EXCEDE

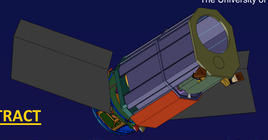
EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Glenn Schneider (gschneider@as.arizona.edu)[1], Olivier Guyon[1], and the *EXCEDE* Technology Development, Science, Mission, and Management Team

Ruslan Belikov[2], Domenick Tenerelli[3], Roger Angel[1], Laird Close[1], Carol Grady[4], Thomas Greene[2], Dean Hines[5], Phil Hinz[1], Paul Kalas[6], Marc Kuchner[7], George Rieke[1], Alycia Weinberger[8], Barbara Whitney[9], Mark Wyatt[10], Christopher Stark[7], Michael 2Lesser[1], Elizabeth Stobie[10], John Marmie[2], George Prout[1]

[1]The University of Arizona, [2]NASA Ames Research Center, [3]Lockheed Martin Corp., [4]Eurkea Scientific, [5]Space Telescope Science Institute, [6]University of California, Berkeley, [7]NASA/Goddard Space Flight Center, [8]Carnegie Institute of Washington, [9]University of Wisconsin, [10]University of Cambridge, [11]National Optical Astronomy Observatory

AUSTIN TX 8-12 JAN 2012



ABSTRACT

We present an overview of the **EXoplanetary Circumstellar Environments and Disk Explorer (*EXCEDE*)**, selected by NASA as a Category III EXPLORER program for technology development and maturation. *EXCEDE* will study the formation, evolution and architectures of exoplanetary systems, and characterize circumstellar environments into stellar habitable zones. EXCEDE provides contrast-limited scattered-light detection sensitivities ~ 1000x greater than HST or JWST coronagraphs at a much smaller effective inner working angle (IWA), thus enabling the exploration and characterization of exoplanetary circumstellar (CS) disks in currently inaccessible domains. *EXCEDE* will utilize a laboratory demonstrated high-performance Phase Induced Amplitude Apodization Coronagraph (PIAA-C) integrated with a 70 cm diameter unobscured aperture visible light telescope. The *EXCEDE* PIAA-C will deliver star-to-disk augmented image contrasts of < 10^{-8} and a 1.2 λ/D IWA of 0.14" with a wavefront control system utilizing a 2000-element MEMS deformable mirror (DM) and fast steering mirror (FSM). *EXCEDE* will provide 144 mas spatial resolution at 0.4 μm with dust detection sensitivity to levels of a few tens of zodis with two-band imaging polarimetry. *EXCEDE* is a science-driven technology pathfinder that will advance our understanding of the formation and evolution of exoplanetary systems, placing our solar system in broader astrophysical context, and will demonstrate the high contrast technologies required for larger-scale follow-on and multi-wavelength investigations on the road to finding and characterizing exo-Earths in the years ahead.

CS Disks: Signposts of Planetary Systems & Tracers of Planets

The mere presence of a debris disk is a signpost for some sort of planetary system.

Spatially resolved imaging reveals its structure and traces the presence of massive planets.

MISSION GOALS

- **To characterize circumstellar environments in habitable zones (HZs) to assess the potential for planets.**
- **To understand the formation, evolution, and architectures of planetary systems.**
- **To develop & demonstrate advanced coronagraphy in space enabling future exoplanet imaging missions.**

SCIENCE OBJECTIVES

EXCEDE WILL UTILIZE OBSERVATIONS OF DUSTY CS DISKS TO:

1. **Explore the amount of dust in Habitable Zones (where dust indirectly traces the level of terrestrial planet bombardment by asteroids and meteorids).**
2. **Help determine if this dust will interfere with future planet-finding missions.**
3. **Constrain the composition of material delivered to planets.**
4. **Investigate what fraction of systems have massive planets on large orbits.**
5. **Observe how protoplanetary disks make Solar System-like architectures.**
6. **Measure the reflectivity of giant planets and constrain their compositions.**

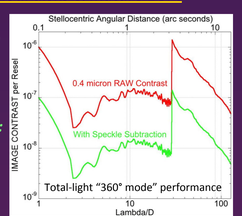
THE NEED FOR *EXCEDE*

EXCEDE fulfills the capability currently lacking in NASA's mission portfolio to achieve today's key exoplanetary science goals.

A large aperture telescope is not require to meet EXCEDE's scientific objectives. Imaging CS dust at small IWA is a contrast, not photon, limited problem.

Imaging Sensitivity to ~ 10 zodi disks & mature EGPs

- Diffraction-limited polarimetric & total light ***imaging in 2-bands: 0.4 & 0.8 μm*** (spatial resolution 0.14" and 0.28").
- ***1.2 λ/D inner working angle (IWA) (IWA at the diffraction limit)***
- ***Raw Image contrasts for science goals:***
  10^{-6} – $^{-7}$ resel^{-1} @ 1.2 – 2.0 λ/D
  10^{-7} resel^{-1} @ 2 – ~25 λ/D
- Photon-limited polarized flux contrast augmentation (x10 – 100)



Using Disks to Discover the Diversity of Planetary Systems

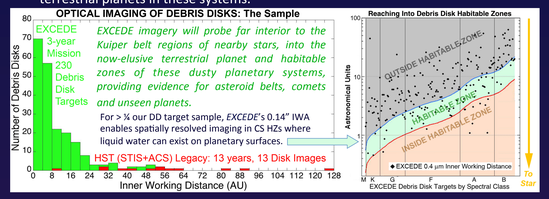
- Scattered-light images provide the greatest insights because they trace dust at a wide range of stellocentric distances, but…
- *No existing coronagraphs have sufficiently small inner working angles and disk-to-star image contrast sensitivity to probe CS disk systems. in their habitable zones (where the Earth resides in our solar system).*
- Dynamical interactions between planets and disks are predicted to play vital roles in generating the architectures of planetary systems, but the inner regions of such systems, today, remain obscured.

HST optical images of CS Disks. *EXCEDE will image ~ 1000x fainter in contrast and at least 3x closer to their stars and at spatial resolutions comparable to the best JWST will deliver.*

S.O. 1: What are the levels of dust in the HZs of exoplanetary systems?

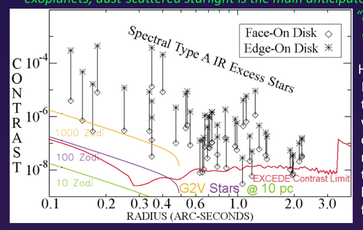
EXCEDE will provide direct images of light-scattering debris disks around a sample of ~ 230 nearby (≤ 100 pc) stars revealing the levels of zodiacal light - a proxy for the:

— richness of planetesimal belts and their degree of gravitational stirring.
— indirect indication of the level of bombardment that might be experienced by terrestrial planets in these systems.



S.O. 2: Will dust in the HZs interfere with planet-finding?

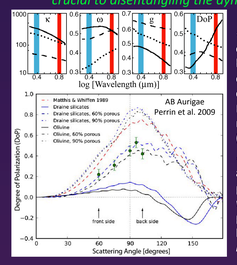
The amount of dust in HZs is key to determining the best strategies to image Earth-like exoplanets; dust-scattered starlight is the main anticipated source of astrophysical "noise" impeding faint exoplanet detection.



However…
It is arguably conceivable that by targeting stars without debris dust, future exoplanet imaging missions may be selecting targets unlikely to have had sufficient initial mass for rich planetary systems.

S.O. 3: What veneer is delivered to planets by asteroids and comets?

Identifying the presence of icy and organic-rich disk grains will give the first clues to the presence of volatiles important for life. EXCEDE's two-band imaging polarimeter is crucial to disentangling the dynamical and compositional history of disks.

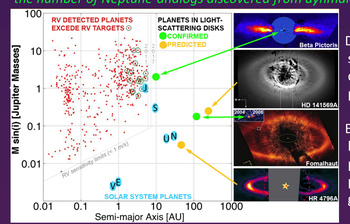


Distinguishing Grain Properties 2-band Polarimetry

- Disks may be full of volatile-rich porous grains that carry H_2O and C to planet surfaces, or compact and bone-dry spherules. Different grains have different λ dependent absorption (κ) and scattering efficiencies (ω), directional profiles (g) and degree of polarization (DoP). Examples show compact ISM-like grains (solid lines), moderate-sized fluffy grains (dotted) and larger grains (dashed) as in some PP disks.
- *EXCEDE* measures the DoP of dust-scattered starlight as a stellocentric function of azimuthal angle. *HST* prototype coronagraphic polarimetry observations of the *very* bright AB Aur CS disk (accessible at *HST* contrasts) place tight constraints on the likely composition of the light-scattering dust in this system. *EXCEDE* will probe *many* more CS disks in this way.

S.O. 4: How many systems have massive planets on large orbits?

EXCEDE's image contrast and spatial resolution (144 mas at 10 pc) will vastly increase the number of Neptune-analogs discovered from dynmaical influences on debris disks.



Dynamically-induced structures in circumstellar disks betray the presence of planetary systems.

EXCEDE will reveal the radial locations of circumstellar planetesimal belts – a powerful indicator of gas-giant and ice-giant planets.

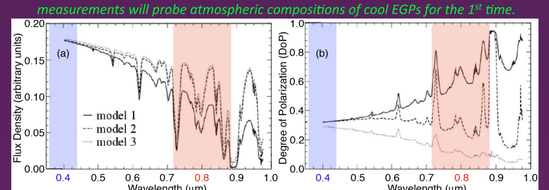
S.O. 5: How do PP disks make Solar-System-like architectures?

EXCEDE images will reveal disk sub-structures including large (> 20 AU) cavities and gaps associated with young Jovian-mass planets, and observationally test models that predict gaps opening in CS disks as a result of tidal interactions with giant planets.

Theoretical models predict material-depleted disk "gaps", observable by *EXCEDE*, evolving over time due to the presence of co-orbiting planets (illustration from Bryden et al 1999).

S.O. 6: What are the albedos & compositions of cool giant exoplanets?

EXCEDE will produce the 1st images of EGPs in the inner (0.5 – 7 AU) regions of mature planetary systems like our own. Simultaneous DoP, color, and total brightness measurements will probe atmospheric compositions of cool EGPs for the 1st time.



Model planetary atmospheres affected by (1) molecular photochemestry , (2) tropospheric clouds and (3) stratospheric haze. *EXCEDE* will inform and arbitrate.

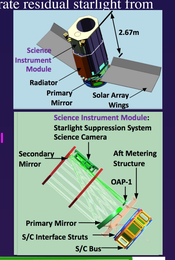
How *EXCEDE* Will Succeed — Three Key Enabling Technologies

(1) A highly efficient coronagraph to block central starlight while imaging the surrounding field to an IWA equal to the diffraction limit.
High-performance Phase Induced Amplitude Apodization (PIAA) coronagraph with *raw* "background"-to-peak contrast ratios:
- 10^{-6} – $^{-7}$ resel^{-1} from 1 – 2 λ/D with a 1.2 λ/D IWA* (*50% throughput)
- ≤ 10^{-7} resel^{-1} with ≥ 90% throughput everywhere beyond a 1 resel annulus (to ≥ 22 λ/D = 2.6" at 0.4 μm, 5.2" at 0.8 μm) circumscribing a 1.2 λ/D coronagraphic mask.

(2) A robust wavefront (WF) control system to deliver a high-quality, stable, wavefront to the coronagraph.
- 2000-element centrally actuated Micro Electro-Mechanical Systems (MEMS) Deformable Mirror (DM) *using the science detector* to measure & correct mid-spatial frequency WFEs (e.g., manifested as "speckles").
- Low Order Wavefront Sensor (LOWFS) using central starlight and Fast Steering Mirror (FSM) to measure/correct Tip/tilt & Focus.

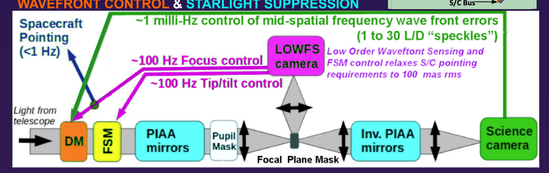
3) Well understood calibration methods to accurately separate residual starlight from genuine source in science images.

EXCEDE Science Payload Description



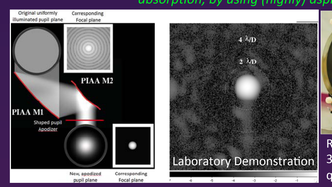
- **70 cm unobscured aperture off-axis telescope**
- **Fine Steering Mirror for high precision pointing control**
- **Low Order Wave Front Sensor for focus & tip/tilt control**
- **MEMS Deformable Mirror for wave front error control**
- **Phase Induced Amplitude Apodization coronagraph**
- **Two-band Nyquist-sampled imaging polarimeter**

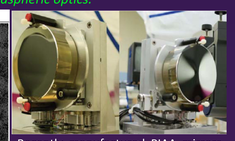
WAVEFRONT CONTROL & STARLIGHT SUPPRESSION



Phase Induced Amplitude Apodization (PIAA) Coronagraphy

PIAA is a lossless beam apodization producing a high contrast image of an on-axis point source with no Airy rings! Ideal for coronagraphy. PIAA apodizes the pupil by geometric redistibution of light, not by selective masking/ absorption, by using (highly) aspheric optics.



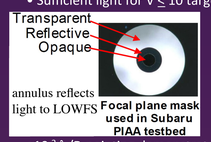


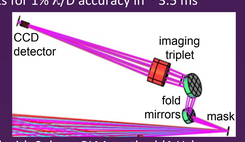
Recently manufactured PIAA mirrors 3.8 nm RMS surface error exceed WF quality requirements for EXCEDE.

Low-Order Wavefront Sensor (LOWFS)

Provides active Tip/Tilt and Focus control with Fast Steering Mirror while relieving spacecraft of highest levels of fine body-pointing control

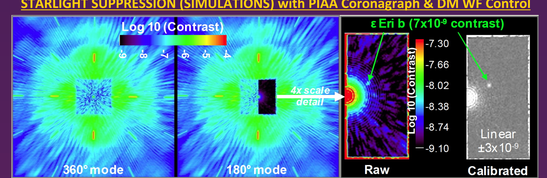
- Measures (telemeters) residual astigmatism
- Uses broadband light from reflective 0.6 – 1.2 λ/D annulus on FPM
- Sufficient light for V ≤ 10 targets for 1% λ/D accuracy in ~ 3.5 ms





- 10^{-3} λ/D pointing demonstrated with Suburu PIAA testbed (1 Hz)
- Faster (100 Hz) LOWFS now operating in SCExAO instrument

STARLIGHT SUPPRESSION (SIMULATIONS) with PIAA Coronagraph & DM WF Control

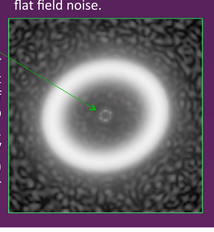


- Image contrasts < 10^{-7} and 10^{-8} are achieved within the DM WF control zone (here 28 λ/D; ~ 7" x 7" @ 0.4 μm with 64² DM) in 360° (disk survey) and 180° (faint-disk follow-up and planet imaging) modes.
- Simulated PSFs with 1 mas target mis-centering and 10 inoperable DM actuators (worse than GPI yield).

Revealing Circumstellar Debris in Habitable Zones

EXCEDE reveals the *inner* regions of circumstellar debris systems, analogous to the main asteroid belt in our solar system, otherwise lost in the glare of their central stars. Right: Simulated image of an HD 181327-like CS debris system with a large (r = 1.7"), bright debris ring (partially observable with HST/ ACS just beyond its effective inner working angle) and a hypothetical 100x fainter, 10x smaller, inner debris belt (r = 0.17") observable with *EXCEDE*.

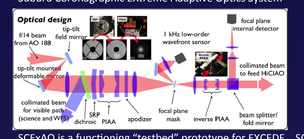
Above: ε Eri b @ 3.3 AU (9 λ/D) 180° WF control mode image simulations with 90% speckle subtraction, photon, and 1.4% flat field noise.



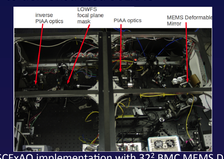
Wavefront Control and Starlight Suppression System (SSS) – Heritage

Key elements in *EXCEDE* SSS similar to demonstrated SCExAO*

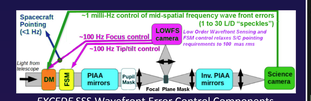
Suburu Coronagraphic EXtreme Adaptive Optics System



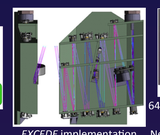
SCExAO is a functioning "testbed" prototype for EXCEDE



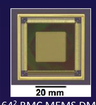
SCExAO implementation with 32² BMC MEMS DM



EXCEDE SSS Wavefront Error Control Components



EXCEDE implementation SSS/SIM design using BMC MEMS DM

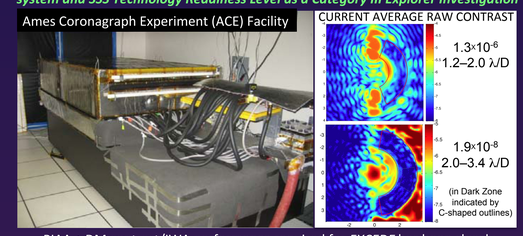


64² BMC MEMS DM (similar to GPI)
New 2000-element device under study for *EXCEDE*

*SCExAO two engineering run on telescope Feb & Sept 2011

Wavefront Control and Starlight Suppression System (SSS) – Testing

The NASA/Ames Coronagraph Testbed will be used to advance the EXCEDE sub-system and SSS Technology Readiness Level as a Category III Explorer Investigation



PIAA + DM contrast/IWA performance required for *EXCEDE* has been closely demonstrated in 0.65 μm monochromatic light at the ACE facility
Category III Technology Development Goal: 20% Bandwidth @ 0.4 μm

EXCEDE Science Camera

- *1242 x 1152 pixel e2V CCD operating at -108C with a 2-stage thermo-electric cooler*
  – *3e⁻ read noise, noise from dark current ~ 3 e⁻ pixel⁻¹ in 1000 s*
  – *High (~ 70%, TBS) QE in both spectral bands*
- *20% wide "B"/"R" spectral bands and filtered Wollaston polarizers*
  – *Passbands: 0.36 to 0.44 μm and 0.72 to 0.88 μm (plus 1% wide "acq" filter)*
- *Image Scale: 59 mas/pixel, critically sampled @ 0.4 μm*
  – Spatial resolution: 144/mas @ 0.4 μm ("B"), 288/mas @ 0.8 μm ("R")
- *Field-of-View (Working Angle Range with 2000-element MEMS Deformable Mirror)*
  – IWA in both bands at resolution limit
  – DM controlled: 5.5" x 5.5" @ 0.4 μm , 11" x 11" @ 0.8 μm
  – DM uncontrolled: 22" x 22" (~ 10^{-6} contrast @ control zone limit)
- *Two-band Polarimetric Imaging**
  – Total light and fractional polarization (DoP) imaging
  – Enables full polarimetric analysis: u, q, p, i, θ, DoP
  *simultaneous Q & U with four (0°, 45°, 90°, 135°) pol angle sampling in each band

EXCEDE TARGETS (4 classes oversubscribing a 3-year DRM by ~ 25%)

- Screened against stellar binarity that would degrade image contrast.
- Span ages from ~ 1 My to several Gyr and spectral types M – B.
- Stellar brightness sufficient for LOWFS & DM WF control.
- Sample sufficiently large to diffuse uncertainties in age estimations.

1) IR Detected Debris Disk (DD) Systems
- 230 targets* with $L_{disk}/L_* \geq 10^{-5}$ and d ≤ 100 pc (in most cases)
  – will re-image with EXCEDE sensitivity the ~ 20 DDs previously resolved by HST.

2) Protoplanetary (PP) Disk Systems
- 54 optically-thick PP & transition disks around T Tau & Herbig Ae/Be stars at d ≤ 150 pc.

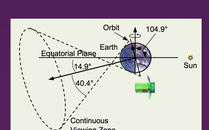
3) The Nearest Stars out to 7 pc
- 49 stars in the immediate solar neighborhood for which *EXCEDE* is capable of imaging zodiacal dust in HZs as faint as tens of zodis.

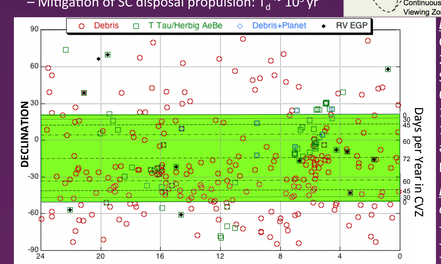
4) Radial Velocity Detected Planetary Systems
- ≥ 9 stars with RV planets potentially within the reach of *EXCEDE*.

* (separately, 6 IR-bright DD targets have RV detected planets)

EXCEDE TARGETS & Orbital Considerations

Selected Orbit Provides:
– Large CVZ (efficient scheduling of most targets)
– Thermal Stability ("follows" terminator)
– Allows (multiple) ONR ad non-CVZ observations
– Mitigation of SC disposal propulsion: T_d ~ 10^5 yr





***EXCEDE* ORBIT**
Circular LEO
2000 km altitude
Sun-synchronous
6 AM asc. Node
105° inclination
127 min period
antisun-cone pointed

***EXCEDE* CVZ**
assuming 5° BEA
-50.3° ≤ δ < +20.5°
72 day mid-pass