Astro2020 Science White Paper: JWST GTO/ERS Deep Surveys

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author: Marcia Rieke University of Arizona
mrieke@as.arizona.edu 520-621-2731

Co-authors:

Santiago Arribas	Centro de Astrobiología, Madrid
Andrew Bunker	University of Oxford
Stephané Charlot	Sorbonne Université Institut d 'Astrophysique de Paris
Steve Finkelstein	University of Texas Austin
Roberto Maiolino	University of Cambridge
Brant Robertson	UC Santa Cruz and Institute for Advanced Study
Chris Willott	Hertzberg Institute of Astrophysics
Rogier Windhorst	Arizona State University

Harvard-Smithsonian Center for Astrophysics:
Daniel Eisenstein Erica Nelson Sandro Tacchella

University of Arizona:
Eiichi Egami Ryan Endsley Brenda Frye Kevin Hainline Raphael Hviding
George Rieke Christina Williams Christopher Willmer Charity Woodrum

Abstract :
Discovering and characterizing the first galaxies to form in the early Universe is one of the prime reasons for building a large, cold telescope in space, the James Webb Space Telescope (JWST). This white paper describes an integrated Guaranteed Time Observer program using 800 hours of prime time and 800 hours of parallel time to study the formation and evolution of galaxies from z ~2 to z~14, combining NIRSpec, NIRCam, and MIRI data in a coordinated observing program. These programs are likely to shape the course of high redshift investigations for the 2020s. NIRCam will be used to image over 200 square arc minutes using a suite of seven wide filters and two medium width filters to create an imaging dataset used for multiple goals including derivation of luminosity functions beyond the current redshift frontier, the early evolution of galaxy morphologies, discovery of the first quenched galaxies, stellar mass buildup in the first billion years, study of morphologies versus redshift, estimation of photometric redshifts, and selection of objects for spectroscopy with NIRSpec. Spectra of several thousand galaxies from the NIRSpec portion of the program will enable studies such as measuring chemical enrichment and the build-up of stellar mass with redshift, disappearance of Lyman-α during reionization, and the role of feedback in shaping the evolution of galaxies. We hope to increase the value of our survey to the community early in the decade and in the scientific life of JWST by releasing some imaging and spectroscopic data prior to the end of the JADES proprietary period.

Overview

The James Webb Space Telescope (JWST) offers new capabilities that radically change observational studies of high-redshift galaxy evolution, and this white paper describes a program to be executed by a collaboration composed of NIRSpec and NIRCam instrument team Guaranteed Time Observers (GTOs) called JADES (JWST Advanced Deep Extragalactic Survey). This program as shown below will substantially redefine our understanding of the high redshift universe. JADES and an ERS program, Cosmic Evolution Early Release Science (CEERS) Survey (PI Finkelstein, STScI ID 1345), will be executed early in JWST's mission, and therefore will be guiding research in this area for much of the decade being considered by Astro2020.

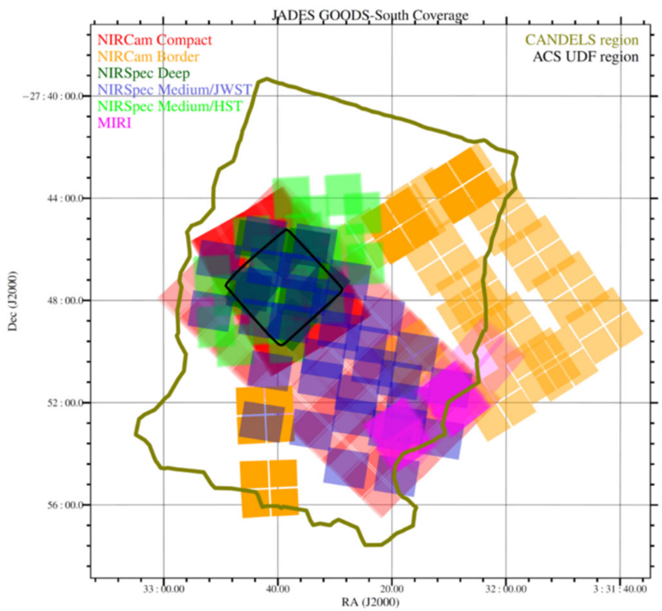

Figure 1: Coverage of the GOODS South field.

JADES targets two well-studied fields, GOODS-N and GOODS-S because of the wealth of ancilliary data and the low galactic and zodiacal backgrounds in these directions. Figure 1 summarizes the area covered in GOODS-S. With NIRSpec, we can take spectra of very faint galaxies (to AB=29 and beyond) out to 5μm; with NIRCam, we can obtain imaging of unprecedented depth with a resolution of 0.04 − 0.10" from the optical to 5μm; and with MIRI, we can complement NIRCam images at wavelengths longer than 5μm. The similar but smaller program, CEERS, will also be executed early in the mission. The latter program includes use of slitless grisms available on JWST.

We seek a deeper understanding of the formation and evolution of galaxies in the early universe and the development of galaxies' physical properties in the context of ΛCDM-based galaxy formation models. Determination of the source of the reionization photons is another important goal. Broadly speaking, spectroscopy (at R=100 to 2700) provides robust redshifts and a flux-census of the rest-frame optical emission lines to $z\sim10$. This allows us to diagnose the galaxies' star formation rates (SFR) and possibly IMFs, metallicities ([O/H], abundances of some individual elements), the ISM dust-reddening, and the ISM excitation, including signatures of AGNs. Low-resolution spectroscopy (R=100) for the brighter objects can also diagnose the stellar populations (especially the stellar ages). High-resolution spectroscopy ($R = 2700$) can diagnose internal galaxy kinematics and outflows. With its multi-slit array, NIRSpec can be used to study large numbers of faint galaxies.

The multi-wavelength NIRCam imaging will allow the detection, selection and characterization of galaxies to $z = 15$ and beyond. It will determine structure, colors, and color maps, and provide rough estimates of strong emission line equivalent widths, and of stellar mass. The imaging depth will be unparalleled, and will enable measurement of luminosity functions to much higher redshift and lower mass than can be done with HST. Deep MIRI imaging will enable a broad chromatic view of a subset of our sample, informing us about differences in the rest-UV and rest-optical structure of galaxies, constraining the presence of evolved stellar populations, and providing a critical check on the star formation rate density determined from UV-bright sources.

An empirical picture of the galaxy population, *p(z, M∗, L∗, SFR(t), Re, q, n, [Fe/H], Mgas/dust, ...)*, across the widest possible range of cosmic epochs – and then understanding galaxy formation from it – is at the heart of the transformational science that JWST was meant to deliver. It is clear that imaging needs spectroscopy (e.g. to determine ionization state and metallicity, kinematics, and robust redshifts), and that spectroscopy needs imaging (galaxy structure, aperture corrections, larger samples) for target selection. Tables 1-3 summarize the imaging and spectroscopy portions of JADES and CEERS.

Table 1: NIRCam Imaging Limits for Deep (~20hrs/band) And Medium (~2hrs/band) Surveys

Sub-survey	Area (□')	5σ Point Source Magnitude (AB)									
		F070W	F090W	F115W	F150W	F200W	F277W	F335M	F356W	F410M	F444W
Deep	46	—	30.2	30.5	30.6	30.6	30.2	29.5	30.1	29.7	29.8
Medium	190	28.7[a]	29.3	29.5	29.6	29.7	29.3	28.7[a]	29.3	28.8	29.0
CEERS	97	—	—	29.2	28.9	29.0	—	29.0	—	28.4[b]	28.6

[a] Only 93 square arc minutes will be covered using these two filters.
[b] Only 58 square arc minutes will be covered using this filter.

Table 2: Emission Line Limits for Deep (28hr prism, 7 hrs grating) and Medium Surveys (~2.4hrs per JWST-selected target, ~1hr per HST-selected target)

Subsurvey	# Targets (prism + gratings)	Limiting Emission Line Prism (2.5 μm)	G140M (1.2 μm)	Sensitivity (5-σ; cgs units) G235M (2.5 μm)	G395M (4.5 μm)	G395H (4.5 μm)
Deep	600	4.3×10^{-19}	9.5×10^{-19}	4.7×10^{-19}	2.9×10^{-19}	4.1×10^{-19}
Medium/JWST	2400	1.4×10^{-18}	1.7×10^{-18}	8.0×10^{-19}	5.0×10^{-19}	7.0×10^{-19}
Medium/HST	Up to 4800	2.3×10^{-18}	3.4×10^{-18}	1.6×10^{-18}	8.5×10^{-19}	—
CEERS Grism	39 □'	F356W:	8×10^{-18}			
NIRSpec	~600		$2\text{-}3\times10^{-18}$	$2\text{-}3\times10^{-18}$	$2\text{-}3\times10^{-18}$	—

Table 3: MIRI Imaging Limits

Subsurvey	No. of Pointings	Area (□')	Exposure Times (Ksec) F770W	F1280W	5σ Point Source Magnitude (AB) F770W	F1280W
Deep/MIRI	4	8	167	—	27.4	—
Medium/MIRI	7	14	5.6	19	25.6	25.0
CEERS[c]	4	9.3			25.5-26.2	24.3

[c] CEERS has 2 pointings that observe only F560W and F770W, the other two get F770W-F2100W.

Science Motivation

The sensitivity and instrumentation of JWST provide a singular opportunity to study the evolution of galaxies from the earliest epochs, <300 Myr after the Big Bang, through the Epoch of Reionization during the first billion years of cosmic history, and on to Cosmic High Noon (z~2, 10.4 billion years ago) where the stellar mass and black hole mass densities of the universe were well-established. Unlike all other previous studies of high-redshift (i.e., $z > 3$) galaxy populations where only rest-frame ultraviolet spectral properties have been accessible, JWST enables for the first time, via its imaging and spectroscopy with NIRCam, NIRSpec and MIRI, photometry and spectroscopy extending from blueward of the (rest-frame) Lyman break to redward of the

Balmer/4000Å break region

At the earliest times in cosmic history (e.g., <300 Myr), the first abundant population of star forming galaxies developed. HST has been used to discover a few candidate galaxies at $z{\sim}10{-}11$ providing a first glance at the primitive galaxy formation process. JWST has the sensitivity and the needed infrared filters to identify UV-selected galaxies at $z > 12$, farther than any tentative HST detections, and can yield source counts to measure the UV luminosity function evolution to at least $z \sim 10$.

Figure 2 shows predictions for number counts of high-redshift sources in our imaging survey. By reaching many magnitudes deeper in the rest-frame optical than ever achieved with Spitzer, JWST can constrain galaxy stellar masses to z ~10. The combined rest-frame UV star formation rate and rest-frame optical stellar masses will enable estimates of the stellar birthrate of galaxies out to $z{\sim}10$, and will thereby deliver our earliest constraints on the efficiency of galaxy formation. The stellar masses measured out to $z \sim 10$ will allow us to infer a bulk star formation rate to $z{\sim}12$ (given the minimum ~100 Myr timescale for the development of strong rest-frame optical breaks), to be compared directly against the star formation rate density measured from any $z{>}10$ UV-selected populations JWST discovers. The [OII](3727Å) emission line will be accessible to NIRSpec spectroscopy at these highest redshifts. This set of independent measures of the early star formation rate density will then reveal how rapidly the cosmic galaxy population develops over just a few Milky Way dynamical times after the Big Bang.

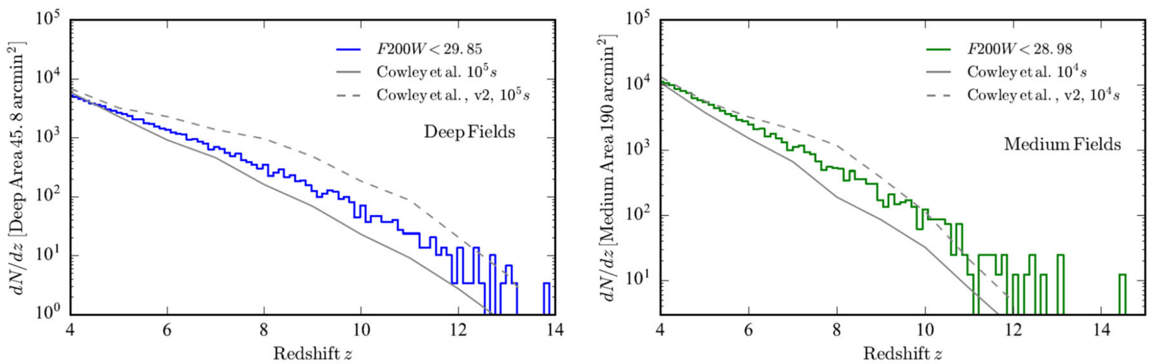

Figure 2:(Left) Cumulative counts N(> z) as a function of redshift in the Deep survey. The smooth curves are predictions from Cowley et al. (2018 MNRAS.474.2352C) for a depth of 100 ksec, similar to our deep survey, and with two different feedback prescriptions. The histogram is the counts from our mock catalog (Williams et al. 2018 ApJS..236...33W), which has been tuned to match a variety of on-sky data sets. (Right) The same, but for the Medium survey.

Our window into these early galaxies becomes dramatically richer at just slightly later times ($z{\sim}8{-}9$) where NIRSpec can measure the rest-frame optical strong lines (e.g., [O III], Hβ, [OII], and Hα/[NII] at $z < 6.8$) while NIRCam reliably probes across both the Lyman and Balmer 4000Å breaks. From previous HST surveys, we anticipate that these cosmic epochs see the first contributions of galaxies to the reionization process. JWST data will simultaneously constrain the evolving rest-frame UV galaxy luminosity density that reflects the evolving ionizing photon production rate and the nebular line emission that reveals the inefficiency of Lyman continuum escape. NIRSpec can also quantify the contamination of the photometric data by nebular line emission, important for accurate rest-frame optical continua and a clear picture of how stellar mass density of the universe builds with time. These unified measurements will result in a more accurate "balancing of the budget" for the cosmic reionization, where we weigh the cosmic ionization rate against the recombination of the intergalactic hydrogen in determining the evolving bulk IGM neutrality. JWST will allow for the first time a Lyman-α reionization analysis for a spectroscopically confirmed sample. Mapping with spectra the "Lyman-α disappearance", measuring the evolving fraction of UV-dropout selected galaxies that show (or not) Lyman-α emission, will track how the increased IGM neutrality at earlier times extinguishes observed line emission in progressively more sources.

Rest-frame optical line spectroscopy at $z\sim6-9$ dramatically extends our knowledge of the chemical enrichment of galaxies and reveals the physical conditions in the warm interstellar medium of early star-forming galaxies. Line excitation diagrams are a well-established way to diagnose the ionization state of the star-forming ISM in these systems; NIRSpec allows us to apply these diagnostics in a new redshift regime, connecting them with the exciting stellar populations. These line diagnostics can reveal AGN contributions. Via the combination of measures of star formation rate in the rest-UV, stellar mass in the rest-optical, and metallicity from nebular lines we will discover whether the fundamental metallicity and mass- metallicity relations are already in place after only $\sim$1 billion years of cosmic history. These data should also reveal how bursty star formation was, and constrain feedback models. We will monitor how these relations evolve into the relations established through ground-based spectroscopy at much lower redshifts.

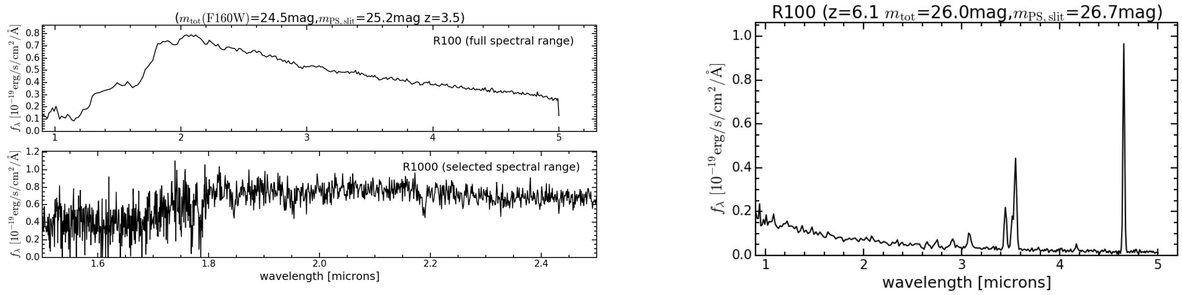

Figure 3: Examples of NIRSpec spectra that we can expect from this survey. *(Left)* "Passive" galaxies at $z\sim3.5$. *(Right)* A star-forming galaxy at $z\sim6$.

Continuing down to later times, JWST will follow how the star formation and AGN activity in the universe begin to peak after the first $\sim$2$-$3 billion years of cosmic history. Here, we can expect JWST to reveal the emergence of morphological structures through superb 2μm imaging and spectroscopic evidence for rotating disks. Ground-based IFU spectroscopy and HST imaging at rest-frame wavelengths of $\lambda<4000$Å have suggested a complex view of how galactic structures are assembled during these epochs, but the sensitivity and resolution of the imaging has been hampered by the size of the HST mirror and restricted wavelength range of its instruments. JWST will resolve galaxies in multiple bands from the rest-UV to the rest-optical, providing spatially-resolved measures of color gradients and stellar population properties. We will finally be able to distinguish the clumpy UV-bright morphology from the rest-optical light on a galaxy-by-galaxy basis, and thereby constrain the role of large-scale gravitational instability in setting galaxy structures at $z\sim2-3$ including constraining when the first bulge components appear. Higher resolution NIRSpec spectroscopy will connect these morphological measures to the dynamics of the galaxies, and through measuring outflows further constrain the role of feedback in shaping these maturing galaxies. Figure 3 shows sample spectra to be expected from NIRSpec. With the addition of Chandra, JVLA, and MIRI observations (starting with our parallels, but eventually including the MIRI GOODS-S survey described in a white paper by G. Rieke), we can connect all of these chemical, dynamical, and morphological characteristics to the presence of nuclear activity, and begin to understand how the growth of supermassive black holes first exerts influence over the properties of otherwise "normal" galaxies as they form.

Throughout these epochs, the development of the galaxy populations remains intimately connected with the structure formation process in our ΛCDM cosmology universe. Rates of star formation, stellar population aging, merging, and dynamical and morphological transformation are ultimately manifestations of the growth of dark matter halos. JWST will provide a new context for understanding the connection between galaxy and dark matter structure formation by aiming to discover the earliest galaxies that form in rare peaks of the density field, establishing both the SFR-halo mass and stellar mass-halo mass relations out to $z\sim10$, watching the emergence of dynamically cold galactic structures, and by observing the assembly of the first massive galaxies that form primarily through dissipationless mergers. The new spectroscopic capabilities allow us to identify physically-associated galaxies in the early universe rather than just projected overdensities, and enable us to distinguish between how central and satellite galaxies evolve further back in time than has previously been possible. The combination of area and depth allow for clustering analyses down to very faint limits on spectroscopically-informed samples with well-constrained redshift selection functions. In all, JWST will allow a more physically complete view of galaxy formation that builds directly from the underlying ΛCDM framework.

Our program and the related early release science program CEERS will be executed in the first year of JWST's projected 10-year mission. We expect that the data legacy from these programs will engender a host of follow-up studies with JWST and ground based telescopes that will pose new questions, and completely change our current view of the high redshift universe.

Topical Summary of Our Program

The Redshift Frontier: Galaxy formation is a self-regulated process, and the ways in which early galaxies respond to the rapid accretion of gas greatly affects even their bulk properties like luminosity and size. JWST will provide our deepest view yet of this early epoch.

The build-up of stellar mass: We will produce a detailed census of star formation rates and stellar masses at high redshift, using the critical rest-UV and rest-optical bands, as well as Hα spectroscopy. We will have information on dynamical masses from emission line widths.

The build-up of metals: With spectroscopic line ratios (e.g. Figure 3), we will measure the gas-phase metallicities of thousands of faint galaxies at $z > 3$ for the first time.

The build-up of quiescent populations: HST has found compact red galaxies at $z = 2$, but JWST's angular resolution and redder bandpass will provide revolutionarily better sensitivity to old stellar populations and their morphology at $z > 3$ to study the emergence of quenched galaxies.

The epoch of reionization: We will study the disappearance of the Lyman-α line over a substantial area to study the spatial structure of reionization.

Searching for kinematic signatures of feedback: We will use the very strong rest-frame optical emission lines to measure velocity profiles and search for outflows.

The role of AGN: By selecting fields with the deepest X-ray data, we will be sensitive to whether AGN are significant contributors to the optical and UV luminosity of our galaxies. We will target Chandra and JVLA sources to produce a substantial spectroscopic survey of the IR-faintest X-ray and radio sources.

The impact of dust extinction on the rest-frame optical spectra of early galaxies: Reddening and dust attenuation in the rest-frame UV and optical spectra (and SEDs) of galaxies are inherently interesting, and must be understood for the interpretation of observables. The combination of multi-band photometry (NIRCam) and multi-line spectroscopy (NIRSpec) enables the study of this issue through SED-fitting and through line diagnostics (Balmer decrement, etc).