THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

What Science Can Improve the Design of a Flagship Exo-Planet Mission: NG Perspective

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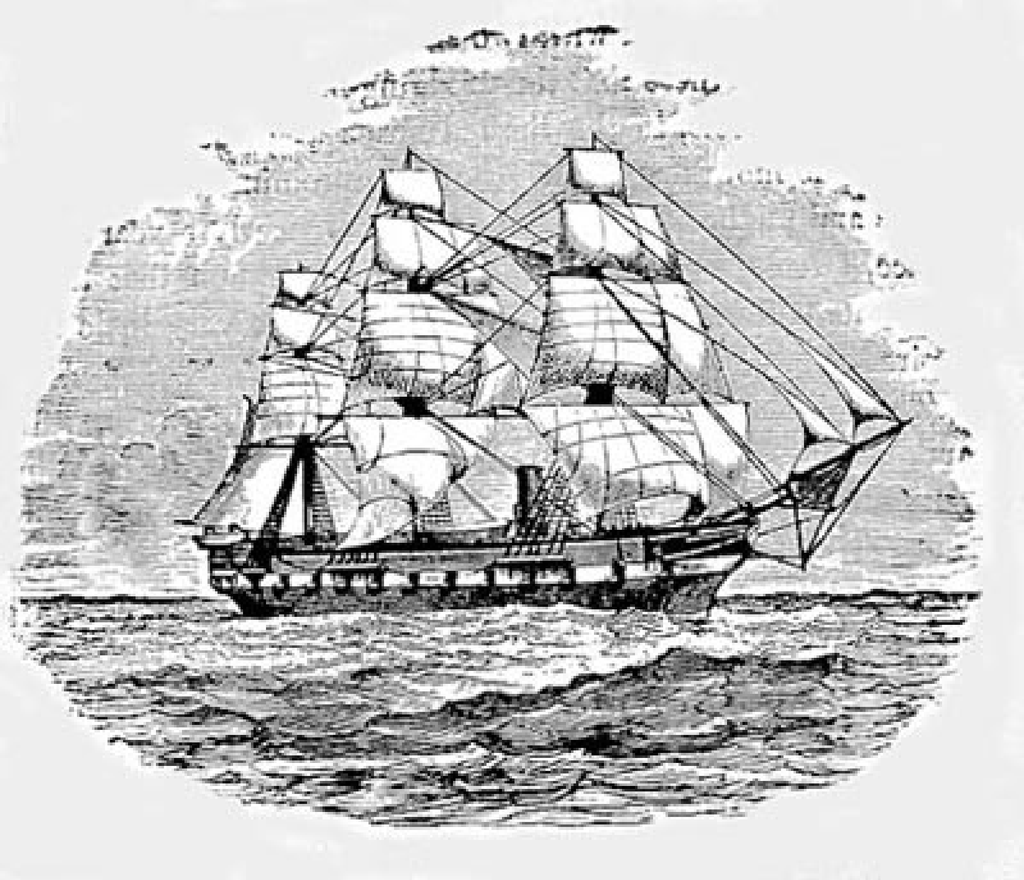


How do we prepare for our voyage of discovery?

Linear Process for Mission Design


Science

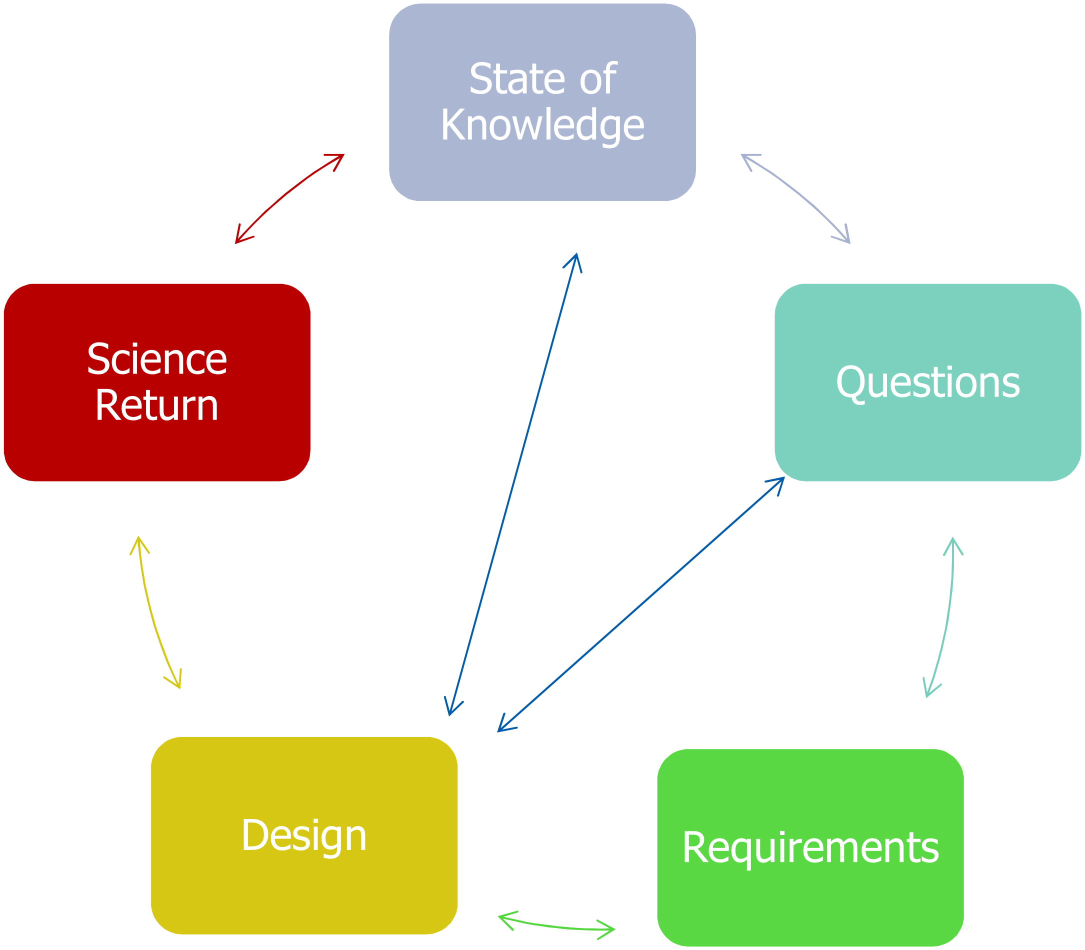
Requirements

Design

Return

- No feedback

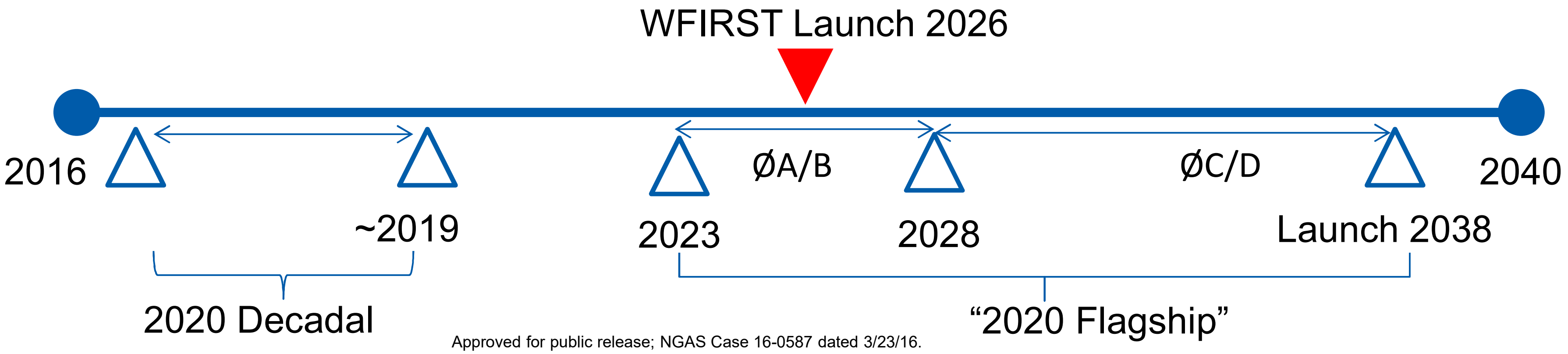
Collaborative Model of Mission Design



- Scientific milieu for exo-planets is rapidly developing
  - Lots of surprises
- Need to respond to developments
- Guide developments

First Step to Answer a Big Question

- What scientific knowledge is most influential in the design of a flagship class exo-planet mission for the 2030’s
  - What should be done between now and 2038-2040 to maximize the science return for this Flagship?
  - Mission after next (N+2)
- Influential information for both science and engineering
- What are the right questions?
  - What drives mission architecture and design into a “corner”?
- Is there a phasing to this work?
- Is some information more valuable?



WFIRST Launch 2026

2016

~2019

2023

ØA/B

2028

ØC/D

Launch 2038

2040

2020 Decadal

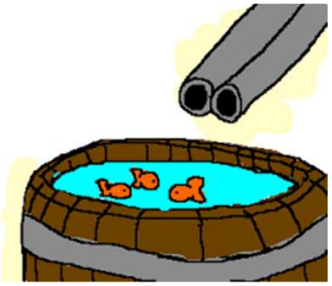
“2020 Flagship”

“Fish in a Barrel” or “Shot in the Dark”?

- What is goal of talk?
  - Establish the link between knowledge of exo-planet targets and missions design
    - Establish collaboration to advance highest effect science
    - Architecture agnostic
  - Ultimate goal is a maximally productive and affordable Flagship mission
    - Don’t do in space what can be done from the ground
    - Science is not static
      - Using the current state of knowledge in a rapidly evolving field and locking in an mission architecture too early is a poor strategy

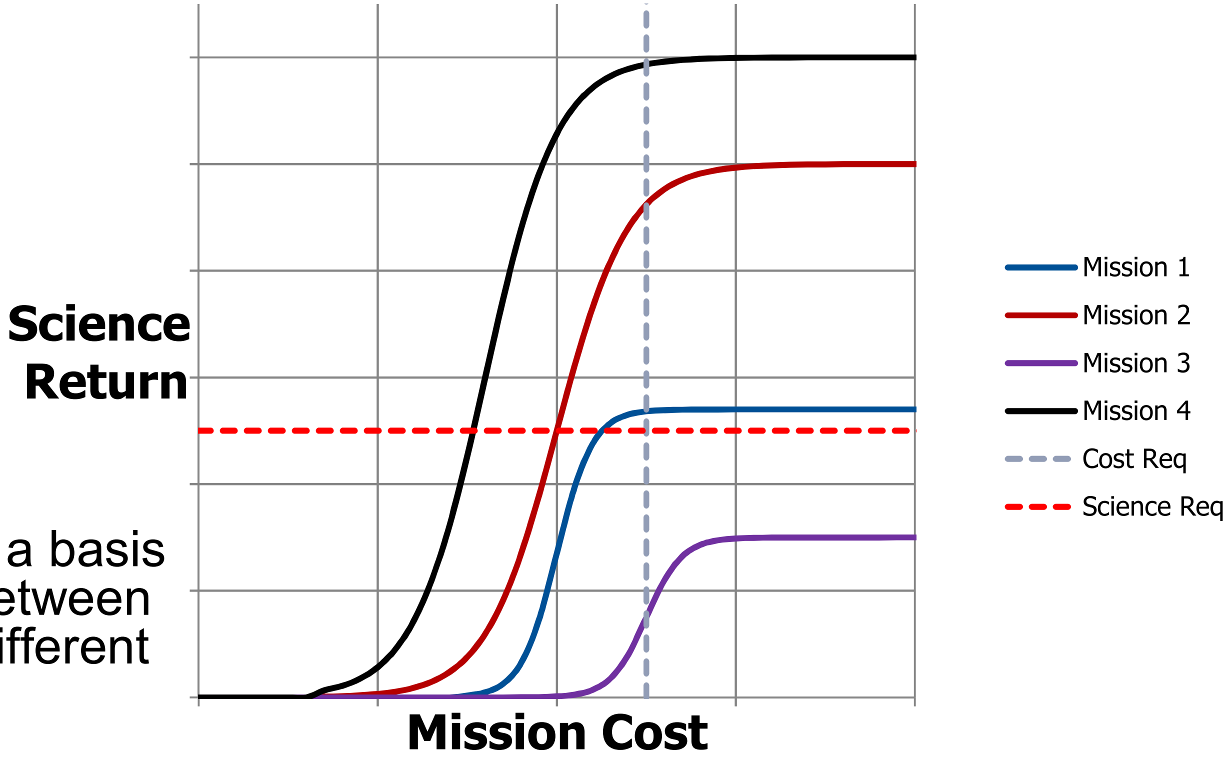
- Why do this? Can it be done?
  - Example of an increased productivity architecture

- How will the goal be accomplished?
  - Review of literature
  - First order physics
  - Creativity
  - Collaboration



What is Scientific Productivity

- What exactly is science return?
  - Census
  - Habitable zone denizens or systems?
  - Terrestrial or all?
  - Orbits
  - Spectrum
  - Time domain
- Objective function(s) for optimization and provides a basis of understanding the tie between how designs respond to different science objectives
  - Sensitivity study



Forget the Cost for a Moment: What is the Question?

- Just tell me what you want, “if you don’t ask, I can tell you what you will get”

- Are we just counting dots?
  - One kind of dots
  - Do systems matter?

- Orbits?
  - How well should they be known?

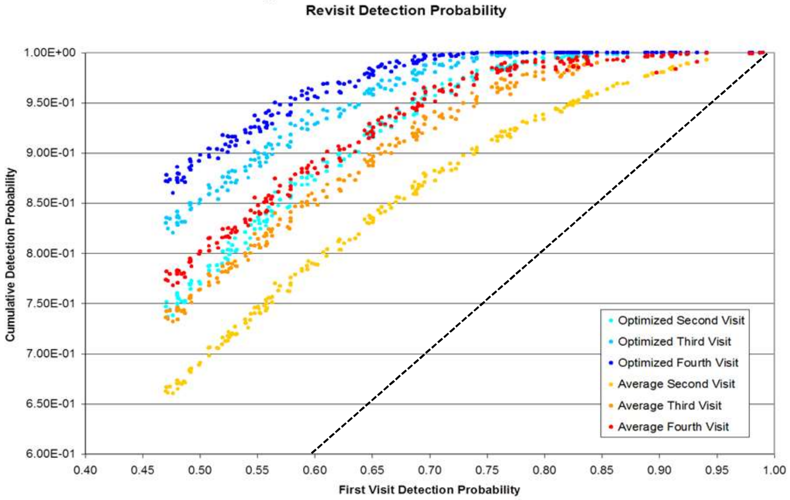
- Characterization
  - Spectrum
  - Polarization
  - Time dependence

- How important is confidence (statistical)
  - Orbits
  - Completeness
  - Are fewer better determined systems (planets) better than many that are more uncertain?

The right answer needs the right question.

Lesson Learned from a Mission Design from Long Long Ago

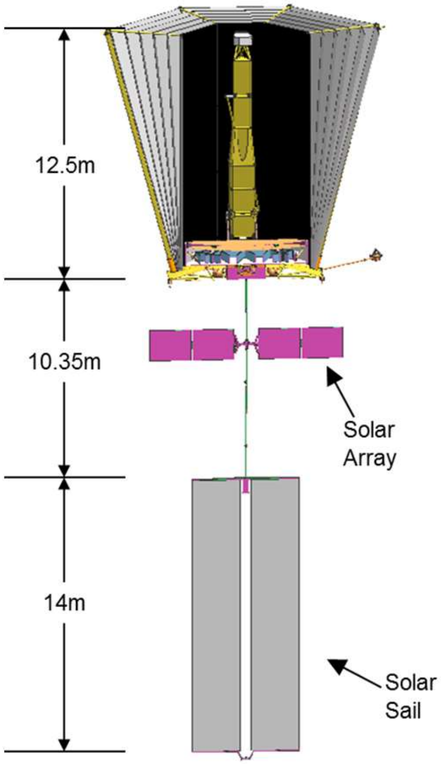
- While studying TPF-C Mission (circa 2004) the question of revisit interval arose
  - Mission requirements were 90% completeness for ~150 targets
- No good answer, so analyzed the problem
  - Found an optimal time to revisit
- 2 optimized visits=4 randomly timed visits



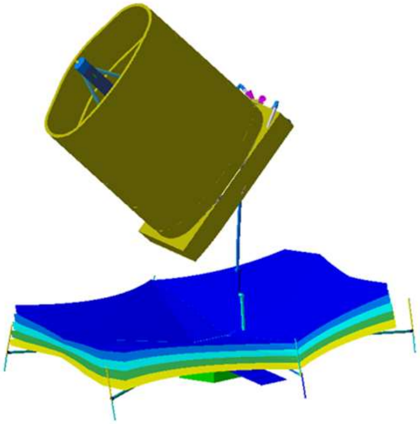
Arenberg, Knutson (2004)

Understanding Revisit Problem Led to Revise Architecture

- 3π sr Field of Regard- enabled optimal revisits and access to more sky (targets)



TPF-C Baseline



NG Concept

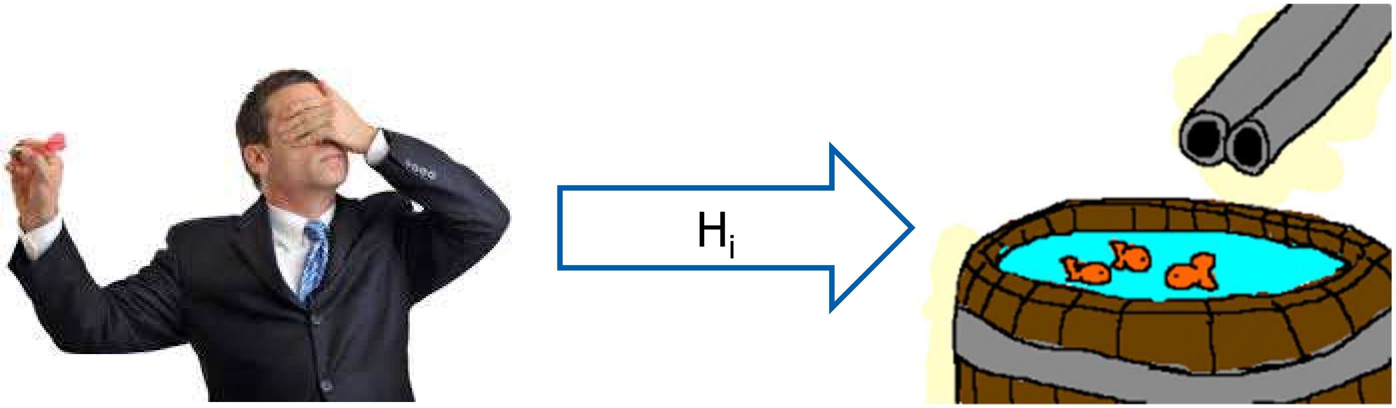
Understanding the science makes for better designs

Maximizing Science Return

- Spend time on known good targets
  - Don't spend time in space sorting them out
    - How can good targets be identified *a priori*?
  - How do we use the time on target most efficiently?

- Can write the science return, R for the cases of no prior history, Ø, and history for the i^{th} target, T_i, H_i

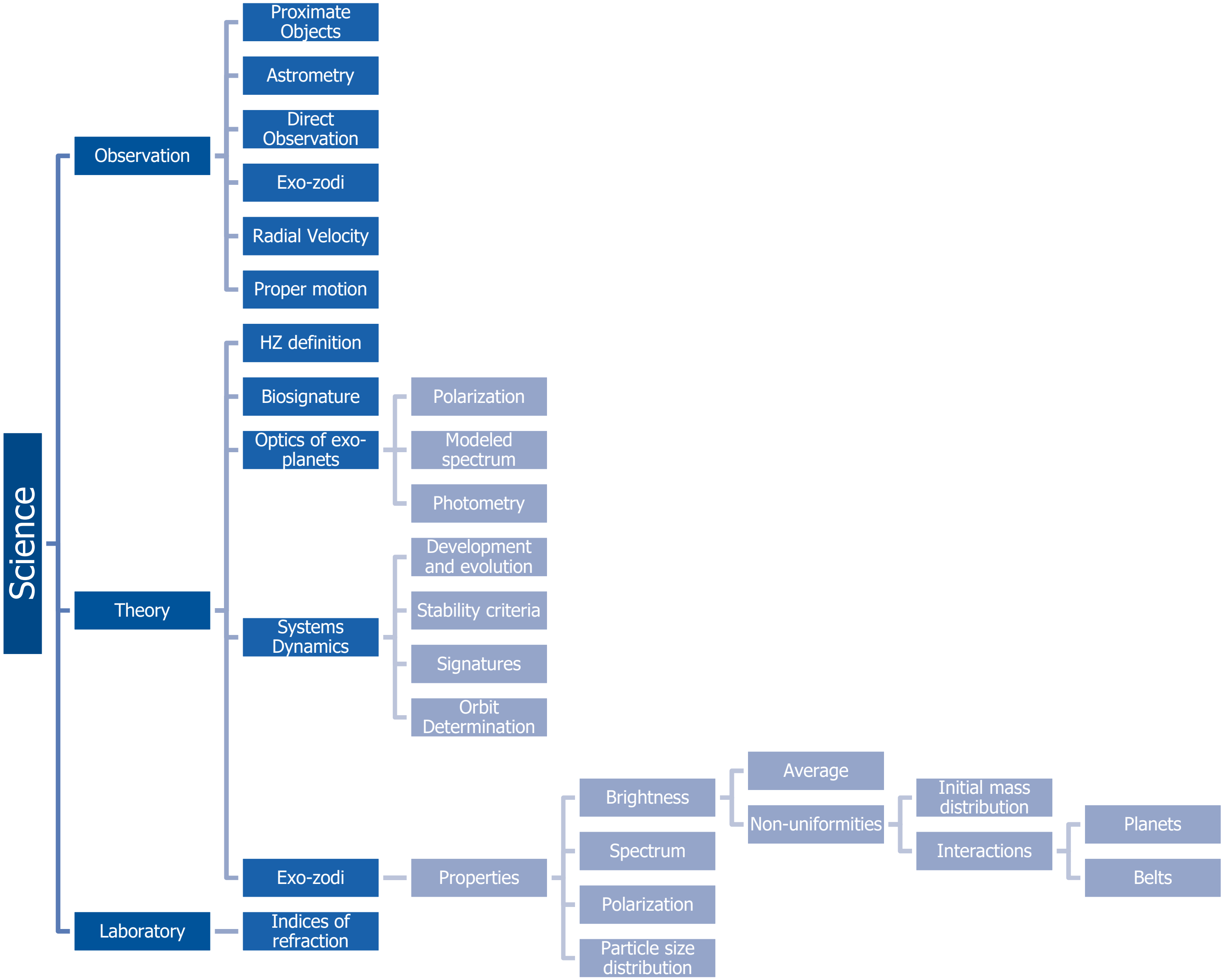
$$R_{\varnothing} = \sum_{i=1}^{N_{\varnothing}} \Pr\left(\eta_i \middle| \varnothing\right) T_i \qquad R_H = \sum_{i=1}^{N_H} \Pr\left(\eta_i \middle| H_i\right) T_i$$



Identifying the H_i

- Want to find the H_i that most rapidly increase $Pr(\eta_i|H_i)$
  - Identify the H_i that imply $\eta_i=0$
    - Systems with NO planets (signatures of planets)
    - Systems with planets by are dynamically forbidden from having a terrestrial planet in the HZ
      - Massive planet in the HZ
    - So much noise or background that a target cannot be detected
  - Review the literature
    - What are the assumptions and parameters that affect scientific yield from current studies
  - Think about the physics
  - Brainstorm

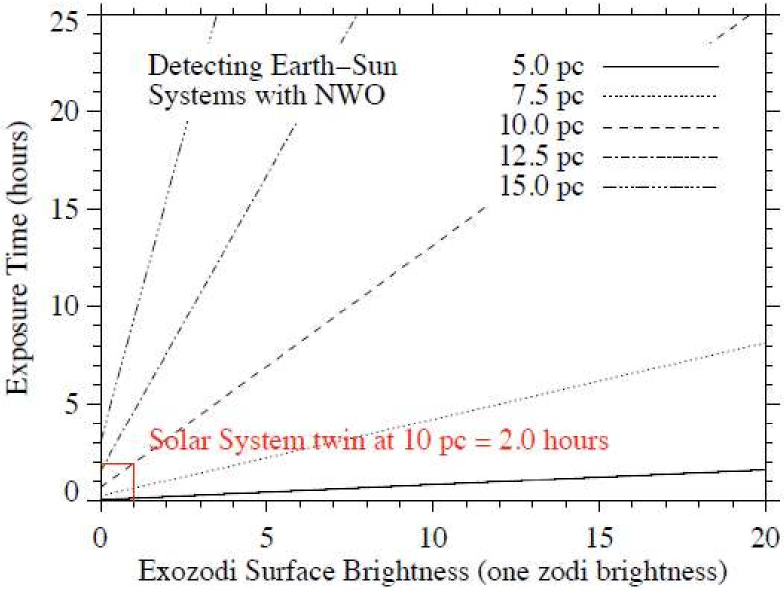
Knowledge Taxonomy Chart



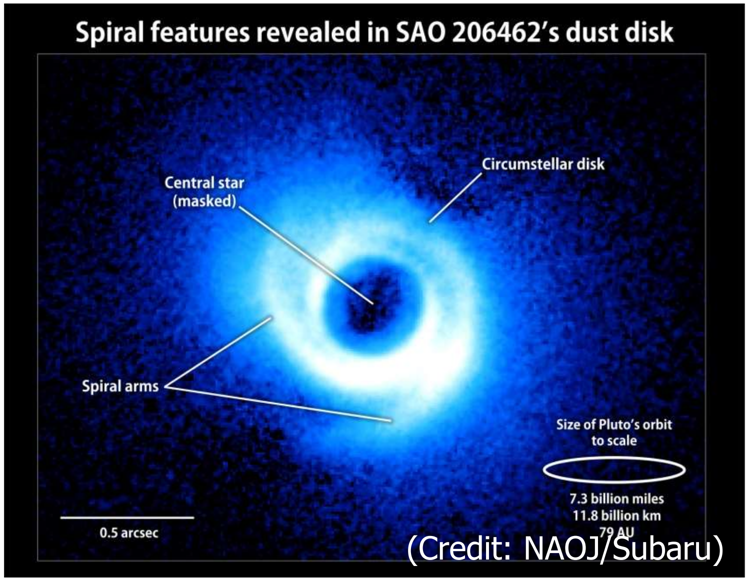
- Science
  - Observation
    - Proximate Objects
    - Astrometry
    - Direct Observation
    - Exo-zodi
    - Radial Velocity
    - Proper motion
  - Theory
    - HZ definition
    - Biosignature
    - Optics of exo-planets
      - Polarization
      - Modeled spectrum
      - Photometry
    - Systems Dynamics
      - Development and evolution
      - Stability criteria
      - Signatures
      - Orbit Determination
    - Exo-zodi
      - Properties
        - Brightness
          - Average
          - Non-uniformities
            - Initial mass distribution
            - Interactions
              - Planets
              - Belts
        - Spectrum
        - Polarization
        - Particle size distribution
  - Laboratory
    - Indices of refraction

Exozodiacal Dust & Terrestrial Planet Direct Detection

- The *Seeking New Worlds* mission hopes to directly image Earth-size planets in the Habitable Zone of nearby stars
- Dust in these extra-solar systems is potentially the largest source of:
  1) Astronomical background light, which would increase the exposure time needed for these observations
  2) Confusion, due to unresolved structures in the dust disks (Kuchner and Noecker 2010)
- From *New Worlds, New Horizons in Astronomy and Astrophysics*: “In the first part of the decade NASA should… accelerate measurements of exozodiacal light levels that will determine the size and complexity of [a next-decade planet imager].”



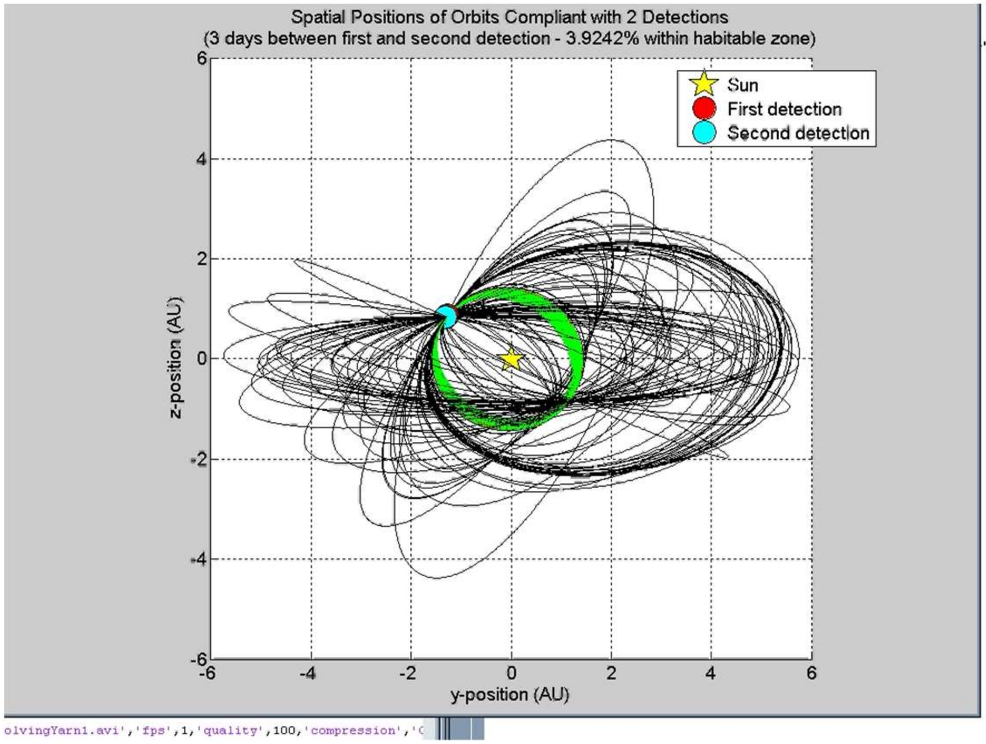
Turnbull et al. 2012, PASP,


Spiral features revealed in SAO 206462’s dust disk

(Credit: NAOJ/Subaru)

Completeness and Orbit Determination

- Additional information about systems will make completeness searches and orbit determination more efficient
  - Inclination, rotation, eccentricity
- What data can be gleaned from observation of the outer system?



Arenberg and Schuman (2007)

Observational Data: Putting Fish In Barrel

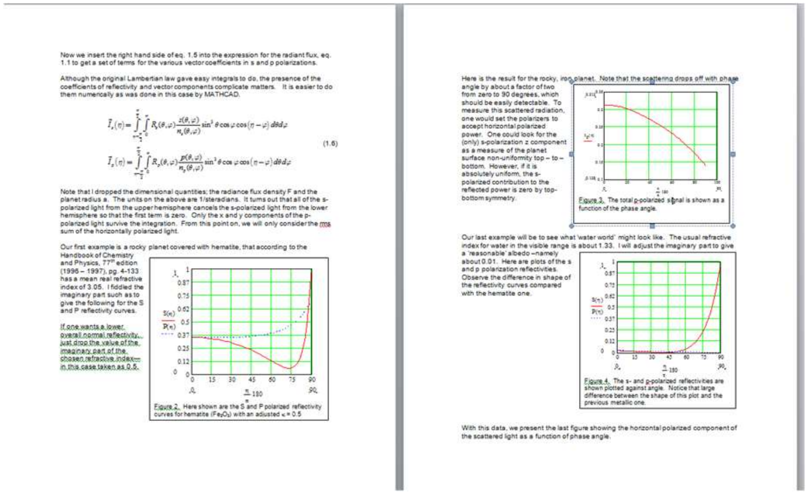
- Does a (potential target) system exhibit and signature of planets of any size?
  - Astrometric wobble
  - RV signature
  - Transiting planet
- Are there no contra-indications of possible habitable zone planets
  - Nothing too massive (and in the wrong orbit) to prevent a stable HZ orbit

System Evolution, Dynamics and Stability

- Are there general rules of thumb for systems?
- Can an observation of outer planet(s) make orbit determination/completeness searches more efficient
- Are there dynamic prohibitions on systems?
  - Does a large planet in or near the HZ prohibit a terrestrial planet?

Optical Modeling and Analysis

- Polarization and photometric data are powerful probes of the planet atmosphere and geology
- Can signal from exo-zodi be used in anyway?
- Understanding the science return can guide selection of system



Now we insert the right hand side of eq. 1.5 into the expression for the radiant flux, eq. 1.1 to get a set of terms for the various vector coefficients in s and p polarizations.

Although the original Lambertian law gave easy integrals to do, the presence of the coefficients of reflectivity and vector components complicate matters. It is easier to do them numerically as was done in this case by MATHCAD.

$$\bar{I}_s(\eta) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{\pi} R_s(\theta,\varphi) \frac{s(\theta,\varphi)}{n_s(\theta,\varphi)} \sin^3\theta \cos\varphi \cos(\eta-\varphi)\, d\theta d\varphi$$
$$\bar{I}_p(\eta) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{\pi} R_p(\theta,\varphi) \frac{p(\theta,\varphi)}{n_p(\theta,\varphi)} \sin^3\theta \cos\varphi \cos(\eta-\varphi)\, d\theta d\varphi \quad (1.6)$$

Note that I dropped the dimensional quantities; the radiance flux density F and the planet radius a. The units on the above are 1/steradians. It turns out that all of the s-polarized light from the upper hemisphere cancels the s-polarized light from the lower hemisphere so that the first term is zero. Only the x and y components of the p-polarized light survive the integration. From this point on, we will only consider the rms sum of the horizontally polarized light.

Our first example is a rocky planet covered with hematite, that according to the Handbook of Chemistry and Physics, 77th edition (1996 – 1997), pg. 4-133 has a mean real refractive index of 3.05. I fiddled the imaginary part such as to give the following for the S and P reflectivity curves.

If one wants a lower overall normal reflectivity, just drop the value of the imaginary part of the chosen refractive index—in this case taken as 0.5.

Figure 2. Here shown are the S and P polarized reflectivity curves for hematite (Fe_2O_3) with an adjusted κ = 0.5

Here is the result for the rocky, iron planet. Note that the scattering drops off with phase angle by about a factor of two from zero to 90 degrees, which should be easily detectable. To measure this scattered radiation, one would set the polarizers to accept horizontal polarized power. One could look for the (only) s-polarization z component as a measure of the planet surface non-uniformity top – to – bottom. However, if it is absolutely uniform, the s-polarized contribution to the reflected power is zero by top-bottom symmetry.

Figure 3. The total p-polarized signal is shown as a function of the phase angle.

Our last example will be to see what 'water world' might look like. The usual refractive index for water in the visible range is about 1.33. I will adjust the imaginary part to give a 'reasonable' albedo –namely about 0.01. Here are plots of the s and p polarization reflectivities. Observe the difference in shape of the reflectivity curves compared with the hematite one.

Figure 4. The s- and p-polarized reflectivities are shown plotted against angle. Notice that large difference between the shape of this plot and the previous metallic one.

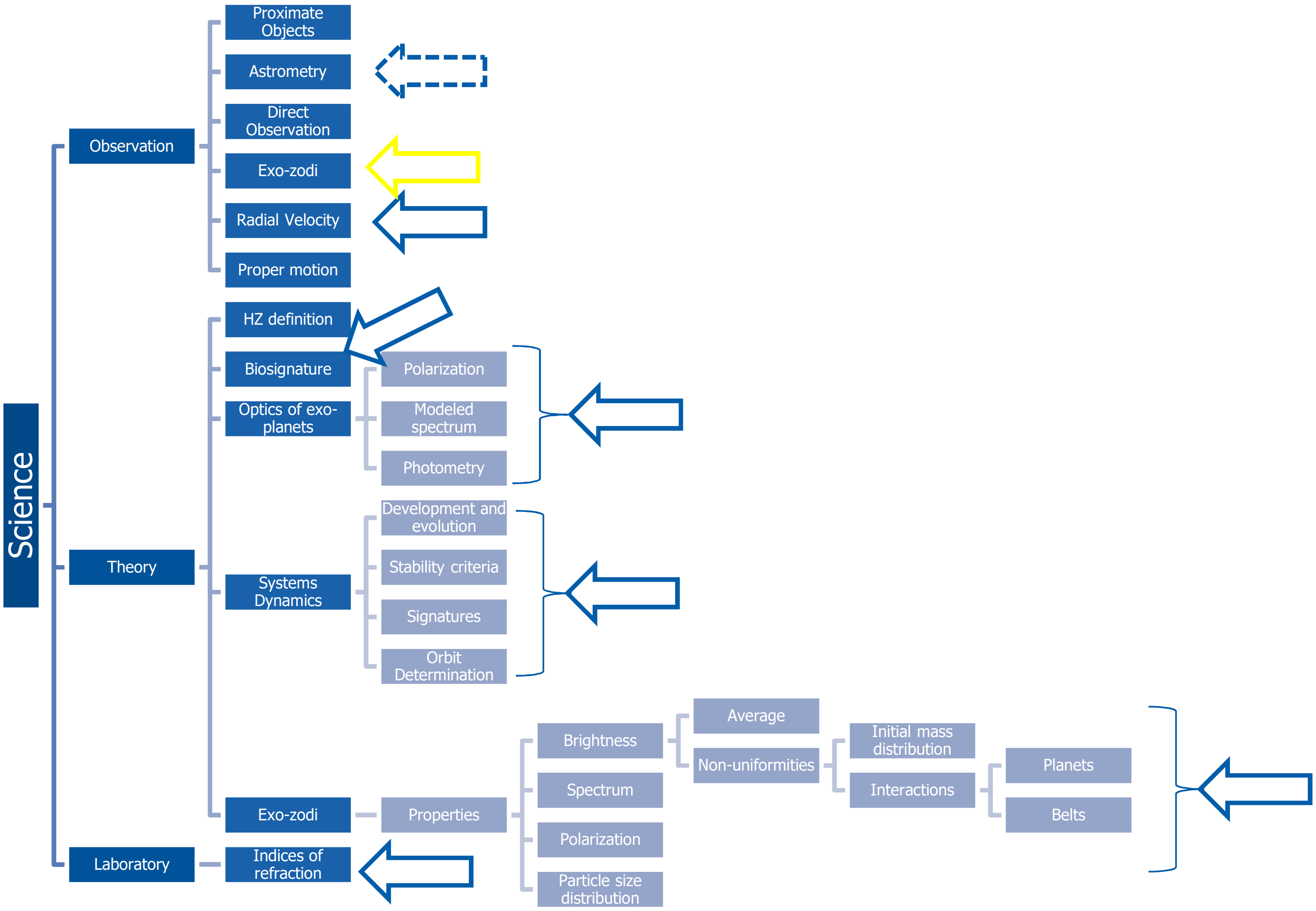
With this data, we present the last figure showing the horizontal polarized component of the scattered light as a function of phase angle.

TRW IOC Livingston to Arenberg (2004)

One more thing…..

- Need a good source of comprehensive indices of refraction
  - Solid, liquids, gases at various conditions of temperature and pressure
  - Both on target planets, but for a system and its contaminants as well
- Extensive literature search
- Laboratory measurements

Summary of First Look Most Interesting H_i



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Conclusion and Next Steps

- Better understanding of the science aspects of an exo-planet mission will improve the system and mission design
- This is a highly iterative process involving science and engineering
- This discussion was the first step on the road to a comprehensive view of the interrelationships and the link to mission performance

Collaboration is key in maximizing science return from our “Challenger” Mission

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