Synergy of Astrometry and Direct Detection

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EXOPAG Jun 24, 2010

Outline

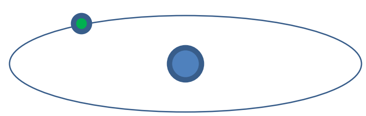
- Discovering Earthlike planets in the HZ of nearby stars.
  - When can a discovery be claimed? (for astrometry/RV for direct imaging) Ast/RV detection as a rule have used ~1% FAP (**False alarm probability**) as the threshold.
  - False positives in transit detection (Kepler) and direct detection (TPF-C, TPF-O) and astrometry (SIM)
    - Statistical false alarms, astrophysical false alarms
- The discovery of an Earth-clone orbiting another star is a **major discovery that requires unimpeachable evidence**.
  - If the FAP is >> 1%, a discovery of an Exo-Earth has **NOT** been made. (A single image of a potential Earth-HZ from a TPF mission has a ~60% FAP)
- Reducing FAP for direct imaging of exo-earths.
  - Measure the orbit of the planet. (with imaging alone, imaging preceded by astrometric discovery) How much does astrometry help an imaging mission discover an Earth, (as opposed to help an imaging mission take the 1st image of a potential Earth)

Discovering Exo-Earths with Direct Detection

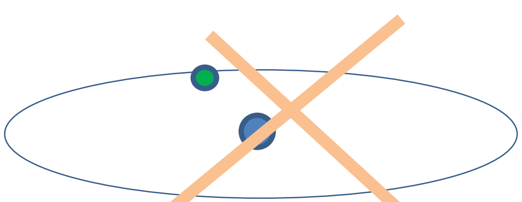
- Assumptions/Issues
  - Most coronagraphic mission studies have assumed that a single image of an Earth is all that is needed to clearly identify an Earthlike (1~10M_e) planet in the habitable zone (0.7~1.5AU scaled to the luminosity of the star)
  - There is an explicit or implicit assumption that a star has either zero planets or 1 Earthlike planet in the habitable zone. But planets come in all sizes and orbits. Neptunes at 2AU can look like an Earth at 1AU, in terms of angular separation and contrast.

Solo star

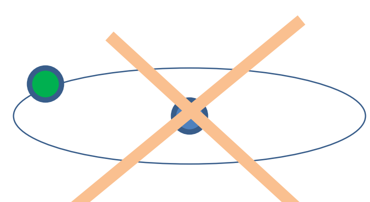
Star + 1 Earth in HZ



In this study, we look at **False Alarms**, in a quantitative way.



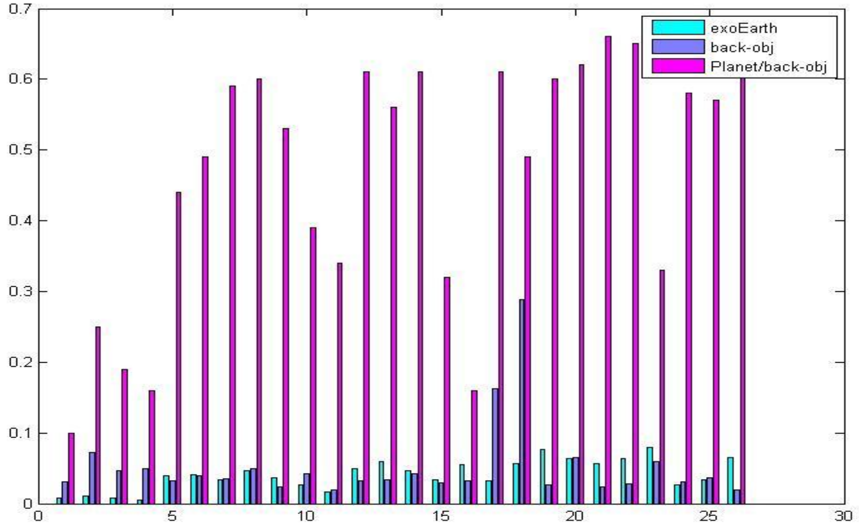
Star + 1 Earth **Not** in HZ



Star + 1 Neptune in HZ

Different Types of False Alarms

- Statistical (SNR) false alarms (not considered here)
- Astrophysical False alarms
  - Background objects (galaxies) Haiman, Spergel, Turner ApJ P630, 2003.
    - Predicted ~10% of TPF images might have a background object.



Prob for each of 26 stars in Brown, Soummer ApJ paper

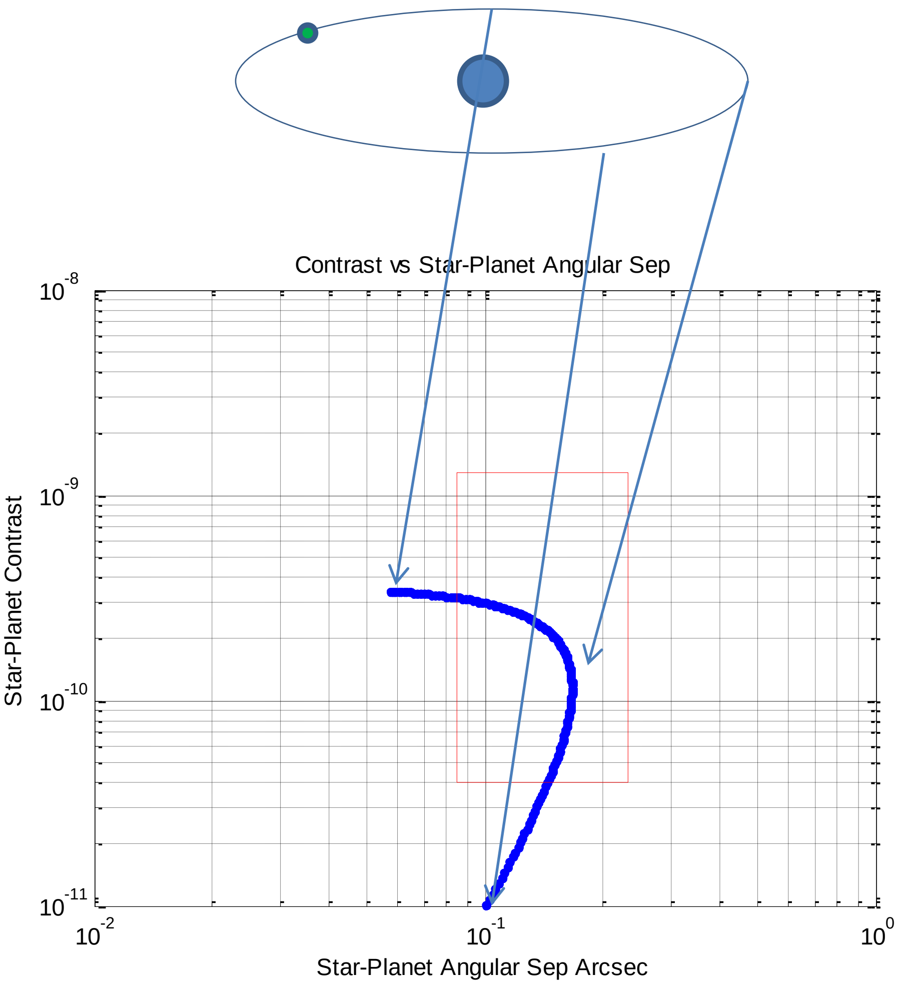
Prob of background
Prob of exo-earth
Prob Ratio (Earth/Background)

Eta_Earth~10%

  - Planets other than Exo-Earths – HZ. (multiple scenarios)
    - Star has planet that are NOT exo-Earths, but in 1 image can mimic an Exo-Earth (more than 50% of the time)

Contrast vs Star-Planet Separation

- In reflected light, the angular separation and the star-planet contrast changes as the planet orbits the star.
- The red box represents the region where a planet "could" be an Exo-Earth in the HZ (habitable zone)
  - 1.2e-10 Earth-Sun contrast at max star-planet separation
  - 4e-11 Instrument limit *
  - 85 mas IWA (JWST+Starshade inner working angle) *
  - 233 mas outer extent of HZ
  - 1.3e-9, 2 R_earth (8 M_earth) planet @ 1AU
- The brightness of an Earth @1AU can **vary by a factor of 8**, and still be detected by the telescope -starshade.
  - With just 1 image, the brightness of the planet does **<u>not</u>** constrain the size of the planet even if the albedo is known.

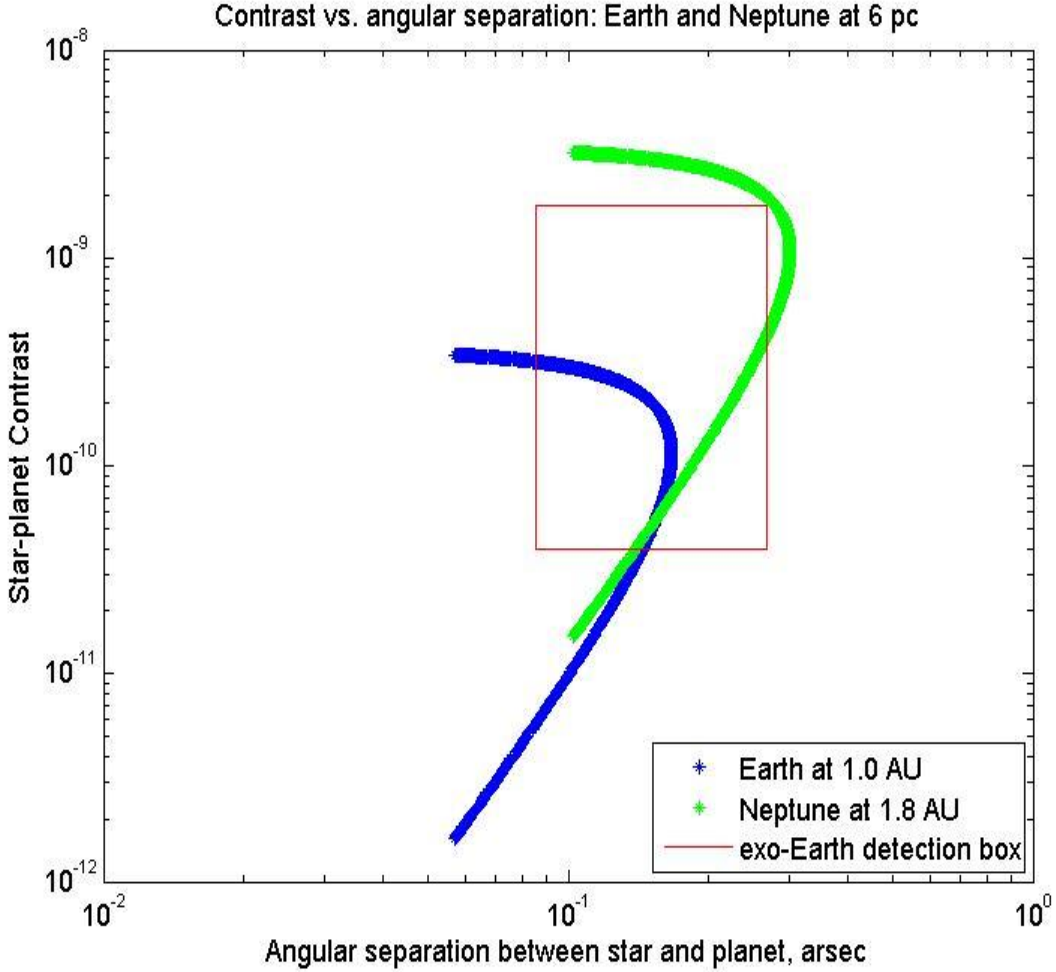


Sun-Earth 1AU @ 6pc

*Mission parameters 85mas IWA, 4e-11 min contrast and 70 visits from Brown & Soummer arXiv:1003.4700v1, 24 Mar 2010

Example of False Alarm(s)

- A variety of planets that are NOT exo-earths in the HZ can be confused with an exo-Earth in the HZ.
- Neptunes, SuperEarths
  - R < 0.7 AU
  - 0.7AU < R < 1.5AU
  - R > 1.5AU
- Earths
  - R<0.7AU
  - R>1.5AU



If you take 2 images of the same star at 2 different epochs, and detect one planet at each epoch, you **<u>don't know</u>** the two images are of the same planet. Two images 3 months apart with the same brightness are most likely images of **<u>two different planets</u>**.

Measuring the orbit

- **The only way to know if a planet is in the habitable zone is to measure its orbit.**
- **This can be done by an astrometric mission, or an imaging mission, or both.**
- **There are six orbital elements:**
  - **Period (or semimajor axis)**
  - **Eccentricity**
  - **Time of periastron**
  - **Inclination**
  - **Longitude of ascending node (angular position of the line of nodes – the intersection of the orbital plane with the plane of the sky)**
  - **Longitude of periastron (angular position of the periastron with respect to the line of nodes)**
- **Need a minimum of 4 images of the planet at different phases along the orbit.**
- **If the completeness of a planet's orbit is 60%, it takes 6 or 7 observations to get 4 images of the planet.**

Example: JWST + starshade

- **External occulters are space-based coronagraph systems that use a specially-shaped starshade occulter separated by tens of thousands of km from the telescope to suppress the starlight.**
- **Can only observe stars in a region 85° to 105° away from the Sun. This is to keep sunlight off the starshade and out of the telescope. We did not account for this in our simulations.**
- **Inner working angle (IWA) is 85 mas.**
- **Minimum detectable contrast is $F_{min} = 4 \times 10^{-11}$**
- **Limited to about 70 pointings by starshade propellant.**
- **Proposed survey of 26 FGK target stars to detect and take spectra of exo-Earths.**
- **Filters F070W (700 nm), F115W (1150 nm), F150W (1500 nm)**
- **Brown, R.A. and Soummer, R. 2010 Ap. J. 715:122; http://arxiv.org/abs/1003.4700v1**

Realistic planet distribution

- **A realistic planet distribution should include the population of Neptune mass planets (10– 100 M_{Earth}) that has recently been revealed.**
- **Microlensing (A. Gould, S. Gaudi):**
  - **Distribution is flat in log(mass) and log(semimajor axis).**
  - **Density of Neptunes is ~0.36 per dex^2 in the phase space of mass and semimajor axis near ~2 AU.**
  - **Occurrence rate ~11% in the HZ.**
- **Geneva RV group:**
  - **50% of G and K stars have rocky or Neptune mass planets inward of 50 day orbits.**
  - **This also gives a phase space density of ~0.36 per dex^2**
- **If planets in the terrestrial mass range (1 to 10 M_{Earth}) have the same phase space density, then η_{Earth}~10%**

Detect-once survey

- **Observe each of the 26 stars once; if an exo-Earth is detected, do not re-observe that star.**
- **Re-observe remaining stars, repeat until 70 observations have been made.**

Realistic planet distribution	η_{Earth}	Number of exo-Earth candidates	Number of exo-Earths	Number of False Alarms	False alarm probability
N	0.1	1.9	1.9	N/A	N/A
N	0.2	3.8	3.8	N/A	N/A
N	0.3	5.7	5.7	N/A	N/A
Y	**0.1**	**4.5**	**1.9**	**2.6**	**0.58**
Y	0.2	7.9	3.8	4.1	0.52
Y	0.3	11.0	5.6	5.4	0.49

High false alarm probability: on average, there is one false alarm per exo-Earth

Removing Confusion

- The huge % of false alarms occur only because we use a single image to declare we've found an Earth in the HZ.
- Multiple images, enough to measure the orbit of the planet, will remove the confusion.
- Two ways to remove confusion
  - Direct detection alone (multiple images)
  - Astrometric detection followed by direct detection.

- Direct Imaging alone (70 total epochs)
  - 4 image of the same planet. (3 to derive an orbit, the 4th to confirm that all 4 dots are from the same planet)
  - If the planet is observable over **50%** of its orbit (outside the IWA, > 4e-11) then **images at 8 epochs** will produce **4 images** of the planet.
- Astrometry then Imaging (70 images)
  - Astrometry finds the Earths, informs the occulter where **not** to look.
  - Astrometric orbit has orbital phase uncertainty due to time between the missions. **Need 2 additional images** (4 attempts)

Results of orbit surveys

η_{Earth}	Exo-earth yield		Probability of no (zero) exo-Earth detections	
	Orbit measurement survey (no prior astrometry)	Orbit confirmation survey (with prior astrometry)	Orbit measurement survey (no prior astrometry)	Orbit confirmation survey (with prior astrometry)
0.1	**0.9**	**4.7**	**0.41**	**0.007**
0.2	1.9	9.1	0.16	<0.001
0.3	2.7	12.0	0.07	<0.001

An imaging mission combined with prior astrometry yields ~5 times as many exo-Earths as a star shade imaging mission alone.

Summary and Conclusions

- JWST with a starshade will most likely find 1 exo-Earth (confirmed orbit) but there is a 41% probability that a starshade addition to JWST will only find false alarms.
- A starshade mission preceeded by SIM, will most likely find ~5 Earths with confirmed orbits, and have just a 0.7% probabilty of finding nothing.
- Star shade missions can do a great job of measuring the spectra of exo-earths. But they are not a viable approach to “discovering” Earths.

Scaling Laws

Astrometry, Internal Coronagraph, Starshade

- Astrometry (photon limited by ref stars)
  - Planet 2X further away requires 4X integration time

- Internal coronagraph (background limited by local/exo-zodi)
  - Planet 2X further away requires 16X integration time.
  - If an internal coronagraph can detect an Earth @ 4AU in 2 hrs. Then an Earth @ 12pc will take 1 week. If 10 attempted images are needed to get an orbit, this 1 target will require 10 weeks of integration time spread over a few years.
  - A 2X larger telescope will decrease IWA by 2X, the average target will be 2X further away, meaning the same # hrs of integration time will be needed per target, on average. But the # targets are increasing as (IWA^-3).

- Starshade (unscaleable)
  - If we want to reduce the IWA of a starshade by 2X, the dia of the shade goes up by 2X, (mass by 4X), the distance to the shade by 4X, and the propellant retarget by 16X. A 2X reduction in the JWST starshade IWA will reduce the # visits from ~70 to ~ 5.
  - The current Starshade will on average find 0.9 Earths. Scaling the star shade either larger or smaller will result in fewer (0) discoveries.

of Attempted Images to Get Orbit

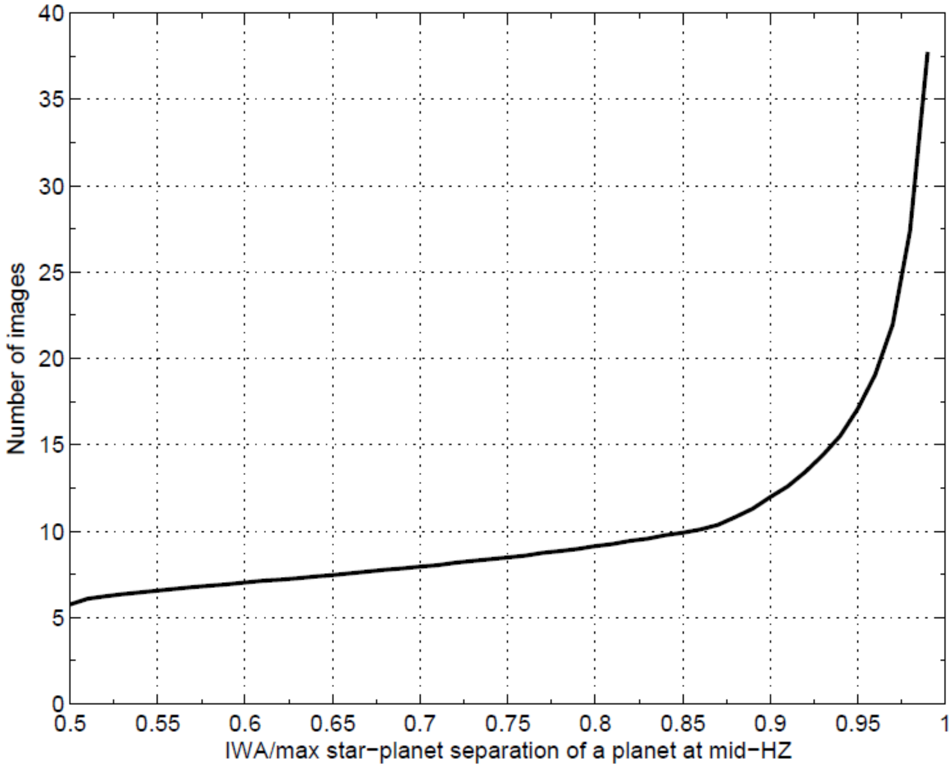


Fig. 5.— The number of images needed to detect a planet 4 times so as to measure and confirm the orbit. When the maximum star-planet separation is close to the IWA, the completeness is low, so more images are required.

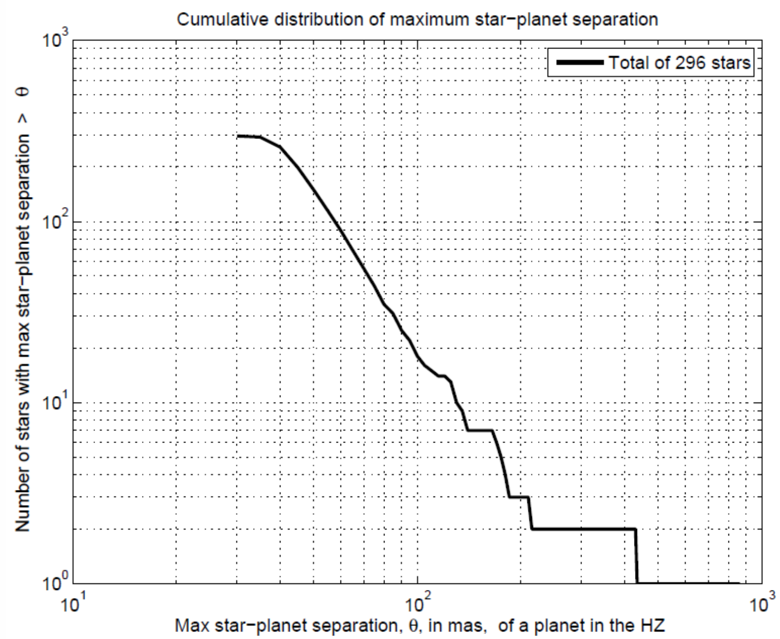
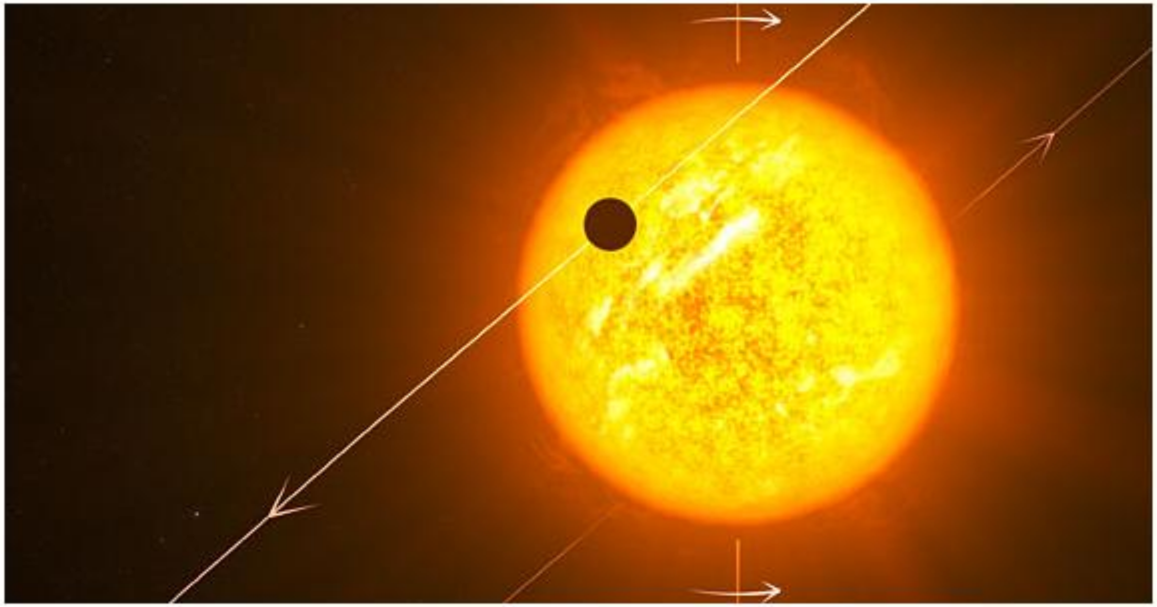


Fig. 3.— Cumulative distribution of the number of stars for which an exo-Earth at mid-habitable zone is separated from its star by more than θ. There are 296 stars with planet separation > 30 mas.

On average
4 images of the planet are needed to confirm an orbit (no astrometry)
2 images of the planet are needed to confirm the orbit (with astrometry)
(1st image after astrometry “pins” the orbital phase)

Turning Planetary Theory Upside Down

13 April 2010



Click to Enlarge

The discovery of nine new transiting exoplanets is announced today at the RAS National Astronomy Meeting (NAM2010). When these new results were combined with earlier observations of transiting exoplanets astronomers were surprised to find that six out of a larger sample of 27 were found to be orbiting in the opposite direction to the rotation of their host star — the exact reverse of what is seen in our own Solar System. The new discoveries provide an unexpected and serious challenge to current theories of planet formation. They also suggest that systems with exoplanets of the type known as hot Jupiters are unlikely to contain Earth-like planets.

Surprisingly, when the team combined the new data with older observations they found that more than half of all the hot Jupiters [4] studied have orbits that are misaligned with the rotation axis of their parent stars. They even found that six exoplanets in this extended study (of which two are new discoveries) have retrograde motion: they orbit their star in the "wrong" direction.

"*The new results really challenge the conventional wisdom that planets should always orbit in the same direction as their stars spin,*" says Andrew Cameron of the University of St Andrews, who presented the new results at the RAS National Astronomy Meeting (NAM2010) in Glasgow this week.

Error Propagation of Astrometric Orbit

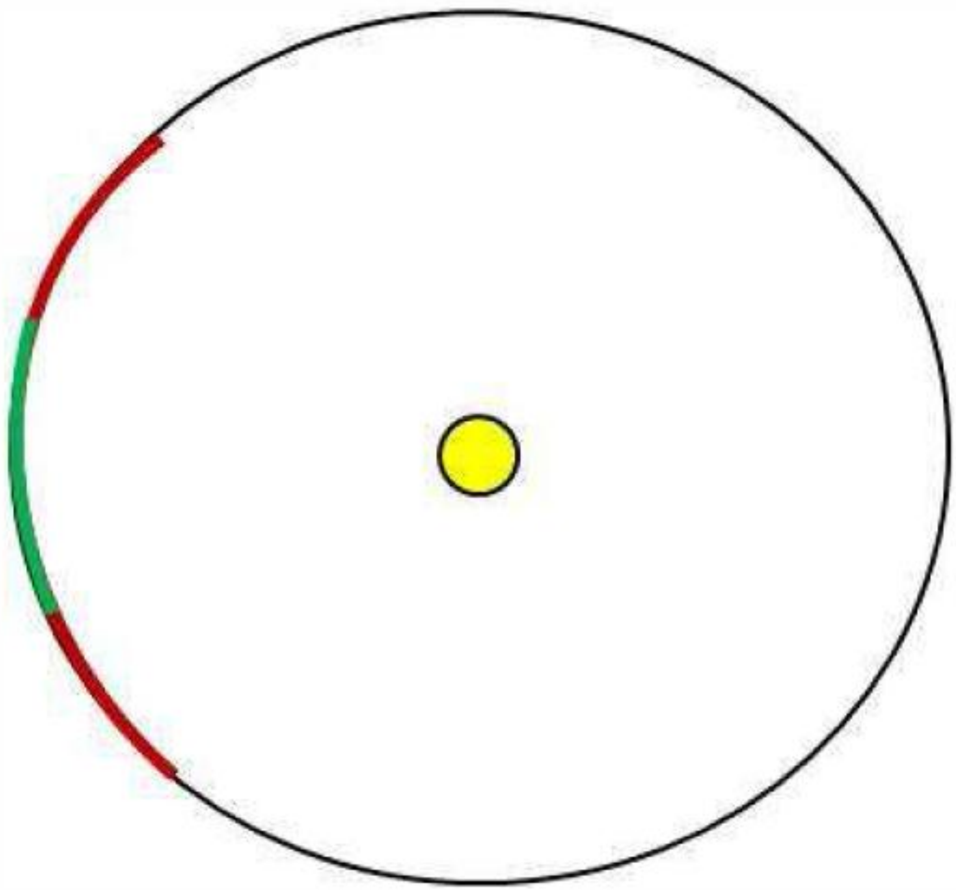


Fig. 2.— Astrometric Orbit Error. The error in phase grows with time, from ±14 days at mid-epoch (green) to ±50 days 5 years after mid-epoch (red).

At the limit of detection,
SNR=6 FAP=1%
Earth-Sun 1AU, 1 year orbit

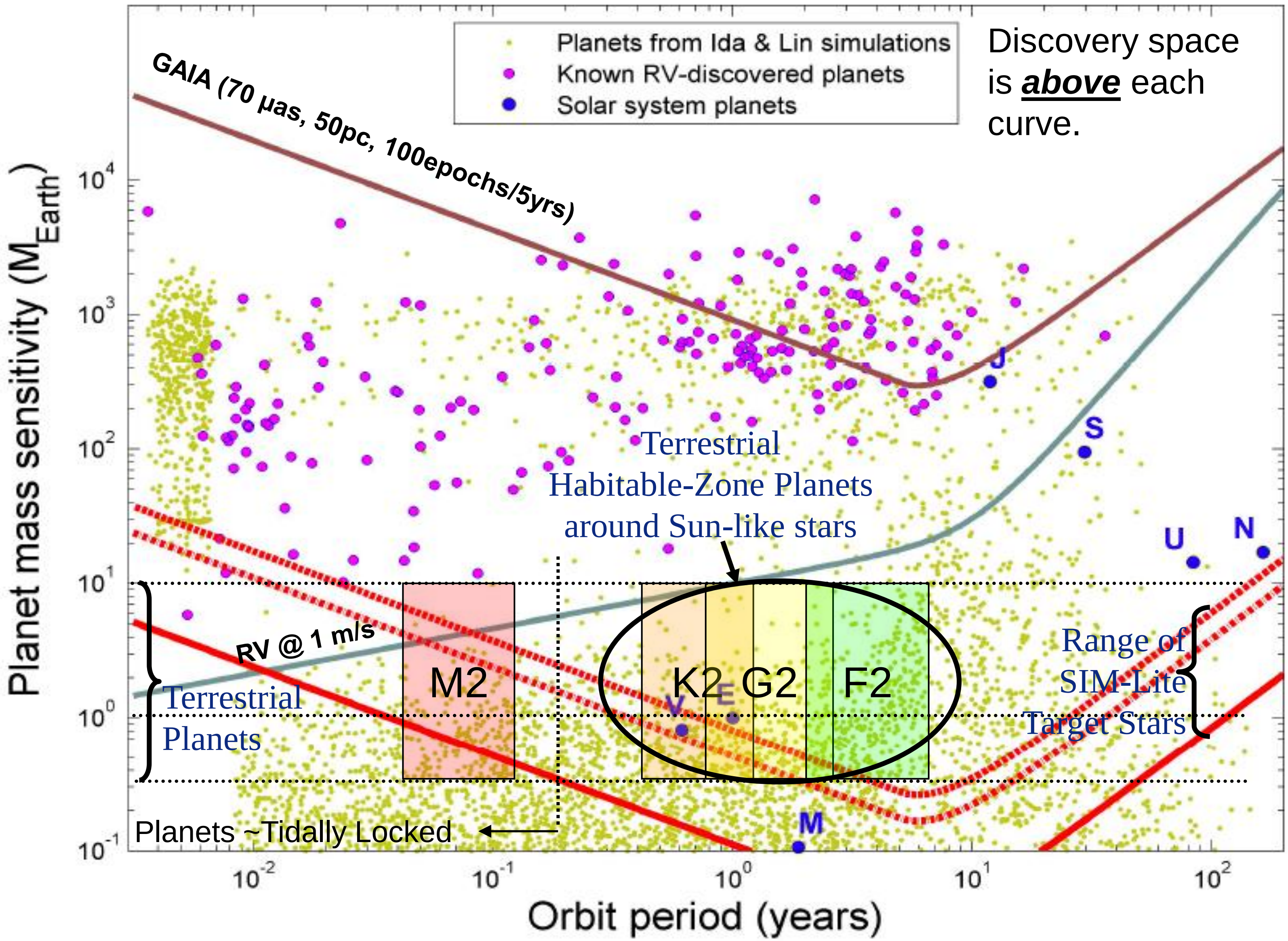
Orbit radius +/- 3%
Orbit phase +/- 14 days (mid epoch) degrades to

Phase +/- 50 days 5 yrs later

However a 2 M_{earth} planet will have ½ the error.

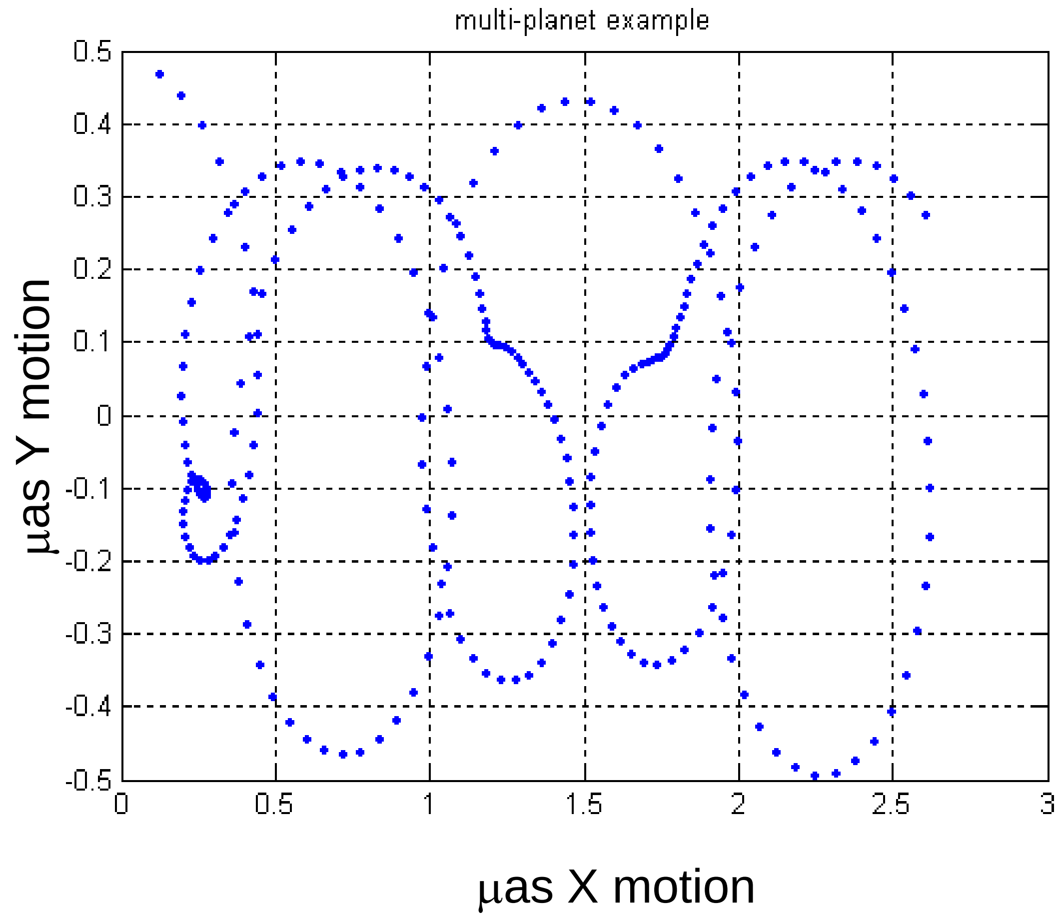
14 days/365 days ~3.8%

SIM Lite will find Earth-Analogs around *nearby sun-like* FGK stars!



Astrometric Detection: Multiple Planets

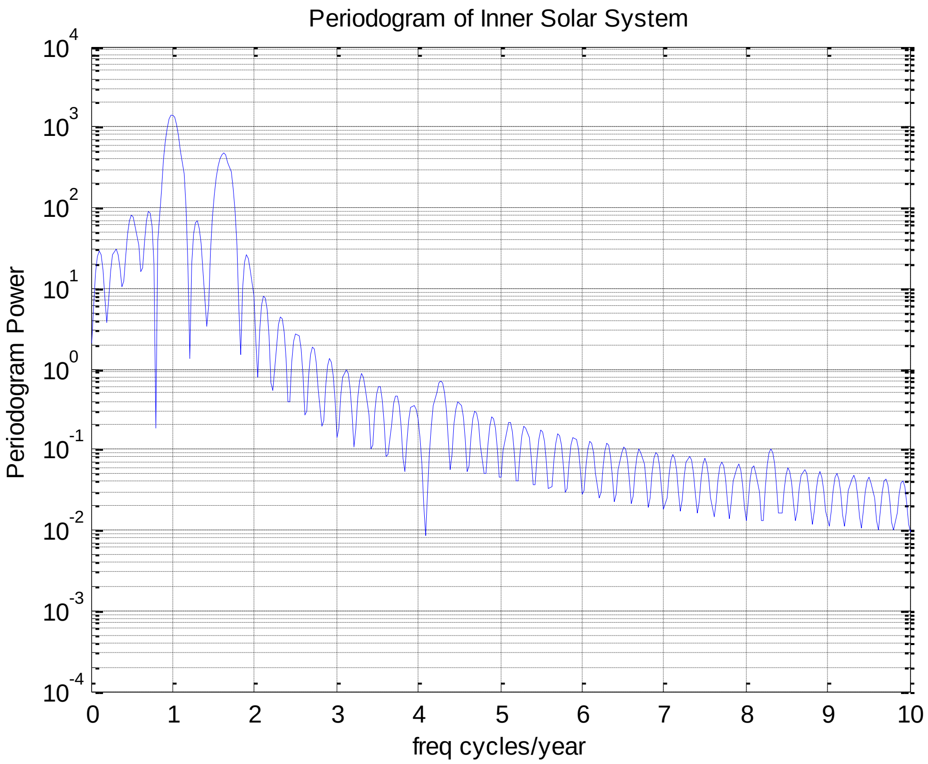
- Astrometry measures the reflex motion of the star due to the motion of all the planets in orbit.
- The astrometric motion shown at right does not include parallax or proper motion of the star. (a small amount of proper motion was added in X to make visualizing the orbits easier)
- General approach is to identify periodic motion of the largest planet with a periodogram, then fit out its orbit. Subtract that motion from the data and find the 2nd largest planet, and so on.



Motion of the Sun @ 10pc due to the inner 4 rocky planets, over 5 years. (no noise)

Periodogram

- The periodogram at right shows two peaks from Earth and Venus.
- The finite length (5yrs) of the data set produces the sidelobes.
- The sidelobes partially hide the peaks from the two smaller planets (Mars, Mercury)
- Consequently it's important to fit a keplerian orbit to the big planets, and subtract out their signatures before looking for the smaller planets in the planetary system.



Double Blind Test

- NASA conducted a double blind test of astrometric detection of multiple planets.
- ~ 5 theory teams to generate “fake” planetary systems
- Data generation team to generate 5 yrs of astrometric data, and 15 years of RV data.
- 5 Data analysis teams to analyze a total of 108 planetary system, with a total of 135 planets, 27 of which were “Earths in the HZ”.

- The results of the data analysis teams were scored according to two statistics
- **Completeness:** What % of planets that “could have been detected” were detected.
- **Reliability:** When a detection was claimed to have been made, was the claim valid?
  - Reliability = 100% - False_alarm%

- If the planet’s signature had an SNR > ~5.8 it “could” have been detected.

Double Blind Study Results

Scoring Category	Phase 1†	Phase 2
Completeness: Terrestrial	18/20	37/43
Completeness: HZ	13/13	21/22
Completeness: Terrestrial HZ	9*/9	17**/18
Completeness: All planets	**51/54**	**63/70**
Reliability: Terrestrial	25/27	38/39
Reliability: HZ	16/16	20/20
Reliability: Terrestrial HZ	12/12	16/16
Reliability: All planets	**64/67**	**66/68**

- Analysts were asked to be aggressive in Phase-1 and conservative in Phase-2. This is reflected in the denominators of the Completeness and Reliability sections.

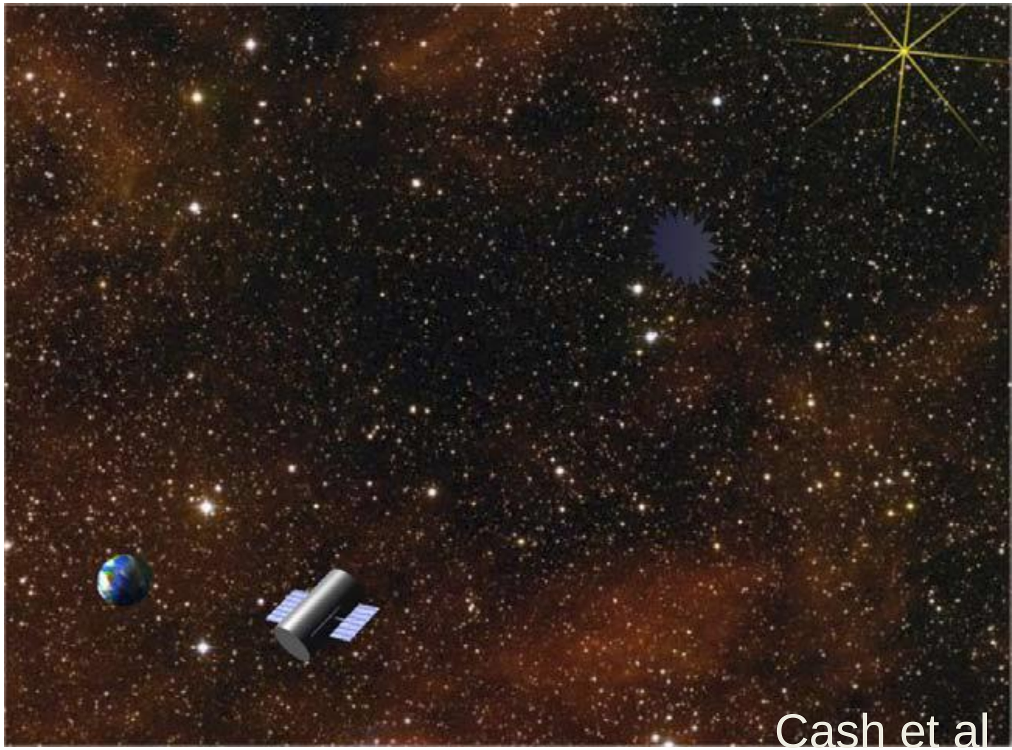
* All 9 T/HZ Phase-1 detected planets were in multiple-planet systems.

**10 of the 17 T/HZ Phase-2 detected planets were in multiple-planet systems

† Results here are from Analysis Team C5 only; Best comparable to Phase-2.

Direct Dection/Imaging

- Imaging (coronagraphic missions) for detecting exo_Earths have been studied for a number of years, both in the thermal IR (contrast ~ 1e-7) and in the visible (contrast ~ 1e-10)
- The major technical challenge has been the huge contrast between the star and planet, that's 0.1 arcsec away.
- One of the newer ideas for direct detection is the starshade - external occulter concept.
  – Potentially an addition to JWST



- ~50m starshade ~80,000km in front of telescope.
- Advantages: No need for extremely accurate wavefront control <λ/10,000, stab ~ λ/500,000
- Disadvantages: Limited number of visits, (~70). Limit from propellant to move the starshade across millions of km. Limited sampling, target between 80~105 deg from Sun.