100 million years after the Big Bang
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Abstract

Dark Energy Camera on the Blanco 4 meter telescope not only has the focal plane size the 4 meters were built for, but also has excellent near infrared response. A DECam Deep Fields program is outlined, which can reach $M^*$ galaxies at redshift 6 at a wavelength of one micron. What reionized the Universe, when did globular clusters form, were there very massive stars and how did they end, and how did supermassive black holes emerge a few hundred million years after the Big Bang? These are some of the questions wide field high z surveys in the infrared will open to observational study.

1 Introduction to the EoR

Until around 400 million years after the Big Bang, the Universe was a very dark place. There were no stars, and there were no galaxies. But is that early epoch relevant to this meeting? Clearly yes, because the meeting is about wide field astronomy. Also, it’s about bulges, and so relevant unless you think our bulge is 100% pseudobulge and started forming after a billion years, rather than $10^8$ years. This question is an open one with some persuasive dynamical evidence and some persuasive stellar populations evidence, which don’t seem to agree on the nature of the bulge. Bulge classification has bifurcated (Kormendy & Kennicutt 2004). There are now classical bulges (formed at high redshift via mergers/accretion/rapid collapse of overdensity) and pseudobulges (formed by secular erosion of disks). The Local Group context is in Table 1. A review of the M31 bulge is given by Mould (2013).

| Galaxy | Bulge/disk | Ref | $M_{BH}(M_{\odot})$ | Ref |
|--------|------------|-----|---------------------|-----|
| M31    | 0.35       | WPS03 | $1.4 \times 10^8$   | B+05|
| Milky Way | 0.15     | BS80 | $3 \times 10^6$     | G+05|
| M33    | 0.03       | RV94 | <1500               | G+01|
| M32    | >1         | G01 | $3.4 \times 10^6$   | vdM+98|

This contribution focuses on classical bulges and their possible formation in the first few hundred million years. A 10 $M_{\odot}$ star forming 100 Myr after the Big Bang would be seen today with a Balmer Jump at 11µm and a Lyman limit at 2.7µm. Such early stars, if they formed at all, are JWST targets.

One of the scariest problems in probing the high redshift Universe is the rapid rise of luminosity distance with redshift. In luminosity distance the epoch of reionization (EoR) from $t = 100$ Myrs extends 80 Hubble radii. We have spent the best part of the 20th century getting a passable picture of one Hubble radius. More powerful telescopes and instruments are needed for the EoR. Here is the list rating a mention here:

- JWST: powerful, but small field, with spectroscopy paramount
- DECam: 1µ and shorter, wide field
- KDUST: 1µ < λ < 3µ, wide field, IR camera TBD, optical GPC AO published
- Las Campanas Transit Survey: wide field (§4)
Since this is CTIO’s 50th anniversary, DECam will be the focus of this contribution.

2 DECam Deep Fields

Our team has commenced work on three fields with the goal: what is doing the reionizing in the EoR? A galaxy luminosity function for deep fields is shown in Figure 1. All 3 are circumpolar.

- Chandra Deep Field South (little data)
- Prime Field (1.5 nights’ data)
- 16h field (no data)

How deep are we going? For reference, M* at z = 6 is Y = 24.0 mag. With the DECam deep fields we are not trying to compete with Hubble (e.g. Illingworth et al. 2013). In their XDF all WFC3 near-IR and optical ACS data sets have been fully combined and accurately matched, resulting in the deepest imaging ever taken at these wavelengths ranging from 29.1 to 30.3 AB mag (5σ in a 0.35” diameter aperture) in 9 filters. The DECam deep fields are competitive in volume at z = 6, not in attaining the highest redshift. An extract from our Prime Field is shown in Figure 2.

The DAOPHOT program (Stetson 1987) provides a CMD from aperture photometry (Figure 3). This photometry is calibrated with E region exposures. A provisional calibration for z and Y is provided by selecting solar type standards from the E region fields and assuming that their I-z and z-Y colors are those of a solar temperature blackbody at their effective wavelengths, with zero color corresponding to a Vega temperature blackbody. We expect to have reliable extinction coefficients after a year’s experience of DECam observing. I dropouts are z = 6 candidates, and some examples are shown in Figure 4.

2.1 Next steps DECam deep fields

We have sought further time to complete these fields and bring them to 26th magnitude.

- With about twice the signal to noise we have here we’ll have viable target lists for Gemini Flamingos redshifts
- Relevant emission lines are CIV etc all the way to [OII] λ3727
- We also seek more time to monitor the deep fields for supernovae (Whalen et al. 2013)
- use the highly efficient Lyman break galaxy monitoring technique (Cooke 2012) to find z ~ 2–4 SLSNe
- SLSNe will rise to peak from 10 – 30 days, stay there for 2 – 20 days, then decline in 20 – 100 days. In the observer frame, this is 75 – 230 day rise, 15 – 150 days near peak, and 150 – 750 day decline for objects at the mean redshift of z ~ 6.5.
- Expected rates: several per field
- Pair Instability Supernovae might be an indicator of a top heavy initial mass function at high z.

There may also be a Supermassive SN chemical signature. SMS SNe produce very little nickel-56 (Heger et al. 2012). Their chemical signature may be distinguishable from those of most very massive (i.e. 140–260 M⊙ ) Pop III explosions (PSNe), which can produce iron-group (Heger & Woosley 2002) elements. Similar to these PSNe, however, SMS SNe would not make any s-process or r-process contributions.
Figure 1: Galaxy counts at 910 nm according to existing deep fields for $z \sim 6$. AB mags at 910 nm $\approx z$ (Beckwith et al 2006).

3 KDUST, formerly PILOT

KDUST is a proposed Chinese Academy of Sciences 2.5m telescope at Dome A (http://kdust.org and Mould 2011). This facility would have significant advantages over existing 2μ survey telescopes, such as VISTA, whose survey work has been so impressive at this meeting. A science case for a very deep survey is under development and itemized in Table 2. Regarding PILOT, see Lawrence et al (2009). The Antarctic advantages are

- almost diffraction limited images
- wide field isoplanatism
- low 2μm background

This combination is only available from the Antarctic plateau, high altitude balloons and space.
Table 2: Prioritized science case for KDUST

| Priority | Field                  | Size | Compar- | K limit | Method and comments          | Vol Dist Speed | Theme |
|----------|------------------------|------|---------|---------|-----------------------------|----------------|-------|
|          |                        |      | etor    |         |                             | Gpc³           | ratio |
| Spatial  | variation galaxy LF    | B    | >HDFVLT | 25      | IAWK-I has 7.5′ field       | 1              | E     |
| Weak     | lensing cosmology       | A    | 15000   | Euclid  | GPC                         |                |       |
| IMF      | from 0.1 to 0.01 M⊙    | B    | 10 fields | VLT     | see WFIRST science case    | 1              | G     |
| Pair     | Instability SN at z > 4 | B    | 100 VLT | 26      | 3.7                         | 1              | T     |
| Kuiper   | belt census and        | C    | 20000   | LSST/PS | GPC                         |                |       |
| Cool     | white dwarfs & the      | B    | 20 fields | VLT     | 27.5 see WFIRST science    | 10*            | 1 G   |
| Planetary| transits               | A    | Kepler  | low scintillation photometry |                | T     |
| Clusters | of galaxies at z > 2   | A    | 100 SPT | 26      | followup redshifts helpful | 2.3            | E     |
| Lyman    | alpha emitters at z > 9| ?    | VLT     | narrowband |                        |                |       |
| Formation| of the first SMBH      | C    | JWST    | AGN at z > 6 |                      | E              |       |
| Formation| globular clusters at z > 6 | C  | JWST    | resolve galaxies at z > 6 |            | E     |
| Y band   | dropouts at z = 10     | B    | 100 VLT | 26      | combine w PSNe survey      | 3.9            | 1 E   |

Speed ratio is $D/\sqrt{(B)}$, assuming no fov difference, where D is telescope diameter and B is background.

GPC = Gigapixel CCD camera

“Theme” is evolving universe, dark universe, transient universe, galactic, see [http://www.caastro.org](http://www.caastro.org)

Anything VLT accessible is priority B, but that should be reassessed if 100 sq deg is really required for 3 of the projects.

Note that none of the present KDUST collaborators have ESO member VLT access.

Field is in sq deg except where stated otherwise.

We assume the KDUST IR camera has a 8.5 arcmin field.

Volume refers to a one mag range in luminosity distance.

The SDSS SN rate is 27000 SNe/yr/Gpc³ (Dilday et al 2010). Massive star SNe may be rarer than that by $(m/10)^{-4}$ simply from IMF considerations.

Units in the distance column are kpc.

WFIRST science case: Green et al (2011) and Spergel et al (2013).

4 Las Campanas Transit Survey

Off axis mirrors can be turned into transit telescopes for deep surveys to 25th mag. They can essentially be mounted in a static mirror cell and pointed at the zenith. For an f/2 GMT mirror a prime focus camera can be positioned on a 16 meter tower beside the mirror, pointing at the mirror center. The first GMT mirror is already available for this purpose. If the AAO built a static mirror cell, and Carnegie transported the mirror to Las Campanas Observatory, it could be set up beside the Magellan Telescope. Only the optics would need rudimentary protection from bad weather. Storage charges in Tucson would be avoided. The LCTS project could run the best part of a decade, repay early investment in the mirrors, build on the ANU’s SkyMapper software system and yield many petabytes of unique data. The proposal is not currently supported by the GMT Board. A design for off-axis corrective optics to flatten the focal plane has not yet been attempted.
5 Concluding thoughts

One of the most powerful facilities for EoR science will be the Square Kilometre Array (Taylor 2013). The long wavelength array to be built in Western Australia will show the first bubbles blown in the neutral hydrogen by the first stars.

We should also ask, ‘What if the EoR looks nothing like this?’ There are possibilities which have received little consideration so far, including Exactly what was happening in the dark sector during the dark ages? Is there a role for Dark stars? Or for Self Interacting Dark Matter?

The DECam EoR Deep Fields and their followup with upcoming higher resolution narrowfield facilities may shed light on

- Bulge properties of first-light galaxies
- High redshift AGN
- SuperMassive Black Hole seeds
- assembly of galaxy mass as a function of look-back time
- Pair production SNe (massive stars) at $M_K = -23$
- Young globular clusters with $10^6$ year free fall times and $M/L$ approaching $10^{-4}$

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Figure 2: A few arcmin of the 140 minute stacked Y band image of the DECam Deep Fields Prime Field direct from the NOAO pipeline.
Figure 3: CMD in the Prime field from our two 2012B nights. The red contours are star counts from the Bahcall-Soneira model of the Galaxy. The spacing is factors of $\sqrt{2}$. The green contours are galaxy counts at $z = 5.5-6.5$ from the Hubble UDF. The black contours are our counts. The dashed line is a completeness line at $z = 25$ mag. We need to go a little deeper to better overlap the high redshift galaxy contours.
Figure 4: Postage stamps of dropout candidates at 24th Y mag. The ordering l-to-r is Y, z, i, and a flux plot is shown at the right for each object. The Y mag is also shown.