The Era of JWST: Measuring First Light, Reionization, and Galaxy Assembly from the L2 Zodi Environment

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UC Irvine Workshop on: “The View from 5 AU”, Th. Mar 25, 2010
Outline

• (1) What is JWST and how will it be deployed?
• (2) What instruments and sensitivity will JWST have?
• (3) Measuring the All Sky Zodi in VI with HST/WFPC2 to few %
• (4) Measuring the HUDF Zodi in BViz with HST/ACS to 0.2%
• (5) How JWST will measure First Light & Reionization, & Galaxy Assembly from the L2 Zodi Environment
• (6) Summary and Conclusions

Appendix 1: Will JWST reach the Natural Confusion Limit?

Sponsored by NASA/JWST & HST
JWST is ∼2.5× larger than Hubble, so at ∼2.5× larger wavelengths: JWST has the same resolution in the near-IR as HST in the optical.
• What is the James Webb Space Telescope (JWST)?

- A fully deployable 6.5 meter (25 m$^2$) segmented IR telescope for imaging and spectroscopy from 0.7 to 29 \(\mu\)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 (AB\(\lesssim 31.5\)) and spectroscopy (AB\(\lesssim 29\) 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 $\gtrapprox 70\%$ of the time, and send data back to Earth every day.
- JWST L2-sky minimizes $\lambda \approx 3 \mu m$; $\sim 10^4 \times$ fainter than ground-based sky.
- Faintest observable JWST objects have $AB = 31.5$ mag $\approx 1$ nanoJy
- Need JWST-UDF systematics and sky-subtr 10 mag fainter than Zodi!
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.
(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
WFPC2 NEP/SEP Zodi sky is $V_{AB} \approx 23.20$ mag/arcsec$^2$

WFPC2 NEP/SEP Zodi sky is $I_{AB} \approx 22.45$ mag/arcsec$^2$
UL: Blank field; UR: $32^2$ modes; LL: sorted; LR: 1-sided mode-fit
UL: Galaxy; UR: $32^2$ modes; LL: sorted; LR: 1-sided mode-fit
UL: Starfield; UR: $32^2$ modes; LL: sorted; LR: 1-sided mode-fit
(3) Zodi BVI Sky-values in entire HST/WFPC2 data base

- **WFPC2 NEP/SEP Zodi sky is** $I_{AB} \sim 22.45$ mag/arcsec$^2$
(4) Zodi BViz sky-values in HUDF to 0.2% of sky


(MIDDLE): Modal BViz sky-values in the HUDF: NOT sky-subtracted.


- HUDF sky-subtraction error $\approx (2–3) \times 10^{-3}$ or $AB \approx 29.0–30.2$ mag/arcsec$^2$
(4) Zodi BViz sky-values in HUDF to 0.2% of sky

Table 1. Measured sky values in $BVi'z'$ (filters) for the HUDF

<table>
<thead>
<tr>
<th>HUDF Filter</th>
<th>Number of Exposures</th>
<th>Mean Sky Value(^a) ($e^{-}/s$) and rms error(^b)</th>
<th>Sky SB(^c) (AB mag arcsec(^{-2}))</th>
<th>Sky Color(^c) (AB mag)</th>
<th>$1\sigma$ Sky-Subtraction error (AB mag arcsec(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>112</td>
<td>0.015909 ± 0.000065</td>
<td>23.664 ± 0.003</td>
<td>$(B-V)_{\text{sky}}=0.800$</td>
<td>29.85 ± 0.05</td>
</tr>
<tr>
<td>V</td>
<td>112</td>
<td>0.070276 ± 0.000297</td>
<td>22.864 ± 0.002</td>
<td>$(V-i')_{\text{sky}}=0.222$</td>
<td>30.15 ± 0.15</td>
</tr>
<tr>
<td>$i'$</td>
<td>288</td>
<td>0.040075 ± 0.000088</td>
<td>22.642 ± 0.002</td>
<td>$(i'-z')_{\text{sky}}=0.065$</td>
<td>29.77 ± 0.20</td>
</tr>
<tr>
<td>$z'$</td>
<td>288</td>
<td>0.020511 ± 0.000047</td>
<td>22.577 ± 0.003</td>
<td>$(V-z')_{\text{sky}}=0.287$</td>
<td>28.95 ± 0.05</td>
</tr>
</tbody>
</table>

\(^a\)From Fig. 4 in Hathi, N. P., et al. 2008, AJ, 135, 156 (astro-ph/0710.0007)

\(^b\)Error is standard deviation of the mean ($\sigma/\sqrt{N}$)

\(^c\)Sky surface brightness values and colors are consistent with the solar colors in AB mag of $(V-i')=0.19$, $(V-z')=0.21$ and $(i'-z')=0.01$ [except for bluest color $(B-V)$], and is dominated by the zodiacal background.

- HUDF sky-subtraction error $\simeq (2-3) \times 10^{-3}$ or AB $\simeq 29.0-30.2$ mag/arcsec$^2$
• Select all isolated, nearly unresolved ($2r_e \lesssim 0''3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops, to $AB = 29.0$ mag.

• Construct average image stack and light-profiles of these dwarf galaxies at $z \sim 4$, $z \sim 5$, and $z \sim 6$.

• If these compact, round objects are intrinsically comparable, each stack has the S/N of $\sim 4300$ HST orbits ($\sim 300$ JWST hrs; Hathi et al. 2008)!
Best fit Sersic profile of 1680 ACS V-band orbit stack: n=0.90
Best fit Sersic profile of 4320 ACS i-band orbit stack: n=0.88
Best fit Sersic profile of 4320 ACS z-band orbit stack: n=1.67
⇒ Dwarf galaxies at $z \approx 4–5$ are disk dominated!

- JWST can do this to $10^{-4}$ or AB $\approx 31.0–32.0$ mag/arcsec$^2$ to $z \lesssim 15$,
- Provided that JWST straylight/rogue path is kept to a minimum: well below Zodi and only at low spatial frequencies.
HUDF Zodi: Dynamical ages of Dwarf Galaxies at \( z \approx 4-6 \)?

- HUDF sky-subtraction error is \( 2-3 \times 10^{-3} \) or \( AB \approx 29.0-30.2 \) mag/arcsec\(^2\).
- Average 4300-orbit compact, round dwarf galaxy light-profile at \( z \approx 6-4 \) deviates from best fit Sersic \( n \approx 1.0 \) law (incl. PSF) at \( r > 0\arcsec 27-0\arcsec 35 \).
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of \( \tau_{\text{dyn}} \approx 0.1-0.2 \) Gyr at \( z \approx 6-4 \) for the enclosed masses.

\[ \Leftrightarrow \text{comparable to SED ages (Hathi}^+ \ 2008, \ AJ \ 135, \ 156; \ astro-ph/0710.0007) \]
\[ \Rightarrow \text{Global starburst that finished reionization at } z \approx 6 \text{ started at } z \approx 6.6? \]
- (5) 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 $\mu$m and MIRI at 5–29 $\mu$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 $\mu$m (UVUBVizYJH). JWST adds 0.05–0.2" FWHM imaging to $AB \simeq 31.5$ mag (1 nJy) at 1–5 $\mu$m, and 0.2–1.2" FWHM at 5–29 $\mu$m, tracing young+old SEDs & dust.
WFC3 Lyman break galaxies at the peak of cosmic SF ($z \sim 1-3$; Hathi $^+$ 2010)

- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$. 
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.
WFC3 ERS 10-band redshift estimates accurate to $\sim 4\%$ with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

- Reliable masses of faint galaxies to AB=26.5 mag, accurately tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?)

ERS shows WFC3’s new panchromatic capabilities on galaxies at $z \sim 0–7$.

- The HUDF shows WFC3 IR’s capabilities at $z \sim 7–9$.

$\Rightarrow$ WFC3 is an essential pathfinder at $z \lesssim 8$ for JWST (0.7–29 $\mu$m) at $z \gtrsim 9$.

- JWST will trace mass assembly and dust content 3–4 mags deeper from $z \sim 1–12$, with nanoJy sensitivity from 0.7–5$\mu$m.
HUDF i-drops: faint galaxies at $z \approx 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \approx 6$ to $AB \leq 27.0$ mag (Malhotra et al. 2005).

(RIGHT) Same mosaic, but stretched to $\lesssim 10^{-3}$ of Zodi sky!!

The CLOSED-TUBE HST has residual low-level systematics: imperfect removal of detector artifacts, flat-fielding, and faint straylight.

The open JWST architecture need perfect baffling and rogue path mitigation to do ultradeep JWST fields (JUDF’s) to $10^{-4}$ of sky.
Objects at $z \gtrsim 9$ are rare (Bouwens$^+$ 2010, Yan$^+$ 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture ($A$), field-of-view ($\Omega$), and $\lambda$-range (0.7-29 $\mu$m).

With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.

To study co-evolution of SMBH-growth and proto-bulge assembly for $z \lesssim 10-15$ requires new AGN finding techniques for JWST.
Our simulations show that \( \sim 50\% \) 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 $8 \lesssim z \lesssim 15$. 
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 must learn all lessons from HST ACS, NICMOS & WFC3:
- Keep straylight/rogue path to an absolute minimum, and out-of-focus.
- Making sky-superflats (MDS mode) will be critical for a 500+ hr JUDF!
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
Baseline “Cup Down” Tower Configuration at JSC (Before)

Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling
JSC currently has 7 KW He capability
Current plan includes 10 trucks of LN2/day during cooldown
Interferometers, Sources, Null Lens and Alignment Equipment are in Upper and Lower Pressure Tight Enclosure Inside of Shroud

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), i.e., demonstration in a relevant environment — ground or space.
- **2007**: Further simplification of sun-shield and end-to-end testing.
- **2008**: Passes Mission Preliminary Design & Non-advocate Reviews.

JSC “Cup Up” Test Configuration (New Proposal)

No Metrology Tower and Associated Cooling H/W.
External Metrology
Two basic test options:
1. Use isolators, remove drift through fast active control + freeze test equipment jitter
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload “floor” to separate ambient pressure and temperature.
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 \( \mu \text{m-Strehl} \gtrsim 0.85 \)). Need WFS-updates every \( \sim \)10 days, depending on scheduling/SC-illumination.
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 $2\frac{1}{2} \times 2\frac{1}{2}$ 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 $2\frac{1}{3} \times 4\frac{1}{6}$ FOV’s.]
(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.
(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 $\sim 10^5 \ \text{sec} \ (28 \ \text{hrs})$.

**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.
Implications of the (2010) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7–9 \quad \Rightarrow \quad$ JWST $z \simeq 8–25$


$\Rightarrow$ First Light & Reionization occurred between these extremes:

• (1) Instantaneous at $z \simeq 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, more likely:
• (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \lesssim 7$. 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 $z \simeq 8$ to $z \simeq 15–20$.

$\Rightarrow$ JWST must cover $\lambda = 0.7–29 \ \mu m$, with its diffraction limit at 2.0 $\mu m$. 
At the end of reionization, dwarfs had beaten the Giants, but ...
"You've done it now, David - Here comes his mother."

What comes around, goes around ...
Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?

- HST data B>20 mag
  - HDFN (Cohen et al.)
  - HDFS (Cohen et al.)
  - 53W002 (Cohen et al.)
  - BBPS (Cohen et al.)
  - HST data B>20 mag

Key for B < 20 mag
- MGC (w/Types)
- DLS (w/Types)
- NDWFS (w/Types)

Key for B < 25 mag
- MGC (Liske et al.)
- HDFN (O96)
- 53W002 (O96)
- HUDF (This paper)

- 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.

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

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

$B_{\text{Vega}}$ (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

$M_B = -20$

$J''_{\text{AB}} (1.35 \mu) \text{ [total mag]}$

Expected sizes in hierarchical models

Natural Conf. limits:

1/50 beams

1/10 beams

1 obj/ beam

(sky is covered)

UDF 100−hr i−band SB−limit

JWST 25−hr SB−limit

JWST 100−hr I−band SB−limit
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:

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

   b. 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 \(2 \times 10^6\) 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]
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