Direct imaging mission planning with precursor radial velocity data: process and validation

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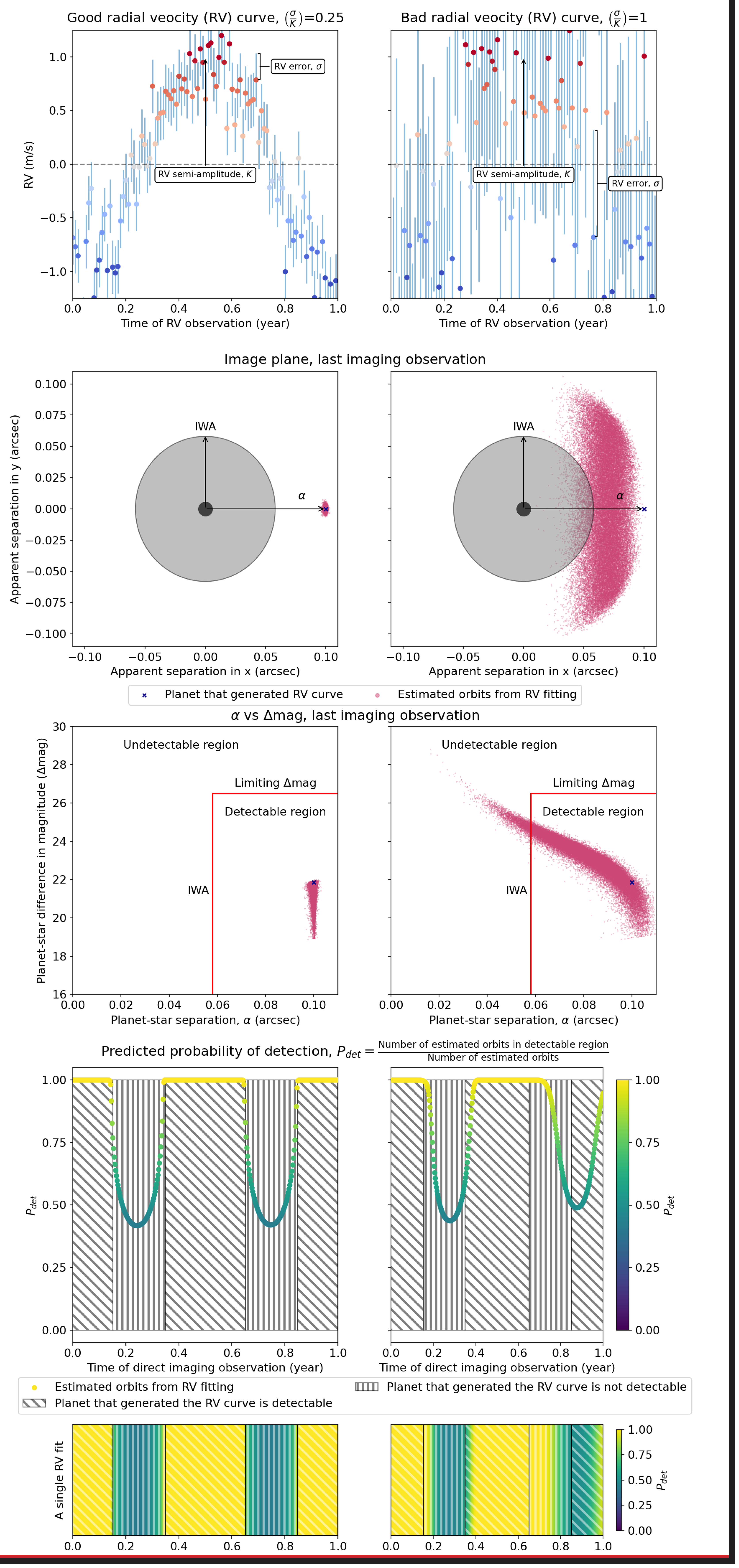
Calculating probability of direct imaging detection



Introduction

The National Academies' Astronomy and Astrophysics 2020 decadal report gave high priority to a space-based flagship telescope that could directly image Earth-like exoplanets. The mission concept studies for such a mission suggested using the radial velocity exoplanet detection technique to inform when observations should be made. This idea shows promise but the exoplanet yield estimates thus far have not simulated the full process of fitting orbital parameters to an RV curve and attempting to make observations based on the fitted parameters. Current yield estimates assume what the final error on an exoplanet's orbital parameters will be, which ignores potential relationships between fitted parameters. Here we show how to calculate the probability of directly imaging an exoplanet detected via radial velocity, explain how that metric can be validated through yield estimates, and demonstrate improvements to tools necessary for the yield calculations.

Using probability of detection for mission planning

- Scheduling direct imaging observations has been done through "completeness"[1][2][3], which represents a target star's probability of having a planet from a specific population of planets without previous information.
- Probability of detection, P_{det}, of an exoplanet uses previous radial velocity data and is a function of the time of observation and integration time. The calculation is shown visually on the left.

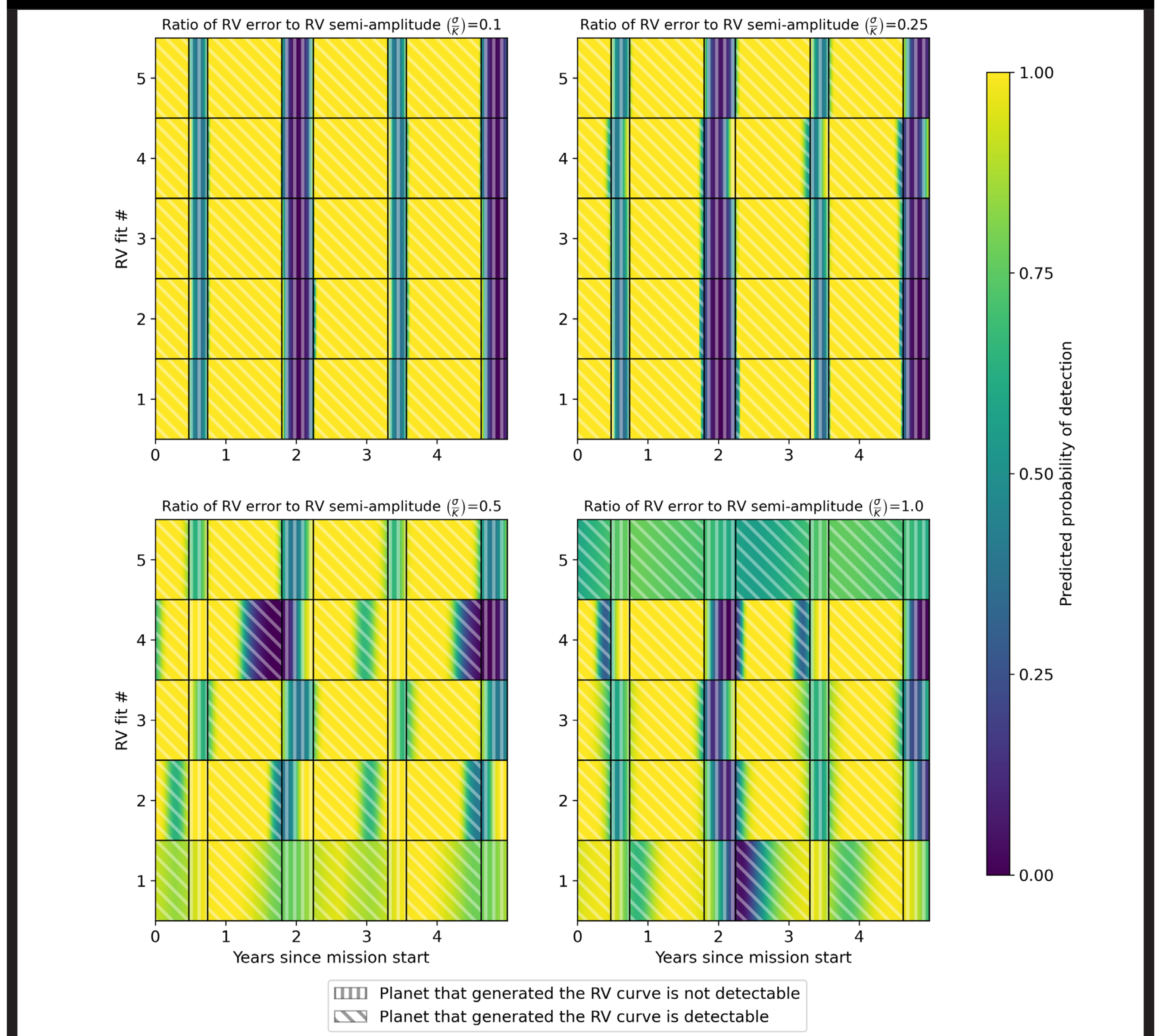
$$P_{\mathrm{det}}(i,t,t_{\mathrm{int}}) = \frac{\#\text{ of estimated orbits for planet } i \text{ where IWA} < \alpha(t) < \text{OWA and } \Delta\mathrm{mag}(t) < \Delta\mathrm{mag}_0(\alpha, t_{\mathrm{int}})}{\#\text{ of estimated orbits for planet } i}$$

- Creating an optimized schedule requires a cost function that incorporates the probability of detection, zodiacal light, target star keepout regions, and slew times.
- We will approach the observation scheduling as an optimization problem where the benefit per observation is

$$B(i,j,k) = \frac{1}{T_k - T_j}\int_{T_j}^{T_k} P_{\mathrm{det}}(i,t,T_k - T_j)dt$$

where i represents a target planet and T_j is the j^{th} time slot.

Predictions degrade as σ/K increases

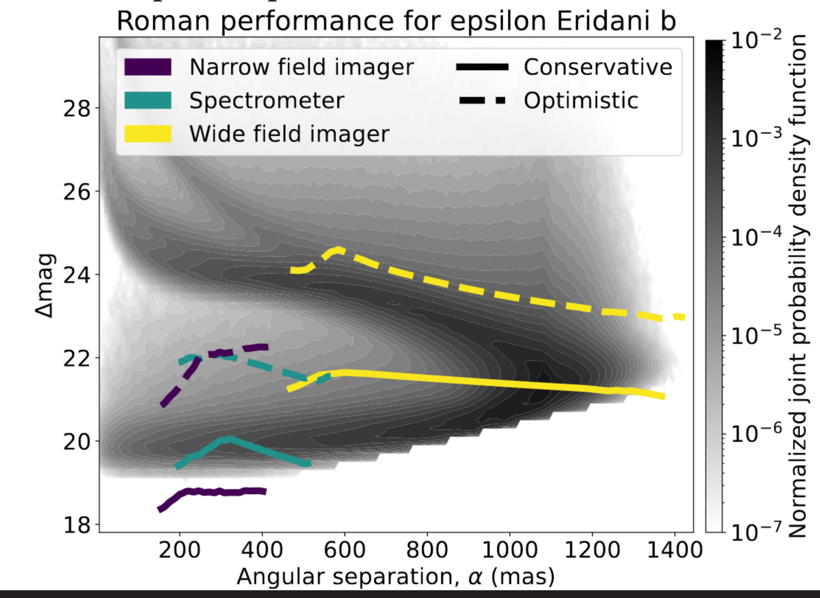


Conclusions

- Probability of detection starts to fail by the time that σ/K=0.5.
- To improve completeness or P_{det} we calculate dimmest detectable Δmag curves as a function of working angle, integration time, and instrument.
- Calculating Δmag from an integration time needs to be done through root finding because the noise term is tied to the Δmag through clock-induced charge.

Improving the limiting Δmag

- In practice the limiting Δmag is a function of separation and integration time, we call the dimmest detectable planet curve. All planets under the curves are therefore detectable.
- We have created routines that calculate the dimmest detectable planet curve for a given instrument. Below is an example that deomstrates the Nancy Grace Roman Space Telescope's ability to observe the exoplanet eps Eri b for various detection scenarios [4].

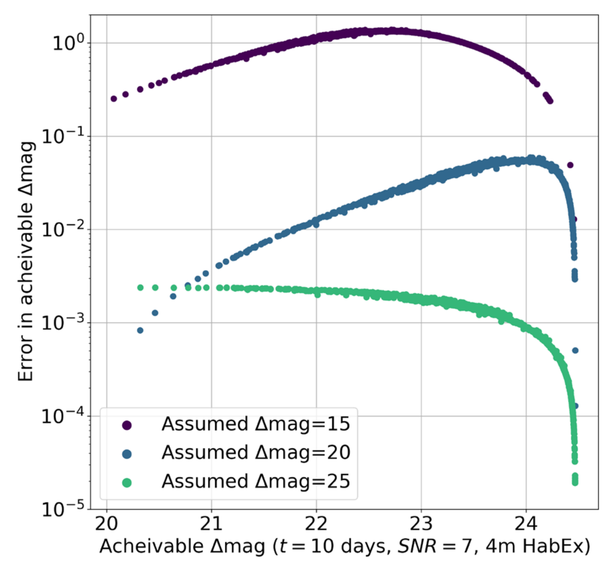


Δmag from integration time

- The equation to calculate the integration time necessary to acheieve a desired SNR is shown below [5].

$$t = \frac{SNR^2 \cdot r_{noise}}{r_{pl}^2 - SNR^2 \cdot n_{spec}}$$

- This can also be inverted to calculate the Δmag of a target planet-star system through the terms of r_{pl}.
- However, r_{noise} is a function of Δmag due to clock induced charge.



- The plot above shows that there are large errors in cases where the planet is bright, Δmag=15, but not for dim planets, i.e. Δmag=25.
- To solve the problem in the plot above, root finding is used to ensure the acheivable Δmag matches the integration time.

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