3 Multiple-Planet Systems

Eric Ford (University of Florida), **Geoffrey W. Marcy** (UC Berkeley), **Michael Shao** (JPL), **Matthew W. Muterspaugh** (UC Berkeley), **Charles Beichman** (NExScI), **Jason Wright** (Cornell University), **Debra A. Fischer** (SFSU), **Joseph H. Catanzarite** (JPL), **Robert Olling** (University of Maryland), **Shrinivas Kulkarni** (Caltech), **Stephen C. Unwin** (JPL), and **Wesley A. Traub** (JPL)

ABSTRACT

SIM Lite will discover rocky planets and ice giants orbiting within a few AU of nearby stars, complementing the gas giants found around those same stars by radial velocity and transit surveys. A set of 60 stars within 20 pc are to be surveyed with the nominal SIM Lite mission, providing a statistically meaningful census of typical architectures of planetary systems. Results from radial velocity surveys suggest that multiple-planet systems are common. SIM Lite will provide the full three-dimensional orbits and the masses for planets in each system, including orbital inclinations and eccentricities, thus establishing the major components and architecture of each planetary system. By extending the census of nearby planetary systems to include terrestrial planets, SIM

Lite can test theories of planet formation and subsequent evolution that are desperately in need of further empirical constraints. By providing precision measurements of planetary masses and full three-dimensional orbits, SIM Lite can search for correlations between planet mass and other properties, providing tests of planet-formation models. Further, SIM Lite can characterize the long-term evolution of planetary eccentricities and inclinations, permitting tests of theories of the origins of multiple-planet systems, including orbital migration and planet–planet gravitational interactions. Mock multiplanet systems have been constructed and used as the basis for simulated SIM Lite and radial velocity measurements and a double-blind search for planets (using separate teams to generate input data and analyze mock observations) has been performed. Even when faced with multiple-planet systems, mock planets with masses as low as 1.0 $M_{\oplus}$ were "detected" by SIM Lite, as long as the astrometric signature (α) of the rocky planet was above the threshold for detection $\alpha_{THRESH} = 5.8\sigma / N^{1/2}$, where σ is the single-observation astrometric uncertainty and N is the number of astrometric observations. Thus, a combination of SIM Lite and radial velocity monitoring has been demonstrated to provide a powerful basis for detecting and characterizing the orbits of terrestrial-mass planets in realistic planetary systems. The proximity of these planetary systems will allow IR and mm-wavelength observatories (e.g., JWST, ALMA) to detect, measure, and resolve dust disks within these planetary systems, providing detailed assessments of the small-body populations (e.g., asteroids, Kuiper belt objects, comets) and their relationship to the arrangement of planets in the system. Finally, the proximity of the planetary systems discovered by SIM Lite will eventually allow coronagraphs and spaceborne observatories to study the planets themselves, using imaging, photometric variability, and spectroscopy.

3.1 Multiple-Planet Systems Are Common

Theoretical models of planetary formation predict the common occurrence of systems with multiple planets. Already, 27 multiplanet systems have emerged from Doppler surveys of nearby stars, as shown in Figure 3-1, despite a significant bias towards finding the most-massive planets on relatively short-period orbits. A complete description of known multiple-planet systems and their properties is given by Wright et al. (2008). Theoretical models of planetary systems undergoing dynamical relaxation predict that mature planetary systems typically contain two or three giant planets (e.g., Adams and Laughlin 2003; Juric and Tremaine 2008). The Doppler discovery of exoplanet systems with at least four planets (HD160691) and five planets (55Cnc), along with the eight major planets in our Solar System, suggests that multiple-planet systems may be the rule rather than the exception. Further, radial velocity (RV) surveys already suggest that 23 percent of surveyed stars show a significant excess of radial velocity variability that could be naturally explained by additional planets (Cumming et al. 2008). If one also accounts for long-term radial velocity trends, then 30 to 50 percent of giant exoplanet host stars show some evidence of additional companions (Wright et al. 2007, 2008). Both the number and fraction of planets in multiple-planet systems are likely to increase as planet searches become sensitive to planets with lower masses and longer orbital periods. In particular, some theoretical models of planet formation predict that low-mass planets will be significantly more numerous and find that even systems with short-period gas giants could contain several low-mass planets regardless of whether the gas giant planets migrated through the terrestrial planet region (Cresswell and Nelson 2006; Mandell and Raymond 2006). Since many, if not most, planets are members of multiple-planet systems, understanding the formation and evolution of multiple-planet systems is essential for understanding planet formation in general.

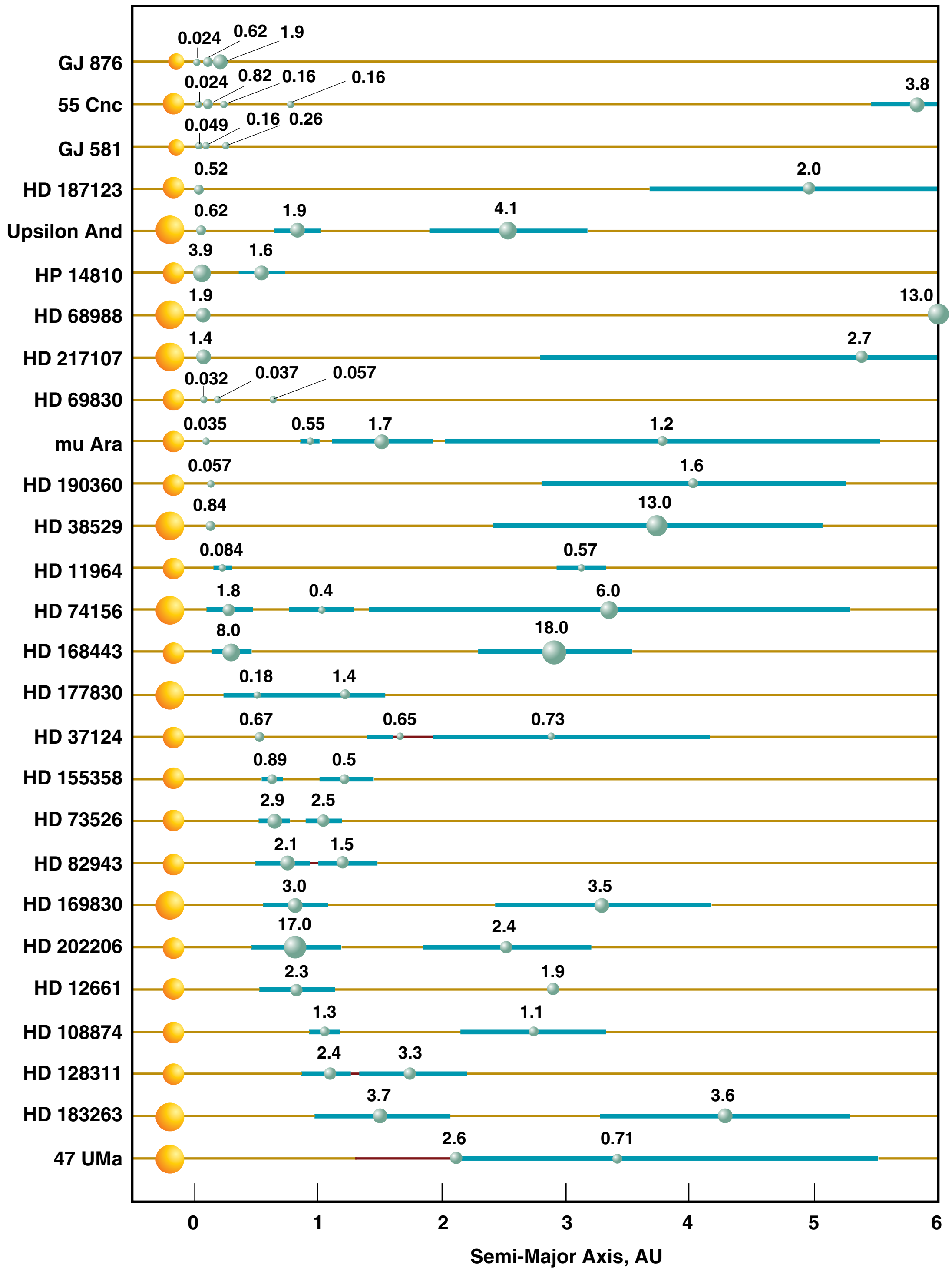


Figure 3-1. Display of semi-major axes and masses for the 27 known multiplanet systems. The diameters depicted for planets are proportional to the cube root of the planetary *m* sin (*i*). The periapsis to apoapsis excursion is shown by a horizontal line. Masses are in M_{Jup}. Despite a significant bias toward finding the most massive planets on relatively short-period orbits, most known multiple-planet systems contain a planet beyond 2 AU, suggesting that many systems currently known to contain a single planet may harbor additional planets at larger separations.

3.2 Observable Properties of Multiplanet Systems

Astrometric observations provide the opportunity to fully characterize the six phase-space coordinates (e.g., positions and velocities) for each planet detected, including all seven orbital parameters (i.e., the planet masses and the six osculating Keplerian orbital elements) for each planet. The combination of both radial velocity and astrometric observations is particularly powerful for studying multiple-planet systems, both to independently verify planets and to establish the full suite of planet masses and orbits. Radial velocity observations contribute by detecting and measuring most of the orbital parameters for short-period planets. Once radial velocities measure the period and phase of a short-period planet, adding astrometric observations can often constrain the planet's inclination and orientation, even if astrometry alone would not be able to detect the short-period planet. In contrast, astrometric observations are most sensitive to long-period planets (up to orbital periods comparable to the time span of astrometric observations). For planetary systems containing giant planets with orbital periods exceeding SIM Lite's mission lifetime, radial velocity observations can again contribute by constraining their orbital periods and modeling out their effects. Thus, the combination of SIM Lite and radial velocity observations is significantly more powerful for measuring the architecture of a planetary system than either method alone (Ford 2006).

While the dynamical signature for a single planet is relatively simple, the dynamical signature for multiple-planet systems can be much more complex and require detailed modeling. Fortunately, simulations have shown that SIM Lite will be able to precisely characterize most systems with multiple giant planets with orbital periods up to the mission lifetime (Sozzetti et al. 2003) and that SIM Lite's detection efficiency for terrestrial planets will only be slightly impacted by the presence of other planets (Ford 2006; §3.5). Those systems that are more challenging typically contain closely spaced planets and/or near mean-motion resonance. For such systems, there can be significant planet–planet interactions, and full *n*-body simulations may be necessary to achieve self-consistent orbital solutions (Laughlin and Chambers 2001). While significant planet–planet interactions complicate the analysis, they also provide an opportunity to measure the strength and time scale of such interactions. When early observations are consistent with multiple orbital solutions, dynamical models can identify which epochs are particularly powerful for constraining models, resulting in increased efficiency of observations (Loredo and Chernoff 2003; Ford 2008). Similarly, by assuming long-term dynamical stability, theorists can reject otherwise plausible orbital solutions and constrain the masses and orbital parameters (e.g., Rivera and Lissauer 2000). As more multiple-planet systems are discovered, dynamical research will play a symbiotic role in planning and deciphering observations.

3.3 Relationship of Giant and Terrestrial Planets

Doppler measurements show that 10.5 percent of stars harbor giant planets (with masses greater than a Saturn mass) within ~7 AU (Cumming et al. 2008). However, there are no firm constraints observationally or theoretically on the occurrence rate of Earth-mass planets. Using our Solar System as a guide, one might expect that long-period Jupiters could often be accompanied by inner terrestrial planets. The formation processes and typical structure of multiplanet systems, including both terrestrial and giant planets, remains poorly known. Currently, theories for the formation of rocky planets suggest that terrestrial planets should be commonplace, regardless of whether or not gas giant planets have had a chance to form (e.g., Wetherill 1996; Raymond et al. 2006). However, theory has a checkered history of predicting exoplanet properties. In particular, the diversity of known giant exoplanets casts doubt on the assumption that our Solar System represents a typical planetary system. By detecting both terrestrial and giant planets across a broad range of orbital separations, SIM Lite will characterize the typical architectures of planetary systems, so humankind can finally answer the fundamental question: "Is our Solar System special?"

Both the diversity of observed planetary systems and theoretical models of planet formation suggest that similar initial conditions can result in widely differing final planetary systems. While theoretical models do not predict the masses or orbits of individual systems, they can predict properties of the exoplanet population as a whole, such as the typical number of giant planets (e.g., Adams and Laughlin 2003), the eccentricity distribution (e.g., Ford and Rasio 2008; Juric and Tremaine 2008), and the correlation between stellar and planet properties (e.g., Robinson et al. 2006). SIM Lite will provide a statistically useful set of planetary systems that will demand theoretical explanations by a combination of deterministic and stochastic processes.

Moreover, protoplanetary disks will be observed directly by JWST, the Atacama Large Millimeter Array (ALMA), and other IR and mm-wavelength instruments. The observed properties of protoplanetary disks and models of planet formation and evolution must adequately predict the properties of exoplanets (Wolf et al. 2007). SIM Lite's ability to measure planet masses to 10 percent and their three-dimensional orbits is crucial for mapping JWST and ALMA observations to actual planets. Comparing these predictions with actual exoplanet detections can provide valuable constraints on models for the formation and evolution (e.g., orbital migration, eccentricity excitation) of planetary systems (e.g., Benz et al. 2006; Ida and Lin 2004ab, 2008ab; Kennedy and Kenyon 2008ab; Figure 3-4).

3.4 Architecture of Multiple-Planet Systems

Studying the architectures of multiple-planet systems can provide insights into planet formation processes, including formation, orbital migration, and subsequent gravitational interactions. Moreover, discovering and characterizing multiple-planet systems would add key information about the orbital properties and habitability of planets (Ford et al. 2008).

For example, it remains unknown if the co-planarity of planetary orbits in the Solar System is a common property of planetary systems in general. Already, spectroscopic observations during transit have measured the Rossiter-McLaughlin effect (the apparent change in radial velocity due to the transit) and constrained the spin-orbit alignment of several short-period giant planets. While existing observations suggest that most short-period, giant, transiting planets have orbital angular momentum nearly parallel to the stellar spin axis, at least one system appears to have a large misalignment (Hebrard et al. 2008). SIM Lite will be able to measure the orbital inclinations of giant planets relative to the inclinations of other planets, particularly at larger orbital separations where tides are not significant. SIM Lite will also be able to measure the relative inclinations of low-mass planets for which Rossiter-McLaughlin observations are impractical. If the low inclinations (and eccentricities) in our Solar System contributed to the habitability of Earth, then our human presence may have biased our ideas about planetary systems, which have long presumed that our Solar System is "normal." In fact, our Solar System could be a relatively rare type of planetary system that did not suffer close encounters between giant planets, allowing the terrestrial planets to form and persist on circular orbits for long enough to give rise to intelligent life (Thommes et al. 2008). Gravitational interactions may be so common among planets in a typical system that such co-planarity is rare. Modeling shows that the final distribution of inclinations of giant planets is influenced by strong planet–planet scattering. In some models, rocky planets might typically be accreted or ejected by giant planets that migrate through the "habitable zone" (Kasting 1993). SIM Lite will measure the co-planarity of planetary systems, a property directly tied to the origin and gravitational interactions of planets in general. Thus, SIM Lite will contribute to testing one variable of the "rare-Earth" hypothesis.

3.5 Origins of Planetary Systems from Dynamical Measurements

Studying the dynamical properties of specific planet systems can provide insights into planet formation processes. Dynamical research is particularly powerful when applied to observations of multiple-planet systems, since the current orbital configuration can provide clues to the dynamical history of these systems. By making precise measurements of the planet masses and their current orbits, SIM Lite will enable theorists to evolve systems forward and backward in time to study the long-term evolution of planets' eccentricities and inclinations. The presence of mean-motion resonances or significant long-term eccentricity evolution can provide strong constraints on the mechanisms involved in their formation, orbital migration, and subsequent gravitational interactions.

3.5.1 Mean-Motion Resonances

Detections of pairs of planets in or near mean-motion resonances provide empirical constraints on models of orbital migration. For example, the GJ876 system contains two giant planets with periods of 30 and 61 days. Long-term radial velocity monitoring of this system has provided empirical evidence that the two Jovian planets are in a 2:1 mean-motion resonance and participate in a secular apsidal lock (Laughlin et al. 2005), providing a wealth of information about the formation, migration, and eccentricity damping of the system during its formation stages. Figure 3-2 shows the velocities from the Keck telescope for GJ876 during the past decade. The odd envelope structure of the radial velocities is well understood in terms of a near commensurability of orbital periods and the precession of both orbits due to the planet–planet interactions. The long-term stability of the system is contingent upon the precise orbital separations that allow the two orbits to precess at the same rate, so as to avoid close encounters that would destabilize the system. The mere presence of such mean-motion resonances provides evidence for orbital migration that allowed the two planets to form on more widely separated orbits before becoming captured into the current resonant location. More-detailed modeling provides constraints on the rate and smoothness of the migration. For GJ876, the amplitude of oscillations about a precise resonance and the currently observed eccentricities place constraints on the mechanisms that caused the eccentricity damping and/or halting of migration (Lee and Peale 2002).

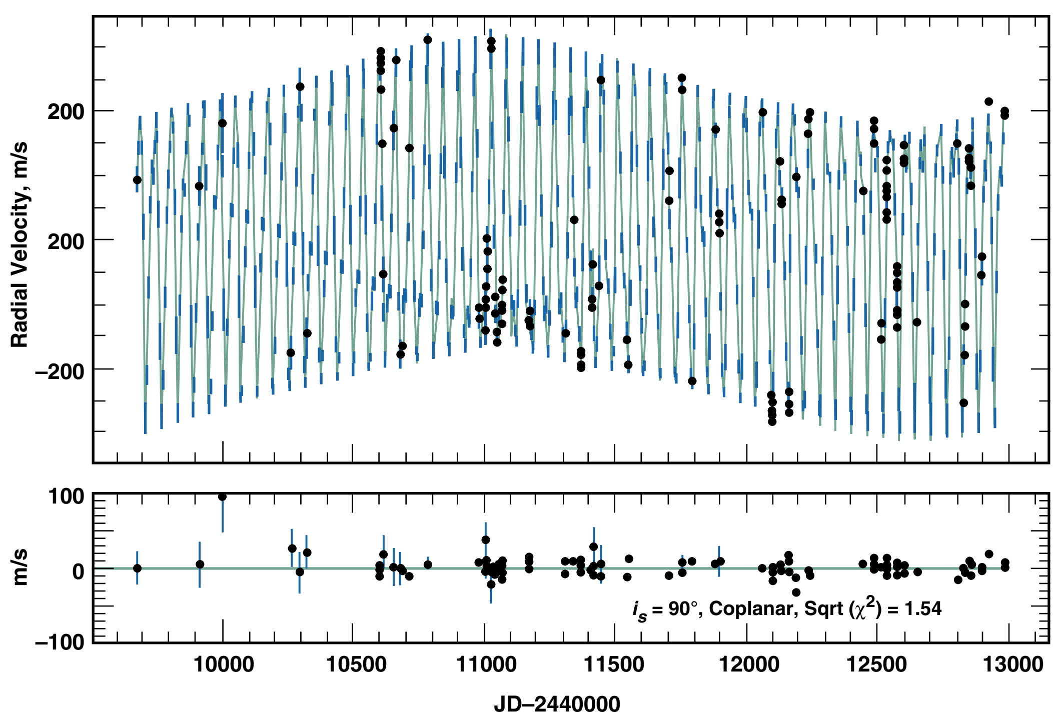


Figure 3-2. Top: Stellar reflex velocity from a self-consistent, coplanar, edge-on three-body integration compared to the GJ876 radial velocities. Bottom: Residuals to the orbital fit. (Figure from Laughlin et al. 2005)

3.5.2 Long-Term Eccentricity Evolution

As another example, the secular evolution of the Upsilon Andromedae planetary system provides evidence for an impulsive perturbation, likely due to a previous close encounter by another planet (Malhotra 2002; Ford et al. 2005). Figure 3-3 (bottom) shows the variation in eccentricity of the outer two giant planets in this system implied by the current RV observations. The periodic recurrence of a very nearly circular orbit for one of the giant planets is unlikely to be a coincidence. It indicates a history in which both planets originally followed nearly circular orbits, but one planet suffered a close encounter with another Jovian planet. That close encounter impulsively perturbed the orbit of the outer planet, leading to the peculiar long-term evolution that is seen today. Such close encounters may be common, perhaps exciting the large eccentricities commonly observed for giant planets. If so, strong scattering of giant planets may play a significant role in sculpting planetary systems in general, with important consequences for the frequency and orbits of terrestrial planets.

The ability to directly measure orbit inclinations also opens the door to qualitatively new tests of planet formation models. Different models of planet migration and eccentricity excitation make different predictions for the secular evolution of planetary eccentricities and inclinations (e.g., Chatterjee et al. 2008). Therefore, testing models of planetary orbital evolution requires astrometric observations to determine if the long-term evolution of orbital inclination correlates with the eccentricity evolution.

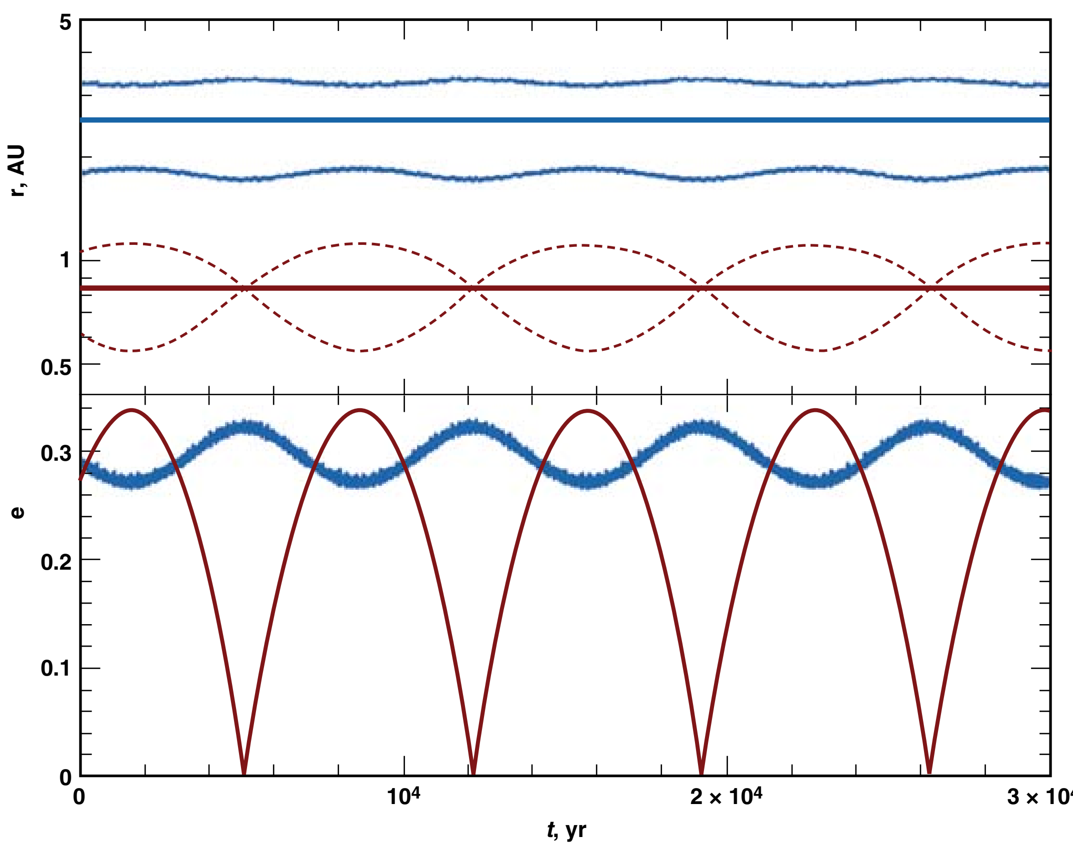


Figure 3-3. Secular evolution of the outer two giant planets orbiting in the planetary system around υ Andromedae. The top panel shows the semi-major axes (thick lines), as well as the periastron and apastron distances (thin lines), for planets c (red) and d (blue). The lower panel shows the evolution of the orbital eccentricity for each planet. Note that both planet c (dashed) and planet d (dotted) have a significant eccentricity at the present time ($t = 0$), but that the eccentricity of planet c returns periodically to very small values near zero (Ford et al. 2005).

3.5.3 Long-Term Dynamical Stability and Long-Period Planets

For multiple-planet systems, the requirement of long-term orbital stability can provide strong constraints on the masses and orbits of planets throughout the entire system. Orbital analysis based only on radial velocities typically benefits from demanding long-term dynamical stability, thereby constraining the inclinations and providing upper limits to the planet masses. Unfortunately, such analyses often leave uncertainties of ~30 degrees in inclination and a factor of ~2 in the planet masses. These uncertainties can cause qualitative uncertainties in the dynamical state of the system. SIM Lite observations can resolve such degeneracies, establishing masses and orbits to better than ~10 percent accuracy, for planets with orbital periods less than the mission duration. For multiple-planet systems, the combination of SIM Lite observations, ground-based radial velocity observations, and long-term orbital stability can place constraints on the masses and orbits of long-period planets and thus provide improved constraints on the properties of other planets closer to the "habitable zone."

3.6 Detectability of Earth-Mass Planets in Multiple-Planet Systems

At first glance, it should not be difficult to extract the astrometric signal of an Earth-like planet from the composite signal of a system of planets around a star. Because each planet contributes an astrometric signal with a different frequency in time, a Fourier analysis of the total signal should reveal the signature of each planet provided there is a large number of observations with sufficient signal-to-noise ratio. However, in reality the case might be not so simple. For example, a planet in an eccentric orbit with a dominating signal (e.g., a Jupiter) might have harmonic terms that are not recognized as such but might look like a separate planet. Or a long-period planet observed over a time shorter than that period would have noise generated at many frequencies owing to the difficulty of distinguishing a proper motion on the sky from a part of an orbit. In order to address these potential concerns, we initiated a double-blind simulation to see how well Earth-like planets (i.e., terrestrial masses, habitable-zone periods) could be detected in multiple-planet systems with SIM Lite, with the help of RV. An additional goal was to see what accuracy by SIM Lite is necessary to achieve a goal of being able to detect Earth-like planets.

The simulation was organized with four teams of scientists, the planet modelers (Team A), the data simulators (Team B), the data analyzers (Team C), and the overall summarizers (Team D).

Team A comprised five groups of planetary system modelers. Each group generated about 150 planetary systems, using their own best estimate of the actual distribution of masses and periods in real systems. The constraints were that the frequency and orbital properties of Jupiter-like planets agree with the Cumming et al. (2008) analysis of a Jupiter-complete sample of RV observations. In addition, the systems were to be stable.

Team B was a single group that took input planetary models, rotated the systems at random, set up realistic observing schedules, generated synthetic astrometric and RV signals, and added noise. A total of 48 planetary systems were generated, of which 32 were random Team A systems, 8 were Solar System analogs (perturbed), 4 were single terrestrial HZ planets, and 4 had only planetesimals or planets below the threshold for detection. To focus on the key variables of planet mass and period, all simulations were for a single star at a fixed point in the sky and at 10 pc. The RV noise was 1 m/s rms, a value that includes expected instrumental as well as astrophysical noise. The astrometric noise for most of the data sets was the expected noise from SIM Lite, 1.0 μas per single observation per axis per star, and therefore a factor of about 1.4 larger for a differential measurement (target with respect to reference) per axis (RA or DEC). The timelines for half of the data were five years of astrometric and 15 years of RV observations. For the other half, the timelines were 10 years of astrometric and 20 years of RV observations. The orbits were calculated assuming independent Keplerian motion, i.e., *n*-body codes were not used.

Team C comprised five groups of data analyzers, competitively selected. Each group was given a set of practice data sets, with and without noise, to validate their code. The groups worked independently to develop their own analysis codes. The groups were given four weeks to analyze all 48 systems described above. The Team C groups were asked to report planet signals detected in the joint astrometric–RV data streams that had a false-alarm probability of less than 1 percent. The exercise was double-blind in the sense that the person distributing the simulated data to the analyzers did not know any details of the systems, so no hints could possibly be transmitted. A brief summary of the results follows.

Reliability of detections is defined as the ratio of true detections to the total of all detections, true plus false. A reliability of 100 percent would mean that no reported detections were false alarms. In the double-blind study, one group had a reliability of 100 percent. Two others were over 80 percent. A fourth was at about 40 percent. (One group was not able to complete the exercise on time.) In principle, this value should have been about 99 percent, if the false alarm rate had truly been 1 percent. However, the short amount of time for the exercise meant that only one group had enough experience to fully weed out false alarms. For this reason, the exercise is being repeated with extra statistical tests added.

Completeness of detections is defined as the ratio of true detections to the total of all detectable planets. A completeness of 100 percent would mean that all detectable planets were reported. (In the double-blind study, a planet with a combined astrometric and RV SNR of 5.8 was considered detectable, Figure 3-4.) Completeness was expected to be 100 percent if the SNR was well above that value. Here the SNR is defined as the amplitude of the true signal, divided by the noise for the entire observing campaign, which is the measurement noise per visit to the star divided by the square root of the number of visits. This definition applies to astrometric as well as RV observations. Over a range of SNR values from about 0.7 to 7000, we found that the completeness did indeed jump sharply from about 0 to 100 percent at a SNR of about 5.8, as expected theoretically. Completeness vs. planet type is shown in Figure 3-5.

The accuracy of results also was close to the theoretically expected values for the key parameters of period and mass. We calculated the expected accuracy using a minimum-variance bound method. Comparing the subjectively correct answers to the actual answers, and scaling that offset by the expected value of the offset, we found a roughly Gaussian distribution, with approximately the expected number (68 percent) of values lying in the range (–1, +1), no significant offset from zero (i.e., no bias), and very few values in the range between plus or minus 1 and 3. However, beyond the 3-sigma point, where essentially no points should fall, we found a handful of cases (about 14 percent); these appear to be situations where the expected error was very small (less than 1 percent in mass or period), and the actual error was more than three times that value. In other words, these were good measurements but not as perfect as theoretically expected.

In overall summary, this first phase of the simulation showed that the answers to our initial questions are: (1) Earths can be detected in realistic multiplanet systems, and (2) the sensitivity needed matches the projected capability of a five-year SIM Lite mission. The mission was defined to be using 40 percent of the available observing time, with the expected noise level and a 6-m baseline, plus the additional help (mostly with long-period planets) from 15 years of RV observations. The first phase of the study is being followed up with a second phase in which planetary systems will be simulated for the 60 best actual stars for planet searching — using actual distances, masses, and luminosities — instead of a hypothetical reference star of one solar mass at 10 pc. In this follow-up, all tentative detections will be subject to an additional statistical F-test and a stability test, as well as given additional time for the analysis, before being reported as probable detections.

Figure 3-4. Results on completeness from the SIM Lite double-blind study. Completeness is the detected fraction of planets. The curve is empirically determined for 1 percent false alarm probablility (Catanzarite et al. 2006). The plotted points are the (number of correct planets)/(number of total planets). The curve shows that at SNR >6, the measured completeness is excellent, as predicted. Here, SNR is the RV SNR and astrometric SNR combined in quadrature.

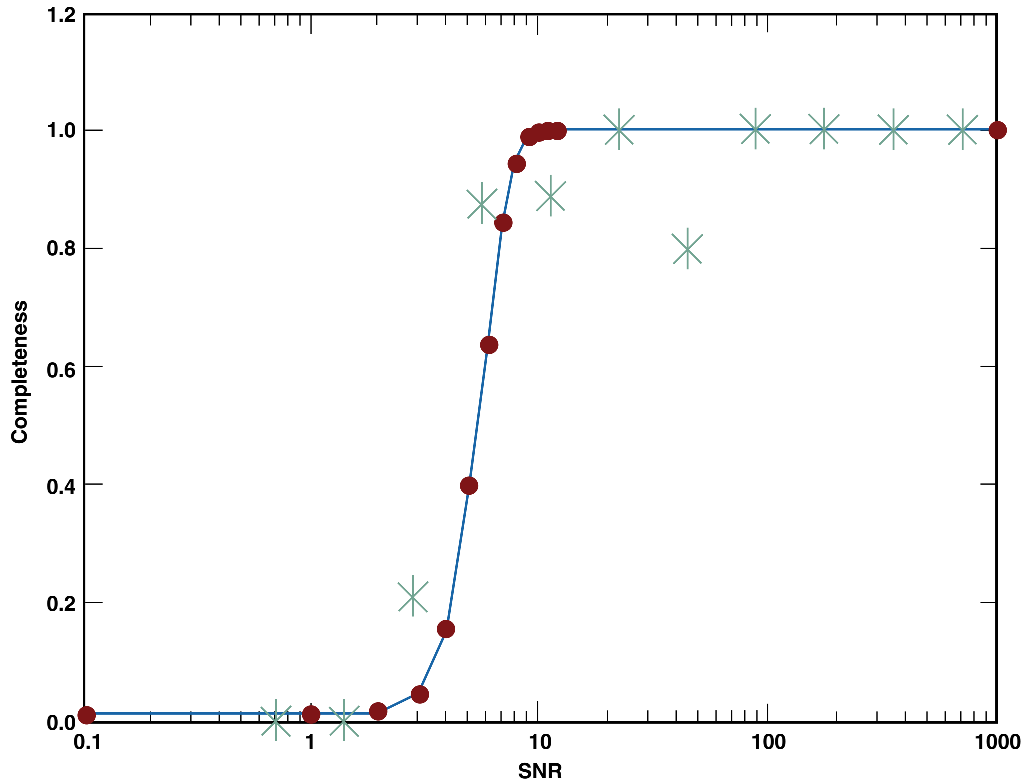
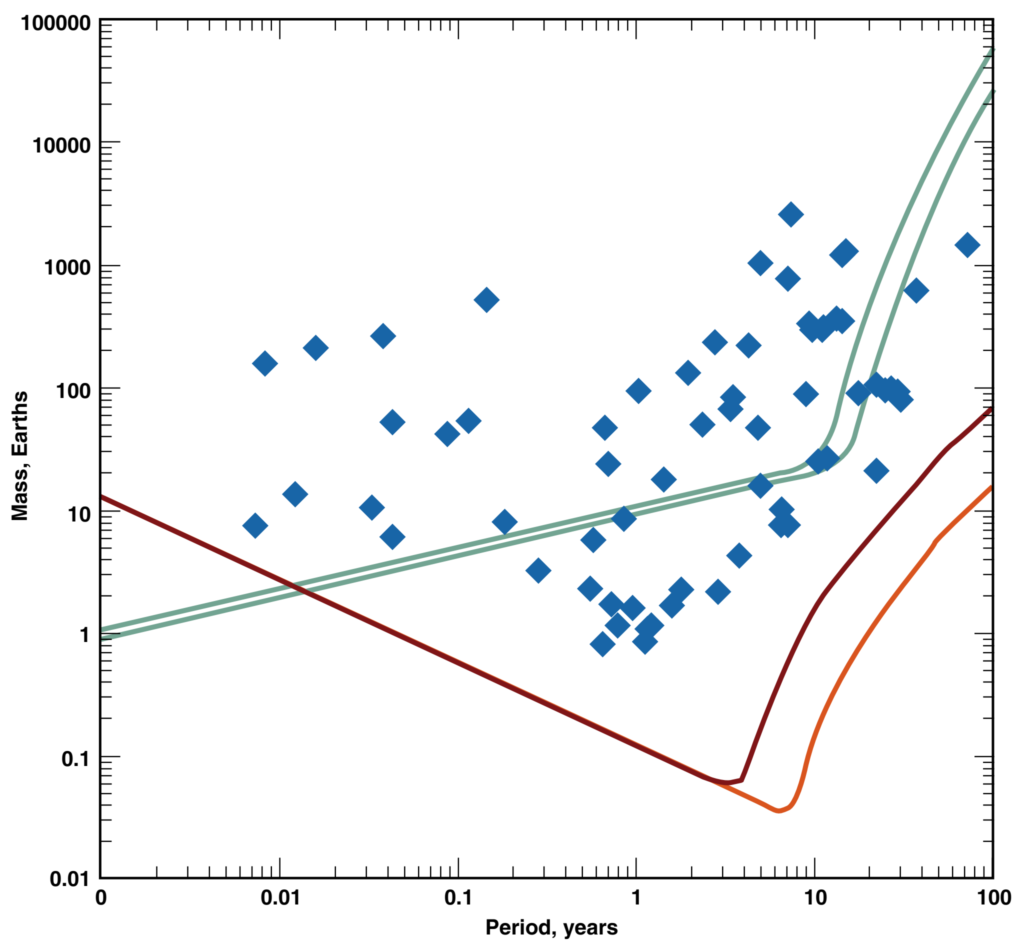


Figure 3-5. From the test systems, there are 70 high-SNR (>6) planets (plotted). Forty-eight of these have periods shorter than 10 years; all should have been detected and all were. The chart shows SNR-based detection limits for RV (blue; upper for 15 years of measurements, lower for 20 years) and SIM Lite (red, upper for a five-year mission, lower for a 10-year mission).



3.7 Relevance to Habitability and Search for Earth-Like Life

While previous exoplanet discoveries have revealed a diverse range of planetary systems, it is not yet clear if planetary systems resembling our Solar System are common or exceedingly rare. Future observational programs will search for planets increasingly similar to the Earth, in terms of their mass, orbital separation, host star, physical size, and atmospheric/surface properties.

The dynamical processes of planetary systems impact the habitability of any terrestrial planets and may have influenced the evolution of life on Earth. For example, in our Solar System, interactions between the giant planets and the planetesimal disk are believed to have triggered the late heavy bombardment of Earth (Tsiganis et al. 2005) and contributed to the delivery of Earth's oceans and of organic molecules to Earth's surface (Morbidelli et al. 2000). Thus, the detection of both the gas giants and the Earth-like planets will stimulate work on dynamical properties of the host planetary system that contribute to habitability. The combination of radial velocity and SIM Lite is uniquely capable of characterizing all major planets in an inner planetary system, allowing theorists to investigate their dynamical histories and implications for planet formation.

Periodic variations in both Earth's rotational and orbital state are believed to be a cause of variations in Earth's climate (Hays et al. 1976). Both the small eccentricities of the Solar System planets and the presence of a massive Moon that stabilizes Earth's obliquity contribute to a stable climate that may have been significant for the evolution of life on Earth. One wonders if typical terrestrial-mass planets maintain nearly constant eccentricities and obliquities, like Earth, or if their stellar irradiation and climate will vary much more widely due to large oscillations in orbital eccentricity and chaotic variations in the obliquity. In order to understand the habitability of a planet, Earth-like or otherwise, it is important to detect and characterize the orbits of all major planets orbiting that host star. For example, a detection of our Solar System that only identified Earth and Jupiter would not provide enough information to understand the secular orbital evolution of the Earth or the role of the giant planets in scattering Kuiper Belt objects and comets. Thus, when searching for planets near the habitable zone, it is important to have significant sensitivity for detecting additional planets at distances much closer and more distant than the habitable zone. The combination of long-term ground-based radial velocity (Tanner et al. 2007; §13.4) and astrometric observations (Cameron et al. 2008) and SIM Lite's high-precision astrometry will provide a unique capability to investigate the dynamical influence of long-period giant planets on potentially habitable planets.

3.8 Strategy for Maximizing Scientific Return of SIM Lite

The rich diversity of planetary systems with multiple giant planets discovered by radial velocity surveys raises the possibility of a comparable or even greater diversity among terrestrial planets. The combination of long-term radial velocity and astrometric observations is astronomers' most powerful method for characterizing the dynamical state of planetary systems. The detection of Earth-like planets will stimulate a variety of questions about the host planetary system:

- Are there signs of large-scale planetary migration, such as other planets in mean-motion resonances, or giant planets at small orbital separations?
- Are there signs of previous violent phases of evolution, such as eccentric or highly inclined planets?
- Will the orbits remain nearly constant or undergo significant long-term evolution?
- What are the implications for the planet's climate, the potential for liquid water, and the possibility of Earth-like life?

Addressing each of these questions will require identifying and characterizing the orbits of all other major planets in the planetary system. Therefore, detections of Earth-like planets by SIM Lite should be accompanied by significant astrometric and radial velocity follow-up observations to determine the architecture of the planetary system and to enable comparisons to our own Solar System. In order to achieve this goal, we offer the following recommendations to maximize SIM Lite's scientific return.

SIM Lite should search for and characterize a wide range of planetary systems, including planets and host stars both similar and dissimilar to our own. This is necessary to appreciate the significance of our Earth and Solar System. In particular, previous exoplanet discoveries have revealed many planets with very unexpected orbital properties. Therefore, SIM Lite should search for terrestrial planets in any location where they could survive — given the constraint of long-term orbital stability — regardless of the predictions of planet formation theories. As there is little dynamical significance to the habitable zone or one Earth-mass, SIM Lite can best contribute to improving our understanding of planet formation in general by observing many planetary systems with a range of planet masses and orbital properties.

Stars already known to host at least one planet should be included among SIM Lite targets. Since stars hosting one giant planet are more likely to harbor additional giant planets, increasing the observing cadence for observations of these target stars can simultaneously improve the dynamical constraints for known planets and increase the sensitivity for detecting additional planets.

In addition to discovering new planets, a significant portion of SIM Lite's observing time should be devoted to intensified follow-up observations that provide precision dynamical constraints for multiple-planet systems. Multiple-planet systems, especially those with significant planet–planet interactions, are typically much more valuable to theorists than several single-planet systems for providing insights into planet formation. Further, the power of dynamical studies increases with the number, time span, and precision of the observations for each particular planetary system. Thus, the SIM Lite observing schedule should allow for intensified observations of particularly interesting multiplanet systems that are identified early in the mission. Theorists should collaborate with observers to identify the most interesting systems to be targeted for intensive follow-up observations.

Coordinated long-term radial velocity monitoring will play an important and complementary role in SIM Lite's quest to characterize the architectures of multiple-planet systems, particularly those with hot Jupiters and/or long-period giant planets, such as Jupiter and Saturn. To understand the orbital evolution of a planet, it is important to detect and characterize the orbital parameters of the other major planets orbiting the host star. In particular, when searching for planets in or near the habitable zone, it is important to have significant sensitivity for detecting additional planets at distances much closer and more distant than the habitable zone.

Detecting Earth-like planets around Sun-like stars may require intensive observations (~250 SIM Lite visits) of a modest number of target stars (~60 in the nominal SIM Lite mission). At the same time, shallow and wide planet searches could provide significant statistical constraints for testing planet formation models. If prior missions/observations determine that terrestrial-mass planets are quite common, astronomers should consider a hybrid observing strategy, including both shallow-wide and narrow-deep planet searches.

Funding for data analysis and theoretical research is essential to maximize SIM Lite's scientific return. The 1991 and 2001 NRC Decadal Surveys concluded that significant funding of theoretical research is necessary to maximize the scientific return of new observatories. Theoretical research in planetary dynamics will play an essential role in the design, analysis, and interpretation of SIM Lite observations. Comparing theoretical models with planets discovered by SIM Lite will require a detailed understanding of observational techniques and uncertainties. Frequent interactions between theorists and observers should provide opportunities for theorists to learn about the observational sensitivities, precisions, uncertainties, systematic effects, biases, etc., that should be considered when interpreting observations.

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