The Earliest Galaxies: Exploring Cosmic Sunrise with Hubble, Spitzer, and JWST

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firstgalaxies.org

figure credit: Adolf Schaller
1970s—1980s  John’s continuing efforts to support Hubble were crucial and inspiring – and a model for what was needed from scientists for a major mission to be successful

1989 – John’s introductory remarks and participation in the Next Generation Space Telescope workshop
1991 – John was Chair, Astronomy Decadal Survey. I was Chair of UV-Optical in Space Panel.
NGST $\Rightarrow$ JWST – key early events

30 years from NGST mission concept to JWST launch!

NGST concept in mid-1980s by Pierre Bely, Peter Stockman and Garth Illingworth

see 2016 STScI Newsletter article
NGST: The Early Days of JWST
newsletter.stsci.edu/early-webb-history
From the introduction to the 1989 NGST workshop:

“We would also like to thank John Bahcall who introduced the workshop by sharing some of his experiences with the HST project. His pertinent remarks about the dedication of those involved in the development of HST emphasized the deep and widespread commitment needed to bring about its successor.”

“International cooperation may be critical for such a major project”. Bahcall

“It’s not often that we have a chance to participate in history”. Danielson (as quoted by Bahcall)
NGST ⇒ JWST – key early events

30 years from NGST mission concept to JWST launch!

1990 Decadal Survey: UV-Optical in Space Panel recommended:

- 6-m passively-cooled infrared telescope
- for launch in 2009 to a high orbit
- derived a cost of $2B in FY90$ (~$4B in 2018$)
1996: *HST and Beyond* study (chair Alan Dressler) has 3 recommendations including an IR telescope “...of aperture 4 m or larger, optimized for imaging and spectroscopy over .... 1-5 μm.”

1996: key step at American Astronomical Society meeting:
NASA Administrator Dan Goldin says: “I see Alan Dressler here. All he wants is a four meter optic that goes from a half micron to 20 microns. And I said to him, "Why do you ask for such a modest thing? Why not go after six or seven meters?"

Dan Goldin later says “go for 8 m”

NASA Office of Space Science AA Ed Weiler requests that Goddard Space Flight Center (GSFC) study NGST
John Mather, and many others at GSFC, take NGST forward

1999: SMD AA Weiler signs Formulation Authorization
NASA initiates NGST

2000: Astronomy Decadal survey makes 8 m NGST top space project
James Webb Space Telescope
galaxies at cosmic dawn
our strange universe

it is all dark matter & dark energy – and a little bit of ordinary matter “icing on the cake”

from WMAP and Planck telescopes
dark energy and dark matter are the 800 lb gorilla(s) in the universe

ordinary matter is, by comparison, a bit mousey...

our strange universe

it is all dark matter & dark energy – and a little bit of ordinary matter “icing on the cake”

from WMAP and Planck telescopes
Telescopes are "time machines".

- Earth to Sun: 8.3 min
- Earth to Saturn: 71-88 min
- Light to Saturn: 4.24 yrs
- Light to stars: about 26,000 yrs
telescopes are "time machines"

2.54 million years

2.27 billion years

13.31 billion years

13.72 billion years

Gn-z11
from the Big Dipper close by in our Milky Way to the most distance galaxy known (GN-z11)
history of everything

today

peak of galaxy growth

first galaxies

first stars

dark ages

billions of years ago

0 11 12 13.3 13.4 13.5 13.7

cosmic background radiation

figure credit: insert adapted from Brant Robertson UCSC
history of everything

Big Bang

today

peak of galaxy growth

first galaxies

first stars

dark ages

cosmic background radiation

billions of years ago

0 11 12 13.3 13.4 13.5 13.7

figure credit: insert adapted from Brant Robertson UCSC
searching for distant galaxies

very distant galaxies look very red in our images
galaxies seen 12.9 billion years ago
what some bright galaxies actually looked like 13 billion years ago!

they are not really red

they are actually very blue!

lots of hot young blue stars
Galaxies in the first billion years

**Bright distant galaxies**
- 5-10,000 light years

**Faint distant galaxies**
- 100-500 light years

**The “Milky Way” now**
- 100,000 light years

Really tiny!

Faint galaxies in the first billion years are measured to be very small.

UGC-12158 – similar to the Milky Way
how we determine redshifts

for redshifts astronomers use “z”

figure credit Aleš Tošovský
hydrogen gas in the universe absorbs the bluest light (ultraviolet) light from galaxies

☞ find the break and it tells how fast the galaxy is moving

☞ change in wavelength gives redshift

z=6 spectrum shifted to red

at z=6 galaxy is moving away at 96% of the speed of light!

z=8 spectrum shifted even more to red
ACS+WFC3/IR: efficient redshifts to z~11

![Graph showing optical ACS and near-IR WFC3/IR wavelengths with z = 3.00 at different wavelengths ranging from F435W to F160W.]

xdf.ucolick.org/
the telescopes and cameras that enabled the exploration of the early universe

 upgraded Hubble ACS in 2002 WFC3 in 2009

 launched Spitzer in 2003

 each new servicing mission resulted in a dramatic change in our ability to explore the early universe

 ACS Hubble SM3B
 Mar 2002

 Advanced Camera for Surveys (ACS): PI Holland Ford Deputy-PI Garth

 Spitzer
 Aug 2003

 WFC3 Hubble SM4
 May 2009
Redshift limits increase with new capability

capability-driven scientific advances

Hubble Probes the Early Universe

1990
Ground-based observatories

1995
Hubble Deep Field

2004
Hubble Ultra Deep Field

2010
Hubble Ultra Deep Field-IR

Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

first stars
first galaxies
reionization epoch
Hubble’s partners for distant galaxies

Hubble
Great Observatory

Chandra
Great Observatory

Spitzer
Great Observatory

VLT – Very Large telescope

Keck & Subaru telescopes

Atacama Large Millimeter Array
ALMA
JWST’s partners for distant galaxies

- Chandra
- Great Observatory
- Hubble
- Great Observatory
- Wide Field Infrared Survey Telescope
- WFIRST
- Great Observatory
- European Extremely Large Telescope
- VLT – Very Large Telescopes
- Keck & Subaru
- LSST – Large Synoptic Survey Telescope
- Atacama Large Millimeter Array
- ALMA
the survey images used for high-redshift galaxy studies

started with HDF-N in Dec 1995
Hubble and Spitzer survey fields for high-redshift galaxies

HUDF: Hubble Ultra-Deep Field

GOODS: Great Observatories Origins Deep Survey
COSMOS: Cosmic Evolution Survey
EGS: Extreme Grossתזs
Frontier Fields
GOODS and CANDELS fields
UDS: Ultra Deep Survey
HUDF/XDF: Hubble Ultra-Deep Field/XMM-Newton Deep Field
**XDF/HUDF** *(eXtreme Deep Field)*

*deepest ever Hubble image*

- 2963 HST images
- from 800 orbits of Hubble
- for a 23 day total exposure on the HUDF!

**all optical ACS data and all infrared WFC3/IR data on the HUDF from 2003-2013 from 19 programs**

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HUDF: Hubble Ultra-Deep Field
Big Bang

relative rate of all star formation

Now

z~2

Big Bang

dramatic change over time of how many stars are forming in the universe

stability characterization archaeology

diversity complexity evolution transition

dramatic growth extreme SF

Lookback Time [Billion Years]

Now

0 2 4 6 8 10 12 14

0 2 4 6 8

0 1 2 3 4 5 6 7 8 9

diverse complexity evolution transition dramatic growth extreme SF

linear figure credit: Pascal Oesch
JWST is mainly infrared
Hubble is mainly optical
why are we going to the infrared?

ILLUSTRIS simulation

Time since the Big Bang: 1.0 billion years
JWST is mainly infrared

Hubble is mainly optical

why are we going to the infrared?
why we go to the infrared

“Pillars of Creation”

visible light

infrared light
why we must go to the infrared
to reach the “first galaxies”

this is the most distant galaxy that we know

and this is what it looks like a visible image
why we must go to the infrared

to reach the “first galaxies”

this is the most distant galaxy that we know

and it can only be seen in infrared images

the even more distant “first galaxies” can only be seen in the infrared
history of everything

Big Bang

time

dark ages

first stars

first galaxies

peak of galaxy growth

today

billions of years ago

0 11 12 13.3 13.4 13.5 13.7

redshift 2 4 6 11 15 20 1100

cosmic background radiation

figure credit: insert adapted from Brant Robertson UCSC
first evidence for when the “first stars” started to shine brightly

found by these funny-looking (and small) radio antennae in the desert of Western Australia.

**Experiment to Detect the Global Epoch of Reionization Signature**

**NEW RESULT**

*published March 01 Nature*

Bowman, Rogers, Monsalve, Mozdzen & Mahesh

National Science Foundation
first evidence for when the “first stars” started to shine brightly

NEW RESULT

published March 01 Nature

first stars become prominent at redshift z~20 (~180 million years)

is this correct?

confirmation?
first evidence for when the “first stars” started to shine brightly

**NEW RESULT**

Published March 01

Nature

is this correct?

confirmation?

first stars become prominent at redshift \(z \sim 20\) (~180 million years)
what do we know about the first galaxies?

the first galaxies must be earlier than GN-z11

i.e., earlier than 400 million years
but not by much – maybe 100-200 million years

Hubble and Spitzer have been reaching into JWST territory!

"close to “Cosmic Sunrise”"
what do these very early galaxies look like?

we do not know!

one hint from a galaxy 12.5 billion years ago
The way to see what faint galaxies really look like… by combining Hubble with a “cosmic telescope”

credit: NASA, ESA, L. Calcada
Hubble Frontier Fields

6 galaxy clusters

Hubble and Spitzer imaging
model gravity in cluster
remove distortions

CL1358-G1 at z=4.92

get ~20X magnified image of distant galaxy 12.5 million years ago

found in 1996 – still the best magnified image we have for a galaxy in the first 2 billion years

cluster of galaxies CL1358 magnifies faint galaxy that lies far beyond

a remarkable fold arc in CL1358
unique insight into the structure of a high redshift galaxy

very rare to see such details

star-forming regions at high redshift are very small

1996 image

2004 image from Hubble’s Advanced Camera

magnified 25X by the cluster

CL1358-G1 probably looks more like this!

CL1358-G1
how will we find more?

>100 clusters have been searched – CL1358G1 is still the best and only one at high redshift

we need a really big telescope and lasers and adaptive optics

30-40 m ELT with adaptive optics needed to see what early galaxies really look like

ELT – Extremely Large Telescope
can JWST find the first galaxies?

will they be so rare that they will be hard to find?

will they occur at such high redshifts that they will be hard for JWST to see?
way fewer galaxies than expected at redshift 10

galaxies are evolving rapidly earlier than 650 million years

there are far fewer galaxies than we (naively) expected at early times

this is a very important result for JWST

2018 publication
what does this mean for JWST and our search for the “first galaxies”? 

galaxies are evolving rapidly earlier than 650 million years
measuring the fluctuations in the 3°K cosmic microwave background

three amazing missions

COBE 1989

WMAP 2001

Planck 2009
measuring the fluctuations in the 3°K cosmic microwave background

three amazing missions

Planck tells us that galaxies started to put out a lot of light at z~10
will JWST see the “first galaxies”?

large 10X drop from expected at $z \sim 11$ + galaxy turn-on at $z \sim 10-11$

suggest dramatic changes in galaxies at $z \sim 10-12$

great for JWST’s “first light” goal since galaxies are turning on at $z \sim 10-12$

likely major changes from $z \sim 10-15$ – where JWST can see them

exciting times ahead at “Cosmic Sunrise” for JWST!
will JWST see the “first galaxies”?  

yes, I think that there is a really good chance that we will

large 10X drop from expected at z~11 + galaxy turn-on at z~10-11

suggest dramatic changes in galaxies at z~10-12

great for JWST’s “first light” goal since galaxies are turning on at z~10-12

likely major changes from z~10-15 – where JWST can see them

exciting times ahead at “Cosmic Sunrise” for JWST!
the dramatic brightening after dawn

desert sunrise
the dramatic brightening after cosmic dawn

“Cosmic Sunrise” – as the first galaxies burst forth around 300 million years after the Big Bang
JWST is the “what’s next” for the earliest galaxies

JWST – full-size model at “South by Southwest”
JWST will be launched on an Ariane 5

simulated images
JWST, along with WFIRST (and similar telescopes) and the ELT, will transform our understanding of distant galaxies in the next decade, but, for distant galaxies, another “next generation telescope” will be needed in the decade beyond.
not the end...
but the beginning...