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# THE QUEST FOR EXTRASOLAR PLANETS

*SIM will be an extraordinarily valuable tool for discovering new planets around other stars. In the last few years, astronomers have found the first planets outside the solar system, using techniques capable of finding massive, Jupiter-like planets. However, SIM will greatly improve upon the existing detection techniques, allowing planets hundreds of times smaller in mass to be discovered. This means that, for the first time in human history, we will be able to discover whether or not our neighboring stars have Earth-like planets, capable of supporting life.*

**Which of the more than hundred billion stars in the Galaxy might be hosting an Earth-like planet? Image: composite of Earth by the GOES-7 satellite and stars from 2MASS sky survey.**

Confirming the existence of planets outside our solar system has long been an unattained goal of astronomy. A decade ago, planets around other stars were earnestly sought but none definitely found. For centuries before that, philosophers and religious thinkers had signified the question of the existence of other worlds with debate about the “uniqueness of Earth.” John Adams, a Founding Father of the United States, discussed the probability of planets around other stars with William Herschel, the Astronomer Royal of England. Meanwhile, artists and authors have freely invented them — and their life forms — unconstrained by facts.

Now extrasolar planets are a reality. With firm discoveries of substellar companions from radial-velocity monitoring in hand, astronomers have entered a new era in the quest. Questions about planets and life on a cosmic scale will be decisively addressed, starting with the Space Interferometry Mission. SIM will be the first in a sequence of space instruments that are designed to study extrasolar planets. Its unique capabilities will bring into new focus the sciences of stars and planets. SIM will be the most important step in the next decade towards understanding planetary systems in their generality and investigating the habitability of other worlds than Earth.

## Detecting Terrestrial Planets

Of the planet-detection methods available, only SIM will be able to detect or rule out Earth-sized planets orbiting nearby stars, and start to address their potential habitability. The mission will be capable of detecting or ruling out large terrestrial planets and determining their statistical occurrence, and will start to address the role of rocky cores in the formation and evolution of planetary systems. SIM will make the planet inventory significantly more complete in the next decade.

The defining capability of SIM for extrasolar planets will be its ability to measure, with unprecedented accuracy, the movements of nearby stars and to follow those movements for the duration of the 5-year mission. The design accuracy of 1 microarcsecond (in a single measurement for astrometry in a narrow-angle field) is numerically equal to the orbital semi-major axis of a Sun-mass star with an Earth-mass companion in an orbit of 1 AU observed from a distance of 3 parsecs. This astonishing accuracy — sufficient to measure the displacement of a stellar photocenter by one-thousandth of a solar diameter at 10 parsecs — is nearly a thousandfold improvement over current astrometric practice.

Because it will be the most sensitive astrometry instrument yet developed, SIM will provide the preeminent technique for studying extrasolar planetary systems. To illustrate that point, SIM could derive astrometric orbits for all but two of the currently known radial-velocity companions with substellar minimum masses, and it could easily detect the astrometric signature of Uranus-mass or Neptune-mass companions orbiting nearby stars. SIM will also be the most informative of all existing techniques, because astrometry — position measurement — documents the true rather than the projected orbit (as with the radial-velocity technique), thus avoiding inclination-angle ambiguity and associated companion-mass uncertainty.

## Complement Other Methods

Notwithstanding SIM's singular sensitivity for indirect planet detection, its most significant contributions will be made in concert with complementary observations by other techniques. Now that we know that extrasolar planets exist, future questions will be more complex, and so will be their answers. The next step in this investigation is to find and study multiple-planet systems, particularly ones with terrestrial planets. Such studies demand the greater exactitude of SIM, and will serve as the gateway to habitability issues as well as to understanding the formation and evolution of planetary systems as systems. On the basis of past experience, the early outcome of such studies will likely be narratives, weaving together fragmentary information about both the star and the orbiting planets from a variety of sources, including critical measurements by SIM. Later, with the arrival of the Terrestrial Planet Finder (TPF), these studies will be supplemented with direct imaging and spectroscopy of planets themselves, now

As a planet moves in its orbit, its primary star describes a miniature version of the same orbit — smaller by the ratio of their masses — around the common center of mass. It is this reflex motion, seen against the backdrop of other stars in the field, that SIM will detect and measure to identify the presence and the properties of a planet. The reflex motion shares all the characteristics of the true orbit of the planet except for the reduced amplitude, enabling SIM to measure directly (and accurately) all other orbital parameters, such as period, eccentricity, and inclination. If an estimate of the mass of the parent star is available, then the mass of the companion can be determined directly from the orbital solution and accurate parallax provided by SIM.

A typical planetary search will require 20 to 50 separate observations, appropriately spaced throughout the life of the mission. Each observation will measure, with microarcsecond precision, the instantaneous position of the primary with respect to several reference stars within about 1 degree. Together, these observations will allow the reconstruction of the primary's orbit as projected on the sky and the determination of the orbital parameters, together with the motion (and possible binarity) of the reference stars themselves. Unlike other SIM observations, planetary searches will rely on the global reference grid only indirectly, as a means to set the scale and control systematic effects. That is, the direct measurements of the orbital motion of the target star will largely be based on narrow-angle astrometry.

SIM will be especially sensitive to planets possessing orbital periods up to its mission length of 5 years; planets with longer orbital periods can also be detected, but with reduced sensitivity as the period lengthens. The expected precision of SIM will allow the study of Earth-mass planets within a few parsecs of the Sun, and of Jupiter-like mass to about 1 kiloparsec. At the edge of its range, SIM will determine orbital periods to about 10 percent, and orbital radii and planet masses to about 30 percent. The orbital elements of most currently known planets can be determined with a precision better than 5 percent. Importantly, SIM's astrometric method does not suffer the inclination-related uncertainties of the radial-velocity method. Because SIM is a pointed instrument, its schedule could readily be adapted during the mission to search for additional planets around stars for which planets are discovered.

possible only for strongly self-luminous bodies, such as brown dwarfs.

### Study Substellar Companions

Even before the discovery of any substellar companions, considerable theoretical efforts were made to understand their genesis. Models were developed separately for the two classes of objects that might be found, namely planets and brown dwarfs or failed stars. Today, with the many substellar companions reported by radial-velocity studies, the most basic issue is their classification. That is, which of these objects were formed by the planetary process, and which by the stellar process — or is a new or hybrid process required? Classification will help clarify the nature and diversity of substellar companions, reconciling the new discoveries with science not as objects in a list but as messengers of underlying principles and processes. SIM will play a critical and timely role in this scientific synthesis.

### Determine Masses

One dimension of the classification debate surrounding substellar companions pertains to mass as an indicator of genesis. We expect a low-mass cutoff for brown dwarfs, associated with the fragmentation process, but we must also be prepared to discover substantial mass evolution of brown dwarfs due to the dynamic environments in which they are immersed at early ages. In the case of planets, we expect an upper-mass cutoff related to the limited density of protoplanetary disks. Neither of these mass cutoffs is well understood. Indeed, brown dwarfs and planets may populate a common mass range, probably 1 to 10 Jupiter masses. Empirically, trying to apply mass as a discriminator between planets and brown dwarfs is currently hampered by two factors: mass uncertainty for the radial-velocity discoveries (due to ambiguity in the inclination angle), and incompleteness in the mass range corresponding to solar system planets (due to inadequate sensitivity). SIM will search for evidence of planets as small as 0.5 to 2 Earth masses orbiting in or near the habitable zones of the 5 to 50 most suitable solar-type stars, and derive orbital solutions and planet masses. SIM's searches of 100 to 200 main-sequence stars will reach down to the level of large terrestrial planets (2 to 20 Earth masses).

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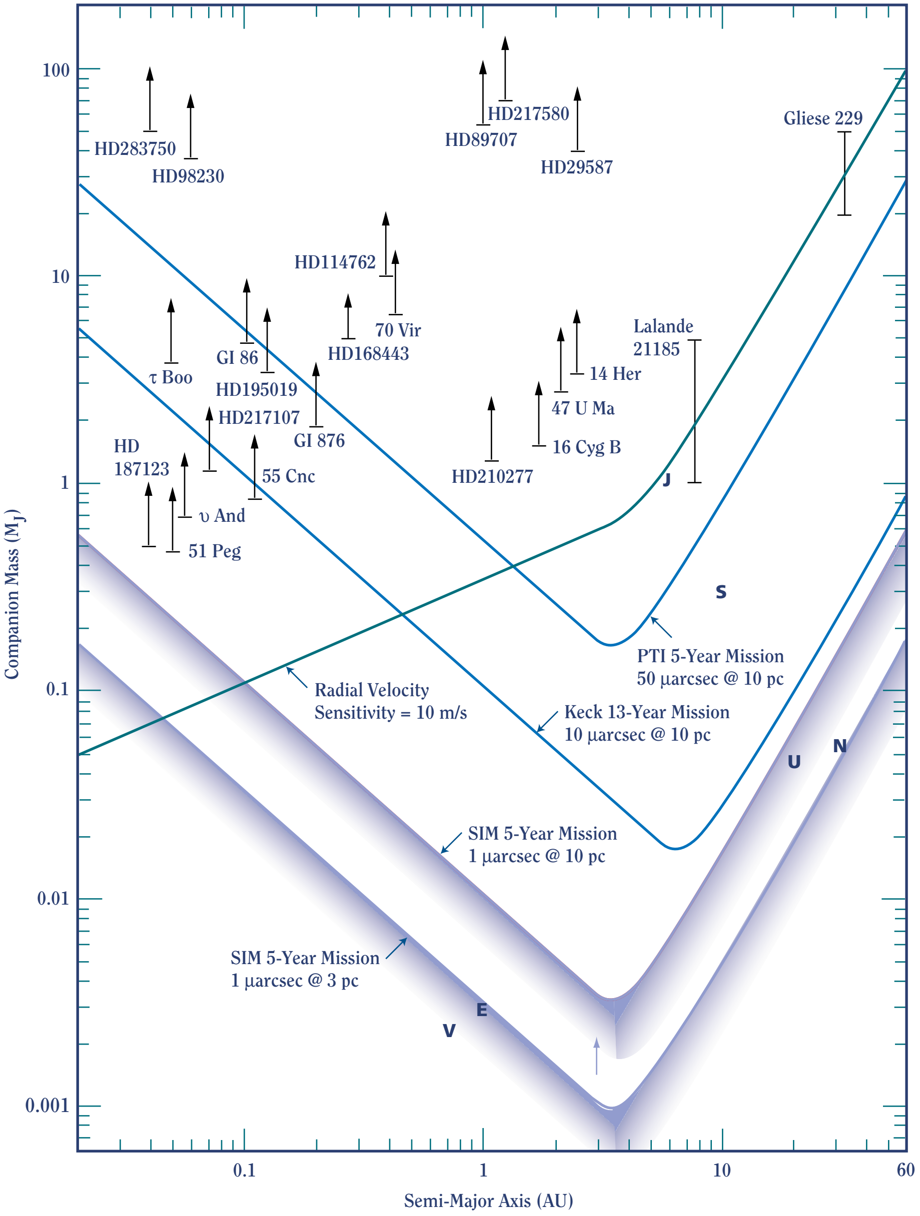
### Measure Orbits

A second dimension of the classification debate pertains to the shape and alignment of the companion orbits. Orbital eccentricity is expected to have a broad distribution for brown dwarfs, as is found for binary stars, but small values are expected for planets due to averaging effects as planets are built up from large numbers of smaller planetary embryos.



**DISCOVERY SPACE**

*Masses and orbital semi-major axes are shown for recently discovered substellar objects. Diagonal lines give the limiting accuracies of current astrometric (blue) and radial-velocity (purple) surveys; SIM's accuracy is shown in red. E=Earth, V=Venus, J=Jupiter, S=Saturn, U=Uranus, N=Neptune.*

In the conventional picture of solar system formation, the gas giants Jupiter and Saturn formed in a two-step process. First, kilometer-size ice and rock planetesimals collided and accumulated into ever-larger bodies, termed planetary embryos. Second, once these embryos reached a mass of approximately 10 times that of Earth, they began to accrete gas from the solar nebula, and grew to their final sizes.

The embryos of Jupiter and Saturn grew fast enough to reach the critical core mass for gas accretion while the solar nebula was still extant. Farther out in the solar nebula, however, where orbital periods lengthen and collisions occur less frequently, the accumulation process proceeded so slowly that the nebular gas was largely dissipated before the cores of Uranus and Neptune reached the critical mass for gas accretion.

This scenario seems to explain the first-order differences between the gas giant planets and the icy outer planets. However, we do not know if the core accretion mechanism has any relevance for other planetary systems. The alternative mechanism — disk instability — does not rely upon the formation of 10-Earth-mass cores in order to form giant planets, but rather forms giant gaseous protoplanets directly from the protoplanetary disk’s gas and dust. One means for differentiating between these two formation mechanisms is to search for intermediate-mass planets with SIM.

SIM will provide crucial insight about the mechanisms of planet formation by detecting planets in the range of 2 to 20 Earth masses around a large sample of nearby stars. It may be that, in many protoplanetary disks, the disk gas is dissipated before collisional accumulation can produce planetary embryos with sufficient mass to accrete disk gas. In such systems, we might expect to find a number of Uranus-mass and Neptune-mass planets, but no giant planets. These “large terrestrial planets” might very well be found orbiting at relatively small distances from their stars, either due to *in situ* formation at 1 AU, or to inward orbital migration to even smaller distances. By detecting 2- to 20-Earth-mass planets, SIM will provide a test of whether or not planet formation occurs elsewhere by the two-step process often thought to account for the formation of Jupiter and Saturn.

However, tidal damping will reduce the eccentricities of brown dwarfs in small orbits, and gravitational perturbations may increase the eccentricity of planets. With respect to alignment, coplanar orbits are expected for multiple-planet systems, as a remnant feature of the flat protoplanetary disk; on the other hand, brown dwarfs should mimic multiple-star systems, which often do not have coplanar orbits. The reported substellar companions with small orbits, about 0.1 AU and smaller, probably have circular orbits due to tidal damping. Of these objects, those with lower minimum mass may be giant planets that have migrated inward from the "ice zone" beyond 3 to 4 AU, or they may be brown dwarfs that have shed mass. The reported companions with higher minimum mass and/or substantial eccentricity may all be brown dwarfs. Three low-eccentricity objects with orbits too wide to be tidally evolved — 47 Uma b, ρ CrB b, and 55 ρ1 Cnc — may have formed as planets in these circular orbits. The planetary-mass companion of the solar-type star 16 Cyg B has high eccentricity, which may have been pumped up by the binary star companion. Orbital coplanarity is not yet useful as a discriminator, because no orbits have yet been solved for a multiple substellar system around a normal star (although 55 ρ1 Cnc appears to be a good candidate for such a system). SIM should bring 100 to 1,000 times better mass sensitivity to observations of stars with known companions, as well as to deeper studies of systems known to lack large companions on small orbits. These observations should discover a variety of multiple-companion systems.

## Probe Stellar Atmospheres

The classification debate's third dimension pertains to the composition and thermal structure of the atmosphere of a substellar companion as revealed by spectrophotometry. This line of research is in its infancy, both observationally and theoretically. Currently, it does not predict spectral differences between brown dwarfs and planets of comparable mass and age. Furthermore, no instruments are now, nor will be, available in the next decade to detect the light of any but the most strongly self-luminous (most massive and/or youngest) substellar companions. Such detections will likely be limited to brown dwarfs on wide orbits. Nevertheless, in the future, with TPF operating, spectrophotometry may become a productive way to classify substellar companions, because unlike mass and eccentricity, which are only two numbers, a photometric spectrum contains a wealth of information about the object itself.

SIM will be an important tool in developing a more complete picture of our stellar neighborhood by probing nearby

Although the formation mechanism of the giant planets is the subject of ongoing research and debate, the terrestrial planets are widely believed to have formed through collisional accumulation of rocky planetesimals, leading to lunar-size planetary embryos, and, after about 100 million years, to Earth-size planets. Given a protoplanetary disk that is quiescent enough to allow centimeter-size solids to remain in orbit at a more-or-less fixed distance, the collisional accumulation process is believed to be a natural and almost inevitable outcome. We would expect that in a planetary system where giant planets did not form or at least did not traverse the innermost few AU, Earth-like planets should exist.

Habitability of a planet appears to require, at a minimum, an orbit permissive of liquid water at its surface or in its crustal layers, and also, perhaps, a well-placed giant planet to shield the planet from life-threatening, ongoing bombardment by wayward comets. The first requirement translates into an orbital period that depends strongly on the spectral type and luminosity of the star. For solar-type stars, this means a fairly narrow range of orbital periods, close to 1 year. SIM will have the ability to search for Earth-like planets with orbital periods that place these planets in the habitable zones of their stars. Within this zone, habitable planets might also exist as satellites to giant planets. Because any giant planets in these systems are easily found as well, given their much larger astrometric signal, SIM will also make it possible to determine whether the second candidate requirement for habitability is met.

stars for planetary systems. The astrometric technique is, of course, applicable throughout the range of companion masses. Massive companions — Jupiter-mass planets and brown dwarfs — are detectable to large distances (a kiloparsec or more), large enough to begin answering questions about the formation of star systems on larger scales. What is the frequency of planetary systems in the local Galactic disk? Do they represent a continuation of known properties of binary stars? What stellar types are preferred? These questions overlap with many others concerning the structure and evolution of our galaxy.