Optimization of Automated Planet Finder Observing Strategy

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Abstract

We evaluate radial velocity observing strategies to be considered for future planet-hunting surveys with the Automated Planet Finder, a new 2.4-m telescope at Lick Observatory. Observing strategies can be optimized to mitigate stellar noise, which can mask and imitate the weak Doppler signals of low-mass planets. We estimate and compare sensitivities of 5 different observing strategies to planets around G2-M2 dwarfs, constructing RV noise models for each stellar spectral type, accounting for acoustic, granulation, and magnetic activity modes. The strategies differ in exposure time, nightly and monthly cadence, and number of years. Synthetic RV time-series are produced by injecting a planet signal onto the stellar noise, sampled according to each observing strategy. For each star and each observing strategy, thousands of planet injection recovery trials are conducted to determine the detection efficiency as a function of orbital period, minimum mass, and eccentricity. We find that 4-year observing strategies of 10 nights per month are sensitive to planets ~25-40% lower in mass than the corresponding 1 year strategies of 30 nights per month. Three 5-minute exposures per night provide a 10% gain in sensitivity over the corresponding single 15-minute exposure strategies. All strategies are sensitive to planets of lowest mass around the modeled K7 dwarf. This study indicates that APF surveys adopting the 4-year strategies should detect Earth-mass planets on < 10-day orbits around quiet late-K dwarfs as well as > 1.6 Earth-mass planets in their habitable zones.

The Automated Planet Finder (APF)

- 2.4-m robotically controlled telescope operating at Lick observatory
- Currently being commissioned
- Half of observing time dedicated to Geoff Marcy & Andrew Howard
- Levy Spectrometer presently installed: ~1 m/s RV precision expected

- Detection of low-mass planets is limited by stellar noise
- Must optimize observing strategy to mitigate modes of stellar noise and make best use of wealth of observing time

OBJECTIVE OF THIS STUDY:
Estimate APF planet detection sensitivity as function of observing strategy. Test stars of different spectral types, each with a unique RV noise model.

Methods

Stellar Noise Models

- Created for main sequence stars of 5 spectral types G2-M2

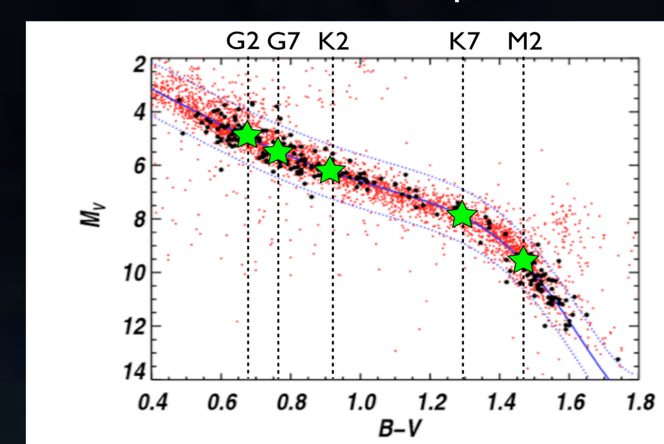


Figure 1: Location on HR diagram of the 5 stars for which RV noise models were created (green).

Granulation Phenomena & p-mode Oscillations

- Modeled by correlating velocity power spectra fitting parameters (Dumusque et al. 2011) with log(g) and converting to RV time series.

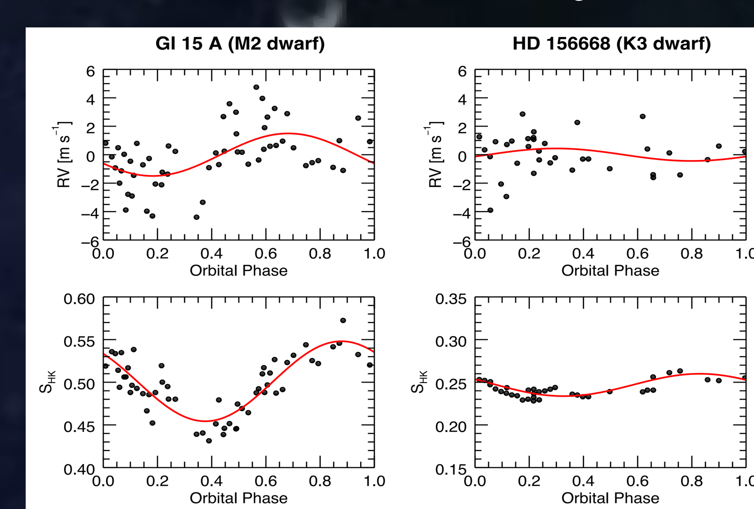


Figure 2: *Top*: RV time-series (black dots) corresponding to a ~250-day window of Eta-Earth Survey observations of M2 dwarf Gl 15 A (left) and K3 dwarf HD 156668 (right), phase folded at the known stellar rotation periods. Signals of known planets have been removed. The best Keplerian fit (red line) for Gl 15 A has semi-amplitude 1.5 m s−1, which is adopted as the magnetic activity noise level for the M2 dwarf model. The best Keplerian fit for HD 156668 is poor and has semi-amplitude 0.5 m s−1, which is adopted as an upper limit on the magnetic activity noise level for the K dwarf models. *Bottom*: Stellar magnetic activity (S_{HK}) measurements simultaneous with RV measurements (top). The S_{HK} variation for the K3 dwarf is weak relative to that of the M2 dwarf (bottom left).

Magnetic activity

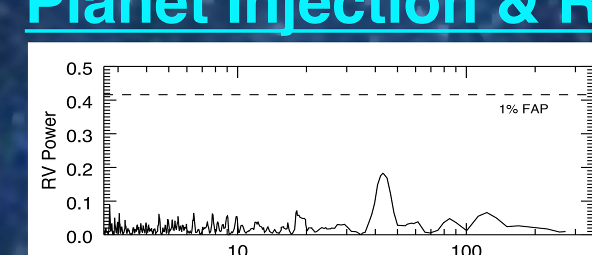
- Modeled as superposition of 3 sinusoids, P = 1, 1/2, 1/3 times stellar rotation period (these modes are known to dominate). Amplitudes derived from observations (See Fig. 2)
- Quasi-coherent

Simulated Observing Strategies

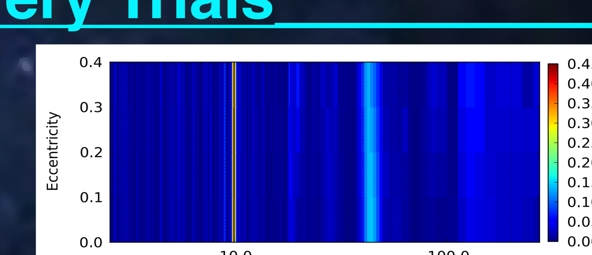
Strategy[a]	Telescope	Exp/Night[b]	$t_{exp}[min]$	Nights/Mon	Mon/Yr[c]	Years	Nights Lost[d]
1N1	APF	1	15	30	8	1	30%
3N1	APF	3	5	30	8	1	30%
1N4	APF	1	15	10	8	4	30%
3N4	APF	3	5	10	8	4	30%
EE	Keck	1	varies[e]	1.25[f]	8	5	30%

[a] APF observing strategies are named using format "nNy" corresponding to n exposures per night for y years. $EE = Eta\text{-}Earth$
[b] Same-night exposures are spaced 2 hours apart
[c] Repeating cycle of 8 months of observing followed by 4 months off
[d] Due to weather and/or technical problems
[e] Expose until ~ 250k counts achieved (a few seconds for the brightest stars)
[f] 10 exposures randomly spaced over 8 months of the year

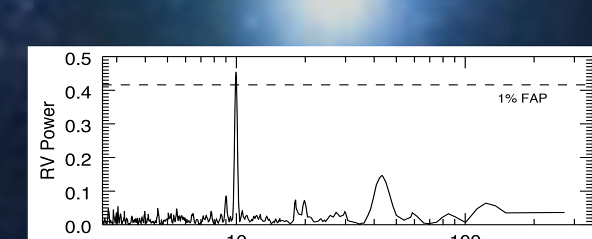
Planet Injection & Recovery Trials



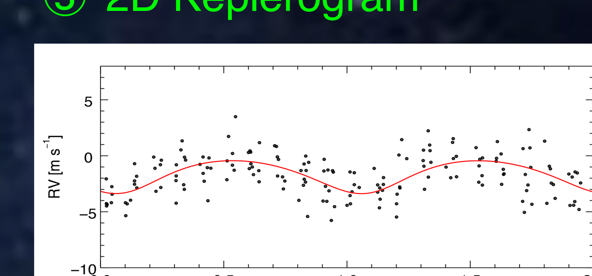
① Noise-only periodogram



③ 2D Keplerogram



② Planet injection



④ Keplerian fit

- Thousands of injection recovery trials carried out over range of planet parameter space
- Repeated for each stellar model and each observing strategy

Results

Detection Sensitivity

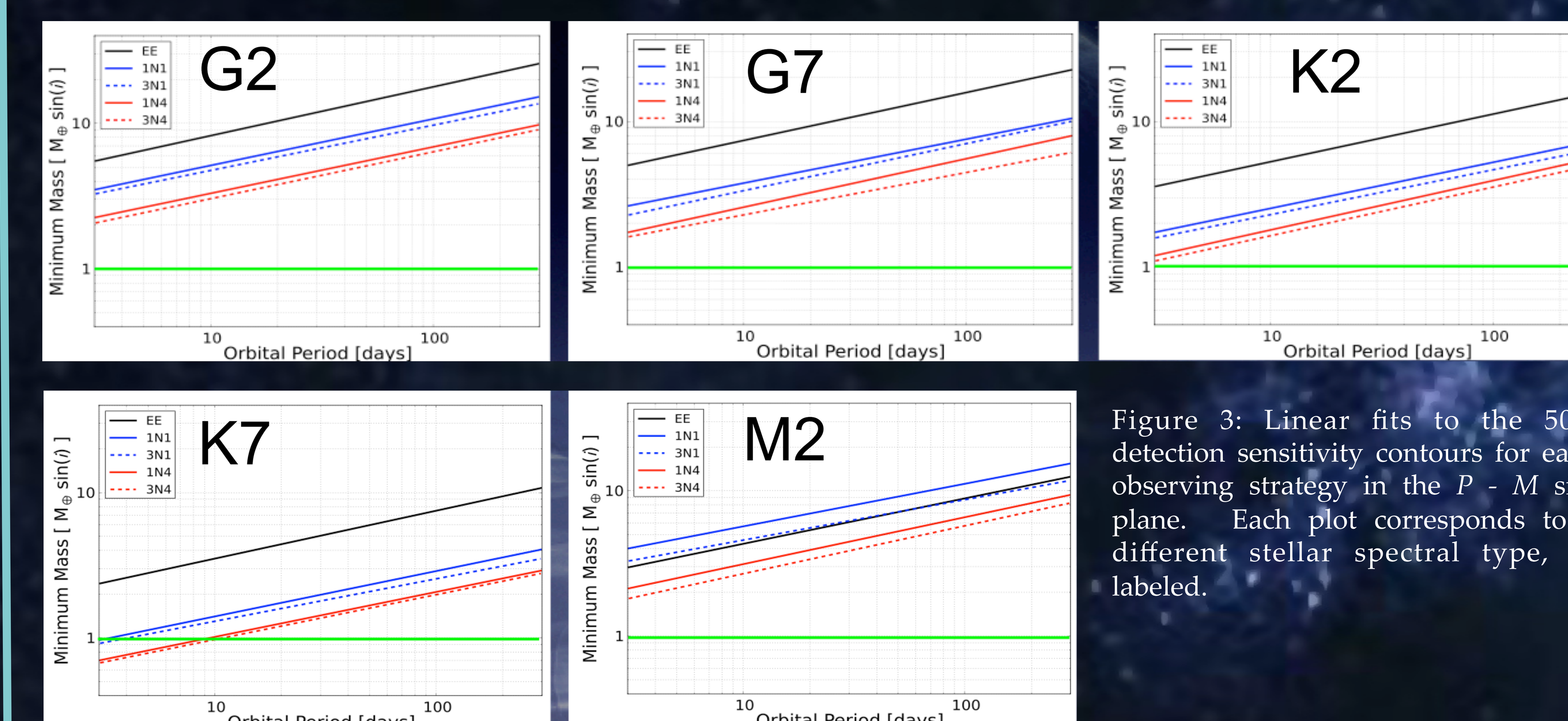


Figure 3: Linear fits to the 50% detection sensitivity contours for each observing strategy in the *P* - *M* sin*i* plane. Each plot corresponds to a different stellar spectral type, as labeled.

Sensitivity of Best (3N4) Strategy

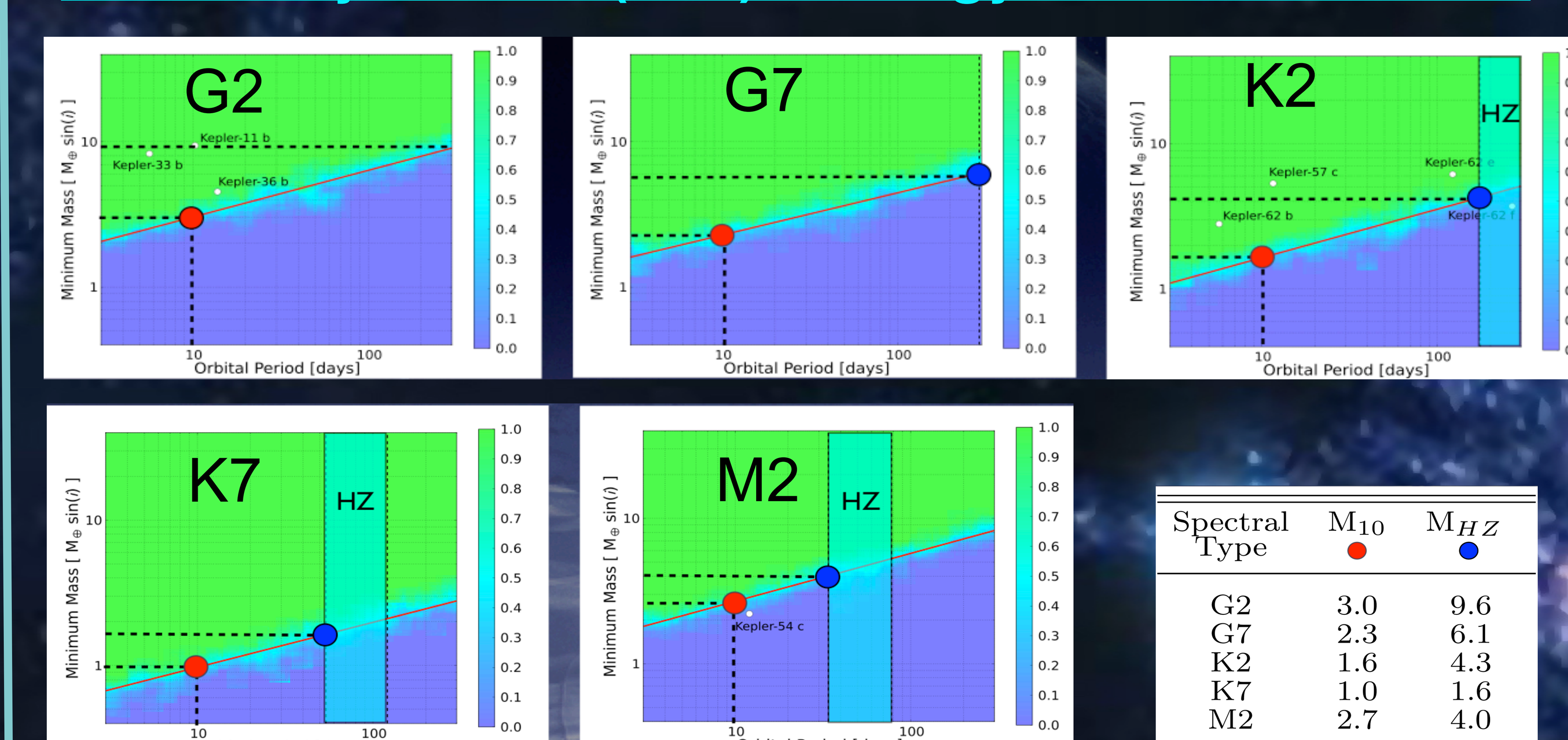


Figure 4: Planet detection sensitivity in the *P* - *M* sin*i* plane derived from 5000 planet injection-recovery trials using the 3N4 strategy, with each plot corresponding to a different stellar spectral type, as labeled. The red lines indicate fits to the 50% sensitivity contours. Known planets detected by Kepler are indicated by white dots. Kepler planet masses are computed using a mass-radius scaling relation from Valencia et al. (2007). Cyan-shaded boxes indicate stellar habitable zones (where ≤ 300 days). Habitable zone boundaries are calculated according to the work of Kopparapu et al. (2013).

Spectral Type	M_{10}	M_{HZ}
G2	3.0	9.6
G7	2.3	6.1
K2	1.6	4.3
K7	1.0	1.6
M2	2.7	4.0

Table: Minimum planet mass detectable at an orbital period of 10 days (M_{10}) and at the inner edge of the stellar habitable zone (M_{HZ}) for each stellar spectral type.

- Sensitivity ultimately limited by stellar magnetic activity at rotation period
- Multi-year time baseline needed to leverage long-term incoherence of magnetic activity
- 4-year strategies of 10 nights/month sensitive to planets ~25-40% lower in mass than corresponding 1 year strategies of 30 nights/month
- 5-min exposures sufficient to mitigate p-modes (minutes-long timescales)
- 3 x 5-min nightly exposures better mitigate granulation modes (hours-long timescales) compared to a single 15-min nightly exposure, improving sensitivity by ~10% (marginal gain possibly negated by increased overhead)
- 3N4 strategy with APF should be 2-3 x more sensitive than current Eta-Earth survey at Keck and sensitive to HZ planets as small as 1.6 Earth-masses

We now have a useful toolkit to guide future APF observations!

References

- Dumusque, X., et al. 2011, A&A , 525, 140
- Kopparapu, R. K. et al. 2013 ApJ , 765, 131