Exoplanet Detections: Which Methods Work?

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Motivation

- Exoplanets give us hints about the Universe's structure
- Several exoplanet detection methods exist
- Methods have varying effectiveness under different conditions

General Procedure For Finding State-of-the-Art

1. Determine “signal” equation used for detections
2. Find state-of-the-art (SOA) signal standard
3. Plot scaling relationship on top of modern-day data

Simulated System

- Jupiter-like planet around a Sun-like star
- As close as the closest imaged solar system (11 pc away)
- Characteristics (i.e., semimajor axis) are same as our Jupiter

Radial Velocity Equation

- SOA: K = 0.5 m/s
- *i* = 90 degrees
- Orbiting Sun-like star

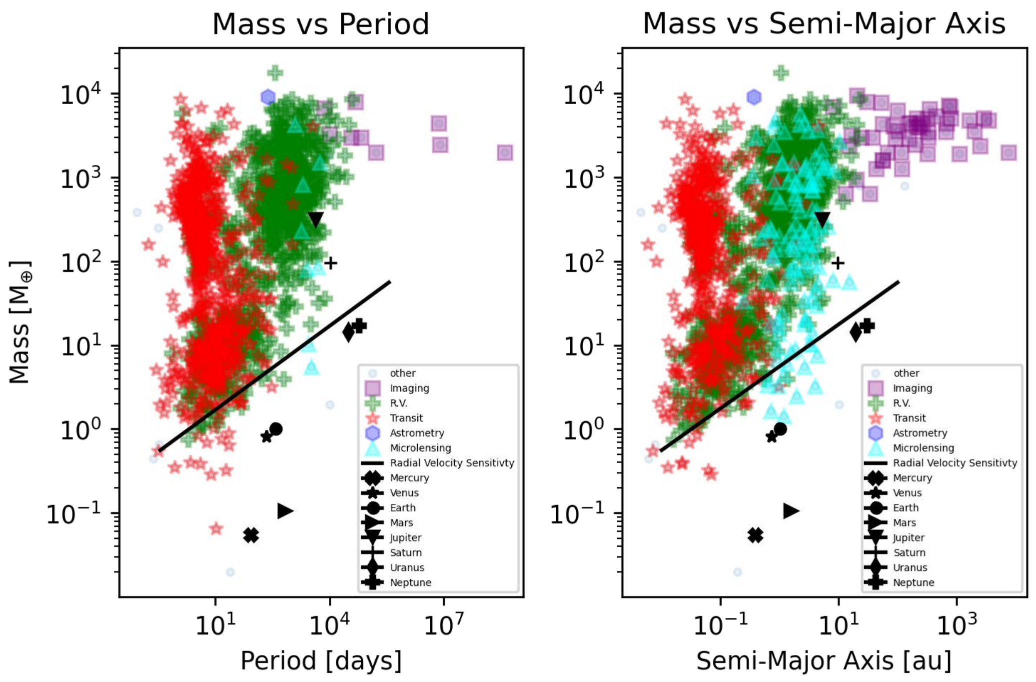
$$K = \left(\frac{M_{\mathrm{exo}}}{M_\star}\right)\sqrt{\frac{GM_\star}{a}}\sin i$$

$$M_{\mathrm{exo}} = 5.59 M_\oplus \left(\frac{a}{1\ \mathrm{AU}}\right)^{1/2}$$

Equations calculated by Lauren

R.V. Limits

- Approximately correct limit on both graphs
- Solar system planets under limit



Graphs made by Tayt + Ethan

Transit Method Equation

- SOA: SNR = 7.1
- 90 day observation period
  - CDPP is 30 ppm
- Orbiting Sun-like star

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{\delta}{\sigma_{\mathrm{CDPP}}}\sqrt{\frac{n_{\mathrm{tr}} \cdot t_{\mathrm{dur}}}{3\ \mathrm{hr}}}.$$

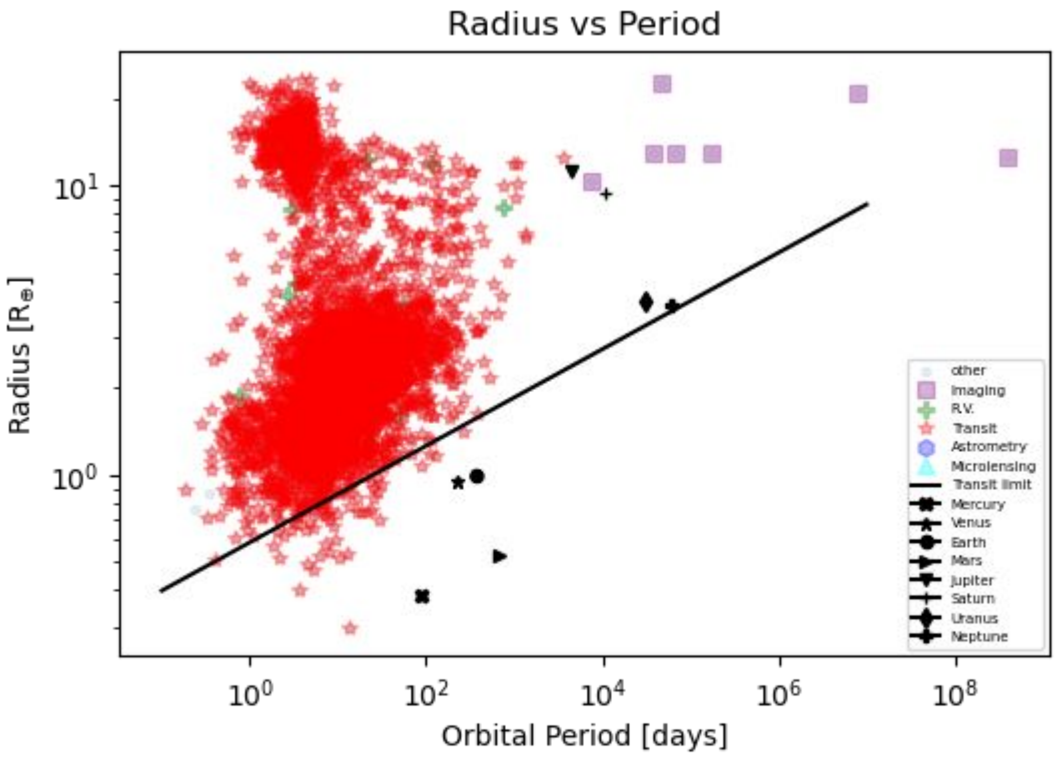
$$\Downarrow$$

$$R_{\mathrm{exo}} = (0.366\ R_{\oplus}) \left(\frac{P}{\mathrm{hr}}\right)^{1/6}$$

Equations calculated by Tayt + Bailey

Transit Limits

- Approximately correct limit
- Solar system planets beneath limit again



Graphs made by Tayt + Ethan

Direct Imaging Limits

- Closest imaged system used for distance
- Observational wavelength of 22.3 micrometers
- SOA: f = 1e-7
- Orbiting Sun-like star

Rayleigh Limit:

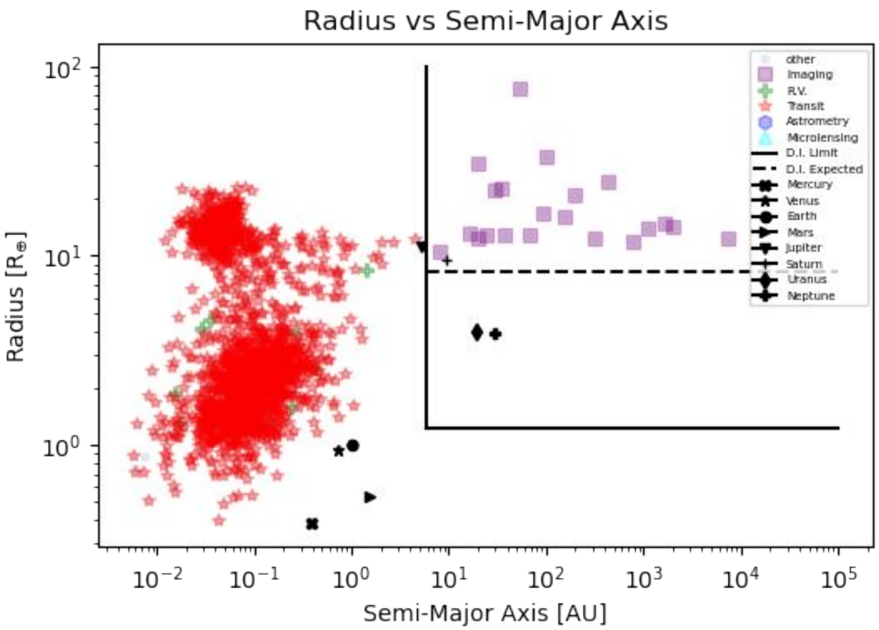
$$\theta \approx 1.22 \frac{\lambda}{D}$$

Star-Planet Contrast:

$$f = \left(\frac{R_{exo}}{R_\star}\right)^2 \cdot \frac{\exp\left[\frac{hc}{\lambda k_B T_\star}\right] - 1}{\exp\left[\frac{hc}{\lambda k_B T_{\mathrm{exo}}}\right] - 1}$$

Direct Imaging Limits

- Exoplanet radius limit calculated appears low
- Dotted line gives expected limit



Graphs made by Tayt + Ethan

Simulated System (Radial Velocity Method)

$$K = \left(\frac{M_{\text{exo}}}{M_\star}\right)\sqrt{\frac{GM_\star}{a}}\sin i$$

- State-of-the-art signal velocity: **0.5 m/s**
- Simulated signal velocity: 7.1 m/s
- Jupiter-like planet can be detected using radial velocity!

Simulations done by Caitlin

Simulated System (Transit Method)

- Probability of transit being aligned correctly is ~0.094%
- State-of-the-art SNR: **7.1**
- Simulated SNR: 163
- Jupiter-like planet might be detected using transit method

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{\delta}{\sigma_{\mathrm{CDPP}}} \sqrt{\frac{n_{\mathrm{tr}} \cdot t_{\mathrm{dur}}}{3\ \mathrm{hr}}}.$$

Simulations done by Caitlin

Simulated System (Direct Imaging Method)

- State-of-the-art star-planet contrast: **1e-7**
- Simulated star-planet contrast: 8.79e-6
- Could be detected! (Sort of...)
- Rayleigh limit is not obeyed for Jupiter analog

$$\theta \approx 1.22\frac{\lambda}{D}$$

$$f = \left(\frac{R_{exo}}{R_\star}\right)^2 \cdot \frac{\exp\left[\frac{hc}{\lambda k_B T_\star}\right] - 1}{\exp\left[\frac{hc}{\lambda k_B T_{\text{exo}}}\right] - 1}$$

Simulations done by Caitlin

Conclusions

- Radial velocity and transit detections perform remarkably well
- Direct imaging limits are incorrect
- Exoplanets have the potential to exist below detection limits

Combined Differential Photometric Precision

- Source: Howard et al., 2012
- “Typical 3 hr… values are 30-300 ppm”
- Equation uses 3 hr time intervals
- 30 ppm maximizes SNR

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{\delta}{\sigma_{\mathrm{CDPP}}} \sqrt{\frac{n_{\mathrm{tr}} \cdot t_{\mathrm{dur}}}{3\ \mathrm{hr}}}.$$

Peak Blackbody Wavelength / Jupiter Temperature

- Source: (Naumov 1965)
- Paper derives peak blackbody emission wavelength as 22.3 micrometers
- Cites a Jupiter temperature of 130 K

Inclination Is 90 Degrees

- Wobble motion perpendicular to viewer
- Most blue/redshift light observed
- Strength of signal greatest

Inclination	Orbital Type	Diagram
0° or 180°	Equatorial	 prograde orbit shown
90°	Polar	
$0° \leq i < 90°$	Direct or prograde (moves in the direction of Earth's rotation)	 ascending node
$90° < i \leq 180°$	Indirect or retrograde (moves against the direction of Earth's rotation)	 ascending node

Rayleigh Limit (Direct Imaging)

- Normal limit gives angular separation, not semimajor axis (a)
- Need to know distance to system to get a
- The closer the system, the more likely Rayleigh Limit is obeyed
- Assume Jupiter is as close as closest imaged exoplanet