Origins Theme’s **Two** Fundamental Questions

- How Did We Get Here?
- Are We Alone?
How Did We Get Here?

*Trace Our Cosmic Roots*

- Formation of galaxies
- Formation of stars
- Formation of heavy elements
- Formation of planetary systems
- Formation of life on the early Earth
Are We Alone?

**Search for life outside the solar system**

Search for other planetary systems

Search for habitable planets

Identify remotely detectable bio-signatures

Search for “smoking guns” indicating biological activities
Missions Supporting the Origins Goals

How Did We Get Here?

- HST
- Spitzer
- JWST
- SOFIA
- FUSE

Are We Alone?

- Keck Interferometer
- SIM
- TPF

Cross Feed Science & Technology
A Vision for Large Telescopes & Collectors

Toward Accomplishing…
... the Impossible!

100-1000m diameter

20-40m diameter

~10m diameter

2.4m diameter

HST

JWST, TPF, SAFIR

Life Finder
Stellar Imager
Planet Image

Operational
Developmental
Conceptual
Unimaginable
JWST Science Themes

1. Big Bang
2. First Stars
3. Galaxies
4. Life
5. Galaxies Evolve
6. Planets

Arrows indicate the progression from the Big Bang to the evolution of galaxies and the emergence of life.
JWST Summary

• **Mission Objective**
  – Study origin & evolution of galaxies, stars & planetary systems
  – Optimized for near infrared wavelength (0.6 – 28 μm)
  – 5 year Mission Life (10 year Goal)

• **Organization**
  – Mission Lead: Goddard Space Flight Center
  – International collaboration with ESA & CSA
  – Prime Contractor: Northrop Grumman Space Technology
  – Instruments:
    – Near Infrared Camera (NIRCam) – Univ. of Arizona
    – Near Infrared Spectrometer (NIRSpec) – ESA
    – Mid-Infrared Instrument (MIRI) – JPL/ESA
    – Fine Guidance Sensor (FGS) – CSA
  – Operations: Space Telescope Science Institute
JWST Requirements

Optical Telescope Element
- 25 sq meter Collecting Area
- 2 micrometer Diffraction Limit
- < 50K (~35K) Operating Temp

Primary Mirror
- 6.6 meter diameter (tip to tip)
- < 25 kg/m² Areal Density
- < $4 M/m² Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

Segments
- 1.315 meter Flat to Flat Diameter
- < 20 nm rms Surface Figure Error
- < 20 nm rms Surface Figure Error

<table>
<thead>
<tr>
<th></th>
<th>Low (0-5 cycles/aper)</th>
<th>4 nm rms</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>CSF (5-35 cycles/aper)</td>
<td>18 nm rms</td>
</tr>
<tr>
<td></td>
<td>Mid (35-65K cycles/aper)</td>
<td>7 nm rms</td>
</tr>
<tr>
<td></td>
<td>Micro-roughness</td>
<td>&lt;4 nm rms</td>
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</table>
OTE Architecture Concept

Secondary Mirror Support Structure (SMSS)

Aft Optics Subsystem

Secondary Mirror Assembly (SMA)
- Light-weighted, rigid Be mirror
- Hexapod actuator
- Stray light baffle

Primary Mirror Segment Assemblies (PMSA)

BackPlane

OTE Clear Aperture: 25 m²

ISIM Enclosure

ISIM Electronics Compartment (IEC)

Deployment Tower Subsystem
Investments Have Reduced Risk

Mirror Actuators
AMSD  SBMD

Mirrors

Mirror System

Wavefront Sensing and Control, Mirror Phasing

1 Hz OTE Isolators

Reaction Wheel Isolators

Half-Scale Sunshield Model

Secondary Mirror Structure Hinges

Primary Mirror Structure Hinges and Latches

Cryogenic Deployable Optical Telescope Assembly (DOTA)
JWST Technology Demonstrations for TNAR

**Mirror Phasing Algorithms**

**Beryllium Primary Mirror Segment**

**Backplane**

**Sunshield Membrane**

**μShutters**

**Cryocooler**

**Cryogenic ASICs**

**Near-Infrared Detector**

**Mid-Infrared Detector**
Technology Development of Large Optical Systems

MSFC is the JWST Primary Mirror Segment Technology Development Lead for JWST

AMSD II – Be, technology selected for JWST

The 18 Primary Mirror segments
AMSD – Ball & Kodak

Specifications
- Diameter: 1.4 meter point-to-point
- Radius: 10 meter
- Areal Density: < 20 kg/m2
- Areal Cost: < $4M/m2

Beryllium Optical Performance
- Ambient Fig: 47 nm rms (initial)
- Ambient Fig: 20 nm rms (final)
- 290K – 30K: 77 nm rms
- 55K – 30K: 7 nm rms

ULE Optical Performance
- Ambient Fig: 38 nm rms (initial)
- 290K – 30K: 188 nm rms
- 55K – 30K: 20 nm rms
Advantages of Beryllium

Very High Specific Stiffness – Modulus/Mass Ratio
Saves Mass – Saves Money

High Conductivity & Below 100K, CTE is virtually zero.
Thermal Stability
Figure Change: 30-55K Operational Range

Beryllium

ULE Glass

Surface Figure With Alignment Compensation

Residual with 36 Zernikes Removed
Mirror Manufacturing Process

- Blank Fabrication
  - HIP Vessel being loaded into chamber

- Machining
  - Machining of Web Structure
  - Machining of Optical Surface
  - Completed Mirror Blank

- Polishing

- Mirror System Integration
Substrate Fabrication

PM Segments SN 19-20
powder in loading container

PM Segments SN 19-20
HIP can prepared for powder loading

PM Segments SN 19-20
loaded HIP can in degas furnace
Fabrication Process

Movie
Quality Control X-Ray Inspection

PM Segment SN 17 after finish machining

PM Segment SN 17 after x-ray

PM Segment SN 18 during finish machining

PM Segment SN 18 during x-ray
Status = Flight Mirror Blank Fabrication Complete

- Be fabrication
- Brush-Wellman

Primary Mirror Segments
Secondary Mirror
Pathfinder Mirror
2 Flight Spares
Axsys Technologies

8 CNC Machining Centers
Axsys Technologies

PMSA Engineering Development Unit

PMSA EDU rear side machined pockets

PMSA EDU front side machined optical surface
Axsys Technologies

Batch #1 (Pathfinder) PM Segments

PMSA #1 (EDU-A / A1)

PMSA #2 (3 / B1)

PMSA #3 (4 / C1)

Batch #2 PM Segments

PMSA #4 (5 / A2)

PMSA #5 (6 / B2)

PMSA #6 (7 / C2)
17 OUT OF THE 18 SEGMENTS of the Primary Flight Mirrors are currently being machined at Axsys Technologies.
Status = Flight Mirror Lightweighting Complete

- Lightweighting
- Axsys

Secondary Mirror

Primary Mirror Segments

Pathfinder Mirror
Production Preparation – CCOS Machines

1\textsuperscript{st} – 4\textsuperscript{th} CCOS machine bases assembled and operational
5\textsuperscript{th} – 8\textsuperscript{th} CCOS machines received and in storage – installation to start 4/4/05
Status = Flight Mirror Polishing Started

- Mirror Polishing
- Tinsley

Pathfinder Mirror
- Coarse grind
- Fine grind

Primary Mirror Segments
PMSA Assembly
PMSA Assy
PMSA Assembly
PMSA Assembly on its way to Optical Test
PMSA Assembly on its way to Optical Test
MSFC JWST Support Effort – Facility Upgrades

- Remove Guide Tube Section, Add GSE Station
- Add Forward He Extension
- New XL Shrouds sections
- Add GSE Support System
- 5DOF Table - **Upgrade**
- East End Dome
XRCF Facility Upgrades in FY ‘05-06
XRCF CCS Assembly

Shroud Reassembly

1 of 3 Shrouds rough cleaning

1 of 3 floors move into clean room

Shrouds move into clean room
XRCF CCS Fit- Check
XRCF Facility With Be AMSD II Mirror
JWST I&T

**JSC Chamber A**

**Chamber size** 55' diam, 117' high

**Existing Shrouds** LN2 shroud, GHe panels

**Chamber Cranes** 4x25t fixed, removable

**Chamber Door** 40' diam

**High bay space** ~102'Lx71'W
JSC “Cup Up” Test Configuration

Auto-Collimating Flats
(used for double pass optical testing).
Commercial DMI’s used for drift sensing, hexapod for control.

Telescope Cup Up
Gravity offloaded and
On Ambient Isolators
Connected to Concrete)

Center of Curvature Null
and Interferometer
Accessible from top

Focal Plane Interferometer
and sources accessible
from below

Isolators used to control
high frequency vibration.

JSC Size, Accessibility, and Large Side Door Access
Make it Well Suited for This Configuration
Chamber A was used for Apollo landers and already includes Nitrogen and Helium systems. Plan is to upgrade it with a new Helium Inner Shroud and Helium refrigerators.
JWST Launch and Deployment

- JWST is folded into stowed position to fit into the payload fairing of the Ariane V launch vehicle.

- Several subsystems deploy during transit to its L2 orbit.
JWST vs. HST - orbit

HST in Low Earth Orbit, ~500 km up.
Imaging affected by proximity to Earth

JWST will operate at the 2nd Lagrange Point (L2) which is 1.5 Million km away from the earth
JWST Optical Path
Off-Axis Annular FOV

Unvignetted FOV shown in black

OTE WFE < 131 nm rms within area bounded by black dashed line

The science instrument placement allocations are shown in blue
JWST Mirror Phasing

- Telescope Deployment
- Focus Sweep
- Segment Search
- Segment - Image Array
- Global Alignment
- Image Stacking
- Coarse Phasing
- Fine Phasing
- Wavefront maintenance
Wavefront Sensing & Control (WFS&C)

- **Global Alignment**
  - Segment WFE < 200 nm rms and < 100 μm rms segment-to-segment piston after Global Alignment

- **Coarse Phasing (Fine Guiding)**
  - Total PM WFE < 1000 nm rms after Coarse Phasing

- **Fine Phasing**
  - Total WFE < 117 nm rms after Fine Phasing; re-phase every 30 days
Keck Demonstration of WFS&C

Preliminary results compared with PCS:
Peak-to-valley edge detection error = 0.45 microns
Rms detection error = 0.12 microns
JWST Phasing Algorithms Demonstrated

**Coarse Phasing**
(Segment to segment piston)

**Fine Phasing**

Before Coarse Phasing

- \( \text{rms}=234 \) nm
- \( \text{pv}=989 \) nm

After Coarse Phasing

- \( \text{rms}=32 \) nm
- \( \text{pv}=120 \) nm

Graph:
- RMS WFE (nanometers)
- Fine Phasing Control Iteration
- Trials: 1, Nov 07, 2, Dec 12, 3, Dec 12, 4, Dec 12, 5, Dec 12, 6, Dec 13, 7, Dec 14
How to win at Astronomy
Aperture = Sensitivity

Big Telescopes with Sensitive Detectors In Space

Sensitivity Improvement over the Eye

Adapted from *Cosmic Discovery*, M. Harwit
JWST Expands on HST Capabilities

HST: 2.4 m diameter Primary Mirror

JWST: 6.5 m diameter Primary Mirror

- JWST has 7x the light gathering capability of the Hubble Space Telescope
- JWST operates in extreme cold to enable sensitive infrared light collection

Room Temperature

< 50 K (~ -223 C or -370 F)
How big is JWST?
Full Scale JWST Mockup
Full Scale JWST Mockup

21st National Space Symposium, Colorado Springs, The Space Foundation
Why go to Space – Wavelength Coverage

NGST Discovery Space

32m class

HST

8m class Grnd-based

SIRTF

Time to make an imaging survey (hr)

Wavelength (μm)
Why Infrared?
JWST Science Theme #1

End of the dark ages: first light and reionization

What are the first luminous objects?
What are the first galaxies?
When did reionization occur? Once or twice?
What sources caused reionization?

... to identify the first luminous sources to form and to determine the ionization history of the early universe.

Hubble Ultra Deep Field
A Brief History of Time

Big Bang

3 minutes

300,000 years

100 million years

1 billion years

13.7 Billion years

First Galaxies Form

Galaxies Evolve

Planets, Life & Intelligence

Particle Physics

Atoms & Radiation

Cosmic Dark Zone

Based Observatories

MAP

COBE

JWST

HST

Ground Based Observatories

Today
History of Time?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WMAP Value</th>
<th>What is it?</th>
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<tbody>
<tr>
<td>Ω_{total}</td>
<td>1.02 +/- 0.02</td>
<td>Total Density</td>
</tr>
<tr>
<td>Ω_{dark}</td>
<td>0.73 +/- 0.04</td>
<td>Dark Energy</td>
</tr>
<tr>
<td>Ω_{matter}</td>
<td>0.27 +/- 0.04</td>
<td>Matter Density</td>
</tr>
<tr>
<td>Ω_{baryon}</td>
<td>0.044 +/- 0.004</td>
<td>Baryon Density</td>
</tr>
<tr>
<td>H₀</td>
<td>71 +/- 4 km/s/Mpc</td>
<td>Hubble Constant</td>
</tr>
<tr>
<td>t₀</td>
<td>13.7 +/- 0.2 Gyr</td>
<td>Age of the universe</td>
</tr>
</tbody>
</table>
When and how did reionization occur?

Reionization happened at $z>6$ or 1 billion years after Big Bang.

WMAP says maybe twice?

Probably galaxies, maybe quasar contribution

JWST Observations:
Spectra of the most distant quasars
Spectra of faint galaxies
First Light: Observing Reionization Edge

- Neutral IGM
- Redshift
- $z < z_i$
- $z \approx z_i$
- $z > z_i$

- Lyman Forest Absorption
- Patchy Absorption
- Black Gunn-Peterson trough
End of the dark ages: first light and reionization

First galaxies are small & faint

Light is redshifted into infrared.

Low-metallicity, massive stars. SNe! GRBs!

JWST Observations

Ultra-Deep NIR survey (1.4 nJy), spectroscopic & Mid-IR confirmation.
First Light

What did the first stars galaxies to form look like?
We don’t know, but models suggest first stars were very massive!
Infrared Light

Light from the first galaxies is redshifted from the visible into the infrared.
The Hubble Deep Field

STScI Science Project: Robert Williams. et al. (1997)
How do we see first light objects?

Deep Imaging: Look for *near-IR drop-outs*

5.8 Gyr  2.2 Gyr
3.3 Gyr  1.8 Gyr
2.2 Gyr  1.0 Gyr
Hubble Ultra Deep Field
- Advanced Camera for Surveys

400 orbits, data taken over 4 months:
Sept-Oct (40 days), Dec-Jan (40 days)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>V</th>
<th>I</th>
<th>z</th>
<th>F435W</th>
<th>F606W</th>
<th>F775W</th>
<th>F850LP</th>
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<td>144</td>
<td>56</td>
<td>56</td>
<td>144</td>
<td>144</td>
</tr>
</tbody>
</table>

JWST is designed to routinely operate in the deep survey imaging mode
Ultra Deep Field

Malhotra et al. 2004

ERO $z \sim 1$

AGN $z = 5.5$

Galaxy $z = 2.5$

Galaxy $z = 5.8$

Galaxy $z = 6.7$

Galaxy $z = 0.48$
New Results from UDF

Images of 21 redshift-6 galaxies taken from the UDF
How do we see first light objects?

The first stars may be detected when they became bright supernovae. But, they will be very rare objects!
How do we see first light objects?

Use a magnifying glass!
The Renaissance after the Dark Ages

Hubble Ultra Deep Field

Here Now

H II

$T_{IGM} \sim 10^4 \text{ K}$

JWST

"Dark Ages"

Igm ~ 10^4 K

JWST

Z ~ 8

Primordial

Galaxy

Big Bang

Here Now

Hubble Deep Field

$T_{IGM} \sim 4 \pi K$
Sensitivity Matters

GOODS CDFS – 13 orbits

HUDF – 400 orbits
JWST Science Theme #2:

The assembly of galaxies

Where and when did the Hubble Sequence form?
How did the heavy elements form?
Can we test hierarchical formation and global scaling relations?

... to determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.

M81 by Spitzer
The Hubble Sequence

Hubble classified nearby (present-day) galaxies into Spirals and Ellipticals.

The Hubble Space Telescope has extended this to the distant past.
Where and when did the Hubble Sequence form? How did the heavy elements form?

Galaxy assembly is a process of hierarchical merging
Components of galaxies have variety of ages & compositions

JWST Observations:
NIRCam imaging
Spectra of 1000s of galaxies
Distant Galaxies are “Train Wrecks”
Unusual objects
Clusters of Galaxies
Unexpected “Big Babies”

Spitzer and Hubble have identified a dozen very old (almost 13 Billion light years away) very massive (up to 10X larger than our Milky Way) galaxies.

At an epoch when the Universe was only $\sim 15\%$ of its present size, and $\sim 7\%$ of its current age.

This is a surprising result unexpected in current galaxy formation models.

Science News reports that Spitzer and Hubble posed a Cosmic Conundrum by finding these very massive galaxies in the early Universe. This challenges theories of structure formation.

JWST Science Theme #3:

Birth of stars and protoplanetary systems

How do clouds collapse?
How does environment affect star-formation?

... to unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.

David Hardy
How do proto-stellar clouds collapse?

Stars form in small regions collapsing gravitationally within larger molecular clouds.

Infrared sees through thick, dusty clouds

Proto-stars begin to shine within the clouds, revealing temperature and density structure.

JWST Observations:
Deep NIR and MIR imaging of dark clouds and proto-stars

Barnard 68 in infrared
How does environment affect star-formation?

Massive stars produce wind & radiation
   Either disrupt star formation, or causes it.

Boundary between smallest brown dwarf stars & planets is unknown
   Different processes? Or continuum?

JWST Observations:
   Survey dark clouds, “elephant trunks” and star-forming regions
Spitzer has Found “The Mountains Of Creation”


L. Allen, CfA [GTO]
The Mountains Tell Their Tale
Interstellar erosion & star formation propagate through the cloud

Young (Solar Mass) Stars are Shown in This Panel
Really Young Stars are Shown in This Panel

Birth of Stars and Proto-planetary Systems

- What is the role of molecular clouds, cores and their collapse in the evolution of stars and planetary systems?
- How do protostars form and evolve?
- How do massive stars form and interact with their environment?
- How do massive stars impact their environment by halting or triggering further star formation. How do they impact the evolution of disks?
- What is the initial mass function down to planetary masses?
- How do protoplanetary systems form and evolve?
- How do astrochemical tracers track star formation and the evolution of protoplanetary systems?
How are Planets Assembled?
Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk

Dust disks are durable and omnipresent

The central star of the Helix Nebula, a hot, luminous White Dwarf, shows an infrared excess attributable to a disk in a planetary system which survived the star’s chaotic evolution.

How are circumstellar disks like our Solar System?

Here is an illustration of what MIRI might find within the very young core in Ophiuchus, VLA 1623.

artist’s concept of protostellar disk from T. Greene, Am. Scientist

approximate field for JWST NIRSpec & MIRI integral field spectroscopy
JWST Science Theme #4:

Planetary systems and the origins of life

How do planets form?
How are circumstellar disks like our Solar System?
How are habitable zones established?

... to determine the physical and chemical properties of planetary systems including our own, and to investigate the potential for the origins of life in those systems.

Robert Hurt
How do planets form?

Giant planets could be signpost of process that create Earth-like planets

Solar System primordial disk is now in small planets, moons, asteroids and comets

JWST Observations:
- Coronagraphy of exosolar planets
- Compare spectra of comets & circumstellar disks
Planetary systems and the Origins of Life

Fomalhaut system at 24 µm
(Spitzer Space Telescope)

Simulated JWST image
Fomalhaut at 24 microns

Malfait et al 1998
Planetary Systems and the Origins of Life

- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestrial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems) and remnant disks?
- What is the source of water and organics for planets in habitable zones?
- How are systems cleared of small bodies?
- What are the planetary evolutionary pathways by which habitability is established or lost?
- Does our solar system harbor evidence for steps on these pathways?
Planetary Systems and the Origins of Life

Model of Vega system at 24 µm (Wilner et al. 2000)

Formalhaut system at 24 µm (Spitzer Space Telescope)

HD141569 (606 nm) (HST/ACS)
The Inner Solar System in 2006

- 340,000 minor planets
- ~4500 NEOs
- ~850 Potentially Hazardous Objects (PHOs)

Landis, “Piloted Flight to a Near-Earth Object”, AIAA Conference 19 Sep 07
Brown Dwarfs Form Like Stars: Can “Planets” have Planets?

A Brown Dwarf With a Planet-Forming Disk

How are habitable zones established?

Source of Earth’s H₂O and organics is not known
   Comets? Asteroids?

History of clearing the disk of gas and small bodies
   Role of giant planets?

JWST Observations:
   Comets, Kuiper Belt Objects
   Icy moons in outer solar system
Search for Habitable Planets

atmosphere

habitability

interior

surface

L. Cook

Sara Seager (2006)
Atmospheres of Extrasolar Planets

Extrasolar Planet Transits
Detecting terrestrial planet atmospheres

Transiting Planet Science

Learn about:
- Global structure
- Atmospheres
- Eccentricity & Obliquity

Courtesy Lori Allen
HD 189733b: First [one-dimensional] temperature map of an exoplanet

970K on night side; 1210K on day side
“warm spot” 30 degrees E of high-noon point.
High “easterly” winds, 6000 mph, carry heat around planet
Precise Spitzer observations indicate elliptical orbit => unseen planet, could be as small as Earth?

Data – flux at 8um over more than half an orbit

Model: Assumes tidal locking of planet to star and extrapolates in latitude.

Search for Life

What is life?

What does life do?

Life Metabolizes

Sara Seager (2006)
All Earth life uses chemical energy generated from redox reactions.

Life takes advantage of these spontaneous reactions that are kinetically inhibited.

Diversity of metabolisms rivals diversity of exoplanets.

Lane, Nature May 2006

Sara Seager (2006)
Bio Markers

Spectroscopic Indicators of Life

Absorption Lines
- CO2
- Ozone
- Water
- “Red” Edge

Example signs of life from chemical spectra.
Credit: NASA JPL
Is there water in an Exoplanet?

Water Signatures in Exoplanet HD189733b
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / G. Tinetti (Institute d’Astrophysique de Paris)

Earth Through Time

Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon

Seager
Countdown to Launch

Planned for 2013 Launch
Any Questions?