SUB-JUPITER RADIUS OCCURRENCE RATE ANOMALY

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CONTENTS

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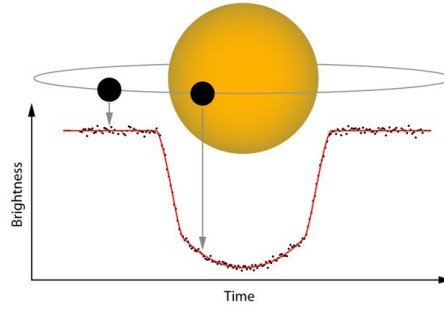## LIST OF TABLES

ABSTRACT

Figure 1: Cartoon of a transiting exoplanet, image taken from NASA exoplanet database

1 INTRODUCTION

Since the first confirmation of an extra-solar planet in 1992[11], the field of exoplanet research has exploded with nearly 1800 planets currently confirmed (as of May 6th, 2014[7]). Since the early 90's the detection techniques employed to discover these exoplanets relied heavily upon tracking the Doppler shift in a host star's spectrum. Such a shift could arise from a large, short period, exoplanet. The radial velocity technique formed the majority of exoplanet confirmations well into the late 2000's[3]. During this time the transit technique started to gain prevalence.

1.1 Transit Technique and NASA's Kepler Mission

Exoplanet transiting refers to the event when a exoplanet passes into the line of sight of the observer to the host star. A host star's light can be monitored over a certain time span; when compared to the light output of similar stars in the same frame - a exoplanet detection can be easily picked out (see figure 1). These light curves allow researchers to determine certain characteristics of the transiting planet. Specifically from one transit one can find the ratio of the radius of the planet compared to the host star. Multiple transits will provide orbital information[10]. The early days of transit discoveries found only large radius planets as these required the least sensitive equipment, and from the fact that the signal to noise ratio of an exoplanet discovery is described by equations 1 and 2.

$$\frac{S}{N} \approx \sqrt{N_t} \frac{\delta}{\sigma} \tag{1}$$

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

The radius of the planet R_p and the radius of the star R_* greatly impacts the S/N, as does the photometric precision σ[1]. Thus, these early discoveries had limited (and small) photometric precision. Therefore, the only planets that had a decent signal to noise ratio were those with large radii. This can be seen in the histogram of radii for all exoplanets discovered by the transit technique up to 2008 (Figure 3 on page 4). Jupiter size planets and larger were common discoveries for the transit technique. It was not until NASA's Kepler mission was launched in 2009[6] that photometric precision was increased to the point that sub-Jupiter planets could be detected[8]. Once Kepler's data began getting published it became clear that not only could
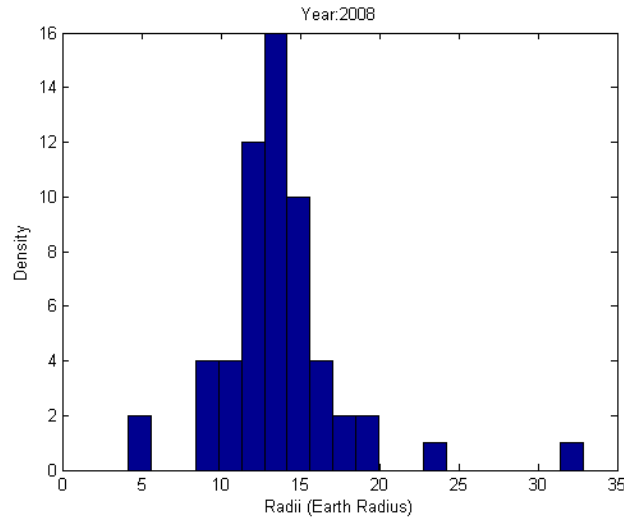
Figure 2: Exoplanet discoveries made by the transiting technique from 1990 to 2008. The radii are measured in Earth Radii, with 10 Earth Radius being roughly the size of Jupiter.

Kepler detect planets down to the sub-Earth size, but it was also able to find planets much more quickly - increasing the exoplanet database size dramatically (Figure 3 on the following page). There are over 1700 exoplanets discovered through the transit, and other techniques (last checked on May 10th 2014[7]). All of these planets provide a good sampling of the potential exoplanets within our galaxy. There has been a number of studies that examine properties of the currently discovered exoplanets (e.g: [2, 5, 4]). This project examines an anomaly in the distribution of exoplanet radii in transiting exoplanets.

1.2 Radii of Discovered Planets

We are specifically curious what the distribution of exoplanet radius has been changing since the introduction of the Kepler mission. Since radius is a primary variable of only the transit technique: most of the analysis will be based upon planets discovered by transiting. However, some planets originally discovered by radial velocity, or other techniques, have been reexamined by telescopes using the transit technique. This allows some analysis of radii of radial velocity exoplanets.

1.3 Data

The data for this study is obtained from NASA Confirmed Exoplanet Database and NASA Exoplanet Candidate Database. This data is updated continuously by the scientific community and managed by NASA, making it a very reliable source. The specific type of data that can be pulled from this source includes publication date, Planetary properties (mass, radius, period, etc), Stellar properties (mass, radius, galactic location, etc), and detection information. A number of planets detected by the transit method up to the current date can be found on figure 3 on the next page. To ensure reliability of data: any exoplanet that was examined was first cross referenced on a different, but still well cited, exoplanet database - Exoplanets.eu. Specifi-
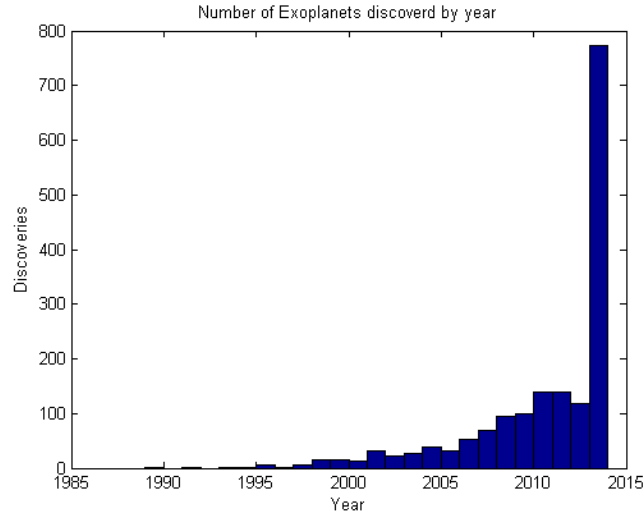
Figure 3: Transit technique discoveries up to April 25th 2014. It is clear that since Kepler's launch in 2009, the exoplanet database has grown substantially.

cally, planet radii were confirmed to be the same across both databases. Any planet that had a significant variation across the sources was neglected from the study.

Issues with this data is that the date listed does not necessarily correspond to the date when technology was sufficient enough to detect said planet, but rather when enough research and/or follow-ups were preformed to make a publication regarding its discovery. This means that the capability of discovering does not scale with publication year. This means that predictions as to when technology will be sufficient enough to detect a planet of a certain radius ($P(R) \propto R^n$, for some n) can not be easily extrapolated. This also means that the planets that show up in either of these databases will be dependent on where research times is being focused.

1.4 Previous Work

Exoplanet occurrence work has been done extensively in the past ([9, 5, 4, 2]). These studies focus on the probability of finding certain characteristics in planets around stars. The methods to preform this are varied. However, several studies ([4, 9, 5]) focus on the total number of planets found with a certain characteristic (e.g: $R = 1 - 1.5R_E$) and divide them by the total number of stars observed within that time-frame. Complexities arise when trying to also account for the the false positive (FPs) rate of the various observations. The methods to categorize FPs vary by study, but a detailed explanation can be found within [9]. This study looks at the overall characteristics of planets discovered to date. Not many publications take a step back and look at the overall picture of discovered planets. The particular characteristic we are currently interested in is the distribution of exoplanet radii.
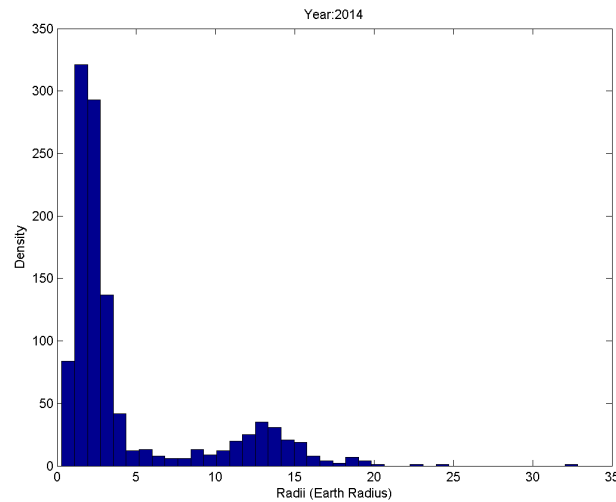
Figure 4: Histogram of Exoplanet radius from 1990 to May 10th, 2014. Detection techniques include transits, radial velocity, and other. The x-axis shows planet radius in units of Earth radii, the y-axis shows number of exoplanets with that radius. Specifically, note the extinction zone at $R \approx (5-10)R_E$.

2   ANALYSIS

We investigate a extinction zone in exoplanet detections with a range of $R \approx (5-10)R_E$. An initial signature of this extinction can be seen in figure 4

2.1   Detection Analysis

As previous

Reference to Figure 5.

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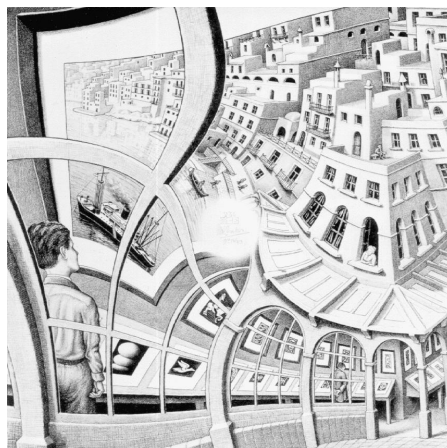

Figure 5: An example of a floating figure (a reproduction from the *Gallery of prints*, M. Escher, from http://www.mcescher.com/).

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2.2 Paragraphs

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$$\cos^3 \theta = \frac{1}{4} \cos \theta + \frac{3}{4} \cos 3\theta \tag{3}$$

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Definition 1 (Gauss)**.** To a mathematician it is obvious that $\int_{-\infty}^{+\infty} e^{-x^2}\,dx = \sqrt{\pi}$.

Theorem 1 (Pythagoras)**.** *The square of the hypotenuse (the side opposite the right angle) is equal to the sum of the squares of the other two sides.*

Proof. We have that $\log(1)^2 = 2\log(1)$. But we also have that $\log(-1)^2 = \log(1) = 0$. Then $2\log(-1) = 0$, from which the proof. $\qquad\square$

3 RESULTS AND DISCUSSION

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3.1.1 *Subsubsection*

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WORD Definition

CONCEPT Explanation

IDEA Text

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- First item in a list
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3.1.2 *Table*

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Table 1: Table of Grades

Name		
First name	Last Name	Grade
John	Doe	7.5
Richard	Miles	2

Reference to Table 1.

3.2 Figure Composed of Subfigures

Reference the figure composed of multiple subfigures as Figure 6 on the next page. Reference one of the subfigures as Figure 6b on the following page.

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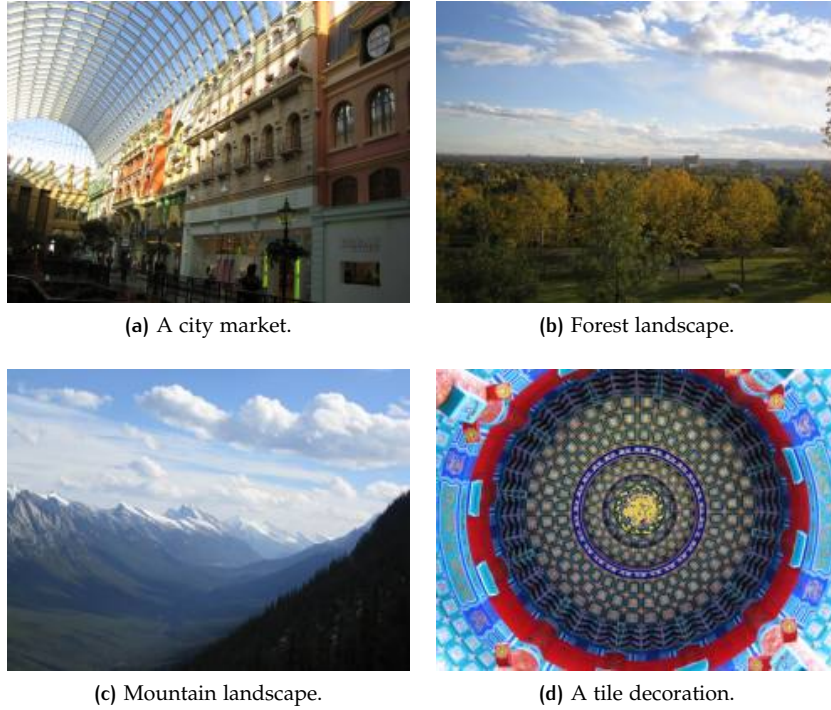
(a) A city market.

(b) Forest landscape.

(c) Mountain landscape.

(d) A tile decoration.

Figure 6: A number of pictures with no common theme.

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