GO science with the WFIRST CGI

Laurent Pueyo (STScI)

Community Astrophysics with WFIRST:
Guest Observer and Archival Science.

March 1st 2016
Parameter space for WFIRST CGI GO science

Compelling science in the uncharted yet unchallenging real estate:

- Science that does not drive the mission requirements.
- Territory only partially covered by ELT circa 2025.
- Synergies with other facilities. Science building upon recent results.

Uncharted yet unchallenging does not mean boring.

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Monday, March 14, 16
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Context: formation and evolution of planetary systems

1-10 Myrs

10-300 Myrs

5 Gyrs
1. Proto-planetary disks and their interaction with exoplanets
Proto-planetary disks: a mm portrait gallery.

Fig. 1.— 1.3 mm dust continuum images of the disks observed with CARMA. Contours start at the significance levels given in each panel and are separated by that same amount. The exception is UZ Tau E/W where a cross indicates the position of UZ Tau W and the dotted contour corresponds to the $4\sigma$ level. Beam sizes and PA are listed in Table 2. Integrated fluxes and source sizes are given in Table 3.

Fig. 1.— Aperture synthesis images of the 870 \(\mu\)m continuum from the sampled disks. Each panel is 4" (500 AU) on a side. Contours are shown at 3\(\sigma\) intervals (rms uncertainties in Table 2). The synthesized beams are shown in the lower left of each panel. Note the detection of a disk around the AS 205 B system in the top left panel (see §4.2), as well as the prominent cleared central regions for the disks around SR 21 and DoAr 44.

Tracing the location of the mm dust and molecular gas with mm observations. ALMA
Proto-planetary disks: a mm portrait gallery.

Isella et al. (2009)

- DG Tau (7σ=25mJy)
- DR Tau (10σ=10mJy)
- DN Tau (3σ=5mJy)
- SR 24 (3σ=13mJy)
- RY Tau (10σ=20mJy)
- GSS 39 (3σ=15mJy)
- UZ Tau E/W (3σ=10mJy)
- DM Tau (3σ=5mJy)
- CY Tau (3σ=7mJy)
- LkCa 15 (3σ=6mJy)
- GO Tau (2σ=7mJy)

Andrews et al. (2009)

Tracing the location of the mm dust and molecular gas with mm observations. ALMA
• gap in mm dust does not correspond to gap in micron dust.

• apparent motion of the dip in the disk.
ALMA+scattered light imaging complementarity

- gap in mm dust does not correspond to gap in micron dust.
- apparent motion of the dip in the disk.
• gap in mm dust does not correspond to gap in micron dust.

• apparent motion of the dip in the disk.
- Hypothetical planet excites spiral arms, carves a gap.
- Local pressure bump forms a vortex which traps mm particles.
- Vortex responsible for bright spot in SW spiral.
- Motion of the SW arm can pinpoint where the planet is.
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• Motion of the SW arm can pinpoint where the planet is.
I. Proto-planetary disks and their interaction with exoplanets:

- Angular resolution is key. Contrast is not challenging.

- How much of this can be done from the ground now?
WFIRST will provide deep, well-calibrated contrast levels not accessible from the ground, and will thus allow direct imaging of sub-Jupiter mass exoplanets in/near habitable zones of Sun-like stars. Such planets will be very challenging for ELTs to observe due to the extreme contrast and ELTs detection limits are currently poorly understood in this regime. Ultimately, WFIRST-AFTA will push the low-mass detection limit for direct imaging further than possible with any other observatory (Figure 2-44).

Figure 2-44: Exoplanet detection limit of the HLC coronagraph on WFIRST-AFTA, compared to other high-contrast systems. The contrast values of RV planets detectable by HLC on WFIRST-AFTA are shown as open blue circles, along with the detection floor set by residual speckle noise (solid blue line, from Figure 2-48); note that this does not include photon noise.

There are two important complementary areas here: (1) WFIRST-AFTA vs. GPI and JWST, and (2) WFIRST-AFTA vs. E-ELT and TMT. Regarding (1) for GPI and JWST, the limiting sensitivities are much poorer in absolute terms (see the labeled curves), but the wavelength range of operation is the near-infrared, where hot, young planets are bright, so the type of planet probed is completely different than for WFIRST-AFTA, which will observe the much more numerous mature, cool planets.

Regarding (2) for the E-ELT and TMT, which have roughly similar sensitivities, the complementarity is that the ELTs will be able to observe planets closer to their stars than WFIRST-AFTA (owing to their 12 to 17 times larger diameters), and collect more photons per planet (allowing a poorer raw contrast but enabling a greater post-processing factor), so the ELTs will be best at observing habitable zones of nearby late-type stars, whereas WFIRST-AFTA will be best at nearby solar-type stars. The shaded blue cloud indicates the range of expected WFIRST-AFTA discoveries of new nearby Neptunes and Super-Earths.

• Angular resolution is key. Contrast is not challenging.

• How much of this can be done from the ground now?
In this section, the performance (as well as the robustness) of the system is studied in the poor condition regime, i.e., a seeing of 1.12 arcsec and two wind speed values of 12.5 and 30 m/s. These measurements have been performed in good T° conditions (< 17°) so that the DM had a relatively good shape at rest. First of all, despite some actuators in saturation (well handled by the anti-wind up and Garbage Collector processes), the loop was stable and robust during all the acquisition process (a few tens of minutes).

- The majority of the well studied mm proto-planetary disks are “too faint” to be observed in the visible with today’s AO systems.
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**Figure 12** Classical PSF for poor conditions

- The majority of the well studied mm proto-planetary disks are “too faint” to be observed in the visible with today’s AO systems.
1. Proto-planetary disks and their interaction with exoplanets:
   - Angular resolution is key. Contrast is not challenging.
   - Current AO systems will only observe archetypal systems.
   - WFIRST and/or ETLs will observe the bulk of these systems.

Given the timescales associated with planet disk interaction every observation is precious.
Archival data for time series observations

Boccaletti et al. (2015): VLT-SPHERE + HST-STIS
Context: formation and evolution of planetary systems
Context: formation and evolution of planetary systems

1-10 Myrs

2. Proto-planets and interactions with their disk

10-300 Myrs

5 Gyrs
What do proto-planets look like?

Spiegel and Burrows (2012)

H-band Evolution

$M_H$ vs. Age (Myr)

$10 M_J$, $5 M_J$, $2 M_J$, $1 M_J$
What do proto-planets look like?

Spiegel and Burrows (2012)

Fig. 1.— The SEDs of accreting circumplanetary disks at 100 pc (black curves) with different disk inner radii ($R_{\text{in}}$). The solid curves represent the cases with $R_{\text{out}} = 1000R_{\text{in}}$ while the dotted curves are calculated with $R_{\text{out}} = 50R_{\text{in}}$. The production of the planet mass and the disk accretion rate ranges from $10^{-7}$ to $10^{-2} M_\odot\text{yr}^{-1}$. For comparison, the red curves are the SEDs of the 1 Myr old planets at 100 pc based on the "hot start" models (SB). The red curve with a brighter flux is from a $10 M_\text{J}$ planet while the red curve with a weaker flux is from a $1 M_\text{J}$ planet. We have also plotted the SEDs based on the "cold start" models as the blue curves (SB). Similarly, the blue curve with a brighter flux is from a $10 M_\text{J}$ planet while the blue curve with a weaker flux is from a $1 M_\text{J}$ planet. Since SB only gives the spectra from 0.8-15 $\mu$m, we also plot the SEDs from the blackbody having the corresponding planet size and effective temperature (labeled along the curves) as the dotted color curves. For another comparison, the green curve is the SED of the protostar GM Aur (model spectrum from Zhu et al. 2012) scaled to 100 pc. At the top of each panel, the black curves indicate the transmission functions of J, H, K, L', M, and N bands.
What do proto-planets look like?

Zhu (2014)

\[
\frac{\dot{M}}{M} = 10^{-8} \frac{M_{\odot}}{\text{yr}}
\]

\[
R_{\text{in}} = 2R_J
\]

\[
M_p \dot{M} = 10^{-5} M_J^2 / \text{yr}
\]

\[
R_{\text{in}} = 4R_J
\]

\[
M_p \dot{M} = 10^{-5} M_J^2 / \text{yr}
\]
Example of LkCa15

LkCa 15 disk

LkCa 15

Kraus and Ireland (2012)
Example of LKCa15

K (mag)

10

8

6

4

15 M_Jup

CEN

SW

NE

K–L (mag)

10

8

6

4

15 M_Jup

Kraus and Ireland (2012)

DISK

NO DISK

TOTAL

K–L (mag)

10

8

6

4

15 M_Jup

CEN

SW

NE

Kraus and Ireland (2012)
2. Proto-planets and interactions with their disk

- Proto-planets are bright. Contrast is not challenging.
- IR observations are key to characterize dust.
- Angular resolution is key. Can JWST get to the proto-planets within small cavities?
Parameter space for WFIRST CGI GO science

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- IR observations are key to characterize dust.

- Angular resolution is key. Can JWST get to the proto-planets within small cavities?
Proto-planets with JWST: using the AMI mode

Greenbaum, Pueyo et al. (2014)

Expected CP Signal with JWST-NIRISS

Expected Signal log(σ_C) vs. Separation / mas

-5.0
-4.5
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
50 100 150 200

F277M
F430M
LkCa15 Separations

 REFERENCES
Ford et al. (2014)
Mawet et al. (2010)
Sivaramakrishnan et al. (2012)
Macintosh et al. (2014)
JWST will find proto-planets in the near IR.

Zhu (2014)

\[
\begin{align*}
\text{log } \lambda F_{\lambda} & \left( \text{erg s}^{-1} \text{cm}^{-2} \right) \\
\text{log } \lambda (\mu m) & \\
\end{align*}
\]

\( R_{in} = 2R_J \)

\( M_p \dot{M} = 10^{-5}M_J^2/yr \)

\( R_{in} = 4R_J \)

\( M_p \dot{M} = 10^{-5}M_J^2/yr \)

\( 10^{-6} \)

\( 10^{-7} \)

\( 10^{-6} \)

\( 10^{-7} \)
JWST will find proto-planets in the near IR.

Key observable: \( \text{Mp} \times \frac{\text{dM}}{\text{dt}} \)
Measuring accretion on a proto-planet

Spectra Differential Imaging  
Coutersy of K. Folette

Close at al. (2013)

With WFIRST no need for simultaneous imaging
H-alpha: proxy for accretion rate

- Accreting proto-planet.
- Contrast $8 \times 10^{-3}$.
- Need continuum to measure $dM/dt$.

Location of the star LkCa15 (light removed)

Sallum, Folette et al. (2015)


1" $\approx$ 140 AU
In this section, the performance (as well as the robustness) of the system is studied in the poor condition regime, i.e. a seeing of 1.12 arcsec and two wind speed values of 12.5 and 30 m/s. These measurements have been performed in good T° conditions (<17°) so that the DM had a relatively good shape at rest. First of all, despite some actuators in saturation (well handled by the anti-wind up and Garbage Collector processes), the loop was stable and robust during all the acquisition process (a few tens of minutes).

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- The majority of the well studied mm proto-planetary disks are “too faint” to be observed with today’s AO systems.
2. Proto-planets and interactions with their disk

- Proto-planets are bright.
- Contrast is not challenging.
- Angular resolution is key.
- JWST will identify them.
- Current AO systems will only observe archetypal systems.

Given the timescales associated with orbits every observation is precious.
Parameter space for WFIRST CGI GO science

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Context: formation and evolution of planetary systems
3. Adolescent-planets and their atmospheres

1-10 Myrs

10-300 Myrs

5 Gyrs

Context: formation and evolution of planetary systems
Historical perspective on Extreme AO systems

2MASSWJ1207334–393254

Chauvin et al. (2004)

778 mas
55 AU at 70 pc

N

E
Historical perspective on Extreme AO systems

2MASSWJ1207334–393254

\[ \sim 10^{-4} \text{ contrast} \]

Chauvin et al. (2004)

778 mas
55 AU at 70 pc

Historical perspective on Extreme AO systems
Historical perspective on Extreme AO systems

2MASSWJ1207334–393254

GPI/H–band

GPI/J–band

Macintosh et al. (2015)

Chauvin et al. (2004)

55 AU at 70 pc
Historical perspective on Extreme AO systems

2MASSWJ1207334–393254

GPI/H–band

GPI/J–band

Macintosh et al. (2015)

~10^{-6} contrast

Chauvin et al. (2004)

Gizis (2002) undertook a 2MASS-based search for isolated low mass objects in the TWA. Gizis (2002) noted also that the proper motion of 2M1207 is consistent with membership in the TW A. Multiple lines of evidence point toward membership of 2M1207 in the TW A and found two late M-type objects which he identified as brown dwarfs. The one of interest in the present paper, 2M1207, showed impressively strong Hα emission in addition to signs of low surface gravity, which both are characteristic of very young objects. Gizis (2002) did not reveal significant IR excess at 3.8 µm, whereas the mid-IR observations of Sterzik et al. (2004, accepted) found an excess emission at 8.7 µm. New observations of Gizis & Bharat (2004) corroborates this discovery that 2M1207 is a young object with some residual accretion ongoing. New high angular resolution observations of Macintosh et al. (2015) show that 2M1207 is a binary system with a companion located at 304 mas, with a separation of 0.8". The contrasts between 2M1207 and its GPCC are reported for multiple lines of evidence point toward membership of 2M1207 in the TW A.
51 Eri b, first cold start candidate

Spiegel and Burrows (2012)

Beta Pic b

51 Eri b

H-band Evolution
Historical perspective on Extreme AO systems

GPI comisionning
Historical perspective on Extreme AO systems

GPI commissioning

25 AU
Historical perspective on Extreme AO systems

GPI commissioning

25 AU

GPI commissioning

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Historical perspective on Extreme AO systems

GPI commissioning

25 AU
The orbit of Beta Pictoris b

GPI spectrum of Beta Pictoris b

Chilcote, Pueyo et al. (in prep)

F$_\lambda$, 10$^{15}$ W/m$^2$/µm

λ µm

Monday, March 14, 16
Brown Dwarfs: empirical sample for context

Beta Pictoris b

Field Objects courtesy of J. Fillippazo and BDNYC group

Chilcote, Pueyo et al. (in prep)
Brown Dwarfs: empirical sample for context

At a fixed brightness, Younger = Less Massive

Figure by Michael Cushing

Brown Dwarf
Star
Planet

Cushing et al. (2014)
Gagne et al. (2015)

Brown Dwarfs

Gagne et al. (2015)

0.3 M_J
13 M_J
211 M_J
73 M_J

Log_{10} (L/L_{Sun})

Age (yr)

Monday, March 14, 16
Brown Dwarfs: empirical sample for context

At a fixed brightness, Younger = Less Massive

They contract as they age, Younger = Larger

Figure by Michael Cushing, inspired by J. Gagné

Gagne et al. (2015)

Cushing et al. (2014)

Deuterium burning

Hydrogen burning

$\log_{10} (R/R_\odot)$ vs. Age (yr)

$6 M_{\text{Jup}}$

$13 M_{\text{Jup}}$

$80 M_{\text{Jup}}$

$0.2 M_\odot$

Monday, March 14, 16
Brown Dwarfs: empirical sample for context

At a fixed brightness, Younger = Less Massive

Figure by Michael Cushing

Brown Dwarf

Star

Planet

They contract as they age, Younger = Larger

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Brown Dwarfs

Gagne et al. (2015)

Cushing et al. (2014)

Gagne et al. (2015)

Monday, March 14, 16
Brown Dwarfs: empirical sample for context

Beta Pictoris b

Young Brown Dwarf = Low gravity

Chilcote, Pueyo et al. (in prep)
Brown Dwarfs: empirical sample for context

Beta Pictoris b

Young Brown Dwarf = Low gravity

Chilcote, Pueyo et al. (in prep)
How do we find low gravity brown dwarfs?

Fainter end of the low gravity sequence incomplete. WFIRST-WFI will address this.
How do we find low gravity brown dwarfs?

Fainter end of the low gravity sequence incomplete. WFIRST-WFI will address this.
What would this planet look like with WFIRST?

Spectrum of Beta Pictoris b with WFIRST will be very easy!
What would this planet look like with WFIRST?

Spectrum of Beta Pictoris b with WFIRST will be very easy!
We can learn more about these planets with WFIRST

Visible spectrum: estimates of gravity and metallicity

Beta Pictoris b

Intermediate gravity

Low gravity

FeH

K I

VO

TiO

VO

Log $F_\lambda$

$\lambda$ $\mu$m

Visible spectrum: estimates of gravity and metallicity

Monday, March 14, 16
Brown Dwarfs: empirical sample for context

![Graph showing spectral energy distribution for 51 Eri b]
Brown Dwarfs: empirical sample for context

![Graph showing the relationship between Log[F_\lambda] and \lambda (\mu m). The graph has a red line with a label indicating 51 Eri b and a downward arrow labeled \sim 10^{-8}.](image)
Brown Dwarfs: empirical sample for context

No low g counterpart: WFIRST-WFI will identify many.

Monday, March 14, 16
No low g counterpart: WFIRST-WFI will identify many.
Low frequency of self-luminous exo-planets

Exo-planet/BD companion at large separations are rare:

- Either they are hiding close in/deeper.
- Or their frequency is low: building up an “empirical evolutionary track” will take time.

Brandt et al. (2014)
Low frequency of self-luminous exo-planets

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Atmospheric composition as a proxy of formation history

- Planet metallicity vs host star metallicity.
- Planet metallicity as a function of separation.
- Molecular abundances in the context of their corresponding ice lines in the primordial disk.
- Impact of incident stellar flux.
parameter space for WFIRST CGI GO science

3. Adolescent-planets and their atmospheres

- Visible contrast ranges 2-3 orders of magnitude. Most of the are “easy”.

- **WFIRST-CGI optical spectrum will be a key element to understand their atmosphere and their formation history,**

Synergies with the WFI will help identify the empirical reference sample to study these atmospheres.
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4. Debris disks and their scattering properties

Context: formation and evolution of planetary systems

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10-300 Myrs

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Context: formation and evolution of planetary systems

4. Debris disks and their scattering properties
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Context: formation and evolution of planetary systems
Context: formation and evolution of planetary systems

4. Debris disks and their scattering properties

See G. Bryden Talk

Monday, March 14, 16
Importance of dust for exo earth imaging missions


40h exposure time
The pseudo zodi problem:

-5–

that the model KB dust density is negligible compared to the zodiacal cloud interior to 5 AU. For this investigation, we explicitly removed all KB dust interior to 5 AU, where the KB dust models become less reliable due to Poisson noise. To further reduce Poisson noise, we azimuthally averaged the Kuiper Belt dust model around the disk's axis of symmetry in steps of 0.36°.

For Figure 1, we masked off the central 0.5 AU of each image.

Exozodi

Pseudo–zodi

Sum

g = 0.3
g = 0.5
g = 0.7
g = 0.9

Fig. 1.— Synthetic visible-wavelength images of exozodi and pseudo–zodi, based on our solar system's debris disk, viewed edge-on as a function of scattering asymmetry parameter g assuming a HG SPF. The central 0.5 AU has been masked off. At a projected separation of 1 AU, the pseudo-zodi becomes brighter than the exozodi for g > 0.7.

As the SPF becomes more forward-scattering, the brightness of the pseudo-zodiacal component increases because dust at larger distances is observed at smaller scattering angles.

We measured the surface brightness of the model disks at a projected separation of 1 AU. We find that the brightness of the pseudo-zodi (Kuiper Belt dust) exceeds that of the exozodi Stark et al. (2015).

Forward scattering grains in the line of sight masquerade as “face on” zodi in an edge on system.

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This is not just a theoretical construction.

The disk around Beta Pictoris is very forward scattering.
This is not just a theoretical construction.

The disk around Beta Pictoris is very forward scattering
Measurements of scattering phase function

Fig. 7.— Illumination-corrected flux as a function of scattering phase angle at the exterior to the belt maximum (lower and upper panels, respectively). The SE and NW halves of the disk are shown in red and black, respectively. The yellow line shows the best fourth degree polynomial fit to the scattering phase function. The dashed green line shows the best fit Henyey-Greenstein phase function, a poor fit to the observed variation.

Repeating this procedure for $a$ ranging from 71 AU to 263 AU in steps of $\Delta a = 2.63$ AU (1 pixel), we obtained the SPFs shown in Figure 8. Because grains beyond the parent body ring should be size-sorted (see Section 4.1.2), with $s$ decreasing with increasing $a$, the normalization of the SPF at a given $a$ is degenerate with the average $Q_{sca}$ and surface density at a given $a$. Additionally, the normalization of a given SPF strongly depends on the behavior of the SPF at small $\theta$, but our observations are limited to $60^\circ \lesssim \theta \lesssim 120^\circ$.
Measurements of scattering phase function

Hedman and Stark (2015)

Fig. 7.— Comparing the SPFs for D68 and the G ring. The upper plot displays the normal-
ized phase curves of the two ring features, showing that they have similar, but not identical
Thus, debris disks would appear a factor of
this imply about debris disks? First, we note that the model G ring SPF near
scattering for debris disks therefore may be greatly underestimated.
0.5
angle
130.5
angle
10
77 mas = 2
3 pixel median boxcar and displayed on a saturated scale for illustrat-
Fig. 15.—

Second, the very forward-scattering model G ring SPF suggests that edge-on disks may
If the model G ring SPF is in fact representative of debris disk SPFs, what would
The left panel of Figure 15 also shows the best-fit 2-component HG function, which does
an 11-image median, subtracted it from the 12-image median, and div-
18 pixels has been applied for illustrative purposes. Stellar position is m-
visible). (b) A close-up of the D68 ringlet from Cassini image N1537019704, obtained during
All images have been individually stretched and have been rotated so that Saturn's north
pole would point upwards. (a) A mosaic of images obtained by the Cassini spacecraft in

Fig. 1.— The general appearance and location of the G ring and D68 within Saturn's rings.

Stark (2015)

Hedman and Stark (2015)

Model G ring SPF (black) over a range of scattering angles observable for a

PSF residuals, then leaving out any one image should not greatly impac-

an 11-image median, subtracted it from the 12-image median, and div-

Our multi-roll observation technique reduces both the impact of te-

Model of G ring
1 HG fit to model @ 60°<θ<120°
2 HG fit to model @ 60°<θ<120°

Average scattering angle < (80
Number of observations
 extents the NE-S
 O.5
angle
130.5
angle
10
77 mas = 2
3 pixel median boxcar and displayed on a saturated scale for illustrat-
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Hedman and Stark (2015)
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.

Next step is to get a large sample of debris disks at various inclinations.
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.

Next step is to get a large sample of debris disks at various inclinations.

Figure 9. Analysis quality scattered-light images of the GO 12228 debris disks discussed in Appendix A. Arrows indicate the full physical and angular extent of the disks (except AU Mic) in AU and arcseconds (scaled differently for each disk), and below the inner working distances realized (though for all disks not at all azimuth angles) with PSFTSC imaging.

Schneider et al. (2014)
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.

Next step is to get a large sample of debris disks at various inclinations.
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4. Debris disks and their scattering properties

- Measurements of the scattering properties of dust at all possible inclinations.
- Take advantage of the polarization split in the CGI imager.
- Important consequences for the planning of future missions.

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What does this mean for the CGI instrument:

- Maybe H alpha filter?
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- Science at a contrast 1-2 orders of magnitude more gentle than the requirements.
- Implication on timing of GO observations.
Parameter space for WFIRST CGI GO science

1. **Proto-planetary disks** and their interaction with exoplanets.
2. **Proto-planets** and interactions with their disk.
3. **Adolescent-planets** and their atmospheres.
4. **Debris disks** and their grains.

- Plenty of exciting science with the WFIRST-CGI
- Synergies with JWST, ALMA, ELTs.

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**Figure 2**: Exoplanet detection limit of the HLC coronagraph on WFIRST-AFTA, compared to other high-contrast systems. The contrast values of RV planets detectable by HLC on WFIRST-AFTA are shown as open blue circles, along with the detection floor set by residual speckle noise (solid blue line, from Figure 2-48); note that this does not include photon noise. Other high contrast systems (Hubble Space Telescope, James Webb Space Telescope, Gemini Planet Imager, and the European Extremely Large Telescope) are shown for 1-hour exposures on fiducial targets, including photon noise.

There are two important complementary areas here: (1) WFIRST-AFTA vs. GPI and JWST, and (2) WFIRST-AFTA vs. E-ELT and TMT. Regarding (1) for GPI and JWST, the limiting sensitivities are much poorer in absolute terms (see the labeled curves), but the wavelength range of operation is the near-infrared, where hot, young planets are bright, so the type of planet probed is completely different than for WFIRST-AFTA, which will observe the much more numerous mature, cool planets. Regarding (2) for the E-ELT and TMT, which have roughly similar sensitivities, the complementarity is that the ELTs will be able to observe planets closer to their stars than WFIRST-AFTA (owing to their 12 to 17 times larger diameters), and collect more photons per planet (allowing a poorer raw contrast but enabling a greater post-processing factor), so the ELTs will be best at observing habitable zones of nearby late-type stars, whereas WFIRST-AFTA will be best at nearby solar-type stars. The shaded blue cloud indicates the range of expected WFIRST-AFTA discoveries of new nearby Neptunes and Super-Earths.
Many astrophysical observations require the imaging of faint objects or nebulosity next to point sources such as stars and unresolved active galactic nuclei. To achieve these observations, several high-contrast imaging techniques have been developed to suppress light from the central bright source in optical through mid-IR wavelengths. The operation of telescopes in space has opened new frontiers in high contrast imaging due to their relative stability and location above the Earth’s atmosphere. The astronomical community is using knowledge gained from current space- and ground-based facilities to plan for future high contrast imaging missions in the next decade. In this workshop, we will explore the legacy of existing space-based high contrast imaging from the Hubble and Spitzer Space Telescopes and investigate how existing scientific observations and coronagraphic techniques may be applied for future observations with the James Webb Space Telescope and the Wide-Field Infrared Survey Telescope to image exoplanets, debris disks, protoplanetary disks, AGN, Solar System objects, and other astronomical objects.
Back up
Importance of dust for future earth-imaging missions

The zodi-level is a key input to exo-earth experimental design.
Where is the zodi coming from?

Dust grains at 1 AU (LBTI) 
\times
Geometric Albedo (?) 
\times
Scattering phase function (??)
=
halo in images of solar system analogs.
Where is the zodi coming from?

Dust grains at 1 AU (LBTI) \times Geometric Albedo (\?;) \times Scattering phase function (\??;) = halo in images of solar system analogs.
Where is the zodi coming from?

Dust grains at 1 AU (LBTI) \times \text{Geometric Albedo} (\chi) \times \text{Scattering phase function} (\chi) = \text{halo in images of solar system analogs.}

Functioning design for detection and characterization

- Solar system model with spectral and spatial information from Haystacks project (PI: A. Roberge)
- Composite of 3 images on channels centered around:
  - 500nm, 600nm and 700nm
  - 10% bandpass each
- Assumptions
  - Perfect wavefront
  - Post processing with no wavefront drifts between science target and star calibrator
  - Only photon noise

See HDST report

Simulated visible light image of a solar system twin seen at 13pc with 12 m telescope and APLC/SP design

Earth

Venus

Jupiter

HDST report (2015) simulations:
M. N’Diaye, L. Pueyo

40h exposure time
The pseudo zodi problem:

That the model KB dust density is negligible compared to the zodiacal cloud interior to 5 AU. For this investigation, we explicitly removed all KB dust interior to 5 AU, where the KB dust models become less reliable due to Poisson noise. To further reduce Poisson noise, we azimuthally averaged the Kuiper Belt dust model around the disk's axis of symmetry in steps of $0.36^\circ$. For Figure 1, we masked off the central 0.5 AU of each image.

Forward scattering grains in the line of sight masquerade as “face on” zodi in an edge on system.
This is not just a theoretical construction.

The disk around Beta Pictoris is very forward scattering.
This is not just a theoretical construction.

The disk around Beta Pictoris is very forward scattering.
Measurements of scattering phase function

Fig. 7.— Illumination-corrected flux as a function of scattering phase angle at and exterior to the belt maximum (lower and upper panels, respectively). The SE and NW halves of the disk are shown in red and black, respectively. The yellow line shows the best fourth degree polynomial fit to the scattering phase function. The dashed green line shows the best fit Henyey-Greenstein phase function, a poor fit to the observed variation.

Repeating this procedure for $a$ ranging from 71 AU to 263 AU in steps of $\Delta a = 2.63$ AU (1 pixel), we obtained the SPFs shown in Figure 8. Because grains beyond the parent body ring should be size-sorted (see Section 4.1.2), with $s$ decreasing with increasing $a$, the normalization of the SPF at a given $a$ is degenerate with the average $Q_{\text{sca}}$ and surface density at a given $a$. Additionally, the normalization of a given SPF strongly depends on the behavior of the SPF at small $\theta$, but our observations are limited to $60^\circ \lesssim \theta \lesssim 120^\circ$.
Comparing the SPFs for D68 and the G ring. The upper plot displays the normal-debris disks may produce a “pseudo-zodiacal” haze of forward-scattered starlight if oriented be problematic for future exoEarth imaging missions. Stark et al. (2015) showed that cold 2010; Golimowski et al. 2011; Lebreton et al. 2012).

Counterparts, potentially explaining the low apparent albedo of some disks (e.g., Krist et al. 2010).

Comparison, isotropic scatterers have a SPF equal to 1 scattering for debris disks therefore may be greatly underestimated.

Conclude that fits to debris disk SPFs, over typical ranges of observable scattering angles, in the right panel, neither HG function fit accurately predicts the model SPF at range of scattering angles accurately predicts the forward scattering peak at.
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.
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Soummer et al. 2014

Choquet et al. 2015, in prep.
Scattering phase function cannot be measured for angles from 0 to 180 on a single system.

Next step is to get a large sample of debris disks at various inclinations.

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Signposts of planetary formation in circumstellar structures

Debris/proto-planetary disks contain by-products/ingredients of planetary formation.

Soummer, Perrin, Pueyo et al., 2014.

Scattering phase function cannot be measured for angles from 0 to 180 on a single system.

Next step is to get a large sample of debris disks at various inclinations.

Choquet et al. in prep.

Soummer et al. 2014

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