Optimizing WFIRST Coronagraph Science

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For Macintosh (PI) WFIRST SIT Team
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The Potential of the WFIRST CGI

Optimizing WFIRST Coronagraph Science

Scientific/Technical/Management

Objectives and Expected Significance

The Kepler mission has revolutionized our understanding of planetary systems, demonstrating that they are both extremely common and extremely diverse; but it has also created new puzzles, including the formation process that led to this diversity, and the nature of the vast numbers of 2-4 \( R_{\text{Earth}} \) planets. The next generation of NASA exoplanet missions will address such questions by focusing on planet characterization as well as planet discovery. The combination of the Transiting Exoplanet Survey Satellite (TESS) with the James Webb Space Telescope (JWST) will enable discovery and then characterization of close-in planets, particularly those orbiting M-type stars. Characterizing planets on wider orbits around higher-mass stars will require other facilities. The unprecedented contrast of the Wide-Field Infrared Survey Telescope (WFIRST) coronagraph instrument (CGI) will enable the first direct imaging and characterization of mature solar systems around nearby, sun-like stars. Fig. 1 shows where the expected scientific results of WFIRST will fall in the context of the next decade. In this proposal we describe an in-depth scientific investigation that will define how WFIRST will discover and characterize nearby planetary systems, using observations of planets and disks to probe the diversity of their compositions, dynamics, and formation.

A selection of the specific science goals for the CGI includes measuring the atmospheric heavy element abundances of a diverse set of mature giant planets; constraining their clouds and photochemical hazes; measuring the orbital inclinations and hence determining masses of the subset of those planets detected by the radial velocity (RV) technique; and constraining the composition and mass of newly discovered planets via optical photometry and spectroscopy. Photometry and spectroscopy from WFIRST will help to establish the nature of \( \approx 2-4 R_{\text{Earth}} \) sized objects, revealing which are truly 'super-Earths' or rather 'sub-Neptunes'. The CGI will study the properties of exozodiacal dust disks and image multiple young extrasolar giant planets discovered by direct imaging in the near-infrared. All this will yield new understanding of the diversity of planetary systems and shine new light on planet formation and evolution.

Figure 1: Known and simulated exoplanets. Those that have been photometrically or spectroscopically characterized are shown as larger circles. Simulated TESS planet discoveries are taken from Sullivan et al. (2015); a subset of these will be characterizable with JWST. Projected WFIRST-studied planets are based on our simulations.

To optimize the ability of the mission to address these goals we will perform end-to-end modeling of CGI observations. These simulations will start with model spectra of planets and images of disks, simulate WFIRST data using these models, account for geometries of specific star / planet / disk systems, and incorporate detailed instrument performance models. Our team's in-depth knowledge of the instrument performance (coronagraphs, wavefront control, camera, spectrograph) will ensure that we develop a high fidelity model of the entire observation and the data analysis pipeline (Fig. 2). These models will enable us to optimize the observing strategy and inform target selection with a full mission simulator and assess what science can be extracted from WFIRST CGI data via information retrievals. These retrievals will quantify how well WFIRST data will be able to measure different planet and disk parameters (e.g., fidelity of atmospheric CH\(_4\) abundance) given various design and mission alternatives. The experience our team has gained from building and observing with high contrast, ground-based, exoplanet imaging instruments (GPI, SCExAO), from our involvement with the current prototype WFIRST CGI coronagraphs, and from development of wavefront control algorithms will inform this extensive modeling and simulation work. The CGI design and operational modes are likely to evolve over the next several years in response to technological, scientific, and experimental developments.

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SIT simulation framework

Updated astrophysical hypothesis

Simulated properties of planetary systems

- Planets albedo vs SMA.
- Mass and orbit distribution.
- Planet spectra forward models
- Disks forward models.

Observatory + instrument model:
- detailed instrument team model specific target selection
- SIT diffractive model
- SIT analytical instrument model

Mission rules:
- specific target selection
- scheduling, overheads
- revisit strategy
- data analysis plan

Generate simulated data:
- instrument response
- Observing sequence
- Detector level noise

Wavefront sensing and control

Raw data products:
- with project level wavefront control
- or with SIT wavefront control
- PSF library

Data analysis

Calibrated data products:
- calibrated faint astrophysical scene (starlight residuals subtracted).
- statistical confidence in bound planet/disk.

Estimation

Astrophysical Observables:
- planet spectra, astrometry
- disk surface brightness, morphology.

Retrievals

Physical properties:
- planet molecular abundances.
- planet orbit/dynamical mass.
- disk geometry and grain properties.

Single Mission realization.

Science metrics
- # planets imaged.
- # planets with measured [M/H].
- # with dynamical mass.
- # zodiacal disks per spectral type

Update Observation Strategy / data analysis plan

Update astrophysical hypothesis
Team Structure

Bruce Macintosh (PI)

Nikole Lewis (Deputy PI)

Science Modeling
Lewis, Debes

Instrument
Cahoy

Simulations
Macintosh

Strategy & DRM
Savransky

Data analysis
Pueyo

Co-Is:
• Nikole Lewis
• Mark Marley
• Roxana Lupu
• Adam Burrows
• Renyu Hu
• John Debes
• Tom Greene
• Marshall Perrin

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Collaborators:

- Rafael Millan-Gabet
- Christian Marois
- Andrew Howard
- Leslie Rogers
- Michael Line
- Natalie Batalha
- Jonathan Fortney
- Amy Simon

- Colin Goldblatt
- Rebekah Dawson
- Gaspard Duchene
- Remi Soummer
- Tyler Robinson
- Caroline Morley
Simulations

• Lead: Bruce Macintosh
Co-Is
• Jeremy Kasdin
• Dmitry Savransky
• John Trauger
• Mike McElwain
Full-physics simulation flow

- SIT generates observing scenarios
- GSFC STOP models of spacecraft
- JPL PROPER optics models
- Astrophysical objects
- Mock data pipeline
- GSFC, STScI IFS response
- Merge
- Instrumental response
- Science data cubes
- PSF subtraction
- Planet property estimation
- Noise sources
Key Simulation tasks

- Develop faster simulation approaches
- Develop open framework to merge astrophysics from other groups.
- Support Turnbull SIT

We will provide a public release of our simulations framework that can be used to evaluate GO/GI science opportunities.
Science modeling

- Lead: Nikole Lewis
- Co-Is:
  - Mark Marley
  - Roxana Lupu
  - Adam Burrows
  - Renyu Hu
  - John Debes
  - Tom Greene
  - Marshall Perrin

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WFIRST-accessible known RV planets span a range of properties.
Step 1: Albedo spectra generation with full-physics models

- Methane Abundance (fCH4)
- Surface Gravity (g)
- Cloud Properties
  - Single Scattering Albedo (ω)
  - Asymmetry factor (g)
  - Optical Depth (τ)
  - Cloud Top Pressure (P)
Planet models

- Full-physics planet models to generate input spectra
- Planets properties will be extremely diverse and different than our solar system
- Parameters including metallicity, clouds, chemistry
- Previous work produces many models; we will organize and curate

![Graph](image-url)

Previous work produces many models; we will organize and curate. Planets properties will be extremely diverse and different than our solar system. Parameters including metallicity, clouds, chemistry.
Step 2: Propagate through CGI models (analytic or full)
Step 3: Use MCMC inversion to recover parameters

Marley et al. (2014)
Lupu et al., in prep
Circumstellar dust
47 UMa + 30 Zodi disk

Disk is detected at low SNR in multiple resolution elements, Planets b (2.1 AU) and c (3.6 AU) are easily seen

PSF-subtracted image

Binned SNR map of disk (peak SNR=15)

SDT report, Schneider & Greene
Disk (Debes et al) flowing through simulation and data pipeline

Model a range of disks (mature zodiacal disks, young debris disks, transitional disks…). Collaboration with Turnbull SIT
We will also use MCMC inversion to retrieve the disk parameters.
Key Science Modeling tasks

- Plan to collate library of theoretical planet and disk spectra/models that will be made available online and identify critical areas on which to focus our modeling efforts (e.g. mini neptunes and super earths)

- Evaluate importance of polarization measurements for planets and disks

- Model orbit-fitting
Instrument operations, requirements

- Lead: Kerri Cahoy
- Co-Is:
  - Jeremy Kasdin
  - Tom Greene
  - John Trauger
  - Mike McElwain
  - Tyler Groff
  - Laurent Pueyo
  - Marshall Perrin
Development of operating scenarios

- Observing scenarios involve three stars per target
- Wavefront reference star (bright)
- Science target
- PSF reference star (matching science target)
- Are all three necessary? How close to a match does it need to be?
Wavefront control convergence

Effective star magnitude: $V = -8$
Roughly equivalent to SN1006

HCIT test results (Cady, Riggs, et al.)

Total Normalized Contrast: $6.6748e-09$

Need to include wavefront control overheads in DRMs. Should wavefront control continue during science?
Can science images generated in wavefront control distinguish speckles and planets?
Key instrument tasks

• Work to push wavefront control algorithms within ExEP / WFIRST

• Co-organize “Stanford meetings” with instrument team

• Setting level 2 requirements
  – Define spatial and spectral sampling
  – Current design overampled spatially and undersampled spectrally
  – Explore dark current vs readnoise
  – Maximize throughput

• Explore polarimetry modes
  – Polarization-dependent aberrations in beam
  – DM can only correct one polarization state for some modes
  – How to split, modulate polarization
  – Scientific value?
DRM and exoplanet strategy

- Lead: Dmitry Savransky
- Co-Is
  - Nikole Lewis
  - Bruce Macintosh
- Collaborators
  - Leslie Rogers
  - Andrew Howard
  - Natalie Batalha
  - Rafael Millan-Gabet
Planets within 30 pc

- Giant planets
- Rocky planets
- Water/ice planets
- Known Doppler planets

Separation (arcsec)

Contrast

- WFIRST

Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars
WFIRST sensitivity space

Completeness LHS 2465

Radius ($R_E$)

Jupiter
Neptune
Earth

Semi-major axis (AU)

Single-star completeness
WFIRST sensitivity space

Average completeness
6 month / 46 star

Radius ($R_E$)

Semi-major axis (AU)

AvgCompleteness H0.4-30

Jupiter

Neptune

Earth
Exoplanet Yield Estimates

<table>
<thead>
<tr>
<th></th>
<th>Giants (4-15 R_E)</th>
<th>Sub-Neptunes (2-4 R_E)</th>
<th>Super-Earths (1-2 R_E)</th>
<th>Total</th>
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<td>Known RV Studies*</td>
<td>16</td>
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<td>0</td>
<td>16</td>
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<tr>
<td>180-day Blind Search</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Total**</td>
<td>18</td>
<td>6</td>
<td>4</td>
<td>28</td>
</tr>
</tbody>
</table>

- RV yield could be augmented by the WIYN program for future RV observations; see poster by Chontos et al
- ** Yield assumes 0.4 jitter and 30x speckle attenuation
DRM optimization

• Add to models
  – Target ID by GAIA, WIYN precision RV
  – RV planet recovery and full characterization
  – Blind search optimization including recovery and orbits
  – Extrasolar zodiacal dust models with varying properties and higher fidelity

Long term: evaluate a range of possible planet populations:
  - Model multiplanet correlations,
  - Bimodal planet formation (Kepler-blind solar analogs)
Image processing

- Lead: Laurent Pueyo
- Co-Is
  - Laurent Pueyo
  - John Debes
  - Mike McElwain
  - Marshall Perrin
- Collaborators
  - Remi Soummer
  - Christian Marois
PSF subtraction and image processing

Karhunen-Loève Image Processing (Soummer et al 2012)

Slide by M. Ygouf
PSF subtraction and data processing

- Ongoing STScI project uses standard algorithms (KL mode / PCA base) against project data.
Estimation of spectrum

- Optimal estimation of recovered planet properties
  - Algorithmic self-subtraction biases
- Properly assess probabilities (false positive and missed-planet) for blind surveys

![KLIP /w 88 modes Central wavelength](image1)

![Graphs showing spectrum extraction with IFS (RDI)](image2)

Ygouf et al. 2015, SPIE proceedings

Ideal case (non-realistic):
- With forward modeling:
  - $4.2 \times 10^{-9}$ contrast
- Perfect calibration of off-axis PSF

Without forward modeling:
- $4.2 \times 10^{-10}$ contrast

Observing Strategies for WFIRST-AFTA (1/3)
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- Marshall Perrin
Long-term tasks that will enable GO/GI science

- Iterative cycles of simulated high-fidelity data
  - This will include public data releases
- Refined science models
  - Improved disk models with consistency with planet models, observations
  - Mini-Neptune and Super-Earth atmospheric models
  - Public releases of models developed in support of SIT effort
- DRM cycles
  - Public release of yield analysis code via github
- GO coronagraph science collaboration
  - Exoplanet topics – young planets and planet-forming disks, self-luminous planets
  - Non-exoplanet science