INSTITUTE OF ASTRONOMY

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DAZLE NEAR IR NARROW BAND IMAGER

Concept Design Review Data Package

Science Case

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1. Introduction

DAZLE, the Dark Ages 'Z' Lyman Explorer, was funded from the PPARC Opportunity Scheme, which was set up to encourage truly innovative research, demonstrating originality and creativity. In 1999, PPARC awarded over £2 million to 11 British scientists, out of 115 applicants (see http://www.pparc.ac.uk/Nw/awards.asp). DAZLE secured the top award, amounting to one quarter of the total grant funds (£573k, later increased to £611k).

DAZLE is intended to be the first imaging instrument optimised to detect faint emission lines in between the intense lines of the OH airglow spectrum which hinders current ground-based observations. In conjunction with the improved image quality now demonstrated with new 6.5-10 m telescopes, DAZLE will be well-suited for searching for early star-forming systems located beyond the redshift range probed by current instruments. The predicted flux limit for detecting unreddened Lyman-α emission at redshifts of 10 corresponds to a star formation rate of only 1 solar mass per year and the available large format detector makes it ideal for wide field survey work.

The DAZLE proposal was written by Richard McMahon, Ian Parry and Craig Mackay from the Institute of Astronomy (IoA) at the University of Cambridge, and Joss Bland Hawthorn from the Anglo-Australian Observatory (AAO). This Science Case is extracted from section 2 of that proposal, with some minor editing to reflect the changes in the DAZLE concept since the proposal was written.

2. Science Goals

How, when and over what time scale, galaxies formed are questions at the forefront of work in both observational and theoretical cosmology. Over the last few years there has been tremendous progress in the study of galaxy formation from both an observational and a theoretical point of view with samples of star forming galaxies being detected at progressively higher redshifts; z~1 (Cowie et al, 1996); z~3 (Steidel et al, 1996); z~4.5 (Hu & McMahon, 1996) and more recently at z=5.74 (Hu, McMahon & Cowie, 1999; see Figure 2).

However tempered with the above successes, we are rapidly approaching a watershed in the study of the high redshift galaxies. This is due to the inherent difficulty of detecting faint continuum emission due to the steadily increasing brightness of the night sky as one goes to and redder wavelengths. This is shown via a flux calibrated sky spectrum in Figure 1.

Whilst the work of Madau et al. (1996) and more recent results from SCUBA (e.g. Barger et al., 1998; Hughes et al., 1998) may indicate that the bulk of the star formation may have occurred in the redshift range 0 to 5, with as little as 5% remaining to be detected before z=5, the study of the physical properties of this 5% that are crucial to continued progress in observational astrophysics since it is only in this regime can we expect to discover and open up new astrophysics in the early universe.

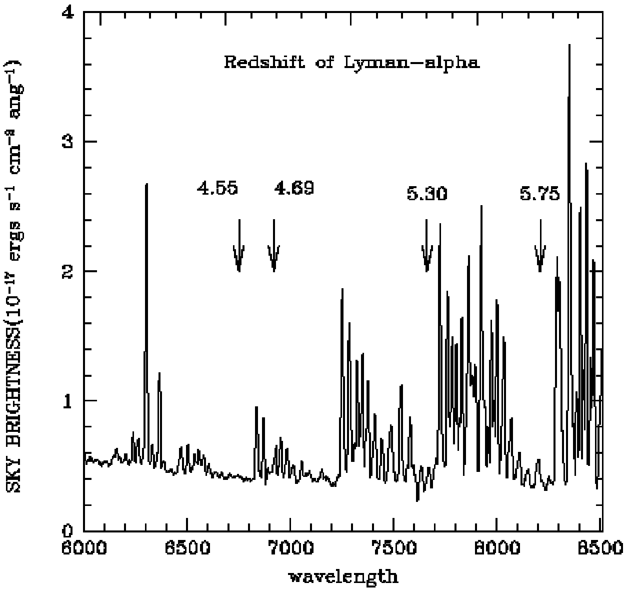

Figure 1: Flux calibrated sky surface brightness per arcsec^2 in part of optical region annotated with the observed wavelength of redshifted Lyman-α . **Note** the intense OH airglow longward of $\sim$ 7000Å. The mean sky brightness is 2-3 times brighter longward of $\sim$ 7000Å compared with wavelengths shorter than 6000Å. However, there are dark regions between the OH picket fence at 7650Å, 8200Å and 9250Å(not shown), corresponding to redshifts of z=5.30, 5.75 and 6.61 respectively. *In these regions the sky is as dark as it is at shorter wavelengths.*

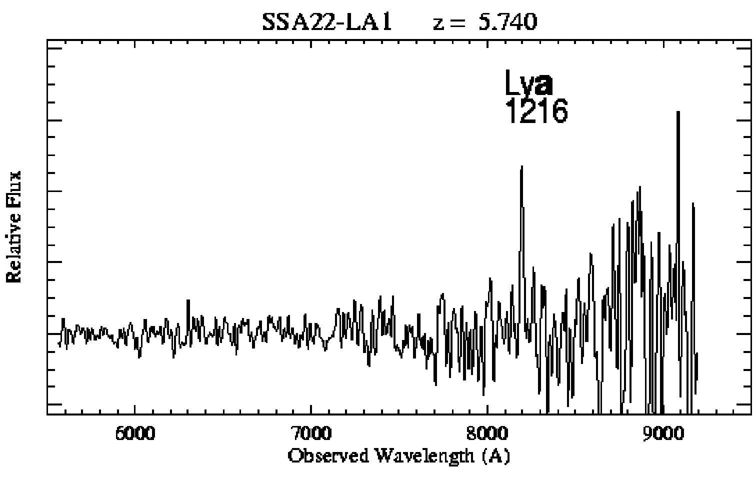

Figure 2: Spectrum of the highest redshift(z = 5.740) galaxy known(June, 1999), recently discovered by Hu, McMahon, Cowie(1999, Ap.J. submitted). A Keck-II 10,800 sec exposure using the 300ℓ /mm grating on LRIS. The line flux is 2.8 $\times 10^{-17}$ergs^{-1}cm^{-2}s^{-1}

In a similar vein, the study of galaxies at the highest redshifts possible is crucial to our understanding of how both stars and galaxies form, since it is at these epochs we expect to be able to directly observe the youngest galaxies as they assemble and form their first stars. To understand the underlying physics behind how stars and galaxies form, we must attempt to make direct observations of discrete objects at the earliest epochs. This can then be combined with the statistical measurements that missions like Planck will make of the CMB that originates from the epoch of last scattering at z~1000.

3. Lyman-α galaxies at high redshift: Proof of concept

Until recently the prevailing paradigm was that a monolithic collapse of galactic spheroids (Eggen, Lynden-Bell & Sandage 1962) with star formation rates of of 10-100 M_Θ yr^{-1} would be easily be detectable via strong Lyman-α emission produced by photoionization from the UV radiation from massive stars. However observations made by Pritchet and Djorgovski failed to detect such a phenomenon which brings the paradigm into question.

Whilst the failure of this previous work could be assigned to suppression of the Lyman-α line via resonance scattering in a dusty medium, there was mounting evidence from studies of the dust content of the gas phase in damped Lyman-α galaxies that some high redshift galaxies (i.e. DLA galaxies) were relatively dust free (e.g. Fall, Pei & McMahon 1989; Pettini et al, 1997). Thus, a few years ago McMahon and Hu (Hawaii) initiated a program to search for high redshift star-forming galaxies via the detection of Lyman-α recombination line emission line at levels ~5 times fainter than previous studies. The survey techniques uses custom-made interference filters with bandwidths of 50-100 Å.

The experiment was designed around two simple premises:

- aim for a detection limit more appropriate to slowly forming disks such as the Milky Way - i.e. 1-3 M_Θ yr^{-1}. (Kennicutt, 1983, 1994)
- search a volume within which we expect ~10 L^* galaxies, based on the local space density of L^* galaxies of $1.4 \pm 0.2 \times 10^{-2}$ h^3_{100} Mpc^{-3} (Loveday et al, 1992) where $h_{100} = H_o /(100 \ \ \mathrm{kms}^{-1} \ \ \mathrm{Mpc}^{-1})$.

This program was successful and found the first evidence for a substantial population of star forming galaxies at redshifts over four, via the confirmation of two galaxies at z=4.55 in the vicinity of the z=4.55 quasar, BR2237-0607 (Hu & McMahon 1996). The inferred star formation rates in these galaxies was ~3 M_Θ yr^{-1}. When this value is combined with the Hubble time of 7 x 10^8 yr at that redshift (H_0=100; q_0=0.5), and assuming constant star formation in the past, the total mass in stars in such galaxies is quite small at ~2 x 10^9 M_Θ when compared with a 'normal' L^* galaxy at the present epoch with ~5 x 10^{10} M_Θ in stars.

These results were thus consistent with the currently popular paradigm of a hierarchical galaxy formation where the bulk of star formation occurs in sub-L^* objects in the redshift range 1-2 rather than a monolithic collapse at z>5. Moreover Hu & McMahon had demonstrated an experimental technique which as we shall see permits the detection of galaxies back to redshifts of ~10. It was also notable that the equivalent widths of the detected emission lines are >50 Å which implies that the star-bursts are young and reddening free (Valls-Gabaud, 1993; Charlot & Fall, 1993).

More recently, Hu, McMahon & Cowie (1999) have extended the search for Lyman-α galaxies via a special purpose filter located in the OH window at 8250 Å (see Figures 1,2), with the discovery of the highest redshift galaxy currently known at z=5.74.

4. A strategy for z ≥ 7

The sustained success in detecting galaxies at higher and higher redshifts using Lyman-α makes it worthwhile to consider whether it is feasible to extend such searches beyond the limits of conventional Si based detectors used in optical astronomy and move into the near infra-red regime of HgCdTe detectors. At z>7, we are starting to probe the first 5% of the history of the Universe and it is the study of this regime that is one of the prime drivers of NGST. In a conventional, H_0=50, q_0=0.5, cosmology, the elapsed time since recombination is ~500 Myrs and comparable with the free-fall collapse time of a galactic halo. This is clearly an important epoch that should be full of observable action, where we may even detect the formation of massive globular clusters.

In the near IR, the broad band sky is 20-50 times brighter than in the optical - e.g. in the H band (λ ~ 1.6 μm) the mean sky level is 2 x 10^{-16} erg cm^{-2} s^{-1} $Å^{-1}$ $arcsec^{-2}$. This is ~50 times brighter than the sky level between the OH lines in the optical. However, as every schoolchild knows, and one can easily verify with a glance out any window on a clear day, the daytime sky is blue. One would expect to make the same observation at night and hence one would expect that in the absence of the OH lines the near IR sky could be actually darker than the optical sky. In a seminal paper, Maihara et al. (1993) showed that this may be true and found that at R=17,000 the OH lines are unresolved and moreover between the OH airglow line emission the background sky was one-fiftieth the average flux in the H band i.e. ~4 x 10^{-18} erg cm^{-2} s^{-1} $Å^{-1}$ $arcsec^{-2}$. Observations of the J band sky near 1.3 microns are shown in Figure 3.

To capitalise on this dark background, one needs to observe the sky at high spectral resolution e.g. R~2000 whereupon the strong OH lines render ~2% of the spectral region useless but the remaining 98% samples the dark sky. Fortuitously the gaps are much wider than a typical galactic sub-units (50-100 km s^{-1}) expected at z>5 (see various HDF/NGST papers; e.g. Loeb (1998), Madau (1998), Rees (1998) Steinmetz (1998)).

As an example, consider a resolution of R=2000, which is well suited for searches for high redshift galaxies since it is well matched to the typical expected line width 100 km s^{-1}. This can be achieved using a Fabry-Perot Tunable Filter (Bland-Hawthorn & Jones, 1998; Jones & Bland-Hawthorn, 1998). Figure 3 shows how R=2000 with a Fabry-Perot bandpass profile avoids the contribution from the OH lines. By observing in a R=2000 band, one obtains a two-fold sensitivity gain from working at a spectral resolution that maximises the line to continuum contrast and also minimises the effect of the OH sky emission.

Note also that the observed equivalent width (W_{obs}) scales as (1+z):

$$W_{obs} = W_{rest} \times (1+z)$$

so that assuming an unabsorbed equivalent width of 100 Å, 50% absorption due to a neutral IGM or the Lyman-α forest, at z=10 the observed equivalent width will be 550 Å. At R=2000, and λ_{obs}=1.3 microns, the bandwidth (FWHM) is 6.5 Å. Thus such a line will appear 4.8 magnitudes brighter in the on-band filter compared with the off-band or a broad band continuum image.

Similar results could be obtained using R=1000 and a more square bandpass achievable with modern interference filter technology.

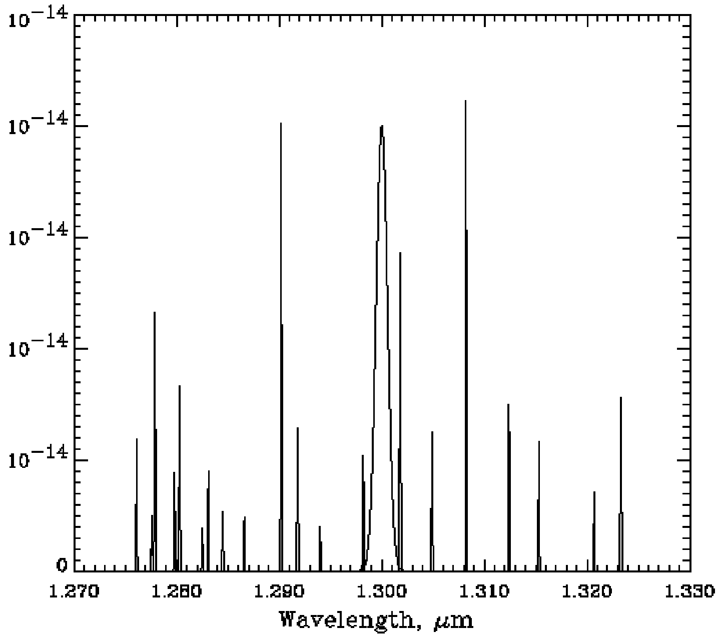

Figure 3: Expanded part of the OH airglow dominated sky around 1.3microns; cf Fig 1 from Maihara(1993, PASP, 105, 940). This would correspond to redshifted Lyman-α in the range z=9.447 to 9.940. Note the intensity of the OH lines compared with a fiducial interline continuum level(S_{sky}) of $\sim$ 7$\times10^{-18}$erg s^{-1}cm^{-2}Å^{-1}arcsec^{-2} . Note, the line intensities are total ie no bandwidth(Å^{-1}). The typical mean sky level contribution from the OH lines in the J and H windows is 2$\times10^{-16}$erg s^{-1}cm^{-2}Å^{-1}arcsec^{-2} and 4$\times10^{-16}$erg s^{-1}cm^{-2}Å^{-1}arcsec^{-2} respectively, corresponding to Vega magnitudes of 16.0 and 14.5. The expected flux($f_{Ly\alpha}$) from a galaxy with a star formation rate of $\sim$ 1 $M_\odot$ yr^{-1} at z$\sim$ 10 ie $\sim$ 2–8 $\times10^{-18}$erg s^{-1}cm^{-2} (see Figure 4). For purely illustrative purposes the sky lines are shown as unresolved at R=17,000 as from Maihara(1993). The gaussian represents a R=1000 passband(FWHM). There are few OH windows at this resolution and the expected transmission profile has wider wings than a gaussian so we propose to use R=2000 ie 150km/sec. At z=10, R=2000 corresponds to: $\Delta\lambda$ = 6.5Å ; Δ z=0.011. The integrated sky brightness(S_{sky}) from the non-OH, sky continuum, within this bandpass is given by: $f_{sky} = \Delta\lambda \times S_{sky}$ and is $\sim$ 3$\times10^{-17}$erg s^{-1}cm^{-2}arcsec^{-2} .

5. Feasibility of a survey for z=10 sub-galactic units

Figure 4 shows the expected Lyman-α line flux for a galaxy with a star formation rate of 1 $M_\Theta yr^{-1}$ for a range of cosmologies. For the purposes of discussion we use the non-zero Λ cosmology where $\Omega_o = 0.3$ and $\Lambda_o = 0.7$. Therefore the expected flux from a z=10 galaxy with a star-formation rate of 1 M_Θ yr^{-1} is ~1 x 10^{-18} erg cm^{-2} s^{-1} . For the strawman DAZLE represented in Table 1, and assuming 0.5" seeing with a detection box of 4 pixels, a 5σ detection would require an exposure of 15,000 secs or 4 hours.

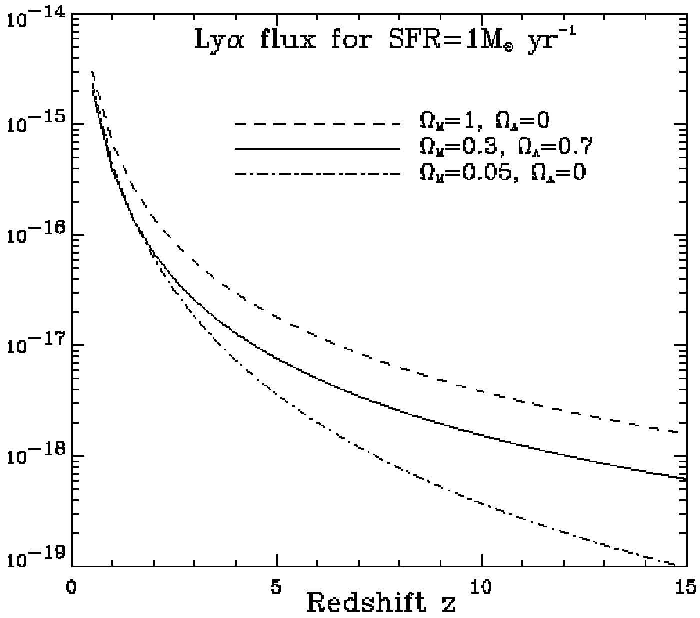

Figure 4: Expected observed Lyman-α line flux for a range of cosmologies. The solid line represents a current best bet Universe(see Perlmutter etal, 1999, ApJ, 517, 565) with $\Omega_M = 0.3$; $\Omega_\Lambda = 0.7$ The conversion from Lyman-α luminosity to star formation rate is taken from Kennicut(1983, ApJ, 272, 54) assuming a Salpeter(1955) Initial Mass Function(IMF) and is given by: $\dot{M} = L(Ly\alpha) \times 10^{-42} \mathrm{erg\ s^{-1}}\ M_\odot\ yr^{-1}$

Table 1: Strawman DAZLE

Detector Array	2048 x 2048
Spatial scale	0.25" $pixel^{-1}$
Field of view	8.5' x 8.5'
Central wavelength	1.3 µm
Spectral resolution	2000
Bandwidth (fwhm)	6.5 Å
Redshift (central)	9.69
Redshift range	0.011
Telescope Diameter	8.0 m
Sensitivity 5σ in 15,000 seconds at 1.3 microns	10^{-18} cgs

The volume surveyed in a single such exposure can be determined from Figure 6 which shows the volume for a redshift slice of dz=0.1. Assuming a redshift resolution of 0.011 and a $\Omega_o = 0.3$, $\Lambda_o = 0.7$ cosmology, the volume surveyed at z=10 is ~400 h^{-3} Mpc^3. The CDM semi-analytical models (cf Baugh, Cole, Frenk & Lacey, 1998) shown in Figure 5 predict that we would expect 1 such galaxy per 50-1000 Mpc^3. Therefore, at worst, it will take 20 nights of 8 m time to detect a sample of 10 or more galaxies and at best we shall detect many hundreds which would open up the possibility of determining the spatial correlation function at z=10. Either result would be very important and open up new parameter space in observational cosmology.

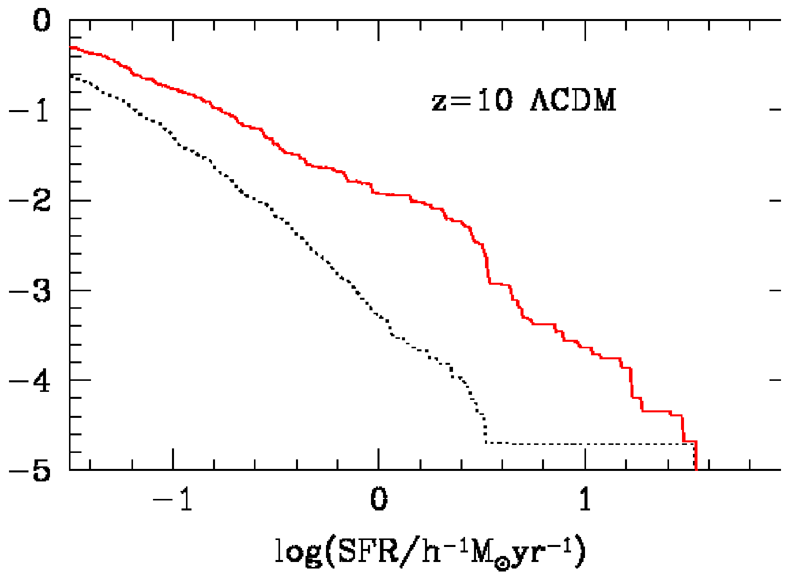

Figure 5: Predicted luminosity function for star forming proto-galactic sub-units at z=10, for $\Omega_M = 0.3$; $\Omega_\Lambda = 0.7$, by Cole,Lacey, Baugh & Frenk (Private communication, 1999). The model is consistent with all available data in the redshift range 0 to 4 including the FIR background. The black dotted line assumes galaxies have a steady star formation rate. The continuous line shows a model, in which more star formation occurs in the form of bursts, particularly at high redshifts. The bursts have a finite duration, typically a few times the dynamical time of the system. There is considerable uncertainty in many of the assumptions underlying these calculations since there are no observational constraints beyond z=4. In particular, the essential "feedback" effects that prevent the "overcooling problem"(eg. White & Rees, 1978, MNRAS, 183, 341) are very poorly understood. The models indicate that one needs to search a volume of 50–1000 Mpc^{-3} in order to detect 1 object.

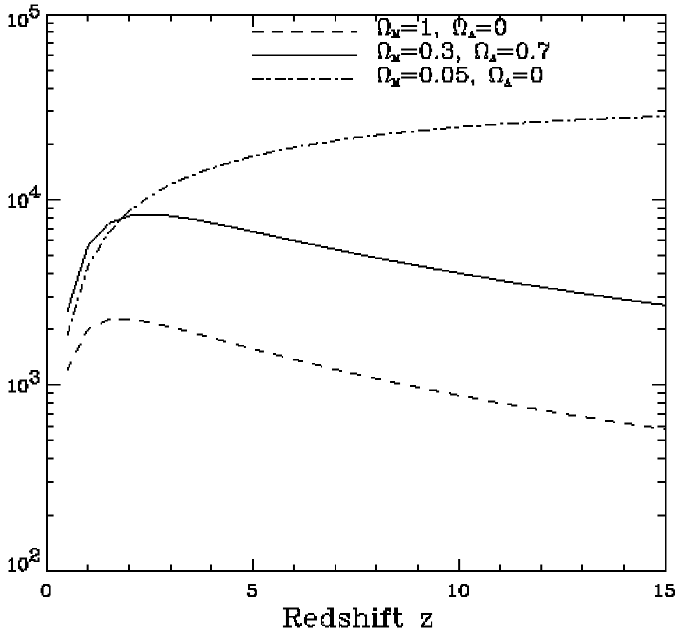

Figure 6: Comoving volume for the DAZLE survey; assuming a redshift slice dz = 0.1, and field of view 8.5'x8.5'

6. Synergy with mm surveys

It is interesting to compare the power of DAZLE with other techniques either existing or planned for the future. We consider two of the premier facilties - i.e. HST and ALMA. One of the most amazing results in recent times has been the detection of a sub-mm source population with a surface density of a ~1 min^2. However, whilst the luminosity density is quite high the space density is much lower than that of local L^* galaxies and the inferred star formation rates are 100 $M_\Theta yr^{-1}$. The key point is that if we are to study the earliest phase of galaxy formation we must make much more sensitive measurements. The mm array ALMA will permit such observations and with an assumed sensitivity of 2 m Jy $Hz^{-1/2}$ (Brown, 1999) it will still require 70 hrs to detect an object with a SFR of ~1 M_Θ yr^{-1} at z>2. However, sensitivity is not the whole story, the instantaneous field of view of an interferometer is determined by the primary beam-width of the individual dishes and in the case of a 15 m dish at 850 microns this is 15" i.e. the beam of JCMT. As we see in Table 2, the volume surveyed in a single ALMA exposure is one third that for DAZLE at a single filter value i.e. dz=0.011.

Table 2: Comparative Survey Volumes

Cosmological Parameters				Survey Volume(Mpc^3)*		
H_o*	Ω_M	Ω_Λ	Ω_{Total}	DAZLE[1]	HDF[2]	ALMA[3]
100	1.00	0.00	1.00	880	2300	40
100	0.30	0.70	1.00	6560	14000	265
100	0.05	0.00	0.05	24000	12000	925

Notes:
* Volumes scale as h^{-3} i.e. for H_o=65 the volumes are 3.64 times
1. DAZLE (Field of view: 8.5' x 8.5'; 9.95<z<10.05)
2. HDF (Field of view: 5.3 $arcmin^2$; 2.0<z<3.5)
3. ALMA (Field of view: 10.0" x 10.0"; 5<z<15)

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