Frontier Science with the James Webb Space Telescope

Oct 20th, 2011

Astrophysics Subcommittee Meeting, NASA HQ
Frontier Science with JWST

Outline
1.) Two Slide Primer
2.) Instrumentation
3.) Frontier Science
   - Solar System
   - Exoplanets
   - Resolved Stellar Pops in the Milky Way
   - Resolved Stellar Pops in the Local Volume
   - First Galaxies and Stars
   - Dark Energy
4.) Community Tools
JWST is Astronomy’s Next Great Observatory

1.) Photon Limited Science
2.) Diffraction Limited Science

- HST
- JWST
- Spitzer
1.) Photon Limited Science 
2.) Diffraction Limited Science

**Diffraction Limits**

**Hubble (D = 2.4 m)**
- ACS @ 0.5 µm = 0.043"
- WFC3 @ 1.6 µm = 0.138"

**Spitzer (D = 0.8 m)**
- IRAC @ 3.6 µm = 0.93"
- IRAC @ 8.0 µm = 2.06"
- MIPS @ 24 µm = 6.18"

**JWST (D = 6.5 m)**
- NIRCam @ 2 µm = 0.063"
- NIRCam @ 4 µm = 0.126"
- MIRI @ 10 µm = 0.317"
- MIRI @ 20 µm = 0.635"

But, Hubble pixels are 0.04 – 0.05” at <1 µm and 0.13” at >1 µm
- Spitzer pixels are 1.2” at <8 µm and 2.55” at 24 µm

→ Hubble can not achieve Nyquist sampling of the diffraction limit
→ Spitzer only achieves Nyquist sampling of limit at λ > 24 microns

JWST NIRCam has two modules, with pixel size 0.0317” at <2.5 µm and 0.0648 at >2.5 µm
JWST MIRI has pixel size of 0.11 arcsec

→ **JWST achieves Nyquist sampling of the diffraction limit at 2 µm, 4 µm, and 7+ µm**
The Hubble UDF (F105W, F125W, F160W)

Simulated JWST
The Near Infrared Camera (NIRCam)
- Visible and near infrared camera (0.6 – 5 micron)
- 2.2’ x 4.4’ field of view, diffraction limited
- Coronographs

The Near Infrared Spectrograph (NIRSpec)
- Multi-object spectrograph (1 – 5 micron)
- 3.4’ x 3.4’ FOV, 0.1” pixels
- R = 1000 and 2700 gratings; R = 100 prism
- 3” x 3” IFU
### The Mid Infrared Instrument (MIRI)
- Mid-infrared camera and spectrograph (5 – 28 microns)
- 1.9’ x 1.4’ imaging FOV, 0.11” pixels
- R = 100 slit spectrograph (5 – 10 micron) and IFU (R = 3000)
- Coronographs

### The Near Infrared Imager and Slitless Spectrograph (NIRISS)
- Infrared imager and slitless spectrograph
- 2.2’ x 2.2’ FOV

### The Fine Guidance Sensor (FGS)
- 2.4’ x 2.4’ imager for target acquisition
- Rapid readout of subarray for ACS control
- 95% probability of finding a guide star anywhere in sky
Program

- Nearly 200 participants
- Mix of invited and contributed talks focusing on science potential
- 40 poster presentations
- 1/3 of total time was reserved for discussion
- PIs described instrument capabilities to deliver forefront science
- Public Talk, Education Display, Hubble 3D viewing, Science Writers Workshop, ...
Science Highlights

• Strong Lensing to Study the Evolution of Galaxies – Tommaso Treu (UCSB)
• High Precision Measurements of H$_0$ – Adam Riess (STScI / JHU)
• Finding the First Cosmic Explosions with JWST – Daniel Whalen (Carnegie Mellon Univ.)
• A Compendium of Kepler Discoveries for JWST Follow Up – William Borucki (NASA ARC)
• Observing the First Galaxies – Richard Ellis (Caltech)
• Solar System Opportunities with JWST – Heidi Hammel (AURA)
• Gas in Protoplanetary Disks – Thomas Henning (MPIA)
• Active Galactic Nuclei with JWST – Jane Rigby (GSFC)
• Star Formation in Galaxies in the Era of JWST – Daniela Calzetti (UMass)
• Mid Infrared Observations of High Redshift Galaxy Evolution – Alexandra Pope (UMass)

https://webcast.stsci.edu/webcast/ (Click “Webcast Archives”)
Frontier Science Opportunities with JWST

Science Highlights

• Exotic Endings for Massive Stars – Shri Kulkarni (Caltech)
• Robust Predictions for High-z Galaxies: What will we Learn with JWST – Andrew Benson (Caltech)
• The “Final Frontier” of Star & Planet Formation: Piled Deeper & Wider – Mike Meyer (ETH, Zurich)
• Exoplanet Discovery and Characterization with JWST – Jeff Valenti (STScI)
• Weaving Circumgalactic Webs: The View from the Webb Telescope – Crystal Martin (UCSB)
• The Evolution of Chemical Enrichment and Outflows at z ~ 1-6 – Alice Shapley (UCLA)
• Probing Galaxy Stellar Mass Assembly in the Universe with JWST – Karina Caputi (Edinburgh)
• Resolved Stellar Populations in the Near IR – Jason Kalirai (STScI)
• Probing the Dissipation of K.E. In Phases of Galaxy Evol. with JWST – Pierre Guillard (Caltech)
• Star Formation in the Milky Way and its Neighbors in the Mid-IR – Christine Wilson (McMaster)

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"There are three main areas in which collaboration with other parts of NASA could benefit the solar system exploration program....the Hubble Space Telescope has a long history of successful planetary observations, and this collaboration can be a model for future telescopes such as the James Webb Space Telescope."

Vision and Voyages for Planetary Science in the Decade 2013-2022

**Hubble, Spitzer, and Herschel**
- Discovery of new moons around Pluto
- Discovery of the largest ring around Saturn
- Characterization of Ceres and Vesta, others
- Discovery of new Kuiper Belt Objects (KBOs)
- Detailed studies of cloud structure in Gas Giants
- Torus of water vapor on Saturn
- Ocean-like water on Jupiter-family comet
- Long-term monitoring of the Martian atmosphere
- And much more...
Solar System Science with JWST

**Pointing Control System**
Enables observations of solar system objects with rates of motion up to 0.03 arcsec per second. Includes all planets and asteroids beyond Earth’s orbit.

**Mars**
- Time-resolved NIR spectroscopy will reveal the variability of atmospheric species including CO₂, CO, and H₂O and constrain radiative and absorptive properties of airborne dust, enabling photochemical and dynamical modeling of the Martian climate.

**Jupiter and Saturn**
- MIR med-res. spectroscopy and IFU data will explore phosphine and methane fluorescence, which link to the vertical dynamics and thermal structure of the upper atmosphere.
- Provide a global context on large-scale weather patterns for high-resolution studies from complementary planetary missions (e.g., Juno and Cassini).
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**Uranus and Neptune**
- Image spectral features from high latitudes in each planet with high sensitivity and map clouds.
- Spectral characterization of H₃⁺, CO in fluorescence, detailed mapping of 5 micron window, search for minor species, and measure isotopic ratios of major elements.
- MIR observations will measure temporal variations in temperature, resolve sources of underlying driving dynamics, and disentangle causes of rotation modulation.
Kuiper Belt Objects (KBOs)

- Image all known KBOs in the MIR
- R = 100 NIR spectroscopy with S/N = 20 in 3 hours (V < 25); R>100 for bright KBOs

1.) Constrain surface compos. (H$_2$O, CH$_4$, CH$_3$OH) & volatile inventories; first spectra at 2.5–5 microns.

2.) Address the dynamical and chemical history of the solar system; test formation theories.
**Solar System Science with JWST**

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**Dwarf Planets**
- Time-resolved imaging of Pluto, Eris, Sedna and other dwarf planets
- IR spectroscopy of large bodies in the outer solar system
1.) Reveal seasonal behaviors and surface compositions.
2.) Track variations in N$_2$ and CH$_4$; discover new organic molecules/ices.
3.) Explore correlations between atmospheric chemistry changes and albedo.

**The Mass of Eris (Hubble + Keck)**
Solar System Science with JWST

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...and much more, including Icy Moons and Comets
Exoplanet Discovery and Characterization with JWST

Kepler
- Planetary candidates in 1st data release
  - 1235 candidates
  - 68 Earth-sized planets
  - 54 candidates in habitable zone
  - 5.4% of stars host Earth sized planetary candidate

Transiting Exoplanet Survey Satellite (TESS)
- Selected NASA Explorer Proposal for Potential Future Mission
### Exoplanet Discovery and Characterization with JWST

<table>
<thead>
<tr>
<th>Application</th>
<th>Planet Type</th>
<th>Res.</th>
<th>JWST Scientific Investigations</th>
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<tbody>
<tr>
<td>Transit Light Curves</td>
<td>Gas Giants</td>
<td>5</td>
<td>- Planet prop. w/ RVs (mass, radius) (\rightarrow) physical structure</td>
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<tr>
<td></td>
<td>Intermediate Mass</td>
<td>5</td>
<td>- Detection of terrestrial transits</td>
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<td>Super Earths</td>
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<td>- Transit timing: detection of unseen planets</td>
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<td>Phase Light Curves</td>
<td>Gas Giants</td>
<td>5</td>
<td>- Day to night emission mapping</td>
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<td></td>
<td>Hot Neptunes</td>
<td>5</td>
<td>- Dynamical models of atmospheres</td>
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<tr>
<td>Transmission Spectroscopy</td>
<td>Gas Giants</td>
<td>3000</td>
<td>- Spectral line diagnostics</td>
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<tr>
<td></td>
<td>Intermediate Mass</td>
<td>100-500</td>
<td>- Atmospheric composition measurements (C, CO(_2), CH(_4))</td>
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</tbody>
</table>

M. Clampin et al. (2009), JWST White Paper,  
“Comparative Planetology: Transiting Exoplanet Science with JWST”

JWST/NIRSpec will measure phase curves of exoplanets around nearby M dwarfs in 1 hour.
Exoplanet Discovery and Characterization with JWST

Atmospheric transmission spectrum (4 hours) for HD209458-like Kepler source using NIRSpec (R=3000). Simulation from J. Valenti

→ JWST can detect water in habitable zone Super Earths.
Local Calibrators

- Star clusters represent excellent tools for testing stellar evolution models
- Constituent stars are coeval, iso-metallic, and co-spatial
- HST has been a game changer, especially at visible wavelengths

A wide-field view of 47 Tuc and the SMC

Complete Stellar Pops of a Cluster
J. Kalirai et al. (2011, submitted)
Local Calibrators

- JWST will be a game changer with IR high resolution, wide field capability

- “Kink” is age insensitive, removes degeneracies
- Accurate fundamental parameters
- New tests of stellar evolution models in the IR
- New generations of pop. synthesis models
- Measure total stellar pop more efficiently

The predicted color-magnitude diagram shape for a coeval population at 10 kpc
JWST will measure $V = 30$ M dwarfs in 10 minutes.

JWST will measure the stellar mass function to the H burning limit in stellar populations out to 25 kpc in <3 hours.
A Simulated Field of Omega Cen and the NIRSpec Microshutter Array (MSA)

Combine JWST photometry with JWST spectroscopy

- NIRSpec will obtain large (~10^4) statistical samples of spectra in dense fields, 10-40% recovery.
- MSA reconfiguration once, no dithering. Sky background exposures are “free”.
- Use cases in globular clusters, star forming regions, Galactic disk, Galactic bulge, *provided user requires statistical sampling of stars.*
Putting it Together

- NIRCam, NIRISS imaging & NIRSpec MOS spectroscopy of clusters, MW components, and star forming regions will provide age & abundances and test formation & assembly models.
- NIR imaging completes stellar inventory of MW pops and informs the Galactic mass budget.
- MIRI imaging & spectroscopy provides $T_{\text{eff}}$, $\log(g)$, and mass for stellar and substellar objects.
Synergy between wide-field ground based imaging, HST ultra-deep imaging and and 10-m spectroscopy

SDSS Field of Streams

SDSS, HST, & Keck work together to yield substructure maps, metallicity, ages, and kinematics of nearby Local Group galaxies.

Brown et al. (2008)
Future synergies between LSST, JWST, and 30-m telescopes will
1.) Push beyond the Local Group
2.) Increase leverage to probe sensitive age variations.


→ JWST will yield the first direct ages in galaxies outside the Local Group in 10 hours.
→ Extended SFH will be efficiently measured with filters well-separated in wavelength and with larger FOVs than Hubble.
Why measure galaxies in the Universe’s first billion years?
• Seeds of today’s galaxies started growing.
• Dark matter halos of massive galaxies first formed.
• Significant metals first formed.
• When the Universe was reionized.

JWST will resolve ambiguities from Hubble and Spitzer in fitting SEDs by spectroscopically characterizing early systems at $z = 9$, and characterizing stellar contributions to $z > 10$. 
A candidate \( z \sim 10 \) galaxy; Bouwens et al. (2011)
Hints from Hubble that a big change is occurring 400 – 600 Myr after the Big Bang.

JWST will provide a robust picture of the number of galaxies and their properties. May need help from gravitational lensing (do homework now).

How do we know if we’ve found the first galaxies? See R. Ellis’ talk on Frontiers webcast.
JWST and First Galaxies

**JWST and 30-m Telescopes Synergy**

“The nature of “first-light” objects and their effects on the young universe are among the outstanding open questions in astrophysics. Here TMT and the James Webb Space Telescope (JWST) will work hand-in-hand, with JWST providing the targets for detailed study with TMT’s spectrometers.”

http://www.tmt.org/science-case
**Properties**
- Thought to be very massive (25 – 500 Msun)
- Form in isolation
- $T_{\text{surface}} \sim 100,000$ K
- Luminous sources of ionizing photons (> $10^{50}$ /s)
- 2-3 Myr lifetimes

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New simulated light curves show late time rise over > 100 days.

Infrared energy diffuses out through dense ejecta of PI SNe...

*can be measured with JWST to z > 10 and maybe 15 with strong lensing in this model.*

Ground based follow up with 30-m telescopes will help distinguish progenitors.
A. Riess’ Talk at Frontiers Meeting

1.) JWST is the only telescope that can measure type Ia SNe out to $z = 3.5$

2.) JWST will characterize Cepheids in further galaxies
   • Calibrate more type Ia SNe
   • Simpler in the IR, less scatter

3.) $H_0$ to 1%, ties down ties local expansion rate.

4.) Planck CMB gives distance scale at $z = 1000$.

Two measurements provide an over constrained problem. Take one of the measurements, vary the cosmological model (i.e., $w$) to match the other.
Frontier Science Opportunities with JWST

JWST and Other Science from the Frontiers Science Meeting

• Gas in Protoplanetary Disks – Thomas Henning (MPIA)
• Star Formation in Galaxies in the Era of JWST – Daniela Calzetti (UMass)
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Scientific Discovery Potential

**Science Goals**
*Science Discoveries*

- The Extragalactic Distance Scale and Hubble Constant
- Source of Gamma Ray Bursts
- Dark Energy and the Universe’s Expansion
- Origin and evolution of Solar System
- The Age of The Universe
- Find Water on Other Planets
- Map the Evolution of Galaxies
- Find the First Stars and Galaxies
- Unveil Newborn Solar Systems
- Imaging and Spectroscopy of Exoplanets
- Gas in Galaxies and Quasar Absorption Lines
- Intensities of Supernovae
- Ages of Stellar Pops Beyond Milky Way
- Supermassive Black Holes
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JWST Exposure Time Calculator – [http://jwstetc.stsci.edu/etc/](http://jwstetc.stsci.edu/etc/)
JWST Email For Community Input – jwst_input@stsci.edu
JWST Facebook Page For Astronomers – “JWST Observer”
JWST Twitter – @auraJWST

ETC Version P1.2
- pyetc 0.96.jwstdev
- pysynphot 0.9.jwstdev
- cobs P1.2

ETC Help
- User's Guide (PDF)
- User's Guide (HTML)
- Release Notes
- News and Known Issues

NIRCAM ETCs
- Imaging

MIRI ETCs
- Imaging
- MRS Spectroscopy

NIRSPEC ETCs
- MSA
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