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

Big Bang

3 minutes

300,000 years

100 million years

1 billion years

13.7 Billion years

Ground Based Observatories

Today

Particle Physics

Atoms & Radiation

First Galaxies Form

Galaxies Evolve

Planets, Life & Intelligence
First Light Stars

First stars (maybe 1000X larger than our own) formed from clouds of hydrogen 50-100 million years after the Big Bang.

These first stars helped ionize the universe.

Because they were so large, they quickly exploded supernova creating elements such as He or collapsed into black holes.

‘O’-class stars are 25X larger than our ‘G’-class Sun.

First Light: Reionization

Neutral ‘fog’ was dissolved by very 1st Generation Stars.

As indicated by Neutral Hydrogen spectroscopy, 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.
How do we see first light objects? Redshift

What is Redshift

The further away an object is, the more its light is redshifted from the visible into the infrared – because of space/time stretching.

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 \( \mu m \))
  – 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
NASA’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

Planetary

Star Formation

Galaxy Evolution

Galaxy Formation

Life
Three Key Facts

There are 3 key facts about JWST that enable 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”
- λ/D_{1.6μm} ~ 0.14”

**JWST**
- 6.5-meter
- T ~ 40 K
- 132” x 164”
- λ/D_{2μm} ~ 0.06”

**SPITZER**
- 0.8-meter
- T ~ 5.5 K
- 312” x 312”
- λ/D_{5.6μm} ~ 2.22”

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

**JWST 44X more sensitive**

Wavelength Coverage

- **HST**
- 1 μm
- 10 μm
- 100 μm

- **JWST**
- 6X more sensitive

- **Spitzer**
- 324” x 324”
- λ/D_{24μm} ~ 6.2”

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 (384,000km)
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
- **NIRSpec**: simultaneous spectra of 100 galaxies
- **MIRI**: first HD view of infrared universe
- **NIRISS**: imagery & spectra of exoplanets
- **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/m² Areal Density
- < $6 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

<table>
<thead>
<tr>
<th>Surface Figure Quality</th>
<th>Minimum RMS 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>

Fun Fact – Mirror Surface Tolerance

Human Hair Diameter is 100,000 nm (typical)

Approximate scale

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

Surface Figure With Alignment Compensation

RES: 0.0070 µm
PV: 0.0023 µm
Data Pts: 140574

ULE Glass

Residual with 36 Zernikes Removed

RES: 0.0005 µm
PV: 0.0030 µm
Data Pts: 161658

Mirror Manufacturing Process

Blank Fabrication

Machining

Polishing

Mirror System Integration
Fun Facts – Mirror Manufacturing

Before

Be Billet

250 kgs

After

Finished Mirror Segment

Be dust which is recycled

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

[Images of 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.

Full Aperture Optical Test Station (OTS)
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

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
BOTS to Tinsley Initial Comparison

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

Cryo-Vacuum Chamber is 7 m dia x 23 m long
JWST Flight Mirror Test Configuration

Primary Mirror Cryogenic Tests
XRCF Cryo Test

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

Survival Temperature
- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

Mirror Fabrication

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

Gold Coated Mirror Assemblies

Mirrors ≥ 98% at 2 µm

Optical Telescope Assembly
Observatory level testing occurs at JSC Chamber A

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

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

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

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

- JWST will operate at the 2nd Lagrange Point (L2) which is 1.5 Million km away from the Earth
- HST in Low Earth Orbit, ~500 km up. Imaging affected by proximity to 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 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

Studying Early Universe: ‘First’ Galaxies

Galaxy GN-z11 is 13.4 B-yrs away, just 400 M-yrs 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).

Some ‘first’ galaxies formed stars 1000X faster than today.
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.
Hubble Ultra Deep Field – Near Infrared

47 Galaxies have been observed at 600 to 650 Myrs after BB.

Hubble Ultra Deep Field – Near Infrared overlaid with Chandra Deep Field South

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.

---

Image of Supernova 1987A, taken in the infrared by Herschel and Spitzer, shows some of the warm dust surrounding it.

CREDIT: Pasquale Panuzzo, SPACE.com, Taylor Redd, 7 July 2011
2\textsuperscript{nd} Generation Stars – 700M yrs after BB

This star is a 2\textsuperscript{nd} 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.

![Image of stars and element composition chart]

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

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.

![Image of Subaru Deep Field with labeled areas]

Clara Moskowitz, SPACE.com, 05 October 2011
The Hubble Sequence

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

The Hubble Space Telescope has extended this to the distant past.

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.

Hubble NIR Image of CL J1449+0856, the most distant mature cluster of galaxies found. Color added from ESO's VLT and NAOJ's Subaru Telescope. CREDIT: NASA, ESA, R. Gobat (SPACE.com 09 March 2011)

JKCS 041 at 3.7 B-yr after BB may be one of the Universe's oldest clusters. In Chandra image, X-ray emission is shown in blue. Image: NASA/CXC/INAF/S.Andreon (Astronomy Now, 10 May 2010)
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

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’ image of Ultima Thule on 1 Jan 2019 supports the Accretion Model of Planetary System Formation.
History of Known (current) NEO Population

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

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
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’ start 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.

ALMA image of the young star HL Tau and its protoplanetary disk. This best image ever of planet formation reveals multiple rings and gaps that herald the presence of emerging planets as they sweep their orbits clear of dust and gas.

Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

ALMA has shown that small ~au-sized disk gaps may be common

Credit: 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
Protoplanetary disks are complex and dynamic

![Diagram of protoplanetary disks](image)

Protoplanetary disk observations require multiple wavelengths

![Graph showing wavelength requirements](image)

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

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

![Image of Eta Corvi System](image)

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

**Habitable Zone**

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

![Image of Habitable Zone](image)

‘Billions of stars’ in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com. 18 March 2015
Where does the water come from?

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk

EXOPLANETS

First Exo-Planet (51 Pegasi) orbiting a ‘Sun-like’ Star was observed in 1995 using Radial Velocity method.

Since then, 1000s of exo-planets have been discovered including 100’s of Earth size exoplanets – mostly via Transit Method.

But what we really want is direct detection with spectroscopy.
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
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.
Kepler – Habitable Zone Planet

Kepler 22b is the first in the habitable zone.

- Kepler-22b is located about 600 light-years away, orbiting a sun-like star.
- It is 2.4 times that of Earth and has a temperature of maybe 20°C

CREDIT: NASA/Ames/JPL-Caltech

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.

CREDIT: NASA/JPL
How Spitzer Observed the Trappist-1 System

Credit: NASA/JPL

Techniques to Detect Exoplanets

Direct Imaging

Detecting an exo-Earth is like looking for a firefly next to a search light on top of the Empire State Building from Los Angeles.
Detection depends on where Planet is relative to its Star.

Revisiting multiple times increases Detection.
Hubble can detect 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.
Exoplanet Populations & Discovery Method
As of 14 December 2017
• Total Confirmed Exoplanets = 3567
• Total found by Kepler = 2525

Kepler’s Verified Planets, by Size
As of May 10, 2016
Final data release: spring 2017
> 100 Habitable Zone Planet Candidates
> 25 smaller than 2 Earth Radii

![Kepler Habitable Zone Planets](https://www.nasa.gov/sites/default/files/thumbnails/image/press-web15_kepler_hz_planets_edit.jpg)

Small Planets come in Two Sizes

![Small Planets come in Two Sizes](https://www.nasa.gov/sites/default/files/thumbnails/image/press-web19_small_planets_two_sizes-edit.jpg)
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.


Nearly All Stars have Planets

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.
Search for Habitable Planets

- atmosphere
- habitability
- interior
- surface

Sara Seager (2006)

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

Atmospheric Spectrum

Spectral Bio-Markers:
- Water (900 nm) easy
- Oxygen (680 nm) hard
- CO2 (1570 nm) harder
- Methane (1800 nm) hardest

Methane is ‘smoking gun’.
Other indicators are ‘red-edge’ and ‘blue-haze’
How to see an Exoplanet’s Atmosphere

One method is absorption spectroscopy during transits.

Another is reflected light spectroscopy

Photometric Variability in Exoplanets

Photometry (brightness or polarization) from planet can vary as it rotates due to:

- Land Mass
- Clouds
- Water

Change in infrared brightness of 2M1207b as measured by Hubble over a 10-hr observation.
Change in brightness suggests presence of clouds that influence amount of infrared radiation observed as the planet rotates.
Beyond JWST

SLS enables even larger telescope Concepts:

- HabEx
- LUVOIR
- OST Far-IR

Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”
Starshade (External Occulter)
Blocks Starlight, Controls Diffraction prior to entering Telescope

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.
Webb: Seeing Farther

With its 6X larger collecting aperture, the Webb telescope will see farther back in time than Hubble to seek the universe’s first light & explore distant worlds.

Countdown to Launch

JWST is

making excellent technical progress
will be ready for launch in 2021
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.