First light study

Stiavelli, Lilly, Gardner, Rieke and the JWST SWG

1. *What is "first light"?*

First light is the appearance of the first stars (Population III) or mini-AGNs in the Universe. JWST is incapable of detecting individual Population III stars directly but could detected them as SNae, thought to be ultra-bright pair instability SNae or, even, Gamma Ray Bursts. While detection of SNae and GRBs from Population III stars should be pursued, in the following we will generally denote by "first light" the appearance of the first galaxies, i.e., associations of stars with luminosity of at least a few 10^8 solar luminosities.

2. *Why do we need JWST ? can it be done from the ground before JWST flies?*

JWST is needed to find the first light sources. It is possible that reionization occurs at low redshift (around 6) but there is no consensus on this and first light preceeds reionization. The following observational results argue for an early first light:

i) Compton optical depth from CMB measurements. Based on the first year WMAP data, Spergel et al. (2003, ApJS, 148, 175) reported an unexpectedly high value of τ (0.17+/-0.04) and interpreted it as evidence of reionization at z~=17. If one assumes a constant generation of ionizing photons a value of τ=0.17 can be obtained if first light occurs at z=50. McTavish et al. (astro-ph/0507503) combine multiple data set to derive a value of τ~=0.09. This would still imply first light at z=12 assuming constant ionizing photon production.

ii) Galaxies at z~=7 with older stellar populations. A few objects have been discovered using Spitzer that have old populations already in place at z=7 or so. Mobasher et al. (astro-ph/0509768, ApJ in press) find that a galaxy at z=6.5 formed the bulk of its stars at z>9. Egami et al. (2005, ApJL, 618, L5) find that a galaxy at z=6.6-6.8 has a stellar population at least 50 Myrs old and possibly several hundreds Myrs old. This would place its formation at z=6.9 or higher.

iii) Lyman α sources at z=6.5. Malhotra and Rhoads (astro-ph/0511196, ApJL submitted) derive a minimum ionized volume fraction of 20-50% at z=6.5 from their sample of Lyman α sources. The only realistic way around this conclusion is that reionization is indeed done by first light sources at z=6-7 and their metallicity is low so that the intrinsic Lyman α EW is very high. This is not very likely but perhaps possible (e.g. Stiavelli et al. 2004, ApJL, 610, L1) but would conflict with evidence of stellar populations formed at z>7. If Malhotra and Rhoads are right reionization took place at z=7 or earlier and first light earlier still.

3. *How can we tell that we have seen first light?*

Given the uncertainties in these measurements a number of techniques will need to be used to identify first light.

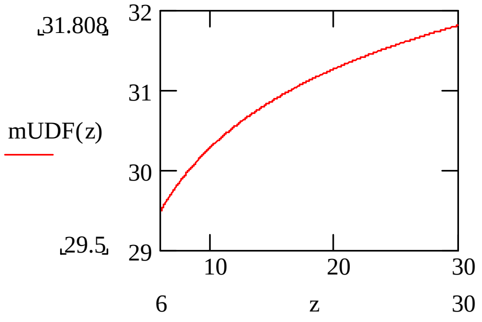
i) LF evolution. Models predict that the LF should evolve significantly for the first galaxies. Their Lstar will be much fainter than the present value and, perhaps, the slope of the mass function will become steeper. More importantly the value of the density of galaxies ϕstar is expected to decrease significantly. We should aim at detecting both a change in the LF slope and Lstar and a change in the number density of objects.
ii) Metallicity. First light galaxies should have much lower metallicity than other objects. Their metallicity may be non-zero because of self-enrichment.
iii) Absence of an older stellar population. First light galaxies should not have older stellar populations.

In the following we will focus mostly on item i) since it is the most relevant for NIRCam and it is the observations that would provide us with the candidates to be followed up spectroscopically by NIRSpec (for the metallicity determination) and MIRI (for the older population search).

4. *Detecting a change in the LF slope and Lstar value*

In order to study the slope and Lstar value of the Lf at z=6 we need to probe below the value of Lstar. Bouwens et al. (astro-ph/0509641) have analyzed the combined GOODS and UDF extended data sets to derive a LF at z=6 extending down to zAB=29.5 (at S/N=8). This is 0.04 Lstar for the z=3 Lstar. They find evidence for both a steepening of the LF (in agreement with Yan & Windhorst 2004, ApJL, 612, L93) and a dimming of Lstar. In order to see similar changes at z>6 we need to reach similar relative depths (see Figure).

z	AB_1350	Fnu (nJY)	lambda (micron)
10	30.284	2.80	1.34
12	30.551	2.19	1.58
15	30.869	1.63	1.95
20	31.267	1.13	2.55



The table gives the required depth (at S/N=8) in AB magnitudes and in nJy. The required sensitivity to identify these objects as Lyman break galaxies is the same for the filter longwards of the break (at the wavelength listed in the table) and shortwards of the break.

Thus, in practice, this measurement requires a sensitivity of 30.3 in F090W, 30.6 in F110W, 30.9 in F150W, 31.3 in F200W, F277W, and F356W. The sensitivity requirement would continue to increase if we considered z>20 (see Figure).

5. *Detecting a change in the number density of high redshift galaxies*

The detection of a drop of a factor, say, 10 in the number density of galaxies might be indicative of having reached the first galaxies. Let's consider what this would imply for a NIRCam observing program obtaining data on a single ultra deep 2.2 by 2.2 arcmin field (using one camera) and on three adjacent 2.2 by 2.2 arcmin fields (using the other camera). This gives as 4.8 sq. arcmin at maximum depth and 14.5 sq. arcmin at one third of the exposure time. The combination of these two areas should give us a result not excessively dependent on changes of the luminosity function. Our predictions will be based, once again, on the Bouwens et al. luminosity function (corrected to match the UDF result to account for completeness effects) and we will assume that a factor 10 drop needs to be detected to 10 sigma, i.e, that we need at least 136 objects from the unevolving z=6 LF. The adopted dropout criterion is a standard one for lower redshift, namely a drop of 1.5 mag across Lymanα, a positive color shortwards of Lymanα, and a color bluer than 1 longwards of Lymanα.

For F115W dropouts at <z>=7.9 the results are summarized in the table below:

F115W dropouts		z=7.9	
Flux (nJy)	num obj	Npointings	Time (rel)
2.8	243.7	1.0	1.0
5	161.68	1.0	0.3
8	98.48	1.4	0.2
14	49.55	2.7	0.11

In order to gather the required number of objects one pointing would be enough even with a limiting depth of 8nJy. Clearly, one field is less desirable from the point of view of cosmic scatter and by observing 3 fields to the depth of 14nJy one will be able to obtain the required statistics and some handle on cosmic scatter. However, note that 14 nJy may be reachable by HST/WFC3.

For 150W dropouts at <z>=9.8 the results are summarized below:

F150W dropouts		z=9.8	
Flux (nJy)	num obj	Npointings	Time (rel)
2.8	237.6	1.0	1.0
5	188.6	1.0	0.3
8	125.3	1.1	0.1
14	66.4	2.0	0.08

Even in this case it is beneficial to probe multiple fields to shallower depth. This particular project is unique to JWST as HST/WFC3 cannot observe beyond 1.7μm.

Let's now consider F200W dropouts at <z>=12.7.

F200W dropouts		z=12.7	
Flux (nJy)	num obj	Npointings	Time (rel)
2.8	124.6	1.1	1.1
5	111.29	1.2	0.4
8	78.45	1.7	0.2
14	42.55	3.2	0.1

Superficially it would appear that 14 nJy is adequate also for this project. However, 14nJy at z=12.7 corresponds to only 0.3 magnitudes below Lstar and such a survey would be extremely sensitive to any variation in the luminosity function parameters. Reaching down to at least one magnitude below Lstar would forces us to 7.5 nJy.

This conditions forces us to observe at least 2 pointings down to 5nJy when applied to F277W dropouts at <z>=17 and 5 pointings down to 2.8 nJy for F356W dropouts at <z>=23.4.

Summarizing a minimal implementation of this project would require:

N pointings	Filter	Flux (nJy)
5	F444W	2.8
5	F356W	2.8
5	F277W	2.8
3	F200W	5
3	F150W	7.5
3	F115W	14

Where we have assumed that exclusion of low redshift interlopers requires data of comparable depth for two bands below the break. In practice, the presence in NIRCam of two arms allowing simultaneous observations at one long and one short wavelength will give us 5 pointings at all wavelengths.