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The Search for Rocky Planets Around the Nearest Stars

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Abstract. Precision Doppler velocity surveys have found ∼95% of the known planets, including all the planets within 100 pc. Over the past decade advances in Doppler velocity precision have uncovered the first neptune- and terrestrial-mass planets. Over the next decade precision-Doppler surveys are poised to find all the Solar System analogs within 50 pc and the first set of terrestrial-mass planets orbiting beyond 0.1 AU.

1. Introduction

Civilizations are defined by their lasting contributions. Pyramids, democracy, algebra, global exploration, the renaissance, and the origins of modern science are the legacies associated with individual civilizations. In the distant future the 20th-century USA may be most positively remembered for the moon landings, regardless of the geopolitical motivation at the time.

The discovery of the first two hundred planets orbiting nearby stars over the past decade has propelled the fields of extrasolar planet studies and astrobiology from near non-existence to major research fronts. The public interest in extrasolar planets has been overwhelming, motivating a new generation of students to study science.

Riding the wave of public interest, NASA has spent the past decade chasing high-tech dreams with expanding billion-dollar budgets, to detect, image, and take spectra of nearby earth-like planets. Now that these programs lie in ruins, we are left to assess the most important contribution that the USA can make to extrasolar planet studies over the next generation.

Photometric transit surveys have turned up a dozen giant planets in small orbits around distant stars. Microlensing studies have found evidence for 2 or 3 planets orbiting unseen stars more than 10,000 parsecs away. Astrometric and interferometric surveys have yet to find a planet and appear several years away from success.

The field of extrasolar planets has been primarily driven by precision-Doppler surveys that concentrate on achieving the highest measurement precision on the nearest stars. About 90% of the 200 planets orbiting nearby stars have been found by two teams with typical allocations of 20 to 100 nights per year on general-purpose telescopes. Continuous improvements in the precision-Doppler technique, combined with hard-won empirical knowledge about the behavior of low-mass stars, has put the Doppler technique on the verge of finding terrestrial-mass planets around nearby stars.

Finding all the planetary systems, including terrestrial-mass planets, around the nearest 1,000 stars is now within reach. The first country to commit the necessary resources to a dedicated all-sky precision-Doppler survey of the nearest 1,000 stars will be long remembered in this new age of discovery. Here, we propose the construction of two 8 m class telescopes dedicated to the detection of earthlike planets in the classical habitable zones of the nearest 1,000 stars.

2. Rocky Planets: Status, Theory, and Predictions

Last year our team discovered the first Doppler planet having a mass likely less than 10 M_{Earth}, namely GL 876d with $M\sin i = 4.9$ M_{Earth} and a likely mass of 7.5 M_{Earth} (Rivera et al. 2005), opening a new era of characterizing planets under 10 M_{Earth}. The observed increase in the numbers of exoplanets toward lower masses and their correlation with stellar metallicity (Marcy et al. 2005), provide support for the standard model of planet formation that involves the growth of dust by collisions into a rocky core (Wetherill & Stewart 1989; Aarseth, Lin, & Palmer 1993; Lissauer 1995; Levison, Lissauer, & Duncan 1998; Kokubo & Ida 2002).

However, the theory of rocky-planet formation remains less than solid. It is not known what fraction of stars form rocky planets, nor how many avoid subsequent ejection from the planetary system. It also remains unknown if rocky cores above $\sim$1 M_{Earth} will quickly accrete gas and volatiles to become ice giants similar to Neptune and Uranus, as has been predicted (Goldreich, Lithwick, & Sari 2004), leaving a desert between those masses—as seen in our Solar System. Moreover, planets of $1-15$ M_{Earth} may retain water in amounts that are comparable to the silicates and iron-peak elements, resulting in a family of "ocean planets" (Raymond, Quinn, & Lunine 2005; Leger et al. 2004). Rocky planets are likely to be common as disks are extraordinarily common around young T Tauri stars, indicating the ubiquity of the building blocks of rocky planets (Hillenbrand et al. 1998; Haisch, Lada, & Lada 2001; Mamajek et al. 2004). Clearly, detections of a statistically useful number of planets between $3-20$ M_{Earth}, along with measurements of their masses, radii, and orbits, will significantly inform the diverse theories.

3. Finding Rocky Planets Around Nearby Stars Now

We have simulated the Doppler signal stemming from an observing run of duration 48 nights, with 25% lost to weather in clumps (due to "fronts"). We present here one such simulation representative of all of them. The planet has a mass of 10 M_{Earth} with an orbital period of 30 d, orbiting a star of mass 0.7 $M_\odot$ (K0V), and observed with a Doppler precision of 1.5 m s^{-1}, as shown in Figure 1. The Doppler amplitude of 2.5 m s^{-1} is visible (to the eye) above the 1.5 m s^{-1} errors, and the periodogram in the bottom panel shows a resulting peak at a power of 11 that indeed sits at 26.8 d. Simulations for all periods under 50 d showed the 10 M_{Earth} planet is easily detectable. Planets of mass down to 3 M_{Earth} are detectable, albeit with increasing difficulty. Thus planets of $5-10$ M_{Earth} can be detected and will have a small false-alarm probability (FAP) for periods under 2 months (Figure 2).

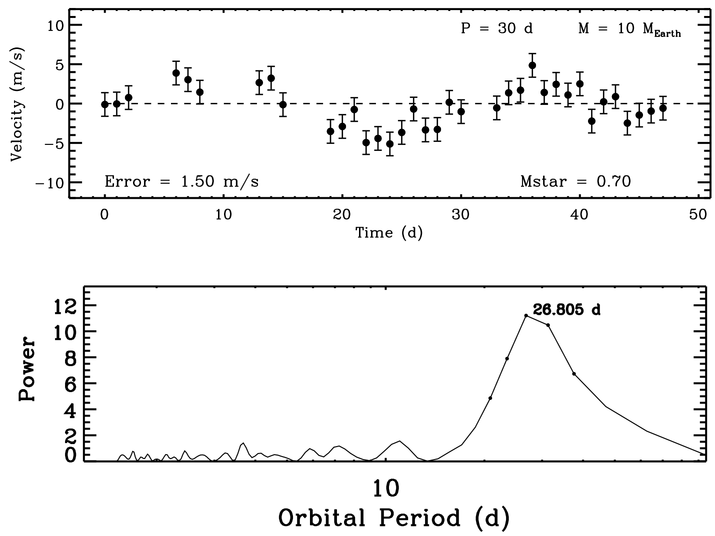

Figure 1. Top: Simulated 48 night observing run of a sun-like star with a 10 M_{Earth} planet in a 30 day orbit. The measurement uncertainties are 1.5 m s^{-1}. Bottom: Resulting periodogram, clearly revealing the 30 d period (at 26.8 d). We are capable of finding terrestrial-mass planets of 3−20 M_{Earth} with our existing technique.

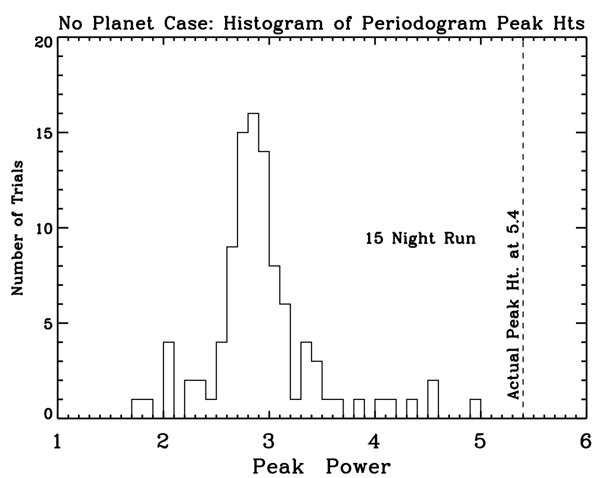

Figure 2. Determination of the False-Alarm Probability (FAP). Shown is the histogram of the highest periodogram peak from each of 1,000 trials in which *no planet* was included but only noise of 1.3 m s^{-1}. The histogram shows that the average periodogram peak would have a height of ∼2.8 if there were no planet, and that none of the peaks was as high as the actual peak height of 5.4 that resulted from the 5 M_{Earth} planet. Thus the false-alarm probability is less than 0.1%, a strong detection.

4. Emerging Candidates for Terrestrial-Mass Planets

Based on our continuing incremental improvement in measurement precision, our allocation on the 3.9 m Anglo-Australian Telescope (AAT) has been increased from 20 to 80 nights per year, including 48 consecutive nights to explicitly go after terrestrial-mass planets. This first extended search for terrestrial-mass planets started 10 Jan 2007 and ended on the morning of 26 Feb 2007. We have several emerging candidates for terrestrial-mass planets from this run.

The top left panel of Figure 3 shows the velocities for a candidate from the 48 night observing run. The rms is 2.0 m s^{-1}, while the median photon-limited uncertainty is 0.8 m s^{-1}. A $\sim$22 d period can be seen by eye. The full set of velocities, shown in the top right panel, have an rms of 2.2 m s^{-1}. A periodogram of the full set of velocities is shown in the bottom left panel, revealing a strong periodicity at 22.2 d. The bottom right panel shows the full set of data phased with the best-fit Keplerian period of 22.15 d. The Doppler semiamplitude is 1.8 m s^{-1} and the minimum mass of the candidate planet is 6.7 $M_{\rm Earth}$. The false-alarm probability of the Keplerian is 8%. One more long observing run is required to confirm this planet.

Another emerging candidate is shown in Figure 4. The top left panel of Figure 4 shows the just-concluded 48 night observing run. The nightly velocity variations are coherent. The velocity rms is 4.1 m s^{-1}. The top right panel shows the last two years of high-precision data. The velocity rms is 4.3 m s^{-1}. The bottom left panel shows the full set of velocities phased at the best-fit Keplerian period of 63.46 d. The semiamplitude of the Keplerian is 5.7 m s^{-1}, and the minimum mass of the planet is 31 $M_{\rm Earth}$. The false-alarm probability for this orbit is less than 0.1%. The velocity rms of the residuals, 2.57 m s^{-1}, remains significantly larger than the internal measurement uncertainty. A periodogram of the velocity residuals to the best-fit Keplerian, shown in the bottom right panel, reveals a strong periodicity at 4.21 d.

The best-fit double Keplerian to the data set is shown in Figure 5. The inner planet with a period of 4.21 d is in a roughly circular orbit with a semiamplitude of 2.7 m s^{-1} and a minimum mass of 6.5 $M_{\rm Earth}$. The velocity rms to the double Keplerian fit is 1.88 m s^{-1}, and the reduced chi-sq is 1.0.

5. The 1,000 Star Terrestrial Planet Search

While the US has focused on high-tech space-based "magic bullets", the plodding ground-based precision-Doppler technique has found nearly all the planets while continuing to incrementally improve until its sensitivity is comparable to, or better than, hoped for Space Interferometry Mission (SIM) specs. For roughly 20% of the taxpayer money already spent on SIM and Terrestrial Planet Finder (TPF), we could have a working system that will find all Solar System analogs and the first substantial set of terrestrial-mass planets around the 1,000 nearest stars.

The first reconnaissance of the nearest 1,000 sun-like stars out to 30 parsecs will be an epochal event, providing the defining map of extrasolar planet studies for generations, providing targets and motivation for future interferometry, direct imaging, and interstellar travel programs. This data set would definitely

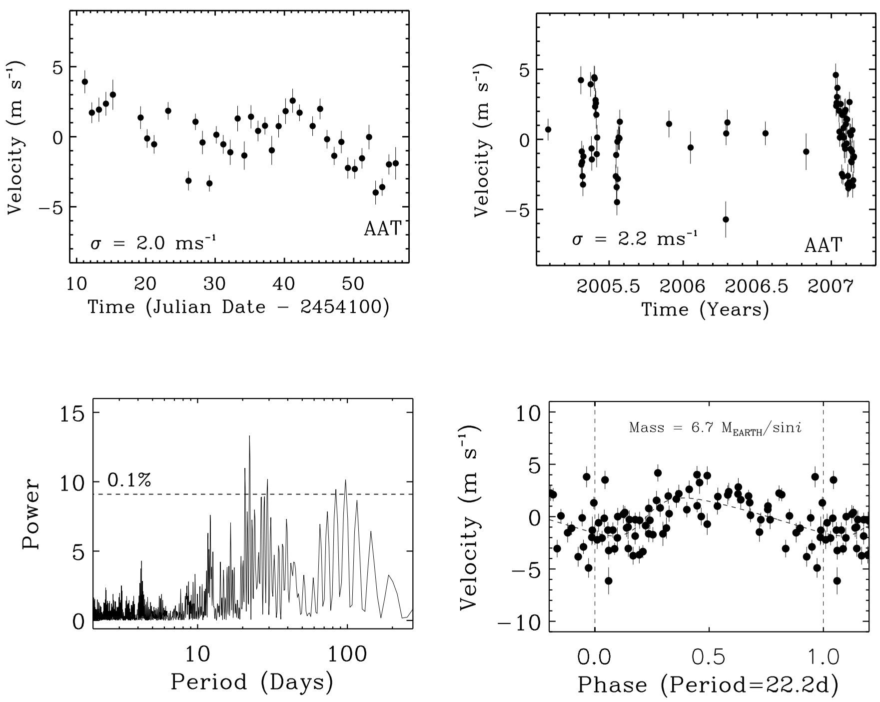

Figure 3. Top left: Candidate observed during the just-concluded 48 night AAT run. A potential 22 d periodicity can be seen by eye. Top right: The full 2 year high-precision Doppler velocity set. Bottom left: Periodogram of the full velocity set reveals a 22 d peak. Bottom right: The full set of velocities phased at the best-fit Keplerian period of 22.2 d. The minimum (Msin i) mass of this candidate is 6.7 M_{Earth}.

answer questions about the fraction of stars that have planetary systems, the ubiquity or scarcity of Solar System and Earth analogs, and drive theoretical studies of planet formation and evolution.

Getting ∼80 nights a year on a 4 m class telescope (AAT, High Accuracy Radial velocity Planet Searcher) provides 1 m s^{-1} coverage for the ∼100 brightest stars, including an occasional ∼50 night observing run on the brightest 50 stars to search for terrestrial-mass planets with orbits out to 20 d. Adding more stars to a 4 m requires enormous increases in telescope time as each star added is fainter than the last, exposure times to reach 1 m s^{-1} precision go over 40 minutes.

Optimistically, 50 nights per year of Keck time might be assigned to a single dedicated 1 m s^{-1} planet search, allowing coverage of 200 stars at 1 m s^{-1}, including an occasional 20 night observing run to search for terrestrial-mass planets in 10 d orbits.

Two dedicated 8 m telescopes, one in the north and one in the south, can survey all 1,000 of the nearest sun-like stars, out to 30 parsecs. Every star in the survey would be observed 3 times a year. Saturn-mass planets orbiting within

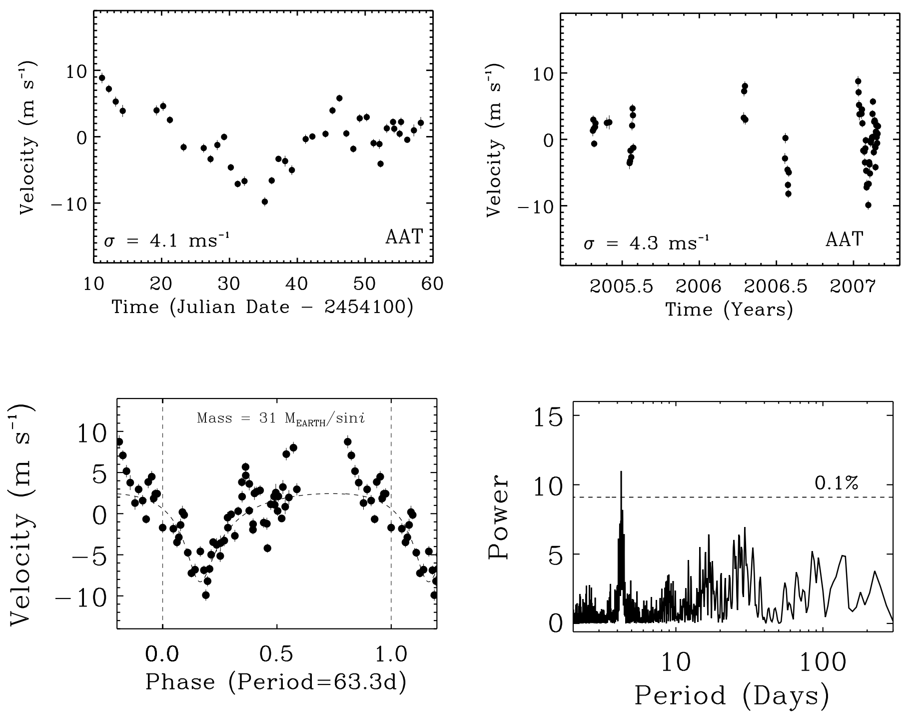

Figure 4. Top left: Candidate observed during the just-concluded 48 night AAT run. Top right: The full 2 year high-precision Doppler velocity set. Bottom left: The full set of velocities phased at the best-fit Keplerian period of 63.3 d. The dotted line is the best-fit Keplerian. The rms to the Keplerian fit is 2.5 m s^{-1}, significantly larger than measurement uncertainty. Bottom right: Periodogram of velocity residuals after removing the 63.3 d Keplerian. A strong peak is seen at 4.21 d.

10 AU would be detectable. Each observing season, 100 stars would be chosen to be observed every possible night for 6 to 8 months, making these surveys sensitive to terrestrial-mass planets in orbits out to several tenths of an AU, including the habitable zone for K and M dwarfs.

Since these would be dedicated telescopes outfitted with identical echelle spectrometers, the cost would be significantly smaller than two general-purpose 8 m telescopes outfitted with a suite of instruments. Based on the cost of the two 6.5 m Magellan telescopes, we are confident that two dedicated 8 m telescopes and matching spectrometers could be built for $150 million, less than one-tenth the cost of SIM. Annual operations cost would also be an order of magnitude less than a space-based mission.

Astrophysics programs like this have no chance in the current US scheme of science funding. NASA can come up with hundreds of millions for enormous space-based efforts. The NSF can fund medium-sized research efforts and an 8 m telescope available to the general community, but not a large dedicated program with a budget of $100+ million. As a result, after spending more than a decade

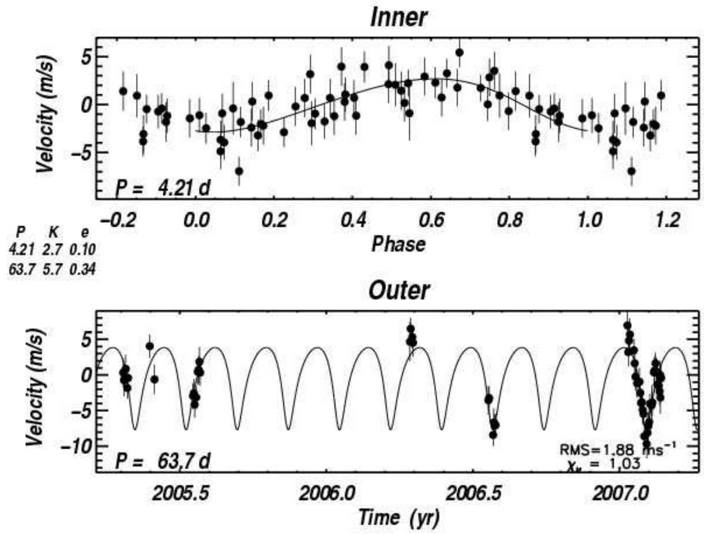

Figure 5. Best double Keplerian fit. Top: Phased velocities of the inner planet in a 4.21 d period, after removing the outer Keplerian. It has a minimum mass $M\sin i = 6.5\ M_{\rm Earth}$. Bottom: The velocities for the outer planet after removing the inner Keplerian.

and $500 million on TPF and SIM, the US stands to lose out on the race to find the nearest habitable planet systems because there is no funding mechanism or vision to fund a dedicated ground-based astrophysics mission, regardless of the significance of the results, and regardless of the complementary advantages over space-based programs.

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