Who is James Webb?

James E Webb was the first administrator of NASA (1961 to 1968)

He supported a program balanced between Science and Human Exploration.
What is FIRST LIGHT?

End of the dark ages: first light and reionization

What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did re-ionization of the inter-galactic medium occur?
What caused the re-ionization?

... 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
First Light Stars

50-to-100 million years after the Big Bang, the first massive stars started to form from clouds of hydrogen. But, because they were so large, they were unstable and either exploded supernova or collapsed into black holes.

These first stars helped ionize the universe and created elements such as He. O-class stars are 25X larger than our sun. ‘First’ stars may have been 1000X larger.

The (modern) Morgan–Keenan spectral classification system, with the temperature range of each star class shown above it, in Kelvin. The overwhelming majority of stars today are M-class stars, with only 1 known O- or B-class star within 25 parsecs. Our Sun is a G-class star. However, in the early Universe, almost all of the stars were O- or B-class stars, with an average mass 25 times greater than average stars today.

First Light: Reionization

Neutral ‘fog’ was dissolved by very bright 1st Generation Stars. At 780 M yrs after BB the Universe was up to 50% Neutral. But, by 1 B years after BB is was as we see it today. 787 M yr Galaxy confirmed by Neutral Hydrogen method.
How do we see first light objects? Redshift

The further away an object is, the more its light is redshifted from the visible into the infrared.

Redshift

To see really far away, we need an infrared telescope.
First Galaxy in Hubble Deep Field

At 480 M yrs after big bang (z ~ 10) this one of oldest observed galaxy. Discovered using drop-out technique. (current oldest is 420 M yrs after BB, maybe only 200 M yrs)

Left image is visible light, and the next three in near-infrared filters. The galaxy suddenly pop up in the H filter, at a wavelength of 1.6 microns (a little over twice the wavelength the eye can detect). (Discover, Bad Astronomy, 26 Jan 2011)

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
Origins Theme’s Fundamental Questions

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

JWST Science Themes

- First Light and Re-Ionization
- Big Bang
- Galaxies
- Life
- Star Formation
- Planetary
- Galaxy Evolution
Three Key Facts

There are 3 key facts about JWST that enables it to perform its Science Mission:

- It is a Space Telescope
- It is an Infrared Telescope
- It has a Large Aperture

Why go to Space

Atmospheric Transmission drives the need to go to space.

Infrared (mid and far/sub-mm) Telescopes (also uv, x-ray, and gamma-ray) cannot see through the Atmosphere
Infrared Light

Why Infrared?
Why do we need Large Apertures?
Aperture = Sensitivity

Adapted from Cosmic Discovery, M. Harwit

Sensitivity Matters

GOODS CDFS – 13 orbits
HUDF – 400 orbits
JWST will be more Sensitive than Hubble or Spitzer

**HUBBLE**
- 2.4-meter
  - T ~ 270 K
  - 123" x 136"
  - $\lambda/D_{1\mu m} \sim 0.14''$

**JWST**
- 6.5-meter
  - T ~ 40 K
  - 132" x 164"
  - $\lambda/D_{1.6\mu m} \sim 0.06''$

**SPITZER**
- 0.8-meter
  - T ~ 5.5 K
  - 312" x 312"
  - $\lambda/D_{5.6\mu m} \sim 2.22''$

**Wavelength Coverage**
- HST
  - 1 μm
  - 10 μm
  - 100 μm

**JWST 6X more sensitive with similar resolution**

**JWST 44X more sensitive**

How big is JWST?

21st National Space Symposium, Colorado Springs, The Space Foundation
How JWST Works

JWST is folded and stowed for launch. Observatory is deployed after launch.

JWST Orbits the 2nd Lagrange Point (L2)
239,000 miles (384,000 km)
930,000 miles (1.5 million km)
Earth Moon L2

JWST has 4 Science Instruments (0.6 to 28 micrometers)

- NIRCam: image the first galaxies
- MIRI: first HD view of infrared universe
- NIRISS: imagery & spectra of exoplanets
- NIRSpec: simultaneous spectra of 100 galaxies
- FGS: sense pointing to 1 millionth degree
- NIRISS: imagery & spectra of exoplanets
JWST Telescope 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/m\(^2\) Areal Density
- < $6 M/m\(^2\) 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

### Fun Fact – Mirror Surface Tolerance

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

Human Hair
- Diameter is 100,000 nm (typical)

PMSA Surface Figure Error
- < 20 nm (rms)
Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations.

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

Machining

Polishing

Mirror System Integration
Fun Facts – Mirror Manufacturing

Before

Be Billet

250 kgs

After

Finished Mirror Segment

21 kgs

Over 90% of material is removed to make each mirror segment – want a little mirror with your Be dust?

Mirror Processing at Tinsley
Tinsley In-Process Metrology Tools

Metrology tools provide feedback at every manufacturing stage:

- Rough Grinding: CMM
- Fine Grinding/Rough Polishing: Scanning Shack-Hartmann
- Final Polishing/Figuring/CNF: Interferometry

PMSA Interferometer Test Stations included:
- 2 Center of Curvature CGH Optical Test Stations (OTS1 and OTS2)
- Auto-Collimation Test Station

Data was validated by comparing overlap between tools

Independent cross check tests were performed at Tinsley and between Tinsley, Ball and XRCF.

Leitz CMM

CMM was sized to test PMSA Full Aperture
Wavefront Sciences Scanning Shack-Hartmann

SSHS provided bridge-data between grind and polish, used until PMSA surface was within capture range of interferometry.

SSHS provide mid-spatial frequency control: 222 mm to 2 mm

Large dynamic range (0 – 4.6 mr surface slope)

When not used, convergence rate was degraded.

Comparison to CMM (222 - 2 mm spatial periods)
8/1/2006 data

Smooth grind

SSHS
4.7 µm PV, 0.64 µm RMS

CMM
4.8 µm PV, 0.65 µm RMS

Point-to-Point Subtraction: SSHS - CMM = 0.27 µm RMS
Full Aperture Optical Test Station (OTS)

Center of Curvature Null Test measured & controlled:
  Prescription,
  Radius &
  Figure

Results are cross-checked between 2 test stations.
Test Reproducibility
(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270

Power
(Radius Delta: 0.02 mm)

Astigmatism:
4.4 nm RMS

Mid Frequency:
4.3 nm RMS

High Frequency:
3.9 nm RMS

Total Surface Delta:
PV: 373 nm
RMS: 7.6 nm

Auto-Collimation Test

Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:
Radius of Curvature
Conic Constant
Off-Axis Distance
Clocking

Note: is not a full-aperture figure verification test
Primary Mirror Segment Assembly at BATC

![Images of primary mirror segment assembly]

Ball Optical Test Station (BOTS)

Tinsley ambient metrology results are ‘cross-checked’ at BATC

**BOTS measurements:**
- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation

![Diagram of BOTS setup]

- Interferometer
- Environmental Enclosure
- 6 DOF Test Stand and Mirror
- CGH
- Enclosure Door
Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.

PMSA Flight Mirror Testing at MSFC XRCF

Cryogenic Performance Specifications are Certified at XRCF
JWST Flight Mirror Test Configuration

Table and Stand-Offs
Table positioning Actuators, 3 places

Primary Mirror Cryogenic Tests
XRCF Cryo Test

- Survival Temperature
- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)
- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

Mirror Fabrication

Spare Mirrors
- EDU (A type) 14.3 nm rms
- C7 238 nm rms
- B1 8.0 µm rms
- SM#1 33 nm rms

Flight Mirrors
- PMS’s

SURFACE FIGURE ERROR
Total PM Composite: 23.2 nm RMS
PM Requirement: 25.0 nm RMS

Gold Coated Mirror Assemblies

Optical Telescope Assembly

Mirrors ≥ 98% at 2 µm
Observatory level testing occurs at JSC Chamber A

Verification Test Activities in JSC Chamber A
- Cryo Position Metrology
- Primary Mirror Stability Test
- Focus Sweep Test (inward facing sources)

Crosscheck Tests in JSC Chamber A
- Pupil Alignment Test
- Rogue Path Test
- Pass-and-a-Half Test
- Primary Mirror WFE Test
- End-to-End WFSC Demonstration

Chamber A:
- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

End-to-end optical testing at JSC July 2017 to Nov 2018
Telescope & instrument module now at Northrop Grumman for integration with the spacecraft bus and sunshield

Integration of Telescope with Spacecraft & Sunshade at Northrop
Mobile Cleanroom Moves JWST to Vibe Test at Northrop

JWST will be transported by ship through Panama Canal to French Guiana for launch during March 2021

Roll on roll off transport ship built in the Netherlands by Merwede Shipyards

- Length 116m
- Displacement about 4200 metric tons
- Garage deck length 95m (plenty of room for STTARS)
- Speed: 15 knots

6900 Nautical Miles
Approximately 20 days

Space Telescope Transporter for Air Road and Sea (STTARS)
JWST Launched on Ariane 5 Heavy

JWST folded and stowed for launch in 5 m dia x 17 m tall fairing

Launch from Kourou Launch Center (French Guiana) to L2

JWST vs. HST - orbit

JWST will operate at the 2nd Lagrange Point (L2) which is 1.5 Million km away from the earth.
L2 Orbit Enables Passive Cryogenic Operation

Second Lagrange Point (L2) of Sun-Earth System
- This point follows the Earth around the Sun
- The orbital period about L2 is ~ 6 months
- Station keeping thrusters required to maintain orbit
- Propellant sized for 11 years (delta-v ~ 93

JWST observes whole sky while remaining continuously in shadow of its sunshield
- Field of Regard is annulus covering 35% of the sky
- Whole sky is covered each year

JWST Deployment
JWST Science Theme #1
End of the dark ages: first light and reionization

What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did reionization of the inter-galactic medium occur?
What caused the re-ionization?

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

Hubble Ultra Deep Field

When and how did reionization occur?

Reionization happened $z > 6$ or $< 1$ B yrs after Big Bang.
WMAP says maybe twice?

Probably galaxies, maybe quasar

Key Enabling Design Requirements:
Deep near-infrared imaging survey (1nJy)
Near-IR multi-object spectroscopy
Mid-IR photometry and spectroscopy

JWST Observations:
Spectra of the most distant quasars
Spectra of faint galaxies
Studying Early Universe: ‘First’ Galaxies

Galaxy GN-z11 is 13.4 B-ys away, just 400 M-ys after BB. It is 25X smaller than and has only 1% the mass of Milky Way, but is forming stars 20X faster (produced by large gas inflow). Other ‘first’ galaxies are forming stars 1000X faster.

Oldest Star Formation – 250M yrs after BB

Oxygen was detected in the very distant galaxy MACS1149-JD1 using the Atacama Large Millimeter/submillimeter Array (APMA) and ESO's Very Large Telescope (VLT) to determine that star formation started at an unexpectedly early stage, only 250 million years after the Big Bang.

Keith Cowing, SPACEREF.com, 16 May 2018
First Galaxies form in Cosmic Web

Ripples in the early universe formed long filaments of hydrogen gas surrounded by ‘dark matter’. Galaxies form at crossing points. Most of universe’s matter is in these filaments and dark matter. This one is 10B light years away.

A filament of the universe’s “cosmic web” is highlighted with parallel curved lines in this image, while a protogalaxy is outlined with an ellipse. The brightest spot (on the lower right side of the ellipse) is the quasar UM287. The other bright spot is a second quasar in the system. The image combines a visible light image with data from the Cosmic Web Imager. CREDIT: Chris Martin/PCWI/Caltech Charles Choi, Space.com, 5 Aug 2015.

Hubble Ultra Deep Field – Near Infrared

Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.
47 Galaxies have been observed at 600 to 650 Myrs after BB.

What came first – Galaxies or Black Holes?
Each of these ancient 700 M yrs after BB galaxies has a black hole.
Only the most energetic x-rays are detected, indicating that the black-holes are inside very young galaxies with lots of gas.
First Black Holes

One theory for ‘first’ black holes is direct collapse of ‘first’ stars.

Below shows disappearance of 25X times our Sun star without a supernova.

WISE is Wide-Field IR ‘finder scope’ for JWST

WISE has found millions of black holes in galaxies previously obscured by dust called hot DOGs, or dust-obscured galaxies.
Oldest & Brightest Quasar – 770M yrs after BB

This Quasar is 770 million years after Big Bang, is powered by a black hole 2 billion times the mass of our Sun and emits 60 trillion times as much light as the sun. How a black hole became so massive so soon after the Big Bang is unknown.

“It is like finding a 6-foot-tall child in kindergarten,” says astrophysicist Marta Volonteri, at the University of Michigan in Ann Arbor.

The spectra of the light from this (and other early light objects) indicate that the Universe was still filled with significant amounts of neutral hydrogen even 770 Myrs after big bang.

Unexpected “Big Babies”: 800M yrs after BB

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 ~15% of its present size, and ~7% of its current age.

This is a surprising result unexpected in current galaxy formation models.
JWST Science Theme #2:

The assembly of galaxies

How did the heavy elements form?
How is the chemical evolution of the universe related to galaxy evolution?
What powers emission from galaxy nuclei?

When did the Hubble Sequence form?
What role did galaxy collisions play in their evolution?
Can we test hierarchical formation and global scaling relations?
What is relation between Evolution of Galaxies & Growth/Development of Black Holes in their nuclei?

... 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.

Formation of Heavy Elements

Carl Sagan said that we are all ‘star dust’.

All of the heavy elements which exist in the universe were formed from Hydrogen inside of stars and distributed via supernova explosions. But observations in the visible couldn’t find enough dust.

Dust is cold, therefore, it can only be seen in IR.

Looking in the IR (with Herschel and Spitzer) at Supernova 1987A, 100,000X more dust was seen than in the visible – the total mass of this dust equals about half of our Sun.
2nd Generation Stars – 700M yrs after BB

This star is a 2nd generation star after the big bang because it has trace amounts of heavy elements – meaning that at least one supernova had exploded before it was formed.

But its existence contradicts current theories because it has too much Hydrogen and too much Helium and not enough Carbon and other heavy elements.

Nola Taylor Redd, SPACE.com, 31 August 2011; CREDIT: ESO/Digitized Sky Survey 2

Chemical make-up of Early Universe

1.8 B yr after BB gamma-ray burst illuminates neighboring galaxies yielding spectra of their chemical makeup.

Metals in the early universe are higher than expected – indicating that star formation in the early universe was much higher than current theory.

GRB 090323 was first detected on 23 March 2009 by NASA’s Fermi space telescope and then the Swift satellite, shortly followed by the ground-based GROND system (Gamma-Ray burst Optical and Near-infrared Detector) at the MPG/ESO 2.2-metre telescope in Chile, as well as ESO’s Very Large Telescope (VLT). The VLT observations revealed that the gamma-ray burst injected light through its host galaxy and another nearby galaxy, which are both seen at a redshift of 3.57, equivalent to 12 billion years ago.

DR EMILY BALDWIN, ASTRONOMY NOW, 02 November 2011
Subaru Deep Field: Ancient Supernova 3.7B yrs after BB
22 of 150 ancient supernovae in 10% of Subaru Deep Field
12 occurred around 3.7B yrs after big bang.
Supernova were 10X more frequent at this time than today.
Supernova helped seed early universe with chemical elements.

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?

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

JWST Observations:
- Wide-area near-infrared imaging survey
- Low and medium resolution spectra of 1000s of galaxies at high redshift
- Targeted observations of galactic nuclei

Distant Galaxies are "Train Wrecks"
Merging Galaxies = Merging Black Holes

Combined Chandra & Hubble data shows two black holes (one 30M & one 1M solar mass) orbiting each other – separated by 490 light-years. At 160 million light-years, these are the closest super massive black holes to Earth.

Theory says when galaxies collide there should be major disruption and new star formation.

This galaxy has regular spiral shape and the core is mostly old stars.

These two galaxies merged with minor perturbations.

Galaxy NGC3393 includes two active black holes

X-ray: NASA/CXC/SAO/G.Fabbiano et al; Optical: NASA/STScI

Charles Q. Choi, SPACE.com, 31 August 2011

Galaxy Clusters

Galaxy clusters are the largest structures in the universe. Bound together by gravity, they require billions of years to form.

Galaxy Clusters have been detected as early at 0.6 B-yrs after big bang.

At 2.6 B-yrs old, this is not the oldest observed galaxy cluster. But, spectra indicates that stars in its constituent galaxies are 1 B-yrs old. Thus, may have started forming about 1.5 B-yrs after BB.

X-ray data (similar to image) shows glow from cloud of very hot gas that holds cluster together. Most of the mass of the cluster is in the gas.
Galaxy Formation

Rings of interstellar dust circulating around Andromeda’s galactic core viewed in Far-IR by the Herschel space observatory.

The brighter the ring, the more active the star formation. Further out rings are extremely cold, only a few tens of degrees warmer than absolute zero.

JWST Science Theme #3:
Birth of stars and protoplanetary systems

- How do molecular clouds collapse?
- How does environment affect star-formation?
- What is the mass distribution of low-mass stars?
- What do debris disks reveal about the evolution of terrestrial planets?

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

David Hardy
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 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” or “pillars of creation” star-forming regions

The Eagle Nebula as seen in the infrared
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.

Key JWST Enabling Requirements:
- High angular resolution near- & mid-IR imagery
- High angular resolution imaging spectroscopy

Barnard 68 in infrared

Spitzer has Found “The Mountains Of Creation”

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


Stellar Shockwave

Shockwave created by Zeta Ophiuchi which is moving towards the left at about 24 kilometres per second.

STARSTUFF IMAGE by Stuart Gary, ABC Science, 20 July 2015
Star Formation in Dust/Gas Cloud

Herschel discovered 700 newly-forming stars condensing along filaments of dust in a never before penetrated dark cloud at the heart of Eagle Nebula. Two areas glowing brightest in icy blue light are regions where large newborn stars are causing hydrogen gas to shine.

SPACE.com 16 December 2009

Cosmic Breeding Ground for Young Stars

Composite image of molecular cloud RCW106 using Herschel. Cloud itself consists of (color coded) gases: hydrogen, oxygen, carbon. Young stars are creating pockets in the cloud. Blue is hot.

Cassie Kelly, Dope Space Pics, February 27, 2017
Impossible Stars

100 to 150 solar mass stars should not exist but they do.

When a star gets to 8 to 10 solar mass its wind blows away all gas and dust, creating a bubble and stopping its growth (see Herschel Image).

The bubble shock wave is creating a dense 2000 solar mass region in which an ‘impossible’ star is forming. It is already 10 solar mass and in a few 100 thousand years will be a massive 100 to 150 solar mass – making it one of the biggest and brightest in the galaxy.

(Space.com, 6 May 2010)

Orion Nebula Protoplanetary Discs

Hubble has discovered 42 protoplanetary discs in the Orion Nebula

Credit: NASA/ESA and L. Ricci (ESO)
All of Life’s Ingredients Found in Orion Nebula

Herschel Telescope has measured spectra for all the ingredients for life as we know them in the Orion Nebula.

(Methanol is a particularly important molecule)

Wired.com Mar 2010

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
Planetary Formation Questions and 2 Models

- 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?

Ultima Thule

New Horizons’ imaging of Ultima Thule on 1 Jan 2019 appears to support the Accretion Model of Planetary System Formation.
History of Known (current) NEO Population

2006

Earth Crossing

Outside Earth's Orbit

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

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.

Follow the DUST
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.


Landis, "Piloted Flight to a Near-Earth Object", AIAA Conference 19 Sep 07
Protoplanetary Disks are Ubiquitous & Diverse

Planets form in the gaps and spiral arms.

Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

ALMA has shown that small \sim \text{au}-sized disk gaps may be common

Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019
Spiral Arms Hint At The Presence Of Planets

Disk of gas and dust around a sun-like star has spiral-arm-like structures. These features may provide clues to the presence of embedded but as-yet-unseen planets.

Near Infrared image from Subaru Telescope shows disk surrounding SAO 206462, a star located about 456 light-years away in the constellation Lupus. Astronomers estimate that the system is only about 9 million years old. The gas-rich disk spans some 14 billion miles, which is more than twice the size of Pluto’s orbit in our own solar system.

Photonics Online 20 Oct 2011

Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019
~ 40 years of Protoplanetary Disk research

Photometric measurement as function of wavelength shows gaps.

Protoplanetary disks are complex and dynamic
Protoplanetary disk observations require multiple wavelengths

Direct Imaging of Planet Formation

ALMA is mm/sub-mm 15-km baseline array telescope producing a 35 mas resolution image. (10 m telescope at 500 nm has 10 mas)

HL Tau is 1 million year old ‘sun-like’ star 450 light-years from Earth in constellation Taurus.

Concentric rings separated by gaps suggest planet formation.

HL Tau is hidden in visible light behind a massive envelope of dust and gas. ALMA wavelength sees through dust.
Eta Corvi System

ALMA measures ‘cold’ Kuiper belt debris.
Spitzer measures ‘warm’ asteroid belt debris.
JWST will provide higher resolution image of asteroid belt.

MacGregor, Disks in Nearby Planetary Systems with JWST and ALMA, AAS 2019

Techniques to Detect Exoplanets

Direct Imaging
Direct Imaging detects planets far from their star

HR 8799 has at least 4 planets
3 planets (‘c’ has Neptune orbit) were first imaged by Hubble in 1998. Image reanalyzed because of a 2007 Keck discovery.
3 outer planets have very long orbits or 100, 200 & 400 years. Multiple detections are required to see this motion.

Denise Chow, SPACE.com; 06 October 2011

HR 8799 Planet (b)

HR 8799 is 129 light-years from earth, 1.5X the size of our sun in the constellation Pegasus, and has at least 4 planets.
HR 8799 Planet (b) is 7X the mass of Jupiter and has water, methane and carbon monoxide in its atmosphere.
Radial Velocity Method finds planets close to stars

61 Virginis (61 Vir) has 3 planets inside of Venus’s orbit.

From their star, the planets have masses of ~5X, 18X & 24X Earth’s mass.

They orbit 61 Virginis in 4, 38 & 124 day periods.

Also, direct Spitzer observations indicate a ring of dust at twice the distance of Neptune from the star.

Bad Astronomy
Orbital schematic credit: Chris Tinney
Techniques to Detect Exoplanets

Transit Method

Transit Method Finds Planets

Kepler (launched in 2009) searched for planets by staring at 165,000 stars looking for dips in their light caused when a planet crosses in front of the star.

Kepler has found over 1000 ‘confirmed’ planets and over 4000 potential planets.
Confirmed Exoplanets versus Time

Exoplanet Census as of 14 Dec 2017
Total Confirmed Exoplanets = 3567
Total found by Kepler = 2525

https://www.nasa.gov/sites/default/files/thumbnails/image/fig10-exoplanetdisc-dec14.jpg
Exoplanet Populations & Discovery Method

Kepler’s Verified Planets, by Size
As of May 10, 2016

Final data release: spring 2017

Small Planets come in Two Sizes

Our galaxy has 100B stars of which 17B are like ours, so our galaxy could have 17B Earth size planets. But only a few will be in Habitable Zone. Also, need a moon.

Nancy Atkinson; Universe Today; January 7, 2013
Habitable Zone

Life requires water. Liquid water can only exist in the ‘Goldilocks’ Zone. The hotter the star, the further away the zone.

![Habitable Zone Diagram](https://example.com/habitable-zone.png)

All Stars may have 1 to 3 HZ Planets

Titius-Bode law (used to predict Uranus) states that ratio between the orbital period of the first and second planet is the same as the ratio between the second and the third planet and so on.

Thus, if you know how long it takes for some planets to orbit a star, you can calculate how long it takes for others to orbit and can calculate their position in the planetary system.

Blue dots show planets measured by Kepler in 151 systems.

Red boxes predicted ‘missing’ 228 planets

Average of 1 to 3 HZ planets per star.

![Planetary System Diagram](https://example.com/planetary-system.png)

'Billions of stars' in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com. 18 March 2015
Kepler Mission

Kepler-11 has a star like ours & 6 mini-Neptune size planets

Kepler 22b is the first in the habitable zone.

Five of six Kepler-11 exoplanets (all larger than Earth) orbit their star closer than Mercury orbits the sun. One orbits inside Venus.

Credit: NASA/AP (Pete Spotts, Christian Science Monitor.com, 23 May 2011.)

Kepler-22b is located about 600 light-years away, orbiting a sun-like star. It's 2.4 times that of Earth, and the two planets have roughly similar temperatures (maybe 22°C).

CREDIT: NASA/Ames/JPL-Caltech

Spitzer Mission: Epsilon Eridani

Epsilon Eridani is a young planetary system only 10.5 light-years away with a structure similar to ours.

Observed with both Spitzer and SOFIA.

Credit: NASA/JPL-Caltech/R. Hurt (SSC)

Samantha Mathewson, Space.com | May 4, 2017
Spitzer Mission: Trappist-1

Trappist-1 is M-class star – i.e. much cooler than our G-class star.

Thus, the Trappist habitable zone is much closer to its star.

M-class stars may not be friendly to life because they have higher radiation environment than our G-class star.

How Spitzer Observed the Trappist-1 System
> 100 Habitable Zone Planet Candidates  
> 25 smaller than 2 Earth Radii

Is There Life Elsewhere in the Galaxy?

Need to multiply these values by $\eta_{\text{Earth}} \times f_B$ to get the number of potentially life-bearing planets detected by a space telescope.  
$\eta_{\text{Earth}} =$ fraction of stars with Earth-mass planets in HZ  
$f_B =$ fraction of the Earth-mass planets that have detectable biosignatures

If:  
\[
\frac{\eta_{\text{Earth}}} {f_B} \approx 1 \quad \text{then } D_{\text{Tel}} \approx 4m \\
\frac{\eta_{\text{Earth}}} {f_B} < 1 \quad \text{then } D_{\text{Tel}} \approx 8m \\
\frac{\eta_{\text{Earth}}} {f_B} \ll 1 \quad \text{then } D_{\text{Tel}} \approx 16m
\]

Kepler is finding that $\eta_{\text{Earth}}$ maybe 1.5% to 2.5% (SPACE.COM, 21 Mar 2011)

Thus, an 8-m telescope might find 1 to 3 Earth twins and an 16-m telescope might find 10 to 20 Earth twins.


Green bars show the number of FGK stars that could be observed 3x each in a 5-year mission without exceeding 20% of total observing time available to community.
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

Where does the water come from?

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk

Proto-Stars produce Water

In a proto-star 750 light-years away, Herschel detected:

Spectra of Atomic Hydrogen and Oxygen are being pulled into the star, and

Water vapor being spewed at 200,000 km per hour from the poles.

The water vapor freezes and falls back onto the proto-planetary disk.

Discovery is because Herschel’s infrared sensors can pierce the dense cloud of gas and dust feeding the star’s formation.

Other Herschel Data finds enough water in the outer reaches of the young star TW Hydrae (175 light- yrs from Earth) to fill Earth's oceans several thousand times over.

(National Geographic, Clay Dillow, 16 June 2011)

Molecular Oxygen discovered in space

Herschel found molecular oxygen in a dense patch of gas and dust adjacent to star-forming regions in the Orion nebula.

The oxygen maybe water ice that coats tiny dust grains.

(SPACE.com, 01 August 2011)
Search for Habitable Planets

atmosphere

habitability

interior

surface

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.

Bio Markers

Spectroscopic Indicators of Life

Absorption Lines
- Water
- Oxygen & Ozone
- CO2
- Methane
- “Red” Edge
- “Blue” Haze
How to see an Exoplanet’s Atmosphere

One method is absorption spectroscopy during transits.

Another is reflected light spectroscopy

Beyond JWST

SLS enables even larger telescope Concepts:

HabEx  
LUVOIR  
OST Far-IR
Controls Diffraction to Reveal Exoplanets in “Dark Hole”
Direct Imaging

Giant Space Telescopes will be able to directly image Planetary Systems using either internal coronagraphs or external star shades.

Simulated image for a 12-m telescope, a 100-m star shade, and 1 day exposure.

R=100 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc

Exposure: 51 ksec on 8-m
4.3 ksec on 16-m

Reflectance $\propto$ (Planet Mass)$^{2/3}$

5 Earth-mass: 8.5 ksec on 8-m

Bkgd: 3 zodi

SNR=10 @ 790 nm

H$_2$O

O$_2$(A)

O$_2$(B)

Marc Postman, “ATLAST”, Barcelona, 2009
Detecting Photometric Variability in Exoplanets

Ford et al. 2003: Model of broadband photometric temporal variability of Earth

Require S/N ~ 20 (5% photometry) to detect ~20% temporal variations in reflectivity.

Need to achieve a single observation at this S/N in < 0.25 day of exposure time in order to sample the variability with at least 4 independent observations per rotation period.

Marc Postman, “ATLAST”, Barcelona, 2009

Detecting Photometric Variability in Exoplanets

Graph shows changes in infrared brightness of 2M1207b as measured by Hubble over the course of a 10-hr observation.

Change in brightness suggests presence of clouds that influence amount of infrared radiation observed as the planet rotates.

CREDIT NASA, ESA, Y. Zhou (University of Arizona), and P. Jeffries (STScI)
Anthony Watts / February 18, 2016
JWST – the First Light Machine

With its 6X larger collecting aperture, JWST will see back in time further than Hubble and explore the Universe’s first light.

Countdown to Launch

JWST is making excellent technical progress
will be ready for launch late 2018
will be the dominant astronomical facility for a decade undertaking a broad range of scientific investigations
1000s of Scientists and Engineers in USA and around the world are working to make JWST.