How will JWST measure First Light, Reionization, and Galaxy Assembly in the post WMAP-7 and WFC3 era?

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HST and JWST changed the career of this radio astronomer ...
Outline

James Webb Space Telescope: NASA’s next Flagship mission after Hubble
Astro 2010 Decadal Survey assumed: JWST science is done ≥2014.

• (1) What is JWST and how will it be deployed?
• (2) What instruments and sensitivity will JWST have?
• (3) How can JWST can measure First Light & Reionization?
• (4) How can JWST measure Galaxy Assembly?
  [With some recent Hubble WFC3 results to support (3) & (4)].
• (5) Predicted Galaxy Appearance for JWST at redshifts z≈1–15.
• (6) Conclusions: JWST pathfinder for Lunar Dark Ages studies at z≥20.

Appendix 1: Will JWST reach the Natural Confusion Limit?

Sponsored by NASA/JWST & HST
(1) What is First Light, Reionization, and Galaxy Assembly?

HST (+WFC3): Hubble sequence & galaxy evolution from $z \approx 0$ to $z \approx 7-8$.

JWST: First Light, Reionization, & (dwarf) Galaxy Assembly at $z \approx 8-20$.

WMAP: H-Recombination at $z = 1091 \pm 1$. Imprints of all foregrounds.
(1) What is First Light and Reionization?

- Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars reionized universe for the first time at $z \lesssim 10 - 30$ (First Light).

- This should be visible to JWST as the first Pop III stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \sim 10 - 30$. 
• (1) What is First Light and Reionization?

- Population III stars with \( \gtrsim 200 \ M_\odot \) at \( z \approx 11–20 \) (First Light).
- First Population II stars (halo stars) form in dwarf galaxies of mass \( \lesssim 10^7 \) to \( 10^9 \ M_\odot \) at \( z \approx 6–9 \), which complete reionization by \( z \approx 6 \) (M. Shull).

\( \Rightarrow \) JWST needs NIRCam at 0.8–5 \( \mu \)m and MIRI at 5–29 \( \mu \)m.
JWST $\sim 2.5 \times$ larger than Hubble, so at $\sim 2.5 \times$ larger wavelengths: JWST has the same resolution in the near-IR as HST in the optical.
Need hard-working grad students & postdocs in ∼2014 ... It’ll be worth it!

(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007 ...
(1) What is the James Webb Space Telescope (JWST)?

- A fully deployable 6.5 meter (25 m²) segmented IR telescope for imaging and spectroscopy from 0.7 to 29 \( \mu \text{m} \), to be launched in June \( \gtrsim 2014 \).
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (\( \text{AB} \gtrsim 31.5 \)) and spectroscopy (\( \text{AB} \gtrsim 29 \text{ mag} \)).
After launch in June 2014 with an Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth. JWST can cover the whole sky in segments that move along with the Earth, observe $\geq 70\%$ of the time, and send data back to Earth every day.
(1) How will JWST be automatically deployed?

- During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit, 1.5 million km from Earth.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: component and system tests at JSC.
- Component fabrication, testing, & integration is on schedule: 6 out of 18 flight mirrors completely done, and at the 45K 2.0µm diffraction limit!
Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m. Primary mirror segments are made (AxSys). Now being polished (Tinsley).
Ball 1/6-model for WFS: diffraction-limited 2.0 $\mu$m images ($\text{Strehl} \gtrsim 0.85$).

Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2011-2013.

In L2, WFS updates every 10 days depending on scheduling/SC-illumination.
Actuators for 6 degrees of freedom rigid body motion

Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.
Redundant & doubly-redundant mechanisms, quite forgiving against failures
JWST’s Wave Front Sensing and Control is similar to that at Keck and HET. Successful WFS demo of H/W, S/W on 1/6 scale model (2 µm-Strehl ≥ 0.85). Need WFS-updates every ~14 days, depending on scheduling/SC-illumination.
(2) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

**Instrument Overview**

**Fine Guidance Sensor (FGS)**
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

**Near Infra-Red Camera (NIRCam)**
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

**Mid-Infra-Red Instrument (MIRI)**
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

**Near Infra-Red Spectrograph (NIRSpec)**
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems
(2) What instruments will JWST have?

All JWST instruments can in principle be used in parallel observing mode:
• Currently only being implemented for parallel calibrations.
JWST offers significant multiplexing for faint object spectroscopy:

- **NIRSpec/MSA** with $4 \times 62,415$ independently operable micro-shutters (MEMS) that cover $\lambda \approx 1–5 \mu m$ at $R \approx 100–1000$.

- **MIRI/IFU** with 400 spatial pixels covering 5–29 $\mu m$ at $R \approx 2000–4000$.

- **FGS/TFI** that covers a $2\!\!:\!\!2 \times 2\!\!:\!\!2$ FOV at $\lambda \approx 1.6–4.9 \mu m$ at $R \approx 100$.

- **NIRCam** offers $R \approx 5$ imaging from 0.7–5 $\mu m$ over two $2\!\!:\!\!3 \times 4\!\!:\!\!6$ FOV’s.
(2) What sensitivity will JWST have?

NIRCam and MIRI sensitivity complement each other, straddling $\lambda \approx 5 \, \mu m$. Together, they allow objects to be found to $z=15–20$ in $\sim 10^5$ sec (28 hrs).

LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a “First Light” galaxy dominated by massive stars, and a 50 Myr “old” galaxy at $z=20$.

RIGHT: Relative survey time vs. $\lambda$ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.
3) How can JWST measure First Light and Reionization?

Can’t beat redshift: to see First Light, must observe near–mid IR.

⇒ This is why JWST needs NIRCam at 0.8–5 µm and MIRI at 5–29 µm.
Implications of the (2010) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7–9 \quad \rightarrow \quad$ JWST $z \sim 8–25$


First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z \sim 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, more likely:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \sim 11$, ending at $z \sim 7$. The implications for HST and JWST are:

  - HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7–9$.
  - For First Light & Reionization, JWST must sample $z \sim 8$ to $z \sim 15–20$.

$\Rightarrow$ JWST must cover $\lambda = 0.7–29 \ \mu$m, with its diffraction limit at 2.0 $\mu$m.
HUDF i-drops: faint galaxies at $z \approx 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \approx 6$ to $AB \lesssim 27.0$ mag (Malhotra et al. 2005).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- Objects at $z \gtrsim 9$ are rare, since volume element is small and JWST samples brighter part of LF. JWST needs the quoted sensitivity/aperture ($A$), field-of-view ($\text{FOV=}\Omega$), and wavelength range (0.7-29 $\mu$m).
10 filters with HST/WFC3 & ACS reaching $AB = 26.5-27.0$ mag ($10-\sigma$) over 40 arcmin$^2$ at 0.07–0.15" FWHM from 0.2–1.7\textmu m (UVUBVizYJH). JWST adds 0.05–0.2" FWHM imaging to $AB \simeq 31.5$ mag (1 nJy) at 1–5\textmu m, and 0.2–1.2" FWHM at 5–29\textmu m, tracing young+old SEDs & dust.
Some science results of the Wide Field Camera Early Release Science data

Galaxy structure at the peak of the merging epoch ($z \approx 1–2$) is very rich: some resemble the cosmological parameters $H_0$, $\Omega$, $\rho_o$, $w$, and $\Lambda$, resp.

Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure. (Rutkowski et al. 2010) $\implies$ “Red and dead” galaxies aren’t dead!

• JWST will observe all such objects from 0.7–29 $\mu$m wavelength.
Lyman break galaxies at the peak of cosmic SF ($z \approx 1-3$; Hathi et al. 2010)

- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$. 

- In the JWST regime at $z \gtrsim 8$, expect faint-end LF slope $\alpha \sim 2.0$!
- In the JWST regime at $z \gtrsim 8$, expect characteristic luminosity $M^* \gtrsim -19$!
ERS 10-band redshift estimates accurate to $\sim 4\%$ with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

- Reliably masses of faint galaxies to $\text{AB}=26.5$ mag, accurately tracing the process of galaxy assembly: downsizing and merging.

ERS shows WFC3’s new panchromatic capabilities on galaxies at $z\sim0–7$.
- The HUDF (Bouwens et al. 2010) shows WFC3’s capabilities at $z\sim7–9$.

$\Rightarrow$ WFC3 is an essential pathfinder at $z\lesssim8$ for JWST (0.7–29 $\mu$m) at $z\gtrsim9$.

- JWST will trace mass assembly and dust content 3–4 mags deeper from $z\sim1–12$, with nanoJy sensitivity from 0.7–5 $\mu$m.
The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust imprinted.

High-resolution HST UV images are benchmarks for comparison with very high redshift galaxies seen by JWST, enabling quantitative analysis of the restframe-\( \lambda \) dependent structure, B/T, CAS, SFR, mass, dust, etc.
With proper restframe UV-optical benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- **(1)** Most disks will SB-dim away at high z, but most formed at \( z \lesssim 1–2 \).
- **(2)** High SB structures are visible to very high z.
- **(3)** Point sources (AGN) are visible to very high z.
- **(4)** High SB-parts of mergers/train-wrecks, etc., are visible to very high z.
(6) Conclusions

(1) JWST Project is technologically front-loaded and well on track:

(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail. JWST will determine:
- The formation and evolution of the first (reionizing) Pop III star-clusters.
- Faint-end LF-slope evol: (how) did dwarf galaxies finish reionization?
- The origin of the Hubble sequence in hierarchical formation scenarios.

(3) JWST will have a major impact on astrophysics after 2014:
- Current generation students, postdocs will use JWST during their career
- JWST defines the next frontier: the (Lunar!) Dark Ages at \( z \gtrsim 20 \).
- JWST provides technology development relevant to LUNAR exploration
Despite NASA’s CAN-do approach: Must find all the cans-of-worms ...
Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements
JWST underwent several significant replans and risk-reduction schemes:

- **2003**: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- **2005**: Eliminate costly 0.7-1.0 $\mu$m performance specs (kept 2.0 $\mu$m).
- **2005**: Simplification of thermal vacuum tests: cup-up, not cup-down.
- **2006**: All critical technology at Technical Readiness Level 6 (TRL-6).
- **2007**: Further simplification of sun-shield and end-to-end testing.
- **2008**: Passes Mission Preliminary Design & Non-advocate Reviews.
Our simulations show that ~50% of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).

Assume only 33% of J-drops are real and at $z \gtrsim 9$. Together with the HUDF and ERS upper limits to $AB \lesssim 28$ mag, the $z \sim 9$ LF is still steep!

Need JWST to measure $z \gtrsim 9$ LF, and see if it’s fundamentally different from the $z \lesssim 8$ LFs. Does a pop-III driven IMF cause a power-law LF?
Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

- $z=7$ LF more firm (see Bouwens), $z=8$ LF refined, $z=9.5$ UL's still stand.
The current WFC3 uncertainties on J-drops are large enough that at $z \gtrsim 8$, a wide range of possibilities is allowed (Yan et al. 2010; astro.0910.0077).

- Need JWST to fully measure the LF and SFR for $8 \lesssim z \lesssim 15$. 
At the end of reionization, dwarfs had beaten the Giants, but ...
What comes around, goes around ...

"You've done it now, David - Here comes his mother."
Faint-end LF-slope at $z \gtrsim 1$ with accurate ACS grism $z$’s to $AB \lesssim 27$ (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- JWST will provide fainter spectra ($AB \lesssim 29$) and spectro-photometric redshifts to much higher $z$ ($\lesssim 20$). JWST will trace $\alpha$-evolution for $z \lesssim 12$.
- Can measure environmental impact on faint-end LF-slope $\alpha$ directly.
- Expect convergence to slope $|\alpha| \equiv 2$ at $z \gtrsim 6$ before feedback starts?
- Constrain onset of Pop III SNe epoch, Type II & Type Ia SN-epochs.
(4) How can JWST measure Galaxy Assembly?

HST helped show how galaxies formed and evolved in the last 12–13 Gyrs:

- Galaxies of all types formed over a wide range of time, but with a notable transition around $z \sim 1–1.5$, when Hubble sequence appears:
- Subgalactic units rapidly merge from $z \sim 7 \rightarrow 1$ to grow bigger units.
- Merger products settle as galaxies with large bulges or disks at $z \lesssim 1$. These evolved mostly passively since then, resulting in the giant galaxies that we see today.

JWST is designed to observe the following re. Galaxy Assembly:

- Formation and evolution of Pop III star-clusters in the first 0.5 Gyr.
- Faint-end LF-slope evolution: (how) did dwarf galaxies finish reionization after 0.5–1 Gyr? Was there a transition to Pop-III objects?
- Measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their SF, mass, Fe/H, and dust distributions, rest-frame structure and type, etc., as function of redshift for $z \lesssim 15$. 
Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?

- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2 \times 10^6$ galaxies/deg$^2$ to AB=31.5 mag ($\sim 1$ nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\sim 1$ and 10 nJy, resp.

- $\Rightarrow$ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM$\lesssim 0''08$).

- $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.
Effective Radius $r_e$ (arcsec)

$B_{Vega}$ (F450W) [total mag]

HDF
Par	Type
E/S0
Sabc
Sd/Irr

$(\Omega_m,\Omega_{\Lambda}) =$
(0.3,0.7)
CDM simuls

RC3:

ESO - LV:

2dF/MGC:

HST I-band diffraction limit

G-b diffraction limit

HST/HDF SB-limit

M$_B$ = −20

JWST 25-hr SB-limit

UDF 100-hr i-band SB-limit

J′$_{AB}$ (1.35 $\mu$m) [total mag]

Expected sizes in hierarchical models

Natural Conf. limits:
1/50 beams
1/10 beams
1 obj/beam
(sky is covered)

GC’s z=7

Natural Conf. limits:
1/50 beams
1/10 beams
1 obj/beam
(sky is covered)
Combination of ground-based and space-based HST surveys show:

• (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:
• (2) At the HDF/HUDF limits, this is not only due to SB-selection effects (cosmological \((1+z)^4\)-dimming), but also due to:

  (2a) hierarchical formation causes size evolution:
  \[ r_{hl}(z) \propto r_{hl}(0) (1+z)^{-1} \]

  (2b) increasing inability of object detection algorithms to deblend galaxies at faint mags ("natural" confusion \(\neq\) "instrumental" confusion).

• (3) At AB\(\gtrsim 30\) mag, JWST and at \(\gtrsim 10\) nJy, SKA will see more than \(2\times10^6\) galaxies/deg\(^2\). Most of these will be unresolved \((r_{hl} \lesssim 0''1\) FWHM (Kawata et al. 2006). Since \(z_{med} \approx 1.5\), this influences the balance of how \((1+z)^4\)-dimming & object overlap affects the catalog completeness.

References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/  [Talk, Movie, Java-tool]
www.asu.edu/clas/hst/www/ahah/  [Hubble at Hyperspeed Java–tool]
http://wwwgrapes.dyndns.org/udf_map/index.html  [Clickable HUDF map]
http://ircamera.as.arizona.edu/nircam/
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