Correctly Accounting for Planets in Multiples when Determining Occurrence Rates

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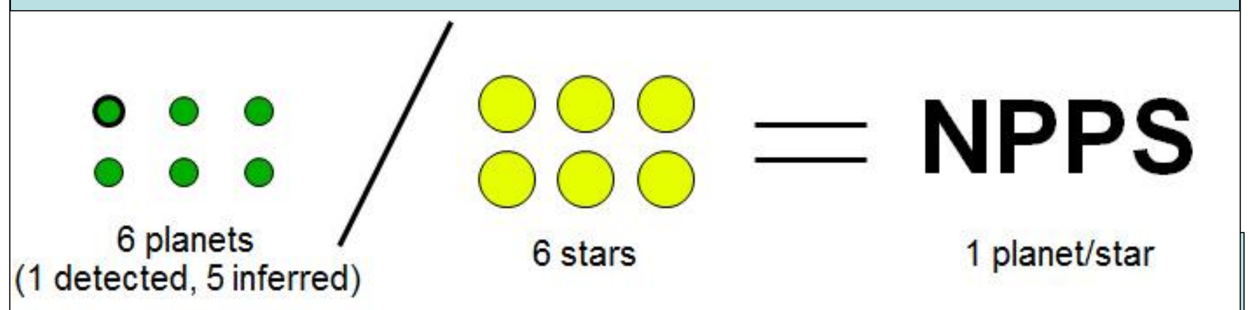
Introduction

Kepler's discovery of systems of multiple transiting planets has opened the doors to a variety of exciting and important scientific investigations. Many scientific questions are addressed by debiasing Kepler's planet candidate population to determine the true underlying frequency of planets and planetary systems. Quantifying the frequency and properties of exoplanetary systems requires debiasing techniques that account for many details not required in more common planet-by-planet occurrence rates. However, the presence of multiple planets in a system can significantly affect the inference of occurrence rates even in planet-by-planet calculations.

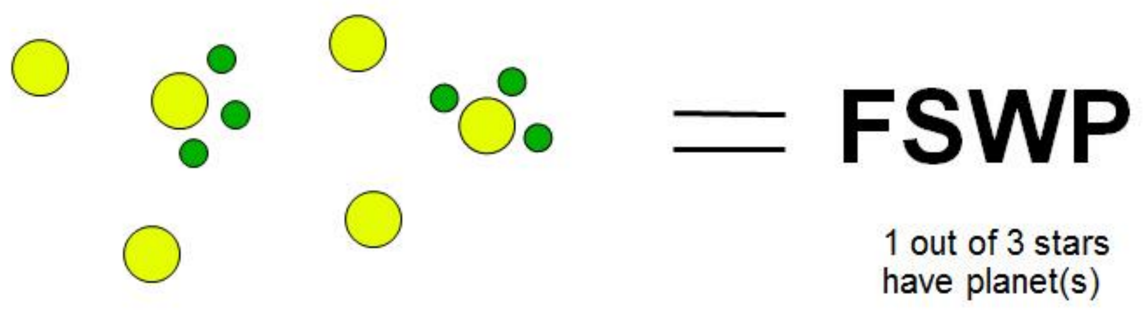
First, we have found that a careful and critical distinction must be made in distinguishing the average Number of Planets Per Star (NPPS) and the Fraction of Stars with Planets (FSWP).

Average Number of Planets Per Star



Most frequency/occurrence studies are actually calculating the average Number of Planets Per Star (NPPS). When occurrence is calculated planet-by-planet without accounting for the complex correlations in detecting planets in multiple systems, the result is NPPS. Understanding NPPS gives us huge insight into planet formation (e.g., period/radius distribution) and other important questions (e.g., eta Earth).

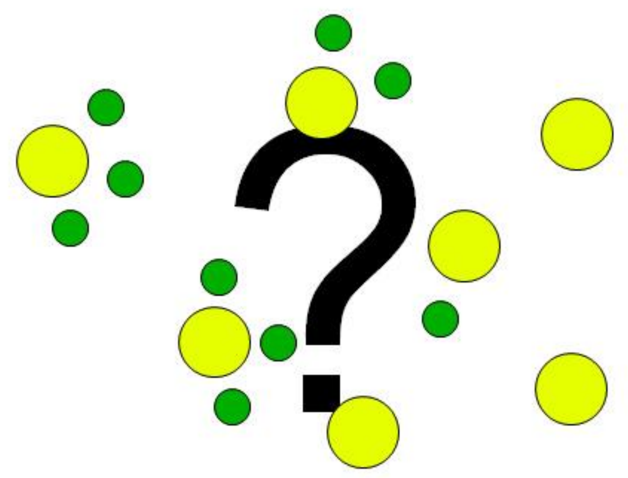
Fraction of Stars with Planetary systems



Determining the Fraction of Stars With Planetary systems (FSWP) requires a detailed analysis that self-consistently includes deriving the multiplicity and inclination distributions as described in the rest of this poster. The frequency/occurrence is calculated system-by-system. FSWP is critical for scientific (What is the efficiency of planet formation?) and observational (How should I design my planet survey?) questions.

FSWP	**x**	**Multiplicity**	**=**	**NPPS**
1/3 1 out of 3 stars		3 each have 3 planets		1 planet/star on average

The true Multiplicity (the average number of planets per star in the actual underlying population) is, by definition, the ratio of NPPS/FSWP. NPPS can be calculated by treating each planet separately, but <u>if a study does not determine the Multiplicity it cannot measure FSWP.</u>



What is eta Earth?
Where is the nearest potentially habitable planet?
What fraction of planetary systems are like the solar system?
How many planets are there?
How many stars form planets?

How to compute NPPS

Using analytical and numerical techniques, we have determined accurate methods for determining the average Number of Planets Per Star. NPPS is the most straightforward occurrence/frequency calculation. Debias geometrically (by inferring how many planets would not have had a transiting orientation) and based on detectability (e.g., for how many stars could you have detected this planet). Do this <u>for all detected planets</u>, regardless of number of detected planets in a system. This yields an accurate estimate of NPPS (with respect to handling multi-transiting systems). Analyses that debias on a planet-by-planet basis *cannot estimate FSWP or the average multiplicity* even though they can determine NPPS.

What should not be done

Using only the most probable planet or the most detectable planet does not accurately handle correlations between transiting probabilities in real exoplanetary multiple systems. <u>To accurately infer NPPS, all planets must be detected and included in the debiasing calculations.</u> In particular, transit search algorithms must continue searching until all planet candidates are found.

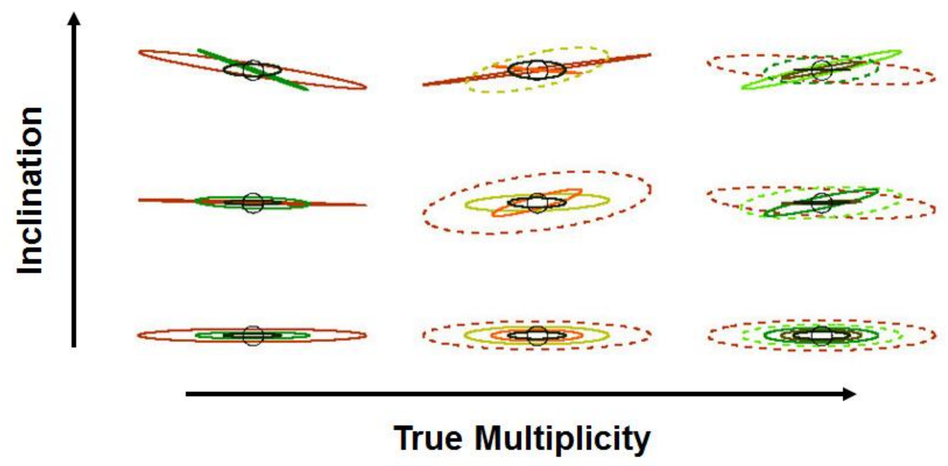
The approximation of calculating FSWP by using only the most probable or detectable planet is only correct if all exoplanetary systems are exactly coplanar. Multiple studies have found that typical inclination distributions for Kepler multiples have widths of 1-2 degrees, and many systems are known to have larger inclinations. Because the transit method is sensitive to inclinations at the <1 degree level, even these small inclinations cause significant errors in the estimation of FSWP that uses only the most probable/detectable planet.

Why does this fail? This method infers the number of "missed planets" due to geometric debiasing and assigns these to stars that have no planets… but in the non-coplanar case, some of these "missed planets" could be in systems with other known planets. Both numerical and analytical models that confirm this result.

This method overestimates the FSWP by an unknown amount.

Incorrectly accounting for planets in multiples can result in estimates of eta Earth that are incorrect by a factor of ~2

How can we measure FSWP?



<u>Answer: Use Kepler's amazing multi-transiting systems to our advantage.</u>

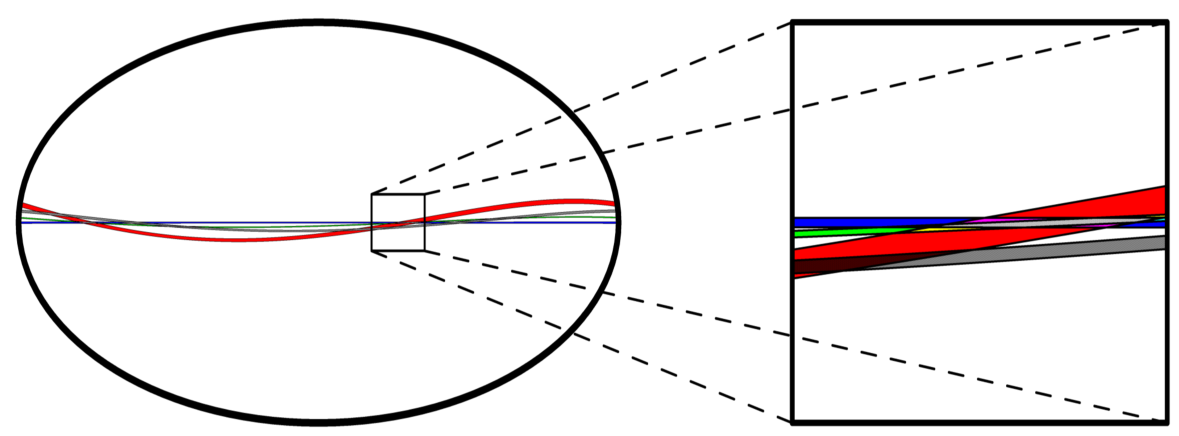
Kepler's multis encode information on the true multiplicity and inclination distributions. Accounting correctly for the multi-transiting geometry can solve for the average multiplicity, the inclination distribution, NPPS, FSWP, and a myriad of other interesting and important information. First steps along these lines are presented in Lissauer, Ragozzine, et al. 2011 and other studies. **DR and EF have funding from NASA's Origins of Solar Systems to expand this work through the development of the planetary system simulator (SysSim).**

Accounting for the multi-transiting geometry can solve for the average multiplicity, the inclination distribution, NPPS, and FSWP.

Multi-Transiting Geometry

Calculations for multi-transiting geometry can be reduced to a differential geometry problem on a sphere. We have developed a new fast efficient code called CORBITS that takes any planetary system and returns the probability that any subset of planets is seen in a transiting configuration. CORBITS will speed and aid analyses that debias Kepler's remarkable results system-by-system in order to determine FSWP. CORBITS will be publicly available and is described in an upcoming paper (Brakensiek & Ragozzine, in prep.) These analyses can preserve the powerful correlations between properties of planets in multi-transiting systems, allowing these information-rich configurations to help construct a precise characterization of the true underlying intrinsic distribution of exoplanetary systems.

Transit regions of the Solar System



The approximate transit regions of the four Solar System inner planets. The colors of the transit regions of Mercury, Venus, Earth, and Mars are red, gray, blue, and green. In the inset, Mercury, Earth, and Mars transit in the light gray region. Using CORBITS, we find that the total area of all such light gray regions is .021% of the area of the sphere. This percentage is also the probability that a random distant observer would be able to see Mercury, Earth, and Mars transiting. Using CORBITS, we have calculated the multi-transiting probability for every set of solar system planets and have found that there is <u>no region of the celestial sphere which would see more than 3 planets transit.</u>

Conclusions

1) **A careful and critical distinction must be made in distinguishing the average Number of Planets Per Star (NPPS) and the Fraction of Stars With Planetary systems (FSWP).**
2) **By definition, the average multiplicity is the ratio of NPPS/FSWP.**
3) **To produce an accurate value of NPPS, analyses must include all detectable planets (e.g., not just the most detectable planet).**
4) **Analyses that study planet by planet cannot accurately estimate FSWP or the average multiplicity, but can infer NPPS.**
5) **Accounting for the multi-transiting geometry can solve for the average multiplicity, the inclination distribution, NPPS, and FSWP.**
6) **We have developed the freely-available CORBITS to efficiently perform calculations for multi-transiting geometry.**
7) **Using Kepler's remarkable dataset, these results will guide future studies of the occurrence rates of individual planets and exoplanetary systems.**

References

Ragozzine & Holman 2010

Lissauer, Ragozzine, et al. 2011

Youdin 2011

Brakensiek & Ragozzine (in prep.)