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Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

Direct Imaging & Spectroscopy of Exoplanetary Systems with the JWST Early Release Science Program

Sasha Hinkley[a], Aarynn L. Carter[b], Shrishmoy Ray[a], Beth Biller[c], Andrew Skemer[b], Elodie Choquet[d], Maxwell A. Millar-Blanchaer[e], Stephanie Sallum[f], Brittany Miles[b], Niall Whiteford[g], Polychronis Patapis[h], Marshall Perrin[i], Laurent Pueyo[i], Karl Stapelfeldt[j], Jason Wang[k,l], Kimberly Ward-Duong[m,i], Julien H. Girard[i], Dean Hines[i], Jens Kammerer[i], Jarron Leisenring[n], Yifan Zhou[o], Michael Meyer[p], Michael C. Liu[q], Mickael Bonnefoy[r], Simon Petrus[r,s], Mariangela Bonavita[t], Gael Chauvin[r], Christine Chen[i,u], Thayne Currie[v], Kielan K. W. Hoch[i], Cecilia Lazzoni[a], Elisabeth C. Matthews[w], Michael McElwain[x], Isabel Rebollido[i], Emily Rickman[y], Glenn Schneider[n], Anand Sivaramakrishnan[i], Jordan M. Stone[z], and the rest of the ERS 1386 Team[1]

[a]Univ. of Exeter, Astrophysics Group, Physics Building, Stocker Road, Exeter, EX4 4QL, UK.
[b]Dept. of Astronomy & Astrophysics, University of California, Santa Cruz, CA 95064, USA
[c]SUPA, IfA, The Univ. of Edinburgh, Royal Obs., Blackford Hill, Edinburgh, EH9 3HJ, UK
[d]Aix Marseille Univ., CNRS, CNES, LAM, Marseille, France
[e]Department of Physics, University of California, Santa Barbara, Santa Barbara, CA, USA
[f]Dept. of Physics and Astronomy, University of California, Irvine, Irvine, CA, USA
[g]Dept. of Astrophysics, AMNH, Central Park West at 79th Street, NY 10024, USA
[h]Institute for Particle Physics & Astrophysics, ETH Zurich, 8092 Zurich, Switzerland
[i]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[j]JPL, Caltech, M/S 321-100, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[k]Department of Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[l]Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
[m]Department of Astronomy, Smith College, Northampton MA 01063, USA
[n]Steward Observatory, University of Arizona, 933 N. Cherry Ave, Tucson, AZ 85721-0065 USA
[o]Department of Astronomy, The University of Texas at Austin, 2515 Speedway Boulevard Stop C1400, Austin, TX 78712, USA
[p]Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
[q]Institute of Astronomy, University of Hawaii, 2860 Woodlawn Drive, Honolulu, HI 96822, USA
[r]Université Grenoble Alpes/CNRS, IPAG, 38000 Grenoble, France
[s]Núcleo Milenio Formación Planetaria-NPF, Universidad de Valparaíso, Av. Gran Bretaña 1111, Valparaíso, Chile
[t]School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA
[u]Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, US
[v]NASA-Ames Research Center, Moffett Field, California, USA
[w]Observatoire Astronomique de l'Université de Genève, 51 Ch. Pegasi, 1290 Versoix, Switzerland
[x]NASA-Goddard Space Flight Center, Greenbelt, MD, USA
[y]European Space Agency (ESA), ESA Office, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[z]US Naval Research Laboratory, Remote Sensing Division, 4555 Overlook Ave SW, Washington, DC 20375

Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, edited by Laura E. Coyle, Shuji Matsuura, Marshall D. Perrin, Proc. of SPIE Vol. 12180, 121800S · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2629919

ABSTRACT

The *direct* characterization of exoplanetary systems with high contrast imaging is among the highest priorities for the broader exoplanet community. As large space missions will be necessary for detecting and characterizing exo-Earth twins, developing the techniques and technology for direct imaging of exoplanets is a driving focus for the community. For the first time, *JWST* will directly observe extrasolar planets at mid-infrared wavelengths beyond 5 μm, deliver detailed spectroscopy revealing much more precise chemical abundances and atmospheric conditions, and provide sensitivity to analogs of our solar system ice-giant planets at wide orbital separations, an entirely new class of exoplanet. However, in order to maximise the scientific output over the lifetime of the mission, an exquisite understanding of the instrumental performance of *JWST* is needed as early in the mission as possible. In this paper, we describe our 55-hour Early Release Science Program that will utilize all four *JWST* instruments to extend the characterisation of planetary mass companions to ∼15-20 μm as well as image a circumstellar disk in the mid-infrared with unprecedented sensitivity. Our program will also assess the performance of the observatory in the key modes expected to be commonly used for exoplanet direct imaging and spectroscopy, optimize data calibration and processing, and generate representative datasets that will enable a broad user base to effectively plan for general observing programs in future cycles.

Keywords: Coronagraphic imaging; Direct imaging; Exoplanet detection methods; Space telescopes; Exoplanet atmospheres

1. INTRODUCTION

As the indirect transit and Doppler detection methods are inherently much less sensitive to wide-separation planets with long orbital periods, the direct imaging technique[1,2] will be the only approach to fully define the outermost architectures of planetary systems (∼10 to hundreds of AU), and provide a more complete understanding of the true frequency of planetary mass companions to nearby stars.[3,4] In the last decade, imaging observations mostly at wavelengths of $\lesssim 2\,\mu$m have produced numerous scattered light images of circumstellar disks,[5] and directly revealed ∼ 10-20, young ($\lesssim 50$ Myr), massive ($\gtrsim 1\,\mathrm{M_{Jup}}$) planets.[6–9] Direct Imaging is also the only technique that will be capable of *characterising* exoplanets at orbital radii $\gtrsim 0.5$ AU, as transit transmission spectroscopy[10] requires multiple transits to achieve a strong signal for Earth-mass planets on Earth-like orbits around Sun-like stars[11] resulting in prohibitively long time baselines. It is also the only technique projected to provide the in-depth characterization of such exo-Earths.[12,13]

By spatially separating the light of the host star and the extremely faint planet, the direct imaging technique is also naturally suited to *direct* spectroscopy of planets themselves, allowing detailed characterization.[7,8,14] In addition to providing information[15,16] on atmospheric properties and compositions, the direct imaging technique can provide powerful estimations of fundamental parameters, e.g. luminosity, effective temperature, and orbital properties.[17] The characterization power of the direct imaging method becomes even more pronounced when combined with other exoplanet detection techniques, such as precise radial velocity monitoring or astrometry,[18–21] to more fully constrain parameters (e.g. planet mass) that are difficult to ascertain with one technique alone.

1.1 JWST

JWST will be transformative for characterizing exoplanet atmospheres at mid-infrared and longer wavelengths (3-28 μm). In addition to a handful of spectra of free-floating brown dwarfs from *The Spitzer Space Telescope* and *Akari* missions,[22,23] direct images of exoplanets from 3 to 5 μm exist,[24–26] but the extremely high telluric background has imposed a strong sensitivity barrier. Transit transmission spectroscopy of transiting "Hot Jupiter" exoplanets using the *Spitzer Space Telescope* exist,[27] but this class of planet has very different properties than young planets studied via direct imaging, or even solar system giant planets. Even further, despite some tantalizing early detections,[28] exoplanets have never been *directly* observed at wavelengths $\gtrsim 5\,\mu$m. To date, much of the instrumentation dedicated to the purpose of high contrast imaging[29–31] has operated at wavelengths $\lesssim 3\mu$m. However, in addition to observing planets closer to the peak of their thermal emission, obtaining exoplanet photometry and spectroscopy at 3-5 μm is a key probe of atmospheric compositions, and dramatically improves differentiation between equilibrium and disequilibrium atmospheric chemistry.[32–34]

JWST utilizes four science instruments operating in the infrared, with three of these operating at wavelengths shorter than 5 μm. NIRCam[35] and NIRSpec[36] are the primary near-infrared imager and spectrograph, respectively, but only NIRCam and MIRI offer a coronagraphic mode. NIRCam offers a series of coronagraphic occulting masks[37] and preflight estimates of the coronagraphic performance suggest that contrasts of $\sim 10^{-4} - 10^{-5}$ within $\sim 1''$ will be achieved. NIRSpec will have numerous capabilities for spectroscopically characterizing the atmospheres of extrasolar planets,[38] including obtaining direct spectroscopy for widely separated companions. NIRISS[39] is equipped with an Aperture Masking Interferometer ("AMI") mode[40] with the goal of obtaining moderate contrast ($10^{-3} - 10^{-4}$) at separations comparable to (and within) the *JWST* diffraction limit of 130-150 mas at $\sim$4-5 μm. MIRI[41, 42] is the only instrument capable of observations at wavelengths longer than 5 μm, and is equipped with four-quadrant phase mask (FQPM) coronagraphs[43] operating at 10.65, 11.60, and 15.50 μm, as well as a classical Lyot coronagraph operating at 23 μm.[44] In addition to offering very good contrast performance at small inner working angles of $\sim \lambda/D$ at wavelengths of 10-16 μm, the 4QPM coronagraph design was chosen during the MIRI design phase as it was one of the few coronagraphs that had been validated both in laboratory testing as well as on sky. Below we describe some of the potentially transformative science that will be done with *JWST* coronagraphy and spectroscopy for characterizing wide-separation giant planets, as well as circumstellar debris disks.

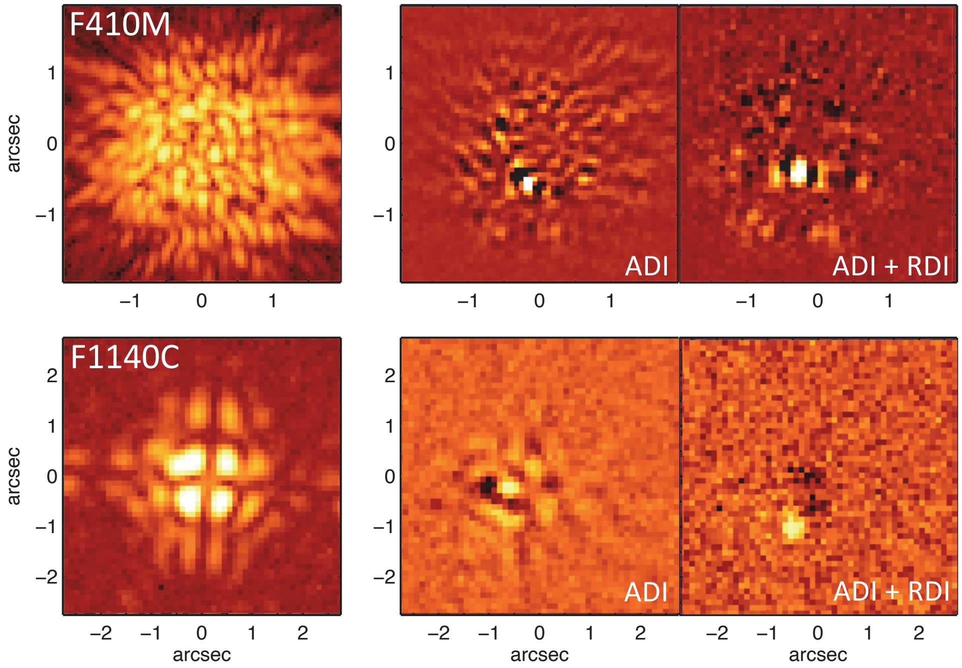

Figure 1. Simulated coronagraphic images of the directly imaged exoplanet HIP 65426b[7] in the 4.1μm NIRCam filter (*F410M, top row*), and the 11.4μm MIRI filter (*F1140C, bottom row*) using the simulation methods described in ref. 45. In each set of figures, the left image shows the coronagraphic point spread function for each bandpass, while the middle and right panels show subsequent image post-processing employing Angular Differential Imaging (ADI) or a combination of ADI with Reference Differential Imaging (labelled "ADI+RDI") that utilizes a small library of images obtained using the small grid dither strategy.

1.2 A New Class of Planets: Wide-Separation Saturn & Neptune Analogues

The exquisite thermal infrared sensitivity afforded by *JWST* means that it will be possible for the first time to directly image sub-Jupiter mass planets, an entirely new class of directly imaged planet.[46] Previous studies[47] have demonstrated the gain in sensitivity when using space-based imaging at infrared wavelengths, similar to those to be used with the *JWST* NIRCam instrument. In the background-limited regime within the field of view, *JWST* will have 50 times the sensitivity of the Gemini Planet Imager[8] operating at 2μm, and 500 times the sensitivity of the Keck/NIRC2 instrument at 4μm.[48] Analogues to our own solar system ice-giant planets should have very cold temperatures, and thus the peak wavelength of their emission will be shifted out of the near- and mid-infrared (1 to $\sim$5 μm) into to the thermal infrared ($\gtrsim$10 μm). The very high telluric background from the ground imposes a stark sensitivity limit, even with new technologies (e.g. adaptive secondary mirrors). Thus, in addition to potentially directly detecting a handful of planets detected by the radial velocity technique, the superior thermal infrared sensitivity of *JWST* will allow imaging for the first time of wide, young Saturn analogues in many cases down to masses of 0.2 $M_{\rm Jup}$. In the most favorable cases, *JWST* will be capable of directly imaging wide young Neptune analogues.[46, 49]

1.3 Studies of Circumstellar Disks with JWST

Exoplanets and circumstellar debris disks go hand-in-hand: the gravitational influence of giant planets in these systems shapes the belts of debris, generated by colliding remnant planetesimals,[50, 51] can exist in stable orbits around a star, and sculpts the dust distribution through scattering, secular interactions and resonances.[52, 53] Indeed, the structure of debris disks reveal dynamical relations between planets and their circumstellar environment, and any evaluation of *JWST's* ability to characterize planetary systems must also include its ability to characterize diffuse, extended emission from circumstellar debris disks.

With nearly an order of magnitude greater angular resolution than *Spitzer*, *JWST* will allow resolved imaging of asteroid belts in other systems for the first time. The very large, contiguous fields-of-view of NIRCam and MIRI, coupled with their high sensitivity, will be critically important for studies of debris disks, providing access to regions at high contrast beyond the control zones ($\sim$0.5-1.0$''$) of ground-based Adaptive Optics systems.[54, 55] In addition to constraining the dust scattering properties, NIRCam observations of debris disks may potentially directly detect the planets responsible for driving the ring structures, or provide very sensitive upper limits on their presence. *JWST* is well poised to address these issues, but the best observing practices need to be established quickly.

In this paper, we describe our upcoming 55-hour Early Release Science (ERS) Program dedicated to the direct imaging and spectroscopy of extrasolar planetary systems, which is described in much more detail in ref. 56. In §2 we provide our rationale for an ERS program dedicated to this task, and in §3 we provide a detailed overview of the observational strategy of our program. In §4 we describe our plans for rapid data processing as well as the Science Enabling Products ("SEPs") our team will deliver shortly after the program is executed, and in §5 we provide a summary and conclude.

2. RATIONALE FOR A JWST EARLY RELEASE SCIENCE PROGRAM

JWST will be a transformative observatory for directly characterizing both exoplanets and their circumstellar environments. It will enable very sensitive, high-fidelity imaging and spectrophotometry of exoplanetary systems in the near/mid-infrared with NIRCam, NIRSpec, and NIRISS, and with MIRI at wavelengths $\gtrsim$5 μm *for the first time*. However, imaging young extrasolar giant planets and disks at very small angular separations from a host star is an extreme technical challenge: at young ages ($\sim$1-100 Myr) even the most massive planets are typically $\sim 10^3$-10^6 times fainter than the host star, and buried in the halo of the instrumental Point Spread Function (PSF). At such a high level of contrast, an exquisite understanding is required of the instrument response, PSF stability, and PSF subtraction techniques during post-processing. To this end, successfully obtaining images of planets and circumstellar disks requires the correct choice of observation mode and extremely careful post-processing.

As described in ref. 48, the last ∼25 years of highly successful coronagraphy and high contrast imaging with *The Hubble Space Telescope (HST)* provides a very useful set of lessons for the best path forward with *JWST*. One clear lesson from the *HST* legacy is that, particularly for non-optimal coronagraphs (e.g., those on board *HST* or even *JWST*), more of the contrast gains come from state-of-the-art starlight suppression work in the image post-processing stage than from suppression at the hardware level.[48,57,58] Indeed, exquisite calibration of the PSF is key, and typically this is carried out by using some variation of the Angular Differential Imaging ("ADI") technique[59] to utilize the rotation of the observatory to disentangle bona fide astrophysical sources (e.g., planets) from the residual scattered starlight. For each individual science image, the task is to use other images in the sequence that do not contain a signal of the planet to construct an optimized, synthetic model of the PSF, typically using least-squares ("LS"),[60] or principal component analysis ("PCA") methods[61] to generate synthetic PSF calibrations that are optimally matched to each science exposure. However, *JWST* will typically only achieve ∼5° of rotation when the spacecraft is rolled slightly, meaning that the sensitivity of *JWST* will be limited at close separations from the star. However, it has now been well demonstrated, especially for space-based imaging such as *HST/NICMOS*[62] with PSF morphologies that are highly stable in time, that using a vast suite of reference PSF images from other epochs/targets can alleviate this problem. Indeed, over its lifetime, *JWST* will provide such an extensive library of images, but not necessarily in the early phases of the mission.

Coronagraphic imaging with *HST* required several cycles to optimize the observing strategy and PSF calibration methods, and the methods are still being refined (e.g. refs. 63 and 64). Further, applying techniques originally developed for the ground to *HST* archival coronagraphic data[62,65] has revealed vastly improved sensitivity to imaging planets and disks including numerous new discoveries from archival data.[57,58,66] Similar methods and algorithms may be applicable to *JWST* images, provided the correct observing strategy and data processing methods are identified as early as possible, and used consistently going forward. Although the *JWST* instruments have been characterized during instrument testing, neither the in-flight performance of each instrument, nor the optimal strategy for obtaining data in flight, or even the optimal ways to post-process the data are well understood.

The finite lifetime of the *JWST* mission means that it is essential to correctly optimize and implement the observing strategies as early as possible for gaining spectrophotometry and images of exoplanets and circumstellar disks. In anticipation of this need, in 2009 the Space Telescope Science Institute (STScI) appointed the *JWST* Advisory Committee (JSTAC) to provide a recommendation on how best to maximize the scientific return of *JWST*. One of the recommendations was to create a clear pathway "to enable the community to understand the performance of *JWST* prior to the submission of the first post-launch Cycle 2 proposals that will be submitted just months after the end of commissioning"[*]. In response, the STScI Director created the *JWST* Early Release Science (ERS) programs, comprised of ∼500 hours of Director's Discretionary Time (DDT). This program was to be characterized by open community access to substantial, representative datasets, in key instrument modes. Along with the SEPs described in §4, this effort will support the broader community in the preparation of future *JWST* proposals, and engage a broad cross-section of the community to familiarize themselves with *JWST* data and its scientific capabilities.[†]

From 2016-2017 numerous members of the community engaged in research related to the direct imaging and spectroscopy of exoplanets and circumstellar disks self-organized to formulate a program designed to address the key questions about *JWST* performance that will inform future proposal cycles. A total of 106 proposals were submitted, and 13 proposals were ultimately selected spanning a range of science disciplines including extrasolar planets, solar system, stellar populations and stellar physics, Galaxies and intergalactic medium, and host galaxies to massive black holes.

3. OVERVIEW OF ERS PROGRAM 1386

Our Program "High Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST" (Program 1386) was ultimately awarded 55 hours of DDT to utilize all four *JWST* instruments, and assess the performance of

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[*] The full description of the recommendations of the JSTAC can be found at: http://www.stsci.edu/jwst/about/history/jwst-advisory-committee-jstac

[†] More information on the ERS programs can be found at: http://www.stsci.edu/jwst/science-planning/calls-for-proposals-and-policy

Table 1. A Table showing the observing configuration for each of the major tasks in our program: coronagraphy of an exoplanet and a circumstellar disk, spectroscopy of a planetary mass companion, and aperture masking interferometry. In addition to the instruments used, targets to be observed (both primary and calibration targets), wavelengths/resolution employed, and observing modes, the table also shows in parentheses the partitions of time dedicated purely to science observations (denoted "$t_{\rm sci}$"), and the time charged to to the observatory ("$t_{\rm obs}$"), which includes observatory overheads. To calibrate some stray light effects discovered during MIRI commissioning, our program was also awarded an additional ∼12 hrs to collect background observations using MIRI, bringing our true time allocation to ∼68 hrs. However, since such a time commitment is not expected to be typical for future observing programs, we have chosen not to list it in this table.

Task (Instruments)	**Targets** ($t_{\rm sci}$, $t_{\rm obs}$)	**λ coverage, $\lambda/\Delta\lambda$**	**$t_{\rm sci}$ (hr)**	**$t_{\rm obs}$ (hr)**
Exoplanet Coronagraphy (NIRCam, MIRI)	Primary: HIP 65426 b (5.0, 10.4) Calibrator: HIP 68245 (2.9, 6.0)	2.50, 3.00, 3.56, 4.10, 4.44, 11.40, 15.50 μm	7.9	16.4
Disk Coronagraphy (NIRCam, MIRI)	Primary: HD 141569A (8.1, 14.2) Calibrator: HD 140986 (5.4,9.6)	3.00, 3.60, 10.65, 11.40, 15.50 μm	13.5	23.8
Spectroscopy of a Planetary Mass Companion (NIRSpec IFS, MIRI MRS)	VHS 1256 b	1-28 μm, R∼1500-3000	2.7	6.3
Aperture Masking Interferometry (NIRISS)	Primary: HIP 65426 (3.0, 4.7) Calibrator: HD 115842 (0.6, 1.8) Calibrator: HD 116084 (1.0, 2.3)	3.8 μm	4.6	8.8
			Total: 28.7	**Total: 55.3**

the observatory in representative modes that are highly applicable to our community going forward. In addition, our team has been tasked to: 1) optimize data calibration and analysis methods; 2) make clear recommendations to our community about the best practices for *JWST* observing; and 3) generate a set of SEPs, tools that will be essential for the broader community to plan for Cycle 2 proposals (§4). The ultimate outcome of this program will be to rapidly establish the optimal strategies for imaging and spectroscopy of exoplanetary systems going forward, and provide the community with a set of tools to help prepare the strongest proposals for Cycle 2 and beyond. A much more detailed description of the program can be found in ref. 56.

At the same time, our program will showcase the transformative science expected from *JWST* related to the direct characterization of planetary systems such as highly sensitive coronagraphy, direct spectroscopy into the thermal infrared, and interferometry. Table 1 provides an overview of the targets we will observe and their basic properties. The exoplanet HIP 65426b[7] and substellar object VHS J125601.92-125723.9b (hereafter "VHS 1256 b")[67,68] are both young companions to their host stars at wide orbital separations, and HD 141569A, is a young (5±3 Myr) circumstellar disk[69] still potentially in the phase of forming a planetary system.

Our program will carry out: 1) coronagraphic imaging of HIP 65426b and 2) HD 141569A at wavelengths extending to 15.5 μm; 3) spectroscopy of VHS 1256b at resolution $R \sim 1500$-3000 out to 28 μm; and 4) aperture masking interferometry of a bright star (HIP 65426) at 3.8 μm. Table 2 lists these four primary science tasks and the instruments they will employ, the primary targets for each of these tasks, as well as the objects selected for calibration. Table 2 also lists the wavelength coverage and spectral resolution, as well as details of the chosen observing mode, e.g. the NIRCam "MASK335R" or MIRI FQPM coronagraphy, NIRSpec Integral Field Spectrograph (IFS) or the MIRI Medium Resolution Spectrograph (MRS). Table 2 also lists the pure "science time" (denoted "$t_{\rm sci}$") dedicated to each of these three tasks, as well as the overall time charged to the observatory (denoted "$t_{\rm obs}$") reflecting spacecraft, observatory, and instrument overheads. In total, our program will utilize 55.3 hours of observing time, with 28.7 of these hours dedicated to pure science observations. A majority of this time will be dedicated to coronagraphic observations of HIP 65426b and HD 141569A (∼40 hours observatory time, ∼21 hours of science). Below we describe each of these components of the program in greater detail.

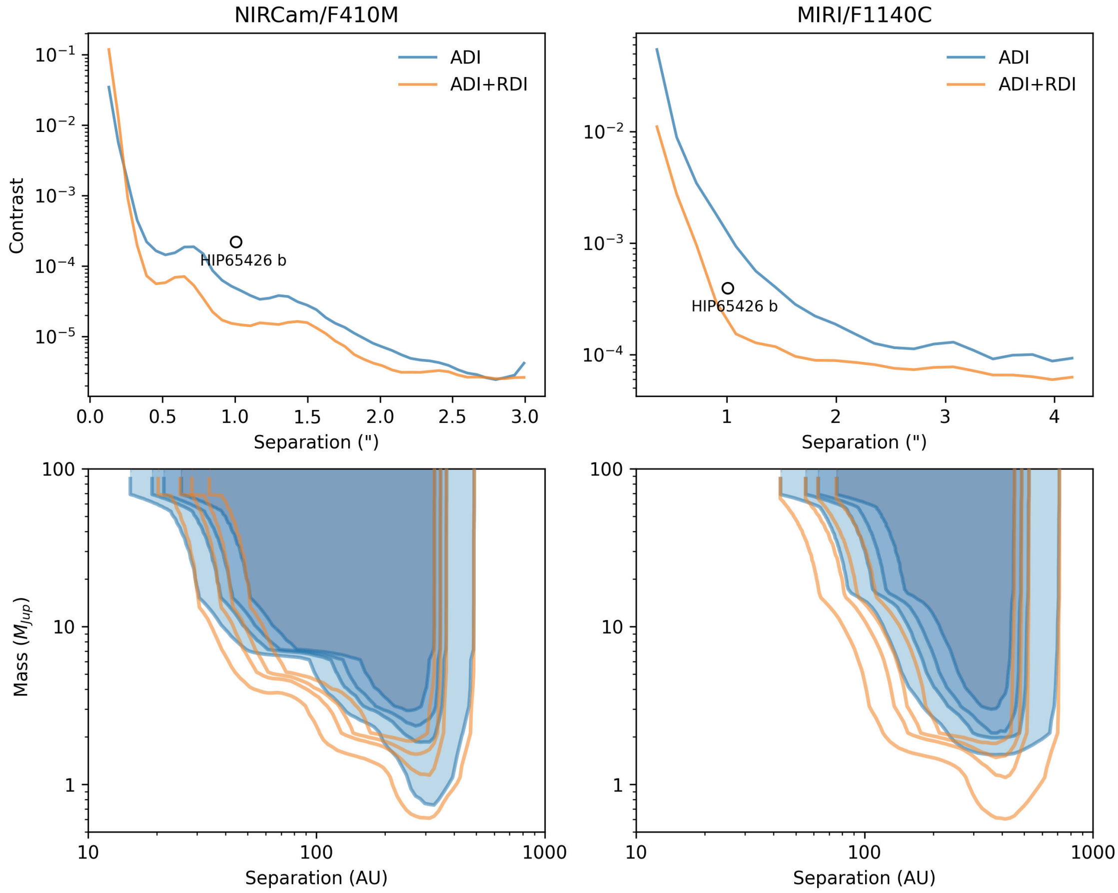

Figure 2. *Top row:* Simulated contrast curves using the updated version of the PanCAKE tool[45] showing the predicted contrast performance in the NIRCam F410M (4.1 μm) and MIRI F1140C (11.4 μm) *JWST* filters. The two sets of curves illustrate the coronagraphic performance using PSF subtraction based both on Angular Differential Imaging (ADI) as well as a combination of ADI and Reference Differential Imaging (RDI), corresponding to the images shown in Figure 1. The theoretical contrast of the HIP 65426b exoplanet is shown by the circular point. *Bottom row:* the corresponding detection probability maps[70] based on these contrast curves with the 30, 60, 70, and 80% detection probability contours highlighted.

3.1 Coronagraphy of an Extrasolar Planet

HIP 65426b is a 6-12 $\mathrm{M_{Jup}}$ planetary mass companion[7] with a wide projected orbital separation of 92 AU, and a young age (14±4 Myr) based on its host star's high probability of membership to the Lower Centaurus Crux association.[71] This was the first major discovery by the SPHERE "SHINE" GTO survey.[4] Initial photometric measurements from 1 to 5μm[72,73] and medium resolution spectroscopy[74] of this object are consistent with a dusty, low surface gravity atmosphere with mid/late-L spectral type. The angular separation of 830 mas and contrast of $\sim 10^{-4}$ relative to the host star make this object an ideal early target to be observed with the NIRCam and MIRI coronagraphs. Figure 1 shows synthetic coronagraphic images calculated using an updated version described in greater detail in ref. 45 of the Pandeia Coronagraphy Advanced Kit for Extractions (PanCAKE).[48,75] PanCAKE is a Python-based package which extends the capabilities of the primary *JWST* exposure time calculator (ETC) Pandeia[76] to be applicable to the coronagraphic observing modes of *JWST*.

Figure 1 also highlights the effect of various image post-processing strategies on the significance of the detection of the underlying planet HIP 65426b. The central panels of Figure 1 show the detection using a simple framework based on ADI, taking advantage of the fact that HIP 65426 will be observed in two configurations separated by a physical "roll" of the observatory of a few degrees. This well-tested methodology is based on the heritage of "roll deconvolution" methods developed for *HST*.[77,78] Figure 1 also shows the improvement in contrast that can be gained by tapping into a larger pool of PSF reference images to perform Reference Differential Imaging ("RDI") as described in refs. 62, 79 and 58, and labelled "ADI+RDI" in the figure. This method takes advantage of the "small-grid dither" strategy in which repeated observations of a calibration star are obtained at six or nine positions separated by sub-pixel spacings, with the goal of more broadly sampling PSF variations due to varying placement behind the corongraphic masks.

Numerous studies[57,58,62,66,79,80] have demonstrated the improved coronagraphic suppression at small inner working angles by tapping into a much larger "library" of reference images. This potential improvement in inner working angle is even more crucial for *JWST* which typically has an angular resolution of ~100-140 mas at 3-4 μm, compared to the ~30-50 mas resolution of 8-10m ground-based telescopes in the near-infrared. This improvement is most pronounced with coronagraphic datasets that a) have a large number of PSF reference images; and b) are highly stable in time, such as is expected to be the case for *JWST*. Indeed, the pool of reference images will inevitably grow over the lifetime of *JWST*, and our ability to suppress starlight at small inner working angles will improve over time as our library of reference images grows. Thus, it is of paramount importance to determine the correct observing strategy early in the mission, so that the community may tap into the most uniform pool of reference images possible. The coronagraphic datasets obtained as part of this ERS program will mark the first step in this process.

To demonstrate the sensitivity of coronagraphic observations using both NIRCam and MIRI, Figure 2 shows the expected achievable contrast corresponding to the various stages of image post-processing at 4.1 μm and 11.4 μm shown in Figure 1. The contrast curves were calculated using a modified version of PanCAKE described in[45] for the F410M and F1140C filters that we will utilise in this program. Rather than the 5σ contrast curves used historically (e.g., ref. 82), the curves are based on a 3×10^{-7} false positive fraction, taking into account the statistical correction due to small angular separations.[83] The contrast curves presented in Figure 2 are also calibrated for the two-dimensional throughput of the coronagraphs as well as the inherent throughput of the Karhunen-Loève Image Projection ("KLIP") subtraction routine[61] which uses a principal component analysis approach to build a synthetic reference image for each science image from a library of reference images. Importantly, these contrast curves also take into account dynamical changes in the wavefront error due to the varying thermal state of the optical telescope element (OTE) due to telescope slews, small variations in the tension of the physical structure of the telescope, or vibrations within the OTE (e.g. due to the OTE stray light baffle/insulation closeouts). For each wavelength, Figure 2 displays a curve assuming only a simple roll subtraction (termed "ADI"). Further, Figure 2 also shows the improvement in contrast by a factor of a ~few to ten that can be gained by taking advantage of the small-grid dither strategy (labelled "ADI+RDI" in the figure). As a calibration strategy for our observations of HIP 65426 b, we will observe the B2IV star HIP 68245, which is close on the sky to HIP 65426, but has ~8 times the brightness in the mid-infrared (K=4.49 versus K=6.77 for HIP 65426). The enhanced brightness of HIP68245 allows us to obtain a nine-point dithered observation of this calibrator without a prohibitively large amount of observing time. Table 2 shows that this calibrator star will

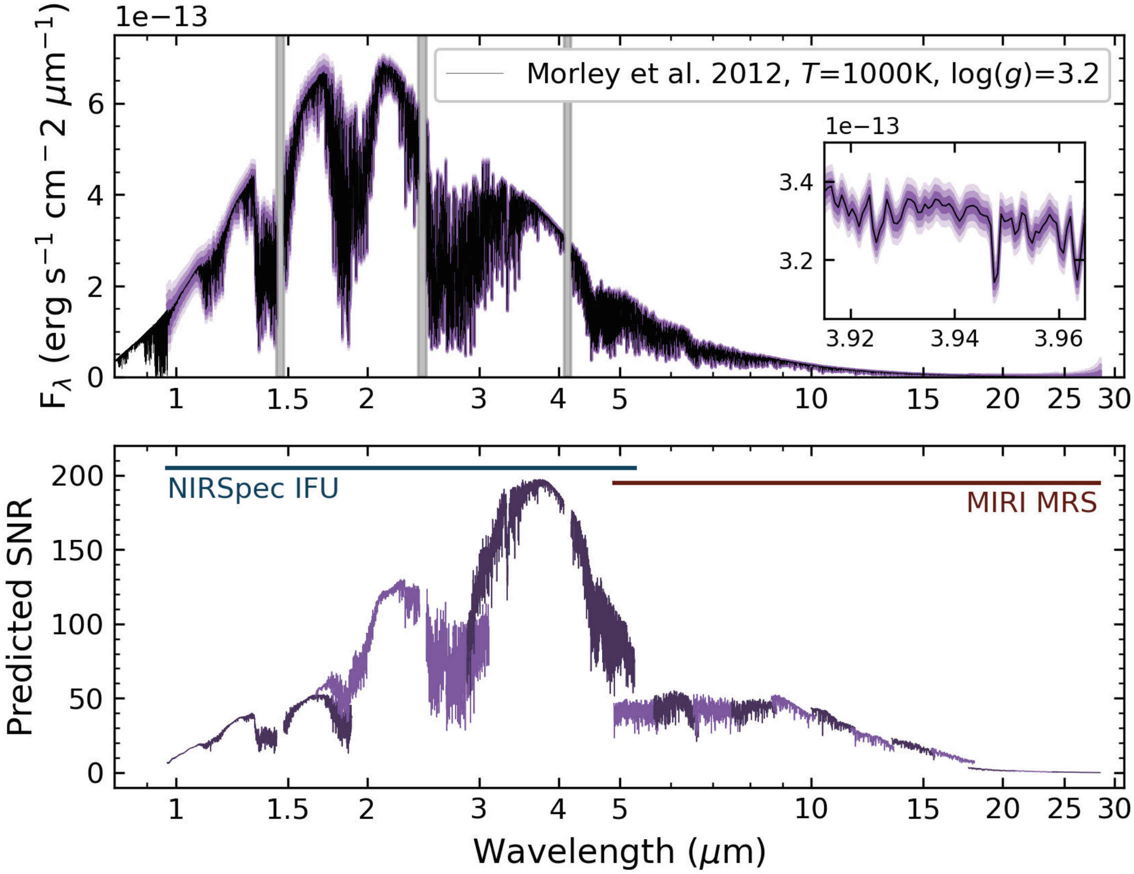

Figure 3. *Top panel:* A synthetic spectrum of the VHS 1256b planetary mass companion we will obtain using NIRSpec and MIRI, reflecting the actual spectral resolution, as well as a subset of the spectral range that will be covered (inset). The purple regions signify the 1, 2, 3σ confidence intervals in the spectrum, while the grey regions indicate portions of the spectrum where no data will be gathered due to detector gaps. The input model spectrum is based on a synthetic model described in ref. 81, which has been used in conjunction with the estimated signal-to-noise ratio defined in the ETC, to determine the confidence intervals shown in the plot. *Bottom Panel:* The predicted SNR for the VHS 1256b spectrum, as determined from the *JWST* ETC.

be observed in roughly half the charged time as our observations of HIP 65426 (6.0 hours versus 10.4 hours), but with nine times the data volume, enhancing the overall calibration process.

To calculate a representative estimation of the sensitivity to low mass companions (in Jupiter masses) as a function of projected orbital separation (in AU) of these observations, the lower panels of Figure 2 also show the corresponding two-dimensional detection probability maps based on the synthetic contrast curves. These detection probability maps, calculated using the Exoplanet Detection Map ("Exo-DMC") Calculator,[70] effectively demonstrate the degree of "completeness" to planetary mass companions as a function of mass and semi-major axis for a given coronagraphic observation. For a given planet mass and semi-major axis, Exo-DMC simulates an ensemble of orbital geometries with varying planetary eccentricity and inclination to determine which fraction of those realizations, identified by the various completeness contours, would be detected based on the supplied single contrast curve, thus providing a measure of the completeness of the observations. This calculation uses the evolutionary models of ref. 33 assuming an age of 14 Myr to convert from a contrast to a physical mass, and so these plots are dependent on the underlying evolutionary models as well the formulation of atmospheric process that they employ.

3.2 Spectroscopy of a Planetary Mass Companion

VHS 1256b[67,68] is a wide separation (∼103 AU), substellar companion ($19\pm5\,\mathrm{M_{Jup}}$) to a young M7.5 binary star.[84,85] While the VHS 1256 system is not a member of any known kinematic young moving groups, the work described in ref. 67 initially derived an age of 150-300 Myr, consistent with its low surface gravity. However, as discussed in ref. 86, the age has been significantly revised to 140±20 Myr, thus placing the mass of VHS 1256b at $11.8\pm0.2\,\mathrm{M_{Jup}}$ or $16\pm1\,\mathrm{M_{Jup}}$. With a spectral type of L7, infrared parallax measurements[87] show that VHS 1256b shares a region in a colour-magnitude diagram with other planetary mass companions that are near the L/T transition, and close to the deuterium burning limit such as HR 8799b, HD 203030B, and 2MASS J22362452+4751425 b.[6,88,89]

As shown in Table 2, we will observe VHS 1256b using the NIRSpec IFS from 1.66 to 5.27 μm with the G140H, G235H, G395H gratings ($\lambda/\Delta\lambda$ ∼1500-3500). Our selected exposure time provides a signal-to-noise ratio (SNR) of >20 across the majority of the wavelength range with many features detectable to a SNR of >100. However, these estimations are based on initial simulations, and the actual data may indeed have different SNR values. To probe silicate cloud features at 8 to 12 μm for the first time ever for low surface gravity objects, we will also perform mid-infrared spectroscopy on VHS 1256b from ∼5 to 28 μm using the MIRI MRS in all four channels with all three dispersers. To improve the sensitivity of the observations and minimize detector effects, we will utilize four dither positions for both the NIRSpec and MIRI observations.

Historically, the main obstacle to obtaining unbiased spectroscopy of planetary mass companions from ground-based spectrographs coupled to AO systems has been contamination from uncontrolled, residual scattered starlight within ∼1-2″.[59,82] The relatively large angular separation (∼8″) of VHS 1256b from its host binary pair means that our JWST observations should have minimal contamination of residual scattered starlight. Thus, JWST Spectroscopy of this object will allow high-fidelity detections of molecules from ∼2 to 28 μm that will be vital for the understanding of cloud physics driven by dust or thermochemical instability under low gravity conditions, as well as searching for evidence of silicate clouds at 8 to 12 μm. The VHS 1256b spectroscopy should also serve as a valuable community dataset for testing spectral extraction algorithms for NIRSpec and MIRI.

Figure 3 shows an example of the signal-to-noise and wavelength coverage for the spectroscopy of the VHS 1256b companion that will be obtained with our program. The figure shows a theoretical model atmosphere of a substellar object with the currently best-fit derived effective temperature and gravity parameters for VHS 1256b.[90] To calculate the effective uncertainty in the model as a function of wavelength, this model was then used as input into the *JWST* ETC, which in turn provides a measure of the expected signal-to-noise as a function of wavelength. Dividing the original model spectrum by this signal-to-noise spectrum effectively provides a measure of the noise as a function of wavelength, and this noise is represented by the purple shaded regions in the figure. The lower panel of Figure 3 shows the SNR as a function of wavelength calculated using the ETC.

3.3 Coronagraphy of a Young Circumstellar Disk

HD 141569A is a young (5±3 Myr) circumstellar disk[91] that has been a well-studied target of past space-based[92,93] as well as ground-based high contrast imaging efforts.[94–96] HD 141569A is also a unique system for our understanding of both protoplanetary disk dispersal processes as well as the early stages of debris disk systems. In terms of disk luminosity, HD 141569A sits at the transition between protoplanetary and debris disks,[97] and so is a rare object caught in transition between the two phases. Thus, from a purely scientific point of view, our ERS observations will help to illuminate whether e.g. the dust within the disk is primordial or secondary, and how the observed morphological structures relate to planet formation. Our observations of HD 141569A will demonstrate the power *JWST* holds for characterizing circumstellar debris disks, allowing us to determine the disk's dust size distribution and composition as a function of radius, and search for planet-induced structures in the mid-infrared for the first time.

Given that it is comprised of at least three concentric disk rings, HD 141569A is also an ideal target to test the sensitivity of *JWST* to extended structures as a function of stellocentric angle, as well as study the effects of various PSF subtraction post-processing algorithms on diffuse structures. We will obtain coronagraphic imaging of HD 141569A from 3.0 to 15.50 μm using both NIRCam and MIRI (Table 1). By utilizing the F300M and F360M NIRCam filters, We will image the disk on and off the 3.0 μm H_2O ice absorption band that is difficult to probe with ground-based telescopes. In addition to using the 10.65μm and 11.4μm MIRI filters, we will image the disk at 15.50 μm, one of the primary wavelengths expected to be used for *JWST* disk imaging going forward. As with the case of the HIP 65426b observations, for a calibration strategy a brighter calibrator star (HD 140986, Table 1) will be used to generate a significant volume of PSF calibration images without a prohibitively large amount of exposure time. The enhanced brightness of HD 140986 (K=3.64 versus K=6.82 for HD 141569A) means that we will require 5.4 hours of calibration observations using a five-point dither strategy, compared to 8.1 hours for HD 141569A.

To extract the signal of the disk in the NIRCam data, we will use the KLIP algorithm to subtract the residual scattered starlight using the dithered images of the calibrator star. We will also use recently-developed PSF subtraction algorithms that are known to better preserve the absolute flux of bright extended structures than PCA-based methods, such as the Non-negative Matrix Factorization[98] and Data Imputation,[99] and present a comparison of the results obtained with the different algorithms. The brightness ratio of the disk between the F300M and F360M filters will allow us to constrain the composition of the dust, in particular the ice fraction in the different belts of the system. This will reveal whether the dust is cometary or asteroid-like in nature, and will provide direct observations of how water is radially distributed in the outer parts ($\gtrsim$50 AU) of this young system. For this analysis, we will use both a forward modeling approach as well as an empirical approach to measure the surface brightnesses and scattering phase functions in both filters. In both cases, we will compare the data to models created with the MCFOST radiative transfer code[100] which can simulate dust belts with various chemical compositions and grain size distributions.

3.4 Aperture Masking Interferometry

Given its 6.5m effective aperture, for the purpose of gaining direct images of self-luminous exoplanets, *JWST* will be ultimately limited by its inner working angle defined by its diffraction limit of $\lambda/D \sim$120-140 milliarcseconds at 3-4 μm. For the nearest star forming regions (e.g., the Taurus Association, ~2 Myr) where the planet formation process is still likely ongoing[101] or has recently ceased (e.g., the Scorpius-Centaurus Association,[71] ~11-16 Myr), with characteristic distances of ~ 140 pc, this angular resolution corresponds to physical separations of 17-20 AU, well outside the typical water ice line separations of ~2-3 AU where planet formation is thought to be most efficient.[102,103] By dividing the full *JWST* pupil into a set of smaller sub apertures, the technique of Aperture Masking Interferometry[104,105] ("AMI,") can provide modest sensitivity inside the diffraction limit of *JWST*. This technique has been used extensively from the ground,[106–109] but never in space, and so obtaining a representative dataset as early as possible is critical for future planning. The NIRISS instrument is equipped with a sparse aperture mask[110] containing seven holes, providing 21 distinct "non-redundant" baselines that can be used with the medium-band NIRISS filters from 3.8-4.8μm (F380M, F430M, and F480M). Figure 4 shows an image of the seven-hole mask, as well as a simulation of the resulting interferogram on the detector using the NIRISS F380M filter generated using the methodology described in ref. 105, assuming a point source for a total integration time

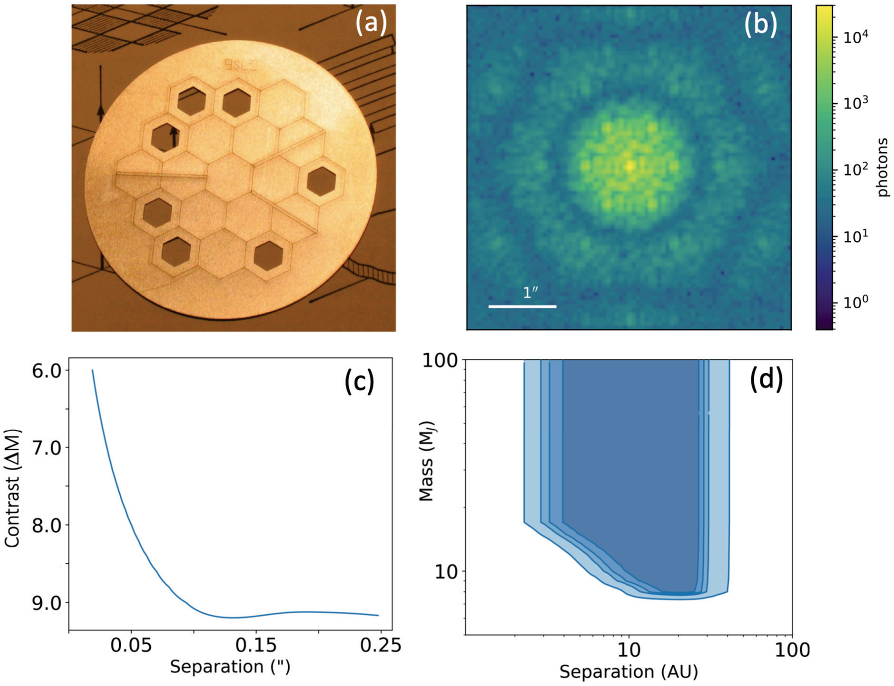

Figure 4. *(a):* An image of the sparse aperture mask installed within the NIRISS instrument[110] for the purpose of performing Aperture Masking Interferometry.[105] *(b):* A simulated NIRISS interferogram in the F380M filter for an integration time of ~1.28 s. *(c):* a simulated contrast curve calculated using the methods described in ref. 105, and *(d)* the corresponding detection probability map showing the 30, 60, 70 and 80% detection probability contours.

of 1.28 s. With the goal of identifying the limiting systematics inherent in AMI observations we will obtain 3.8 μm sparse aperture masking observations of the HIP 65426 system. Past studies (refs. 18, 111) have demonstrated that systems with already-identified wide separation planets may also have additional planets at smaller angular separations, and this effort will place constraints on any additional companions in this system. Our proposed observations of the HIP 65426 system are predicted to reach a contrast ranging from 7 to ~9 magnitudes within the 120 mas *JWST* diffraction limit at 3.8 μm, providing sensitivity to substellar companions within ~14 AU for this system (Figure 4, lower panels).

4. SCIENCE ENABLING PRODUCTS FOR THE BROADER COMMUNITY

Our team will be responsible for delivering a set of SEPs described in more detail below that will be widely available, and will assist the community in preparing future *JWST* proposals. A final working group will have the task of ensuring the quality of the SEPs. This working group will validate the utility of our internal SEPs for preparing future proposals and provide immediate feedback to the individual working groups regarding the quality of the SEPs. In this section we describe in detail each of the SEPs our consortium will deliver:

Coronagraphic imaging simulator: We will widely distribute an update[45] to the *JWST* simulation tool PanCAKE[48,75] that is an adaptation of the *JWST* ETC *Pandeia*. This tool will model the impact on coronagraphic imaging due to details of the observatory such as target acquisition offsets, time evolution of the incoming stellar wave front, spacecraft rolls, and small grid dithers. This tool will also preserve all the capabilities of the *Pandeia* simulator for generating coronagraphic scenes with MIRI and NIRCam, but with added accessibility and functionality.

High-Contrast Imaging Analysis Pipeline: We will release a publicly available Python-based high-contrast imaging pipeline to process *JWST* NIRCam and MIRI coronagraphic imaging data and generate contrast curves based on the existing PyKLIP pipeline,[112] a Python adaption of the commonly used KLIP algorithm that implements several sophisticated state-of-the-art methods for PSF subtraction and forward modelling of systematics. We will test our pipeline against other leading high-contrast pipelines to ensure consistent results. An online manual will describe the algorithm and provide a tutorial to run the pipeline using the ERS HIP 65426 data. This pipeline will be optimized for detecting point-sources, but will also produce scientifically usable images of resolved structures, which we will test and document using the HD 141569A images. By the Cycle 2 proposal deadline, users will be able to simulate realistic scenes with the modified version of PanCAKE that will be provided, which can then be interfaced with PyKLIP to produce realistic simulated reductions. The pipeline will also enable immediate analysis of data from future *JWST* cycles.

Contrast Curves: We will use our coronagraphic NIRCam/MIRI imaging and NIRISS aperture masking data of HIP 65426 to provide contrast curves showing the point source sensitivity of *JWST* as a function of wavelength and stellocentric angle. To reflect various post-processing strategies, we will provide multiple curves per bandpass of contrast (in units of delta-magnitude) vs. angular separation.

Aperture Masking Analysis Pipeline: We will release a publicly available Python-based pipeline to process simulated NIRISS AMI data generating a contrast curve and detection tests for single point-source companions. This will be in place prior to the Cycle 2 proposal deadline along with an online tutorial to guide users to reproduce our team's results. The pipeline will enable rapid sensitivity estimates for proposers in future cycles, as well as fast analysis of future datasets.

Communication of Best Practices: The wide variety of *JWST's* high-contrast modes will spawn numerous technical questions about best practices for observations and data post processing. For example, the best strategy for utilizing *JWST* in its coronagraphic mode for various point source science cases is *a priori* not obvious. This same question has been an active area of research in the high-contrast imaging community for the past decade, even for ground-based efforts.[80, 113] For *JWST*, there is an expectation that RDI will be more effective than ADI due to its limited ability to achieve large roll angles, but it is a clear goal of this program to establish the point in an observation sequence where one method becomes beneficial relative to another. While our ERS program is not intended to be comprehensive, we will make clear recommendations to future *JWST* proposers about the following:

1. For what observing scenarios does RDI become more effective than ADI? We will also establish whether this crossover point depends on the variety of PSF subtraction, e.g. the Locally Optimized Combination of Images versus KLIP.[60, 61]
2. At what angular separations does AMI achieve contrast that is superior to coronagraphic imaging?
3. To what extent do small grid dithers for PSF reference stars improve the final contrasts?

5. SUMMARY & CONCLUSIONS

The ERS program described in this work will utilize all four *JWST* instruments to carry out the first *direct* characterisation of planetary mass companions at wavelengths beyond $\sim 5\mu$m, as well as image a circumstellar disk in the mid-infrared with unprecedented sensitivity. Specifically, our program will carry out:

- **Coronagraphy of an Extrasolar Planet:** Our program will gather photometric measurements of an extrasolar planet with unprecedented sensitivity from 3-5 μm, as well as gather the first-ever coronagraphic observations beyond 5 μm. Our team will produce tools to aid the community in preparing future *JWST* proposals such as an update to the *JWST* coronagraphic imaging simulator PanCAKE, a standalone high-contrast imaging analysis pipeline, as well as contrast curves that define the coronagraphic performance of *JWST*.
- **Spectroscopy of a planetary mass companion:** We will obtain spectroscopy beyond 20 μm of the planetary mass companion VHS 1256b. This dataset will represent an accurate performance of the spectroscopic capabilities of *JWST* using NIRSpec and MIRI, and will be a valuable resource for the community to prepare proposals related to spectroscopy going forward.

- **Coronagraphy of a circumstellar disk:** We will obtain corongraphy out to 15.50 μm of HD 141569A, a young circumstellar disk, providing an understanding of *JWST's* sensitivity to extended structures as a function of stellocentric angle, and sampling the disk brightness on and off the 3.0 μm H_2O ice feature.
- **Aperture Masking Interferometry:** To evaluate the sensitivity of *JWST* near its fundamental diffraction limit of $\lambda/D\sim$120-140 milliarcseconds at wavelengths of 3-4 μm, we will carry out observations of the HIP 65426 system. These observations will have sensitivity to substellar companions in this system within $\sim$14 AU, as well as identify the limiting systematics inherent in AMI observations.

We have assembled a broad and representative consortium that comprises a large fraction of the entire high contrast imaging community. Our team members range from senior experts with decades of experience in exoplanet and disk imaging with *HST*, infrared astronomy (e.g., *Spitzer*) and adaptive optics, to early career researchers advancing the state-of-the-art in high contrast image processing and exoplanet atmosphere modelling. Through a series of calls and open consortium in-person meetings, we have drawn inclusively on a wide range of perspectives in identifying the highest priority investigations needed prior to Cycle 2. In addition to the scientific outcomes highlighted in this work, our program will also (critically) assess the performance of the observatory in the key modes expected to be commonly used for exoplanet direct imaging and spectroscopy, optimize data calibration and processing, and generate representative datasets that will enable a broad user base to effectively plan for general observing programs in future cycles. While this ERS program directly addresses the direct imaging of young, Jovian-mass planets with *JWST*, this effort marks an important milestone in the long term effort to image much lower mass, terrestrial planets with future large-scale space missions.

ACKNOWLEDGMENTS

This project was supported by a grant from STScI (JWST-ERS-01386) under NASA contract NAS5-03127. We are extremely grateful to the countless engineers, technicians and scientists that have worked for the past few decades to make JWST a reality, and we are thankful that our team will be able to present some of the first science from this remarkable observatory. We also acknowledge the significant harm caused to members of the LGBTQIA+ community in the Department of State and NASA, while under the leadership of James Webb as Under Secretary of State and NASA Administrator, respectively.

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