Exoplanet Probe to Medium Scale Direct Imaging Mission Requirements and Characteristics - (SAG9) Final report

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Complete SAG9 group (~40 members, open membership to the community)
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SAG9 Initial Charter

- The ExoPAG Study Analysis Group 9 (SAG-9) will define metrics by which the science yield of various exoplanet probe-scale to medium-scale direct-imaging mission designs can be compared and evaluated in order to facilitate a well-informed decision process by NASA.
- SAG-9 will focus on mission sizes that can be considered on shorter timescales than a flagship, with a particular emphasis on missions with probe-scale costs (under $1B). The work will build on the methodology developed by SAG-5 (Exoplanet Flagship Requirements and Characteristics), defining science goals, objectives and requirements, further detailed into "Musts" and "Discriminators".
- SAG-9 will establish the minimum science thresholds ("Musts") for such missions, and develop quantitative metrics to evaluate the marginal performance increase beyond the threshold science using "Discriminators".
- Key questions to be studied by this group include:
  - What is the minimum threshold science to justify an exoplanet probe-scale direct imaging mission?
  - What are the additional science goals that can be used as "discriminators" to evaluate science performance beyond the minimum thresholds?
  - What are the possible achievements from the ground by plausible launch date, and overlapping the expected mission lifetime?
  - What quantitative metrics for these "discriminators" can we provide to help define the weighting process to be used in the comparison of mission concepts?

SAG-9 re-focused goals

- SAG9 refocused its goals to avoid duplication with the AFTA-SDT and the two STDTs (Exo-C/Exo-S) commissioned just after SAG9 started:
  - Complementarity of direct imaging with other techniques and missions
  - Design Reference Missions (DRMs)

- Highlight of results and contributions from SAG9:
  - DRM studies:
    - *Performance vs. mission scale for probe/super-probe/medium missions*
    - *Sensitivity analysis of AFTA performance on known RV planets for IWA, Resolution, throughput*
  - Cross-validation of exposure time calculations between different groups
  - Defining goals for precursor RV surveys for imaging missions
    - *precursor discussions to in-depth funded study (Howard & Fulton, 2014)*
    - *precursor discussions to the new precision RV instrument for WIYN telescope*

Future direct imaging missions/ground instruments

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
8m Class	VLT + SPHERE	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	Gemini + GPI	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	LBT/AO	Young + Older Super-jupiters: detection + photometry (1–5 μm)															
	Subaru/ScExAO	Super-jupiters: detection + photometry (1–2 μm)															
30m Class	GMT/ExAO?														No approved concept; Super-earths?		
	TMT/ExAO?														No approved concept; Super-earths?		
	EELT/EPIC												HZ low-mass planets, few Earth analogs, old GPs in reflected light (1–1.7 μm)				
	EELT/METIS												MIR imaging spectroscopy of disks and planets (3–10 μm)				
Space	HST	Photometry of exceptionally bright super-jupiters (1–1.7 μm)															
	JWST				Young GPs + Few Older Jovian planets (2 M_J at 4pc): detection + LR/MR spectroscopy. Disk Imaging + MR spectroscopy; IWA 0.5" 10^{-5} (1–5 μm)												
	WFIRST-2.4m Coron?									Jupiter analogs and disks, RV planets, Imaging+Spectra, 10^{-9} IWA 0.1" (0.3–1 μm);							
	Probe-class Off-Axis Mission?									Jupiter analogs; Disks and some RV planets, Imaging+LR Spectra, 10^{-9}–10^{-10} IWA 0.1"–0.3" (0.3–1 μm)							

Credit: D. Apai

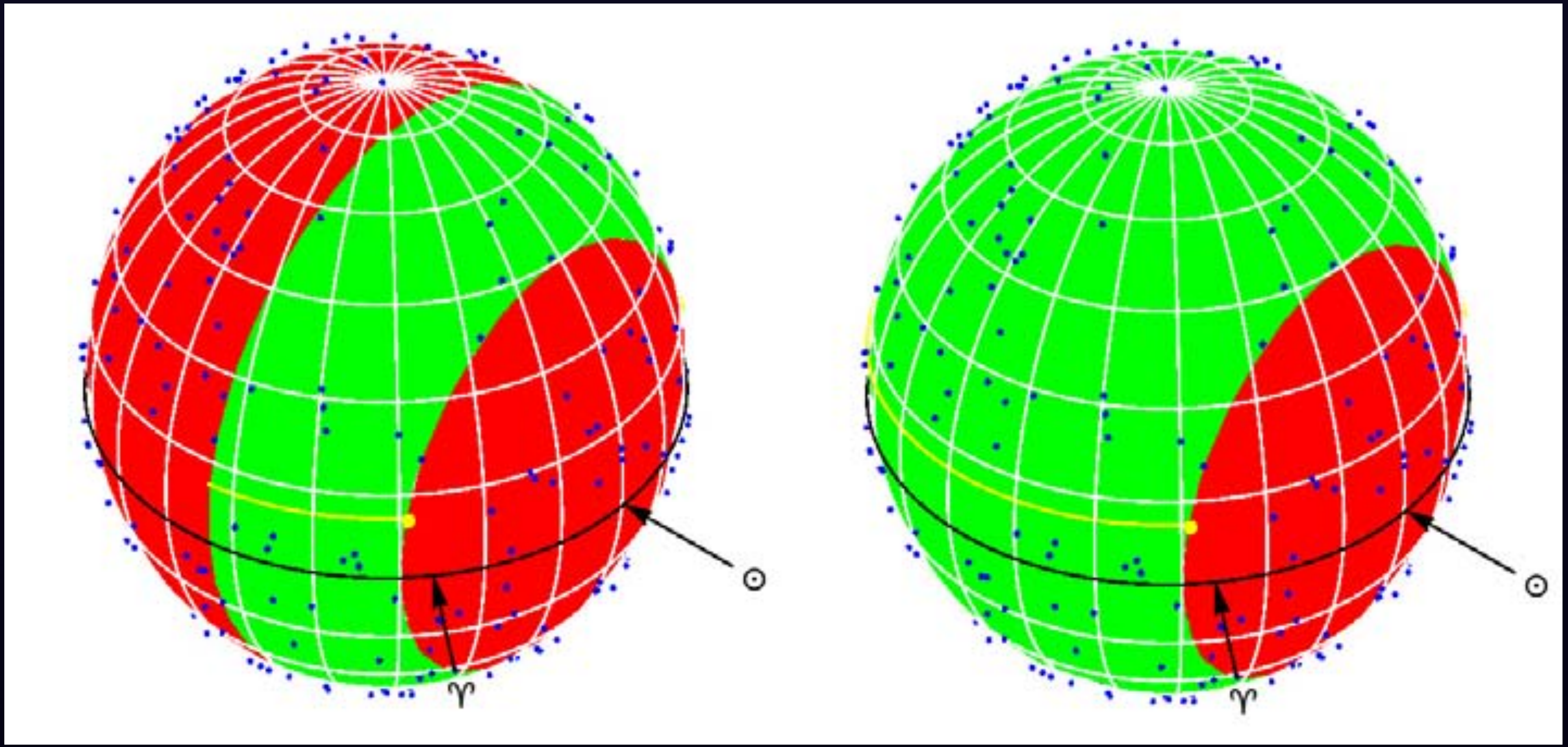
Design reference missions (DRMs)

- DRM Science Metric: number of RV planets characterized
  - Merit function is the information rate, i.e. completeness per unit time
  - About 30 parameters included in the merit function:
    - *IWA, Resolution, detector parameters, telescope diameter, sharpness, albedo, radius of planet, etc.*
    - *At each step in the DRM the merit function is calculated with remaining planets in play. Next target scheduled has the highest merit function*
- Several DRMs Developed for SAG-9 by R. Brown
  - Sensitivity with mission scale: probe/large probe/AFTA
  - Sensitivity for AFTA with different parameters (IWA, throughput, resolution), mass estimation
    - *R. Brown, 2015, ApJ "True Masses of Radial-Velocity Exoplanets"*

Credit: Bob Brown

Sensitivity to scale (probe/medium) and design Coronagraph/Starshade

- Criterion #1: Permitted pointing (observing window)
- Criterion #2: systematic limits (contrast and IWA)
- Criterion #3: wavelength range for spectral characterization
- Criterion #4: observing time fits in observing window



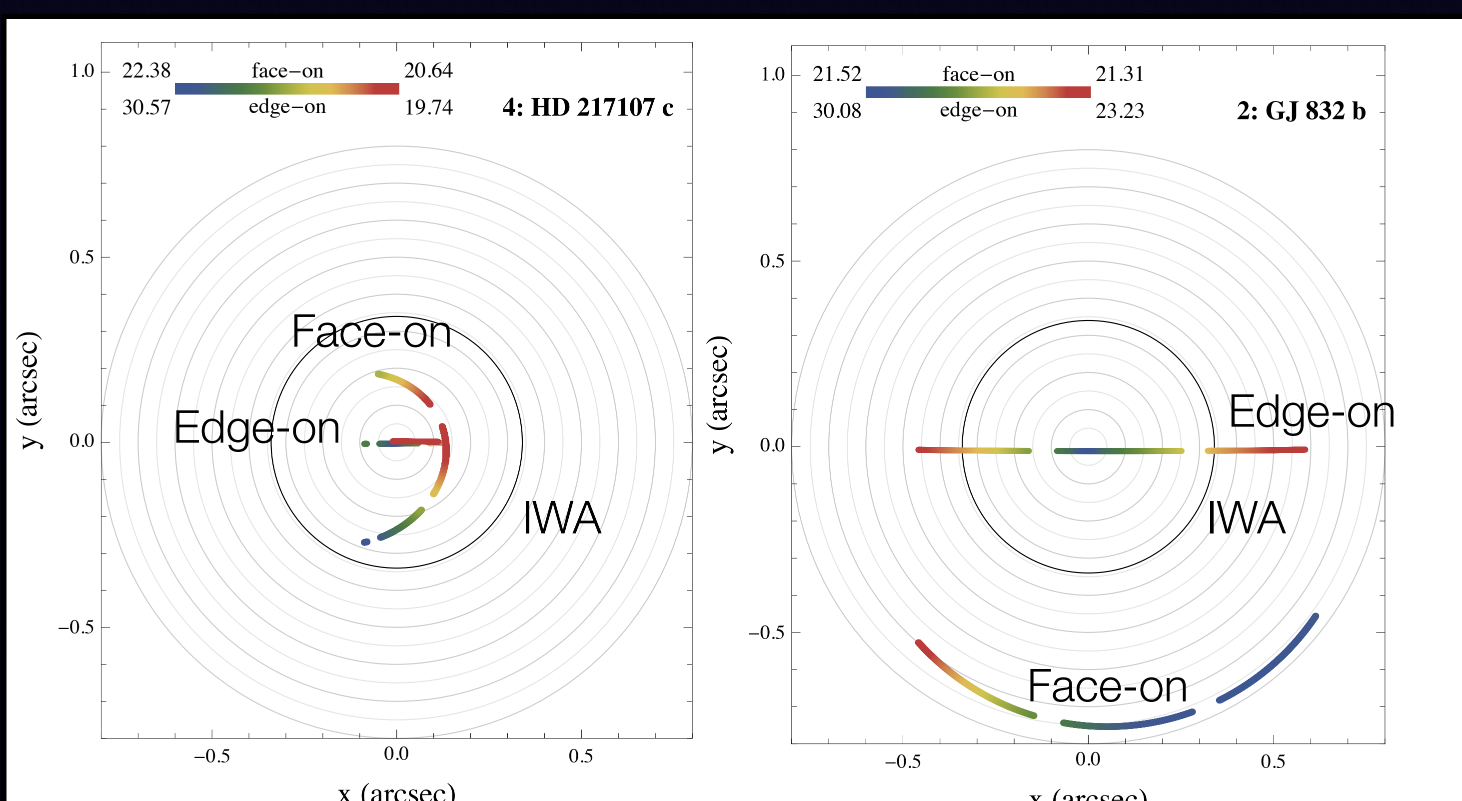
Field of regard at a given time (green: permitted pointings)
Starshade probe coronagraph probe

Credit: Bob Brown

Detectability of RV planets with imaging

- Detectability and maximum orbital separation a(1+e)/d > IWA
  - Acceptable proxi for target pre-selection but incomplete because unknown inclination and limited mission lifetime compared to orbital period
  - This underlines importance of actual DRM calculations for target selection

	RV exoplanet	d (pc)	m_s ($m_\odot$)	$m_p \sin i$ ($m_♃$)	a (au)	ϵ	ω_p	period (days)	periapsis (JD −2450000)	$a(1+\epsilon)/d$ (arcsec)
1	epsilon Eri b	3.22	0.82	1.05	3.38	0.25	186.00	2500.	−1060.00	1.31
2	GJ 832 b	4.95	0.45	0.64	3.40	0.12	124.00	3416.	1211.00	0.77
3	55 Cnc d	12.34	0.91	3.54	5.47	0.02	74.00	4909.	3490.00	0.45
4	HD 217107 c	19.86	1.11	2.62	5.33	0.52	18.60	4270.	1106.32	0.41
5	mu Ara c	15.51	1.15	1.89	5.34	0.10	237.60	4206.	2955.20	0.38



- Example where 5 planets satisfy the max separation criterion
- HD127107c never comes out of IWA during the 3 year mission
- GJ832b comes out of IWA but too faint and ruled out for time constraints

Credit: Bob Brown

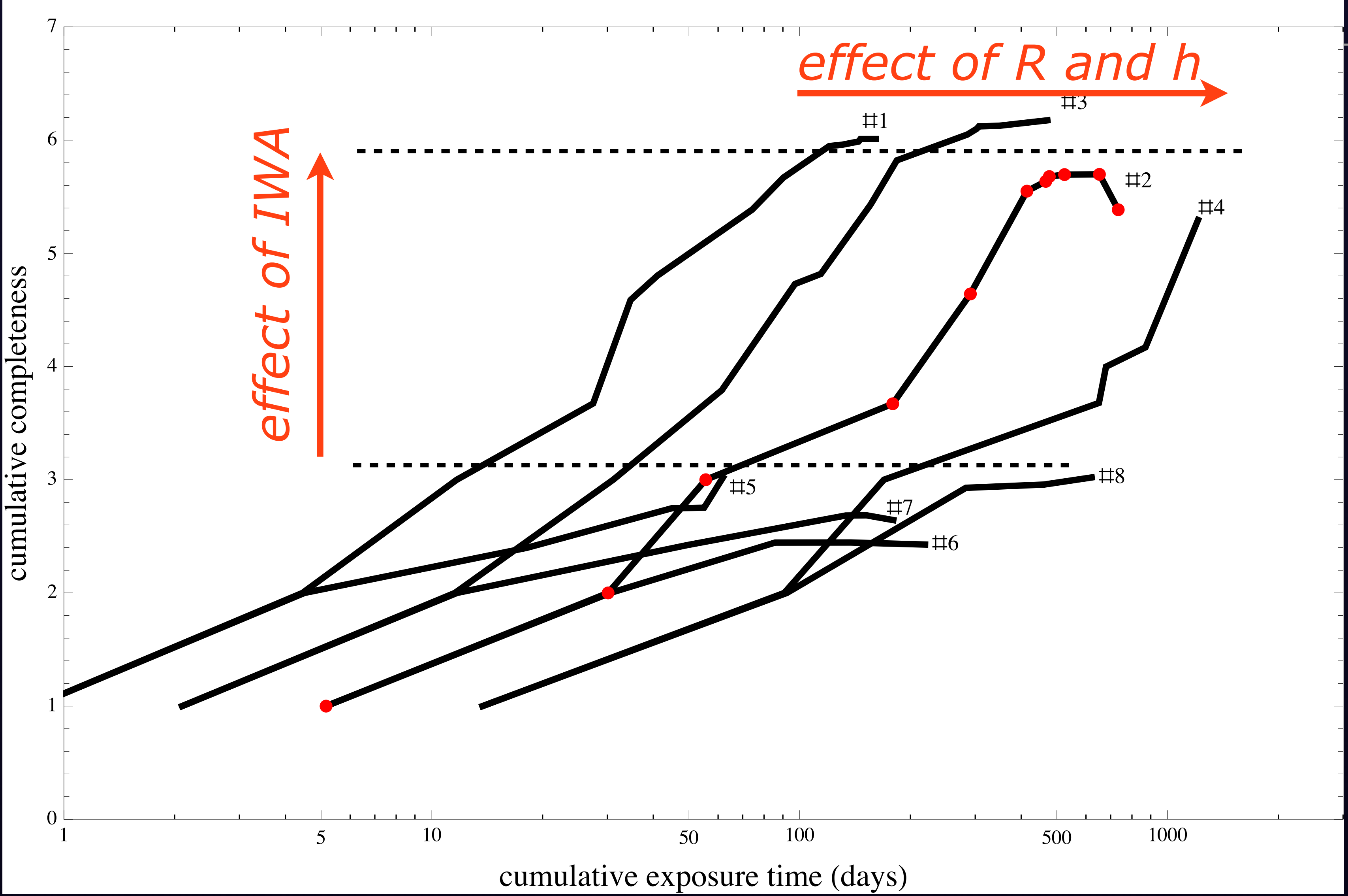
AFTA sensitivity to IWA, R, throughput

- Science metric (i.e. expected number of currently known RV planets characterized) for different efficiency (h) and resolution (R) and IWA
  - Result averaged from 100 DRMs computed for each combination of parameters (IWA, throughput, resolution)

IWA	0.200"				0.274"			
h	0.05		0.3		0.05		0.3	
R	20	50	20	50	20	50	20	50
50 d	2.50	1.00	4.78	3.64	2.00	1.00	2.74	2.42
100 d	3.63	2.00	6.00	4.84	2.45	2.00	2.74	2.71
200 d	4.75	3.00	6.04	5.73	2.45	2.49	2.74	2.71
400 d	5.48	3.76	6.04	6.18	2.62	2.49	2.74	2.71

Credit: Bob Brown

AFTA sensitivity to IWA, R, throughput



- All these DRMs run out of RV planets, not time (except case #4: IWA= 3λ/D, *R*=50, throughput *h*=5%)
- main effect of *h* or *R* is to move the DRM to the right, i.e. increase all exposure times (factor 10 total time increase)
- IWA has a factor of two impact on this DRM

case number	IWA (arcsec)	h (efficiency)	R (resolution)	Comment
1	0.200	0.3	20	original, 3λ/D
2	0.200	0.05	20	...low h
3	0.200	0.3	50	...high R
4	0.200	0.05	50	...low h, high R
5	0.274	0.3	20	new, 4λ/D
6	0.274	0.05	20	...low h
7	0.274	0.3	50	...high R
8	0.274	0.05	50	...low h, high R

Credit: Bob Brown

Target list for these DRMs comparions

- ~15 already known RV planets (mid-2014) pre-selected with maximum separation proxi, i.e. a(1+e)/d<IWA
  - Few more ~20 targets if a little less strict (0.19 arcsec)

	mag	*d*	*a*	*T*	ϵ	ω	T_0	$a(1+\epsilon)/d$
epsilon Eri b*	2.78	3.22	3.38	2500.	0.25	6.	1940.	1.312
47 UMa c*	4.34	14.06	3.57	2391.	0.10	295.	5441.	0.279
mu Ara c*	4.35	15.51	5.34	4206.	0.10	58.	5955.	0.378
55 Cnc d*	5.03	12.34	5.47	4909.	0.02	254.	6490.	0.452
upsilon And d	3.51	13.49	2.52	1278.	0.27	270.	6938.	0.237
14 Her b	5.68	17.57	2.93	1773.	0.37	23.	4373.	0.229
HD 154345 b	5.96	18.59	4.21	3342.	0.04	68.	5831.	0.237
HD 39091 b*	4.98	18.32	3.35	2151.	0.64	330.	820.	0.300
HD 190360 b*	4.91	15.86	3.97	2915.	0.31	13.	6542.	0.329
HD 87883 b*	6.57	18.21	3.58	2754.	0.53	291.	4139.	0.301
GJ 832 b*	6.43	4.95	3.40	3416.	0.12	304.	4211.	0.769
HD 217107 c*	5.35	19.86	5.33	4270.	0.52	199.	4106.	0.408
HD 134987 c	5.71	26.21	5.83	5000.	0.12	195.	4100.	0.249
GJ 849 b	8.19	9.10	2.35	1882.	0.04	355.	4488.	0.269
GJ 179 b	9.40	12.29	2.41	2288.	0.21	153.	8140.	0.238

Credit: Bob Brown

RV completeness for nearby stars

- RV census of nearby Sun-like stars is fairly complete for giant planets in <5.5 year orbit
- Out of the 54 stars within 5pc
  - 9/54 = 17% have at least one planet
  - 7/36 = 19% of F5-M5 stars have at least one planet
  - 6/36 = 17% of F5-M5 stars have at least one giant planet
  - 5/36 = 14% of F5-M5 stars have at least one giant planet in a <5.5 yr orbit
- Consistent with Cummings et al. (2008)
  - 10.5% of Sun-like stars (F5-M5, but mostly G and K) host a giant planet with <5.5 yr orbit
  - 17-20% have a giant planet within 20 AU

- RV surveys for nearby M stars is quite incomplete (too faint for direct imaging with small telescope in any case)

Credit: Nick Cowan / Andrew Howard

RV support for direct imaging

- What can RV do now in preparation of future DI mission?
- Process established by SAG-9 to define such surveys:
  - Define the science goals for a RV survey in support of a future DI mission
  - Define/refine a direct imaging target list for RV surveys (starting with ExoCAT catalog by Turnbull/Traub/ExEP)
  - Coordinate with RV teams to determine survey parameters:
    - *Cadence, precision and time baseline*
    - *Existing overlap with existing RV surveys (bright/known stars)*
    - *Determine and scope resources (telescope time, work) needed to complete such RV surveys for future DI mission*
  - Determine if additional resources are needed for RV surveys and investigate path forward for funding.
    - *Howard & Fulton study (2014)*
    - *High-precision RV instrument on WIYN telescope announced by NASA*
    - *Brown 2015 shows that mass estimation is limited by RV precision and systematics*

Science cases for precursor RV survey

- Masses estimates for Giant Planets at >0.1-0.2 arcsec
- Masses estimates for some sub-Neptunes (~10MEarth)
- Mass upper limits for other planets
- Identify RV trends at and beyond HZ separation
- In-depth study of special-interest target stars
  - Most interesting targets are brightest stars brighter than mag ~7-8, since giant planet typically mag<30
  - Planets with separation <~5AU most interesting (i.e. <~1e9 contrast)
  - IWA in 0.1-0.2 arcsec depending on starshade or internal coronagraph type, stars within 50pc
  - Kepler: hot-jupiter tend to be lonely, then is it worth continuing to monitor them?
  - 4000 stars within 20pc, 85% M dwarfs, not good targets for probes (ELTs, ATLAST)
  - Role of Gaia, but bright limit (improved recently) and precision

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- In-depth study of special-interest target stars
  - Kepler shown they are frequent in Kepler field, so assume here they are also frequent around nearby stars
  - Hard to do for probe/medium size - focus on sep<2-3AU, nearby (10-20pc) earlier types for more photons
  - Focus on a few, ~20 stars (preliminary short list from Exo-S)

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  - Identify possible giant planet interacting with HZ in order to rule-in or rule-out most of the targets for HZ searches (relevant for Flagship mostly
  - Simple criterion (e.g. 3-Hill sphere radius) can be sufficient for broad brush purposes to rule-in/rule-out target for observations (Turnbull)
  - Identify the upper-limit mass of possible existing planets from non-detections a a function of separation.

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  - RV trends useful beyond HZ at larger separation
  - Ruling out "Nemesis" companions to the star that will disturb HZ (Flagship), RV only part of the picture (imaging etc.)
  - Trends indicating sub-Neptunes? could be difficult if multiple planets, but to investigate for target selection purposes

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- Identify RV trends at and beyond HZ separation
- In-depth study of special-interest target stars
    - e.g. Alpha Cen: very high contrast, but large separation.
    - contrast from the other star 1e8 - possible post-processing/DM diversity being investigated (Belikov)
    - other particular stars of interest

Mass estimation of RV planets

- Brown 2015 found that single-visit imaging combined with current RV orbital solutions are not sufficient to determine planet masses to 10% accuracy
  - Uncertainties in RV orbits from current measurement errors and systematics are the main limitation. Rougher estimates (e.g. within a factor 2 possible for some targets)
  - Science discussions are needed to determine the requirement on mass accuracy and DRMs can determine what data and observing scenarios are needed.
  - These results emphasize the need for more high-precision RV data points prior to direct imaging mission, and improving techniques to overcome RV systematic errors (e.g. star spots

Mass estimation of RV planets

- Possible avenues to improve planet mass determination:
  - Multiple direct imaging visits should improve constraints on inclination, as is currently done with direct imaging alone (hence better mass when combined with RV data)
  - Scheduling challenges exist for multiple imaging visits because of current RV orbit uncertainties with highly obscured orbits (semi-major axis ~ IWA), and long planet periods comparable to mission duration
  - Contribution from potential GAIA astrometry
  - Mass accuracy improvement with additional RV data between now and launch
  - Case of multiple-planet systems where additional dynamical constraints exist
  - Simultaneous orbital determination with all data (RV, imaging, astrometry

Conclusions

- SAG-9 refocused goals to avoid overlap with Exo-C/S and AFTA-SDT
- Main results:
  - DRM studies as a function of scale and coronagraph/starshade approach
  - Sensitivity study to main parameters for AFTA
    - *Resolution and Throughput impact total mission time but preserve the same number of characterized planets*
    - *IWA directly impacts the number of characterized planets regardless of mission time (factor ~2 between 3 and 4λ/D)*
  - Cross-validation and reconciliation of various exposure time calculations
- Initiated community discussions on RV surveys for direct imaging
  - 2014 focused study by Howard & Fulton
  - New RV facility announced by NASA
  - Established a process to define RV surveys needed for future direct imaging missions (to be continued beyond SAG-9)
  - Brown 2015 emphasizes need for continued RV observations with increased precision and reduced systematics