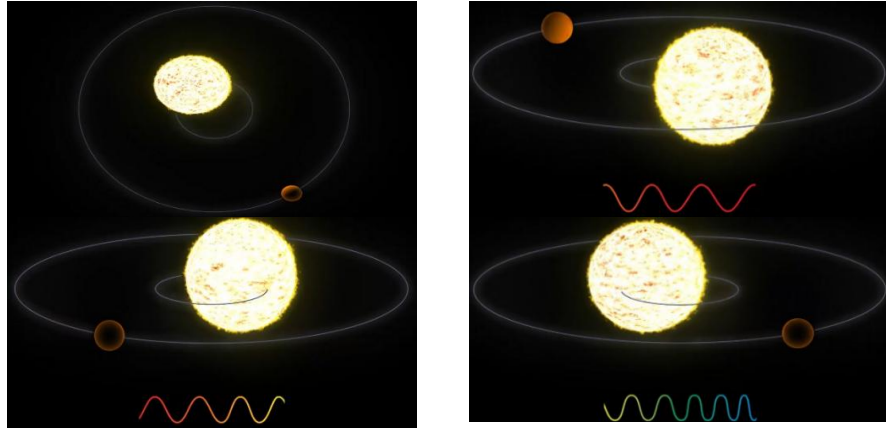


Figure 1.4. The working principle of the radial velocity method, which is one of the exoplanet detection techniques (5 Ways to Find a Planet, 2025; Radial Velocity, 2025).

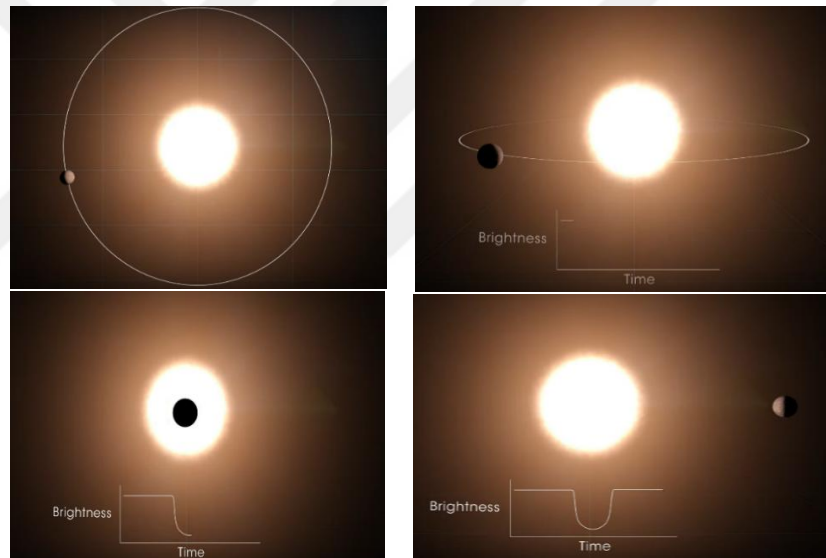


Figure 1.5. The working principle of the transit method, another widely used technique in exoplanet detection (5 Ways to Find a Planet, 2025; Transit Method, 2025).

1.3.1 Types of Exoplanets

Exoplanets are studied by determining their fundamental properties—such as mass, radius, and density—through various detection methods. While the relationship between mass and radius offers insights into their internal structures, dynamic features like orbital periods also play a key role in understanding the evolution of planetary systems. At this stage, four distinct

types of exoplanets, classified by scientists according to their characteristics, can be mentioned (What Is an Exoplanet?, 2025):

- **Neptune-like (mini-Neptunes):** These planets resemble Uranus and Neptune in our Solar System with atmospheres composed primarily of hydrogen and helium. However, they are smaller than Neptune but larger than Earth. Although mini-Neptunes are not present in our system, they share similar characteristics with Neptune-like planets.
- **super-Earths:** Typically, terrestrial or rocky in composition, these planets are more massive than Earth but lighter than Neptune. Some possess atmospheres, while others may be atmosphere-free.
- **Gas Giants:** This class includes exoplanets—especially Hot Jupiters—that orbit very close to their host stars and are exposed to intense stellar radiation. They are usually the size of Saturn or Jupiter, or even larger.
- **Terrestrial Planets:** These are Earth-sized or smaller, mostly composed of rock and metal. Some may have oceans, atmospheres, or other factors necessary for life.

In this context, to understand the sizes of especially super-Earth and mini-Neptune class planets, when Figure 1.6 is looked at from left to right, Earth, GJ 1214 b (super-Earth), Neptune, and GJ 436 b (mini-Neptune) planets are shown. Also, in Figure 1.7, the host star of the TOI-700 system is given as a yellow circle, the super-Earth planet is given as pink, and the mini-Neptune planets are given as brown. The halos around the planets represent the maximum possible radius for super and mini planets. Neptune, shown in blue, and Earth, shown in green on the far right, show how it would look if it were assumed that the TOI-700 system orbited it. All parameters of the system are real parameters taken from the NASA Exoplanet Archive (NEA) database, but to be able to enlarge with scaling, the radius of the star has been enlarged by 5 times, the radius of the planets has been enlarged by 50 times, and the semi-major axes of the planets have been enlarged by 200 times. Detailed information about this system is given under the heading “Results”.

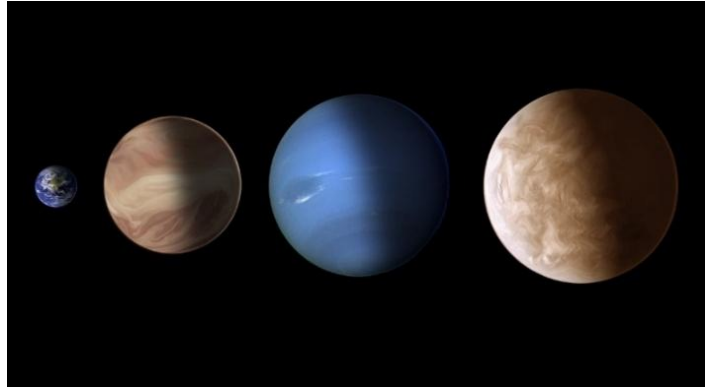


Figure 1.6. Comparison of Neptune in our Solar System and Earth with a super-Earth and a mini-Neptune (Source: NASA, 12/31/2013).

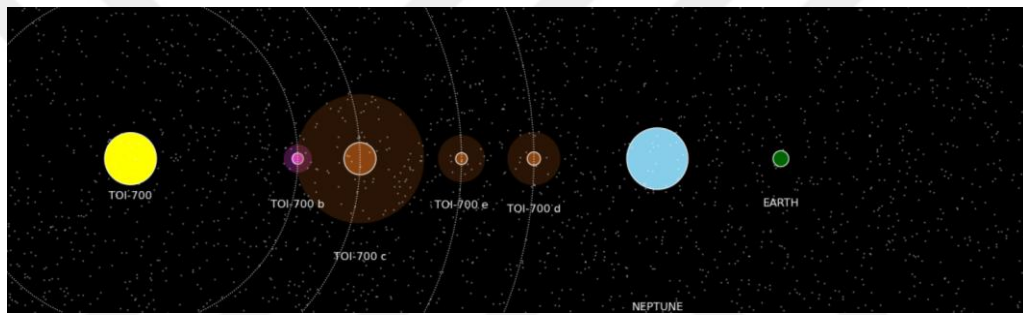


Figure 1.7. An image of super-Earths and mini-Neptunes in the TOI-700 system is simulated for this study.

After scientists were able to classify exoplanets as described above, they focused on the atmospheres of exoplanets, one of the most important factors for life, to find an answer to the question of "Are we alone?" that humanity has been asking since the formation of the Universe by producing more specific questions.

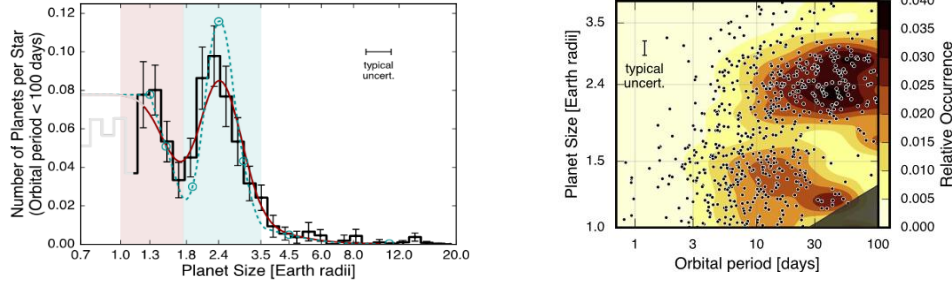


Figure 1.8. Relationship between the radius distribution and orbital periods of exoplanets (Fulton et al., 2017; Fulton & Petigura, 2018).

1.4 Atmospheres of Exoplanets

Although extensive information has been obtained about the parameters of exoplanets through these studies that have continued to the present day, what is still known about the chemical composition and atmospheric characterization of these planets is still limited. Understanding the atmospheres not only provides information about the evolutionary process and formation of a planet but also provides important information about the habitability and biodiversity of the planet, as it is one of the elements of life.

After the first exoplanet discoveries were made and important star and planetary parameters were reached by various methods, scientific studies carried out by classifying these exoplanets advanced, and studies were expanded to reach the demographic features of these grouped systems. Thus, as shown in Figure 1.1, the astrophysics community went through two major turning points. The first of these occurred in the early 1990s with the launch of the Hubble Space Telescope, Kepler Space Telescope/K2, and Spitzer Space Telescope, and the second with the launch of the James Webb and TESS Space Telescopes in the early 2010s.

Thanks to these telescopes, three main methods that astrophysicists currently use to study the atmospheres of exoplanets emerged. These are: transmission spectra, emission spectra, and phase curves, but transmission and emission spectra are suitable for planets detected by the transit method, not for exoplanets detected by radial velocity (Timmermans, 2024; Zhang, 2022). Because these methods work by observing the atmosphere of a planet as it

passes in front of its star, which means that the gases in the planet's atmosphere can absorb the light from the star (transmission) or the light emitted from the planet's atmosphere (emission) can only be observed when the planet is in transit.

1.4.1 Transmission Spectroscopy

Transmission spectroscopy is directly related to the transit method because when a planet transits (shown in the blue box in the left panel of Figure 1.11), some of the light from its star passes through the planet's atmosphere, and molecules in the atmosphere absorb certain wavelengths. However, since planets are very small compared to their stars, it is extremely difficult to detect these light variations. Therefore, large and sensitive telescopes are required to capture these fine details.

Since each element has its own unique spectral fingerprint, these lines can be used to determine the chemical composition of planetary atmospheres with these telescopes. Stars also emit light over a wide range of wavelengths, and this spectrum is shown in Figure 1.10. The left panel of Figure 1.9 shows how two planets with wide (top) and narrow (bottom) atmospheres filter the starlight during a transit. It is seen that the planet with a wide atmosphere contains hydrogen, while the planet with a narrow atmosphere does not contain hydrogen (Timmermans, 2024). If a planet's atmosphere absorbs certain wavelengths, the absence of these wavelengths provides information about which molecules are present in the atmosphere. As a result, when a planet transits, it is possible to determine its atmosphere and composition by examining the missing wavelengths in the starlight. This method is called transmission spectroscopy (National Academies of Sciences Engineering and Medicine, 2018; Perryman, 2018; Timmermans, 2024). The right panel of the same figure shows which elements and compounds dominate the atmospheres

of the discovered exoplanets, depending on their mass and radius (National Academies of Sciences Engineering and Medicine, 2018).

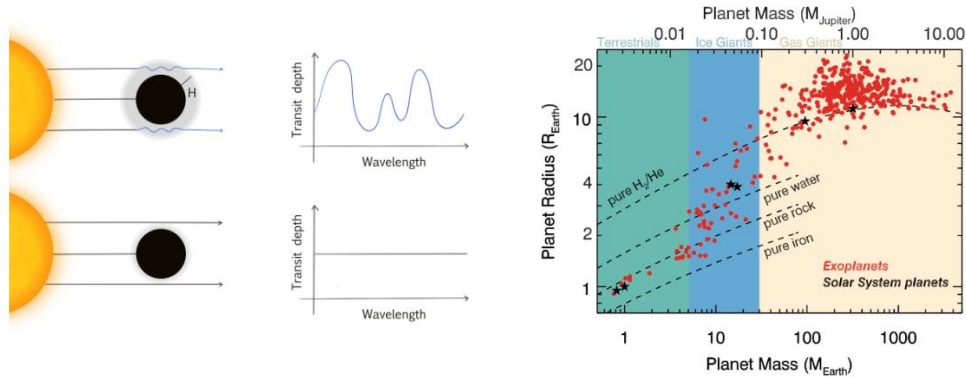


Figure 1.9. Composition and light-absorbing properties of exoplanet atmospheres (National Academies of Sciences Engineering and Medicine, 2018; Timmermans, 2024).

1.4.2 Emission Spectroscopy

The method of analyzing starlight when planets pass in front of a star is called emission spectroscopy (Zhang, 2022). In this case, the secondary eclipse of starlight is shown in the red box in the left panel of Figure 1.11. The differences in the spectrum it examined during and after this eclipse. The atmosphere of the planet absorbs and scatters the starlight, creating characteristic emission lines at certain wavelengths, which are visualized in the right panel of the same figure by shifts in the spectral lines due to the orbital motion of the planet (National Academies of Sciences Engineering and Medicine, 2018). By examining these lines, the elements and compounds present in the atmosphere of the planet are revealed, and thus information about the structure of the atmosphere is obtained (Perryman, 2018; Zhang, 2022).



Figure 1.10. Transmission and emission signatures of elements detected in exoplanet atmospheres (Source: Webb Telescope, 07.07.2022).

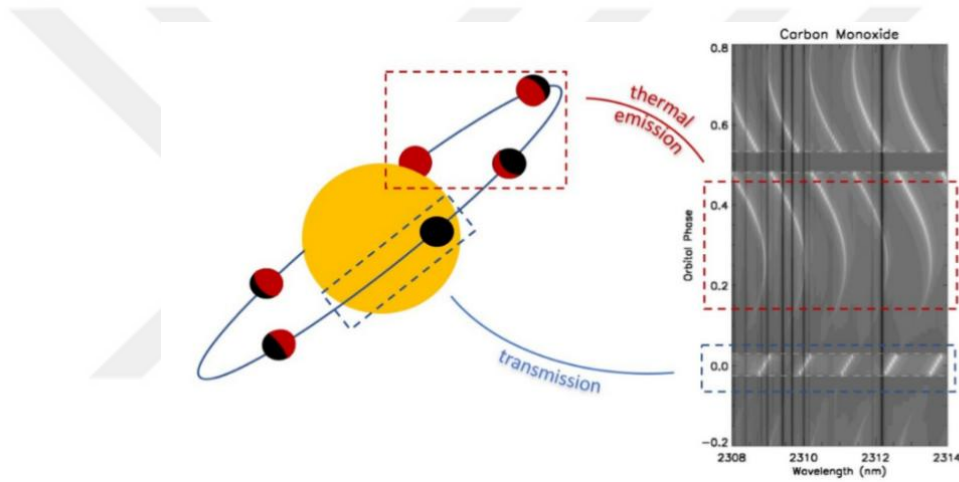


Figure 1.11. Investigation of exoplanet atmospheres through high-resolution spectroscopy (National Academies of Sciences Engineering and Medicine, 2018).

1.4.3 Phase Curves

The flux change between transit and eclipse corresponds to the phase curve. The reason for the flux change is that the planet shows different states along its orbit (Zhang, 2022). When revealing the atmospheric structure thanks to phase curves, the results of transmission and emission spectra are used. This situation is visualized in Figure 1.12 as transit and secondary eclipse spectroscopy. The left side of the figure shows the transmission spectrum obtained by analyzing the light filtered from the atmosphere of the planet as it passes in front of the star.

The right side shows the emission spectrum measured when the planet passes behind the star. The effect of these two methods on the phase curve is shown in the lower part (National Academies of Sciences Engineering and Medicine, 2018). Therefore, it is understood from the phase curve results that transmission spectroscopy is used during transit and determines the chemical composition of the atmosphere; emission spectroscopy is used during secondary eclipse, and the temperature and chemical composition of the dayside of the planet can be analyzed. In addition, phase curve observations can provide more information about heat transport in the atmosphere, cloud formation, and wind patterns (Timmermans, 2024; Winn, 2010; Zhang, 2022).

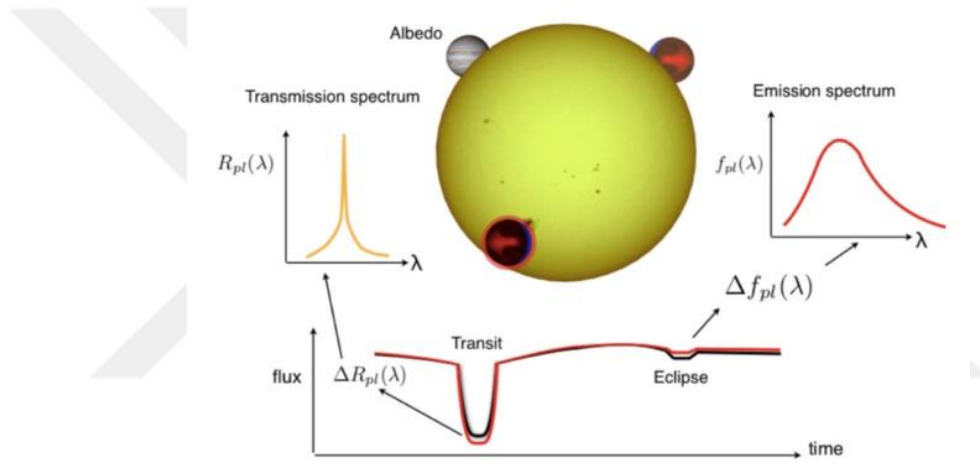


Figure 1.12. Representation of emission and transit spectra with phase curves (National Academies of Sciences Engineering and Medicine, 2018).

1.5 Characterization of Confirmed Exoplanet Atmospheres

Phase curves, along with transmission and emission spectroscopy, provide essential tools for understanding exoplanetary atmospheres. As previously mentioned, these observations are now supported by advanced space telescopes. The telescopes indicated in Figure 1.1 have detected numerous exoplanets using various discovery techniques and have examined their atmospheres in detail. Thanks to these ongoing studies and upcoming missions, scientists' efforts to understand exoplanets and their atmospheres are accelerating.

Table 1.1. Major space telescopes, some exoplanets it has discovered, and the discovery methods.

Telescope	Agency	Exoplanets	Detection Methods	Reference
Hubble (1990)	NASA/ESA	HD 209458 b, WASP-121 b	Transit Photometry Spectroscopy	(Hubble Space Telescope, 2025)
Spitzer (2003)	NASA	55 Cancri e, TRAPPIST-1	Infrared Spectroscopy Transit Method	(Spitzer Space Telescope, 2025)
CoRoT (2006)	CNES/ESA	CoRoT-7 b, CoRoT-2 b	Transit Photometry	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)
Kepler/K2 (2009)	NASA	Kepler-22 b, Kepler-452 b	Transit Photometry	(Kepler/K2, TESS Space Telescopes, 2025)
Gaia (2013)	ESA	Gaia-1 b, Gaia-2 b	Astrometry	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)
TESS (2018)	NASA	TOI-700 d, LHS 3844 b	Transit Photometry	(Kepler/K2, TESS Space Telescopes, 2025)
CHEOPS (2019)	ESA	WASP-189 b	Transit Photometry Light Curve Analysis	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)

Table 1. 1. (continue). Major space telescopes, some exoplanets it has discovered, and the discovery methods.

Telescope	Agency	Exoplanets	Detection Methods	Reference
James Webb (2021)	NASA/ESA/ESA	WASP-39 b, TRAPPIST-1 b	Infrared Spectroscopy Transit Spectroscopy	(James Webb Space Telescope, 2025)
Roman (Future)	NASA/ESA	-	Microlensing Direct Imaging	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)
PLATO (Future)	ESA	-	Transit Photometry	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)
Ariel (Future)	ESA	-	Spectroscopy	(CoRoT, Gaia, CHEOPS, Roman, PLATO, Ariel Space Telescopes, 2025)

As shown in Table 1.1, studies on exoplanet atmospheres have become more detailed since 1990 through the use of various observational techniques and analytical methods, as illustrated by the telescope missions discussed in Figure 1.1 and the methods presented in Figure 1.2. As atmospheric components have been identified through these methods, scientists have developed various approaches and hypotheses to better understand the evolution of these atmospheres over time. One of the most widely accepted approaches to atmospheric escape in the literature is the “photoevaporation” hypothesis (Murray-Clay et al., 2009). According to this hypothesis, if the difference between the measured mass and the calculated minimum mass is consistent, especially low-mass exoplanets may gradually lose their atmospheres due to high-energy radiation (XUV) received from their host stars. This process is explained by the photoevaporation mechanism, in which X-

rays and ultraviolet (UV) radiation emitted by young and active stars heat the upper layers of a planet's atmosphere, causing gases to reach escape velocity and disperse into space (Owen & Estrada, 2020; Wise, 2019).

There are also studies examining this hypothesis in three different categories. One of these is the studies conducted under the effect of extreme ultraviolet (EUV) rays on atmospheric loss (Font et al., 2004; Wise, 2019), while the second is the studies conducted under the effect of far ultraviolet (FUV) rays on atmospheric loss (Gorti & Hollenbach, 2009; Wise, 2019). The third and last category is the effect of XUV rays on atmospheric loss (Owen et al., 2010; Wise, 2019).

The mechanisms proposed to explain the atmospheric loss process in exoplanets are not limited to photoevaporation. If a discrepancy is found between the mass differences mentioned above, then other mechanisms such as Roche Lobe overflow, the effect of stellar winds, magnetic field effects (Vissapragada, 2022), tidal interactions, disk-driven migration, planetary collisions (Murray-Clay et al., 2009), core-powered and contraction (Transit Method, 2025) may also contribute to the atmospheric loss.

The main purpose of this thesis is to evaluate the atmospheric loss processes of exoplanets within the framework of the photoevaporation hypothesis with mass, radius, and density parameters, and to analyze the effects of this mechanism on the physical parameters of the planets. Using data from the NASA Exoplanet Archive, it was investigated how the atmospheric loss of exoplanets transitioning between different planet classes in multiplanetary systems changes, and which factors affect it.

In this context, the role of photoevaporation in planet groups classified according to different radius and density criteria was analyzed, and calculations of atmospheric escape processes were performed. The findings provide important implications for understanding the atmospheric evolution of planets in the mini-Neptune and super-Earth classes. In addition, this study provides important contributions to literature by showing that photoevaporation is consistent for many confirmed planets and provides new frameworks for future observational studies.

2. MATERIALS AND METHOD

In this section, details about the datasets, analysis methods, calculations, and statistical evaluation processes used to evaluate the atmospheric loss processes of exoplanets are presented.

2.1 Datasets Used in the Analysis

The NASA Exoplanet Archive (NEA) database is a dynamic database that is updated regularly, adding parameters for each confirmed exoplanet and updating old data; currently, the current exoplanet count as of March 25, 2025, is 5,862 as shown in Photo 2.1.

There are many different datasets in this database, but two main sets of large-scale data stand out: Planetary Systems (PS) and Planetary Systems Composite Data (PSCD). The Planetary Systems dataset contains measurements from multiple different sources for the same planet, while the Planetary Systems Composite Data dataset provides a single, combined record of the most reliable or up-to-date measurements for each exoplanet.

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Planetary Systems Composite Data

Planet Name

Host Name

Number of Stars

Number of Planets

Discovery Reference

Orbital Period [days]

Orbit Semi-Major Axis [au]

Planet Radius (Earth Radius)

Planet Mass or Mass*sin(i) (Earth Mass)

Planet Density (g/cm³)

Irradiation Flux (Earth Flux)

Stellar Effective Temperature (K)

Stellar Radius (Solar Radius)

Stellar Mass (Solar Mass)

11 Com b

11 Com

2

1

Liu et al. 2008

323.21^{+0.08}_{-0.05}

1.178±0.000

12.2

4914.0^{+13.1}_{-38.7}

14.9

4874

13.76^{+2.03}_{-2.05}

2.09^{+0.44}_{-0.63}

11 UMi b

11 UMi

1

1

Dollinger et al. 20

516.21997±3.20000

1.53±0.07

12.3

4685±795

13.8

4213±46

29.75±2.84

2.78±0.09

14 And b

14 And

1

1

Sato et al. 2008

186.76^{+0.11}_{-0.12}

0.77±0.000

13.1

1131⁺³⁸₋₃₉

2.76

4888

11.55^{+1.12}_{-0.93}

1.78^{+0.43}_{-0.29}

14 Her b

14 Her

1

2

Bulter et al. 2003

1765.03860^{+1.8709}_{-1.0706}

2.774^{+0.009}_{-0.009}

12.6

2569⁺⁵¹⁹₋₃₈₁

7.03

5336±25

0.93±0.01

0.910±0.1130

16 Cyg R b

16 Cyg R

3

1

Cochran et al. 199

786.50000±1.00000

1.66±0.03

13.5

596±25

1.26

5750±8

1.13±0.01

1.08±0.04

17 Sco b

17 Sco

1

1

Tata Pinto et al. 21

578.38^{+2.01}_{-2.00}

1.45±0.02

12.9

1373⁺⁴⁸₋₃₅

3.51

4157⁺¹¹₋₁₈

25.92^{+3.74}_{-3.74}

1.22^{+0.14}_{-0.13}

18 Del b

18 Del

2

1

Sato et al. 2008

982.85^{+1.08}_{-0.97}

2.476±0.002

12.5

2596⁺³¹₋₂₄

8.23

4980

8.80^{+1.81}_{-0.46}

2.16^{+0.39}_{-0.20}

1RXS J160929.1-210524 b

1RXS J160929.1

1

1

Lafrancière et al. 21

330

18.947

3000±300

2.54

4080⁺³⁹⁸₋₃₉₈

1.313180^{+0.11593}_{-0.11607}

0.735^{+0.28}_{-0.30}

24 Boo b

24 Boo

1

1

Takanashi et al. 20

30.33^{+0.09}_{-0.11}

0.194±0.000

13.9

201⁺¹¹₋₁₄

0.574

4816

12.19^{+1.45}_{-1.26}

1.05^{+0.27}_{-0.15}

24 Sex b

24 Sex

1

2

Johnson et al. 20

452.6^{+0.1}_{-0.1}

1.333^{+0.004}_{-0.009}

13.4

832.48^{+62.83}_{-125.71}

1.44

5086±44

4.9±0.08

1.54±0.08

24 Sex c

24 Sex

1

2

Johnson et al. 20

683.0^{+10.4}_{-10.4}

2.08^{+0.05}_{-0.02}

13.9

273.32^{+111.24}_{-40.32}

0.559

5086±44

4.9±0.08

1.54±0.08

2MO437 b

2MASS J0437217.1

1

1

Gaidos et al. 2021

118.0±1.3

13

1271±110

3.18

3100±100

0.84±0.11

0.17^{+0.01}_{-0.02}

2MASS J01033863-5515561 AB b

2MASS J0103386.2

1

1

Delorme et al. 20

81

12.3

4132±110

12.2

0.19±0.02

2MASS J01225093-2439505 b

2MASS J0122505.1

1

1

Dowler et al. 2013

52±8

11

7708.5±794.5

30.4

3530±50

0.3664500±0.0

0.40±0.05

2MASS J02182210-3925225 b

2MASS J0218221.1

1

1

Arigau et al. 2015

156±10

18.1±0.3

4418±350

5.77

3084±78

0.281±0.013

0.10±0.011

2MASS J0249-0557 c

2MASS J0249-05.2

1

1

Dupuy et al. 2018

190±200

12.4

3657⁺¹¹³₋₁₁₈

10.9

2859.0±157.0

0.3159599±0.0

0.046^{+0.017}_{-0.011}

2MASS J03590989+2009391 b

2MASS J0359098.1

1

1

Michel & Mugraue

57±27

12.2

5721±110

17.3

2943.0±157.0

0.2897780±0.0

0.2849990±0.0

2MASS J04114489+2301513 b

2MASS J0411448.1

1

1

Todorov et al. 201

15.0

12.9

2363.6±794.5

6.55

2936.0±192.0

0.2319180±0.0

0.019

2MASS J11011826-7732383 b

2MASS J1101182.1

1

1

Michel & Mugraue

296±0

11.9

8099⁺⁹¹⁷⁹₋₂₂₂₅

29

Showing records 1 to 19 of 5862 (5862 total)

DOI: 10.26133/NEA13

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Photo 2.1. Screenshot of the dataset taken from NASA Exoplanet Archive (Source:¹, 24.03.2025).

The NASA Exoplanet Archive database includes measurements made by all telescopes listed in Figure 1.1 except Gaia, CHEOPS, and telescopes that have not yet been launched. In Photo 2.1, the parameters used in this study in the NASA

Exoplanet Archive PSCD dataset are shown in red boxes. In addition, under the “Select Column” heading, parameters for many more planets, stars, systems, and discovery methods can be accessed in addition to the selected parameters.

2.2 Assumptions and Selection Criteria for the Examined Exoplanets

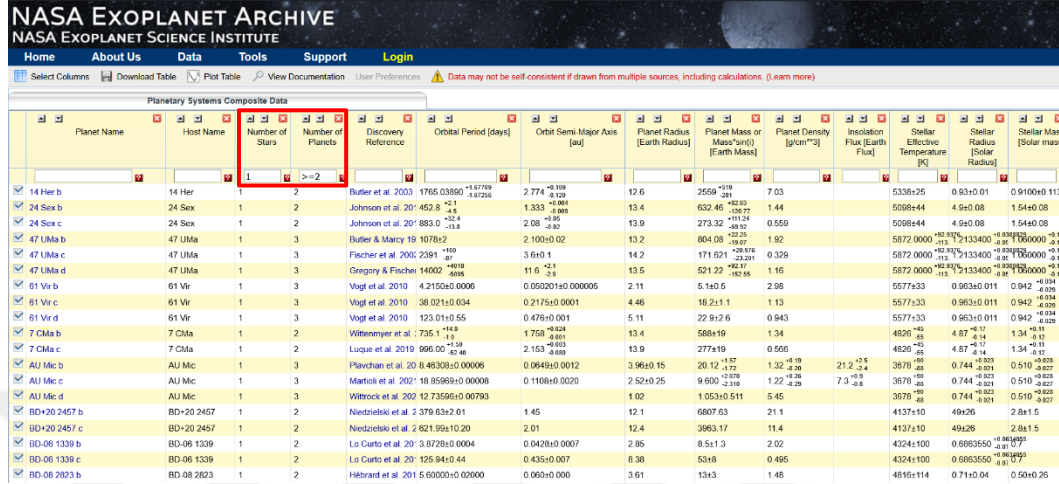
The dataset used in this study was generated from the parameters in the NASA Exoplanet Archive release dated December 25, 2024. This release contains data for a total of 5,832 confirmed exoplanets, and among these, systems with only **one star** and systems with at **least two planets** were selected. This selection is because multiple exoplanet systems provide a suitable environment for testing the photoevaporation model, since the effect of the uncertain XUV history of the host star can be eliminated by scaling one planet to another (Owen & Estrada, 2020). In addition, examining planets crossing the “radius valley” is an important factor in the selection of these systems (Fulton et al., 2017; Owen & Estrada, 2020; Owen & Wu, 2013, 2017).

On one side of the radius valley lie gaseous planets, while on the other side are rocky planets. In systems containing at least two planets, it is required that neither planet is of the same type—i.e., both cannot be super-Earths or mini-Neptunes. The discovery of planets that retain a hydrogen/helium atmosphere (mini-Neptunes) via the transit method allows for the precise determination of their radius. Consequently, the estimations of minimum core mass can be made more accurately for planets in this class using the equation provided below (Owen & Estrada, 2020):

$$M_g \geq 5.1M_{\oplus} \left(\frac{R_R}{1.5R_{\oplus}} \right)^4 \left(\frac{a_R}{a_g} \right)^{\frac{8}{5}} \left(\frac{\eta_g}{\eta_R} \right)^{\frac{4}{5}} \quad (2.1)$$

where M_g is the minimum core mass of the gaseous planet (mini-Neptune); R_R is the radius of the rocky planet (super-Earth); a_R is the semi-major axis of the rocky planet; a_g is the semi-major axis of the gaseous planet, and η_g , η_R are the mass loss efficiencies of the atmospheres of the gaseous and rocky planets, respectively.

As a result of the selection made according to these determined criteria, multiplanetary systems were determined, and the number of target planets was reduced from 5,832 to 2,221 (Photo 2.2).



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Planetary Systems Composite Data

Planet Name	Host Name	Number of Stars	Number of Planets	Discovery Reference	Orbital Period (days)	Orbit Semi-Major Axis [au]	Planet Radius [Earth Radius]	Planet Mass or Mass (Jup)	Planet Density [g/cm ³]	Insolation Flux [Earth Flux]	Stellar Effective Temperature [K]	Stellar Radius [Solar Radius]	Stellar Mass [Solar Mass]
14 Her b	14 Her	1	2	Butler et al. 2003	1765.03890	1.0719	2.774	8.109	12.6	2569	519	0.93±0.01	0.9100±0.1130
24 Sex b	24 Sex	1	2	Johnson et al. 201	452.8	2.1	1.333	8.109	13.4	632.46	1.44	5.08±0.44	4.9±0.08
24 Sex c	24 Sex	1	2	Johnson et al. 201	883.0	3.4	2.08	8.109	13.9	273.32	0.559	5.08±0.44	4.9±0.08
47 UMa b	47 UMa	1	3	Butler & Marcy 19	1078±2	2.100±0.02	13.2	804.08	13.2	604.08	1.92	5.872±0.000	5.872±0.000
47 UMa c	47 UMa	1	3	Fischer et al. 2005	2391	1.19	3.6±0.1	14.2	171.624	19.07	0.329	5.872±0.000	5.872±0.000
47 UMa d	47 UMa	1	3	Gregory & Fischer 14002	4008	11.6	11.6	13.5	521.22	162.58	1.16	5.872±0.000	5.872±0.000
61 Vir b	61 Vir	1	3	Vogt et al. 2010	4.2150±0.0006	0.05020±0.000005	2.11	5.1±0.5	2.11	5.1±0.5	2.98	5.577±0.33	0.963±0.011
61 Vir c	61 Vir	1	3	Vogt et al. 2010	38.02±0.034	0.217±0.0001	4.46	16.2±1.1	4.46	16.2±1.1	1.13	5.577±0.33	0.963±0.011
61 Vir d	61 Vir	1	3	Vogt et al. 2010	123.01±0.55	0.476±0.001	5.11	22.9±2.6	5.11	22.9±2.6	0.943	5.577±0.33	0.963±0.011
7 Cma b	7 Cma	1	2	Wittenmyer et al. 2005	735.1	1.19	1.759	8.109	13.4	568±19	1.34	4.82±0.45	4.87±0.14
7 Cma c	7 Cma	1	2	Lucas et al. 2019	966.00	2.46	2.163	8.109	13.9	277±19	0.566	4.82±0.45	4.87±0.14
AU Mic b	AU Mic	1	3	Pfandrich et al. 20	8.46308±0.00006	0.0649±0.0012	3.96±0.15	20.12	1.57	1.32	21.2	3678	0.744
AU Mic c	AU Mic	1	3	Martoli et al. 2002	18.8596±0.00008	0.1108±0.0020	2.52±0.25	9.600	2.10	1.22	7.3	3678	0.744
AU Mic d	AU Mic	1	3	Wittebeck et al. 2002	12.7359±0.00793	1.02	1.053±0.511	5.45	1.02	1.053±0.511	5.45	3678	0.744
BD+20 2457 b	BD+20 2457	1	2	Niedzielski et al. 2	379.63±0.01	1.45	12.1	6807.63	12.1	6807.63	21.1	4137±10	49±26
BD+20 2457 c	BD+20 2457	1	2	Niedzielski et al. 2	621.99±0.20	2.01	12.4	3963.17	12.4	3963.17	11.4	4137±10	49±26
BD-06 1339 b	BD-06 1339	1	2	Lo Curto et al. 20	3.6728±0.0004	0.0429±0.0007	2.85	8.51±1.3	2.85	8.51±1.3	2.02	4324±100	0.6935±0.0099
BD-06 1339 c	BD-06 1339	1	2	Lo Curto et al. 20	125.94±0.44	0.435±0.007	8.38	53±8	8.38	53±8	0.495	4324±100	0.6935±0.0099
BD-06 2823 b	BD-06 2823	1	2	Hébrard et al. 201	5.6000±0.02000	0.060±0.000	3.61	13±3	3.61	13±3	1.48	4816±114	0.71±0.04

Photo 2.2. Determining the number of stars and planets in the NASA Exoplanet Archive to create the dataset. (Source:¹, 25.03.2025).

Finally, the final dataset was constructed by including all parameters marked with a red box in Photo 2.1: planet name, hostname, number of stars, number of planets, discovery reference, orbital period [P, unit: days], semi-major axis [a, unit: au], planet radius [R_p , unit: $R_\oplus$], planet mass [M_p , unit: $M_\oplus$], planet density [ρ_p , unit: g/cm³], insolation flux [F, unit: W/m²], stellar effective temperature [T_s , unit: K], stellar radius [R_s , unit: R_*], and stellar mass [M_s , unit: M_*].

2.2.1 Radius and Density

After determining the number of target lists and the final dataset as described above, the columns in the downloaded dataset were renamed and prepared for analysis using Python code. For three different scenarios, datasets of exoplanets with specific ranges of radius (R_p) and density (ρ_p) were processed and selected. Although Photo 2.3 illustrates how this selection was made only for scenario 1, the same procedure was applied to the other two scenarios as well.

The threshold values determined for the radius allow the planets to be classified as mini-Neptunes or super-Earths. In the first scenario, this threshold value is $2 R_{\oplus}$, with mini-Neptunes having values greater than $2 R_{\oplus}$ and super-Earths having values less than $2 R_{\oplus}$. In the second scenario, the threshold value is $1.8 R_{\oplus}$, and in the third scenario, it is $1.5 R_{\oplus}$. In each scenario, planets above the threshold value are defined as mini-Neptunes, and planets below the threshold value are defined as super-Earths. This classification is made following the radius valley literature, as explained in detail in Sections 1.3 and 2.2 (Borucki et al., 2011; Fulton et al., 2017; Lopez & Fortney, 2013; Owen & Estrada, 2020; Owen & Wu, 2013, 2017).

In addition to the radius criterion, the density ranges were selected to correspond to those reported in the literature for super-Earths and mini-Neptunes, as illustrated in Photo 2.3 (Brinkman et al., 2023). For scenario 1, planets with a density less than 2 g/cm^3 were considered mini-Neptunes, while those with a density greater than 3 g/cm^3 were classified as super-Earths. Similarly, in scenario 2, mini-Neptunes were defined as planets with a density less than 3 g/cm^3 , and super-Earths as those with a density greater than 4 g/cm^3 . In the final scenario, the density threshold was set to less than 4 g/cm^3 for mini-Neptunes and greater than 5 g/cm^3 for super-Earths.

These radius selections are an important physical feature because they are one of the effective parameters in the expression used to determine the minimum core mass of exoplanet systems, given in Equation (2.1). However, classifying only by radius may not always be sufficient; therefore, density criteria were also added to the analysis. Thus, the planets determined according to the radius range were correctly classified in the category they should belong to by taking their densities into account. Therefore, the radius and density criteria used in determining the exoplanets in the dataset can be summarized under three different scenario headings as follows:

1. Scenario

mini-Neptune: $R_p > 2R_{\oplus}$ and $\rho < 2 \text{ g/cm}^3$; **super-Earth:** $R_p < 2R_{\oplus}$ and $\rho > 3 \text{ g/cm}^3$

2. Scenario

mini-Neptune: $R_p > 1.8R_{\oplus}$ and $\rho < 3 \text{ g/cm}^3$; **super-Earth:** $R_p < 1.8R_{\oplus}$ and $\rho > 4 \text{ g/cm}^3$

3. Scenario

mini-Neptune: $R_p > 1.5R_{\oplus}$ and $\rho < 4 \text{ g/cm}^3$; **super-Earth:** $R_p < 1.5R_{\oplus}$ and $\rho > 5 \text{ g/cm}^3$

In line with the criteria determined for these three different scenarios mentioned above, the final dataset was subjected to radius and density conditions, and sub-target lists were created. Systems were grouped according to their hostnames and sub-planets classified by name in each system were associated with the hostnames they belong to (for example, while the hostname, which is the name of the system in the dataset, is listed under “Kepler-36”, the planets belonging to the system are indicated with the names “Kepler-36 b” and “Kepler-36 c”). In addition, a new column called “Result” was added according to the planets’ meeting the radius and density conditions in the relevant scenarios, and the planets were labeled as “mini” or “super” (Photo 2.3).

```
result = []
for radius, density in zip(df["radius"], df["density"]):
    if radius > 2 and density < 2:
        result.append("mini")
    elif radius < 0:
        result.append("Invalid")
    elif radius < 2 and density > 3:
        result.append("super")
    else:
        result.append("Other")

df["Result"] = result

grouped_by_h = df.groupby('hostname')
selected_rows = grouped_by_h.filter(lambda x: set(x['Result']) == {'mini', 'super'})
```

Photo 2.3. Code block for processing the radius and density criteria in scenario 1.

After these selections were made, the three different scenario conditions were applied to the existing dataset containing 2,221 exoplanets, and the remaining number of exoplanets for each scenario is presented in Table 2.1.

Table 2.1. The number of exoplanets remaining in the datasets after applying the radius and density selections.

Cuts	Definitions	Number of Exoplanets
Cut-0	Total number of exoplanets without filter	5832
Cut-1	1 star ≥ 2 planets	2221
Cut-2 (a)	mini-Neptune: $R_p > 2R_{\oplus}$ and $\rho < 2 \text{ g/cm}^3$ super-Earth: $R_p < 2R_{\oplus}$ and $\rho > 3 \text{ g/cm}^3$	174
Cut-2 (b)	mini-Neptune: $R_p > 1.8R_{\oplus}$ and $\rho < 3 \text{ g/cm}^3$ super-Earth: $R_p < 1.8R_{\oplus}$ and $\rho > 4 \text{ g/cm}^3$	400
Cut-2 (c)	mini-Neptune: $R_p > 1.5R_{\oplus}$ and $\rho < 4 \text{ g/cm}^3$ super-Earth: $R_p < 1.5R_{\oplus}$ and $\rho > 5 \text{ g/cm}^3$	344

2.2.2 Semi-Major Axis and Insolation Flux Calculations

Even though the semi-major axis and insolation flux parameters shown in Photo 2.1 were added to the dataset, there are some systems in this dataset with missing semi-major axis values. In addition, inconsistencies between the insolation flux values and the literature were detected in some systems. To correct these missing and erroneous data and to eliminate the lack of semi-major axis data in the minimum core mass calculations shown in Equation (2.1) and to avoid errors, semi-major axis and insolation flux calculations were made and added to the dataset. While the semi-major axis calculations, which are one of these two parameters, were made only for systems with this value missing, the insolation flux calculations were made from scratch for all systems. The calculation results of these two parameters were used instead of NEA parameters throughout the study. Since the error propagation will be taken into account in the calculations to be made in the next stages of the analysis, two different error margin percentages of 10% and 20% were considered for all parameters with missing error margin and added to the dataset.

```

index_to_update = df[(df['radius'].notnull() & df['re1'].isnull() & df['re2'].isnull()) |
    (df['mass'].notnull() & df['me1'].isnull() & df['me2'].isnull()) |
    (df['per'].notnull() & df['pere1'].isnull() & df['pere2'].isnull()) |
    (df['smass'].notnull() & df['smasse1'].isnull() & df['smasse2'].isnull()) |
    (df['srad'].notnull() & df['srade1'].isnull() & df['srade2'].isnull()) |
    (df['stemp'].notnull() & df['stempe1'].isnull() & df['stempe2'].isnull())].index

df.loc[index_to_update, "re1"] = df.loc[index_to_update, "radius"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "re2"] = df.loc[index_to_update, "radius"].apply(lambda x: x * -0.10)

df.loc[index_to_update, "me1"] = df.loc[index_to_update, "mass"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "me2"] = df.loc[index_to_update, "mass"].apply(lambda x: x * -0.10)

df.loc[index_to_update, "pere1"] = df.loc[index_to_update, "per"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "pere2"] = df.loc[index_to_update, "per"].apply(lambda x: x * -0.10)

df.loc[index_to_update, "smasse1"] = df.loc[index_to_update, "smass"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "smasse2"] = df.loc[index_to_update, "smass"].apply(lambda x: x * -0.10)

df.loc[index_to_update, "srade1"] = df.loc[index_to_update, "srad"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "srade2"] = df.loc[index_to_update, "srad"].apply(lambda x: x * -0.10)

df.loc[index_to_update, "stempe1"] = df.loc[index_to_update, "stemp"].apply(lambda x: x * 0.10)
df.loc[index_to_update, "stempe2"] = df.loc[index_to_update, "stemp"].apply(lambda x: x * -0.10)

```

Photo 2.4. Code block where a 10% error margin is added for values with missing uncertainties. The ± 1 (positive) and ± 2 (negative) error margins at the end of parameter names are used throughout this section and the entire study.

➤ Semi-Major Axis Calculations

The semi-major axis values of the planets were obtained using Kepler's 3rd law. According to Kepler's third law, there is a certain ratio between the orbital period of a planet and its semi-major axis. The law is expressed observationally as $P^2 \propto a^3$. Before Newton, this law was an experimental finding only related to planetary motions. However, Newton brought this law to a more general form by explaining it with gravity. According to Newton's law of universal gravitation, if a planet is assumed to move in a circular orbit around a star, the centripetal force is expressed as follows:

$$F_c = \frac{GM_s m_p}{r_p^2}$$

where G is the Universal Gravitational Constant ($6.674 \times 10^{-11} \text{ N m}^2/\text{kg}^2$), M_s is the mass of the star, m_p is the mass of the planet, r_p is the distance between the planet and the star (orbital radius), and F_c is the centripetal force. This force produces the motion of the planet due to its centripetal acceleration (a_c):

$$F_c = m_p \frac{v^2}{r_p}$$

Here, v represents the orbital velocity of the planet.

If these two equations are equated:

$$\frac{GM_s m_p}{r_p^2} = m_p \frac{v^2}{r_p}$$

Consequently, the expression for the orbital velocity of the planet is derived as

$$v^2 = \frac{GM_s}{r_p}$$

The relationship between the orbital speed of a planet and its period “ P ” (orbital period) is expressed as follows:

$$v = \frac{2\pi r_p}{P}$$

If this expression is substituted into the equation for v^2 found above:

$$\left(\frac{2\pi r_p}{P}\right)^2 = \frac{GM_s}{r_p}$$

and the expression is rearranged, and both sides are multiplied by r_p :

$$\frac{4\pi r_p^2}{P^2} = \frac{GM_s}{r_p} \Rightarrow \frac{4\pi r_p^3}{P^2} = GM_s$$

Solving for r_p :

$$r_p^3 = \frac{GM_s P^2}{4\pi^2} \tag{2.2}$$

Therefore, the semi-major axis “ a ” of the planet’s orbit in Equation (2.2) is obtained as:

$$a = \left(\frac{GM_s P^2}{4\pi^2}\right)^{\frac{1}{3}} \tag{2.3}$$

The final formula, which is related to the semi-major axis and the period, is obtained as in Equation (2.3). The $\pm$ error margins of the calculated semi-major axis values are calculated as follows and added to the dataset.

One of the error estimation methods involves taking the partial derivative of the semi-major axis expression given by Equation (2.3) with respect to mass. To perform this, a change of variable is first made:

$$a = u^{\left(\frac{1}{3}\right)}; u = \frac{GM_s P^2}{4\pi^2}$$

Taking the partial derivative of the semi-major axis with respect to mass is then expressed as:

$$\frac{\partial a}{\partial M_s} = \frac{1}{3} u^{\left(\frac{-2}{3}\right)} \frac{\partial u}{\partial M_s}$$

The term $u^{\left(\frac{-2}{3}\right)}$ is related to the semi-major axis as follows:

$$a^3 = \frac{GM_s P^2}{4\pi^2}; u = a^3 \Rightarrow u^{\left(\frac{-2}{3}\right)} \Rightarrow (a^3)^{\left(\frac{-2}{3}\right)} \Rightarrow a^{(-2)} \Rightarrow u^{\left(\frac{-2}{3}\right)} = \frac{1}{a^2}$$

Therefore, the partial derivative becomes:

$$\frac{\partial a}{\partial M_s} = \frac{1}{3} u^{\left(\frac{-2}{3}\right)} \frac{\partial u}{\partial M_s} \Rightarrow \frac{1}{3} \frac{1}{a^2} \frac{GP^2}{4\pi^2}$$

Replacing the term $\frac{GP^2}{4\pi^2}$ with $\frac{a^3}{M_s}$, the derivative of the semi-major axis with respect to mass becomes:

$$\frac{\partial a}{\partial M_s} = \frac{1}{3} \frac{a}{M_s}$$

The same method can be applied to find the partial derivative of the semi-major axis with respect to the period:

$$a = u^{\left(\frac{1}{3}\right)}; u = \frac{GM_s P^2}{4\pi^2}$$

$$\frac{\partial a}{\partial P} = \frac{1}{3} u^{\left(\frac{-2}{3}\right)} \frac{\partial u}{\partial P}$$

The term $u^{\left(\frac{-2}{3}\right)}$ is related to the semi-major axis as follows:

$$a^3 = \frac{GM_s P^2}{4\pi^2}; u = a^3 \Rightarrow u^{\left(\frac{-2}{3}\right)} \Rightarrow (a^3)^{\left(\frac{-2}{3}\right)} \Rightarrow a^{(-2)} \Rightarrow u^{\left(\frac{-2}{3}\right)} = \frac{1}{a^2}$$

Therefore, the partial derivative becomes:

$$\frac{\partial a}{\partial P} = \frac{1}{3} u^{\left(\frac{-2}{3}\right)} \frac{\partial u}{\partial P} \Rightarrow \frac{1}{3} \frac{1}{a^2} \frac{2GM_s P}{4\pi^2}$$

Replacing the term $\frac{2GM_s P}{4\pi^2}$ with $\frac{a^3}{P^2}$, the derivative of the semi-major axis with respect to period becomes:

$$\frac{\partial a}{\partial P} = \frac{2}{3} \frac{a}{P}$$

As a result, the general error propagation formula is obtained as follows:

$$\Delta f = \sqrt{\left(\frac{\partial f}{\partial x} \Delta x\right)^2 + \left(\frac{\partial f}{\partial y} \Delta y\right)^2 + \dots}$$

This general expression is rearranged for the semi-major axis as follows:

$$\Delta a = \sqrt{\left(\frac{\partial a}{\partial M_s} \Delta M_s\right)^2 + \left(\frac{\partial a}{\partial P} \Delta P\right)^2}$$

Substituting the obtained partial derivatives $\frac{\partial a}{\partial P}$ and $\frac{\partial a}{\partial M_s}$ into the Δa formula:

$$\Delta a = a \left(\frac{1}{3} \frac{\Delta M_s}{M_s} + \frac{2}{3} \frac{\Delta P}{P} \right) \quad (2.4)$$

The error propagation equation is thus obtained as in Equation (2.4).

```

G = 6.67408e-11
nan_amax_df = df[df['amax'].isna()]

def calculate_semi_major_axis(row):
    P = row['per']*24*3600
    M = row['smass'] * 1.989e30
    Amax = ((G * M * P**2) / (4 * np.pi**2))**(1/3)
    Amax_AU = Amax / 1.496e11
    return Amax_AU

df.loc[df['amax'].isna(), 'amax'] = df.loc[df['amax'].isna()].apply(calculate_semi_major_axis, axis=1)

def calculate_amax_error1(row):
    P = row['per']
    pe1 = row['pere1']
    M = row['smass']
    sme1=row['smasse1']
    final_amax= row['amax']

    calc_amax1 = final_amax * ((1/3 * (sme1 / M) + 2/3 * (pe1 / P)))
    return calc_amax1

df.loc[df['amaxe1'].isna(), 'amaxe1'] = df.loc[df['amaxe1'].isna()].apply(calculate_amax_error1, axis=1)

def calculate_amax_error2(row):
    P = row['per']
    pe2 = row['pere2']
    M = row['smass']
    sme2=row['smasse2']
    final_amax= row['amax']

    calc_amaxe2 = final_amax * ((1/3 * (sme2 / M) + 2/3 * (pe2 / P)))
    return calc_amaxe2

df.loc[df['amaxe2'].isna(), 'amaxe2'] = df.loc[df['amaxe2'].isna()].apply(calculate_amax_error2, axis=1)

```

Photo 2.5. Code block for the semi-major axis calculation defined in Python with parameters for the created dataset.

In Photo 2.5, the relevant Python code lines containing the expressions in Equation (2.3) and (2.4) are shown with red arrows. As a result, the error spread corresponding to the semi-major axis derived from the formula of Kepler's 3rd law associated with the period was calculated, and $\pm$ error margins were determined accordingly.

➤ Insolation Flux Calculations

The result of the insolation flux calculation is derived from the Stefan-Boltzmann law. This law defines the amount of energy a blackbody radiates per unit area. When a blackbody is considered as an object with a surface temperature T , the amount of energy radiated per unit surface area is:

$$F = \sigma T^4$$

Here, F represents the energy flux per unit surface area (W/m^2), T is the surface temperature of the object (Kelvin), and σ is the Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$).

To relate this expression to the total luminosity (L) of the star, the surface area of the star is calculated with the following sphere surface area formula:

$$A = 4\pi R_s^2$$

Here, A represents the total surface area of the star (m^2), and R_s represents the radius of the star (m).

The total energy emitted from the entire surface of a star is expressed as the product of the energy flux per unit surface area and the surface area, as shown below:

$$L = F \times A \rightarrow L = (\sigma T^4) \times (4\pi R_s^2)$$

If this expression is rearranged for luminosity, it becomes:

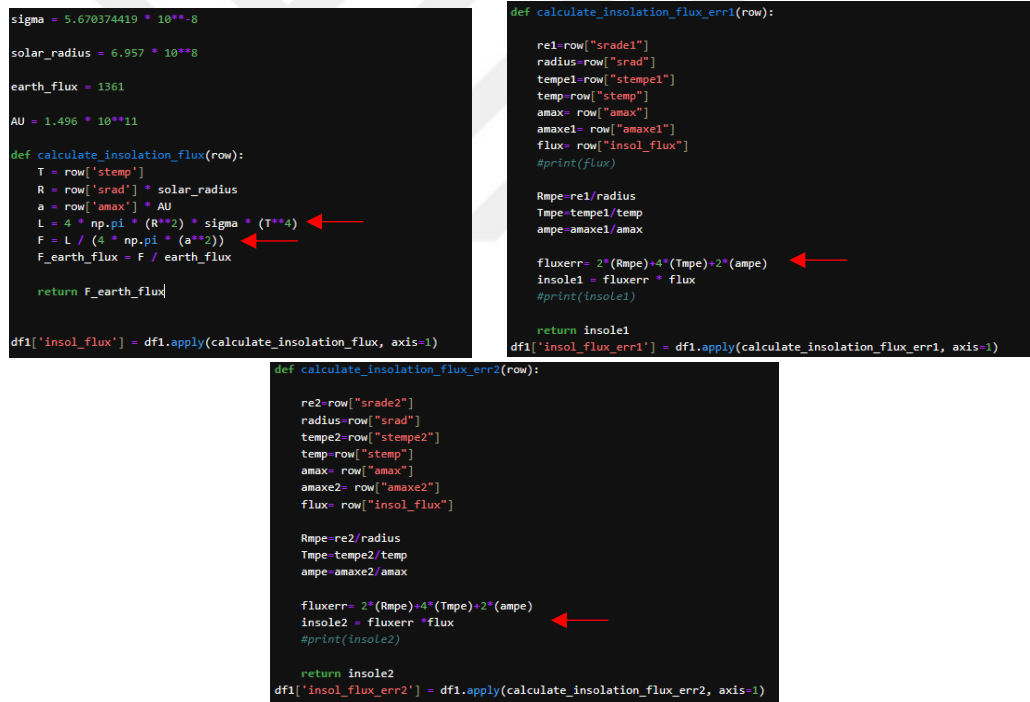
$$L = 4\pi R_s^2 \sigma T^4 \quad (2.5)$$

The flux (F) received by a planet from the star is related to luminosity by the following expression:

$$F = \frac{L}{4\pi a^2} \quad (2.6)$$

Here, F is the flux received by the planet (W/m^2), L is the total luminosity of the star (watts), and a is the distance from the planet to the star (in meters).

In the upper left panel of Photo 2.6, the relevant Python code lines containing the expressions in Equations (2.5) and (2.6) are shown with red arrows. As in the error spread calculations for the semi-major axis, similar error spreads were calculated for the insolation flux, and in the upper right panel and middle lower panel of the same photo, the relevant Python code lines are shown with red arrows, and the $\pm$ error margins were determined accordingly.



```

sigma = 5.670374419 * 10**-8
solar_radius = 6.957 * 10**8
earth_flux = 1361
AU = 1.496 * 10**11

def calculate_insolation_flux(row):
    T = row['stemp']
    R = row['srad'] * solar_radius
    a = row['amax'] * AU
    L = 4 * np.pi * (R**2) * sigma * (T**4)
    F = L / (4 * np.pi * (a**2))
    F_earth_flux = F / earth_flux
    return F_earth_flux

df1['insol_flux'] = df1.apply(calculate_insolation_flux, axis=1)

```

```

def calculate_insolation_flux_err1(row):
    re1=row["srade1"]
    radius=row["srad"]
    tempe1=row["stempel"]
    temp=row["stemp"]
    amax= row["amax"]
    amaxel= row["amaxel"]
    flux= row["insol_flux"]
    #print(flux)

    Rmpe=re1/radius
    Tmpe=tempe1/temp
    ampe=amaxel/amax

    fluxerr= 2*(Rmpe)+4*(Tmpe)+2*(ampe)
    insole1 = fluxerr * flux
    #print(insole1)

    return insole1
df1['insol_flux_err1'] = df1.apply(calculate_insolation_flux_err1, axis=1)

```

```

def calculate_insolation_flux_err2(row):
    re2=row["srade2"]
    radius=row["srad"]
    tempe2=row["stempel2"]
    temp=row["stemp"]
    amax= row["amax"]
    amaxe2= row["amaxe2"]
    flux= row["insol_flux"]

    Rmpe=re2/radius
    Tmpe=tempe2/temp
    ampe=amaxe2/amax

    fluxerr= 2*(Rmpe)+4*(Tmpe)+2*(ampe)
    insole2 = fluxerr * flux
    #print(insole2)

    return insole2
df1['insol_flux_err2'] = df1.apply(calculate_insolation_flux_err2, axis=1)

```

Photo 2.6. Code blocks for the flux are calculated based on radiation (luminosity) and its error propagation.

2.2.3 Mass Loss Efficiency

Mass loss efficiency (η) represents a model that expresses how effectively the atmosphere of a planet loses mass due to high-energy radiation from the star (Owen & Estrada, 2020; Owen & Wu, 2017). Two different mass loss efficiency models were used in this thesis to understand which model gives the best results under different planet types and physical conditions, and to test the sensitivity of the model.

➤ Constant Mass Loss Efficiency

The constant mass loss efficiency is the first mass loss efficiency model defined and used throughout this study. In this context, the definition is as follows:

$$\eta = 0.1$$

➤ Mass-Loss Efficiency Dependent on Atmospheric Escape Velocity

In the second defined mass loss model, the mass loss efficiency is inversely proportional to the square of the atmospheric escape velocity (v_{esc}) (Owen & Estrada, 2020; Owen & Wu, 2017):

$$\eta = 0.1 \left(\frac{v_{esc}}{15 \text{ km s}^{-1}} \right)^{-2}$$

Thus, larger planets lose their atmospheres more easily, while smaller planets lose their atmospheres more easily. Therefore, a mini-Neptune would need to have a larger mass than a super-Earth to retain its atmosphere. This minimum core mass is determined by both η and observable parameters, such as Equation (2.1).

```
eff_1=0.1
df["eff_1"]
mass = df["mass"]
radius = df["radius"]
escape_velocity = np.sqrt(2 * G * mass / radius)
eff_2 = 0.1 * (escape_velocity / 1.5e6) ** (-2)
df["eff_2"] = eff_2
```

Photo 2.7. Code block for two different mass loss efficiency definitions.

As a result, two different mass-loss efficiency models were included in the analysis calculations, as shown in Photo 2.7. Additionally, in order to observe how the results are affected when the first model, based on a constant efficiency parameter η , is modified, changes were made, and the corresponding outcomes are presented in Appendix 2.

In multiplanetary systems, to ensure the selection of only one rocky (super-Earth) and one gaseous (mini-Neptune) planet from multiple super-Earths and mini-Neptunes (such that one planet from each category is located below and above the radius valley as described in Section 2.2.1), grouping was carried out based on the hostnames of the systems to separate the two categories as “super” and “mini” (Photo 2.8). In this grouping, for super-Earths, the planet with the largest semi-major axis among multiple super-Earths was selected; for mini-Neptunes, the one with the smallest semi-major axis was chosen among the candidates (Photo 2.9). A detailed explanation of this selection method is presented in Appendix 3, as described in the paper by Owen and Estrada 2020.

```
def calculate_mcore_values(df):
    results = []

    for hostname, group in df.groupby('hostname', dropna=True):
        super_planets = group[group['Result'] == 'super']
        mini_planets = group[group['Result'] == 'mini']
```

Photo 2.8. Code block view of the groupings based on two different categories for the created sub-target lists (Table 2.1).

```
if len(super_planets) > 0:
    max_amax_index = super_planets['amax'].idxmax()
    super_name = super_planets.loc[max_amax_index, 'name']
    super_radius = super_planets.loc[max_amax_index, 'radius']
    super_radius_err1 = super_planets.loc[max_amax_index, 're1']
    super_radius_err2 = super_planets.loc[max_amax_index, 're2']
    super_amax = super_planets.loc[max_amax_index, 'amax']
    super_amax_err1 = super_planets.loc[max_amax_index, 'amax1']
    super_amax_err2 = super_planets.loc[max_amax_index, 'amax2']
    super_mass = super_planets.loc[max_amax_index, 'mass']
    super_mass_err1 = super_planets.loc[max_amax_index, 'me1']
    super_mass_err2 = super_planets.loc[max_amax_index, 'me2']
    super_insol = super_planets.loc[max_amax_index, 'insol_flux']
    super_insol_err1 = super_planets.loc[max_amax_index, 'insol_flux_err1']
    super_insol_err2 = super_planets.loc[max_amax_index, 'insol_flux_err2']
    super_density = super_planets.loc[max_amax_index, 'density']
    super_dense1 = super_planets.loc[max_amax_index, 'dense1']
    super_dense2 = super_planets.loc[max_amax_index, 'dense2']
    super_eff_2 = super_planets.loc[max_amax_index, 'eff_2']
    super_eff_1 = super_planets.loc[max_amax_index, 'eff_1']

else:
    continue

if len(mini_planets) > 0:
    min_amax_index = mini_planets['amax'].idxmin()
    mini_ref = mini_planets.loc[min_amax_index, 'ref']
    mini_year = mini_planets.loc[min_amax_index, 'year']
    mini_name = mini_planets.loc[min_amax_index, 'name']
    mini_radius = mini_planets.loc[min_amax_index, 'radius']
    mini_radius_err1 = mini_planets.loc[min_amax_index, 're1']
    mini_radius_err2 = mini_planets.loc[min_amax_index, 're2']
    mini_amax = mini_planets.loc[min_amax_index, 'amax']
    mini_amax_err1 = mini_planets.loc[min_amax_index, 'amax1']
    mini_amax_err2 = mini_planets.loc[min_amax_index, 'amax2']
    mini_mass = mini_planets.loc[min_amax_index, 'mass']
    mini_mass_err1 = mini_planets.loc[min_amax_index, 'me1']
    mini_mass_err2 = mini_planets.loc[min_amax_index, 'me2']
    mini_insol = mini_planets.loc[min_amax_index, 'insol_flux']
    mini_insol_err1 = mini_planets.loc[min_amax_index, 'insol_flux_err1']
    mini_insol_err2 = mini_planets.loc[min_amax_index, 'insol_flux_err2']
    mini_density = mini_planets.loc[min_amax_index, 'density']
    mini_dense1 = mini_planets.loc[min_amax_index, 'dense1']
    mini_dense2 = mini_planets.loc[min_amax_index, 'dense2']
    mini_eff_2 = mini_planets.loc[min_amax_index, 'eff_2']
    mini_eff_1 = mini_planets.loc[min_amax_index, 'eff_1']
```

Photo 2.9. Code blocks were created to determine the systems to be included in these groups and to use the parameters of these groups under the labels “super” (left panel) and “mini” (right panel).

2.2.4 Error Margins

In addition to the three different radius and density scenarios discussed in Section 2.2.1, the last criterion is to add the error margins of the relevant parameters to the minimum core mass calculations with random numbers. The error margins of the parameters used in the calculation processes are considered in two different cases: only positive error margins and both positive and negative ($\pm$) error margins.

➤ Positive Error Margins

Before defining the minimum core mass formula shown in Equation (2.1) in the Python code as in Photo 2.11, 2,000 different samples were randomly generated using the Markov Chain Monte Carlo (MCMC) method using only positive values of the error margins of the relevant parameters, and 1,000 of them were selected. To simulate the probabilistic distributions for the positive error margins of these parameters, together with the radius, semi-major axis, and mass parameters, definitions were made as in Photo 2.10.

```
super_radius_random = np.random.normal(super_radius, super_radius_err1,2000)
super_radius_random = super_radius_random[super_radius_random>0][:1000]

super_amax_random = np.random.normal(super_amax, super_amax_err1,2000)
super_amax_random = super_amax_random[super_amax_random>0][:1000]

super_mass_random = np.random.normal(super_mass, super_mass_err1,2000)
super_mass_random = super_mass_random[super_mass_random>0][:1000]

mini_radius_random = np.random.normal(mini_radius, mini_radius_err1,2000)
mini_radius_random = mini_radius_random[mini_radius_random>0][:1000]

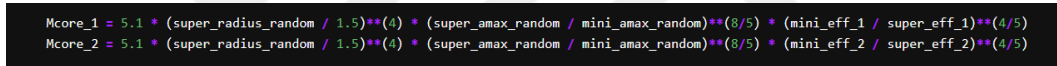
mini_amax_random = np.random.normal(mini_amax, mini_amax_err1,2000)
mini_amax_random = mini_amax_random[mini_amax_random>0][:1000]

mini_mass_random = np.random.normal(mini_mass, mini_mass_err1,2000)
mini_mass_random = mini_mass_random[mini_mass_random>0][:1000]
```

Photo 2.10. Code block defining the parameter uncertainties corresponding to the positive error margins, labeled with “_err1”, along with the planetary parameters for the “super” (upper panel) and “mini” (lower panel) categorization.

To compute the probabilistic distributions of systems within the sub-target lists based on 1,000 different samples generated using the MCMC method, and to construct their distributions as histograms by incorporating the associated uncertainties into the minimum core mass formula shown in Equation (2.1), two different mass loss efficiency models were implemented in the Python code as shown in Photo 2.11.

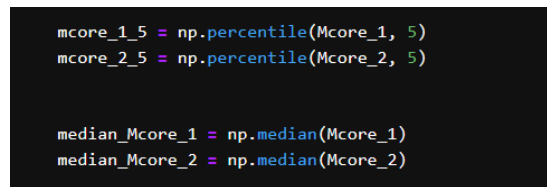
Here, the same two formulas are defined using two different naming conventions (1 and 2), not to be confused with the parameter names shown in Photo 2.9. Instead, these represent the two different mass loss efficiency models discussed in Section 2.2.3. Throughout the study, the suffix “1” in variable names (outside of parameter names) refers to calculations using the constant η model, while the suffix “2” indicates calculations based on the escape velocity dependent η model.



```
Mcore_1 = 5.1 * (super_radius_random / 1.5)**(4) * (super_amax_random / mini_amax_random)**(8/5) * (mini_eff_1 / super_eff_1)**(4/5)
Mcore_2 = 5.1 * (super_radius_random / 1.5)**(4) * (super_amax_random / mini_amax_random)**(8/5) * (mini_eff_2 / super_eff_2)**(4/5)
```

Photo 2.11. The minimum core mass formula in Equation (2.1) (Owen & Estrada, 2020).

For this reason, “Case 1” and “Case 2” were defined for the processes where only positive error margins were used, and the median value for the minimum core mass and the 5% percentile value for the error margin of the minimum core mass median value were taken as the error margin, and both cases and two different mass loss efficiencies were determined (Photo 2.12).



```
mcore_1_5 = np.percentile(Mcore_1, 5)
mcore_2_5 = np.percentile(Mcore_2, 5)

median_Mcore_1 = np.median(Mcore_1)
median_Mcore_2 = np.median(Mcore_2)
```

Photo 2.12. Code block where the minimum core masses (median_Mcore_1, median_Mcore_2) and the margins of error in the minimum core mass (mcore_1_5, mcore_2_5) are defined.

After obtaining the minimum core masses as in Photo 2.12, the mass differences were calculated to derive the probabilistic histogram distributions. The reason for this is that exoplanets close to their stars are exposed to high temperatures, intense radiation, and strong stellar winds, and their atmosphere evaporates and disappears (Owen & Estrada, 2020). Therefore, the results of the mass differences provide evidence for the “photoevaporation” hypothesis described in Section 1.5. If the measured mass of the planet exceeds its calculated mass as a result of mass discrepancy, this is the strongest evidence that the atmosphere has been lost by photoevaporation.

```
Mg = data['mini_mass'].values
#print(Mg)
Mgerr = data['mini_mass_err1'].values
median_Mcore_1 = data['median_mcore_1'].values
median_Mcore_2 = data['median_mcore_2'].values
Mgme1 = data['Mgme1'].values
Mgme2 = data['Mgme2'].values
hostname = data['hostname'].values

Residual_mass1=Mg-median_Mcore_1
#print(Residual_mass1)
Residual_mass2=Mg-median_Mcore_2
#print(Residual_mass2)

Mcore_err_1 = median_Mcore_1 - Mgme1
#print(Mcore_err_1)
Mcore_err_2 = median_Mcore_2 - Mgme2
#print(Mcore_err_2)
residual_hata_pay11 = np.sqrt(Mgerr**2 + Mcore_err_1**2)
#print(residual_hata_pay11)
residual_hata_pay12 = np.sqrt(Mgerr**2 + Mcore_err_2**2)
#print(residual_hata_pay12)
```

Photo 2.13. Code block was created in Python for the mass differences of Case 1.

As seen in Photo 2.13, the measured masses of the planets, the positive error margins of the measured masses, the calculated masses for two different mass loss efficiencies, and the error margins determined with a 5% percentile value for the calculated masses depending on two different mass loss efficiencies, and the hostnames of the systems are listed. Mass difference calculations were obtained for each exoplanet in the sub-target list, depending on two separate η 's, by subtracting the calculated mass from the measured mass of the planet, as defined in the same photograph. To determine the error margins of these mass differences obtained, the 5% percentile value was subtracted from the calculated mass, as shown with red arrows in Photo 2.13, and found for both η . These error margins were determined by taking the square root of the sum of the squares of the error margins of the measured and calculated masses using the error propagation formula explained in the heading “Semi-Major Axis Calculations” and are shown with green arrows in

Photo 2.13. As explained above, the process until the calculation of the error margins of the calculated masses for Cases 1 and 2 is the same, but the process shown with green arrows in Photo 2.13 corresponds to Case 1, while in Case 2 this calculation was made only by taking the square root of the square of the measured mass. Therefore, the distinction between Cases 1 and 2 emerges in this way.

➤ Positive and Negative ($\pm$) Error Margins

All the processes explained up to Photograph 2.9 are valid at this stage as well, and the differences created are processed as “Case 3” and “Case 4”. Therefore, apart from including $\pm$ margins of error for these two cases, the radius, semi-major axis, and mass parameters of the “super” and “mini” categories defined in Photo 2.10 and their margins of error were used for Case 3 and Case 4 as in Photo 2.14.

```
super_combined_radius_err=(super_radius_err1**2 + super_radius_err2**2)**0.5
super_radius_random = np.random.normal(super_radius, super_combined_radius_err,2000)
super_radius_random = super_radius_random[super_radius_random>0][:1000]

super_combined_amax_err=(super_amax_err1**2 + super_amax_err2**2)**0.5
super_amax_random = np.random.normal(super_amax, super_combined_amax_err,2000)
super_amax_random = super_amax_random[super_amax_random>0][:1000]

super_combined_mass_err =(super_mass_err1**2 + super_mass_err2**2)**0.5
super_mass_random = np.random.normal(super_mass, super_combined_mass_err,2000)
super_mass_random = super_mass_random[super_mass_random>0][:1000]

mini_combined_radius_err=(mini_radius_err1**2 + mini_radius_err2**2)**0.5
mini_radius_random = np.random.normal(mini_radius, mini_combined_radius_err,2000)
mini_radius_random = mini_radius_random[mini_radius_random>0][:1000]

mini_combined_amax_err=(mini_amax_err1**2 + mini_amax_err2**2)**0.5
mini_amax_random = np.random.normal(mini_amax, mini_combined_amax_err,2000)
mini_amax_random = mini_amax_random[mini_amax_random>0][:1000]

mini_combined_mass_err = (mini_mass_err1**2 + mini_mass_err2**2)**0.5
mini_mass_random = np.random.normal(mini_mass, mini_combined_mass_err,2000)
mini_mass_random = mini_mass_random[mini_mass_random>0][:1000]
```

Photo 2.14. Parameter uncertainties are defined for the “super” (upper panel) and “mini” (lower panel) categorization, calculated as the square root of the sum of squares of the $\pm$ error margins, labeled with “_combined_err”, along with the planetary parameters.

The formula based on the two mass loss efficiencies in Photo 2.11 was kept constant for Case 3 and Case 4, and the minimum core masses and their margins of error were used as negative margins of error for 5% percentile values and positive margins of error for 95% percentile values , as in Photo 2.15.

```

mcore_1_5 = np.percentile(Mcore_1, 5)
mcore_2_5 = np.percentile(Mcore_2, 5)
mcore_1_95 = np.percentile(Mcore_1, 95)
mcore_2_95 = np.percentile(Mcore_2, 95)

median_Mcore_1 = np.median(Mcore_1)
median_Mcore_2 = np.median(Mcore_2)

```

Photo 2.15. Minimum core masses (median_Mcore_1, median_Mcore_2), negative margins of error in minimum core mass (mcore_1_5, mcore_2_5), and positive margins of error (mcore_1_95, mcore_2_95).

After obtaining the minimum core masses and error margins, the calculated mass differences are as in the relevant Python code Photo 2.16, and there are different situations in the parameter definitions than in Case 1 and Case 2. Therefore, these parameters are, respectively, the measured masses of the planets, the $\pm$ error margins of the measured masses, the calculated masses belonging to two different mass loss efficiencies and the negative error margins determined with the 5% percentile value for the calculated masses again depending on the two different mass loss efficiencies, the positive error margins determined with the 95% percentile value and the hostnames of the systems.

For the mass differences, there are differences obtained by subtracting the calculated mass from the measured mass, which was also carried out in Cases 1 and 2. To determine the negative error margins belonging to these mass differences obtained for two different mass loss efficiencies, it was found by subtracting the 5% percentile values belonging to two different η from the calculated mass, as shown by the red arrows in Photo 2.16. For positive error margins, the 95% percentile values for two different η were found by subtracting them from the calculated mass, as shown by the blue arrows in Photo 2.16.

```

Mg = data['mini_mass'].values
#print(Mg)
Mgerr = data['mini_combined_mass_err'].values
median_Mcore_1 = data['median_mcore_1'].values
median_Mcore_2 = data['median_mcore_2'].values
Mgme1_5 = data['Mgme1_5'].values
Mgme2_5 = data['Mgme2_5'].values
Mgme1_95 = data['Mgme1_95'].values
Mgme2_95 = data['Mgme2_95'].values
hostname = data['hostname'].values

Residual_mass1=Mg-median_Mcore_1
#print(Residual_mass1)
Residual_mass2=Mg-median_Mcore_2
#print(Residual_mass2)

Mcore_err_1n = median_Mcore_1 - Mgme1_5
Mcore_err_1p = median_Mcore_1 - Mgme1_95
Mcore_err_2n = median_Mcore_2 - Mgme2_5
Mcore_err_2p = median_Mcore_2 - Mgme2_95
Mcore_err_1= np.sqrt(Mcore_err_1n**2 + Mcore_err_1p**2 )
Mcore_err_2= np.sqrt(Mcore_err_2n**2 + Mcore_err_2p**2 ) |
residual_hata_pay1 = Mgerr+Mcore_err_1
#print(residual_hata_pay1)
residual_hata_pay12 = Mgerr+Mcore_err_2
#print(residual_hata_pay12)

```

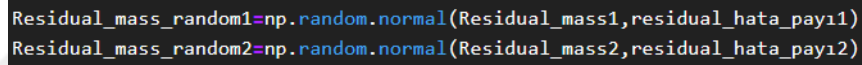
Photo 2.16. A code block was created for the mass differences of Case 3.

In addition, as shown with orange arrows in Photo 2.16, the squares of the negative error margins of the calculated masses were added, and their square roots were taken. The same process was repeated by adding the squares of the positive error margins and taking their square roots. The final error margin, contrary to what was explained under the heading “Positive Error Margins”, was obtained by adding the combined error margins of the measured masses and the $\pm$ error margins of these calculated masses in order not to repeat the process, and these final error margins are shown with green arrows in Photo 2.16. While the process shown with green arrows in Photo 2.16 corresponds to Case 3, the error margin calculation in Case 4 was carried out using only the measured mass itself. This difference emerged to observe the differences between the cases where the measured mass and calculated mass error margins were taken (Case 1 and Case 3) and the cases where only the measured mass error margins were taken (Case 2 and Case 4), as explained in Cases 1 and Case 2.

2.3 Residual Mass and Signal-to-Noise Ratio Calculations

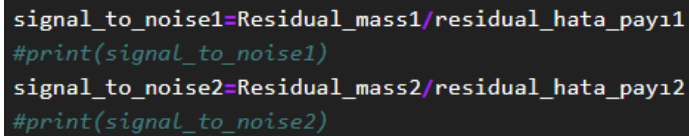
In this section, details will be given for the calculations of the residual mass (ΔM), which is obtained by subtracting the calculated minimum core mass values from the measured exoplanet mass, and the signal to noise ratio (σ), which is determined by dividing the residual mass by the error margin of the residual mass.

For all examined exoplanets, residual mass values were obtained by subtracting the median value of the minimum core mass from the measured mass values (as listed in the NASA Exoplanet Archive) for both mass loss efficiency models. The uncertainties in the residual mass were computed as described previously in Section 2.2.4: for Case 1 and Case 2, by subtracting the 5% percentile of the minimum core mass distributions from the measured mass uncertainties; and for Case 3 and Case 4, by subtracting the 5% percentile (negative) and 95% percentile (positive) values, respectively. These calculations were incorporated into the analysis code as shown in Photo 2.16. Random sampling using the MCMC method was applied to both the residual mass and its uncertainty, and the resulting distributions for both mass loss efficiency scenarios were defined as shown in Photo 2.17. Therefore, to assess the statistical significance of systems consistent or inconsistent with the photoevaporation hypothesis and to obtain their sigma values, the residual masses were divided by their respective uncertainties for each mass loss efficiency model, as illustrated in Photo 2.18.



```
Residual_mass_random1=np.random.normal(Residual_mass1,residual_hata_pay1)
Residual_mass_random2=np.random.normal(Residual_mass2,residual_hata_pay2)
```

Photo 2.17. Code lines for the random distributions generated by the MCMC method for residual masses and residual mass error margins.



```
signal_to_noise1=Residual_mass1/residual_hata_pay1
#print(signal_to_noise1)
signal_to_noise2=Residual_mass2/residual_hata_pay2
#print(signal_to_noise2)
```

Photo 2.18. Lines of code for signal-to-noise ratios.

As a result, the materials, analysis processes, and applied methods used in this study are explained in detail. First, the data collection process and the assumptions used are discussed, and then the calculation methods applied to analyze the obtained data are presented step by step. As a result of these analyses, important data that can answer the main purpose of the study, the photoevaporation hypothesis, and the atmospheric loss process in exoplanets have been obtained. In the next section, the findings, graphs, and tables obtained from these analyses are presented in detail.

3. RESULTS

This section presents the findings of the analyses conducted to test whether the photoevaporation mechanism can explain the mass losses in the exoplanet atmosphere. The data obtained within the scope of the hypothesis test were evaluated together with the physical and orbital properties of the planets included in the scenarios described in Section 2.2.1 and the sub-target sets shown in Table 2.1, and it was examined whether the photoevaporation effect was statistically significant. The findings were reported systematically and from general to specific within the framework of the research question. Initially, six systems selected from the sub-target lists and included in the photoevaporation hypothesis were reported, and then all systems in the sub-target lists were analyzed collectively.

3.1 Radius-Mass Relationship of Exoplanets

The graph in Figure 3.1 shows the mass and radius parameters and error margins taken from the NEA database for six systems selected from among 2,221 systems that meet the conditions of a single star and at least two planets, presented in Table 2.1. The radius conditions determined in all three scenarios match the planets of the selected systems belonging to the mini-Neptune class. Only positive error margins were used in Case 1 and Case 2. For visualization purposes in these scenarios, negative error margins were created by taking the negative counterparts of positive error values. However, the findings of these two Cases in the graph in Figure 3.1 were not included in the section.

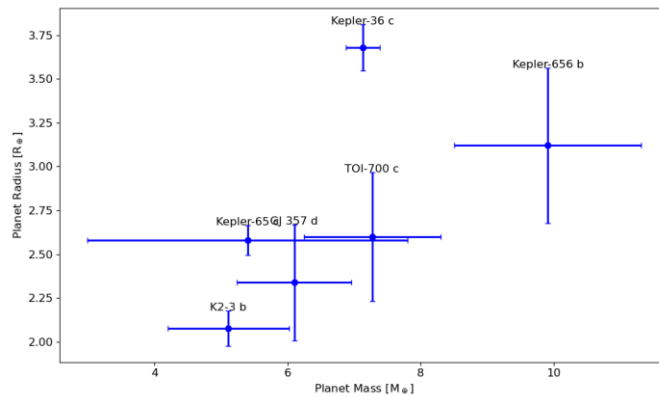


Figure 3.1. Scatter plot of planetary radius versus planetary mass.

In Case 3 and Case 4, $\pm$ margins of error were used directly. Since the parameters were the same in the four scenarios and only the margins of error changed, the content was repeated, so only the graph for Case 3 was presented. Case 3 was created with parameters containing measured and calculated mass data as previously explained in Section 2.2.4.

3.2 Relationship Between the Insolation Flux of Exoplanets and Their Measured Mass and Radius

In Figure 3.2, the graphs of the calculated insolation flux (Section 2.2.2) versus the measured mass (upper panel of Figure 3.2) and radius (lower panel of Figure 3.2) are presented for a selected sample of 6 systems to enable comparison of their mass and radius. In both graphs, the axes are shown on a logarithmic scale. In the calculations performed under four different scenarios (Case 1–4), the conditions defined for Case 1–2 and Case 3–4 are the same as those discussed under the heading " Radius-Mass Relationship of Exoplanets " above.

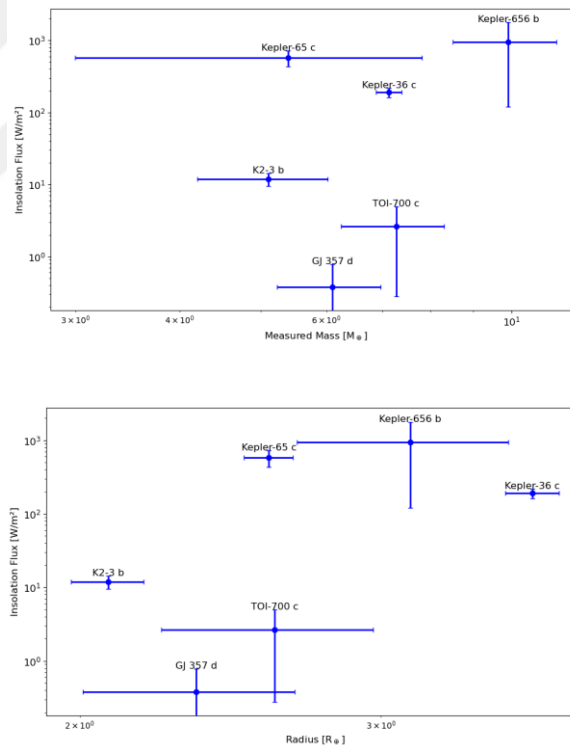


Figure 3.2. Scatter plot created using the calculated insolation flux parameters and the mass, radius parameters from the NEA.

3.3 Calculated Minimum Core Mass Distributions of Exoplanets

In this section, histograms representing the minimum core mass distributions for the sample of six different systems shown in Figures 3.1 and 3.2 have been generated. These were obtained using the Python code provided in Photo 2.11, which applies the minimum core mass formula given in Equation (2.1), incorporating the relevant uncertainties and utilizing two different definitions of mass loss efficiencies.

➤ Kepler-36

The Kepler-36 system, selected from the cut-2 (a) sub-target list created from the NEA data in Table 2.1. Located 1,772 light-years away from Earth, this system has two planets in total, Kepler-36 b (super-Earth) and Kepler-36 c (mini-Neptune). In Figure 3.3, the minimum core mass distribution histograms of the mini-Neptune planet of this system, Kepler-36 c, are presented for scenario 1 (**mini-Neptune**: $R_p > 2R_{\oplus}$ ve $\rho < 2 \text{ g/cm}^3$; **super-Earth**: $R_p < 2R_{\oplus}$ ve $\rho > 3 \text{ g/cm}^3$).

The graphs illustrate the relationship between minimum core mass and probability density, featuring an x-axis corresponding to the range over which the core mass of the planet Kepler-36 c is distributed. The y-axes in these same graphs represent the probability densities of the minimum core masses for this system. All masses in these graphs are given in terms of Earth mass ($M_{\oplus}$). The top left and right panels of Figure 3.3 correspond to Case 1 and Case 2, respectively. The blue distribution curves represent a constant η , while the orange distribution curves represent η dependent on escape velocity. The vertical dotted lines indicate the measured mass of planet c, with the surrounding bands showing the uncertainties in the measured mass. The blue and red dashed lines represent the calculated minimum core mass corresponding to the positive error margins within the 95% confidence level (CL). The bottom left and right panels of the same figure correspond to Case 3 and Case 4, respectively. In these two panels, the solid light and dark gray lines represent the calculated minimum core mass values. The green and purple dashed lines indicate the positive error margins defined at the 95% CL, while the blue and red dashed lines represent the negative error margins defined at the 5% CL.

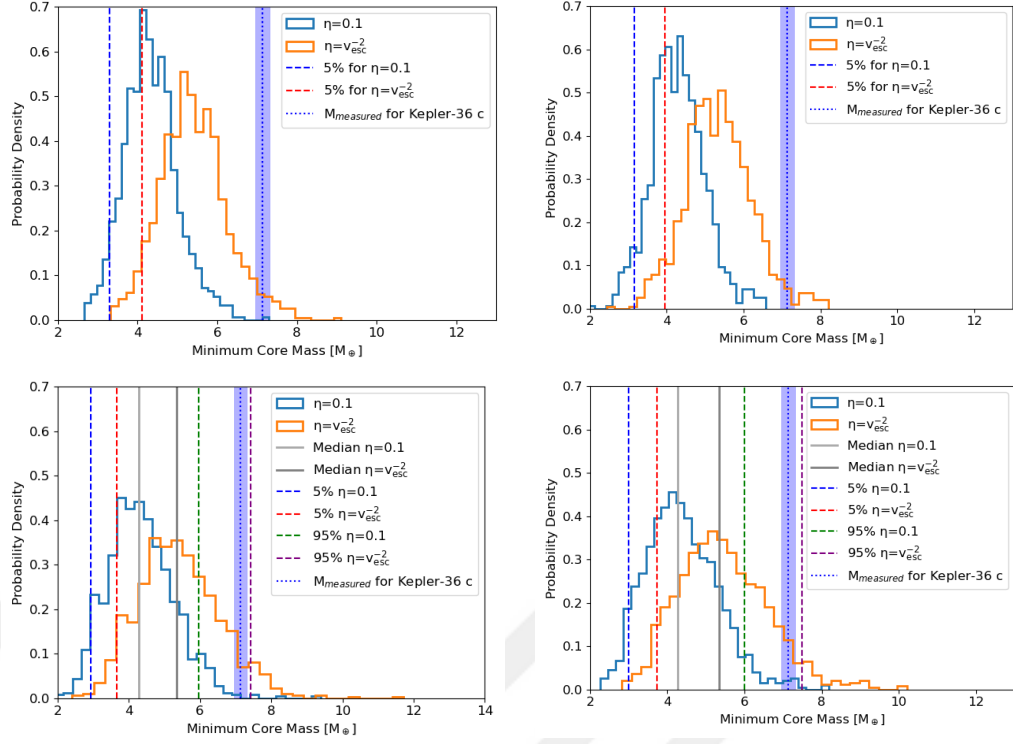


Figure 3.3. Histograms of the minimum core mass distributions for four different cases of the planet Kepler-36 c.

In Figure 3.3, the mass value due to 1st η corresponding to Case 1 in the upper left panel is $3.29M_{\oplus}$, while the mass value due to 2nd η is $4.11M_{\oplus}$. In the upper right panel of the figure, the mass due to Case 2 and 1st η is $3.16M_{\oplus}$, while the mass due to 2nd η is $3.95M_{\oplus}$. Similarly, the mass value due to 1st η associated with Case 3 in the lower left panel is $4.28M_{\oplus}$, while the mass value due to 2nd η is $5.34M_{\oplus}$. Finally, in the lower right panel of the figure corresponding to Case 4, the mass due to 1st η is $4.27 M_{\oplus}$, while the mass value due to 2nd η is $5.33M_{\oplus}$.

➤ GJ 357

The second system is the GJ 357 system, which was selected from the cut-2 (b) sub-target list created from the NEA data in Table 2.1. Located 31 light-years away from Earth, this system has three planets in total: GJ 357 b (potentially super-Earth), GJ 357 c (potentially super-Earth), and GJ 357 d (mini-Neptune). In Figure 3.4, the minimum core mass distribution histograms of the mini-Neptune planet of this system, GJ 357 d, are presented for scenario 2 (**mini-Neptune**: $R_p > 2R_{\oplus}$ ve $\rho < 2 g/cm^3$; **super-Earth**: $R_p < 2R_{\oplus}$ ve $\rho > 3 g/cm^3$).

The graphs illustrate the relationship between minimum core mass and probability density feature an x-axis corresponding to the range over which the core mass of the planet GJ 357 d is distributed. The y-axes in these graphs represent the probability densities of the minimum core masses for this system, and all masses are given in Earth masses ($M_{\oplus}$).

For Case 1 in the upper left panel of Figure 3.4, the mass value corresponding to the 1st η model is $0.52M_{\oplus}$, and the mass value corresponding to the 2nd η model is $0.43M_{\oplus}$. In Case 2 shown in the upper right panel, the calculated mass for 1st η is $0.51M_{\oplus}$, and for 2nd η is $0.42M_{\oplus}$. In Case 3 in the lower left panel, the mass due to 1st η is $1.09M_{\oplus}$, and the mass due to 2nd η is $0.90M_{\oplus}$. Finally, for Case 4 in the lower right panel, the mass value for the 1st η model is $1.11M_{\oplus}$, and the mass value for the 2nd η model is $0.91M_{\oplus}$.

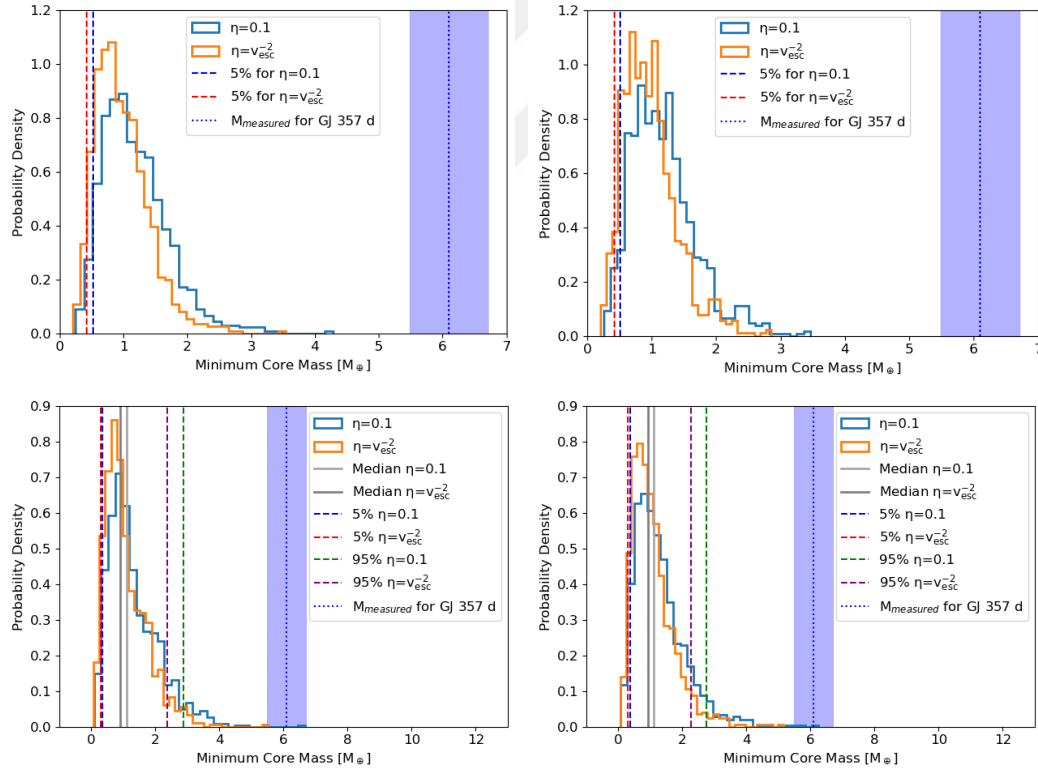


Figure 3.4. Histograms of minimum core mass distributions for four different cases of the planet GJ 357 d.

➤ TOI-700

Another exoplanet system is the TOI-700 system, which was again selected from the cut-2 (c) sub-target list created from the NEA data in Table 2.1. Located 102 light-years away from Earth, this system has a total of four planets: TOI-700 b (super-Earth), TOI-700 c (mini-Neptune), TOI-700 d (potentially super-Earth), and TOI-700 e (super-Earth). In Figure 3.5, the minimum core mass distribution histograms of the mini-Neptune planet TOI-700 c of this system are presented for the 3rd scenario (**mini-Neptune**: $R_p > 2R_\oplus$ ve $\rho < 2 \text{ g/cm}^3$; **super-Earth**: $R_p < 2R_\oplus$ ve $\rho > 3 \text{ g/cm}^3$).

The graphs illustrate the relationship between minimum core mass and probability density, featuring an x-axis corresponding to the range over which the core mass of the planet TOI-700 c is distributed. The y-axes in these graphs represent the probability densities of the minimum core masses for this system. All masses presented in these graphs are given in Earth masses ($M_\oplus$).

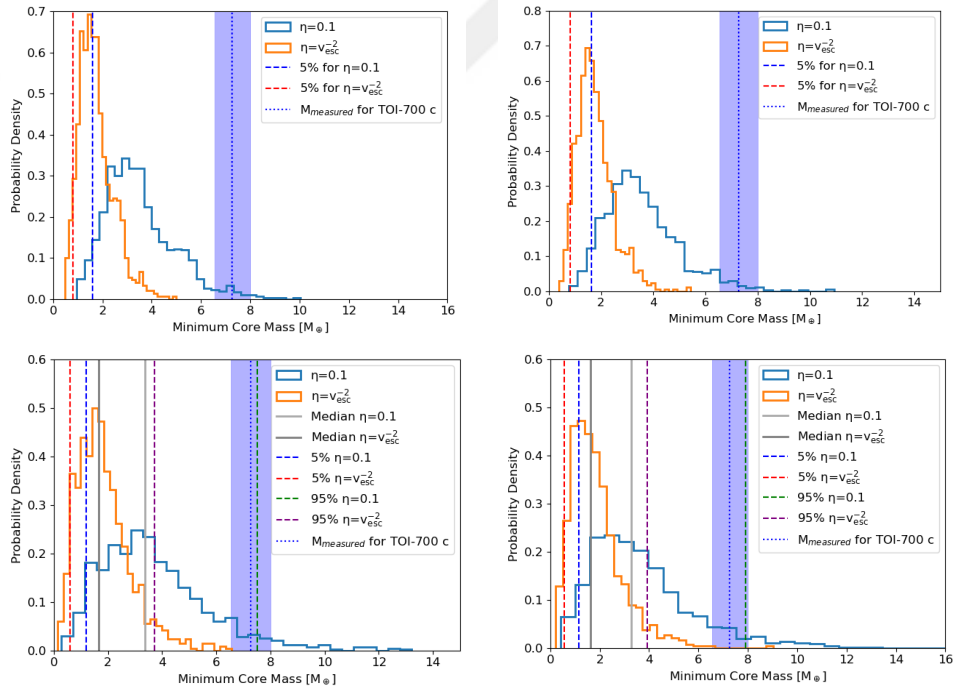


Figure 3.5. Histograms of minimum core mass distributions for four different cases of the planet TOI-700 c.

In Case 1 in the upper left panel of Figure 3.5, the mass calculated with the 1st η model is found to be $1.59M_{\oplus}$, and the value calculated with the 2nd η model is $0.79M_{\oplus}$. In the calculations for Case 2 presented in the upper right panel, the mass value obtained for 1st η is $1.64M_{\oplus}$, and for 2nd η is $0.81M_{\oplus}$. According to Case 3 in the lower left panel, the mass determined based on the 1st η model is $3.37M_{\oplus}$, while the value corresponding to the 2nd η model is $1.67M_{\oplus}$. In Case 4 shown in the lower right panel, these values are calculated as $3.26M_{\oplus}$ and $1.62M_{\oplus}$, respectively.

➤ **Kepler-656**

The fourth exoplanet system, the Kepler-656 system, which was again selected from the cut-2 (a) sub-target list created from the NEA data in Table 2.1. Located 2,904 light-years away from Earth, this system has two planets in total, Kepler-656 b (mini-Neptune) and Kepler-656 c (potentially super-Earth). In Figure 3.6, the minimum core mass distribution histograms of the mini-Neptune planet of this system, Kepler-656 b, are presented for scenario 1 (**mini-Neptune**: $R_p > 2R_{\oplus}$ ve $\rho < 2 \text{ g/cm}^3$; **super-Earth**: $R_p < 2R_{\oplus}$ ve $\rho > 3 \text{ g/cm}^3$).

The graphs illustrating the relationship between minimum core mass and probability density feature an x-axis corresponding to the range over which the core mass of the Kepler-656 system is distributed. The y-axes in these graphs represent the probability densities of the minimum core masses for this system. All masses presented in these graphs are given in Earth masses ($M_{\oplus}$).

For Case 1 shown in the upper left panel of Figure 3.6, the mass value was calculated as $8.64M_{\oplus}$ with the 1st η model and $5.54M_{\oplus}$ with the 2nd η model. In Case 2 in the upper right panel, the calculated mass was obtained as $9.57M_{\oplus}$ for the 1st η and $6.14M_{\oplus}$ for the 2nd η . In Case 3 presented in the lower left panel, the mass corresponding to the 1st η was determined as $19.19M_{\oplus}$, and the mass corresponding to the 2nd η was determined as $12.31M_{\oplus}$. Finally, in Case 4 in the lower right panel, these values were calculated as $20.04M_{\oplus}$ and $12.85M_{\oplus}$, respectively.

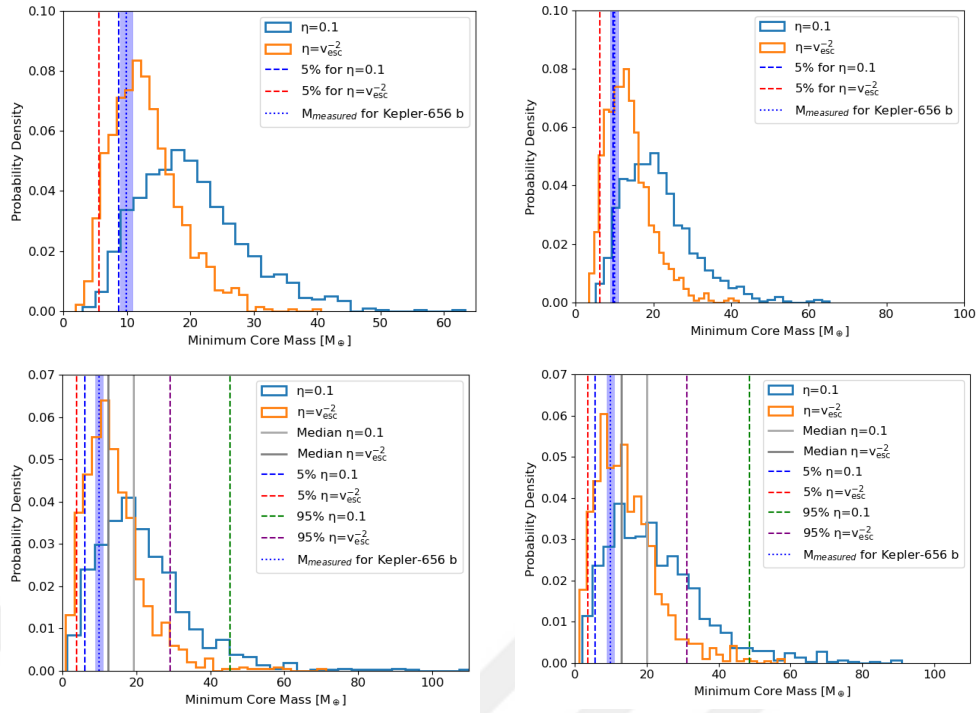


Figure 3.6. Histograms of the minimum core mass distributions for four different cases of the planet Kepler-656 b.

➤ Kepler-65

A different exoplanet system, the Kepler-65 system, which was again selected from the cut-2 (b) sub-target list created from the NEA data in Table 2.1. Located 991 light-years away from Earth, this system has a total of four planets: Kepler-65 b (potentially super-Earth), Kepler-65 c (mini-Neptune), Kepler-65 d (potentially super-Earth), and Kepler-65 e (gas giant). In Figure 3.7, the minimum core mass distribution histograms of the mini-Neptune planet of this system, Kepler-65 c, are presented for scenario 2 (**mini-Neptune**: $R_p > 2R_{\oplus}$ ve $\rho < 2 \text{ g/cm}^3$; **super-Earth**: $R_p < 2R_{\oplus}$ ve $\rho > 3 \text{ g/cm}^3$).

The graphs illustrate the relationship between minimum core mass and probability density feature an x-axis corresponding to the range over which the core mass of the Kepler-65 system is distributed. The y-axes in these graphs represent the probability densities of the minimum core masses for this system. All masses presented in these graphs are given in Earth masses ($M_{\oplus}$).

For Case 1 in the upper left panel of Figure 3.7, the mass obtained according to the 1st η model was determined as $5.47M_{\oplus}$ and $6.75M_{\oplus}$ according to the 2nd η model. In Case 2 shown in the upper right panel, the mass calculated with the 1st η model was $5.40M_{\oplus}$, while it was found as $6.67M_{\oplus}$ with the 2nd η model. In Case 3 in the lower left panel, the mass value was calculated as $7.43M_{\oplus}$ based on the 1st η model and $9.17M_{\oplus}$ based on the 2nd η model. For Case 4 in the lower right panel, these masses were obtained as $7.50M_{\oplus}$ and $9.25M_{\oplus}$, respectively.

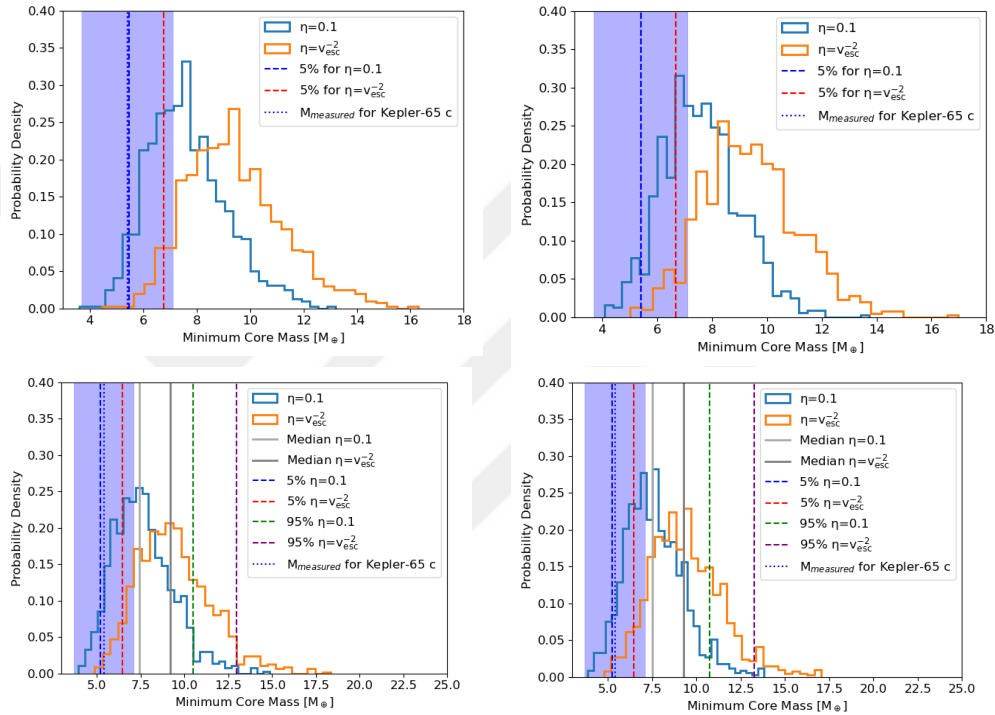


Figure 3.7. Histograms of the minimum core mass distributions for four different cases of the planet Kepler-65 c.

➤ K2-3

The last system is the K2-3 system, which was selected from the cut-2 (c) sub-target list created from the NEA data in Table 2.1. Located 114 light-years away from Earth, this system has three planets in total, K2-3 b (potentially super-Earth), K2-3 c (potentially super-Earth) and K2-3 d (potentially super-Earth). In Figure 3.8, the minimum core mass distribution histograms of the mini-Neptune planet of this system, K2-3 b, are presented for the 3rd scenario (**mini-Neptune**: $R_p > 2R_{\oplus}$ ve $\rho < 2 \text{ g/cm}^3$; **super-Earth**: $R_p < 2R_{\oplus}$ ve $\rho > 3 \text{ g/cm}^3$).

The graphs illustrate the relationship between minimum core mass and probability density feature an x-axis corresponding to the range over which the core mass of the K2-3 system is distributed. The y-axes in these graphs represent the probability densities of the minimum core masses for this system. All masses presented in these graphs are given in Earth masses ($M_{\oplus}$).

In Case 1 presented in the upper left panel Figure 3.8, the mass calculated with the 1st η model is $11.15M_{\oplus}$, and according to the 2nd η model, it is $7.54M_{\oplus}$. In Case 2 in the upper right panel, the mass value is obtained as $10.43M_{\oplus}$ for the 1st η , and $7.06M_{\oplus}$ for the 2nd η . In Case 3 in the lower left panel, the mass corresponding to the 1st η is $21.38M_{\oplus}$, while according to the 2nd η model, this value is $14.46M_{\oplus}$. In Case 4 shown in the lower right panel, the relevant masses are calculated as $22.13M_{\oplus}$ and $14.97M_{\oplus}$, respectively.

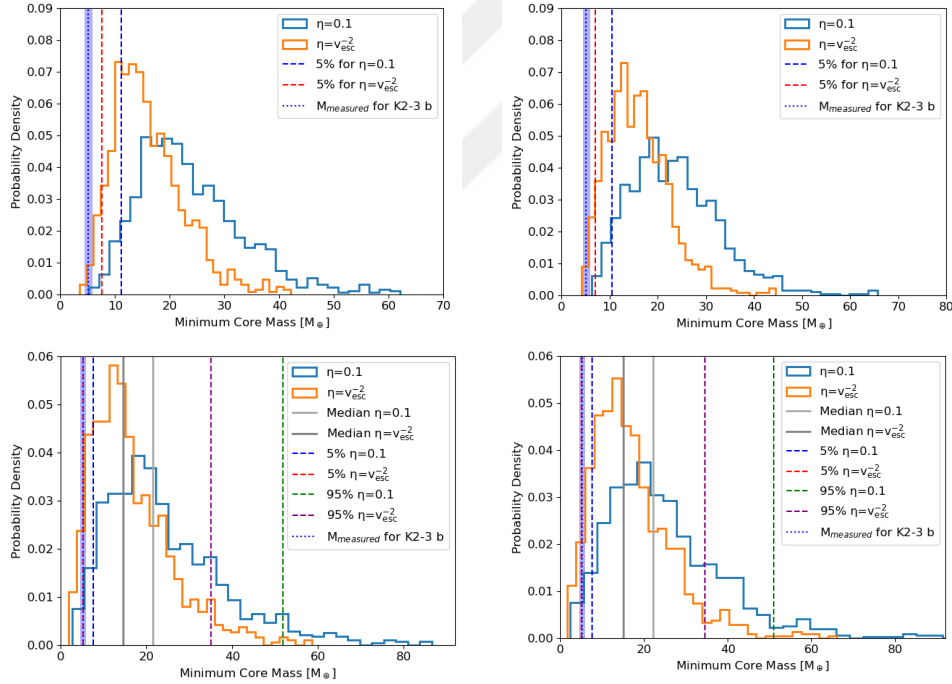


Figure 3.8. Histograms of minimum core mass distributions for four different cases of planet K2-3 b.

3.4 Relationship between Measured and Calculated Masses of Exoplanets

In the graph of Figure 3.9, the measured masses for each planet are compared with the minimum core masses calculated for different atmospheric

escape efficiencies (η). The green columns represent the measured masses obtained from observational data. The orange columns in the upper left (Case 1) and right (Case 2) panels of Figure 3.9 correspond to the masses calculated under the $\eta = 0.1$ model, and the error margins added to these columns show the values corresponding to only the positive error margins determined with 95% CL. The blue columns in the lower left (Case 3) and right (Case 4) panels of the same figure represent the masses calculated under the escape velocity dependent mass efficiency, and are the positive error margins determined with 95% CL, while the negative error margins are determined with 5% CL.

The error bars placed above each column represent the uncertainty ranges of the corresponding values, and these uncertainties have been derived as explained in Section 2.2.4. Furthermore, in the graphs of Figure 3.9, only the positive error margins, as described in Sections 3.1 and 3.2, are included. The reason for not including the graphs for the uncertainties of Case 1 and Case 2 in Figure 3.9, while adding the graphs for Case 1 and 2 in addition to Case 3 and 4, is to make the calculated masses of the selected six systems clearer².

Mass values are given on a logarithmic scale and in units of Earth mass ($M_{\oplus}$), making it possible to compare both low- and high-mass planets on the same axis. The graph contains data for the mini-Neptune class of planets Kepler-36 c, Kepler-656 b, GJ 357 d, Kepler-65 c, K2-3 b, and TOI-700 c, respectively. Planet names are placed obliquely on the horizontal axis.

The graphs created for four different cases below represent Case 1, Case 2, Case 3, and Case 4, respectively. When the cases are evaluated within themselves, there are no significant changes in Case 1 and Case 2 because the calculated masses are not very different from each other, and only positive error margins are used. On the other hand, more significant differences emerge in Case 3 and Case 4 due to both the different calculated mass values and the inclusion of $\pm$ error margins. In addition, when Cases 1-3 and Case 2-4 are compared, significant changes are observed in both the error margins and the calculated mass columns.

² Explanation regarding why the case and error margin information explained in Section 2.2.4 is not included in the graphs in Sections 3.1 and 3.2 but is found in Sections 3.4 and 3.5.

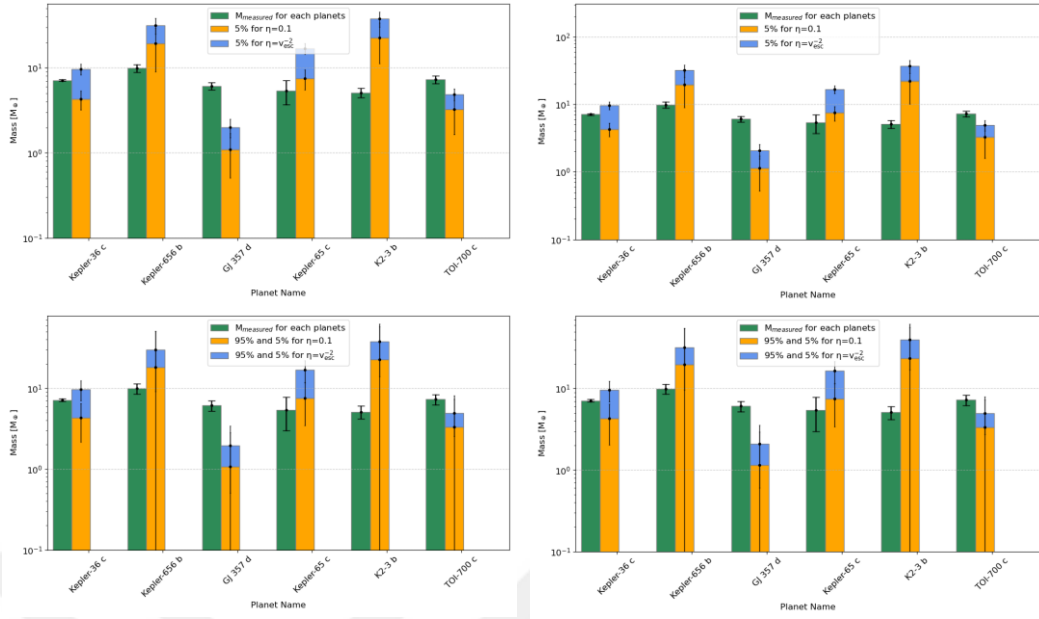


Figure 3.9. Comparison of the measured and calculated masses of six selected planets with their respective error margins for four different cases.

3.5 Relationship Between the Difference of Measured and Calculated Masses of Exoplanets

Figure 3.10 shows the differences between the observed mass values for each planet and the measured and calculated masses under different atmospheric escape scenarios. The green columns represent the measured total masses of the planets, while the pink and blue columns show the residual masses (ΔM) obtained under the assumptions of constant mass loss efficiency and escape velocity-dependent mass loss efficiency, respectively.

The left and right upper panels of Figure 3.1 correspond to Case 1 and Case 2, respectively, where the calculated masses have only positive error margins, determined by 95% CL. The left and right panels of the same figure are Case 3 and Case 4, respectively, where the calculated masses have positive error margins with 95% CL and negative error margins with 5% CL. As in Figure 3.15, the error bars added to each column show the uncertainty range of the relevant value².

In this context, negatively oriented bars indicate that the calculated mass of the planet is greater than its measured mass. The planets are listed along the

horizontal axis as Kepler-36 c, Kepler-656 b, GJ 357 d, Kepler-65 c, K2-3 b and TOI-700 c, respectively. Masses are given in units of Earth mass ($M_{\oplus}$).

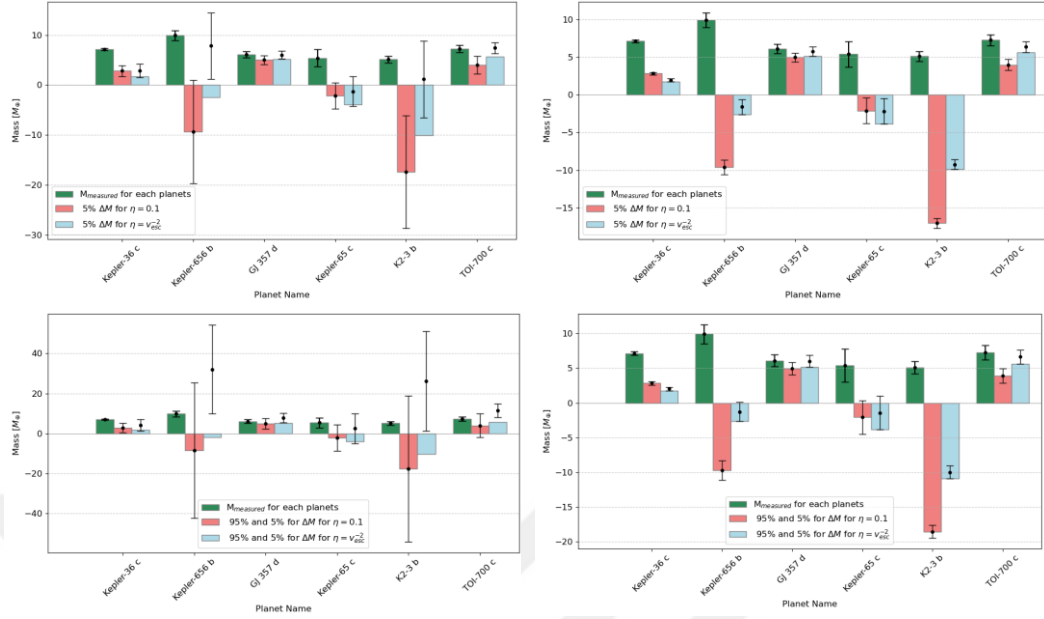


Figure 3.10. Comparison of the differences obtained by subtracting the calculated masses of the planets from the measured mass of the planet, with the margins of error, for four different cases.

Therefore, in Figure 3.10, there are noticeable changes for each case. The reason for this is that when the calculated masses are subtracted from the measured masses and their differences are taken, the resulting values do not contain similar values.

3.6 Calculated Mass Distributions of Exoplanets

Violin plots show the distributions of numerical data for one or more groups using density curves. The width of each curve corresponds to the approximate frequency of data points in each region. Figure 3.11 shows violin plots obtained using the minimum core mass distributions of six different exoplanets. The distributions obtained for each planet based on two different modeling approaches are compared. The pink violin graphs in the upper left (Case 1) and right (Case 2) panels of Figure 3.11 represent the masses calculated under the $\eta = 0.1$ model. The median of the orange lines on them represents the median value, while the ends represent only the positive error margins determined by the 95% CL. The blue violin graphs in the lower left (Case 3) and right (Case 4) panels of the same figure represent the masses calculated for which the mass loss efficiency depends on the

escape velocity, while the median of the blue lines on them is the median value. The blue lines at the ends represent the values corresponding to the positive error margins determined by 95% CL and the negative error margins determined by 5% CL.

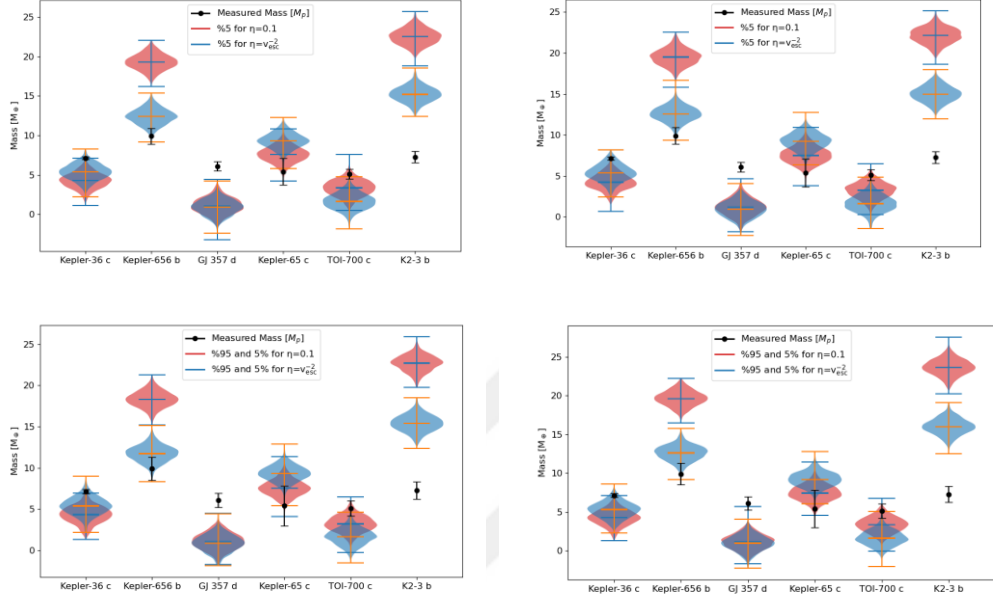


Figure 3.11. Visualization of the violin graphs of the six selected planets for four different situations.

In addition, the measured planetary masses reported in the literature and the uncertainties associated with these values are also included using black circle symbols and error bars². The planets Kepler-36 c, Kepler-656 b, GJ 357 d, Kepler-65 c, TOI-700 c, and K2-3 b are shown on the horizontal axis, respectively, and the masses are expressed in terms of Earth mass ($M_{\oplus}$) on the vertical axis.

Unlike Figure 3.10, no clear and distinct changes are observed. However, as explained in Figure 3.9, when evaluating each of the graphs created for the four different cases individually, no noticeable difference is observed in Case 1 and Case 2. This is because only the positive error margins are considered, and the calculated masses are very close to each other. On the other hand, in Case 3 and Case 4, the inclusion of both positive and negative error margins, along with the differences in the calculated mass values, leads to more distinct separations in the results. Additionally, when comparing Case 1 with Case 3 and Case 2 with Case 4, notable differences are observed in both the error margins and the mass values.

3.7 Relationship Between the Insolation Flux of Exoplanets and Residual Mass

The graphs in Figure 3.12, which are similar to the graphs created in Figure 3.2 with the results of the insolation flux calculations described in Section 2.2.2, are plotted against the residual mass calculation results described in Section 2.3 and shown in Section 3.5.

The red lines seen in the graph represent the residual masses obtained with the first mass loss efficiency model, which is a constant η . The left panel of Figure 3.12 corresponds to Case 3, and the error margins added to it are given as positive error margins at 95% CL and negative error margins at 5% CL.

Similarly, the blue lines show the residual masses obtained with the second mass loss efficiency model η , depending on the escape velocity. The graph in the right panel of the figure corresponds to Case 4, and the error margins on it is given as 95% CL for positive and 5% for negative error margins, as explained for Case 3.

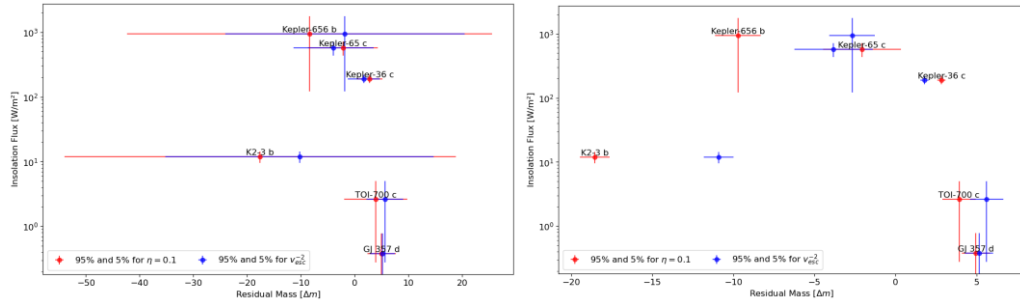


Figure 3.12. Scatter plot of residual masses versus calculated insolation flux for six selected systems.

In the graphs provided in Figure 3.12, unlike the graphs presented in Figures 3.9, 3.10, and 3.11, no quartet is given. As explained in Sections 3.1 and 3.2 and with the same purpose as the graphs added to Figure 3.2, only Case 3 and Case 4 are presented.

As can be seen from the figure, since all the results are different for the four cases in the residual calculations, there are also significant differences between Case 3 and Case 4. In the graph, it is seen that the insolation flux values

corresponding to the y-axis are constant in the calculation results, and the differences in the residual masses and their error margins along the x-axis are seen. As previously stated in Section 2.2.4, the $\pm$ error margins of the measured and calculated masses were used in Case 3, and only the $\pm$ error margins of the measured mass were used in Case 4.

3.8 Histograms of Exoplanet Residual Mass and S/N Ratio

In the histograms of residual mass (ΔM) and S/N ratio (sigma, σ) in this section, the residual mass calculations for the selected six exoplanet systems, as described in Section 2.3 and shown in Section 3.5, are included. These systems are also part of the sub-target lists in Table 2.1, and the results of the hypothesis test conducted for photoevaporation across three different scenarios for all systems are presented.

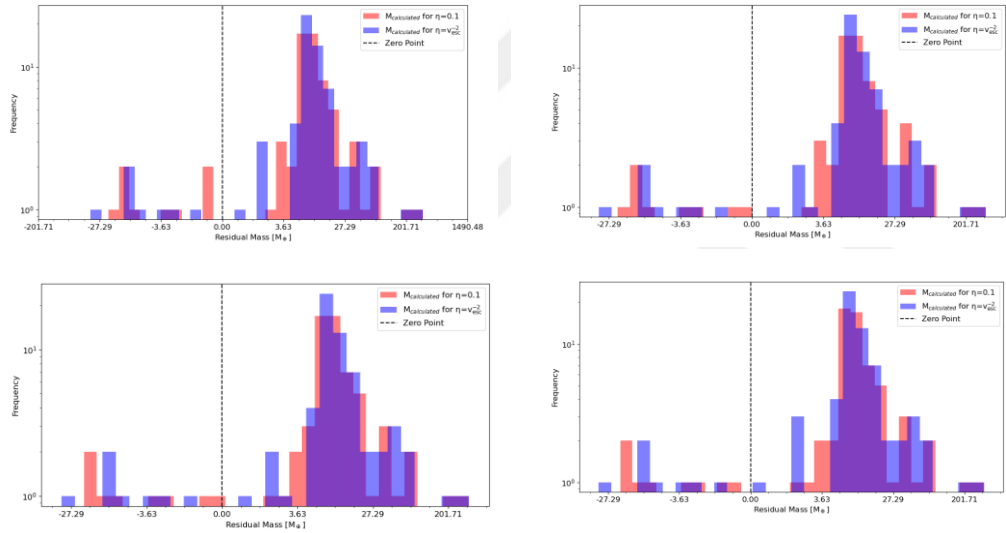


Figure 3.13. Histogram of residual masses versus frequency generated for the four cases corresponding to the conditions of scenario 1, which is the first of the sub-target lists.

As seen in Figure 3.13, there are residual mass histograms obtained for all exoplanet systems under scenario 1 and its sub-target list. As seen in the graphs, pink distributions represent constant mass loss efficiency, and blue distributions represent mass loss efficiency depending on escape velocity (v_{esc}). Purple distributions show exoplanet populations where pink and blue distributions intersect.

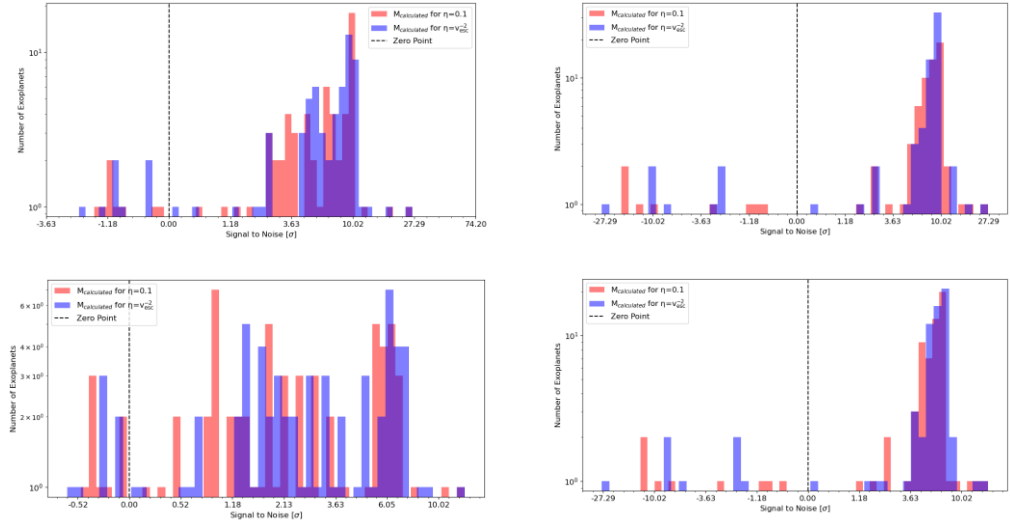


Figure 3.14. Histograms of the number of exoplanets versus sigma for the four cases created under scenario 1, which is the first of the sub-target lists.

Figure 3.14 shows the graphs of the parameters obtained by dividing the residual masses by the error margins in the residual masses, as explained in Section 2.3, using the residual mass histograms given in Figure 3.13. These graphs were created to find out the significance of the mass values of exoplanets previously studied within the scope of the photoevaporation hypothesis.

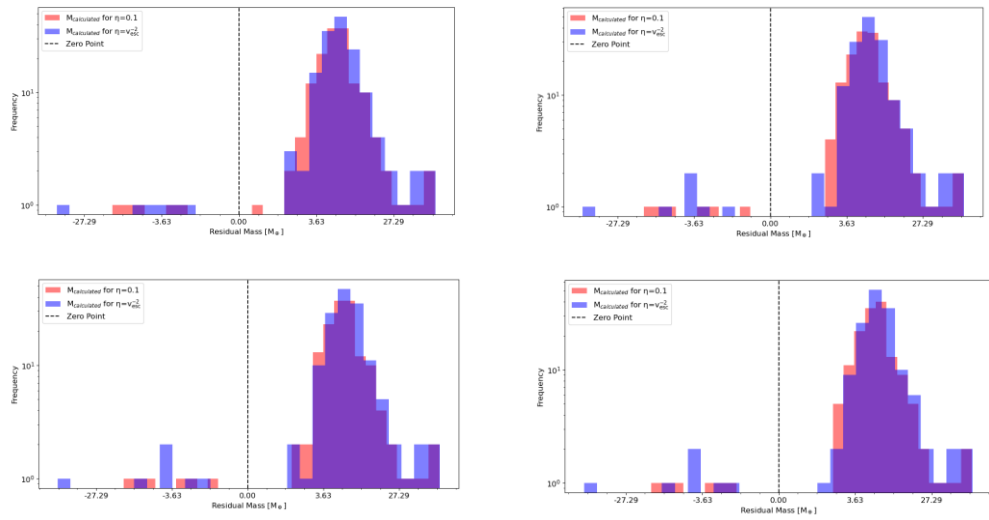


Figure 3.15. Histogram of residual masses corresponding to the frequencies obtained according to the four different cases of scenario 2, within the scope of the second sub-target list.

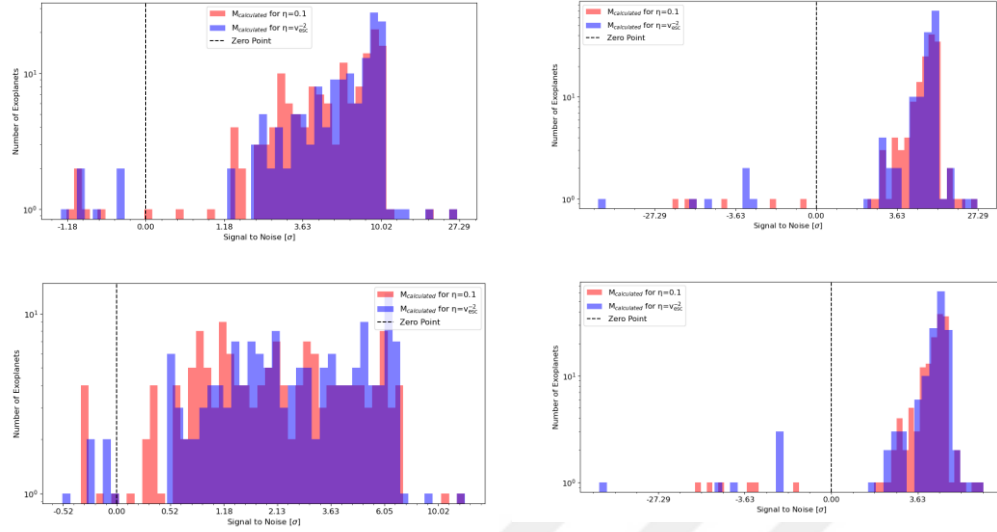


Figure 3.16. Histograms of the number of exoplanets calculated according to sigma values in the direction of the four cases defined in scenario 2, belonging to the second of the sub-target lists.

Figure 3.15 shows the residual mass histograms for all exoplanet systems analyzed under scenario 2 and its sub-target list. In addition to the color information explained for Figure 3.13, these histograms are given in units of Earth mass ($M_{\oplus}$) in all residual mass frequency graphs, and the masses are shown on the x-axis. The y-axis corresponding to the frequencies is presented logarithmically.

Figure 3.16 shows the graphs showing the sigma values corresponding to the residual mass histograms presented in Figure 3.15. There are significant differences between the distributions of the sigma values shown in the graph and the distributions in the graphs created for residual mass versus frequency. In addition, as in the residual mass distribution graphs, the y-axes are given logarithmically in all S/N ratio graphs.

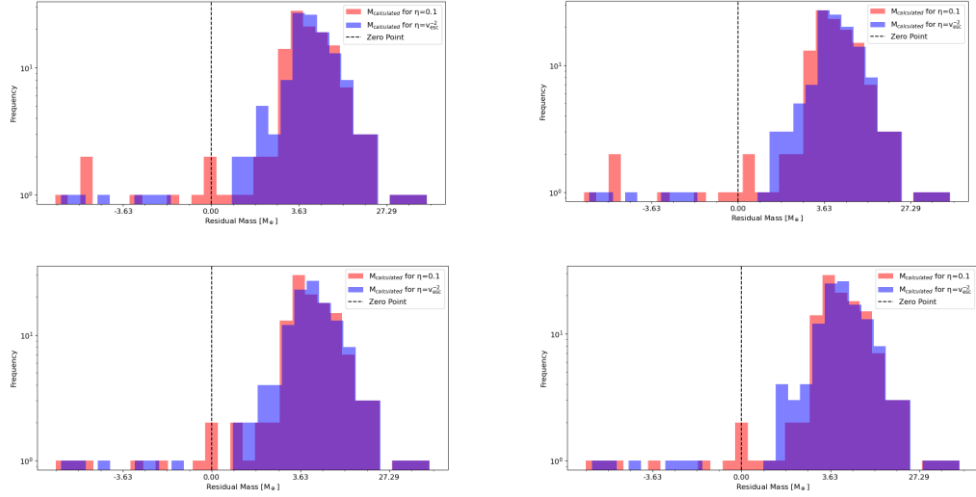


Figure 3.17. Residual mass histogram of the third sub-target list obtained with frequency data generated according to the four cases in scenario 3.

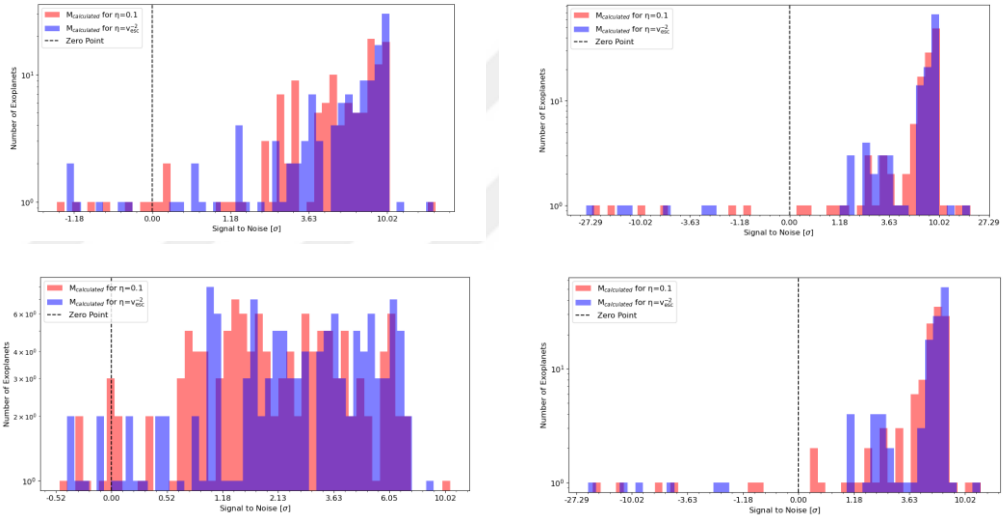


Figure 3.18. Histograms show the distribution of exoplanet numbers on a sigma basis according to the third sub-target list for the four different cases evaluated under scenario 3.

Figure 3.17 presents histograms of the residual mass distributions for all exoplanet systems included in the sub-target list determined under scenario 3.

Figure 3.18 shows the graphs showing the sigma values corresponding to the residual mass histograms given in Figure 3.17. In these graphs, the degree to which the residual mass distributions of the analyzed exoplanet systems differ statistically

from the photoevaporation model defined in the literature and the significance levels are numerically expressed.

All the residual mass and sigma graphs presented here were created by considering the case differences explained in Section 2.2.4. Additionally, all the graphs and tables presented under the Results section, as well as those in Appendix 2, are provided for the cases obtained by adding a 10% margin of error to the parameters missing uncertainty values, as illustrated in Photo 2.4 under Section 2.2.2. However, as an example, the minimum core mass histograms for the Kepler-36 system, presented under the heading "Calculated Minimum Core Mass Distributions of Exoplanets," were obtained by adding a 20% error margin to the missing parameter uncertainties and are provided in the appendix (Appendix 1).

3.9 S/N Tables Constructed from the Residual Masses of Exoplanets

The tables below, based on the residual masses shown in Figures 3.14, 3.16, and 3.18 of Section 3.8, present the signal-to-noise (S/N) ratios expressed in sigma for all systems identified as negative under the defined scenarios for each sub-target list. These tables include the “super” or “mini” planet classifications of the systems, along with the quantitative sigma values calculated to evaluate how significantly each of the four different cases supports the photoevaporation hypothesis proposed in the literature.

Table 3.1. Based on the histogram graph in Figure 3.14, the names of all systems with negative mass differences in the first sub-target list and the first scenario, and the sigma values calculated for each system considering two separate mass efficiencies are shown.

super name	mini name	Case 1	Case 2	Case 3	Case 4
		σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)
DMPP-1 c	DMPP-1 c	-0.10 (0.47)	-0.67 (1.91)	-0.04 (0.16)	-0.48 (1.35)
HD 96700 c	HD 96700 b	-1.18 (-0.88)	-13.26 (-7.12)	-0.40 (-0.29)	-9.92 (-5.43)
Kepler-114 c	Kepler-114 d	-0.20 (-0.36)	-0.98 (-2.15)	-0.07 (-0.12)	-1.10 (-1.98)
Kepler-33 b	Kepler-33 c	-1.54 (-2.05)	-2.70 (-29.22)	-0.49 (-0.64)	-2.58 (-27.99)
Kepler-430 c	Kepler-430 b	-1.26 (-0.99)	-19.47 (-10.88)	-0.36 (-0.28)	-13.11 (-7.22)
Kepler-65 d	Kepler-65 c	-0.82 (-1.33)	-1.20 (-2.23)	-0.33 (-0.53)	-0.86 (-1.59)
Kepler-656 c	Kepler-656 b	-0.91 (-0.37)	-9.69 (-2.63)	-0.25 (-0.08)	-6.93 (-1.91)
Kepler-769 c	Kepler-769 b	-1.14 (-0.92)	-17.16 (-10.68)	-0.31 (-0.25)	-11.70 (-7.22)

Table 3.2. In this table of the histogram shown in Figure 3.16, the names of the systems with negative mass differences in the second sub-target list and the second scenario, and the sigma values obtained with two different mass efficiencies are shown.

super name	mini name	Case 1	Case 2	Case 3	Case 4
		σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)
Kepler-200 c	Kepler-200 b	-0.60 (-0.38)	-4.99 (-2.72)	-0.15 (-0.09)	-3.04 (-1.51)
Kepler-2000 c	Kepler-2000 b	-1.20 (-0.95)	-17.64(-10.30)	-0.34 (-0.26)	-11.61 (-6.65)
Kepler-246 c	Kepler-246 b	-0.95 (-0.72)	-11.40 (-6.70)	-0.30 (-0.22)	-8.36 (-4.98)
Kepler-272 c	Kepler-272 d	0.02 (-0.91)	-0.34(-110.80)	-0.01 (-0.05)	-2.64(-106.38)
Kepler-65 d	Kepler-65 c	-0.82 (-1.30)	-1.24 (-2.28)	-0.33 (-0.53)	-0.86 (-1.59)
Kepler-656 c	Kepler-656 b	-0.91 (-0.34)	-9.89 (-2.76)	-0.27 (-0.11)	-6.34 (-1.53)

Table 3.3. In the third sub-target list and third scenario, the names of the systems with negative mass differences in the histogram in Figure 3.18, and the sigma values determined for two different mass efficiencies are shown.

super name	mini name	Case 1	Case 2	Case 3	Case 4
		σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)
K2-3 d	K2-3 b	-1.54(-1.32)	-26.24 (-15.21)	-0.48(-0.41)	-20.34 (-11.95)
Kepler-114 b	Kepler-114 c	0.92 (-0.73)	3.42 (-6.20)	0.28 (-0.23)	2.21 (-4.89)
Kepler-134 c	Kepler-134 b	-0.13 (0.37)	-0.92 (1.55)	-0.03 (0.11)	-0.73 (1.04)
Kepler-1669 d	Kepler-1669 c	-0.66(-0.36)	-6.58 (-2.78)	-0.20(-0.11)	-4.81 (-2.09)
Kepler-235 c	Kepler-235 b	-0.29 (0.24)	-1.38 (1.66)	-0.11 (0.04)	-0.98 (1.17)
Kepler-354 d	Kepler-354 b	-1.20(-1.05)	-19.06 (-13.34)	-0.33(-0.28)	-12.91 (-8.97)
Kepler-415 b	Kepler-415 c	5.15 (-1.33)	8.02 (-29.58)	1.46 (-0.40)	5.62 (-22.05)
Kepler-656 c	Kepler-656 b	-0.86(-0.33)	-9.24 (-2.34)	-0.28(-0.11)	-6.49 (-1.62)

In this section, all findings obtained within the scope of the study are presented through graphs and tables, and the analysis results performed for each scenario and sub-target list are presented in detail. In this context, distributions and comparisons regarding basic parameters such as residual masses, sigma values , and exoplanet numbers are shared with visual support. In the next section, the scientific meanings of the findings presented here will be examined; the similarities or differences of the obtained results with existing studies in the literature will be discussed. In addition, a general evaluation will be made by discussing the potential causes and possible effects of the findings within the framework of the assumptions and limitations of the study.

4. DISCUSSION

When the results obtained from the detailed analysis of all confirmed exoplanets in the NEA database and six different exoplanet systems selected from among them are examined under the heading of Results, it is seen that the vast majority of them lost their atmospheres with the “photoevaporation” hypothesis in the literature and that it is statistically significant. In this context, systems predicted to lose their atmospheres with the photoevaporation hypothesis in the literature (if their calculated mass is not more than their measured mass) are considered “consistent”, while planets losing their atmospheres with a mechanism other than photoevaporation (if their calculated mass is more than their measured mass) are considered “inconsistent”. Therefore, this study aims to examine the explainability of the atmospheric losses of exoplanets with various parameters, starting from the selected six different exoplanet systems and expanding the scope to all confirmed exoplanets in the NEA database.

4.1 Interpretation of the Radius-Mass Relationship of Exoplanets

The exoplanets analyzed in this study are classified based on density and radius (Table 2.1), in which the radius valley stands out as an important distinguishing criterion. The radius valley is a distinct gap observed in the radius distribution of planets, and the planets in the lower part of this gap are defined as super-Earths, and those in the upper part are defined as mini-Neptunes (Fulton et al., 2017; Owen & Estrada, 2020; Owen & Wu, 2017).

The graph presented in Figure 3.1 shows the relationship between the mass and radius parameters of the six analyzed planets. Although this graph does not provide direct information about the atmospheric loss, it is valuable in terms of making initial inferences about the physical structure of the planets.

This graph shows the mini-Neptune planets of the systems that meet the conditions of the sub-target lists in Table 2.1. Planets that have a large radius, high mass, low density, and a semi-major axis far from their star and are gaseous belong to the mini-Neptune class. In the system where each planet is located in the graph, there are also super-Earth class planets. These planets are rocky super-Earths with

small radius, low mass (Fulton et al., 2017; Lopez & Fortney, 2014; Marcy et al., 2014; Owen & Estrada, 2020; Owen & Wu, 2013, 2017), low density, and a semi-major axis close to their star. Considering all these parameters, it is thought that the mini-Neptune planets in the systems in Figure 3.1, unlike the super-Earths in the same system, did not completely lose their atmospheres and become super-Earths; they were planets that partially preserved their atmospheres and remained as mini-Neptunes due to various factors.

Although these six systems are generally considered to have remained as mini-Neptunes without completely losing their atmospheres, partial atmospheric losses observed in Kepler-36 c (Owen & Estrada, 2020), GJ 357 d (Kaltenegger et al., 2019), and TOI-700 c (Gilbert et al., 2020) can be explained under the photoevaporation hypothesis, according to the literature. However, the same does not seem to apply to Kepler-65 c (Mills et al., 2019), K2-3 b (Diamond-Lowe et al., 2022), and Kepler-656 b (Berger et al., 2020), as their calculated minimum core masses exceed their measured total masses. Therefore, for these systems that are inconsistent with the photoevaporation hypothesis, it suggests that different processes may be responsible for atmospheric loss. Considering factors such as gravitational force or their distance to the host star, these planets may have experienced atmospheric loss through mechanisms other than photoevaporation, such as stellar wind effects or magnetic field interactions.

These observations are in direct agreement with the theoretical frameworks presented in the literature. Small-radius planets generally have low mass and therefore weak gravity. This physical property facilitates atmospheric loss by increasing the rate at which the atmosphere escapes from the surface. Such planets are often called super-Earths and can lose their atmospheres, especially under the intense XUV radiation emitted by young stars (Lopez & Fortney, 2014; Owen & Estrada, 2020; Owen & Wu, 2013, 2017). In contrast, large-radius, high-mass mini-Neptune planets are better able to preserve their atmospheres due to their strong gravity.

As proposed in the study, it is quite challenging to explain the atmospheric loss processes of exoplanets and their demographic structure solely based on the

mass-radius relationship. However, the density derived from the mass and radius parameters can provide more direct insight into a planet's atmospheric retention capacity (Brinkman et al., 2023). Therefore, low-density mini-Neptunes tend to retain their thick atmospheres due to their higher masses, whereas high-density super-Earths possess thinner atmospheres and are more prone to atmospheric loss because of their lower masses. In this context, it has also been argued that, in addition to density, the distance from the star (semi-major axis) plays a significant role in atmospheric evolution (Appendix 3). For instance, it is frequently emphasized in the literature that super-Earths, when located at smaller semi-major axes—meaning closer orbits to their host stars—can lose their atmospheres due to high XUV exposure, transitioning from mini-Neptune sizes to super-Earths (Lopez & Fortney, 2014; Owen & Estrada, 2020; Owen & Wu, 2013, 2017). On the other hand, mini-Neptunes residing at larger orbital distances are less affected by this radiation and can retain their atmospheres for longer periods, thereby remaining as mini-Neptunes. However, some intriguing systems have been identified where planets, despite being located at relatively large semi-major axes, still exhibit super-Earth characteristics (Owen & Estrada, 2020) (Appendix 3).

In this context, Figure 3.1 shows that an interpretation of atmospheric loss limited to mass and radius data alone may be incomplete within the scope of the literature.

This study not only reveals the mass-radius-density relationship in line with the literature but also presents a multi-parameter analysis framework for understanding the evolution of exoplanet atmospheres. In this respect, the study makes an original contribution to the literature by adopting not only a confirmatory but also an explanatory approach.

4.2 Interpretation of the Relationship Between the Insolation Flux of Exoplanets and Their Measured Mass and Radius

In this study, the measured mass and the insolation flux (W/m^2) data calculated accordingly for different exoplanet systems are comparatively examined in the upper panel of Figure 3.2. The insolation flux versus planet radius is given in the lower panel of the same figure. The relationship between the insolation flux and

the planet mass ($M_{\oplus}$) and radius ($R_{\oplus}$) is evaluated with the help of two separate graphs. The data examined with the error margins in all systems revealed that the amount of energy received from the star shows different distributions in certain mass and radius ranges. The data in Table 2.1 show that the mini-Neptune class planets in the range of about 2–4 $R_{\oplus}$ in the systems collected under three different scenarios are clustered in different positions concerning the insolation flux.

In the upper panel of Figure 3.2, planets with high insolation fluxes, such as Kepler-656 b and Kepler-65 c, as well as planets with low fluxes, such as GJ 357 d and TOI-700 c, are particularly noteworthy in terms of comparison with their masses and the observation of different evolutionary processes. In the lower panel of the same figure, it is observed that exoplanets in the 2–3 $R_{\oplus}$ range are exposed to lower insolation fluxes, while those above about 3 $R_{\oplus}$ have much higher insolation flux values.

In the literature, the photoevaporation hypothesis suggests that planets can lose their atmospheres, especially if they have low mass, when exposed to insolation flux between 100–1000 W/m^2 (Fulton et al., 2017; Lopez & Fortney, 2014; Owen & Estrada, 2020; Owen & Wu, 2013, 2017). In this context, it is thought that Kepler-65 c, in particular, may be a planet that has partially lost its atmosphere due to its low mass and high insolation flux value. GJ 357 d, on the other hand, may be less affected by the radiation effects of its star due to both its low mass and low exposure to insolation flux. Similarly, the distributions of radius and insolation flux imply that the radius of planets exposed to high irradiance decreases over time due to atmospheric loss, as predicted by the photoevaporation hypothesis, and that a larger radius can be preserved under lower irradiance (Fulton et al., 2017; Lopez & Fortney, 2014; Owen & Wu, 2013, 2017).

Therefore, when it is considered that each of the systems in the graph experience atmospheric loss regardless of whether it is by photoevaporation mechanism, it is predicted that low-mass and high-insolation flux planets (such as Kepler-65 c) tend to lose more atmosphere when looking at how much or little atmosphere they lose, while high-mass and high-insolation flux planets (such as Kepler-656 b) can resist this effect more due to their mass. In addition, it can be

concluded that intermediate-mass planets (K2-3b) can partially preserve their atmospheres well in low-insolation flux regions. In addition, it is observed that there is a separation in the radius distribution of planets receiving high radiation, while planets under low radiation have a wider radius range for the planetary radius and radiation relationship. This is especially consistent with the hypothesis that planets with a radius of $2.5\text{--}3 R_{\oplus}$ go through similar evolutionary processes with photoevaporation at different radiation levels.

These findings are of great importance in testing and updating theories on the atmospheric evolution of planets. The combined evaluation of mass and radiation reveals that classifications based on only one parameter are insufficient and that multi-dimensional analyses are necessary.

This visual analysis of the mass and radiance plane in the upper panel of the figure provides an original contribution to the literature by comparing extreme examples. In addition, the lower panel of the figure provides one-to-one comparative interpretations with detailed radiance and radius data for specific exoplanets. Such plots allow us to determine not only general trends but also the evolutionary positions of individual planets.

4.3 Interpretation of the Calculated Minimum Core Mass Distributions of Exoplanets

The findings of all minimum core mass graphs presented in Section 3.3 are discussed for four different cases. Considering the calculated minimum core masses and measured masses of the six selected samples for consistency and inconsistency with photoevaporation mentioned in the introduction of the Discussion section, the planets Kepler-36 c (scenario 1), GJ 357 d (scenario 2) and TOI-700 c (scenario 3) are found to be consistent with photoevaporation, while the planets Kepler-656 b (scenario 1), Kepler-65 c (scenario 2) and K2-3 b (scenario 3) are found to be inconsistent with photoevaporation. The vertical dotted lines with uncertainty bands seen in the four panels of the graphs of all minimum core mass distributions presented in Figures 3.3 to 3.8 represent the measured masses of the planets. The calculated mass distributions (orange and blue) and the calculated masses corresponding to the error margins determined within 95% CL for Cases 1-2 are

shown with blue and red dashed lines. Similarly, for Cases 3-4, the light and dark gray solid lines represent the calculated minimum core masses.

➤ **Kepler-36**

As seen in Figure 3.3, the measured mass for Cases 1-2 of the planet Kepler-36 c is to the right of the calculated minimum core masses. Similarly, the measured mass for Cases 3-4 is to the right of the calculated minimum core masses.

This situation is the clearest indication that Kepler-36 c, which has lost its atmosphere, experienced atmospheric loss in a manner consistent with the photoevaporation mechanism. Therefore, the small variations in the calculated masses arising from the presented case differences have not had a negative impact on testing the mechanism.

When looking at the literature, one of the calculations made for Kepler-36 c was given in the Owen and Estrada 2020 article, and the minimum core mass was found to be $4.99 M_{\oplus}$ under the 95% upper limit (Owen & Estrada, 2020).

Therefore, in this study, all minimum core mass values calculated for different mass loss efficiencies for Kepler-36 c remained below the measured mass of the planet, $7.13 M_{\oplus}$, which is included in the NEA database and confirmed by the transit method, and provided evidence that it lost its atmosphere by photoevaporation. Thus, a result confirming the literature was obtained for Kepler-36 c, whose observational mass was measured by the transit method. In this context, the original contribution of the study is not only to verify the hypothesis, but also to systematically examine it under other parameters and conditions.

➤ **GJ 357**

The visual representation in Figure 3.4 is important in establishing the structural boundaries of the planet GJ 357 d and provides a direct reference point for testing the photoevaporation mechanism. The calculated masses in Cases 1-2 and 3-4 are below the mass of $6.10 M_{\oplus}$ predicted by the radial velocity method in the NEA database. These masses are observed in all versions of the panel and are

maintained despite changes in the parameter sets. This shows that the model produces consistent results under different assumptions.

Although photoevaporation-based analyses for the GJ 357 d system are limited in the literature, it has been clearly stated in studies that particularly relatively low-mass and short-period exoplanets (Lopez & Fortney, 2014; Owen & Wu, 2017) experience atmospheric loss. In this context, the minimum mass results obtained are consistent with model predictions assuming that GJ 357 d has lost its atmosphere. However, it should be taken into account that the mass used in the NEA database is the mass predicted by the radial velocity method and that there is no observational mass confirmed by the transit method.

According to the hypothesis under consideration, the fact that all minimum core masses calculated under different atmospheric loss efficiencies of the planet are well below the measured mass is considered an indication of atmospheric loss by the photoevaporation mechanism.

These findings directly demonstrate the effect of the photoevaporation mechanism on GJ 357 d and suggest that planets exposed to high-energy radiation lose their atmospheres over time and become more compact. This interpretation is in line with the “XUV flux threshold effect” proposed by reference (Lopez & Fortney, 2014) in particular and has sufficient physical basis to explain the current structure of the planet.

The analysis for this planet not only confirms the hypothesis, but also provides a methodological contribution to the literature by systematically examining how the atmospheric loss pattern changes under different parameter sets. In this way, a stronger physical framework is established for the evolution of the planet, and a new comparison area is created over GJ 357 d, one of the rarely studied systems.

➤ TOI-700

The graphical representation in Figure 3.5 provides a critical visual reference for determining the internal structural boundaries of the TOI-700 c planet and for assessing the validity of the photoevaporation mechanism.

The minimum core mass distributions shown with orange and blue curves and the corresponding calculated masses of Cases 1-2 and 3-4 are below the observed mass value of $7.27 M_{\oplus}$, which is the mass of the planet confirmed by the transit method and included in the NEA database. This situation can be observed in all variants of the panel and does not disrupt the model despite the changes in the parameter sets used. This finding reveals that the model provides stable and consistent outputs under various assumptions.

Previous studies on the TOI-700 system (Gilbert et al., 2020) emphasized that the planet has largely retained its structural integrity and that the atmosphere is likely to be preserved due to low stellar activity. This study, however, presents a case that could overturn this view, considering that the mass value used is an observational mass value; the possibility that the planet has lost its atmosphere is evaluated in the context of photoevaporation models.

The hypothesis is based on the assumption that if the calculated minimum core masses are below the measured masses, this is consistent with the planet losing its atmosphere by photoevaporation. All calculations for TOI-700 c fulfill this precondition and support the validity of the hypothesis for this planet.

Therefore, these results show that TOI-700 c can lose its atmosphere even in a low-density stellar environment.

This analysis provides a critical contribution to the literature trend by showing that atmospheric loss is possible even in systems with low stellar activity and close to the habitable zone, such as TOI-700. It also introduces parametric diversity to planetary evolution models by testing the planet's atmospheric loss history under different efficiency scenarios.

➤ **Kepler-656**

In Figure 3.6, the structure enables an easy evaluation of the positional relationship between the mass distributions obtained under different parameters for the planet Kepler-656 b and its observed mass.

For the minimum core mass distributions shown by the orange and blue curves in the graphs, the calculated masses in Cases 1 and 2 produce values below the observed mass of the planet, $9.91 M_{\oplus}$, which is in the NEA database and confirmed by the transit method; while the calculated masses for Cases 3 and 4 are located above the observed mass of the planet, $9.91 M_{\oplus}$. Since the majority of the distributions in these four cases lie to the right of the measured mass, it can be said that they are highly inconsistent with photoevaporation.

There is no specific information in the literature regarding the directly calculated mass value of the planet Kepler-656 b. However, as mentioned in reference (Berger et al., 2020), it is anticipated that, in addition to Kepler-656 b being considered as a possible explanation for photoevaporation, other possible scenarios may also be effective. Thus, it is understood that the values below the measured mass for Cases 1-2 and the values above the measured mass for Cases 3-4 are consistent with the information in the literature for the planet Kepler-656 b, whose mass was measured by the transit method.

The different findings observed between Cases 1-2 and 3-4 indicate that additional models and observations are needed to better understand the role of photoevaporation in the evolutionary processes of planets.

Although there are no direct mass calculations for Kepler-656 b in the literature, the presence of mass calculations for four different cases in this study will facilitate studies that will examine the planet's properties in more detail.

➤ **Kepler-65**

In Figure 3.7, each panel allows for an evaluation of how the mass distributions obtained under different conditions for Kepler-65 c relate to the observed mass. The minimum core mass distributions, represented by the orange

and blue curves, show that the calculated masses in Cases 1–4 are positioned to the right of the measured mass of $5.40 M_{\oplus}$, as reported in the NEA database for the planet discovered via the radial velocity method and confirmed through the transit method. Since the calculated masses exceed the observed mass, these estimations appear to be inconsistent with the photoevaporation effect.

There is no directly calculated mass value in the literature for the planet Kepler-65 c. As mentioned in reference (Mills et al., 2019), there are inferences that Kepler-65 c offers a possible explanation in terms of photoevaporation. However, this study presents a situation that may overturn this view; the possibility of the planet losing its atmosphere by a mechanism other than photoevaporation is considered, because the measured mass of the planet was predicted by the radial velocity method and confirmed by the transit method.

The hypothesis presented in this study was investigated by examining the role of the photoevaporation effect on the mass distribution of the planet. Comparing the distributions in Figure 3.7 with the observational mass is an important place to evaluate the accuracy of this hypothesis.

The fact that the calculated masses are above the observational mass in all cases shows that the photoevaporation effect is not valid in these cases.

This situation falsifies the validity of our hypothesis and reveals interesting systems, emphasizing that mechanisms other than photoevaporation may also play a role in planetary evolution.

Although direct mass calculations for Kepler-65 c are not available in the literature, the minimum core masses calculated for four different cases in this study provide opportunities for studies that will examine the properties of this planet in more detail.

➤ K2-3

Figure 3.8 provides an opportunity to analyze the relationship between the calculated mass distributions obtained for K2-3 b and the observed mass under different scenarios.

The minimum core mass distributions shown by the orange and blue curves in the graphs, the calculated masses for Case 1 and Case 2, respectively, are a certain amount above the observed mass of the planet, $5.11 M_{\oplus}$, which is found in the NEA database and discovered by the radial velocity method and confirmed by the transit method. On the other hand, the calculated masses used for Case 3 and Case 4 also reflect estimates that are well above the observed mass. In these four cases, it can be said that the photoevaporation effect is inconsistent with these scenarios, since the majority of the mass distributions obtained for Cases 1-4 are to the right of the observed mass, and the calculated masses are above the observed value.

There is no directly calculated mass value for the planet K2-3 in the literature. However, as stated in reference (Diamond-Lowe et al., 2022), this planet can't have lost its atmosphere due to the photoevaporation mechanism. Considering that the measured mass value was initially predicted by the radial velocity and then confirmed by the transit method, the results in this study also support the literature.

The hypothesis put forward in this study aims to examine the effect of photoevaporation on the mass distribution of the planet. Comparison of the distributions in Figure 3.8 with the observational mass is important in testing the validity of the hypothesis.

The fact that the calculated masses are higher than the observed masses in all scenarios shows that the photoevaporation effect is not valid, which invalidates the photoevaporation hypothesis in the literature. At the same time, this finding emphasizes that evolutionary mechanisms other than photoevaporation can affect the mass of the planet.

Although direct mass calculations for planet K2-3 are not available in the literature, the minimum core mass estimates obtained under four different scenarios

in this study provide a valuable basis for further investigation of the planet's properties.

4.4 Measured and Calculated Masses of Exoplanets, Interpretation of the Differences Between the Masses, and Violin Plots

Figure 3.9, where the results obtained from the minimum core mass estimates are presented in comparison with the measured and calculated mass values from six different samples, clearly shows the distinction between systems consistent and inconsistent with the photoevaporation mechanism. In each panel of the bar graphs created for four different scenarios, the green colored columns represent the observationally measured masses of the planets, while the yellow and blue colored columns represent the calculated minimum core masses corresponding to different scenarios. This graphical presentation provides an important reference in both qualitative and quantitative terms when evaluating the validity of the photoevaporation hypothesis on a system-specific basis.

The three planets evaluated to be consistent with photoevaporation are Kepler-36 c, GJ 357 d and TOI-700 c. When the panels belonging to these three planets are examined, it is seen that the observed mass values for GJ 357 d and TOI-700 c, except for Kepler-36 c, are higher than the calculated minimum core masses. This situation is consistent with one of the basic assumptions of photoevaporation, which is that "the current mass of the planet should be equal to or greater than the remaining mass (core) after the loss of the atmosphere". In this context, the planets GJ 357 d and TOI-700 c are strongly consistent with evolutionary scenarios that can be explained by photoevaporation. Although Kepler-36 c is classified as consistent with photoevaporation, it presents a situation that contradicts this classification because the calculated core mass in the graphs is higher than the observed mass. However, the fact that the difference observed here is not large suggests that it may be due to uncertainties in this system or the effects of model parameters. Therefore, it is clear that Kepler-36 c needs to be supported by more advanced observations and detailed models to better understand the atmosphere loss mechanism.

On the other hand, planets considered inconsistent with photoevaporation include Kepler-656 b, Kepler-65 c, and K2-3 b. In the panels for each of these planets, it is clear that the calculated minimum core masses are systematically and significantly higher than the observed masses. These differences are too large to be explained by small modeling errors or measurement uncertainties alone. Therefore, these results contradict the hypothesis that these planets evolved by photoevaporation. Alternative explanations should be considered, such as the dominant role played by atmospheric loss mechanisms other than photoevaporation in these systems (e.g., gravitational escape, magnetic field effects, or interaction with high-energy particles), or that the planets did not have dense atmospheres from the beginning.

As a result, utilizing the bar charts in Figure 3.9, the consistency of six different systems with the photoevaporation hypothesis can be comparatively assessed, and which systems are consistent or inconsistent with this mechanism can be clearly distinguished. This comprehensive visualization is an important tool for understanding the evolutionary history of the planets and testing different scenarios of atmospheric loss processes. It also reveals the need for further analysis based on parametric diversity to understand the differences between the planets.

Figure 3.10 visualizes the consistency of the planets with the photoevaporation mechanism or the situations that contradict this mechanism in a simpler but equally powerful way. The graph, as in the previous figures, is evaluated under four different scenarios, each presented separately in a different panel. Thanks to this structure, detailed analysis can be made on a planetary basis, and general trends can also be evaluated comparatively.

The green bars in the figure represent observational mass measurements in the NEA database. However, the pink and blue bars show the differences obtained by subtracting the calculated minimum core masses from the measured masses for each scenario. Whether these differences are positive or negative is the key determinant of whether the current mass of the planet is consistent with the predicted core mass in the photoevaporation scenario. Positive differences indicate that the observed mass of the planet is greater than the calculated minimum core

mass, and therefore that even with the loss of the atmosphere, the remaining core is still smaller than the observed mass, i.e., has undergone an evolution consistent with photoevaporation. Negative differences, on the other hand, indicate that the calculated masses are greater than the observed masses, and therefore that the planet may have undergone an evolution that cannot be explained by the photoevaporation scenario.

When evaluated in this context, the fact that the pink and blue columns of the planets Kepler-36 c, GJ 357 d and TOI-700 c remain at positive values strongly supports that these systems have an evolutionary history consistent with the photoevaporation effect. In particular, the fact that the previously calculated mass for Kepler-36 c in Figure 3.9 was higher than the measured mass gave the impression of inconsistency with photoevaporation at first glance. However, according to the difference analysis in Figure 3.10, it is seen that the observed mass for Kepler-36 c is higher than the calculated minimum core mass. This suggests that the possible inconsistency in Figure 3.9 is due to measurement uncertainties or possible deviations in model parameters. In this context, the validity of the previous inference that Kepler-36 c may be inconsistent with photoevaporation is eliminated, and the view that the system may have undergone an evolution consistent with the photoevaporation process is established on a more solid ground.

On the other hand, the negative differences observed in the panels of Kepler-656 b, Kepler-65 c and K2-3 b planets provide results that are in serious conflict with photoevaporation. In these systems, the blue and pink bars lean towards negative values, indicating that the observed masses fall short of the minimum core masses calculated based on the scenario. The fact that these differences are significant indicates that there are systematic differences that cannot be explained by modeling uncertainties alone and suggests that photoevaporation is not an effective mechanism of atmospheric loss in these systems. In these planets, atmospheric loss may need to be explained by more complex physical processes or other mechanisms (e.g., magnetic fields, stellar winds, low initial atmospheric mass).

In general, this difference analysis method presented in Figure 3.10 stands out as a highly functional tool in testing the validity of the photoevaporation hypothesis. Compared to direct comparisons made on the mass values calculated in the previous figures, the evaluation of the differences provides a simpler and more comparative analysis. In addition, this approach contributes to obtaining more reliable results by balancing the measurement deviations that may occur in inter-system comparisons. In this respect, Figure 3.10 is of critical importance in testing the hypothesis put forward in the study and allows for more robust inferences to be made regarding the atmospheric evolution of the planets.

In Figure 3.11, another representation for the calculated mass estimates obtained for the measured mass and minimum core mass is a representation presented in the form of violin plots, instead of histograms. Thanks to this presentation format, the density profile, central tendencies, and probability densities of each distribution can be observed more visually. Such plots allow the evaluation of the mass distributions of each planetary system, which are discussed in detail in Section 4.3, from an alternative perspective. In Figure 3.11, as in the previous histogram distributions (Figures 3.9 and Figure 3.10), the analysis was performed by considering four different cases (Case 1–4), and these cases were visually presented in four separate panels.

Using violin plots more clearly reveals the overlaps and divergences between the distributions, and thus demonstrates the consistency or inconsistency with the photoevaporation hypothesis in a much more striking way. In this context, the overlap of the violin curves of the planets Kepler-36 c, GJ 357 d, and TOI-700 c, i.e., the significant overlap of their mass distributions with the observed mass values, strongly supports the photoevaporation hypothesis for these planets. These overlaps show that both the calculated minimum core masses are in ranges consistent with the observed masses and that a large portion of the probability densities are below the observed masses. This suggests that these systems may have lost their atmospheres via photoevaporation and that their remaining masses can be explained by this mechanism.

On the other hand, the violin curves observed in the Kepler-656 b, Kepler-65 c, and K2-3 b systems are shifted away from the observed mass to higher values, and are concentrated in areas that do not coincide with the observed mass. This apparent separation shows that these planets are inconsistent with the photoevaporation scenario and that their minimum core masses are higher than the observed values. This situation suggests that other physical mechanisms, other than photoevaporation, may be at play to explain the atmospheric loss of these planets. These separations are observable on the graph, and the fact that the probability densities are far outside the observed mass value reveals this inconsistency.

In particular, violin plots reflect the shapes and spreads of distributions more precisely, giving an idea about the behavior of the entire distribution, not just the mean or median values. In this respect, Figure 3.11 stands out as a powerful analysis tool that brings together statistical evaluations in testing the photoevaporation hypothesis.

As a result, the findings obtained in this visual are both consistent with the previous graphs and provide important clues about the validity of the hypothesis. This comparison made on the violin graphs provides a more detailed view of how different planetary systems differ from each other in terms of atmospheric evolution, and provides a deeper perspective on the extent to which the photoevaporation mechanism is valid.

4.5 Interpretation of the Relationship Between the Insolation Flux of Exoplanets and Residual Mass

Figure 3.12 presents the residual mass (i.e. difference) values of the systems that play a critical role in testing the photoevaporation hypothesis, concerning the insolation flux they receive from their stars, for two different cases. In these graphs, the difference between the measured and calculated masses of the planets (Δm) is shown on the horizontal axis, while the insolation flux (W/m^2) is shown on the vertical axis on a logarithmic scale.

The top panel of the figure corresponds to Case 3, where it can be observed that the masses for the Kepler-656 b, Kepler-65 c, and K2-3 b systems fall

significantly below zero. These negative Δm values indicate that the measured masses are much lower than the minimum core masses calculated according to the photoevaporation model. This reveals that these three planets are inconsistent with the photoevaporation hypothesis. On the other hand, the planets Kepler-36 c, GJ 357 d, and TOI-700 c show positive Δm values, demonstrating consistency with the model. It can be said that these systems have undergone atmospheric loss processes that can be explained by photoevaporation, and that their current measured masses support this process.

The lower panel of the same figure is related to Case 4. The results show generally similar trends to the first graph, but a particularly striking change is observed for the planets Kepler-36 c, K2-3 b, and Kepler-656 b.

When both graphs are evaluated together, it becomes clear that photoevaporation is highly sensitive not only to the insolation flux received from the star but also to the structural properties of the planet and the parameter assumptions used.

In conclusion, these two graphs provide strong examples that both support and question the validity of the photoevaporation hypothesis in specific systems. In particular, the clarification of the effect of different parameter choices on system behavior requires a clearer test of the hypothesis with higher accuracy observations and modeling in the future. Atmospheric loss mechanisms other than photoevaporation should also be taken into consideration at this point, and alternative explanations should be developed, especially for systems with inconsistent results.

4.6 Interpretation of Residual Mass–S/N Ratio Histograms and Tables of Exoplanets

This section covers the evaluation of the values obtained as a result of the statistical analysis of the measured and calculated mass differences (residual mass) within the framework of the three sub-target lists and three scenarios presented in Table 2.12. Two different types of graphs were created for each sub-target list: The first one is the histograms showing the residual mass distributions for all exoplanet

systems in the lists; the second one is the sigma (S/N) histograms prepared to evaluate the significance levels of the systems on the left of these histograms.

These graphs are of critical importance in terms of revealing the traceable effects of the photoevaporation mechanism, which is one of the main objectives of the research. In this context, three of the six sample systems considered throughout the analysis, Kepler-36 c, GJ 357 d, and TOI-700 c, are located on the right side of zero in the residual mass histograms, i.e., on the side where the measured mass is greater than the calculated mass. This can be considered as strong evidence that the relevant systems carry out atmospheric loss via the photoevaporation mechanism. On the other hand, Kepler-656 b, Kepler-65 c, and K2-3 b systems are located on the left side of zero in the histograms, i.e., on the side where the calculated mass is greater than the measured mass, and thus show inconsistency with photoevaporation.

In this context, the areas where the residual mass values are positive (right side of zero) represent systems where the photoevaporation mechanism is active and the atmosphere is lost by this mechanism. The areas where negative values are observed indicate systems where the atmospheric loss occurs by processes other than photoevaporation or by alternative mechanisms. Sigma histograms, created to more clearly evaluate the significance levels of the systems in question, provide a statistically supporting tool for these interpretations.

Figures 3.13 and 3.14 show the results obtained under the first scenario with the first sub-target list, and the analysis was performed on four different cases. When the residual mass histograms in Figure 3.13 are examined, it is seen that the vast majority of the exoplanet sample population is located to the right of zero, and this situation confirms that the atmospheric loss is dominated by the photoevaporation mechanism, which is frequently stated in the literature. The sigma histograms in Figure 3.14 allow the numerical evaluation of the significance levels of the exoplanets left of zero. The sigma (σ) value of each system is given in Table 3.1, where these data correspond, and negative sigma values represent inconsistency with photoevaporation, and positive sigma values represent consistency.

In Table 3.1, in the first scenario, the data belonging to the K2-3 system were not evaluated due to the radius criteria; however, the Kepler-656 and Kepler-65 systems were included in the analysis. The 2.33 sigma value obtained in the second variation of the four cases for Kepler-65 is statistically within the acceptable limits of inconsistency with photoevaporation. The Kepler-656 system, on the other hand, showed values exceeding the 5 sigma level in many cases. Although this is not a statistically significant result, it is a finding that needs to be verified with alternative analyses in response to the possibility of systematic errors, since it should be within scientifically meaningful confidence intervals to prove that Kepler-656 did not lose its atmosphere by photoevaporation.

Similar evaluations were also conducted for the second sub-target list and the second scenario. When examining the residual mass and sigma histograms shown in Figures 3.15 and 3.16, along with the corresponding Table 3.2, the Kepler-656 and Kepler-65 systems once again come to the forefront. In this analysis, the Kepler-65 system reached a maximum significance level of 2.31 sigma, which can again be interpreted as an indication of marginal inconsistency. On the other hand, Kepler-656 once again exceeded the 5 sigma threshold, failing to demonstrate a reliable confidence level that would rule out the possibility of explaining this system via the photoevaporation mechanism.

Finally, in the analysis conducted under the third sub-target list and third scenario, this time the Kepler-65 system was eliminated; only the Kepler-656 and K2-3 systems were evaluated. In Table 3.3, corresponding to the residual mass and S/N histograms in Figures 3.17 and 3.18, significance values were obtained at the levels of 27 sigma for K2-3 and 10 sigma for Kepler-656. These values are quite high in terms of statistical confidence interval and do not provide a reliable interval.

In addition, this study presents two main scientific outcomes. First, the findings showing that the vast majority of exoplanets in the sample have lost their atmospheres through the photoevaporation mechanism support the validity of this mechanism and make significant contributions to the literature. Second, the study aimed to identify systems that deviate from the general trend and exhibit atmospheric loss at a level that cannot be explained by photoevaporation. However,

within the scope of this analysis, a statistically significant separation of such systems could not be achieved, and thus, the full realization of this second objective was not possible. Therefore, to more clearly identify such systems, deeper analyses, the inclusion of alternative theoretical models, and new observational data are required.



5. CONCLUSION

This study aimed to statistically test and evaluate the photoevaporation hypothesis, which is proposed to play an important role in the evolution of exoplanet atmospheres, based on residual mass (measured and calculated mass differences) and S/N ratio histograms. The analyses performed under three different scenarios and three sub-target lists showed that the majority of the systems in the sample gave results consistent with photoevaporation. These findings support the idea that stellar radiation is a dominant mechanism triggering atmospheric loss, especially in low-mass exoplanets with short orbital periods.

The residual mass distributions and accompanying sigma histograms used in the analyses revealed not only the direction of the mass differences but also the level of statistical significance of these differences. In this way, more in-depth inferences could be made regarding the systems in which the photoevaporation mechanism may be valid and in which different processes may be effective. However, the high sigma values obtained should be considered with caution, especially in some systems (e.g., K2-3, Kepler-656, and Kepler-65), considering model dependency, radial velocity or transit method measurements, and systematic error possibilities.

In this context, although the photoevaporation hypothesis provides a strong explanatory framework for studies on exoplanet atmosphere evolution, it is concluded that it may not be sufficient to explain all systems. In particular, the existence of systems where atmospheric loss cannot be explained statistically by photoevaporation indicates that alternative mechanisms (e.g., core-powered and contraction, magnetic field effects, or stellar winds) should be taken into account.

The results of the research provide an important window into the evolution of exoplanet atmospheres over time, while also giving rise to new research questions. In this context, various suggestions are presented to both expand the methodological scope of the current study and pave the way for advanced analyses that will contribute to the literature.

First, parametric sensitivity analysis should be performed by systematically varying the parameters used in models based on the photoevaporation hypothesis, such as XUV flux, planet density, and orbital radius. This approach will provide a clearer understanding of which variables cause deviations in model outputs for certain systems.

However, it is important to include not only photoevaporation but also other physical processes that may cause atmospheric loss. Consideration of alternative mechanisms, such as stellar winds, geophysical processes, and magnetic field effects, may contribute to a better explanation of systems that are particularly inconsistent with photoevaporation at high sigma.

Furthermore, since atmospheric loss processes are sensitive to the age and evolutionary stage of the star, the use of evolutionary models that take into account time-varying stellar activity is also recommended, so that photoevaporation effects can be assessed more realistically.

On the other hand, with high-precision spectroscopic data from instruments such as the James Webb Space Telescope, atmospheric composition, molecular signatures, or traces of thermal escape can be directly observed in some systems. Combining such observational data with residual mass analyses would significantly enhance the accuracy of the models.

Finally, although the current study tested a limited number of systems that might be inconsistent with photoevaporation by using all available systems from the NEA database, future studies would greatly benefit from being repeated with larger exoplanet samples obtained from missions such as Roman, Ariel, and PLATO. Such an expanded sample would not only increase statistical reliability but also enable more general and robust conclusions to be drawn.

In conclusion, this study demonstrates that the photoevaporation hypothesis provides a valid and robust explanation for many exoplanet systems. However, the deviations and statistical inconsistencies observed in some systems indicate that the atmospheric loss processes cannot be explained by a single mechanism. Therefore,

it is of great importance to continue exoplanet atmospheric evolution studies in a framework that integrates both observational and theoretical tools with interdisciplinary approaches. Such holistic approaches will not only test the accuracy of existing models but will also allow the development of new planet formation and evolution scenarios.



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APPENDICES

APPENDIX 1 Minimum Nucleus Mass Graphs Calculated with 20% Error for the Kepler-36 System

In this section, as explained in Section 3.8, the minimum core mass histograms obtained by adding a 20% error margin to the missing error margins of the relevant parameters of the Kepler-36 system are presented as an example. The process of obtaining these histograms is the same as that presented in Section 3.5, except that the percentage of error margins added to the missing error margins presented in Photo 2.4 in Section 2.2.2 is changed from 10% to 20%.

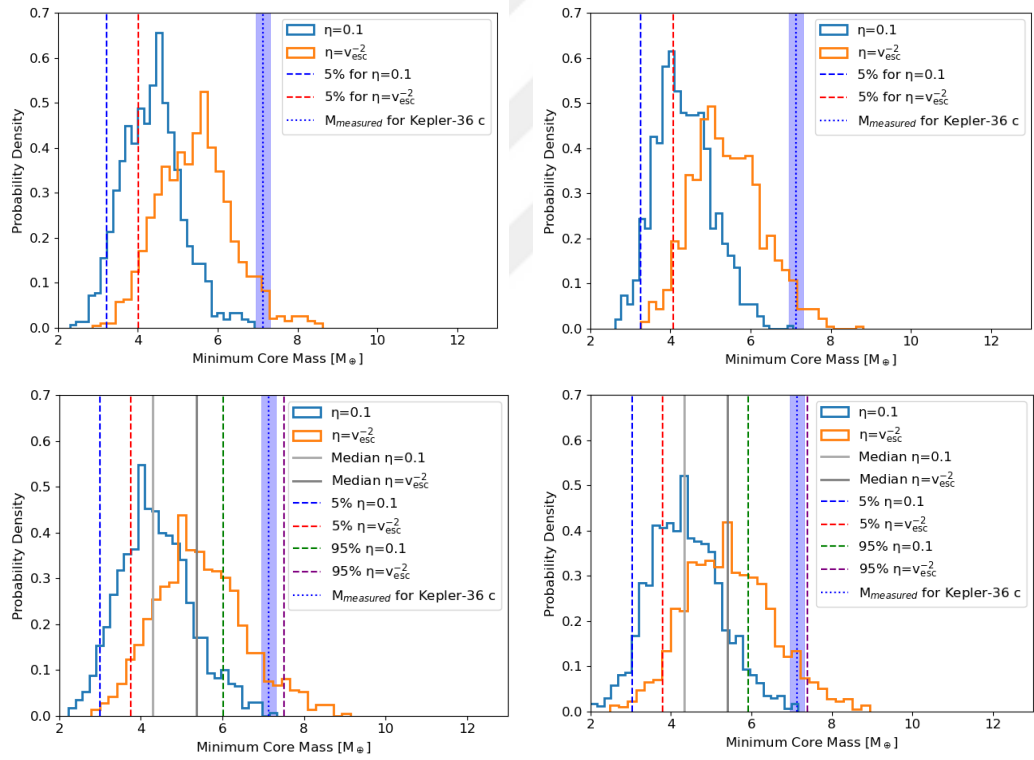


Figure 1. 1. Histograms of the minimum core mass distributions for four different cases of the planet Kepler-36 c.

APPENDIX 2 Residual Mass Graphs and S/N Table for $\eta=0.2$

A change has been made to the mass loss efficiency explained in Section 2.2.3 and shown in Photo 2.7. The findings of Figure 3.13, Figure 3.14, and Table 3.1, produced from the first sub-target list (Table 2.1, Cut-2 (a)) within the scope of scenario 1 when $\eta=0.1$, have also been produced for the cases where $\eta=0.2$.

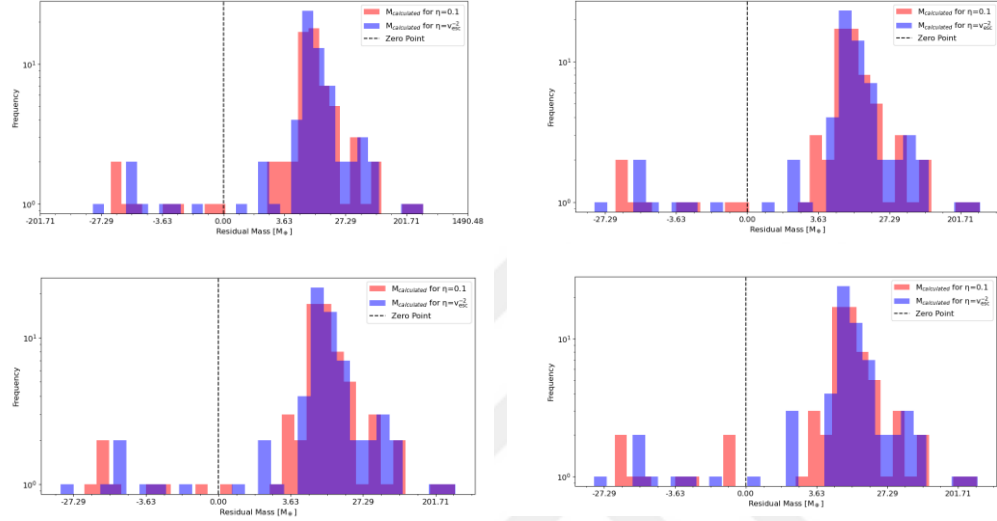


Figure 2. 1. Residual mass histogram of the first sub-target list obtained with frequency data generated according to the four cases in scenario 1.

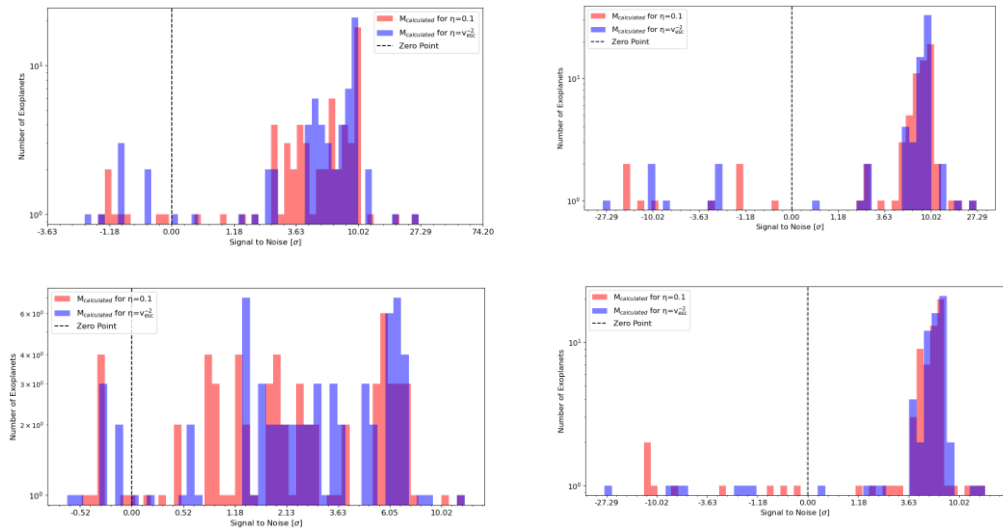


Figure 2. 2. Histograms show that the distribution of exoplanet numbers on a sigma basis according to the first sub-target list for the four different cases evaluated under the first scenario.

Table 2. 1. In this table, the names of all systems with negative mass differences and the sigma values calculated for two separate mass efficiencies within the scope of the first sub-target list and the first scenario, based on the histogram graph in Figure 2.2, which was produced from the residual mass histogram graphs in Figure 2.1.

super name	mini name	Case 1	Case 2	Case 3	Case 4
		σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)	σ_1 (σ_2)
DMPP-1 c	DMPP-1 c	-0.10 (0.44)	-0.30 (2.19)	-0.04 (0.16)	-0.23 (1.54)
HD 96700 c	HD 96700 b	-1.13 (-0.83)	-13.92 (-7.61)	-0.37 (-0.27)	-9.94 (-5.45)
Kepler-114 c	Kepler-114 d	-0.25 (-0.41)	-1.40 (-2.62)	-0.04 (-0.09)	-0.48 (-1.28)
Kepler-33 b	Kepler-33 c	-1.47 (-1.90)	-2.71 (-29.34)	-0.50 (-0.66)	-2.62 (-28.35)
Kepler-430 c	Kepler-430 b	-1.16 (-0.91)	-19.02 (-10.56)	-0.33 (-0.25)	-12.96 (-7.12)
Kepler-65 d	Kepler-65 c	-0.83 (-1.34)	-1.29 (-2.33)	-0.34 (-0.54)	-0.89 (-1.62)
Kepler-656 c	Kepler-656 b	-0.92 (-0.39)	-9.39 (-2.43)	-0.28 (-0.12)	-6.71 (-1.77)
Kepler-769 c	Kepler-769 b	-1.11 (-0.90)	-16.71 (-10.34)	-0.32 (-0.26)	-12.32 (-7.70)

Appendix 3 Reason for the Selection Shown in Photo 2.9

The fact that the outermost planet (i.e. with the largest semi-major axis) in an exoplanet system is in the super-Earth category and has lost its atmosphere, while a more inner (smaller semi-major axis) mini-Neptune has preserved its atmosphere cannot be explained by the photoevaporation mechanism, and such systems are considered as “interesting systems” in the literature. Because, according to the general expectation in the literature, super-Earths are expected to be closer to their star (small semi-major axis), while mini-Neptunes are expected to be in more distant (large semi-major axis) orbits (Owen & Estrada, 2020). This distribution determines whether the planets can retain their atmospheres depending on the amount of high-energy (XUV) radiation they are exposed to.

However, as shown in the study by Owen and Estrada 2020 (Owen & Estrada, 2020), contrary to this expectation, it has been observed that in some systems the outermost planet is a super-Earth (having lost its atmosphere) (Kepler-100 d and Kepler-142 d) while the innermost planet is a mini-Neptune (having retained its atmosphere) (Kepler-100 c and Kepler-142 c). In this case, according to the photoevaporation model, the inner planet must have a certain minimum mass to retain its atmosphere. If the observational data are significantly lower than this minimum mass, the system cannot be explained by photoevaporation and is therefore defined as a remarkable, i.e., interesting, system.

In this context, the aim of the study was to scan the systems that comply with the semi-major axis condition specified in Photo 2.9 and to detect interesting systems that do not comply with this type of model.