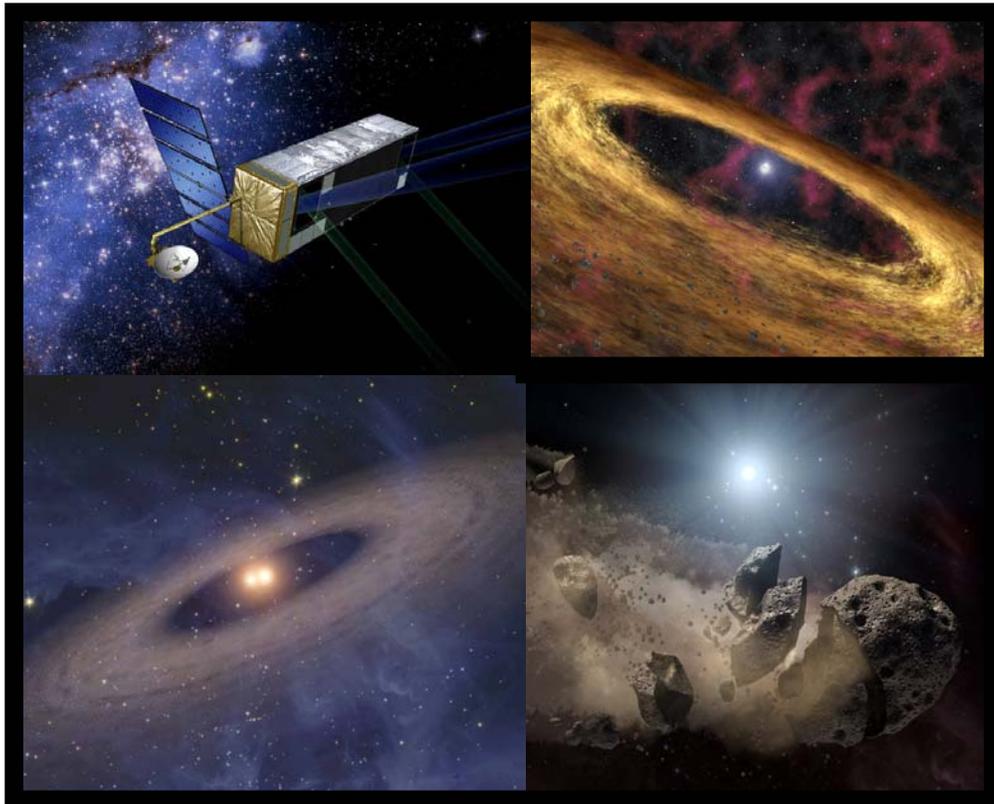


**NO PLANET LEFT BEHIND:  
Investigating Planetary Architecture and Diversity  
with SIM Lite**



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# No Planet Left Behind: Investigating Planetary Diversity and Architecture with SIM Lite

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## 1. Abstract

The evidence is mounting that star formation necessarily involves planet formation. We clearly have a vested interest in finding other Earths but a true understanding of planet formation requires completing the census and mapping planetary architecture in all its grandeur and diversity. Here, we show that a 2000-star survey undertaken with SIM Lite will uniquely probe planets around B-A-F stars, bright and binary stars and white dwarfs. In addition, we show that the high precision of SIM Lite allows us to gain unique insights into planet formation via accurate measurements of mutual inclinations.

## 2. Introduction

Our understanding of extrasolar planetary systems has grown exponentially over the past decade and half. In addition to familiar designations of rocky planets, giant planets and icy giants we now have new names such as “Hot Jupiters”, “Eccentric Giants”, “Hot Neptunes” and “Super Earths”.

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The first wave of these discoveries was driven by precision Radial Velocity (RV) studies. The transit method is now contributing handsomely to the detailed studies (radius, composition) of the hot Jupiters. COROT and Kepler (launch in 3 weeks!) will determine the statistics of rocky planets.

Recently, the ExoPlanet Task Force (ExoPTF)<sup>1</sup> reviewed the state of the field. Their strategy consisted of addressing the following fundamental questions (in priority order) over the next decade and half:

1. What are the physical characteristics of planets in the habitable zones around bright, nearby stars?
2. What is the architecture of planetary systems?
3. When, how and in what environments are planets formed?

Other white papers (e.g. Marcy-Shao, Traub-Kastings, Beichman) address the first and last question. Here, we address the second question.

## 3. Planetary Diversity & Architecture

For the Solar system, the observations and measurements strongly support the bottom-up (dust to rocks to planetary cores), also known as Safronov model for planet formation. In contrast, the prevailing hypothesis for the formation of brown dwarfs (and

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<sup>1</sup><http://www.nsf.gov/mps/ast/exoptf.jsp>

stars) is a top-down (gravitational condensation) scenario.

The discovery of 51 Pegasi b, a Jupiter with an orbital separation of only 0.05 AU (as opposed to 5.2 AU for Jupiter), was a dramatic illustration of the limitations of the standard model for planet formation.

Observation have now established a strong correlation between the metallicity of stars and the occurrence of an planet (identified by RV approach). The sense of connection (metals to planets) as well as whether this correlation is proportional (low metallicity, fewer or lower mass planets as opposed to a sharp transition) are being debated heavily.

It is well known that most stars are in binary or multiple systems. A full understanding of planet formation should naturally address the issue of planets around and in binary (and multiple) star systems.

Finally, the current extra-solar planet sample is dominated by those found using the RV technique, namely stars with spectral type FGK. OBA stars have no strong absorption features and M dwarfs have prominent lines but primarily in the near-IR. Binaries with small angular separation pose additional difficulties for observations.

These gaps in our knowledge show the importance of a comprehensive search for planets in every conceivable ecological niche: stars with varying metallicity, binary stars and stars across the entire mass spectrum.

Apart from these astrophysical “biases”, the search techniques have their own biases: RV and transits favor close in planets whereas astrometry gains ascendancy with longer pe-

riod planets. Both RV and astrometry are limited by the duration of the survey. Microlensing, while sensitive, is limited to statistical studies. Imaging techniques will be valuable but the meaningfully powerful instruments are a decade away.

Mapping planetary architecture would be immensely aided by having sensitive astrometric measurements. Fortunately, recent advances in technology will soon see astrometry fulfilling its expected promise.

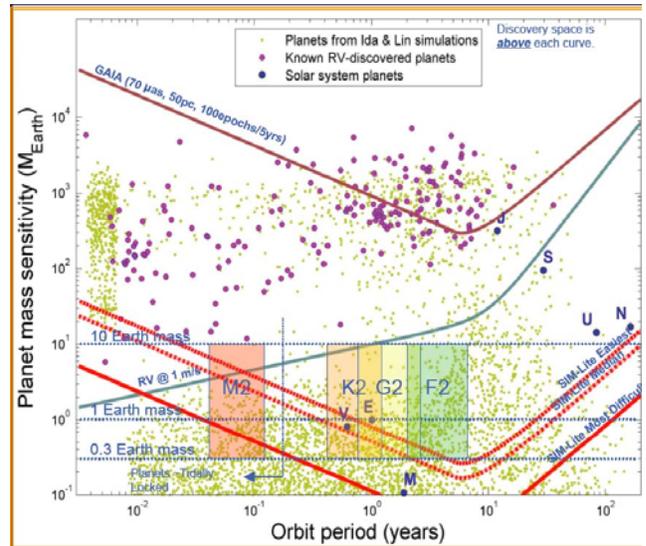


Fig. 1.— Phase Space of SIM Habitable Zone planet search and the GAIA planet search.

#### 4. The Decade of Astrometry

Ground-based interferometers have already demonstrated GAIA-like single-epoch (or better) performance for close binaries ( $20 \mu\text{arcsec}$ ; Muterspaugh et al. (2008)); seeing-limited imaging and HST/FGS observations have achieved precision of sub-milliarcsecond for relative astrometry (Lazorenko 2006; Pravdo et al. 2006; Benedict

et al. 2008); and adaptive optics observations show great promise of beating  $100 \mu\text{arcsec}$  (Cameron et al. 2009).

The main limitation for ground-based interferometric and AO astrometry is the availability of suitably bright reference stars. As a result ground-based interferometry is ideally suited to exploring planets in binary systems. AO observations with large telescopes is well suited to probing planets around faint targets especially at low Galactic latitudes (M dwarfs, brown dwarfs). But for most stars, the requirement of reference stars makes space based astrometry a must. This basic conclusion has been discussed and reaffirmed by two decadal reviews (1990 and 2000) and again reaffirmed recently by ExoPTF.

GAIA (expected launch of late 2011) is expected to achieve single epoch astrometric precision of  $55 \mu\text{arcsec}$  (for the range 6–13 mag). With an average of 84 visits to an object GAIA has very good sensitivity to detect Jupiter mass objects around a very large number stars.

SIM Lite is designed for both wide and narrow angle astrometry. Three planet searches have been envisaged with SIM Lite: an ultra-deep sub-microarcsecond search of nearby Earth-like planets around nearby Sun-like stars (PI: Shao, PI: Marcy; hereafter, HZ search), a search for planets around young stars (PI: Beichman) and a broad search. This latter search is the topic of this paper. The phase space covered by GAIA and the SIM habitable zone search is shown in Figure 1.

Over the range 0–13 mag SIM Lite can easily achieve  $5 \mu\text{arcsec}$  single-epoch preci-

sion. With 10% of SIM Lite time one can survey nearly 2,000 stars at this single-epoch sensitivity (visiting each star 150 times). We call this as the “Broad Survey with High Precision” (BSHP for short) and discuss the potential astrophysical returns of this survey. The relative phase space between GAIA and BSHP is shown in Figure 2.

## 5. Planets around B- and A-type Stars

RV studies, by necessity, have targeted FGK stars. For example, the bulk of the California and Carnegie Planet Search probe the mass range  $0.8\text{--}1.2 M_{\odot}$  (Valenti & Fischer 2005; Takeda et al. 2007). The intermediate- and high-mass main sequence stars ( $M_{*} > 1.4 M_{\odot}$ ) suffer from fewer spectral lines, rapid rotation and surface inhomogeneities (Saar et al. 1998; do Nascimento et al. 2003; Galland et al. 2005; Wright 2005). By cleverly observing evolved versions of these stars, Johnson et al. (2007) find that the planet occurrence rate increases with increasing stellar mass.

SIM Lite is well positioned to undertake a comprehensive survey of hundreds of type A and B stars. For example, SIM Lite will be able to detect a  $19M_{\oplus}$  planet on a 4 year orbit around a  $2M_{\odot}$  A-type star located at 30 pc with 150 50-second visits. Similarly, a  $130M_{\oplus}$  planet can be detected around a  $6M_{\odot}$  B-type star located at 100pc.

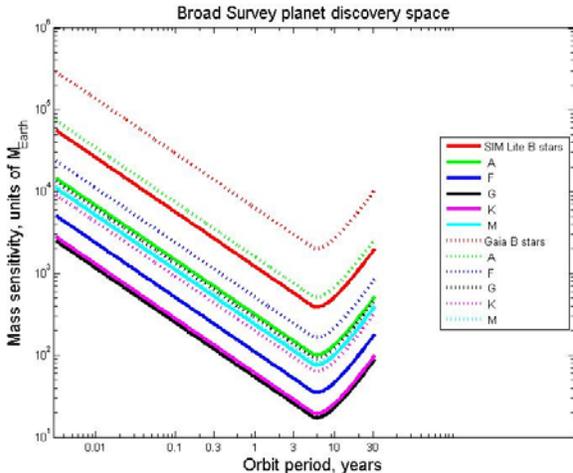


Fig. 2.— Phase space of SIM Lite Broad Survey with High Precision relative to that of GAIA. SIM Lite enjoys a clear advantage over GAIA for BAF stars. Nearby GK and some F and M stars will be observed intensively by the SIM Lite HZ search (see previous Figure).

## 6. Planets and Host Star Metallicity

Jovian-like planets are preferentially found around metal rich stars (Santos et al. 2004; Fischer & Valenti 2005). Recent observational findings suggest that this well-established result does not hold for Neptunian-like planets. Sousa et al. (2008) find a wide spread in metallicities for stars hosting Neptunian-like planets and find that the Jupiter-to-Neptune ratio is higher for higher metallicity stars. These results suggest that the mass of the largest planet in any given system is determined by the metallicity of the host star. This trend is expected from planet formation theories based on the core-accretion process provided that the host star metallicity is representative of the metallicity in the planetesimal disk (Bean et al.

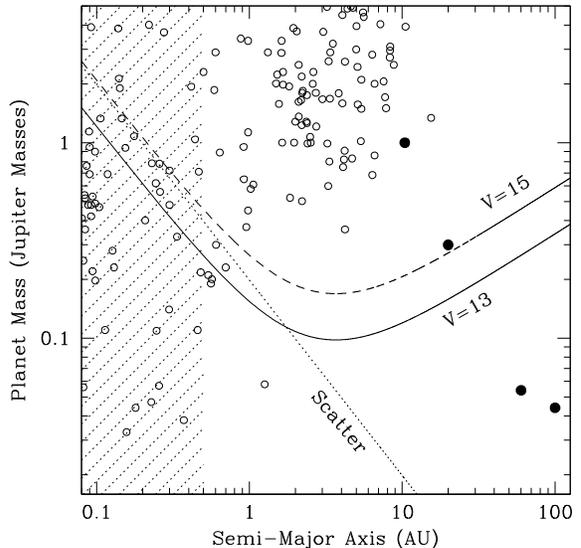


Fig. 3.— The discovery space for a five-year astrometric planet search around white dwarfs (distance 10 pc). See text (§8.1) for explanation of the dotted line. The solid points indicate the positions of the solar system planets assuming the Sun loses half its mass. Similarly, the open circles indicate the positions of the detected radial velocity planets (Butler et al. 2006) if they spiraled out by a factor of two during the evolution to a white dwarf. Planets in the shaded region will be swallowed up by the red giant precursor phase.

2006). This suggests that lower-mass planets might even be preferentially found orbiting metal-poor stars. A SIM Lite survey (discussed in the previous section) will be able to test whether the planet-metallicity relation holds for A- and B-type stars.

## 7. Binary & Bright Stars

GAIA is not able to observe stars brighter than 6 mag. For stars with  $6 < V < 13$  saturation is avoided by dumping the ac-

cumulated charge. As a result GAIA has a flat astrometric performance to 13 mag (after which photon noise becomes important). For bright stars a surrounding region (proportional to the brightness) is not observable. This limitation means that a range of binary stars (with at least one bright companion) are not accessible to GAIA.

The absolute V magnitudes of dwarfs is as follows: G5 (5.1), G0 (4.4), F5 (3.4), F0 (2.6), A5 (2.0), A0 (0.7), B5 (-1.1) and B0 (-4.7). The following stars are not accessible to GAIA:  $\alpha$  Centauri (G2V), Sirius A (sp type A0), Altair (A7), Procyon (F5), Regulus (B8), Alkaid (B3) and so on.

Next, the neighborhood restriction discussed above excludes planet searches around fainter members of a bright star. Ground-based interferometers equipped with dual-beam correlators (phase referencing) have already demonstrated GAIA-like precision for planet searches (cf. the PHASES project, Muterspaugh et al. (2008)). A SIM Lite + VLTI program targeting suitable binaries would offer the best of both worlds: high precision over a 5-yr period and a 25-yr search for distant companions.

## 8. Planets around White Dwarfs

Eventually, the majority of stars evolve to become white dwarfs. It is a natural question to ask what happens to a pre-existing planetary system as the star evolves. For planets sufficiently far from their parent stars, the mass loss in the later evolutionary phases results in an adiabatic expansion of the orbit, so that the planets spiral outwards, but oth-

erwise remain bound. For the closest planets, however, the out-spiral is not sufficiently fast, and the planet is, at some point engulfed by the expanding host. Tidal interactions between the star and the planet also influence where this boundary lies. In addition to the general astrophysical interest, this question has an anthropocentric (if morbid) interest, in that studies show that the long-term survival of Earth in the face of the Sun's evolution is uncertain, as it lies near the boundary, where different treatments of tidal and wind effects can yield different answers (Rasio et al. 1996); see also (Duncan & Lissauer 1998; Villaver & Livio 2007).

Lack of strong and/or narrow absorption lines limit RV precision to  $10 \text{ km s}^{-1}$  (except for the very special cases of pulsating white dwarfs (Mullally et al. 2008)). Furthermore, the red-giant phase of the host star leads to spiraling of inner planets. Astrometry is ideally suited to probe planets around white dwarfs. The astrometric method is further favored by the proximity of white dwarfs (122 within the local 20 pc; Holberg et al. (2008)).

A five year astrometric program<sup>2</sup> probes precisely the original  $\sim 1AU$  region of anthropocentric interest. Assuming a traditional initial-final mass relation  $M_f = 0.49M_\odot \exp(0.095M_i)$  (e.g. Wood (1992)), conservation of angular momentum during the main sequence to white dwarf transition implies that a final (circular) orbit with a period of five years around the white

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<sup>2</sup>Two hundred visits with SIM Lite over a five year period. Integration time of 15s (V=13; solid line) and 30-s (V=15; dashed line); see Figure 3

dwarf corresponds to an original semi-major axis

$$a_i = 1.05 AU \frac{e^{0.127 M_i}}{M_i} \left( \frac{P_f}{5 \text{ yr}} \right)^{2/3}. \quad (1)$$

A SIM Lite white dwarf planet search will probe planets down to roughly a Neptune mass at original distances 0.5–2 AU (Figure 3).

### 8.1. DAZd White Dwarfs

Approximately 2% of all white dwarfs with cooling ages  $< 0.5$  Gyr show evidence for an infrared excess (Farihi et al. 2009) and some show evidence for metal pollution (Kilic et al. 2006; Jura et al. 2007). These are attributed to the tidal disruption of a planetary minor body, either a comet or asteroid (Alcock et al. 1986; Jura 2003) to form a disk that reprocesses stellar light and slowly accretes onto the star.

Because a white dwarf progenitor swells to radii  $\sim 1 AU$  during prior evolutionary stages, asteroids that approach close enough to be tidally disrupted must be scattered inwards at late times by planetary bodies (Debes & Sigurdsson 2002). Planets large enough to scatter significantly without accreting must have a mass:  $M > 20 M_{\oplus} \left( \frac{a}{1 AU} \right)^{-1}$  where  $a$  is the semi-major axis (shown as dotted line in Figure 3). The SIM Lite white dwarf program will probe a significant fraction of the parameter space occupied by planets that generate these dusty disks through asteroid scattering. The sample of  $V < 15$  white dwarfs is large enough to test the hypothesis that most of this par-

ticular class of white dwarfs have surviving planetary systems.

## 9. Insight through Precision

It has long been appreciated that mutual inclination (the inclination of planets with respect to each other) and eccentricity give fundamental insight into details of planet formation. Astrometry (and imaging) is uniquely suited to measuring inclinations.

Among the great variety of planetary systems uncovered by the radial velocity studies are a number of multiple planet systems (32 as of Feb 14, 2009). Sometimes interactions result in resonant states. For example, a 3:1 mean motion resonance is claimed in HD 60532 (Desort et al. 2008; Laskar & Correia 2009).

SIM Lite is particularly well suited to probing these subtle but key diagnostic dynamical clues for planets with  $a > 0.5 AU$ . True mass determination is clearly essential for a correct understanding of the dynamics of the system (stability, identification of mean motion resonances and secular resonances). Next, the mutual inclinations of eccentric planets shed light on the prior evolution of the system (e.g. diffusive scattering processes should lead to approximate energy equipartition in radial and vertical motions, whereas resonant processes need not do so). In addition, determining the mass ratio and resonance configuration of multiple planet systems will place constraints on the strength of eccentricity damping during migration and the rate of planetary the migration itself (Lee & Thommes 2004).

Separately, should the orbit of a planet be inclined significantly with respect to the binary orbit, Kozai oscillations can significantly affect the orbital parameters of the system (Holman et al. 1997; Wu & Murray 2003). Furthermore, a statistically significant correlation between the sense of rotation for stellar orbits and planetary orbits may provide information on the degree to which the binarity affects the formation of a planetary system.

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