Finding an Earth Analog

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1. Motivations

- Determine detection limitations with state of the art techniques
- Could an Earth-like planet orbiting a Sun-like star be detected with current methods?
- How does this affect our current understanding of exoplanet demographics?

2. Methods

- Find current limitations and determine effectiveness of:
  - Radial Velocity
  - Transit
  - Astrometry
  - Direct Imaging

2a. Radial Velocity

Using the expression for RV signal:

$$K = \frac{M_p}{M_\star}\sqrt{\frac{G * M_\star}{a}}\, sin\ i.$$

Variables: K= RV semi-amplitude (detection signal), Mp= planet mass, G= Gravitational constant, M_*=star mass, a= semi-major axis, sin i = inclination

Assumptions: edge-on inclination (sin i =1) , M_*=0.5 solar masses

State-of-the-art detection signal (ESPRESSO and EXPRES): K=0.5 m/s

Detection Signal Line and Earth analog Detection signal

ESPRESSO: (Pepe et al., 2020) EXPRES: (Blackman et al., 2020)

2b. Transit

Using equations for transit duration and transit depth:

$$f = \left(\frac{R_p}{R_*}\right)^2$$

Transit duration: $$t_{\text{transit}} \approx \frac{2R_*}{v_{\mathrm{K}}}$$

F = Transit Depth, Rp = Radius of planet, R* = Radius of star, vK = velocity of planet

State of the art detection signals: Transit Least Squares Algorithm

Assuming an orbital period of 360 days

Transit searches operate with a minimum transit duration of 0.00125 times the orbital period = 38880 seconds (Hippke)

2c. Astrometry

Using Astrometric detection signal, which is the angular separation as seen from Earth:

$$\theta = \frac{m_p}{m_\star}\frac{a}{d} = \left(\frac{G}{4\pi^2}\right)^{1/3} \frac{m_p}{m_\star^{2/3}}\frac{P^{2/3}}{d}$$

State of the art detection: (GRAVITY) 100µas

REF: GRAVITY (Abuter et al., 2017)

2d. Direct Imaging

Using equations for star-planet contrast (f) and angular separation (theta):

$$f = \left(\frac{R_p}{R_*}\right)^2 \frac{\exp(h\nu/k_B T_*) - 1}{\exp(h\nu/k_B T) - 1} \sim 10^{-6} \qquad \theta \sim 1.22\frac{\lambda}{D}$$

Rp = Radius of planet, R* = Radius of star, v = frequency of light, h = planck’s constant, kb = Boltzmann constant, T = Temp of planet, T* = Temp of star, lambda = Wavelength, D = Diameter of the telescope, theta = angular resolution of telescope

State of the art detection: (Gemini Planet Imager, SPHERE)

Detects f > 10^-7 (Wallace)

Can resolve down to ~0.7arcsec, using GEMINI (McBride et al., 2011)

3. Results

So, can we detect an Earth-like planet around a Sun-like star using current techniques?

No.

3a. Radial Velocity

The semi-amplitude for an Earth analog is:

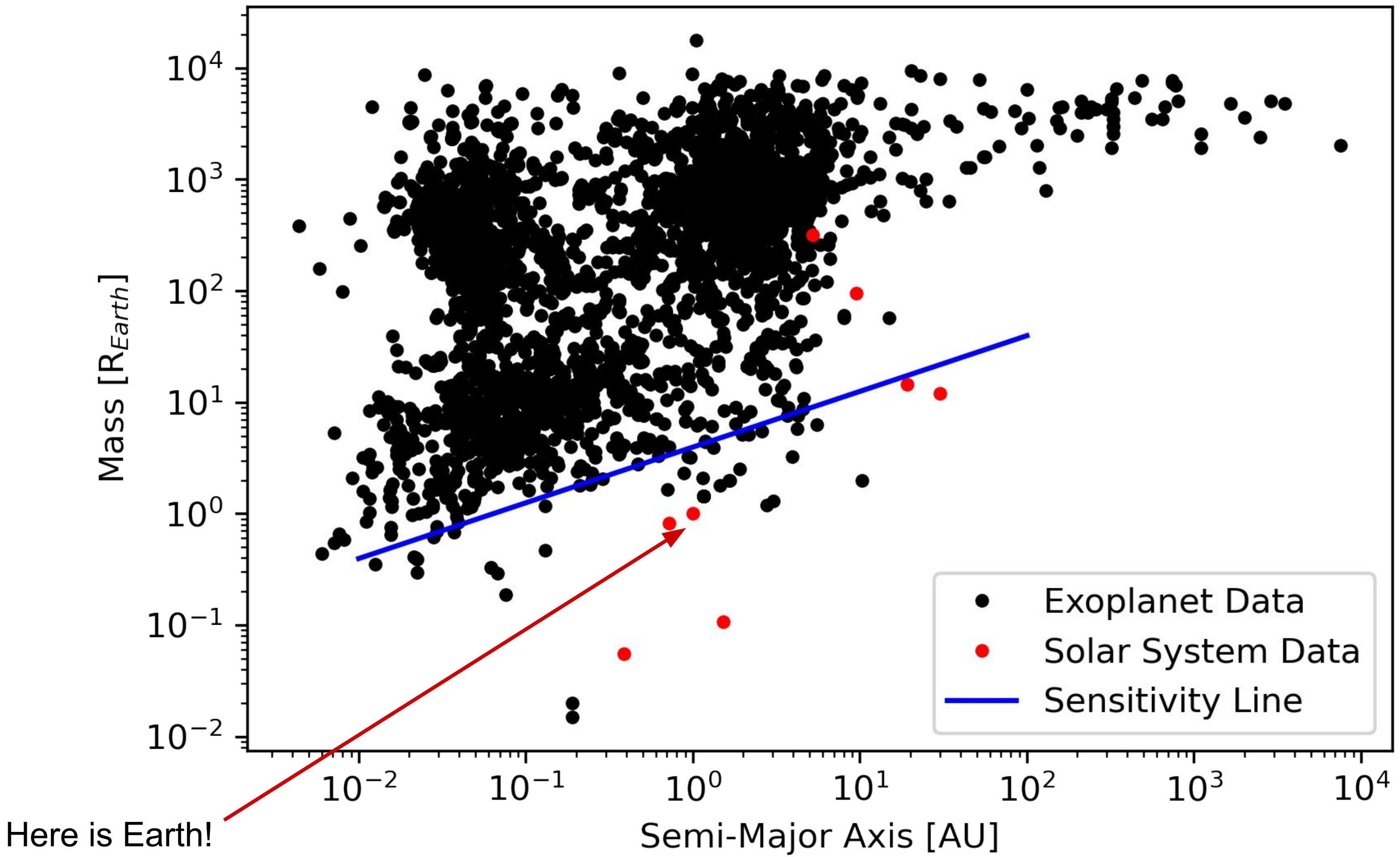
K = 8.944 x 10^-2 m/s (~0.09m/s)

Current techniques:

EXPRESSO: K=0.25m/s to 0.5 m/s

EXPRES: (ideally) K >0.1m/s

Current RV methods will not detect an Earth analog



Mass [R_{Earth}]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Semi-Major Axis [AU]
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
Exoplanet Data
Solar System Data
Sensitivity Line
Here is Earth!

3b. Transits

Transit Depth = 8.389 x 10^-3 kilometers

Transit Duration = 4.252 x 10^3 seconds

Transit searches operate with a minimum transit duration of 0.00125 times the orbital period (Hippke)

0.00125(360 days) = 38880 seconds

Would not be able to detect an Earth like planet this way

3c. Astrometry

Earth Analog signal:

$\Theta = 3.639 \times 10^{-14}$ Radians

State of the art detection signal:

$\Theta = 100 \mu as = 4.8481368 \times 10^{-10}$ Radians

The Earth analog cannot be detected using Astrometry!

3d. Direct Imaging

Star-planet contrast: f = 8.389 x 10^-5

Gemini currently detects f > 10^-7 (Wallace)

This result doesn't make sense!

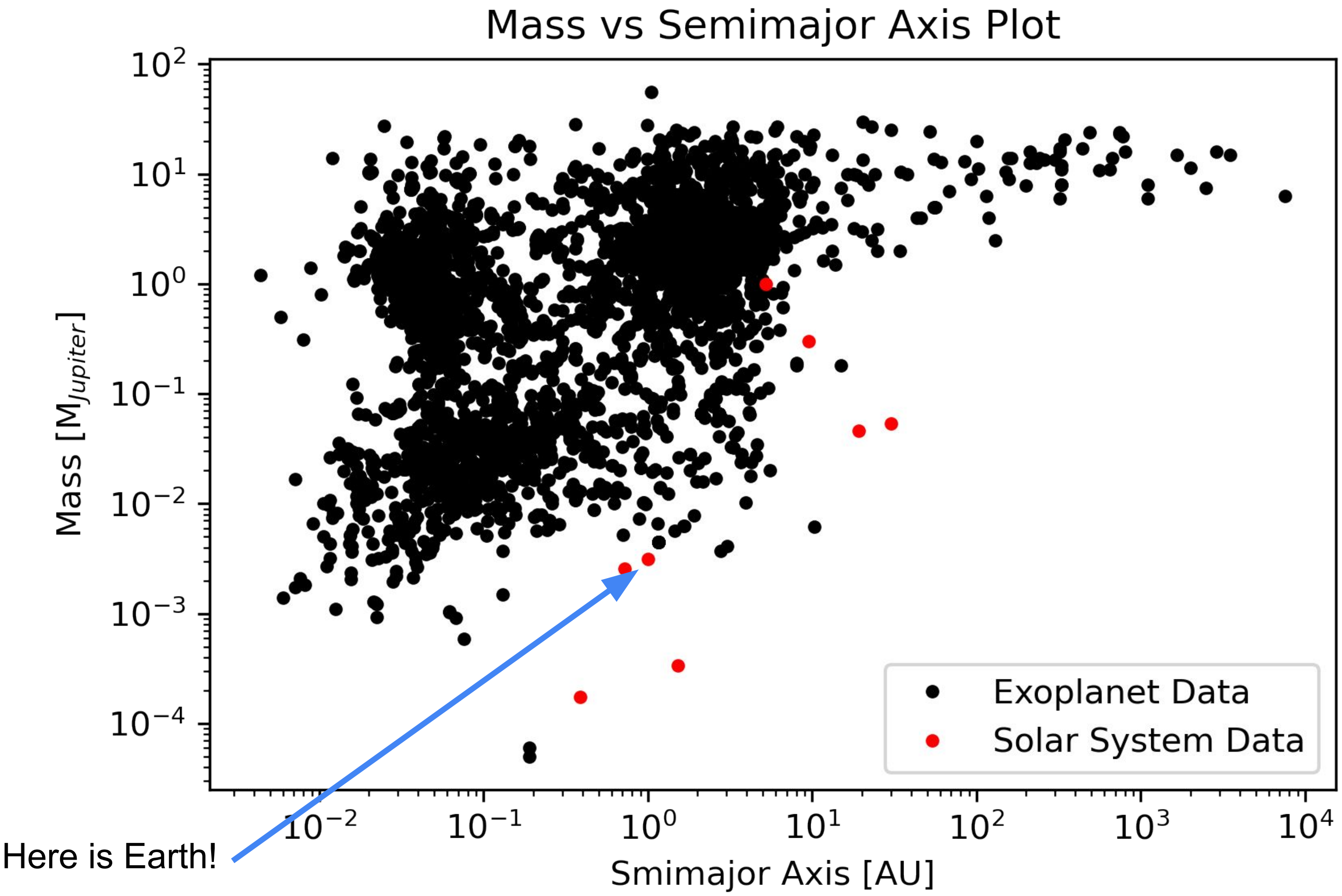
Θ[arcsec]=206265*d/D

Angular diameter:
Here, d=orbital radius of planet ,D=distance to star

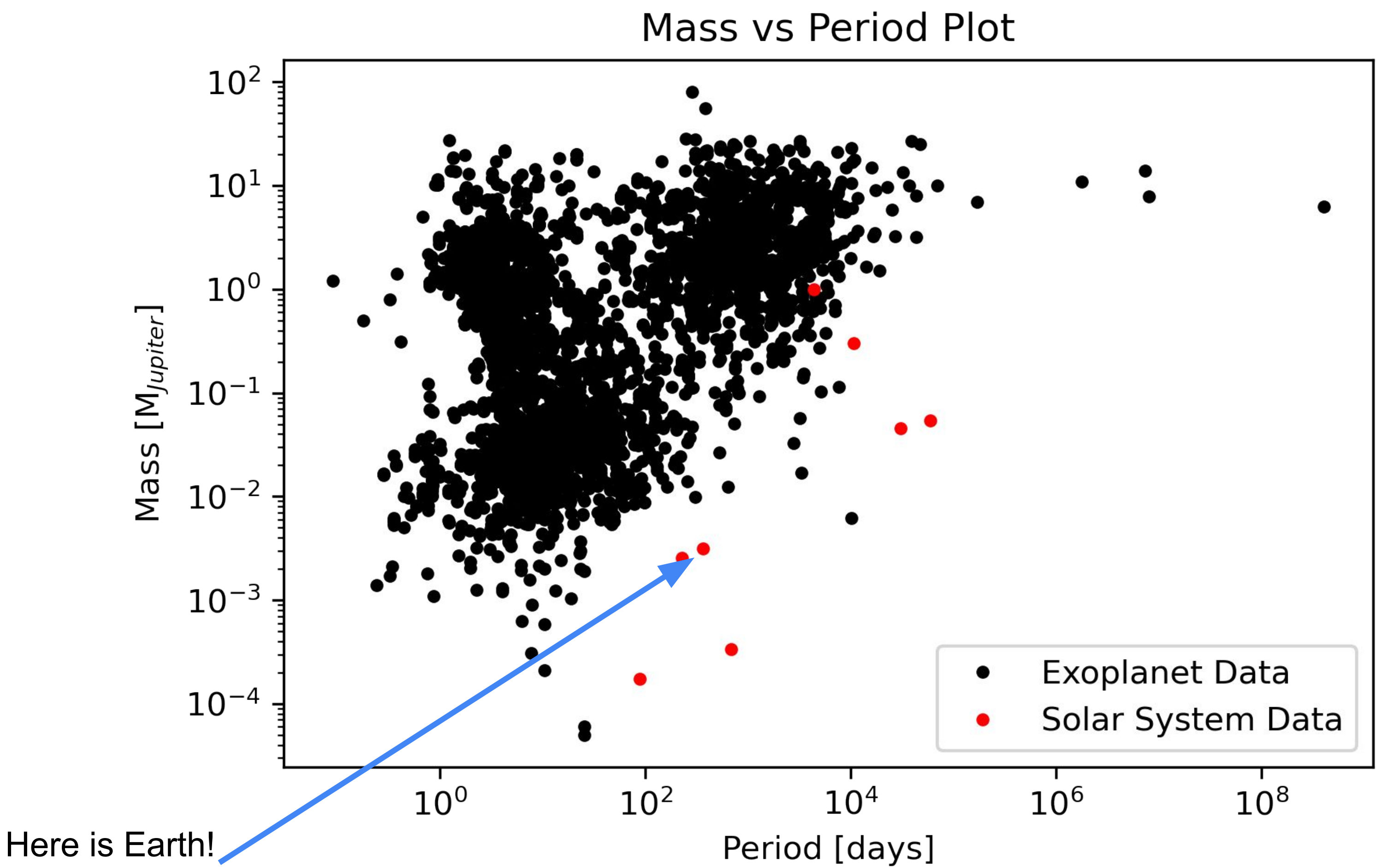
Θ=206265(1/8.251e+7)≅0.17 arcsec

If the planet is only d=1AU from its star and it is being observed from around D=400pc (approximately the average distance to current known planets), its angular resolution is ~0.1 arcsecs (current sensitivity ~0.7arcsec)

The Earth analog could not be resolved by direct imaging!



Mass vs Semimajor Axis Plot
Mass [M_Jupiter]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
Smimajor Axis [AU]
Exoplanet Data
Solar System Data
Here is Earth!



Mass vs Period Plot
Mass [$M_{Jupiter}$]
Period [days]
Exoplanet Data
Solar System Data
Here is Earth!

4. Conclusions

- We do not have the capability to detect Earth like planets around sun like stars with our current methods
- Our current data and demographics for exoplanet populations is affected by this limitation
- The limitations of our technology should be considered when holistically evaluating current confirmed exoplanet populations

Citations

J. Kent Wallace, Rick S. Burruss, Randall D. Bartos, Thang Q. Trinh, Laurent A. Pueyo, Santos F. Fregoso, John R. Angione, J. Chris Shelton, "The Gemini Planet Imager calibration wavefront sensor instrument," Proc. SPIE 7736, Adaptive Optics Systems II, 77365D (15 July 2010); https://doi.org/10.1117/12.858269

[1]Hippke, M. and Heller, R., “Optimized transit detection algorithm to search for periodic transits of small planets”, <i>Astronomy and Astrophysics</i>, vol. 623, 2019. doi:10.1051/0004-6361/201834672.
https://ui.adsabs.harvard.edu/abs/2019A%26A...623A..39H/abstract