MINIMUM MASS EXTRASOLAR NEBULA DERIVED FROM THE MASS OF EXTRASOLAR PLANETARY SYSTEMS

IVAN ANTE JAKOVČEVIĆ

Supervisor: Associate Professor dr. Dejan Vinković

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Department of Physics
Faculty of Science
University of Split

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Abstract

The closest planets in the majority of extrasolar planetary systems discovered so far are closer and much more massive than Mercury, and even more massive than Earth. Such big rocky planets are called super-Earths and we still do not have a complete understanding of their fomation process. We will assume the planets were created locally, at their current position with no migration assumed. In an attempt to understand consequences of such an assumption we construct a minimum mass extrasolar nebula of solid material for each of the planetary systems, which represents the minimum mass of the collapsed nebula needed for their in-situ formation. This work takes in consideration stars ranging from 2000K to 10000K and their planets within 1 AU from two tables: KOI Kepler planet candidates and Exoplanet confirmed planets. We compared our results to the work of Raymond and Cossou (2014). From the data we retrieved estimates for two density profiles of extrasolar planetary systems, that of the confirmed planets and of the candidate planets, showing that the mean extasolar planetary mass distribution is very different from that of our Solar System.

Chapter 1

Introduction

For years the planet and mass distribution of the Solar system have been thought to be common to any extrsasolar multiplanetary system. Recent technology upgrades and inovations have enabled us to detect and analyze far away planets like never before. These observations show that the majority of explored extrasolar systems are not Solar-like. Many of them have huge close-in rocky planets, some of which have radii 2-5 $R_\oplus$ (2-5 Earth radii), masses even exceeding 10 $M_\oplus$ and orbits very close to their stars. Such planets are typically called superEarths and the term does not imply other characteristics (e.g. stellar temperature), sources generally agree on an upper bound of 10 Earth masses. They are not to be mistaken with hot jupiters, which are very massive planets close to their stars with gas constituting the majority of their mass. Because of the theoretical limitations on formation of hot jupiters close to the star we believe hot jupiters have formed far away and have migrated to their current locations.

In this paper we will assume planets have formed in-situ, which means they are created locally at their current position with negligible amount of migration. We will assign each planet a minimum mass extrasolar nebula (MMEN), which is the planet's mass spread on a thin disk surrounding its star and resembling the amount of gas/solid material needed for its formation. This shoud help us to better understand the minimum amount of solid material needed for planetary formation within the protoplanetary nebula.

Chapter 2

Construction of the Minimum Mass Extrasolar Nebula

2.1 The program input and statistics

For the purpose of constructing the MMEN we will use two sets of data, the first set being a table of Exoplanet confirmed planets[1] and the second a table of KOI candidates[2]. We have chosen two mass-radius relationships, the first being for planets of $R < 1.5R_{\oplus}$ (Valencia et al., 2007):

$$\frac{M}{M_{\oplus}} = (\frac{R}{R_{\oplus}})^{3.7} \tag{2.1}$$

and the second for planets of $R > 1.5R_{\oplus}$ (Lissauer J. J. et al., 2011):

$$\frac{M}{M_{\oplus}} = (\frac{R}{R_{\oplus}})^{2.06} \tag{2.2}$$

We have selected multiplanetary systems with at least two planets inside 1 AU from their parent star. Due to the lack of data in both databases (e.g. planet mass values, stellar mass values) we have first filtered all the planets from two databases with these criterions :

- the planet must have a given mass, if not it shall be calculated form its radius, thus either the planet mass or the planet radius must be provided
- planet mass must be in the limit $M <= 30M_{\oplus}$
- planet radius must be in the limit $R <= 5R_{\oplus}$
- the effective temperature of the host star must between 2000K and 10000K
- stellar mass must be given
- the orbit semi-major axis of each planet must be given
- the planet must be part of a multiplanetary system with at least two planets interior to 1 AU

Planet composition can vary and therefore so can their masses for a given radius. The mass-radius relationships given at (2.1) and (2.2) are only estimates and best fits and might not exactly describe the planet's mass for a given radius.

[1] http://exoplanetarchive.ipac.caltech.edu/cgi-bin/ExoTables/nph-exotbls?dataset=planets
[2] http://exoplanetarchive.ipac.caltech.edu/cgi-bin/ExoTables/nph-exotbls?dataset=cumulative

Table 2.1: The number of planets in the two databases, the number of extrasolar systems selected, and the total planets recovered.

Data table	Amount of planets	Rejected	systems selected	Total planets selected	Uses (2.1) and (2.2) [%]
Exoplanet Confirmed	1743	1273	192	470	87,7
KOI planet candidates	7305	7041	122	264	100

Most of the planets were rejected because they were the only planet orbiting their star and as such did not pass our criterion for being a multiplanetary system. The rest were rejected due to the lack of data. In the end we obtained 192 stellar systems (470 planets) from the Exoplanet confirmed database and 122 stellar systems (264 planets) from the KOI candidates database as seen in Table 2.1. We predict for the results of the MMEN of the confirmed planets to be somewhat more precise than that of the candidate planets, since the approximate equations (2.1) and (2.2) have to be used for all the candidates as seen in Table 2.1.

Table 2.2: Different mass ranges of the selected planets.

Range	Exoplanet confirmed	KOI Candidate
$M < 2M_{\oplus}$	74	79
$2M_{\oplus} <= M <= 5M_{\oplus}$	213	115
$5M_{\oplus} <= M <= 10M_{\oplus}$	133	51
$10M_{\oplus} <= M <= 30M_{\oplus}$	54	19

where $M_{\oplus}$ is the mass of Earth.

For the purpose of comparing the results to the work of Raymond and Cossou (2014) we show in Table 2.3 how many systems have only two planets interior to 1 AU and how many have three or more.

Table 2.3: Extrasolar systems with two and those with three or more interior to 1 AU, relative to their parent host star.

Data table	2 planets	3 or more
Exoplanet Confirmed	130	62
KOI planet candidates	104	18

We are now ready to construct the minimum mass of the collapsed extrasolar nebula that was necessary for planetary creation for each of the selected extrasolar multiplanetary systems and compare the results.

2.2 Calculataing The Minimum Mass Extrasolar Nebula

In our work the minimum mass of the extrasolar nebula is the minimum mass of the solid material within the nebula that was required for the formation of rocky planets. We will constrict ourselves on the mass of the planets below $30M_{\oplus}$ within 1 AU from the host star. For the construction of the MMEN we will use the same methods as Raymond and Cossou (2014) creating a surface density profile for each of the planets. We first focus on calculating the area onto which we spread the mass of the planets. For the closest planet we will extrapolate to get the first area radius coordinate r_{inner} as follows:

$$r_{inner} = \frac{a_1}{\sqrt{a_1 a_2}} \tag{2.3}$$

where a_1 and a_2 are the orbit semi major axis of the first and second planet respectiveley. For the second area radius r_{outer} we will take the geometrical mean between the first and second planet orbit semi major axis as follows:

$$r_{outer} = \sqrt{a_1 a_2} \tag{2.4}$$

We now have the two radii between which we will spread the mass of the closest planet to its host star. The surface density is then calculated:

$$\Sigma = \frac{M_{planet}}{\pi(r_{outer}^2 - r_{inner}^2)} \tag{2.5}$$

where Σ is the surface density of the protoplanetary disc between the two radii r_{inner} and r_{outer} for the observed planet given in [g/cm^2] and M_{planet} the mass of the planet. Only the first and the last planet of every stellar system use extrapolated first and last area radii respectively. For example the outer most radius of the last planet's surface density area is calculated by extrapolating beyond the end point as follows:

$$r_{outer} = \frac{a_n}{\sqrt{a_n a_{n-1}}} \tag{2.6}$$

where a_n and a_{n-1} are the radius of the orbit semi-major axis of the last and penultimate planet respectively. All other planets that are in between the closest and most distant from their star use the formula 2.4 for both their first and second area radii. After we have calculated each planets surface density, we calculate the best fit for the given distribution of surface densities Σ_i compared to their orbital distances a_i for each stellar system, and plot them as lines indicating the rising or falling of the surface density with respect to the distance from its parent host star.

2.3 Calculation of the Scaled MMEN

Evolutionary tracks for a set of stellar masses were taken from Dotter, A., et al. (2007). Each evolutionary track was saved in a separate file. Luminosity is calculated by finding two mass files which limit the required stellar mass. In each file we interpolated between two values of luminosity around time=1Myr, and after that interpolated between the two resulting values relative to the difference between the current stellar mass and the mass files taken in consideration. 1 Myr is used as an approximate time of planetary formation.

For the purpose of calculating the area for the surface density calculation of each planet we used the methods and formulas provided in (2.3),(2.4) and (2.6). The surface densities were calculated with (2.5), while the surface density slopes for the stellar systems were derived from the least squares method of the given distribution. In the least squares method we were looking for a relationship of:

$$\Sigma = \Sigma_0 (\frac{r}{[1AU]})^\alpha \tag{2.7}$$

As we know from the work of Sean M. Andrews et al. (2013) the mass of the protoplanetary disc is proportionate to the mass of the host star. So in order to compare the surface density profile of an extrasolar planetary system to that of the protosolar nebula, we shall require scaling on both Σ and r. For proper scaling we also revert to the work of Vinković, D. & Jurkić, T. (2007) and find that the size of the protoplanetary disk scales with luminosity as $L_\star^{1/2} \propto r_{in}$, where $L_\star$ is the host star luminosity and r_{in} is assummed to be the sublimation radius of the disc. In order to scale the surface density profiles of extrasolar planetary systems so they can become comparable to the surface density profile of the Solar system we obtain:

$$\Sigma^{'}(r^{'}) = \Sigma_0^{'} {r^{'}}^{\alpha} \tag{2.8}$$

where $\Sigma_0^{'} = \Sigma_0 \frac{L_\star}{M_\star}$, $r^{'} = \frac{r}{\sqrt{L_\star}}$, $L_\star$ the luminosity of the host star in Solar luminosities and $M_\star$ the mass of the host star in Solar masses.

Chapter 3

Results

The obtained results for the linear equations of the median slopes are shown below and compared to other MMSN Chambers (2001) and MMEN Raymond and Cossou (2014):

Table 3.1: Results for the linear equations of the median slopes obtained with (2.7)

Resource	Line equation $\log\Sigma = \log\Sigma_0 + \alpha\log r$	Surface density relationship $\Sigma = \Sigma_0 r^\alpha$ $[g/cm^2]$
Confirmed MMEN	Y=1.71 - 1.61X	$\Sigma = 51.64r^{-1.61}$
Candidates MMEN	Y=0.33 - 2.67X	$\Sigma = 2.13r^{-2.67}$
Conf. and Cand. MMEN	Y=1.34 - 1.9X	$\Sigma = 22.13r^{-1.9}$
Raymond and Cossou MMEN	Y=2.06 - 1.524X	$\Sigma = 116r^{-1,524}$
MMSN	Y=0.47712 - 0.947X	$\Sigma = 3.0r^{-0.9474}$
MMSN Chambers	Y=0.77815 - 1,5X	$\Sigma = 6r^{-1,5}$

where $Y = \log\Sigma$ and $X = \log r$.

Table 3.2: Results for the linear equations of the median slopes obtained with (2.8)

Resource	Line equation $\log\Sigma = \log(\Sigma_0\frac{L_\star}{M_\star}) + \alpha\log\frac{r}{\sqrt{L_\star}}$	Surface density relationship $\Sigma = \Sigma_0 r^\alpha$
Confirmed planets MMEN	Y=2 - 1.58X	$\Sigma = 97.72r^{-1,58}$
Candidates planets MMEN	Y=0.54 - 2.71X	$\Sigma = 3.5r^{-2.71}$
Conf. and Cand. MMEN	Y=1.58 - 1.9X	$\Sigma = 38.54r^{-1.9}$

where $Y = \log\Sigma$, $X = \log\frac{r}{\sqrt{L_\star}}$, $L_\star$ the luminosity of the host star in Solar luminosities and $M_\star$ the mass of the host star in Solar masses.

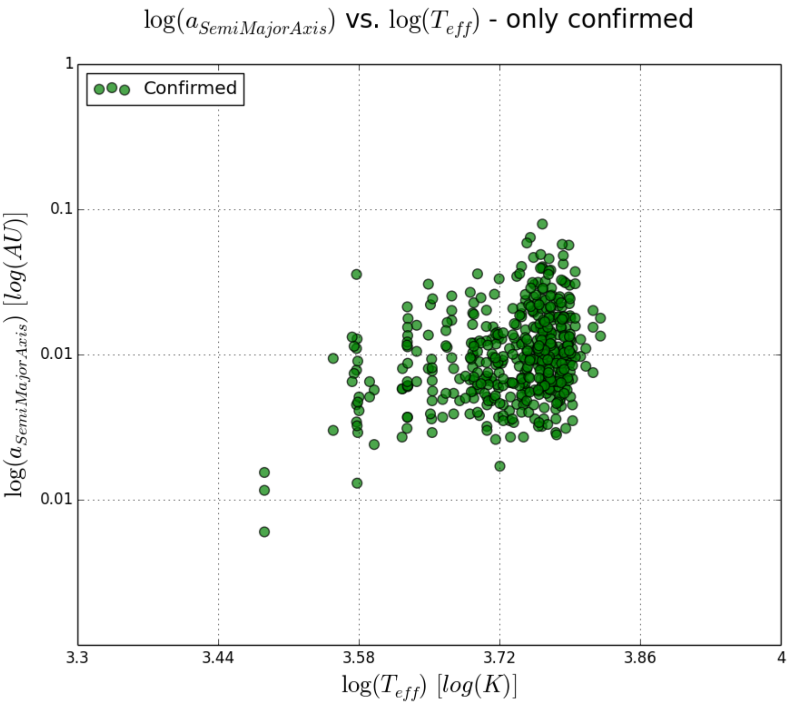

Figure 3.1: Confirmed planets with respect to the effective temperature of their host star. The majority of host stars extracted from the Exoplanet confirmed database have T_{eff} in the range 4400K and 6300K

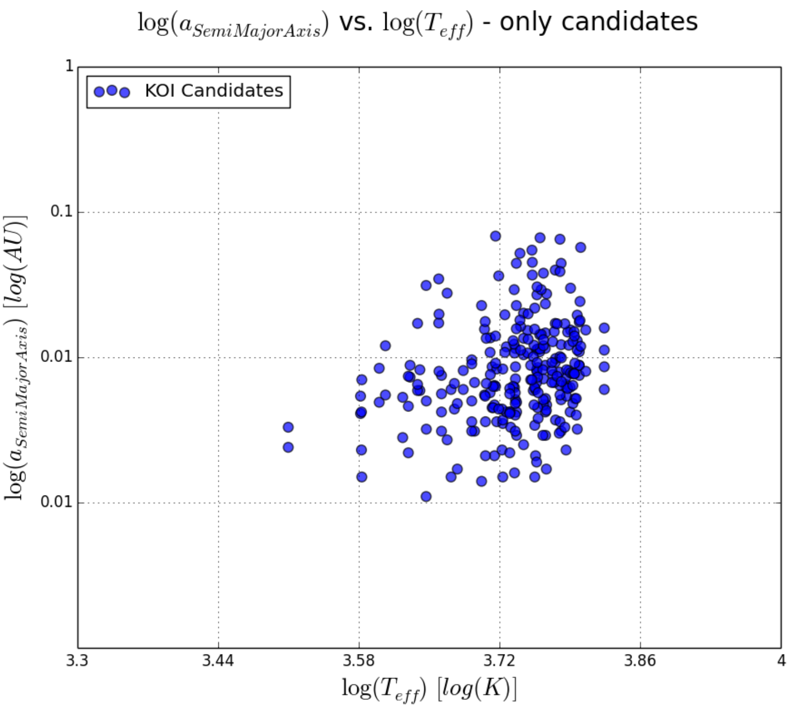

Figure 3.2: Candidate planets with respect to the effective temperature of their host star. The majority of host stars extraced from the KOI planetary candidate database have T_{eff} in the range 4800K and 6400K

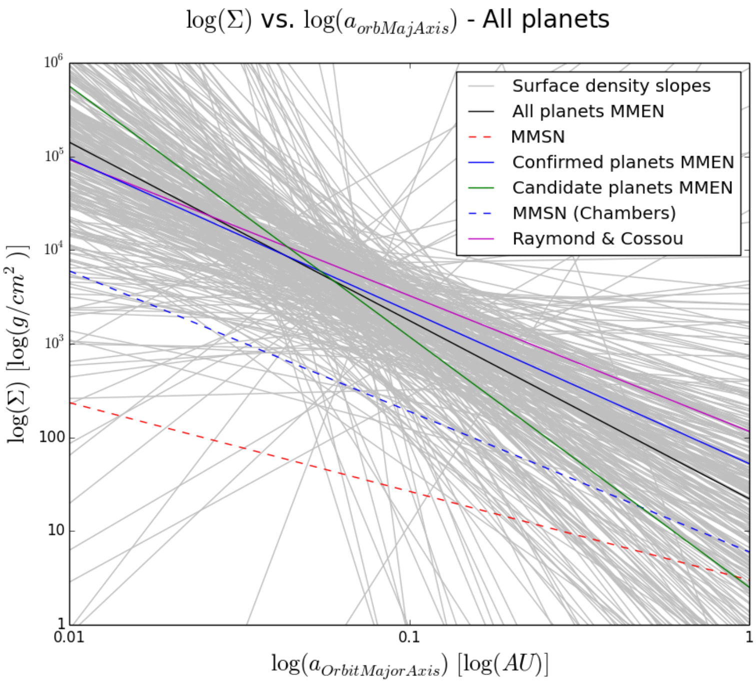

Figure 3.3: The surface density profiles Σ of both the confirmed and candidate planets with respect to the orbital distances $a_{SemiMajorAxis}$ of their planets.

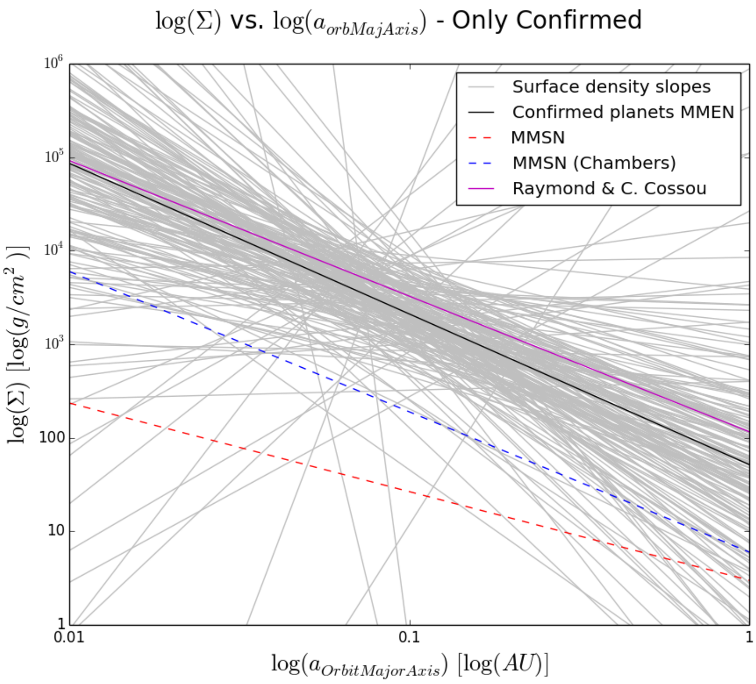

Figure 3.4: The surface density profiles Σ of only the confirmed planets with respect to the orbital distances $a_{SemiMajorAxis}$ of their planets.

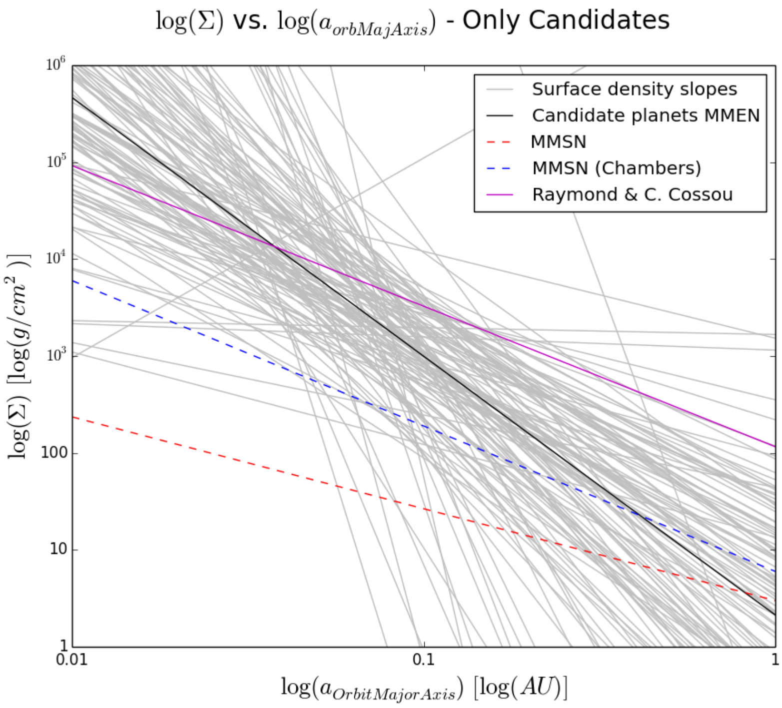

Figure 3.5: The surface density profiles Σ of only the candidate planets with respect to the orbital distances $a_{SemiMajorAxis}$ of their planets.

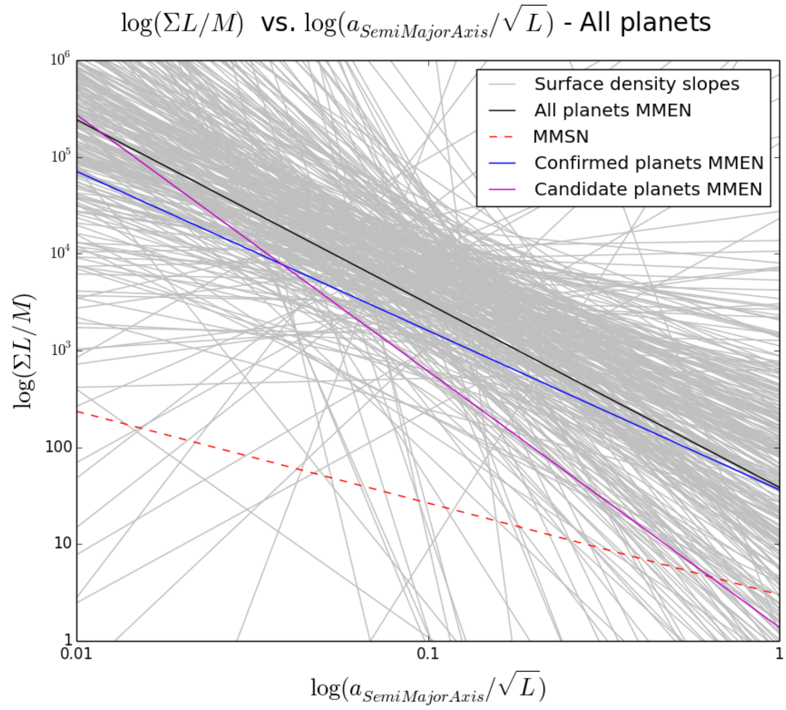

Figure 3.6: The scaled surface density profiles Σ of both the confirmed and candidate planets with respect to the scaled orbital distances $\frac{a_{SemiMajorAxis}}{\sqrt{L}}$ of their planets, where L is the luminosity of the parent host.

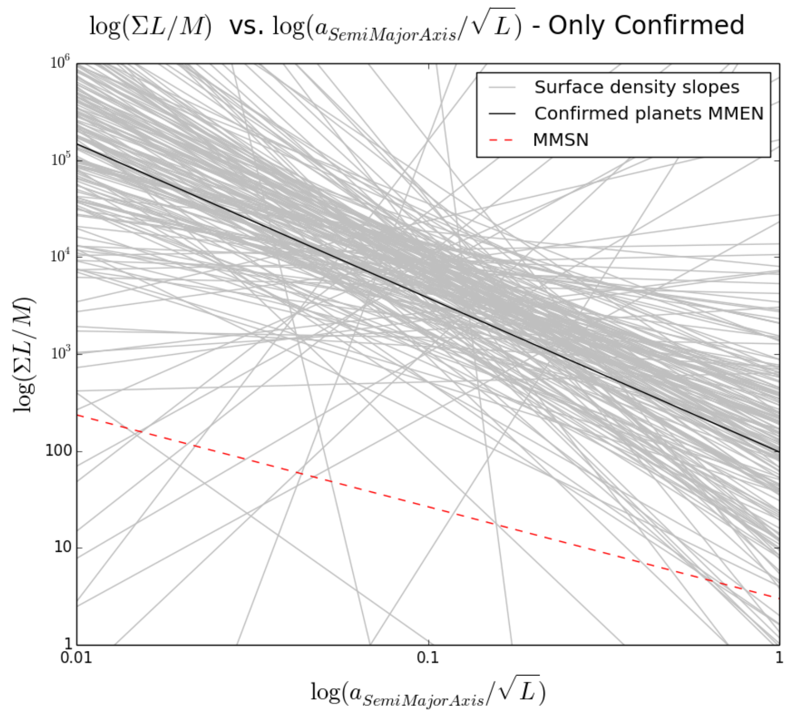

Figure 3.7: The scaled surface density profiles Σ of only the confirmed planets with respect to the scaled orbital distances $\frac{a_{SemiMajorAxis}}{\sqrt{L}}$ of their planets, where L is the luminosity of the parent host.

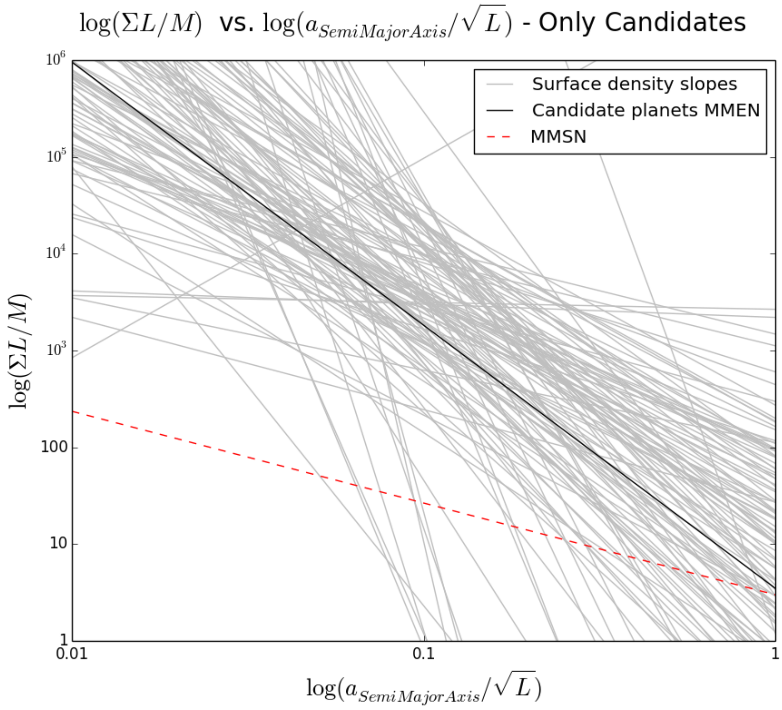

Figure 3.8: The scaled surface density profiles Σ of only the candidate planets with respect to the scaled orbital distances $\frac{a_{SemiMajorAxis}}{\sqrt{L}}$ of their planets, where L is the luminosity of the parent host.

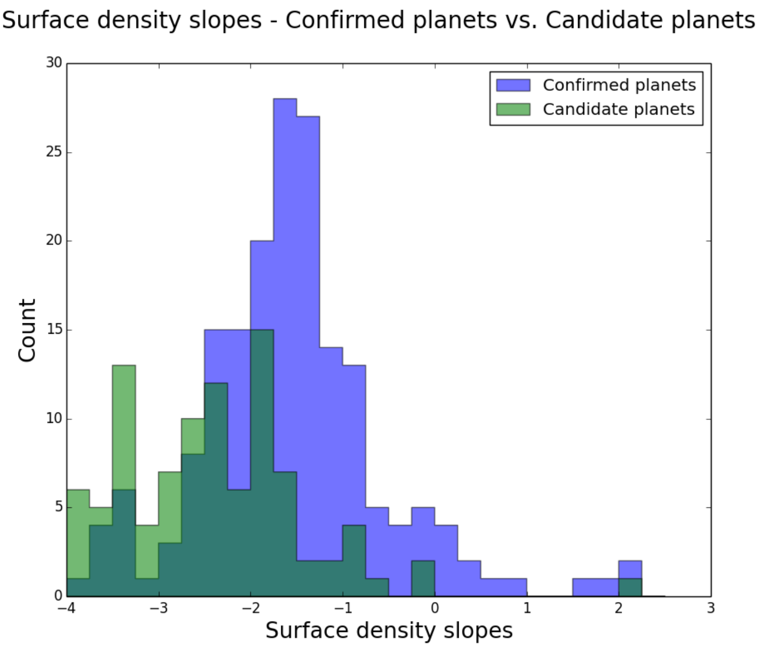

Figure 3.9: The histogram shows how the calculations for the surface density slopes of the confirmed planets $\Sigma \sim a^{x}_{SemiMajorAxis}$ compare to those of the candidate planets with respect to the same parameters for at least two planets interior to 1AU from the host star.

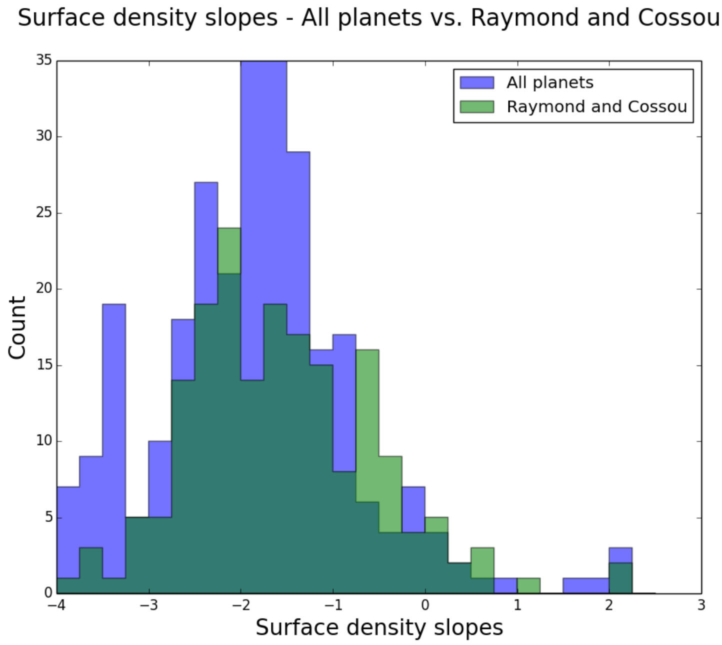

Figure 3.10: The histogram shows how the calculations for the surface density slopes of all the planets together compare to the results of Raymond and Cossou (2014). Here we searched for at least 2 planets interior to 1 AU from the host star.

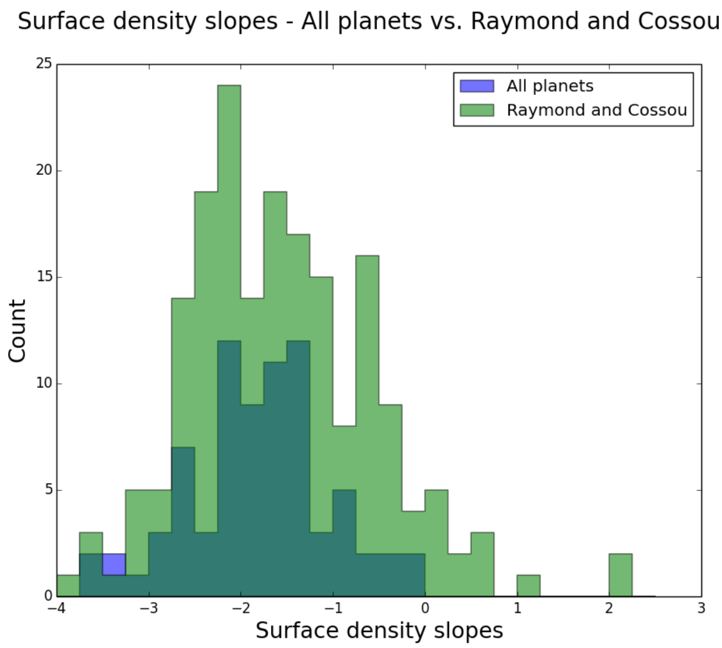

Figure 3.11: The histogram shows how the calculations for the surface density slopes of all the planets together compare to the results of Raymond and Cossou (2014) when re-run the program to search for at least 3 planets interior to 1 AU from the host star.

The distibution of the planets can bee seen from Figures 3.1- 3.2 from which we conclude that the mean host temperature is approximately between 4500K and 6300K. For comparison the Sun has an effective temperature of about 5777K. Yet, the surface density profiles show 3.3- 3.5 that the Solar system's mass distribution is quite different from the majority of extrasolar systems explored which can be confirmed in Table 3.1.

The deviation of the candidate planets surface density slopes relative to those of the confirmed planets was expected due to the fact that 87,7% of the confirmed planets and 100% of the candidate planets needed to use equations (2.1) and (2.2) to calculate their mass. The KOI candidate database did not provide any planetary mass calculations. If we look at Table 2.2 we see that 89,9% and 92,8% of the confirmed and candidate planets respectively have masses up to $10M_{\oplus}$, which would logically imply that they must have similar mean surface density slope distributions. But, as seen in Figure 3.9 they are very different which leads us back to another conclusion. From Table 2.3 we see that 67.7% and 85,2% of the confirmed and candidate planets respectively have only 2 planets interior to 1 AU from their host. This might partially answer why we have such deviations. Calculating the best fit between two surface density values for given radii will return a straight line. For three or more surface density values the magnitude of the best fitted line could vary relative to the magnitude of the surface density of the individual planet at a given radius, since planetary composition varies as well.

In 2.3 we calculated the scaled MMEN with respect to the Solar System. We must note that there is a diffrerence between the unscaled MMEN and the scaled MMEN as expected and seen in Figures 3.3 and 3.6. The difference is not in the surface density slope angles, but rather in the surface density magnitude at a given point which can be seen in Figures 3.3 - 3.8 and confirmed comparing Tables 3.1 and 3.2. The scaled MMEN makes more sense if we wish to compare the surface density profiles of the extrasolar systems to the surface density profile of the Solar System.

We now plotted histograms to compare how the surface density slopes of all the different distributions are related. We have compared the slopes from our confirmed and candidate planets for 2 planets interior to 1 AU from their host star as seen in Figure 3.9.

The surface densities we obtained for all the planets combined and at least 2 planets interior to 1 AU from their host star are compared to the work of Raymond and Cossou (2014) and can be seen in Figure 3.10

We next re-ran our program searching for a minimum of 3 planets interior to 1 AU from their host star. We used the original mass values from the Exoplanetary confirmed database where given and the results can be seen in in Figure 3.11. We see that when we look for at least 3 planets interior to 1 AU from the host star that we have a smaller sample size than that of Raymond and Cossou (2014), while the surface density slope distributions are quite similar. We expected such a good match due to having the same criteria as Raymond and Cossou (2014), regarding the count of the planets interior to 1 AU from their host, and due to the fact that in their work, they calculate all the planet masses with equations (2.1) and (2.2) and restrict the planetary masses to $30M_{\oplus}$.

Chapter 4

Conclusions

We have shown the deviations of the surface density slopes caused by changing the input parameters to accept only systems with 3 planets interior to 1 AU from its host star which can be seen in Figure 3.11 and compared to Figure 3.10.

From Figure 3.9 and 3.10 we see that the surface density slope distribution of the confirmed planets is grouped around $\alpha = -1.5$, while the surface density slope values for the candidate planets are rather distributed more evenly over the range $4 <= \alpha <= -1.5$. Our surface density slope distribution is very different from that of Raymond and Cossou (2014) as seen in Figure 3.10, and Figure 3.11 shows why. When we changed the input filtering from two to minimally three planets interior to 1 AU from each host star our results became similar to the results of Raymond and Cossou (2014), which then explains why we had such a difference in Figure 3.10.

The analysis using 2 or more planets interior to 1 AU from their host star substantially supports the fact that the majority of extrasolar planetary systems we selected have super-Earths interior to 1 AU from their star, which would imply in-situ formation. But we see support for this theory only from the data retrieved from the confirmed planets (e.g. see Figure 3.3). The data retrieved from the candidate planets however shows the opposite, and suggests migration.

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