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DOCUMENT

EChO in the context of the JWST and ELTs

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1 INTRODUCTION

This technical note discusses the EChO mission in relation the James Webb Space Telescope (JWST) and the planned ground-based Extremely Large Telescopes (ELT). We briefly describe the expected JWST and ELT capabilities and their relation to the science of EChO. EChO, JWST and E-ELT observations will be highly complementary and mutually beneficial. E.g. JWST will provide state-of-the-art measurements for a selected number of planets, mostly over a limited wavelength range. The E-ELT will mostly provide targeted observations for some planets at ultra-high spectral resolution at specific wavelengths. The role of EChO will be to provide the broad picture and glue together the pieces of the puzzle.

2 ECHO IN CONTEXT OF THE JWST

JWST is the largest space telescope ever conceived with the spatial resolution of an equivalent telescope diameter of 5.8 m (6.5 m point to point across the hexagonal shape) and 25 m^2 "clear" area[1]. It is designed to operate over the visible (~0.6 μm) to mid-infrared waveband (28 μm) providing very high sensitivity imaging and spectroscopy of faint astronomical targets. It is a true observatory with multiple capabilities, instruments and operating modes. JWST is scheduled for launch in late 2018. Although it is primarily designed for observations of very faint targets (in the μJy range), it is also recognised that JWST will do a great deal of ground breaking exo-planetary science and a number adaptations to the instruments have been made to allow this to happen.

Table 1 summarises the JWST instruments and operating modes that will be useful for exo-planet transit spectroscopy. Studies of the performance of the instruments for transit spectroscopy have been carried out notably for NIRISS and NIRSpec (Dorner Phd Thesis Universite de Lyon 2012, Clampin 2010 see also the NIRSPEC website at *http://www.cosmos.esa.int/web/jwst/exoplanets*). Both primary and secondary eclipse measurements over the full waveband from 0.6 to 28 μm are possible with the combination of the instruments and modes on JWST. However, both its extremely high sensitivity and observatory nature mean there are some significant restrictions on the type and number of targets that will be observable. Some of these are indicated in table 1 together with the primary observing modes expected to be used for transit spectroscopy. In addition to these instruments/modes there are a number of direct imaging possibilities using JWST – for a full summary see the exo-planet "white papers" (*http://www.stsci.edu/jwst/doc-archive/white-papers*). The instantaneous wavelength coverage and spectral resolutions of JWST and EChO are compared in figure 1.

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[1] The effective area is not disclosed – for MIRI we use 22 m^2 to account for reflectivity and diffraction losses.

1.1 Observing constraints

The particular difference between JWST and EChO is that to cover the core band of interest (0.55-11 μm) with JWST, even for targets which do not saturate the detectors, requires the use of at least two instruments – NIRSpec and MIRI in prism mode – operated serially. Although, the sensitivity in these modes is without question very much higher than EChO could ever reach, it is also the case that JWST will be restricted to fainter targets – roughly K~>8.5 magnitude. However, unlike EChO, to get the entire spectrum one must patch together observations from different instruments. These will be taken, necessarily, at different observing times and with, generally, separate re-pointings to the target. In order to do this without adding systematic noise requires high accuracy inter-instrument calibration combined with extremely high temporal stability. EChO has the advantage that is designed from the outset to deliver both these aspects.

Brighter targets will be observed using the medium resolution grating spectrometer modes on JWST. Here the issue of covering the wavelength range becomes even more marked as is will require three grating settings for NIRSpec and three for MIRI (see appendix for an example). This implies six separate observations of a target to cover a single transit (primary or secondary). This would a) not be a very efficient use of JWST time and b) the ability to piece together six separate spectra with the accuracy required will require detailed and dedicated calibration observations. In principle a more efficient observations method would be to identify the targets and spectral regions of interest then use the grating modes to home in on species of interest that would benefit from the higher resolution observations.

Table 1: JWST instruments and observing modes useful for transit spectroscopy

Instrument	Mode	Resolving power	Wavelength range (μm)	Comments
NIRISS	Grism, cross-dispersed, slit-less	700	0.6 - 2.5	Saturates at J = 7 Saturates at K<~9 at some part of band
NIRCam	Grism, slit-less	2000	2.4 - 5.0	Not proposed for transit spectroscopy in SODRM
NIRSpec	Prism, wide slit (1.6")	100	0.6 - 5.0	Saturates at J<~10.75 (see appendix)
NIRSpec	Grating, wide slit (1.6")	1000 or 2700	(0.7)1.0 - 1.8 1.7 - 3.0 2.9 - 5.0	Uses three grating settings to cover wavelength range
MIRI	Prism, 0.6" slit or slit-less	100	5.0 - 11.0	Saturates at 2.9 Jy at 10 μm (K ~ 6)
MIRI	IFU (0.2" - 0.27"/pixel)	2400 – 3600	5.0 - 7.7 7.7 - 11.9 11.9- 18.3 18.3 - 28.3	Each band uses three sub-bands with separate gratings.

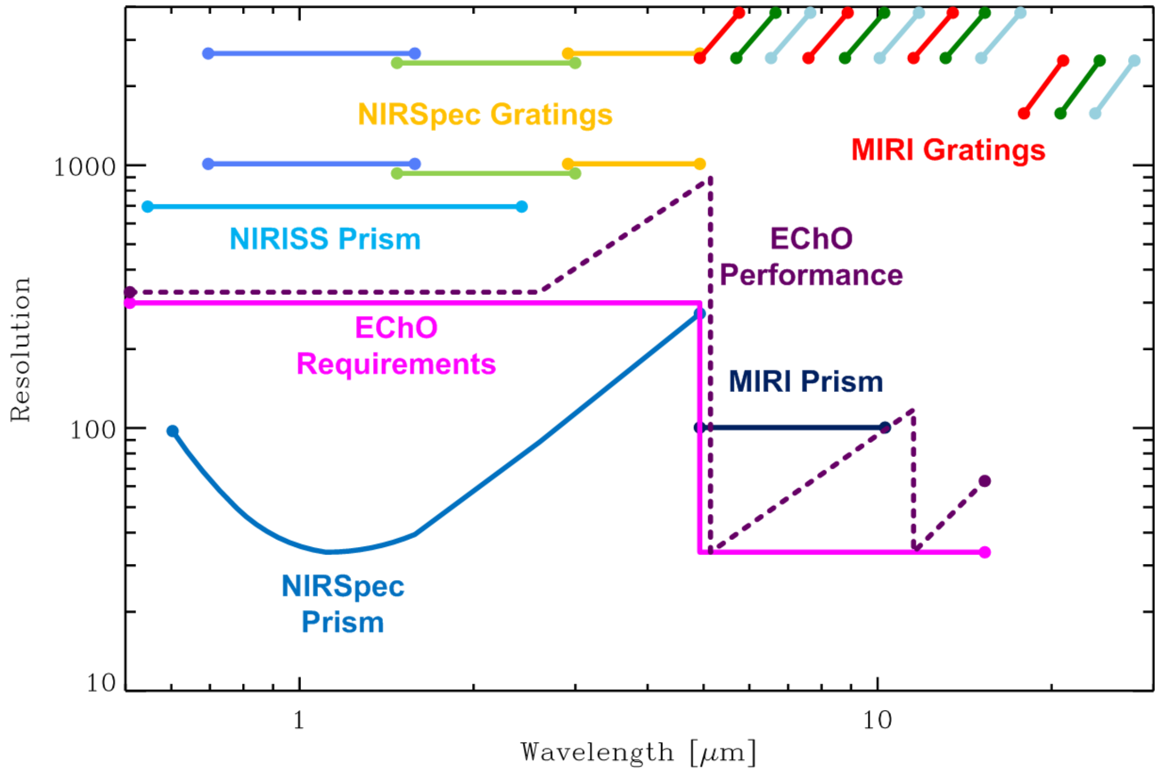

Figure 1: Wavelength coverage and spectral resolution of JWST spectrometers and the EChO instrument. NIRISS, NIRSpec and MIRI have to be used sequentially in any mode. Lines of the same colour on the diagram indicate instantaneous wavelength coverage.

1.2 The SODRM

In the event that both missions launch according to their respective schedules (late 2018 for JWST and 2023 for EChO) there should be at least one year of overlap between the missions allowing synergistic observing programmes to be enacted. Before EChO is launched, and again assuming it launches on time, JWST will have about three years observing time available, enabling the JWST observing teams to conduct a first census of exo-planet spectra targeting the most promising candidates. A first cut, and it must be emphasised, notional observing programme for the JWST is encompassed in the Science Observations Design Reference Mission (the SODRM) which is available for inspection at *http://www.stsci.edu/jwst/science/sodrm/jwst/science/sodrm/*. Briefly this consists of a number of observing programmes built around seven science themes designed to allow the mission team test the observation planning tools. Although the split between the science themes is notional it is a useful guide as to how the JWST is likely to be operated and, once the mission planning begins in earnest, will allow the impact of such things as multiple visits to transit objects to be assessed in the light of observatory operational efficiency. For our purposes it allows a first look at the kind of targets and information that will already be available to EChO by the time of its launch.

Figure 2 show the breakdown of JWST observing time in the SODRM and table 2 gives more detail on the allocated time for each science theme. In the appendix a table is given with the next level of detail on the observing programmes under the "exo-planet" theme. One can follow the links given here to inspect the individual programme proposals. Analysis of the exo-planet programmes shows that there are three main transit spectroscopy programmes utilising NIRISS, NIRSpec and MIRI. The NIRSpec programme has about 25+ targets, NIRISS 15 targets, and MIRI 9 targets. These programmes will take a total of 930 hrs on target time. The information available on line makes no mention of slews or set up time. Overall, 37% of the JWST exo-planet theme time is dedicated to transit spectroscopy making it around 6% of the observation time. Again, these numbers are all notional and may increase or decrease once real proposals are evaluated by the time allocation process. However, it is a useful guide to the number of targets that will have been observed by the time EChO becomes operational. Typically then some tens of targets will have been assessed in the visible and NIR band and about ten to fifteen may have been observed across the full NIR/MIR range in both primary and secondary transit. To optimise the use of EChO, we would need to critically assess whether these targets should be re-observed, some will be too faint in any event, and what advantage there might be to doing so. One possibility would be that the rather higher calibration precision offered by EChO for a subset of the JWST targets could be used to provide templates to allow the high resolution spectra to be accurately pieced together. Once both observatories are in operation, a truly synergistic observing programme can be built with EChO rapidly identifying targets of interest for JWST's higher resolution spectrometers to be used to full advantage.

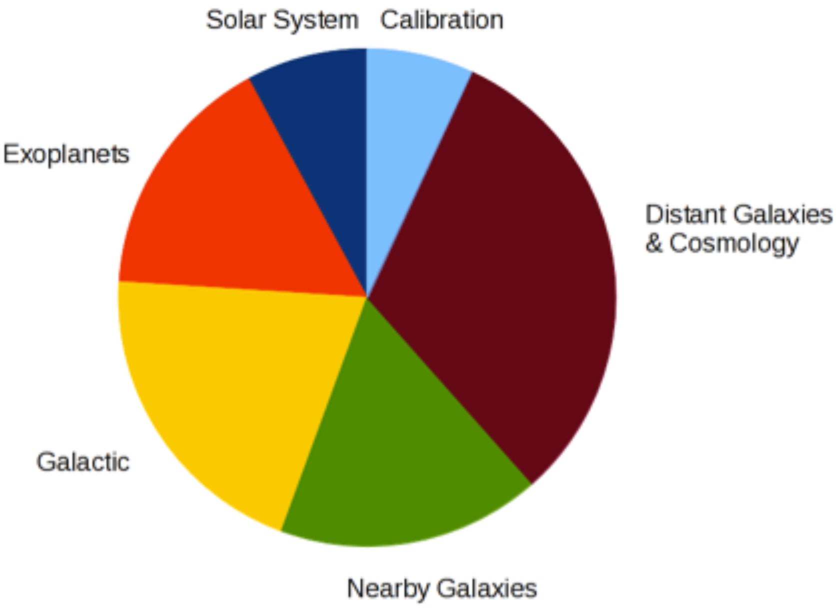

Figure 2: Pie chart showing the fractional breakdown of the notional JWST observing programme over the first few years of operation taken from the SODRM

Table 2: **Breakdown of the science theme allocated observing time in the SODRM**

Category	# of Programs	Total Time [days]	Percentage of Total Time
Solar System	8	51.3	7.9%
Exoplanets	14	104.4	16.1%
Galactic	19	132.3	20.4%
Nearby Galaxies	13	111.3	17.2%
Distant Galaxy & Cosmology	16	204.5	31.5%
Instrument Calibration	40	31.9	4.9%
Observation Calibration	2	13.0	2.0%
Total	112	648.7	100.0%

1.3 Conclusions on JWST & EChO

In an ideal world one would hope that both EChO and JWST were available contemporaneously to allow the maximum efficiency to be extracted from the precious observing time resources. In the optimistic scenario that both missions launch on schedule, JWST will have observed some tens of transiting objects in at least the visible and NIR band and ten or so objects across the full band of interest. Given the observing constraints on the observatory these are likely to be at the fainter end of the EChO target list and will offer the first glimpse of the variety of objects that EChO will fully reveal. Once EChO is launched it will enhance the JWST programme by allowing it to be used in the most efficient way to provide a level of spectroscopic detail that EChO cannot provide.

2 EChO and the Extremely Large Telescopes

With the EChO launch and operation foreseen in the early 2020s, it is expected that one or more of the next-generation ground-based telescopes, a.k.a. Extremely Large Telescopes (ELTs), will be operational, and will be extensively used for exoplanet characterization studies. Here we briefly describe the expected ELT capabilities and their relation to the science of EChO. Bottom line: ELT and EChO observations will be highly complementary and mutually beneficial.

2.1 Exoplanet atmosphere observations from the ground

Ground-based observations of exoplanet atmospheres have many challenges and limitations. First of all, large parts of the electromagnetic spectrum are blocked from view. In particular in the near- and mid-infrared wavelength regimes, key areas of the exoplanet spectra are inaccessible due to absorption by mainly water and carbon dioxide in the Earth atmosphere. Secondly, it is very challenging to calibrate ground-based observations to a 10^{-4} level such that they become usable for exoplanet studies. This because, 1) telluric absorption at this level is highly variable and directionally dependent, 2) atmospheric seeing results in a variable input to the scientific instrument, and 3) ground-based instrumentation itself is less stable than that in space, due to unavoidable rotation angle variations and/or flexure due to changes in the direction of gravity during observations. Also, particularly important for infra-red observations, the thermal stability of ground-based instruments is much less well behaved, and the thermal background from the sky and telescope are highly variable - and beyond 5 micron the dominant noise source, making high-precision ground-based transit or secondary eclipse spectroscopy practically impossible from the ground at >5 micron.

Despite the fact that the collecting areas of future ground-based telescopes will be up to three orders of magnitude larger than that of EChO, it are these calibration issues that will make the ELTs for exoplanet characterization only usable in very specific ways. The ground-based calibration can generally be tackled in two ways. Firstly, by using multi-object photometry/spectroscopy which uses nearby star(s) to calibrate out the telluric components. Broad- and narrow-band photometric observations have resulted in a dozen or so secondary eclipse detections from the optical to the near-infrared, and recently particular success has been reached with multi-object spectroscopy using FORS2 on the Very Large Telescope on the warm Super-Earth GJ 1214b by Bean et al. (2010). A drawback of this method is that it requires reference stars, of a similar apparent magnitude as the target, within the field of view (FoV) of the instrument. The brighter the star, the more unlikely this is, and therefore, in general this method cannot be used for the best (brightest targets). This is particularly an issue for the ELTs with even smaller FoV than the current generation of 10m class telescopes. Only systems consisting of late M-dwarfs, which are faint enough such that most of them will have stars of similar magnitude within the instrument FoV, will be observable with the ELTs in this way. In addition, this technique does not solve for the differential instrumental effects between stars. Indeed, the rotation-angle-dependent flat-field seems to currently limiting the multi-object spectroscopic performance of FORS@VLT.

A second method is making use of a very different technique - spectroscopy at very high spectral dispersion (typically R=100,000). At this resolution, molecular bands in exoplanet spectra are resolved into hundred(s) to thousands of individual lines, whose signals can be combined to enhance the molecular detections. Only astrophysical information over small wavelength scales are preserved, hence the line-contrast is being measured with respect to a local (pseudo-)continuum. Using this technique, the atmospheric effects that change relatively slowly with wavelength, such as absorption/scattering by clouds, hazes, and dust in the Earth atmosphere, and variable slit-losses due to seeing variations do not affect the photometric precision, since the absolute transit and secondary eclipse signals are not used, only the variations in the transit/eclipse depth at very small wavelength scales are measured. Telluric molecular absorption, e.g. due to water, methane, carbon dioxide, and other molecules are (at least in the atmospheric windows) restricted to specific wavelengths, and can be removed using principle component analyses. Due to changes in the radial component of the orbital velocity of the targeted exoplanet (up to 150 km/sec for hot Jupiters), those molecular lines produced in the planet atmosphere significantly move in the spectrum during observations, making it possible to filter out all stationary components in the spectra leaving the planet spectrum intact. This technique has been used very successfully using CRIRES on the VLT, for both exoplanet transmission spectroscopy (Snellen et al. 2010) and emission spectroscopy (e.g. Brogi et al. 2012).

2.2 The planned ELTs and their capabilities

Currently, three next-generation ground-based telescopes are on the drawing board, the European ELT (E-ELT - http://www.eso.org/public/teles-instr/e-elt.html), the Giant Magellan Telescope (GMT - http://www.gmto.org/), and the Thirty-Meter Telescope (TMT - http://www.tmt.org/). Table 1 provides information on the telescopes and foreseen instrumentation relevant for transting exoplanet characterization. Note that on the time of writing, funding has not been completely secured for neither of the three telescope projects. The earliest deployment for any of these will be the early 2020s. Also, the instrumentation for the telescopes has by no means been finalized, and a significant fraction of these instruments may never be developed, or change significantly in their characteristics.

Telescope	Diameter	Instrument	Spectral Range	Instant coverage	spectral dispersion
E-ELT	39 m	METIS	2.9-5.3 μm	0.1 μm	R=100,000
		HIRES	0.4-2.3 μm	0.4-2.3 μm	R=100,000
		MOS	0.4-1.7 μm	0.4-1.7 μm	R<30,000
GMT	24.5 m	MOS	0.4-1.0 μm	0.4-1.0 μm	R<5000
		NIR-HRS	1.0-5.0 μm	?	R~50-100,000
		G-CLEF	0.4-1.0 μm	0.4-1.0 μm	?
TMT	30 m	WFOS	0.3-1.0 μm	0.3-1.0 μm	R<7,500
		HROS	0.3-1.0 μm	0.3 -1.0 μm	R~50-90,000
		IRMOS	0.8 - 2.5 μm	0.3 μm	R=2,000-10,000
		MIRES	9-18 μm	8-14 μm	R=100,000
		NIRES	1-5 μm	~2 μm	R=100,000

Table 1. Planned next-generation telescopes and their instrumentation relevant to transiting exoplanet characterization science.

Currently, the MOS-type transmission and secondary eclipse observations on the VLT and other 10m class telescopes are limited by instrumental effects. It indicates that the next step in performance will have to come from specific instrument design. It is not yet clear whether the envisaged multi-purpose MOS instruments on the ELTs will be optimized for exoplanet characterization.

In contrast, exoplanet atmospheric characterization is an important science case for the ELT high-resolution spectrographs, in particular for METIS and HIRES on the E-ELT (of which I.S. is on both science teams). While the E-ELT will perform spectroscopy on bright stars ~25 times faster than the VLT, the HIRES spectrograph will have a cross-disperser, meaning that the instantaneous spectral range is also significantly larger than currently achieved with CRIRES - implying that spectral features can be detected with the ELT at a signal-to-noise 5 to 10 times higher than with the VLT today for the same exposure time.

2.3 Synergies between the ELTs and EChO

High-resolution spectroscopy on the ELTs will enable be highly complementary, relevant, and beneficial to EChO. The EChO spectra, which will be obtained over a large instantaneous wavelength range, are crucial for measuring the most important planet atmosphere parameters - the temperature-pressure profile and main molecular abundances. With these parameters determined by EChO, high-resolution ELT observations, providing planet differential transmission and day-side spectra at specific wavelengths, can be calibrated and used to target other, specific aspects of the planet atmospheres. For the best observable targets, e.g. those targeted by EChO in the deep survey and meteorology survey, the ELTs can provide information on the rotation of the planet and high-altitude wind speeds using the absorption line profiles – important ingredients for global circulation models (e.g. See Showman et al. 2013 for theoretical simulations). Using the high-dispersion technique, the line-contrasts can be measures for a large part of the planet orbit, meaning that variations in molecular abundance ratios (when linked to EChO observations) and/or the atmospheric temperature-pressure profile could be traced from the night, morning, to evening-side of the planet, revealing the influences of possible photo-chemical processes. It may even be possible to detect different molecular isotopologues and determine isotope ratios, giving insights in the evolutionary history of the atmospheres. Other examples of synergies between the ELTs and EChO are for detecting trace gases in the planet atmospheres with only weak molecular features only marginally detected with EChO. Interesting spectral regions for specific planets can be identified by the EChO surveys and subsequently targeted with the ELTs.

3. References

Brogi et al. 2012, Nature 486, 502
Clampin 2010, Proceedings of the conference In the Spirit of Lyot 2010: Direct Detection of Exoplanets and Circumstellar Disks. October 25 - 29, 2010. University of Paris Diderot, Paris, France. Edited by Anthony Boccaletti.
Snellen et al. 2010, Nature 465, 1049
Showman et al. 2013, ApJ 762, 24
Bean et al. 2010, Nature 468, 669

Appendices

A1: NIRSpec Grating efficiencies

Figure A1 shows an example of the medium resolution grating passbands for NIRSpec. These are used serially to build to full NIRSpec passband. Three separate grating settings are required therefore to cover the full NIR band. Note also that in grating mode the efficient passband of NIRSpec realistically begins at between ~0.8-0.9 μm as the PCE short-ward of this implies relatively long integration times compared to the peak PCE at 1.2 μm.

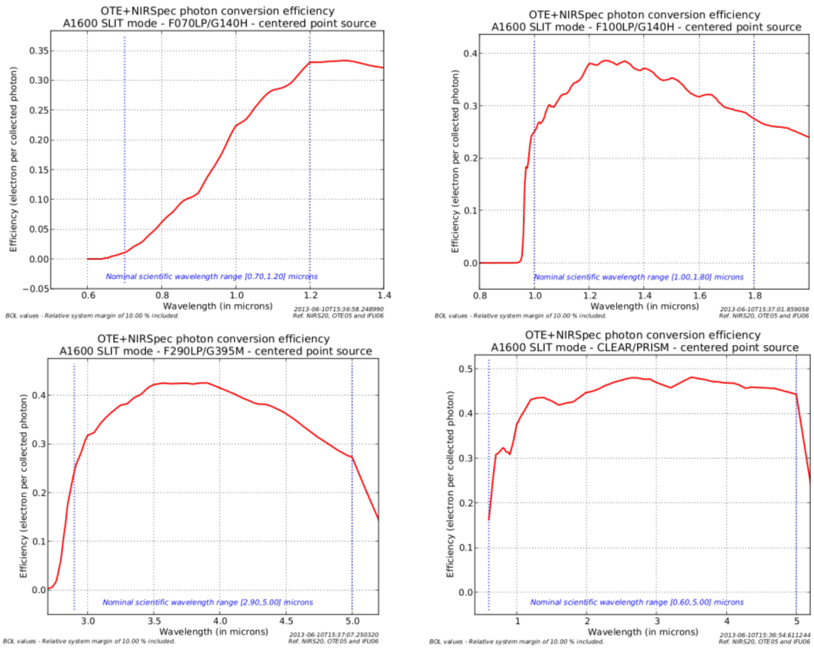

Figure A1: The efficiency of the NIRSpec moderate resolution gratings and the prism mode – taken from *http://www.cosmos.esa.int/web/jwst/exoplanets*

A2: NIRSpec Saturation Limits

Figure A2 shows the calculated J-band magnitudes where the various NIRSpec grating and Prism modes will saturate.

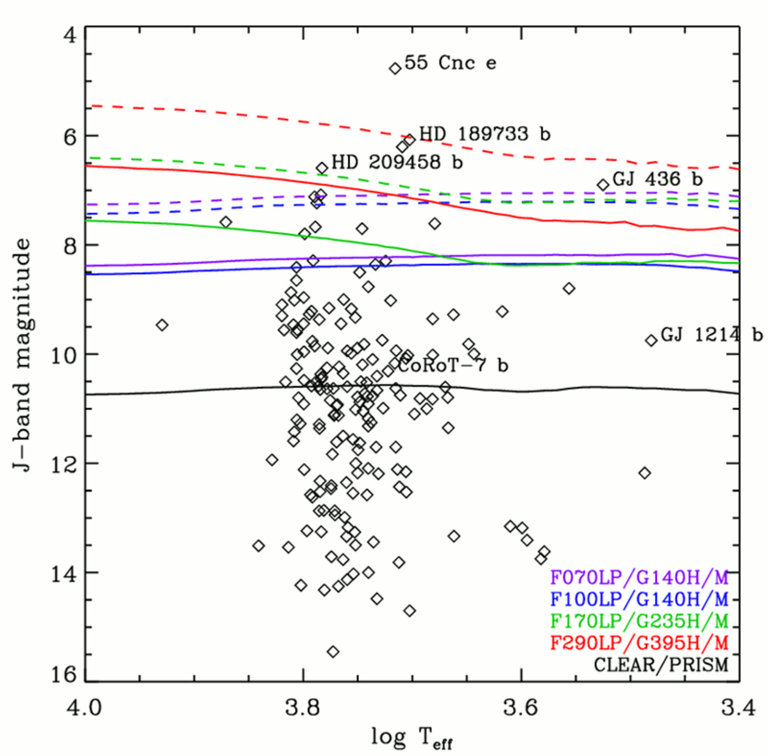

Figure A2:NIRSpec saturation limits taken from http://cosmos.esa.int/web/jwst/exoplanets

A2: MIRI Detailed Spectroscopic Passbands

Table A2 gives more detail on the wavelength coverage of the MIRI moderate resolution spectrometer (MRS). Note that to fully cover the range from ~5-11 μm requires three grating settings operated serially as with NIRSpec.

Table A2: Moderate Resolution Spectrometer Characteristics

Name and wavelength range (microns)	FOV (arcsec)	sub-band name	wavelength range (microns)	Resolving power
Channel 1 4.86 - 7.74	3.0 X 3.9	A B C	4.87 - 5.82 5.62 - 6.73 6.49 - 7.76	2450 - 3710 2450 - 3710 2450 - 3710
Channel 2 7.43 - 11.84	3.5 X 4.4	A B C	7.45 - 8.90 8.61 - 10.28 9.94 - 11.87	2480 - 3690 2480 - 3690 2480 - 3690
Channel 3 11.44 - 18.20	5.2 X 6.2	A B C	11.47 - 13.67 13.25 - 15.80 15.30 - 18.24	2510 - 3730 2510 - 3730 2510 - 3730
Channel 4 17.53 - 28.75	6.7 X 7.7	A B C	17.54 - 21.10 20.44 - 24.72 23.84 - 28.82	2070 - 2490 2070 - 2490 2070 - 2490

A3: Detailed SODRM Exo-planet Observing Programme

Table A3 replicates the on-line table detailing the notional exoplanet theme observing programme in the JWST Design Reference Mission. Inspection of the various detailed proposals gives a useful insight into the type of observing programme that will be possible with JWST. Each programme is discussed in detail and can be examined by clicking on the hyperlinks in the table.

Table A3: Detailed exoplanet science theme observing programme in the JWST SODRM

Number	Time (hr)	Title	NIRCam	NIRSpec	NIRISS	MIRI
93030	519.0	Direct Observations of Planetary systems: MIRI				X
93031	144.5	Direct Observations of Planetary systems: NIRCam	X			
93032	99.8	Direct Observations of Planetary systems: NIRISS			X	
93035	69.0	Direct Imaging of Planetary Systems around White Dwarfs	X			X
93040	21.7	High S/N NIRCam Observations of an Earth Analogue Around a Nearby Sun-like Star	X			
93041	492.1	Transit, Eclipse, and Orbital Phase Spectroscopy of Exoplanets with NIRSpec		X		
93042	129.3	Determining the Frequency of Hot Earths				X
93044	170.6	Imaging and Spectroscopy of Transiting Exoplanets-MIRI				X
93050	278.2	Search for giant planets in the Taurus star-forming regions			X	
93051	49.5	Long wavelength follow-up of planets found by ground-based extreme adaptive optics planet finders			X	
93052	116.5	Search for giant planets around young low-mass stars			X	
93053	118.7	Transit spectroscopy of a habitable Earth-like planet around an M dwarf			X	
93054	149.6	Transit spectroscopy of exoplanets with NIRISS			X	
93055	140.5	Phase curves of hot Jupiters with NIRISS			X	