How Many Earths Are Enough?

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ABSTRACT

The goals of NASA's Terrestrial Planet Finder (TPF) and ESA's Darwin missions are to find and characterize terrestrial planets in the habitable zones of other stars, and to search for evidence of life in the atmospheres of any planets found. A key issue that must be addressed is the size of the sample of stars that must be searched before the scientific community, the funding agencies, and the public at large will be satisfied that an expensive space observatory will have a high probability of success. This question lies at the heart of the definition of TPF/Darwin. In this paper, I discuss some of the parameters that bound the size of the TPF/Darwin sample and outline a science program to improve our knowledge so that we can make timely decisions about the scope and expense of TPF/Darwin.

1. INTRODUCTION

NASA and ESA are studying and investing in key technologies for a mission to detect and characterize terrestrial planets beyond our solar system. NASA's Terrestrial Planet Finder (TPF) and ESA's Darwin mission are presently under consideration for a collaborative project to be launched sometime around 2015. Two architectural classes of observatory are presently under study by NASA [1]: a coronagraph operating in visible and near-IR wavelengths and a nulling interferometer operating in the thermal infrared. In addition, within each architectural class, two missions of different scope are under consideration: a large mission capable of studying more than 150 stars (a formation flying IR interferometer or a coronagraph on an 8-10 m telescope) and a smaller mission capable for studying 25-50 stars (a structurally connected interferometer or a coronagraph on a ~ 4 m telescope). Over the next 3 years a combination of technology readiness and predicted mission risk, cost, and schedule will lead the TPF/Darwin projects to recommend, first, which architectural class to pursue and, second, what scope of mission is required. The architectural decision is planned for 2006. The question of scope will be decided in time to enter into Phase A around 2007 for a launch in 2015.

To a large extent, the *scope* of TPF/Darwin will be determined by the number of stars that must be surveyed to assure, with a high degree of confidence, the success of the mission. We first try to understand what constitute ``success" and then how to achieve it.

2. $\eta_\oplus$ AND THE NUMBER OF STARS TPF/DARWIN MUST SURVEY

Perhaps the most vexing problem facing TPF/Darwin is defining what we mean by a "successful" mission. A reliable estimate of the frequency of Earth-like planets in the habitable zone, $\eta_\oplus$, is an essential step in the determination of how many stars TPF/Darwin must survey to ensure, at some confidence level, a high probability of finding one or more terrestrial planets in the habitable zones of those stars.[1] In practical terms, if we knew that $\eta_\oplus$ were of order unity (or greater than unity since our solar system demonstrates that multiple terrestrial planets located within a broadly interpreted "habitable zone" are certainly possible), then TPF/Darwin could be sized to study the nearest few stars and be assured of success. If, on the other hand, we knew $\eta_\oplus$ to be low, e.g. < 0.01, we would have to study hundreds or thousands of stars to ensure a comparable likelihood of success. Thus, there is an urgent need to either constrain $\eta_\oplus$ by theoretical extrapolation from existing observations or to determine $\eta_\oplus$ directly from future observations.

This issue feeds directly into the cost and scope of the TPF/Darwin mission because the distance to which one must observe to examine a specific number of stars scales roughly as $\eta_\oplus^{-1/3}$. Since the diameter of the telescope (and the baseline of an interferometer) required to achieve a given sensitivity and angular resolution scales as the stellar distance, the cost of TPF/Darwin will increase with decreasing $\eta_\oplus$. If the cost of a (ground-based) telescope scales as $(Diameter)^{2.6}$, then by analogy the cost of TPF might scale at least as steeply as $\eta_\oplus^{-0.9}$. Introducing new technologies such as formation flying will lead to jumps in the cost vs. $\eta_\oplus$ curve that are challenging to assess.

[1] The TPF Science Working Group (TPF-SWG) has adopted a broad interpretation of the habitable zone to encompass the range between the orbits of Venus (0.7 AU) and Mars (1.5 AU) and nominally centered on 1 AU. These values scale with the square root of the luminosity of the parent star.

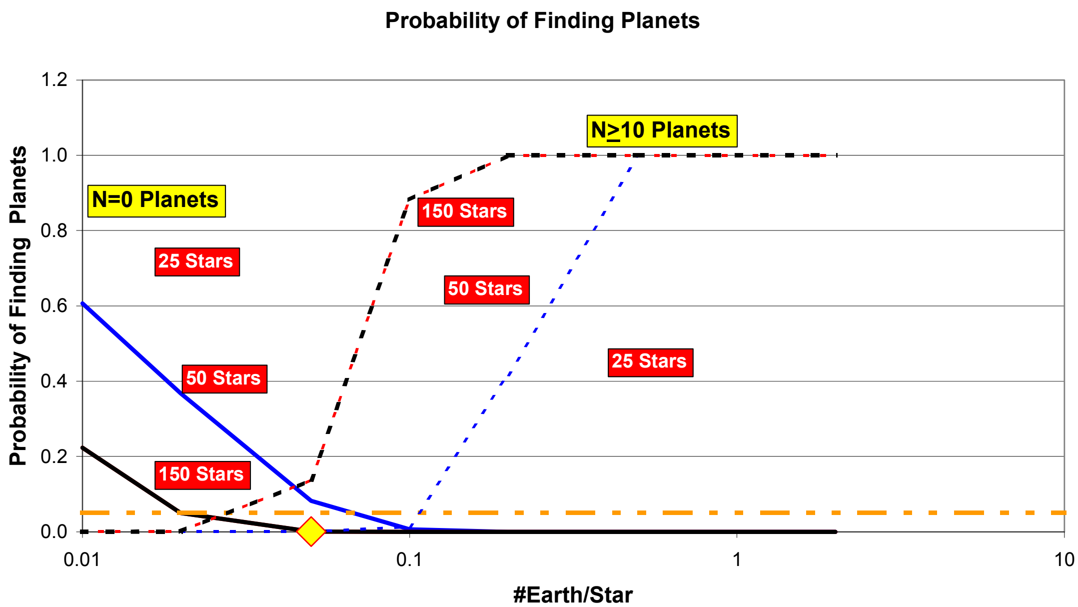

Figure 1. The solid lines show the probability of finding NO terrestrial planet in the habitable zone as a function of $\eta_\oplus$ for three different sample sizes. The dotted lines show the probability of finding 10 or more terrestrial planet in the habitable zone as function of $\eta_\oplus$ for three different sample sizes. The horizontal dashed line marks a 5% probability. The diamond indicates the probability of finding NO planets for a survey with the sample size and sensitivity of the pioneering UBC planet survey [2] that (unfortunately) failed to find any giant planets.

We do not yet know how the choice of architecture, e.g., an IR interferometer or a visible coronagraph, depends on distance and thus on $\eta_\oplus$. The TPF/Darwin projects will examine whether one architecture is preferable for nearby systems ($\eta_\oplus$ high) and another architecture for more distant systems ($\eta_\oplus$ low). Most probably, the choice of *architecture* (interferometer vs. coronagraph) will be set by technology readiness while the *scope* of the mission (aperture, baseline, cost and schedule) will be set by average stellar distance and thus by $\eta_\oplus$.

This question of how many Earths are enough can be posed in a number of ways: 1) how many stars should TPF/Darwin survey to ensure some high probability of finding a terrestrial planet; or 2) what constitutes a significant negative result should TPF/Darwin fail to find any terrestrial planets; 3) how many earth-like planets should TPF/Darwin be capable of finding, given some assumption about the frequency of Earths, to ensure an interesting program of comparative planetology. A simple game of probabilities helps to focus the discussion. Poisson statistics can be used to determine the probability of detecting a particular number of planets, N_{detect} given an expected number of planets, $N_{detect} = N_* \times \eta_\oplus$ in a sample of N_* stars. Fig. 1 shows plots of the probability that TPF/Darwin might detect either 0 (solid curves) or at least 10 planets (dotted curves) as a function of N_* for 3 different survey sizes:

$$\textit{Probability}(N_{detect}=0) = \textit{Poisson Distribution}\,(N_{detect}=0,\ N_* \times \eta_\oplus) \quad (1a)$$

$$\textit{Probability}(N_{detect}\geq 0) = \textit{Poisson Distribution}\,(N_{detect}\geq 10,\ N_* \times \eta_\oplus) \quad (1b)$$

In this figure the probability of finding either NO planets at all ($N_{detect} = 0$; solid curves) or finding at least 10 planets ($N_{detect} \geq 10$; dotted curves) is shown for sample sizes of N_* = *25, 50,* and *150* stars and for $\eta_\oplus$ from 0.01 to 2 terrestrial planets in the habitable zone per star. Note that there are no assumptions about astrophysics, instrumental sensitivity, or observing scenarios built into this figure. The TPF–SWG is presently assessing how a realistic survey would be affected by practical issues such as detection efficiency, temporal sampling strategy, orbital eccentricity and inclination, fraction of the habitable zone examined, etc.

The plots suggest that for $\eta_\oplus \sim 0.1$ (a value comparable to the presently known incidence of giant planets within

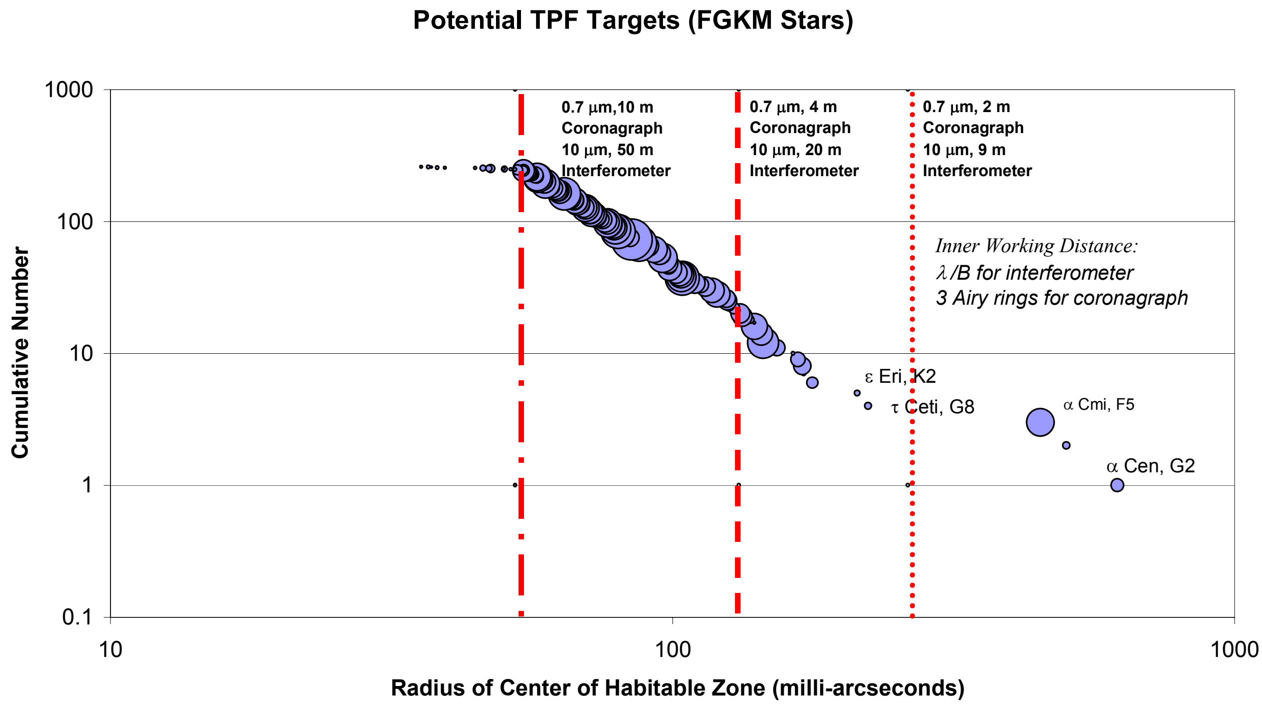

Figure 2. The figure shows the cumulative number of the closest ~250 FGKM stars for which the subtended angle of the habitable zone is larger than a certain value (milli-arcseconds). The vertical bars denote the inner working distance of coronagraphs and interferometers of various sizes.

3 AU of their parent stars [2]), one must survey completely at least 30 stars to be assured at roughly the 95% confidence level of finding at least 1 planet. Similarly, one must study about 175 stars to be assured at the 95% confidence level of finding at least 10 planet for the same $\eta_\oplus \sim 0.1$. The TPF-SWG has used numbers of 30 and 150 stars to bound the scope of TPF for the ongoing architecture studies.

It is important to point out that the Darwin team has suggested that TPF/Darwin should survey at least 500 stars to be assured of mission success. Reconciling these two viewpoints, a smaller, more affordable but riskier number of stars for TPF vs. a larger, more expensive, but more robust number of stars for Darwin will be an important point of discussion among the two teams in the coming years.

As a cautionary note Fig. 1 includes a survey whose final outcome we would like to avoid on a 1-2 billion dollar space mission. A diamond is placed at roughly the point giving the probability that the pioneering UBC radial velocity survey [3] would come up with NO giant planets, assuming a sample size of 25 stars and fraction of stars with giant planets of 5%, appropriate to their instrumental sensitivity. Given these parameters, the UBC scientists had a 30% chance of coming up empty handed as they eventually did. This symbol stands as a warning to TPF/Darwin about the dangers of examining too small a sample.

With the parameterization of Fig. 1, specifying TPF's goals reduces to specifying the value of $\eta_\oplus$ that we would find scientifically interesting in the case of an upper limit ($\eta_\oplus < 0.01, 0.1, 0.5$) and/or the number of planets ($N_{detect} \geq 1, 5, 10$) that we would like in our final sample. The TPF and Darwin Science Working Groups are addressing these issues from the mutually opposing viewpoints of scientific desirability vs. technological feasibility and mission cost.

In the coming years the TPF and Darwin SWGs must define a mission that the community will accept as compelling, e.g. one for which either the probability of finding NO stars is less than, say, 5%; and/or of finding at least 10 planets would be greater than, say, 25% based on a capability of surveying N_* stars for an agreed-to value of $\eta_\oplus \sim 0.1$. As described below, NASA is formulating a precursor science roadmap to ensure that information on $\eta_\oplus$ is available to support key decisions as to the architecture and scope for TPF/Darwin.

Table 1. Ongoing and Planned Planet Searches To Constrain Frequency of Earth Like Planets		
Technique/Facility	*Mass Limit*	*Timetable*
Radial Velocity		
Keck, Lick, ESO, HET	10-15 $M_\oplus$	On-going
Astrometry		
Palomar	1 $M_{Jupiter}$ @ 10 pc	On-going
HST	1 $M_{Jupiter}$ @ 10 pc	On-going
Keck-Interferometer	10-15 $M_\oplus$ @ 10 pc	2008
VLTI	10-15 $M_\oplus$ @ 10 pc	2008
SIM	3 $M_\oplus$ @ 3-10 pc	2013
Transits		
Ground-based searches	1 $M_{Jupiter}$ @ 150-5,000 pc	On-going
MOST	>10 $M_\oplus$ in day-month periods around few dozen stars.	2003
COROT	2- 8 $M_\oplus$ in <2 month periods around 10,000 stars	2006
Kepler (NASA)	> 1 $M_\oplus$ in <year periods around 100,000 stars	2007/8
Eddington (ESA)	> 1 $M_\oplus$ in <year periods around 50,000 stars	2007/8
Microlensing		
Ground-based surveys	< $M_{Jupiter}$ @ >4,000 pc	On-going

The most critical instrumental factor determining the number of stars TPF/Darwin will be able to survey is the *inner working distance* of the coronagraph or interferometer. Raw sensitivity is less of an issue than angular resolution for stars within about 15 pc [1]. Fig. 2 shows how the cumulative number of stars that TPF/Darwin can survey increases as the angular extent of the habitable zone decreases. The figure suggests that a range of 30 to 150 stars implies a factor of two range in inner working distance, from 125 mas to 65 mas. Being able to observe the 500 stars suggested for Darwin would require about 40 mas resolution. Achieving the requisite stellar nulling at the appropriate angular separation represents the chief technological challenge for TPF/Darwin.

3. PRECURSOR SCIENCE PROGRAM

Happily, the determination of $\eta_\oplus$ is a research goal of great intrinsic scientific interest in addition to its importance as an input parameter to the system engineering to TPF/Darwin. There are a number of highly relevant research activities now underway that will constrain or determine $\eta_\oplus$ over the next decade. In the coming years, SIRTF will address the incidence of Kuiper Belts while the Keck and VLT-I interferometers will probe the amount of material in inner (asteroidal) zodiacal clouds. The amount of solid, dusty material may be one indicator of the amount matter tied up in larger, planetary sized bodies. The French (CNES) transit experiment, COROT, will give initial indications of the incidence of rocky planets in short period orbits. More definitive experiments for determining $\eta_\oplus$ will be the Kepler (NASA) and/or Eddington (ESA) transit experiments. Finally, the Space Interferometer Mission (SIM) will study TPF/Darwin stars directly, looking for planets as small as 3 $M_\oplus$ at 10 pc.

Unfortunately, not all of this information is likely to be available on the timescale needed to make decisions about the architecture or scope of TPF/Darwin. The combination of on-going observational programs capable of finding planets of a few (<10 $M_\oplus$) terrestrial masses (Table 1) coupled with improvements in our theoretical understanding of the formation of rocky planets and their stability in realistic planetary systems will allow for educated extrapolations to the incidence of terrestrial planets in the habitable zone. NASA will fund a number of these observational programs and theoretical investigations both for their intrinsic interest as well as for their value to design decisions for TPF.

4. CONCLUSION

This conference demonstrates that the search for habitable planets, and life, beyond the solar system is at the forefront of scientific research and of planned activities of NASA and ESA. The challenge of developing observing techniques adequate to survey an adequate number of stars to be confident of finding at least one such planet is a daunting one. But, as other papers in these proceedings suggest, good progress is being made in developing the appropriate capabilities. The next few years will also see dramatic progress in determining, or at least reducing the uncertainty in, the number of terrestrial planets in the habitable zones of nearby stars which is perhaps the most important single number in the design of TPF/Darwin.

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