HOW JWST CAN MEASURE FIRST LIGHT, REIONIZATION AND GALAXY ASSEMBLY

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Abstract We summarize the design and performance of the James Webb Space Telescope that is to be launched to an L2 orbit in 2011, and how it is designed to study the epochs of First Light, Reionization and Galaxy Assembly.

Keywords: James Webb Space Telescope — population III stars — reionization — galaxy formation — galaxy evolution

1. The James Webb Space Telescope and its Instruments

The James Webb Space Telescope (JWST) is a fully deployable 6.5 meter segmented IR telescope (25 m^2 collecting area) optimized for imaging and spectroscopy from 0.6μm to 28μm, to be launched by NASA in 2011 (Mather & Stockman 2000). After its launch, JWST will make a several month journey to the Earth–Sun Lagrange point L2, during which it will be automatically deployed in phases, its instruments will be tested, and it will then be inserted into an L2 halo orbit. JWST has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB $\lesssim$ 31.5-32 mag) and spectroscopy (AB $\lesssim$ 29 mag). From L2, JWST can cover the whole sky in segments that move along in RA with the Earth. It will have an observing efficiency $\gtrsim$ 70%, and send data back to Earth every day. The JWST science requirements are described by Gardner et al. (2004) and its instruments in the websites below. In summary, JWST has the following instruments:

- **NIRCam:** Near-Infrared Camera made by an UofA + Lockheed + CSA consortium will do imaging from 0.6–5.3μm using a suite of broad-, medium-, and narrow-band filters. NIRCam uses two identical and independently operated imaging modules, with two wavelengths observable simultaneously via a dichroic that splits the beam around 2.35μm. Each of these two channels has an independently operated $2'.2\times4'.6$ FOV. Both channels are Nyquist-sampled: the short wavelength channel at 2μm with $0''.0317$/pixel, and the and long wavelength at 4μm with $0''.0648$ /pixel. NIRCam's ten 2k×2k HgCdTe arrays will be passively cooled.

• **NIRSpec:** The Near-Infrared Spectrograph made by an ESA + GSFC consortium will do spectroscopy with resolving powers of R$\sim$100 in prism mode, of R$\sim$1000 in multi-object mode using a micro-electromechanical array system (MEMS) of micro-shutters that can open slitlets on previously imaged known objects, and of R$\sim$3000 using long-slit spectroscopy. All NIRSpec spectroscopic modes have a $\sim3'.4\times3'.4$ FOV.

• **MIRI:** The Mid-InfraRed Instrument made by an UofA + JPL + ESA consortium will do imaging and spectroscopy from 5–28μm. MIRI is actively cooled by a cryostat and its expected lifetime is at least 5 years. The NIRCam and MIRI sensitivity complement each other straddling 5μm in wavelength, and together allow the first starforming objects to be found to redshifts z=15–20 in $\gtrsim 10^5$ sec (28 hrs) integration times. To see First Light, JWST must observe in near–mid IR, and so need NIRCam at 0.8–5μm and MIRI at 5–28 μm.

• **FGS:** The Fine Guidance Sensor is made by CSA and provide stable pointing at the milli-arcsecond level. It will have sufficient sensitivity and a large enough FOV to find guide stars with $\gtrsim$95% probability at any point in the sky. The FGS will have three simultaneously imaged fields of view of $2'.3\times2'.3$, one of which feeds a pure guider channel, one feeds a guider channel plus a long wavelength R$\sim$100 tunable filter channel with light split by a dichroic, and another feeds the short wavelength tunable filter R$\sim$100 channel.

JWST has fully redundant imaging and spectroscopic modes. It will not be serviced at L2, and therefore will undergo an extensive series of ground-testing and thermal vacuum testing in 2008–2009, after its main construction phase in 2004–2008. The main NASA contractor is Northrop Grumman Space Technology ("NGST") in Redondo Beach (CA).

2. Measuring first light, reionization & galaxy assembly

• **First Light:** WMAP (Spergel et al. 2003) has shown that First Light may have happened in two epochs (Cen 2003): (1) Population III stars with 200-300 $M_\odot$ at z$\simeq$15–25 (First Light). These Pop III star clusters and their extremely luminous supernovae should be visible to JWST at z$\simeq$25 to z$\simeq$15; This epoch was likely followed by a second Dark Ages, since Pop III supernovae heated the IGM, which could not cool and form normal Pop II halo stars until z$\simeq$15 to z$\simeq$10; (2) Population II stars (halo stars) form in dwarf galaxies of mass=10^6 to 10^9 $M_\odot$ at z$\simeq$6–10. This will be visible to JWST in the luminosity function (LF) of the first star-forming galaxies from z$\simeq$10 to z$\simeq$6.

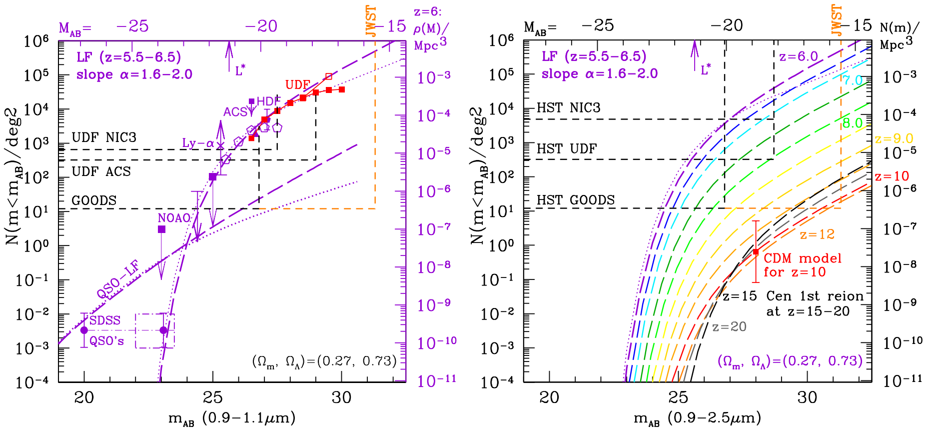

Fig. 1.a (LEFT) The UDF has shown that luminosity function of z≃6 objects is very steep, with faint-end Schechter slope |α|≃1.8–1.9 (Yan & Windhorst 2004b). Dwarf galaxies and not quasars therefore likely completed the reionization epoch at z≃6 (Yan et al. 2004a). This is what JWST likely will observe in detail. **Fig. 1.b (RIGHT)** HST/ACS can detect objects at z$\lesssim$6.5, but its discovery space A.Ω.Δlog(λ) cannot map the entire reionization epoch. NICMOS similarly is limited to z$\lesssim$8–10. JWST will be able to trace the entire reionization epoch from First Light at z≃20 to the end of the reionization epoch at z≃6.

- **Reionization:** The UDF has shown that luminosity function of z≃6 objects (Yan et al. 2004b) is very steep, with a faint-end Schechter slope |α|≃1.8–1.9 after correcting for incompleteness of the ACS i-band dropout samples (Fig. 1a). This steep LF may have provided enough UV-photons to complete the reionization epoch at z≃6 (Yan & Windhorst 2004a). Hence, dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. The Pop II stars in dwarf galaxies cannot have started shining pervasively much before z≃6–8, or no neutral H-I would be seen in the foreground of z$\gtrsim$6 quasars (Fan et al. 2003), and so dwarf galaxies likely ramped up their formation gradually from z≃10 to z≃6. This is what JWST will observe in detail.

HST/ACS can detect objects at z$\lesssim$6.5, but its discovery space A.Ω.Δlog(λ) cannot map the entire reionization epoch. NICMOS similarly is limited to z$\lesssim$8–10. JWST will be able to trace the entire reionization epoch from First Light at z≃20 to the end of the reionization epoch at z≃6. With proper survey strategy (area *and* depth), JWST can trace the entire reionization epoch, i.e. detect the first star-forming objects. For this to be successful in realistic or conservative model scenarios, JWST needs to have the quoted sensitivity/aperture (A), field-of-view (FOV=Ω), and wavelength range (0.7-28μm).

- **Galaxy Assembly:** Galaxies of Hubble types formed over a wide range of cosmic time, but with a notable phase transition around z≃1.0: (1) Subgalactic units rapidly merge from z≃7 to z≃1 to grow bigger units; (2) Merger products start to settle as galaxies with giant bulges or large disks around z≃1. These evolved mostly passively since then (as tempered by the cosmological constant, see Windhorst et al. this Vol.), resulting in the giant galaxies that we see today. JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame type as a function of redshift or cosmic epoch. The uncertain rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust superimposed. This complicates the comparison with very high redshift galaxies as seen by JWST, although with good images a quantitative analysis of the restframe-wavelength dependent morphology and structure can be made (e.g., Odewahn et al. 2002; Windhorst et al. 2002). JWST can measure how galaxies of all Hubble types formed over a wide range of cosmic time, by measuring their redshift distribution as a function of rest-frame type (Driver et al. 1998). For this, the types must be well imaged for large samples from deep, uniform and high quality multi-wavelength images.

With proper restframe-UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure over a wide range of cosmic time, as following: (1) Most disks will SB-dim away at very high redshifts ($z\simeq 15$–20), but they likely formed at $z \lesssim z_{form} \simeq$ 1–2 anyway; (2) High SB structures are visible to $z\simeq 10$–15; (3) Point sources (Pop III star clusters and AGN) are visible to $z\simeq 15$–20; (4) High SB-parts of mergers/train-wrecks are visible to $z\simeq 10$–15. This is what JWST will observe in detail.

The complete Windhorst poster and talk at this conference can be found at www.asu.edu/clas/hst/www/wfpc2/midUV/cy09index.html (click on data).

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