The HUDF09 program: exploring the nature of galaxies in the first 700 million years with WFC3 and ACS

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These results are based on data from the original HUDF and the WFC3/IR and ACS cameras as proposed under GO11563 by the HUDF09 team:

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a resource for high-redshift galaxies see:
firstgalaxies.org
http://firstgalaxies.org/

for astro-ph links to papers see:
http://firstgalaxies.org/hudf09
firstgalaxies.org/hudf09

AAS galaxies in the first 700 million years GDI firstgalaxies.org
Hubble’s new Wide Field Infra-Red Camera (WFC3/IR) has revealed redshift $z \sim 8$ galaxies, just 600-700 million years after recombination.

This is just 6 years after Hubble revealed $z \sim 6$ galaxies (950 million years after recombination) using the Advanced Camera for Surveys (ACS)

substantial samples of $z \sim 7$ & $z \sim 8$ galaxies are being derived from both the still-incomplete HUDF09 program and the ERS program

the $z \sim 7$ and $z \sim 8$ samples are enabling a characterization of the properties of galaxies just 600-800 Myr from recombination

these galaxies lie in the heart of the reionization epoch and will provide further constraints on the role played by galaxies

combining Hubble data with Spitzer data is setting constraints on the mass density and on even earlier populations at $z \sim 10-11$
NICMOS – 72 orbits

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WFC3/IR – 16 orbits
WFC3/IR vs NICMOS

to find a z~7 galaxy took ~100 orbits with NICMOS – with WFC3/IR it takes a few orbits

WFC3/IR has a discovery efficiency ~40X NICMOS

comparing the old and new Hubble infrared cameras

WFC3/IR

NICMOS

z~7 galaxies

2.2" x 2.2"

Oesch et al

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WFC3/IR is ~6X larger in area than NICMOS and much better matches ACS

3.4 arcmin

ACS

2.2 arcmin

NICMOS
CDF-S region is rich in data (HST, Spitzer, Chandra, etc)

ERS data taken
only ~1/3 of HUDF09 data taken (on HUDF)

February 2010 HUDF05-2 data to be taken
remainder to be taken later in 2010

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searches for $z \sim 7-8$ objects in HUDF09

HUDF09 WFC3/IR data taken in late August 2009

very competitive area!

within two weeks three groups had submitted papers on $z \sim 7-8$ galaxies, followed within a month by a fourth group, and recently by a fifth group

Bouwens et al, Oesch et al
Bunker et al
McLure et al
Yan et al
Finkelstein et al

$z \sim 7-8$ galaxies are just 600-800 million years from the big bang

AAS  galaxies in the first 700 million years  GDI  firstgalaxies.org
galaxies at z~8 from the HUDF09 team

the two highest redshift z~8 galaxies

<table>
<thead>
<tr>
<th>ACS filters</th>
<th>WFC3/IR</th>
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<tr>
<td>V</td>
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ACS filters are used for relatively low resolution imaging, while WFC3/IR is used for higher resolution images.

redshift

z~8.4

z~8.7

not detected

detected

WFC3/IR resolution helps separate galaxies from (rare) faint stars.

searches conducted using the very robust and well-tested photometric “dropout” technique

verified spectroscopically at z~2-6

extensive testing for contamination from photometric scatter, spurious sources, lower redshift sources....

the other three z~8 galaxies

all are H~28-29 mag sources!

Bouwens, Illingworth et al

2.4'' x 2.4''

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HUDF09 team found 16 $z \sim 7$ and 5 $z \sim 8$ galaxies

HUDF09 WFC3/IR

HUDF09 image $\sim 2.2'$

boxes $\sim 2.5''$

$z \sim 8$
Bouwens et al

$z \sim 7$
Oesch et al

AAS galaxies in the first 700 million years GDI firstgalaxies.org
these early galaxies are small

1.8” x 1.8”

Oesch/Carollo et al

z~7 galaxies show considerable sub-structure

size scales as $(1+z)^m$ where $m = 1.12 \pm 0.17$

galaxies become very small at early times – does not appear to be a surface brightness effect (from simulations on lower redshift sources and stacking analysis)
these early galaxies are very blue

UV-continuum slope $\beta$ depends upon the age, metallicity, and dust content of a star-forming population.

UV-continuum slope $\beta$ most sensitive to changes in dust content but recent studies have shown that the dust content of lower luminosity, $z>6$ galaxies must be essentially zero.

dust free at $\beta < \sim -2.4$

at $\beta < \sim -2.8$ standard population models do not fit (even low metal abundance models).

$\beta$ is the power law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

Bouwens/Illingworth et al

AAS galaxies in the first 700 million years GDI firstgalaxies.org
these early galaxies are very blue

UV-continuum slope $\beta$ most sensitive to changes in dust content – but dust content of lower luminosity, $z>6$ galaxies is zero

so changes at $z>6$ must be due to other effects

cannot be fit with standard population models

galaxies become very blue at early times – suggesting possibly that metals are very deficient

$\beta$ is the power law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

Bouwens/Illingworth et al
luminosity functions

The new z~7 luminosity function indicates that the very steep slope persists to higher redshift.

Luminosity functions (LF) are key for determining the UV luminosity density and star formation rate densities.

Existing z~4-6 luminosity functions show that the slope is very steep at the faint end below L* (α ~ -1.75).

The bulk of the integrated UV flux at high-redshift comes from sub-L* low luminosity galaxies.

The changes in the LF with redshift are primarily at the bright end.

AAS galaxies in the first 700 million years GDI firstgalaxies.org
our new results

the star formation rate density

UV luminosity density

the history of star formation in galaxies in the universe

Bouwens/Illingworth et al

AAS  galaxies in the first 700 million years  GDI  firstgalaxies.org
these galaxies formed stars much earlier

Hubble and Spitzer results combine to show us that $z \sim 8$ galaxies could well have been forming stars two-three hundred million years earlier (at $z > 10-11$).

Some individual $z \sim 8$ Spitzer 3.6 μm images

$z \sim 8$ summed Spitzer images

3.6 μm

4.5 μm

Model fit is BC03 CSF $0.2Z_\odot$ $\log M = 9.3$

$z \sim 7.7$ and 300 Myr (SFH weighted age = $t/2$)
our new results

the Hubble and Spitzer data allow us to establish the mass density at these early times

the history of the mass buildup in galaxies in the universe

Labbé/Gonzalez et al

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can we go beyond $z \sim 8$ (to $z \sim 10$?)

our SED fits suggest that star formation is underway at $z \sim 10-11$ or even earlier – can we see higher redshift galaxies?

some early results from Yan et al suggested that $z \sim 10$ galaxies existed in large numbers – this appears not to be the case

searches are still ongoing – we recently reported the possible detection of 3 $z \sim 10$ sources

after correcting for our estimate of the contamination, we derived constraints on the star formation rate density, and also set an upper limit from the current HUDF09 data

Bouwens/Illingworth et al

AAS galaxies in the first 700 million years GDI firstgalaxies.org
what these new observations tell us

SUMMARY

Hubble’s new Wide Field Infra-Red Camera (WFC3/IR) has revealed galaxies 13 billion years ago (at redshifts z~7 and z~8), just 600-800 million years from the big bang

these galaxies are small, low mass objects (half-light radii of just 0.7 kpc at z~7-8)

they are extremely blue in color and are probably very deficient in heavier elements

they give us estimates for the mass density and the star formation rate density that extends from just ~5% of the age of the universe

combining these results with Spitzer data suggests that these galaxies were forming stars ~300 million years earlier, at z>10-11 (with recent possible detections being found at z~10)

these galaxies fall in the heart of the “reionization” epoch, but our estimates are still low for the contribution of galaxies to reionization: we still don’t know if galaxies could have reionized the universe!!