THE GAIA ASTROMETRIC SURVEY OF THE SOLAR NEIGHBORHOOD AND ITS CONTRIBUTION TO THE TARGET DATABASE FOR DARWIN/TPF

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ABSTRACT

We evaluate the potential of the ESA Cornerstone Mission GAIA in helping populate the database of nearby stars (d < 25 pc) for subsequent target selection for DARWIN/TPF. The GAIA high-precision astrometric measurements will make it an ideal tool for a complete screening of the expected several thousands stars within 25 pc in order to identify and characterize (or rule out the presence of) Jupiter signposts. GAIA astrometry will be instrumental in complementing radial velocity surveys of F-G-K stars, and will more effectively search for massive planets the large database of nearby M dwarfs, which are less easily accessible with precision spectroscopy. The ability to determine the actual planet masses and inclination angles for detected systems, especially those with low-mass primaries (M < 0.6 M⊙), stems as a fundamental contribution GAIA will make toward the final target selection for DARWIN/TPF, thus complementing exo-zodiacal dust emission observations from ground-based observatories such as Keck, LBTI, and VLTI.

Key words: planetary systems; astrometry; stars: statistics; instrumentation: miscellaneous.

1. INTRODUCTION

The nearest stars to our Sun, within a conservative distance d < 25 pc, will constitute the ancillary database for which the actual target list for DARWIN/TPF will be derived. The final selection will be made on the base of characteristics such as spectral type, age, metallicity, multiplicity, presence of sub-stellar companions such as giant planets, and possible evidence for rocky planets. It is remarkable how for the vast majority of the stars in our immediate vicinity largely lacks such fundamental information. To date, about 2600 stars are known within 25 pc, but the total number, scaled from the better-known sample within 5 pc, should be around 8000. So the database today is likely to be only 30% complete, and data for the presently known sample suffer from large uncertainties. In particular, the database of low-luminosity M dwarfs lacks probably about 80% of the total population within 25 pc. A complete census of this part of the sample of nearby stars has a special connection to defining the DARWIN/TPF target list. Conventional wisdom has it that M stars are not expected to have habitable rocky planets because such planets would need to be so near their primaries that tidal friction would halt or slow the planets’ rotation, rendering them sterile. However, some research indicate that a substantial atmosphere can redistribute heat around an otherwise too-slowly rotating planet. Also, a typical M0 star has 1/2 the mass of the Sun, and would heat a planet to terrestrial temperatures at the position of Mercury’s orbit where tidal breaking might not be severe. Thus, we suggest that the large database of nearby M dwarfs should be kept under focus by future studies dedicated to the selection of the optimal target list for DARWIN/TPF.

2. THE NEARBY SINGLE STAR DATABASE

The best targets for DARWIN/TPF are likely to be single stars. Within a radius of 25 pc, 584 such stars are known today. Again assuming the number of single stars scales with the volume, and extrapolating directly from the well-known sample of 21 such objects existing within 5 pc, one would conclude (lower right panel of Fig 1) that ~75% of the reservoir of single stars is still missing. The radial velocity information about the existence of giant planets is available only for a fraction of the known objects, the 100 or so moderately luminous F, G, and early K type stars. The lack of knowledge for the majority of the lower luminosity stars known today (and for all late K and M dwarfs not identified yet as nearby stars) is clear when the distributions of stellar objects in the solar neighborhood as a function of V magnitude, mass, and distance are compared to the analogous distributions for the planet-hosting stars, as shown in the upper right and left and lower left panels of Fig 1. Radial velocity surveys are reaching now completeness out to 50 pc for the bright F-G stars (V < 8), and for planetary companions more massive than Jupiter in the orbital radii range < 3–4 AU.
Only a limited number of K and M dwarfs has been monitored so far for planets with comparable sensitivity to the one routinely reached nowadays in the case of F and G dwarfs. Such objects will need careful studies in the coming years, as they will likely constitute the majority of the list of targets for DARWIN/TPF. To this end, information from radial velocity measurements (including spectroscopic orbits for detected planetary mass companions) will have to be complemented by precision astrometry.

3. TARGET LIST SELECTION CRITERIA

Once a database of stars has been searched based on spectral type, metallicity, age, and distance information, the criteria to be adopted for refining the list of possible targets focus on their Habitable Zones and Exclusion Zones. The Habitable Zone \([1]\) is conventionally defined by the distance from a given star at which the temperature is such that water can be present in the liquid phase. The center of the Habitable Zone (whose distance depends on the mass of the parent star \(M_\star\)) can be roughly identified by the formula:

\[
\frac{T_{HZ}}{T_\oplus} = \left(\frac{M_\star}{M_\odot}\right)^{7/4},
\]

where \(T_\oplus\) is the Earth’s orbital period. The inner and outer boundaries of the Habitable Zone for main sequence dwarfs are placed at roughly \(T_{HZ, in} \approx 0.7 \times T_{HZ}\) and \(T_{HZ, out} \approx 2 \times T_{HZ}\), respectively. The Exclusion Zone \([8]\) is operationally defined by the dynamical con-
Figure 2. Left: the Habitable Zone (green) and Exclusion Zone (red) in our Solar System. Right: for 14 Her, harboring a gas giant planet with a minimum mass of $\sim 3.3 \text{ M}_J$ orbiting with a period of 4.4 yr, the formation of a terrestrial planet could still have occurred in principle in a narrow region inside the Habitable Zone.

constraint:
\[ T_G > 6 \times T_R, \]  
which states that for a rocky planet to form in the Habitable Zone of a star then a giant planet must form on an orbital period $T_G$ at least six times larger than the period $T_R$ of the rocky planet. This constitutes a more stringent constraint than the one based on the dynamical stability analysis of the orbits in the Habitable Zone of a star already hosting a gas giant, as this approach does not take into account the possibility that such rocky planets may have actually formed in these systems, at such privileged distances, in the first place. As of today, only one star, among the F and G type objects within 25 pc from the Sun, is known to harbor a giant planet at an orbital radius such that in principle the formation of a rocky object in its Habitable Zone might not have been prevented: this is the bright ($V = 6.61$), nearby ($d = 18.15$ pc) G dwarf 14 Herculis (14 Her). Fig. 2 summarizes the concepts of Habitable and Exclusion Zones as they have been realized in our solar system and in the 14 Her planet-star system.

In light of these constraints, a given star may then be selected as a DARWIN/TPF target if one of the three following conditions apply:

1) A rocky planet in its Habitable Zone has been already detected by other means (the highest priority targets);

2) A ‘Jupiter signpost’ has been detected at an orbital radius from the star such that it has not precluded the possible formation of Earth-sized bodies in the region where water is liquid;

3) Close scrutiny of the star has not produced any detection of giant planets for a wide range of orbital radii, thus planetesimal accumulation in the inner regions has been in principle free to occur.

Today, the information needed to make these selections is available in part for only a limited number of F-G type stars within 25 pc, thanks to precision (3-5 m/s) ground-based radial velocity measurements. As discussed above, only 1 star within 25 pc falls into the second class, while, due to insufficient sensitivity of present-day instrumentation, no objects have been found that fulfill criterion 1). The need to extend the surveys to late-type objects and lower planet masses is thus clear.

4. HOW MANY TARGETS FOR DARWIN/TPF?

Beside a number of technological challenges, today the most important source of uncertainty for DARWIN/TPF from a scientific point of view is the fact that the frequency of terrestrial planets $\eta_\oplus$ is completely unknown. Naive extrapolations based on the current database of gas giants would be arbitrary at best. During the next 5-10 years transit photometry missions from space (Kepler, Eddington) will have the sensitivity to detect Earth-sized objects transiting on the disk of their parent stars, thus it will become possible to derive a first estimate of $\eta_\oplus$. However, these results will not be conclusive, and a scientifically meaningful search for habitable planets with DARWIN/TPF should be designed so that a null result (no habitable planets found) be statistically significant. In other words, DARWIN/TPF should examine enough stars, with enough sensitivity and operational lifetime, so that we can draw valid statistical conclusions about the prevalence and properties of rocky planets found in other solar systems.

The two architectures for DARWIN/TPF presently under study by the National Aeronautics and Space Administration (NASA) and by the European Space Agency (ESA) are $a)$ an IR nulling interferometer operating either on a fixed structure or in a separated spacecraft configuration, and $b)$ a monolithic telescope with a coronagraph and/or apodized aperture operating at visible wavelengths. Fig. 3 shows the projected location and width of the Habitable Zone (in milli-arcseconds) for the 584 stars known within 25 pc from the Sun. For comparison, the limiting resolutions of the abovementioned architectures are
over-plotted, for a variety of values of the monolithic telescope diameter $D$ or the interferometric baseline $B$. As a general result, in order to sample at least a few hundred targets, telescopes in the visible with $D \geq 10$ m or interferometers with $B \geq 100$ m will be required. If the selection of targets was limited only to the few tens or so of luminous F-G-K dwarfs, the failure to find habitable planets could raise questions about the relevance of the sample, not about the frequency of terrestrial planets. For this reason, the final target list for DARWIN/TPF could be broadened to include a significant number of M dwarfs. Only a few of them have been searched so far for planets, and many of them have not been discovered yet as nearby stars to our Sun. The GAIA all-sky astrometric survey has the potential to crucially help filling this important gap in our knowledge of the database of nearby stars to our Sun.

5. THE ROLE OF THE GAIA SURVEY

The size of the stellar sample out to 150-200 pc to be investigated for planets (hundreds of thousands of objects) constitutes the most significant contribution GAIA will provide to the science of extra-solar planets (e.g., 3, 4). Table 1 shows how, given reasonable assumptions on the planetary frequency as a function of orbital radius, on the detection threshold, and on the accuracy of orbit determination, GAIA will be capable of discovering thousands of planets around relatively nearby main-sequence stars, and it will accurately measure the orbital characteristics and actual masses for a significant fraction of the detected systems 2.

| $\Delta d$ (pc) | $N_\star$ | $\Delta a$ (AU) | $N_d$ (1) | $N_m$ (2) |
|-----------------|-----------|----------------|-----------|-----------|
| 0-100           | $\sim 61000$ | 1.3 - 5.3     | $\geq 1600$ | $\geq 640$ |
| 100-150          | $\sim 114000$ | 1.8 - 3.9     | $\geq 1600$ | $\geq 750$ |
| 150-200          | $\sim 295000$ | 2.5 - 3.3     | $\geq 1500$ | $\geq 750$ |

Thus, the results derived from GAIA high-precision astrometric measurements will help decisively improve our understanding of orbital parameters and actual mass distributions, and they will provide important data to determine the correct theoretical models of formation, migration, and dynamical evolution.
Figure 4. GAIA planet discovery space as a function of orbital radius, stellar spectral type (F-G-K-M, from top left to bottom right), and distance from the observer (5 and 25 pc, solid and dashed-dotted-dotted green lines, respectively). For reference, the blue dotted segment identifies the star’s Habitable Zone. The dashed-dotted purple lines identify the planet discovery space for 3 m/s precision radial velocity measurements.

With the current payload design [4], the range of planetary masses between 1 Earth-mass and a few Earth-masses will only be marginally accessible to GAIA’s all-sky survey. Its astrometric accuracy will be sufficient to address the issue of their existence only around a handful of the closest stars, within a few pc from the Sun. The most tantalizing targets for DARWIN/TPF, those for which Earth-sized bodies in their Habitable Zones have already been detected, are thus likely to be found by SIM (see for example [6]). Nevertheless, GAIA’s contribute to the search for rocky, possibly habitable planets will be significant. In particular, GAIA has the potential to complement radial velocity measurements in order to identify good targets for DARWIN/TPF responding to selection criteria 2) and 3). With an expected single-measurement precision of 8-10 µas at V=13 or brighter, GAIA will be capable of monitoring the vast majority of the nearby stars within 25 pc with sufficient accuracy to confirm Jupiter signposts detections by radial velocity techniques. In particular, GAIA will extend the spectroscopic surveys at the faint end (late K through M dwarfs), where the size of the sample and detectable orbital period ranges from ground will likely be limited by telescope time constraints.

For any particular star, the boundary of discovery space for astrometry and radial velocity—the dividing line between detectable and non-detectable—is found by equat-
ing the minimum signal (the astrometric signature or the radial velocity semi-amplitude, respectively) required for discovery to the actual magnitude of the gravitational pull induced by the planet on its parent star \( \mathcal{M}_p \). For a given stellar mass (and distance from the observer in the astrometric case), it is then possible to determine the minimum detectable mass \( M_{p,\text{min}} \) as a function of the semi-major axis of the planetary orbit \( a_p \). To take into account the loss in sensitivity for periods \( T \) longer than the mission length \( L \) (set to 5 yr for GAIA, and 10 yr for ground-based radial velocity surveys), we have parameterized \( M_{p,\text{min}} \) in the two cases as follows:

\[
M_{p,\text{min}}^{(A)} = \begin{cases} 
\kappa \times \sigma_A \times \frac{M_\star d}{a_p}, & T \leq \lambda L \\
\kappa \times \sigma_A \times \frac{M_\star d}{a_p} \times \sin^{-2} \left( \frac{\pi \lambda L}{2T} \right), & T > \lambda L
\end{cases}
\]

\[
M_{p,\text{min}}^{(RV)} = \begin{cases} 
\kappa \times \sigma_{RV} \times \sqrt{M_\star a_p}, & T \leq \lambda L \\
\kappa \times \sigma_{RV} \times \sqrt{M_\star a_p} \times \sin^{-2.4} \left( \frac{2\pi L}{T} \right), & T > \lambda L
\end{cases}
\]

In the plane defined by the mass of the planet \( M_p \) and the orbital semi-major axis \( a_p \), these parametric equations identify families of curves with the same shape, having an absolute minimum at the value of \( a_p \) corresponding to a period in years equal to the fraction \( \lambda \) of the time-span of the observations where the sensitivity is greatest.

Fig. 4 shows the minimum detectable planet mass \( (M_p) \) by GAIA as a function of orbital radius, stellar mass, and distance from the Sun (assuming a single-measurement error \( \sigma_A = 10 \mu\text{as} \) on the one-dimensional coordinate measured by GAIA along the scan direction). For comparison, the equivalent detection curves are also plotted for ground-based radial velocity surveys with an adopted single-measurement precision \( \sigma_{RV} = 3 \text{ m/s} \), and assuming that integration times can be modified in order to reach the same sensitivity on stars of different spectral type. For both techniques, a signal three times larger \( (\kappa = 3) \) than the measurement precision is required for secure detection. For orbital periods exceeding the time-span of observations \( (T > \lambda L) \), with \( \lambda = 7/8 \) the loss in sensitivity (i.e. increasingly larger values of \( M_{p,\text{min}} \) needed for detection) for spectroscopy is faster than for astrometry, as the radial velocity amplitude decreases as the orbit gets larger.

The GAIA astrometric survey will provide, for all detected giant planets for which an orbital solution can be obtained, two fundamental parameters which are needed in order to probe the actual validity of a potential DARWIN/TPF target. First of all, it will derive meaningful estimates of the actual mass of a planet, allowing theorists to establish whether dynamical interactions may have prevented a rocky planet in the Habitable Zone from forming. Second, it will measure the inclination of the orbital plane, thus complementing studies of exo-zodiacal cloud emission from the system under investigation (with ground-based facilities such as Keck, VLT, and LBTI), and allowing in turn to carefully select possible targets in which the orbital inclination is not too close to edge on (as the presence of zodiacal emission in systems with inclination angles \( \alpha > 60^\circ \) may hamper the planet finding capabilities of DARWIN/TPF).

6. CONCLUSIONS

Precision astrometry during the next decade will begin complementing effectively planet searches based on radial velocity measurements. In its global astrometric survey, GAIA will search for the presence of massive planets all expected stars within 25 pc from the Sun, including the large database of M dwarfs. For all potentially interesting systems for DARWIN/TPF according to selection criteria 2) and 3), GAIA has the potential to refine the selected lists by providing meaningful estimates of two fundamental parameters, actual planet mass and orbital inclination, or by ruling out the presence of massive objects that may have hampered rocky planet formation. The data GAIA will provide on the presence (or absence) of Jupiter signposts orbiting the faint end of the stellar sample in the solar neighborhood will constitute very valuable knowledge that will crucially complement the information coming from other techniques at the moment of the final selection of targets for DARWIN/TPF.

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