– 1 –

Astro2020 Science White Paper:
Direct Imaging and Spectroscopy of Exoplanets with the James Webb Space Telescope

Thematic areas:

- ■ Planetary Systems
- □ Formation & Evolution of Compact Objects
- □ Stars & Stellar Evolution
- □ Galaxy Evolution

- ■ Star and Planet Formation
- □ Cosmology & Fundamental Physics
- □ Resolved Stellar Populations
- □ Multi-Messenger Astronomy & Astrophysics

Principal Author:
Name: Charles A. Beichman[a,b]
Institution: NASA Exoplanet Science Institute, Jet Propulsion Laboratory,
    California Institute of Technology
Email: chas@ipac.caltech.edu
Phone: 818-653-8220
Co-authors: David Barrado[h], Ruslan Belikov[d], Beth Biller[r], Antony Boccaletti[m], Adam Burrows[q], Camilla Danielski[g], Elodie Choquet[af], Rene Doyon[aa], Jonathan Fortney[w], Andras Gaspar[v], Alistair Glasse[ac], Thomas P. Greene[d], Sasha Hinkley[y], Renyu Hu[l], Tiffany Kataria[l], John Krist[l], David Lafrenière[aa], Pierre-Olivier Lagage[g], Jonathan Lunine[i], Mark Marley[d], Dimitri Mawet[c], Tiffany Meshkat[a], Michael Meyer[ab], Rebecca Oppenheimer[ad], Michael Perrin[s], Laurent Pueyo[s], Michael Ressler[l], George Rieke[v], Marcia Rieke[v], Thomas Roellig[d] Eugene Serabyn[l], Joshua E. Schlieder[j], Andy Skemer[w], Remi Soummer[s], Kate Su[v], Pascal Tremblin[g], Olivia Venot[ae], Marie Ygouf[a]

[a]Infrared Processing and Analysis Center (IPAC)◇ [b]NASA Exoplanet Science Institute◇ [c]California Institute of Technology◇ [d]NASA Ames Research Center◇ [e]American Museum of Natural History◇ [f]Arizona State University◇ [g]CEA Saclay, France◇ [h]Centro de Astrobiología,Spain◇ [i]Cornell University◇ [j]NASA Goddard Space Flight Center◇ [k]Harvard-Smithsonian Center for Astrophysics◇ [l]Jet Propulsion Laboratory, California Institute of Technology◇ [m]LESIA, CNES, France◇ [n]Massachusetts Institute of Technology◇ [o]MPIA, Heidelberg◇ [p]Notre Dame University, Lebanon◇ [q]Princeton University◇ [r]Royal Observatory, Edinburgh, UK◇ [s]Space Telescope Science Institute◇ [t]SRON, Netherlands◇ [u]University of Amsterdam◇ [v]University of Arizona◇ [w]University of California, Santa Cruz◇ [x]University of Colorado, Boulder◇ [y]University of Exeter, UK◇ [z]University of Leuven, Belgium◇ [aa]Université de Montréal, Canada◇ [ab]University of Michigan◇ [ac]U.K. Astronomy Technology Centre◇ [ad]American Museum of Natural History◇ [ae]LISA, Université Paris-Est, France ◇ [af] Laboratoire Astrophysique Marseille, France

Abstract

Coronagraphic imaging and direct spectroscopy of young planets with the James Webb Space Telescope (JWST) will add new insights into our understanding of the formation and evolution of exoplanets. This White Paper focuses on how JWST will add to our knowledge of young giant planets located at orbits beyond a few AU for the closest stars and a few 10s of AU for more distant ones. Companion White Papers concentrate on the study of mature planets via transit spectroscopy (White Paper by Greene et al.) and on the connection between exoplanets and planets within our own solar system (White Paper by Lunine et al.)

1. Introduction: The rapidly expanding study of exoplanets is revealing the processes of planet formation and placing the Solar System in a broader context. While the community has made good first steps in characterizing the physical and chemical properties of a small number of directly imaged planets, many important questions remain including:

- What are the physical and chemical processes at work in the atmospheres of exoplanets?

- How does atmospheric composition vary as a function of key exoplanet characteristics, such as mass, radius, level of insolation and location within the planetary system?

- What can we learn about the formation of exoplanets from, for example, differences in their atmospheric carbon-to-oxygen (C/O) ratios or overall metallicities compared to those of their host stars?

- Do massive planets found on distant orbits (>10 AU) have a different formation mechanism, e.g disk fragmentation vs. core accretion, compared to those on closer orbits?

- Can we distinguish between "hot start" vs. "cold start" (low vs. high initial entropy) states for forming massive planets to test different formation mechanisms?

- How does the presence of planets affect the structure of circumstellar disks? Can we locate unseen giant planets by studying their gravitational affects on disk systems imaged with HST, ALMA, and by JWST itself?

- What can the composition of circumstellar disk material tell us about the formation of planets?

- Do young planetary systems with known massive (few M_{Jup}) planets also contain lower mass planets?

JWST is poised to make substantial advances in all of these areas. The projects described here utilize all four of JWST's instruments and come from the Guaranteed Time Observers (GTO) and the recently selected Early Release Science (ERS) observers. The broader community will come up with many new projects, some of these before launch, but the most important and most innovative uses of JWST will doubtless come after launch as we learn about the telescope and the instruments and more importantly as we learn more about exoplanets themselves.

2. Capabilities for Direct Imaging: JWST's advantages for exoplanet imaging derive from its large aperture, operation at wavelengths $\lambda > 3$ μm (where young planets are brightest), the stability of its Point Spread Function (PSF) and its great sensitivity due to the low background space environment. The smallest Inner Working Angles (IWA) of the NIRCam coronagraphs are $4\lambda/D$ corresponding to $0.4'' \sim 0.6''$ at 3.0 and 4.4 μm. The effective IWA for the MIRI Four Quadrant Phase Masks (4QPMs) is roughly λ/D, or $0.4''$ at 11.4 μm. Contrast limits at $1''$ are predicted to approach 10^{-5} for NIRCam and 10^{-4} for MIRI (Figure 1; Perrin et al 2018; Beichman et al 2010; Krist et al 2007; Boccaletti et al 2015; Danielski et al 2018). The NIRISS Aperture Masking Interferometer (AMI) uses the 6.5 m aperture of JWST as an interferometer to explore IWAs as small as $0.5\lambda/D \sim 0.08''$ at contrast ratios of 10^{-3} to $\sim 10^{-4}$ at 3-5 μm (Artigau et al 2014). The performance of the coronagraphs will depend on the stability of the telescope pointing and wavefront error (WFE). While cryo-vacuum thermal tests of the Optical Telescope Element (OTE) provided measurements over representative timescales (Perrin et al. 2018), the ultimate performance of JWST will not be known until in-orbit check-out reveals the typical level of WFE drift over the duration
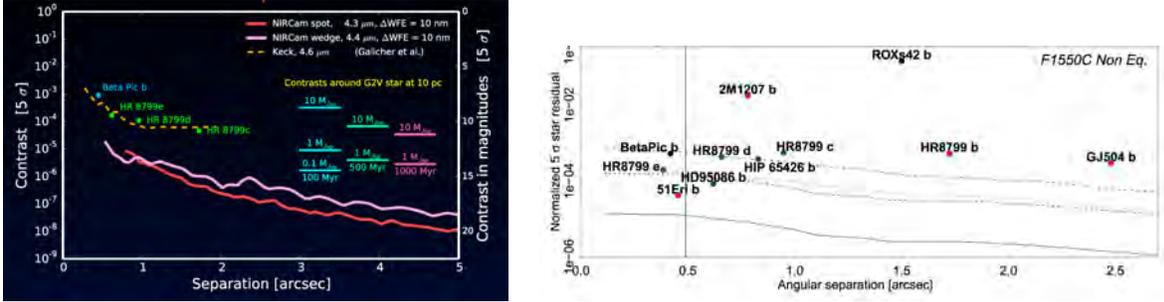
Fig. 1.— The expected contrast of NIRCam (left, 4.6 μm) and MIRI (right,15.5 μm) coronagraphs depends on the level and stability of JWST's Wave Front Error (WFE) but should approach 10^{-5} at $1''$ and 10^{-4} at 1-2$''$ for NIRCam and MIRI, respectively, for WFE drifts over a range of timescales (Perrin et al 2018; Danielski et al 2018). A comparison with Keck coronagraphy at 4.6 μm is shown (Galicher et al 2011). The figures show the detectability (5σ) of exoplanets as a function of angular separation for NIRCam (Beichman et al 2010) and MIRI (Danielski et al 2018). In the MIRI plot, the colored dots encode different planet temperatures (red $<$100 0K, green 1000-1500 K and blue 1500-2000 K. The different line formats reflect different planet models.). JWST's long wavelength sensitivity will enable it to study $<$1 M$_{Jup}$ planets located outside of $\sim$1$''$ for the first time.

of an observation, including the effects of slews to reference stars. However, it is likely that new observing strategies and advanced data reduction techniques will provide significant improvements in performance once real data become available. JWST will spur development of techniques for high-contrast imaging from space which will be directly applicable to WFIRST and to future direct imaging flagships.

3. Planet Demographics: Even though JWST does not offer substantial advantages in angular resolution relative to 8-10 m telescopes on the ground, at separations outside $\sim$1$''$ NIRCam's and MIRI's unmatched sensitivity at λ $>$3 μm will enable the detection of lower and more typical planet masses ($<$ 1 M$_{Jup}$) compared with the $>$ 5M$_{Jup}$ now possible from the ground. MIRI will be able to detect young planets for the first time at wavelengths longward of 5 μm. At these masses, the evolutionary models are very uncertain so that the detection of these lower mass planets (Uranus to Saturn mass) will foster a theoretical activity to provide more accurate evolutionary and atmospheric models, e.g. Linder et al 2018. NIRCAM and MIRI also have Outer Working Angles significantly larger than typical ground-based coronagraphs (20$''$ and 24$''$, respectively) which can extend planet searches to hundreds of AU around the host stars.

Hour-long observations at 4.5 μm can identify planets with masses below that of Saturn in previously known planetary systems, e.g HR 8799 (ID#1194)[1], 51 Eri (ID#1412) and HD95086 (ID#1195). Similar searches will be made for $\sim$1 M$_{Jup}$ planets within 2$''$–10$''$ radius around some of the nearest, brightest debris disk systems, e.g. Vega, ϵ Eri and Fomalhaut (ID#1193). For example, depending on exactly where it is located in its 3.5 AU orbit, NIRCam should be able to detect the $\sim$0.8 M$_{Jup}$ planet ϵ Eri b (Mawet et al 2018). At very small angular separations (0.08$''$ - 0.2$''$), the AMI mode of NIRISS can look for additional massive planets in known systems. Program ID#1200 will target HD 95086 and HD 115600 whose disk morphologies suggest the presence of planets in

---

[1]The ID numbers are active links to detailed descriptions of approved GTO or ERS programs available at the JWST website: https://jwst.stsci.edu/observing-programs/approved-gto-programs. See also the table in the references for a complete list of approved exoplanet-related programs.
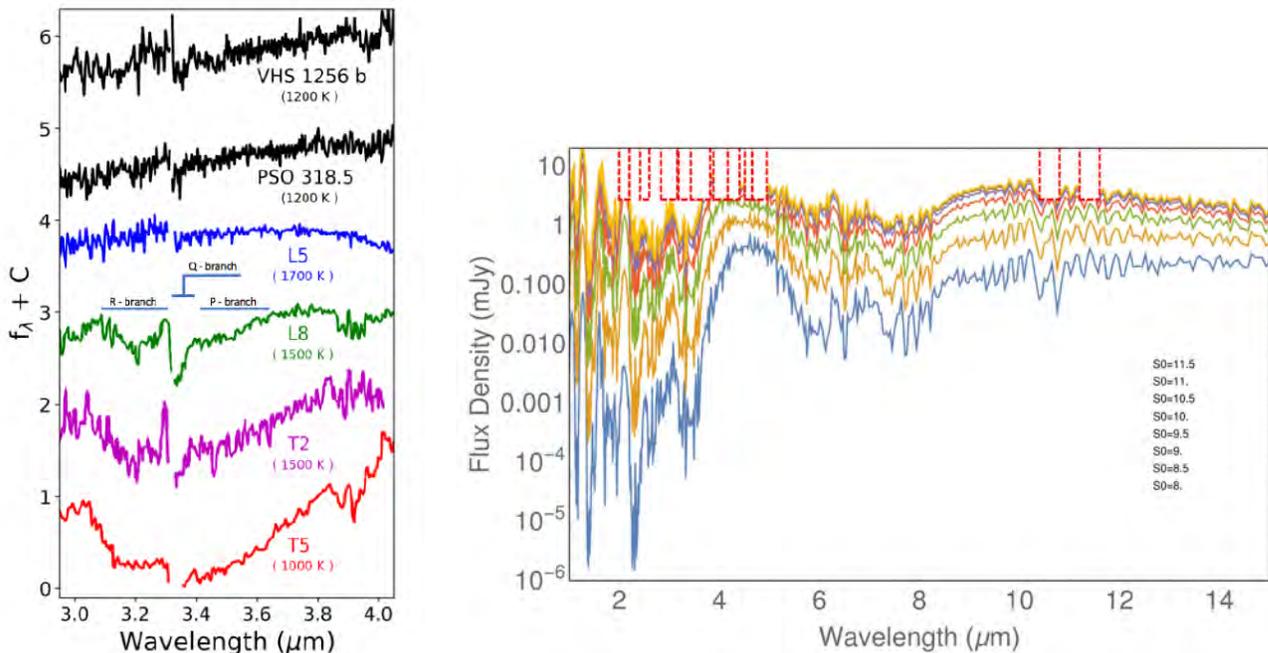
Fig. 2.— left) JWST spectra will reveal the presence of molecules such as H_2O, CO, CH_4, NH_3. Ground based spectra of two low gravity analogs to the HR8799 planets (VHS1256b (ID#1386) and PSO 318.5) and a range of L and T dwarfs suggest the power of spectroscopy (here using CH_4) to characterize atmospheric properties such as vertical mixing and non-equilibrium chemistry. right) Illustrative model spectra of a 2 Myr old, 2 M_{Jup} planet at 10 pc for a number of different initial entropy values ("hot start" to "cold start" (Spiegel and Burrows 2012). Red rectangles at the top show a number of NIRCam and MIRI filters. MIRI will study young planets at wavelengths longward of 5 μm for the first time.

this separation range. The AMI mode is also well matched to probe the gap of many young proto-planetary transition disks and will explore whether giant planets in formation can explain their structure ID#1242.

Furthermore, observations of the youngest and closest M stars (often too faint for ground-based adaptive optics imaging) offer the prospect of detecting planets with masses as low as a Uranus's in orbits as small as 10-20 AU (ID#1184; Schlieder et al. 2015). An Early Release Science program will make NIRCam, MIRI and NIRISS coronagraphic images of the newly discovered exoplanet HIP 65426b (ID#1386).

Extensive ground-based imaging at 1-3 μm with coronagraphs on 8-10 m telescopes has found that the incidence of gas giants around nearby young stars is low: 0.6% of nearby young stars have planets in the range 5-13 M_{Jup} on orbits between 30-300 AU orbital separations (Bowler 2016). By determining whether the outer regions of planetary systems host planets less massive than 1 M_{Jup}, JWST will address the origins of these distant planets. For example, the discovery of a large population of low mass planets at large separations might suggest migration and/or near-ejection of planets formed via core accretion. Alternatively, the failure to find more distant, lower mass planets (Fernandez et al 2019) would suggest that *in situ* formation via disk fragmentation might be beginning to fail below the nominal Jeans mass of a few M_{Jup} (Forgan et al 2011; Rodriguez et al

2011).

NIRISS's AMI high angular resolution ($0.5\lambda/D$) will be used to investigate the presence and properties of very young ($<$ 10 Myr) exoplanets located in more distant star forming regions (ID#1200 and ID#1202). The wide-field slit-less spectroscopy mode (R$\sim$100) of NIRISS will be used to investigate the presence and properties of very young ($<$ 10 Myr) and isolated exoplanets, down to masses of 1-2 M_{Jup}, located in more distant star forming regions. (ID#1202). Quantifying this population of isolated planets may help to constrain the processes of dynamical ejection from young multiple planet systems.

4. Planet Characterization: The NIRCam and MIRI coronagraphs will be used to characterize previously imaged exoplanets across a suite of NIRCam and MIRI filters (Figure 2). From this information, it will be possible to infer a planet's total luminosity, effective temperature, and thus radius (ID#1241,ID#1193,ID#1194), making it possible to estimate its initial entropy which is a direct indicator of its formation mechanism via a "hot" or "cold" start process (Marley et al 2007; Spiegel and Burrows 2012). JWST's sensitivity is such that at wavelengths of 3$\sim$15 μm it can image young planets at separations of $\sim$1$''$ and beyond in just a few minutes of integration time. NIRCam's medium passband filters will be used to characterize exoplanet atmospheres, measuring both the continuum and searching for signatures of CH_4, CO and CO_2. MIRI's three 4QPM filters will isolate a band of NH_3 expected in cool ($<$1000 K) objects.

The recent National Academy of Science's report on Exoplanet Strategy recommended that "NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission." While the report emphasized transit spectroscopy of mature planets, we note here that JWST will also enable direct spectroscopy of the atmospheres of young gas giant exoplanets which will avoid many of the ambiguities inherent in atmospheric characterization from transit transmission spectroscopy. Observations using NIRSpec's slit or IFS (R$\sim$ 1,000) and MIRI's Low and Medium Resolution Spectrometers (LRS, R$\sim$100; MRS, R$\sim$2,500) will yield broad wavelength spectra of more widely separated planets for direct comparison with models such as those shown in Figure 2, e.g. (ID#1188 and ID#1275). While some of these targets will be challenging due to the proximity of the host star (HR8799e), others will be straightforward due to the faintness of the host star (2MASS1207-3239b), or to the very wide separation between the planet and host, e.g. VHS 1256b (8$''$, ID#1386), GU Psc (42$''$,ID#1188), and WD0806-66 (130$''$; ID#1276).

5. Jovian Mass Brown Dwarfs: Some of the cold, nearby free-floating Brown Dwarfs (BDs) discovered by WISE are older (5-10 Gyr) analogs to the young, hot Jupiters (5-13 M_{Jup}) discovered by direct imaging (Kirkpatrick et al 2010, Beichman et al 2014). Thus late T and Y dwarfs are excellent laboratories for studies of atmospheric conditions and composition (ID#1189, ID#1414). Objects like WISE0855+0714, located only 2.2 pc away and having an effective temperature of $\sim$250 K (Luhman 2014), will be studied by all 4 JWST instruments to obtain spectra and to look for possible companions (ID#1228-1230). Other programs will look for hot, young, free-floating Jovian-mass BDs using NIRCam imaging in star formation regions such as Orion (ID#1256).

6. Circumstellar Disks and Planets: As suggested by Figure 3, JWST will open a dramatic new era in the study of circumstellar disks, both debris disks orbiting mature stars and those surrounding young stars as revealed dramatically by ALMA (Andrews et al. 2018). JWST will explore their structure and composition, as well as their interactions with planets. There is a rich literature of models describing the interaction between planets and disks creating multiple rings, gaps, and various asymmetries in our own and other planetary systems (Wyatt et al 2006, 2008; Ertel et al 2012; Zhang et al 2018). JWST will resolve asteroid-belt analogs, and may detect some of the larger

planets responsible for the structures in asteroidal or exo-zodiacal disks (Stark et al 2008). β Pic (Lagrange et al 2010) is an example of a warped disk and HD202628 is an example of an eccentric, shepherded ring system (Krist et al 2012). Resolving the emitting regions can break the degeneracy between grain size and location, greatly improving our understanding of the disks. Smith and Wyatt (2010) suggest that MIRI will be able to resolve almost all of the A star debris disk systems previously detected at 24 and 70 μm.

NIRCam and MIRI will play complementary roles in advancing our understanding in this area. NIRCam will look for the planets and evidence for icy grains while MIRI's coronagraphs will provide compositional and structural information in the closest debris disk systems, e.g. ID#1183, ID#1294, ID#1411. MIRI might even find evidence for time-variable phenomena in the most extreme systems (Meng et al 2017; ID#1206).

7. Conclusion: JWST's sensitivity at wavelengths longer than 3 μm offers dramatic new capabilities for coronagraphic imaging beyond 1″. NIRCam and MIRI will be able to reach lower mass planets than is possible from the ground, e.g. Saturns and even Uranus-sized objects around the nearest stars, and thus extend our understanding of the demographics of gas and ice giant planets on orbits as close as 5-10 AU for the closest stars and 10s of AU for more distant ones. Our characterization of the architectures of exoplanetary systems will be woefully incomplete without JWST's sensitivity to low-mass planets at wide separations.

NIRCam and MIRI coronagraphy will establish the effective temperature and luminosity of these objects leading to estimates of planetary radius and initial entropy and thus yield clues as to the importance of "hot start" vs "cold start" formation mechanisms. Narrow and medium band filter photometry may detect specific molecular species, such as CO and NH_3. Imaging of disks in scattered light and thermal emission will reveal structural and compositional information and perhaps lead to the detection of the planets responsible for these structures. Spectroscopy of more widely separated objects using NIRSPEC and MIRI will yield new insights into the atmospheres of young planets, and in the case of free-floating Brown Dwarfs, into the atmospheres of Giga-year old 3-5 M_{Jup} objects.
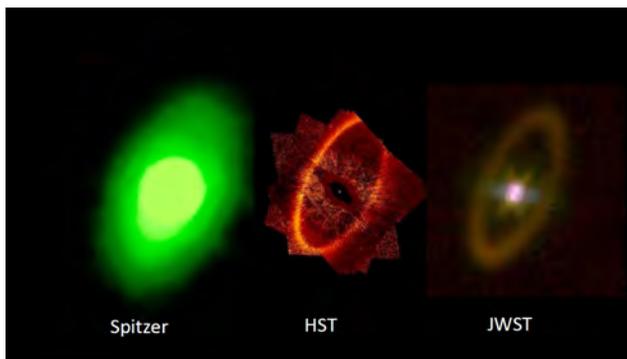

Fig. 3.— A comparison of the Spitzer 24 μm (Su et al 2016) and HST visible light images (Kalas et al 2008) of the Fomalhaut disk with a simulation of a MIRI composite image at 15.5, 23 and 25.5μm (courtesy A. Gaspar). The disk seen at visible wavelengths is fully resolved with $\sim$1″ resolution in the MIRI image. The offset of the ring from its star has been attributed to the interaction with one or more planets (Ertel et al 2012).

References

Andrews, S. et al 2018, ApJ,869,41 ◇ Artigau, E. et al 2014, SPIE, 9143E,40A ◇ Beichman, C.A. et al. 2010, PASP, 122, 162 ◇ Beichman, C.A et al. 2014, ApJ, 783, 68 ◇ Boccaletti, A. et al 2015. PASP, 126, 633◇ Bowler, B. 2016 PASP, 128, 102001 ◇ Danielski,C. et al, AJ, 156,256 ◇ Ertel, S. et al. 2012, A&A, 544, A61 ◇ Fernandez, R.B. et al 2019, https://arxiv.org/abs/1812.05569◇ Forgan,D. & Rice, K. 2011, MNRAS, 417, 1928 ◇ Galicher, R et al., 2011, ApJ, 739, L41 ◇ Kalas, P. et al 2008, Science, 322, 1345 ◇ Krist, J. E. et al 2007, SPIE, 6693E ◇ Krist, J. E. et al. 2012, AJ, 144, 45 ◇ Lagrange, A.-M. et al. 2010, Science, 329, 57 ◇ Linder,E. F. et al 2018, A&A, submitted,https://arxiv.org/abs/1812.02027 ◇ Marley, M. S. et al. 2007, ApJ, 655, 541 ◇ Luhman, K. 2014, ApJ, 786,18 ◇ Mawet, D. et al 2018, https://arxiv.org/pdf/1810.03794.pdf◇ Meng, H. et al 2017, ApJ, 836, 34 ◇ Miles, B.E. et al 20189, ApJ, 869, 18 ◇ Morley C. V. et al. 2014, ApJ, 787, 78 ◇ Perrin, M. et al, Proc. SPIE 2018, 10698, 1069809 ◇ Rodriguez, D. R., Zuckerman, B., Melis, C., & Song, I. 2011, ApJ, 732, L29 ◇ Schlieder, J. E., et al. 2015, arXiv:1512.00053 ◇ Smith, R. & Wyatt, M. 2010, A & A, 515,A95 ◇ Spiegel, D. S. et al. 2012, ApJ, 745, 174 ◇ Stark, C. C. et al. 2008, ApJ, 686, 637 ◇ Su, K. et al 2016, ApJ,818, 45 ◇ Wyatt, M. C. 2006, ApJ, 639, 1153 ◇ Wyatt, M. C. 2008, ARAA, 46, 339 ◇ Zhang, S. et al 2018, ApJ, 869, L47.

Approved GTO and ERS Programs for Exoplanets, Disks and Brown Dwarfs

ID	Title	Team Lead	Inst.[1]
Direct Imaging and Spectroscopy			
1184	Survey of Nearby Young M Stars	J. Schlieder et al.	1
1188	Direct Spectroscopy of Non-transiting Exoplanets	K. Hodapp et al.	2, 3
1193	Coronagraphic Imaging of Young Planets and Debris Disks	C. Beichman et al.	1,2
1194	Characterization of the HR 8799 Planetary System	C. Beichman et al.	1,2
1195	Coronagraphic Imaging of Young Planets	C. Beichman et al.	1
1200	Architecture of Directly-imaged Planetary Systems	J. Rameau et al.	4
1241	2 Coronagraphic Imaging of Exoplanets	M. Ressler et al.	2
1270	Characterizing the TWA 27 System	S. Birkmann et al.	2,3
1274	Extrasolar Planet Science with JWST	J. Lunine et al.	1
1275	Spectroscopic characterization of PSO J318	P.-O. Lagage et al.	2,3
1276	Spectroscopic Observations of WD 0806-661B	P.-O. Lagage et al.	1,2,3
1277	Coronographic Observations of Young Exoplanets and Spectroscopic Observations of ROSS 458 ABc	P.-O. Lagage et al.	2,3
1278	Spectroscopic Observations of Brown Dwarfs	P.-O. Lagage et al.	2
1292	ROSS 458 ABc	J. Lunine et al.	3
1412	Characterizing 51 Eridani Exoplanetary System	M. Perrin et al.	1
1386	High Contrast Imaging of Exoplanets[2]	S. Hinkley et al.	1,2,3,4
Physics of Brown Dwarfs			
1189	Y-Dwarfs	T. Roellig et al.	1,2,3,4
1202	NIRISS Survey for Young Brown Dwarfs and Rogue Planets	A. Scholz et al.	4
1209	Probing the Cloud Properties of SIMP0136+0933	E. Artigau et al.	4
1228	The Physics of Brown Dwarfs -1	C. de Oliveira et al.	3
1229	The Physics of Brown Dwarfs -2	C. de Oliveira et al.	1,3
1230	The Physics of Brown Dwarfs -3	C. de Oliveira et al.	1,2,3,4
1256	Brown Dwarfs and Free-floating Planetary Mass Objects in Orion	M. McCaughrean et al.	1
1413	2 Coronagraphy of the Substellar Companion GJ 758 B	L. Pueyo et al.	2
1414	Integral Field Spectroscopy of HD 19467 B	M. Perrin et al.	3
Debris Disks			
1183	Coronagraphic Imaging of Scattered light Debris Disks	A. Gaspar et al.	1,3
1206	Extreme Debris Disks and Disk Variability	G. Rieke et al.	2
1282	2 Protoplanetary and Debris Disks Survey	T. Henning et al.	2,3
1294	Spectroscopy of the Beta Pictoris Debris Disk	C. Chen et al.	2
1411	Coronagraphy of the Beta Pictoris Debris Disk	C. Stark et al.	1,2

[1]*NIRCam-1; MIRI-2;NIRSPEC-3;NIRISS-4;* [2]*Early Release Science Program*