# 1 The VISTA-UKIRT Ultra Deep Survey (VUUDS): Exploring the universe of galaxies at z > 6

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## 1.1 Abstract:(10 lines max)

We propose to use VISTA to obtain ultra-deep, public, images at $J$,$Y$ & $Z$ of the equatorial Subaru SXDS field currently being imaged by WFCAM as the deepest component of UKIDSS. The resulting VISTA-UKIRT Ultra Deep Survey (VUUDS) will combine the strengths of ESO's two near-infrared survey facilities to provide an unparalleled dataset enabling the first meaningful study of galaxies at $z = 6-10$. Targetted on the field with the deepest, multi-colour optical $(B, V, R, i', z')$ data, the resulting 9-colour, 1 sq. degree, fully-sampled dataset will facilitate the study of the evolution and clustering of a wide range of galaxy types over a vast range in redshift ($z \simeq 1-10$). The availability of deep mid-IR, radio and planned sub-mm (SCUBA2) imaging, further enhances the legacy value of this survey, especially for the study of the cosmic history of dust-enshrouded star-formation. By exploiting the strengths of both VISTA and WFCAM, this unique survey can be completed by 2012, ready for timely infrared spectroscopic follow-up with KMOS and JWST.

# 2 Description of the survey: (Text: 3 pages, Figures: 2 pages)

## 2.1 Scientific rationale:

### VUUDS: a uniquely powerful combination of ESO's two infrared survey resources

The UKIDSS Ultra Deep Survey (UDS) is now underway with WFCAM (Fig. 1). Designed to reach $5\sigma$ detection limits of $K(AB) = 25$; $H(AB) = 25.4$, $J(AB) = 25.9$ over 0.77 sq. degrees, it is as deep as the deepest existing near-infrared survey, and covers an area 500 times larger (Franx et al. 2003). It is the first survey of sufficient depth and size to conduct a meaningful survey of a representative volume of the high-redshift universe.

However, as we explain below, the UDS will not have sufficient depth at short near-infrared wavelengths ($Z$, $Y$ and $J$) to properly exploit its unparalleled depth at $H$ and $K$ in the search for galaxies at the highest redshifts $z > 6$. This is in part because the UDS was designed to safely image $L^*$ galaxies at more modest redshifts ($z \simeq 3 - 4$), and in part because WFCAM is most efficient at $H$ and $K$.

In this proposal we therefore propose to supplement the 300 nights of UKIRT investment in the UDS with a comparable investment of VISTA time focussed on providing ultra-deep $Z$, $Y$ and $J$-band imaging. As we explain below this will revolutionize our understanding of the universe through the crucial and as yet uncharted epoch corrresponding to $z = 6 - 10$. By imaging a contiguous field, our survey will also have enormous lasting legacy value for a wide range of studies of (especially the reddest) galaxies at more modest redshift.

Our approach brings together two key ESO resources, VISTA & UKIDSS, which have sometimes been regarded as in competition. It plays to the strengths of both facilities, and offers by far the most efficient route to completing a contiguous ultra-deep survey of the high-redshift universe in time for spectroscopic follow-up with JWST in 2012/13. This dual-facility approach is made possible by the fact that the UDS is targetted on the equatorial field of the Subaru-XMM SXDS survey, a field which offers the added attraction of the deepest available optical, multi-colour, imaging ($B, V, R, i', z'$) over an area comparable to the VISTA field-of-view (see Fig 2b).

### BACKGROUND

**The current frontier in observational cosmology: z = 7**
Several lines of evidence lead to the conclusion that the epoch corresponding to redshift $z = 7$ is a key one in the history of the universe. First, the most distant spectroscopically confirmed objects lie at $z \simeq 6.5$ (Hu et al. 2006; Fan et al. 2003). Second, quasars discovered at $z > 6$ display a complete Gunn-Peterson trough, suggesting that $z = 6 - 7$ may correspond to completion of the re-ionisation of the Universe (Djorgovski et al. 2001; Becker et al. 2001). Third, while early results from the WMAP satellite suggested that re-ionisation may have commenced much earlier (e.g. $z = 17$; Spergel et al. 2003; Kogut et al. 2003) and proceeded gradually, or in two stages, confirmation of this has yet to emerge (although the new WMAP results will now be released on 16th March). It thus remains possible that re-ionisation occurred rapidly at redshifts $z = 7 - 8$. Fourth, and key to this proposal, a single confirmed galaxy at $z = 7$ or higher redshift has yet to be found (e.g. Shioya et al. 2005). At present this failure can be attributed to the limitations of existing data, but it is in stark contrast to the discovery of several hundred convincing candidates for galaxies at $z = 5 - 6$ (e.g. Bouwens et al. 2006; Taniguchi et al. 2005). Fifth, virtually all claims for the discovery of galaxies at $z > 6.5$ have all been shown to be false or extremely unconvincing (Mobasher et al. 2005; Dunlop et al. 2006 in prep). The only convincing current candidates for galaxies in this redshift regime are 4 possible $z$-drop galaxies uncovered by Bouwens et al. (2004) in the 6 sq. arcmin covered by NICMOS on the HST within the UDF (Fig. 2a). The lack of wider-area data at the necessary depth has prevented further progress.

**Why is z ≥ 7 uncharted territory?**
The dramatic recent progress in galaxy research at redshifts $z = 5 - 6$ can be attributed to the fact that the Lyman-break selection technique (e.g. Steidel et al. 1999) can now be successfully applied out to $z \simeq 6$ using two *optical* filters to identify the existence of a strong Lyman break at $\lambda_{rest} = 1215$Å (e.g. Bunker et al. 2006). At $z \simeq 6$, candidate star-forming galaxies can be fairly straightforwardly isolated as objects with $i - z > 1.3$,

especially if a fairly blue colour can be confirmed at longer wavelengths (e.g. $z - J < 0.5$; Eyles et al. 2005). The clean selection of such objects thus requires very deep $i$-band imaging (achievable with HST over small areas), but only moderately deep $z$-band and $J$-band supporting data.

To apply the same selection technique at $z = 7 - 10$ requires the isolation of $z$-drop, $Y$-drop, and ultimately $J$-drop galaxies. This is hard for two reasons. First, even if they exist, galaxies at, say, $z \simeq 7.5$ are expected to be $\simeq 2 - 3$ times fainter than their $z = 5.5$ counterparts due to cosmological dimming. Second, applying selection criteria such as $z - J > 0.8$; $J - H < 1.2$ (as adopted by Bouwens et al. 2004) requires the combination of ultra-deep $z$-band optical imaging, with deep $J$, $H$, $K$ near-infrared imaging. At higher redshifts, ultra-deep $Y$-band and then $J$-band imaging is required to establish the existence of the Lyman break (see Figs 3 & 4). This is clearly a major challenge, and hence has only seriously been attempted over a few square arcmin (Bouwens et al. 2004; 2005). However, by combining the power of VISTA at short near-infrared wavelengths with the deep $H$ and $K$-band data now being obtained through the UKIRT UDS it will be feasible to perform this experiment over an area of $\simeq 1$ sq. degree (equivalent to $150 \times 150$ Mpc (comoving) at $z \simeq 6$). On a timescale of $\simeq 5$ years from commencement of VISTA observations, this combined dual-facility survey can, for the first time, establish the evolution of the galaxy luminosity/mass function at $z > 6$, and map the large scale structure displayed by the young galaxy population at this crucial epoch.

## 2.2 Immediate objective:

### Survey requirements – Key Science Drivers

The number density of galaxies above a given mass threshold is obviously unknown at $z > 6$. However we can calculate the survey depths required to guarantee a major scientific return by i) extrapolating from the small area surveys undertaken to date, and ii) establishing the minimum depths depth required to test the 'null hypothesis' that the galaxy luminosity function unchanged since $z = 5.5 - 6.0$ (Bouwens et al. 2006).

**z = 7:** To assess the requirements for a meaningful survey of the $z = 7$ universe we start from the only claimed successful search for $z$-drops based on HST NICMOS + ACS imaging of a 6 sq. arcmin sub-region within the Hubble UDF (Bouwens et al. 2004). Their selection process is summarized in Fig. 2a, taken from their paper. To minimize contamination with dusty red galaxies at $z = 2 - 3$ and with L,M,T stars, they sought galaxies with $(z - J) > 0.8$, $(z - J) > 0.66(J - H)$; $J - H < 1.2$ and found 4 convincing candidates, the brighter two at a depth of $J(AB) = 26.5$. We have performed a similar search using the VLT ISAAC and HST ACS data in the surrounding wider-area (130 sq. arcmin) GOODS-South field to a depth of $J(AB) = 24.3$, and found *no* comparable candidates (McLure et al. 2006, in prep.). Therefore, to ensure the detection of a significant sample of (several hundred) candidate galaxies at $z = 7 - 8$, we need to reach a detection limit $J(AB) = 26.5$ $(5\sigma)$, with sufficient accompanying depth in $H$ (and ideally also $K$) to allow the existence of blue near-ir colours to be confirmed. This will enable us to perform 'UDF science' over an area approaching a 1 sq. degree.

Second, we can estimate the expected number of $z = 7 - 8$ galaxies based on the known prevalence of $z = 5 - 6$ galaxies as a function of magnitude (Bouwens et al. 2006). To do this we note that, for objects as blue as the young galaxies uncovered as $i$-drops at $z \simeq 5.8$ (e.g. Eyles et al. 2005) the effect of cosmological dimming (a factor of $\simeq$2 in flux between $z = 6$ and $z = 7$) is partially offset (by $\simeq 0.25$ mag) by the k-correction, provided one continues to sample the spectrum longward of the Lyman break (see Fig. 4). This means that $z = 6$ $i$-drops with $z < 26$ should be visible as $z$-drops with $J < 26.5$ if moved to redshift $z = 7$. On this basis, if we assume the galaxy luminosity function to be unchanged between $z = 6$ and $z = 7$, we would predict our survey will reveal $\simeq 500$ galaxies in the redshift range $z = 7 - 8$. Obviously this calculation also demonstrates that a failure to find significant numbers of $z = 7$ galaxies in this study will have important implications. The importance of deep VISTA $J$-band imaging is therefore clear.

Working with detections at $J(AB) = 26.5$, we require to reach $z(AB) < 28$ $(2\sigma)$ to isolate $z \simeq 7$ galaxy candidates. While the Subaru SDXS data at $B, V, R, i'$ all achieve a limiting mag $> 28$, the $z'$ data fall 1 mag. short of this goal. This situation could be rectified with further Subaru observations. Here, for internal consistency, we propose to rectify it with VISTA Z-band observations (see Fig 3a & Fig 4a).

At $z = 7$ the addition of accompanying $Y$-band data to the pre-existing data at shorter and longer wavelengths is also extremely powerful. As discussed by Hewett et al. (2006) the $Y$-band holds the key to distinguishing cool stars (which peak in the $J$-band) from *unresolved* $z = 7$ objects, as it can establish that the spectrum continues to rise into the $Y$-band, before dropping rapidly at shorter wavelengths (see Figs. 3a and 4a).

**$z = 8$:** At this redshift, the power of deep $Y$-band observations becomes even clearer, as do the necessary depth requirements. As shown in Figs. 3b and 4b, $Y - J$ colour is an extremely steep function of redshift around $z = 8$. A $Y$ detection is not the issue here, as the Gunn-Peterson effect will ensure essentially zero flux shortward of $\lambda_{rest} = 1215$Å. The key point is that the $Y$-band $2\sigma$ limit must be deep enough to establish the existence of $Y$-drop galaxies with $J$-band detections at our adopted limit $J(AB) = 26.5$. This sets the required $Y$-band $2\sigma$ limit at $Y > 28$, equivalent to a $5\sigma$ detection at $Y = 27$. 150 $Y$-drop galaxies at $z = 8-9$ would be expected within VUUDS if the galaxy luminosity function was unchanged from $z = 6$.

**$z \simeq 9-10$** The search for galaxies at $z = 9-10$ must inevitably be regarded as speculative, especially given the failure of Bouwens et al. (2005) to find any convincing $J$-drop candidates in the deepest NICMOS fields down to a limit of $H(AB) < 26.5$. However, as with the other deep HST studies, the area probed in this work is very small ($\simeq 13$ sq. arcmin), and with VUUDS we have the opportunity to perform this same experiment over 200 times the area, only 0.5 mag. shallower. This search will be meaningful because 30 $J$-drop galaxies at $z = 9-10$ would be expected to the $H$-band limit of the UDS ($H(AB) < 26$) if the galaxy luminosity funtion was unchanged from $z = 6$. However identifying unambiguous $J$-drops at these depths is challenging, and a second key drawback (other than small area) of the Bouwens et al. (2005) study was the lack of supporting data at any wavelengths other than the $J$ and $H$ supplied by the NICMOS parallels. In this respect, both the deep $K$-band data from the UDS, and the deep $Y$-band image proposed here will be invaluable and crucial for confirming the reality of any potential $J$-drops in the SXDS field.

**Galaxies at $z = 5-6$** Through deep narrow-band imaging, Ouchi et al. (2005) have detected 515 potential Ly-$\alpha$ emitters in the SXDS field at $z = 5.7$, and spectroscopically confirmed 20 of them. However, less than half of the Lyman-break population can be discovered through this technique at $z \simeq 3$ (Steidel et al. 1999), and the fraction may be even smaller at the highest redshifts. We therefore have an excellent opportunity to determine this fraction within the SXDS, by completing our own multi-colour search for Lyman-break galaxies at $z = 5-6$. In addition, the narrow band technique is tightly confined to the redshift window $5.60 < z < 5.75$. A complete survey of $i'$-drop galaxies in the field is therefore required to define the galaxy mass function and to extend this study to $z = 6.5$. Third, it is also obviously important for us to isolate $z = 6$ galaxies using exactly the same techniques as described above for $z = 7$, if we are to draw robust and self-consistent conclusions about galaxy evolution between these two redshifts. The existing $i'$-band limit is $i' < 27.8$, and so $i'$-drops ($i' - Z > 1.3$) can be uncovered to a $Z$-band depth of 26.8, well-matched to the $Z$-band VISTA imaging justified above. At this depth we can expect uncover $\simeq 2000$ such galaxies within VUUDS.

**Red galaxies at $z < 5$** While the focus of this proposal has been on the highest redshifts, VUUDS will also have a major impact at more modest redshifts, especially for the reddest galaxies. As shown in Fig. 1, even from the UKIDSS early data release, it is clear there exists a large population of distant red galaxies (DRGs) with $J - K > 1.35(AB)$, and indeed many objects with $J - K \simeq 2$. This re-affirms the legacy value of VUUDS because, by improving the $J$-band depth with VISTA to $J(AB) = 26.5$ ($5\sigma$), we will be able to securely identify all DRGs down to the $K = 25$ limit. This is especially important for the obscured counterparts of sub-mm sources; several of the SHADES $850\mu m$ sources uncovered by SCUBA in the SXDS (Mortier et al. 2005) are undetected in the SXDS optical data. The SXDS field has been imaged by Spitzer as part of the SWIRE survey and, as key field in the SCUBA2 Cosmology Legacy Survey will be imaged to the confusion limit at 450 and 850 $\mu m$ in 2007/2008. VUUDS can therefore be exploited to delineate the cosmic history of dust-enshrouded star-formation.

**Large-scale structure at high** Finally, a key goal is to measure the strength of galaxy clustering, especially at the highest redshifts. Our survey will span $\simeq 150 \times 150$ Mpc (comoving) at $z = 7$, and strong clustering is expected due to the strong bias at such early times (e.g. Kashikawa et al. 2006). Our sample should be large enough, and the redshift windows narrow enough, to facilitate a good measurement of clustering strength, and to compare this with the structure already uncovered in this same field at $z = 5.7$ by Ouchi et al. (2005).

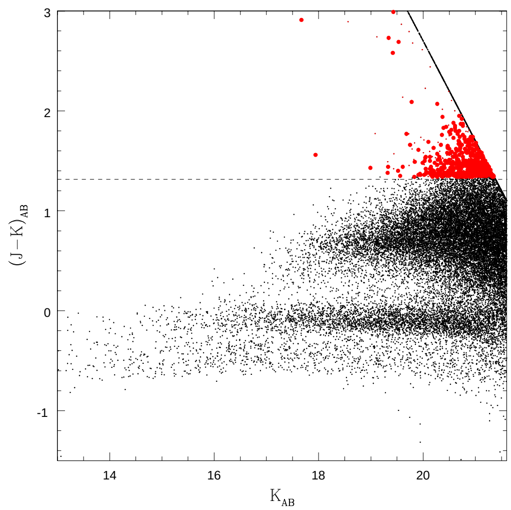


Figure 1: Early UKIDSS Science Verification Data (reaching $K(AB) = 22.5$, $J(AB) = 23.0$) has already produced the largest sample of Distant Red Galaxies (DRGs) to date, with 477 candidate galaxies showing $J - K > 1.35(AB)$ colours over the 0.8 sq degree field. At the full depth of the UKIDSS UDS ($K(AB) = 25$, $J(AB) = 26.5$) we anticipate a sample of over 6000 DRGs (based on extrapolation from the FIRES survey; Franx et al. 2003).

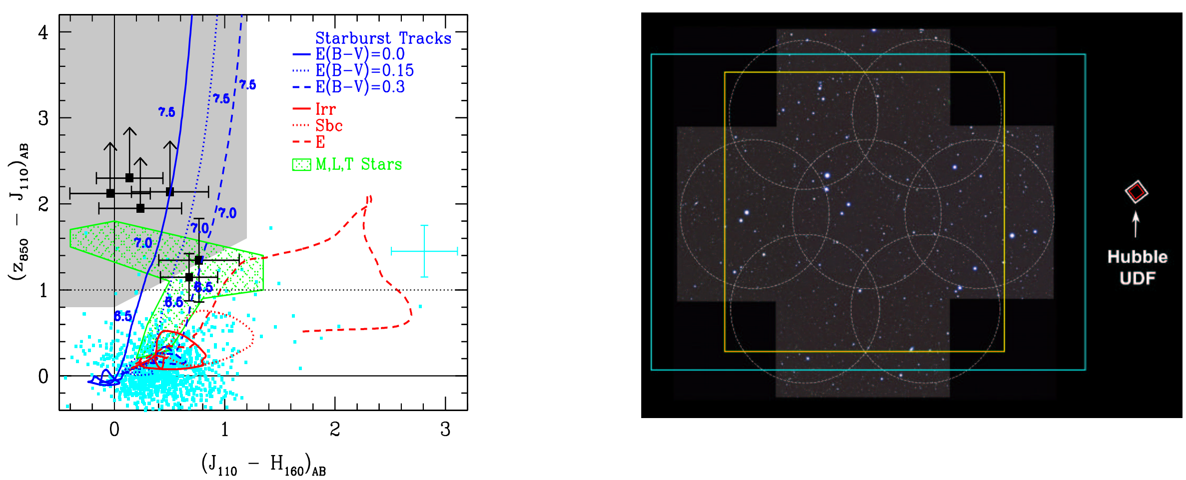


Figure 2: **LH Plot:** A diagram illustrating the selection of $z = 7 - 8$ galaxy candidates in the Hubble UDF by Bouwens et al. (2004). A colour cut $z - J > 1.5$, coupled with $J - H < 1.2$ is required to separate extreme redshift galaxies from lower-redshift interlopers and cool stars. **RH plot:** Diagram showing our proposed VISTA imaging (pale blue rectangle) and the WFCAM UDS pointing (yellow square) overlaid on the existing SXDS optical image. The dashed circles indicate the XMM coverage of the field. Also shown, for comparison, is the size of the ACS and NICMOS coverage of the UDF (small white and red squares respectively).

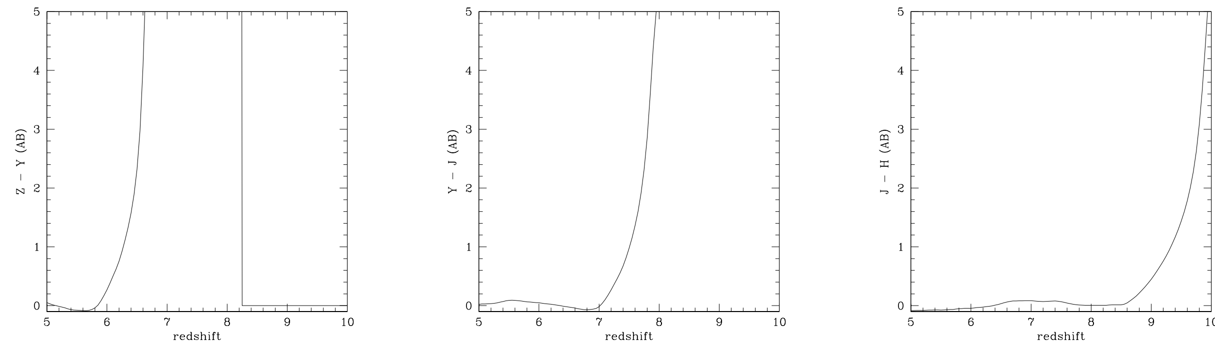


Figure 3: The impact of redshift on the observed $Z-Y$, $Y-J$ and $J-H$ colour of a galaxy with an SED comparable to confirmed $z = 5.5 - 6.0$ Lyman-break galaxies such as SMB03#1 (Eyles et al. 2005). The plots show the impact on the observed near-infrared colours as the template galaxy is moved from redshift $z = 5$ out to $z = 10$ (note that by $z > 8.2$ the $Z-Y$ colour becomes essentially meaningless as both the $Z$ and $Y$ passbands are expected to be devoid of flux.)

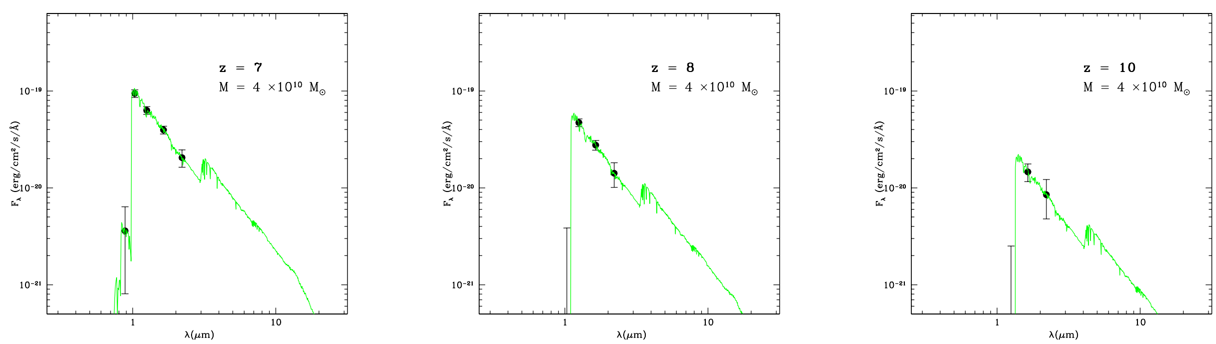


Figure 4: **LH Plot:** a simulation of the observed SED expected from a moderate-mass $z \simeq 6$ galaxy such as SMB03#3 (Eyles et al. 2005) if placed at $z = 7$, $z = 8$ and $z = 10$. The error bars shown on the photometric points correspond to the depth of the VISTA $Z$, $Y$ and $J$-band imaging proposed here, and final design depths at $H$ and $K$ of the UKIRT UDS.

**References**

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# 3 Are there ongoing or planned similar surveys? How will the proposed survey differ from those? (1 page max)

The UKIRT UKIDSS UDS is the only ultra-deep near-infrared currently underway over a scale approaching 1 square degree. Through this VISTA proposal we aim to further strengthen this survey, in effect producing a unique dataset for the ESO community which will remain unrivalled for many years to come (we note that the current Canadian survey plan with WIRCAM on the CFHT is to undertake a substantially shallower survey, more comparable in depth and area to the UKIDSS DXS, or the VIDEO survey currently being proposed for VISTA by Jarvis et al.).

We are aware that at least one alternative ultra-deep survey is being proposed for VISTA in this current public survey round, for the COSMOS field (P.I. Franx), and possibly also for Chandra Deep Field South (CDFS). We also note that at least one of these surveys is sparse sampled (i.e. based on a single paw-print).

The survey proposed here differs from any of these potential alternative strategies in several crucial ways.

**1.** The VUUDS field provides the deepest available optical data over a field of $\simeq 1$ sq degree, with the SXDS Subaru Suprime-Cam imaging reaching $2\sigma$ AB-magnitude limits of $B = 29.1$, $V = 28.2$, $R = 28.2$, $i' = 28.1$, $z' = 27.1$ within 2-arcsec diameter apertures. This is of enormous value in confirming the reality of $i$-drop and $z$-drop candidates, and substantially enhances the legacy value of the survey. In this respect the CDFS is not really competitive because the GOODS ACS data, which reach comparable (or in fact slightly shallower, except in the $z'$-band) depths only extend over 130 sq. arcmin. COSMOS is certainly better served. However, the unique feature of COSMOS, namely the F814W single-orbit ACS imaging, is of little relevance for the study of galaxies at $z > 4$, as it delivers meaningful magnitude limits a full magnitude shallower than the SXDS Subaru imaging at $i'$-band (when ultilised with 1-2 arcsec aperture magnitudes for combination with ground-based data). COSMOS also has Subaru Suprime-Cam imaging, but typically 0.5 magnitudes shallower than the SXDS.

**2.** The VUUDS field is already the site of the UKIRT UKIDSS UDS. Therefore deep near-infrared imaging is already well underway, and a complete $Z, Y, J, H, K$ survey to the depths of relevance can be completed far more efficiently than by starting afresh in a new field of no obvious additional merit. Not only will WFCAM provide 2 years of data in advance of commencement of the VISTA observations, but if the VISTA component is approved, the WFCAM strategy can become focussed on the deep $H$-band and $K$-band imaging after 2007. This will accelerate the survey, delivering $z > 6$ candidates for timely follow-up with, for example, KMOS in 2011/12. It will also ultimately allow the UKIRT UDS to deliver increased depth at $H$ and $K$, due to the availability of time originally scheduled for $J$-band beyond 2007.

**3.** Due to the fact the $H$ and $K$ band data are being supplied by UKIRT, we can afford to image a contiguous area at $Z, Y, J$ with VISTA to the required depth. This strategy has many benefits over the alternative of a single paw-print, including i) improved flat-fielding and more even coverage (the VISTA detectors are not very uniform and contain a lot of defects), ii) the ability to cross-calibrate photometry from overlap regions (the instrument was designed to be used in this way), iii) much improved ability to search for structures on scales of $\sim 10$ arcmin, iv) much better overlap with existing multi-frequency data for a wide range of science goals, v) a simplified window function for clustering analysis, and vi) obviously improved legacy value.

In summary, there are sound arguments for performing more than one ultradeep survey with VISTA (and the COSMOS and VUUDS fields are well separated in RA). However, whatever the final portfolio of surveys, we think it is clear that VUUDS is undeniably the most compelling ultra-deep survey. Targetted in the field with the best supporting optical data, and building on the 2-year head start provided by the UKIDSS UDS, VUUDS can rapidly provide a unique resource for the ESO community to undertake the first meaningful study of the universe of galaxies at $z = 6 - 10$.

# 4 Observing strategy: (1 page max)

The observing strategy for VUUDS is extremely straightforward. We intend to observe one filled 1.5 sq.deg VISTA tile centred on the SXDS/UDS field (RA 02:18:00.00, Dec −05:00:00.00) in each of the $Z, Y \& J$ filters.

## 4.1 Seeing constraints and image quality

In order to match the image quality of the supporting data in the SXDS/UDS field (optical from Subaru, $H + K$ from UKIRT) we require the FWHM of the final stacked mosaics to be $\simeq 0.8$ arcsec. Consequently, we require a seeing constraint of $< 0.8$ arcsec in all filters, and plan to observe using a 5-point jitter pattern and 2x2 microstepping to improve the sampling of the instrumental point-spread function.

## 4.2 Observing blocks

For all three filters, using on-chip integration times (DITs) in the background-limited régime produces OBs which exceed the one hour maximum length, if each OB is designed to fill a VISTA tile (Npaw=6). Consequently, we intend to adopt individual OBs which observe half of one complete tile (Npaw=3) within the OB limit of one hour (including overheads). Ideally, such half-tile OBs would be linked such that they were observed closely in time, although this is not strictly essential.

## 4.3 Combining facilities

By the time VISTA surveys commence in 2007, WFCAM will have completed a full 2 years of observations within the UDS. $J$-band observations form an important part of the initial 2-year strategy, but the main focus is on deep $K$-band. If the VISTA component of this survey is supported, we would propose, from late 2007, to direct the UKIRT observations towards $K$ and $H$ *only*, while VISTA concentrates on the shorter wavelengths.

We stress that the $J$-band depth proposed with VISTA is deeper than planned with WFCAM over 7 years. Nevertheless the time saving within the WFCAM component will be substantial because $\simeq 50\%$ of the $\simeq 2000$ hours in the UDS 7 year plan has been scheduled for $J$-band. Thus, not only will VISTA provide $Z$, $Y$ and deeper $J$-band data than ever envisaged for the UDS, it will also release WFCAM to concentrate on improving the depth at $H$ and $K$ as rapidly as possible (and indeed potentially enhancing the depth of the survey at these longer wavelengths).

# 5 Estimated observing time:

As justified in the science case, we require final AB depths of $Z = 27.0$, $Y = 27.0$ and $J = 26.5$ ($5\sigma$, within a 2 arcsec diameter aperture). Assuming median seeing of 0.8 arcsec, and default settings for sky brightness and airmass, the VISTA exposure time calculator predicts the following exposure times per pixel:

| Filter | Exp.Time (hours) | Med. Seeing arcsec | $5\sigma$ detection (AB, $2''$ diam) | $5\sigma$ detection (Vega, $2''$ diam) |
|---|---|---|---|---|
| Z | 205 | 0.8 | 27.0 | 26.5 |
| Y | 460 | 0.8 | 27.0 | 26.4 |
| J | 305 | 0.8 | 26.5 | 25.7 |

## 5.1 Time justification: (1 page max)

All of the following calculations are based on the predictions of the VISTA exposure time calculator, and assume a median seeing of 0.8 arcsec, an airmass of 1.2 and default values for sky brightness in all three filters:

For the $Z-$band observations we will use a 5-point jitter pattern, 2x2 micro-stepping and DIT=45 s with NDIT=1. Using this set-up, a single exposure loop (Npaw=6) takes 6794 s, and will reach a $5\sigma$ detection limit in a 2 arcsec diameter aperture of $Z = 23.7$ (AB). Therefore, to reach our desired final depth of $Z = 27.0$(AB) we require 400 exposure loops which, including overheads and assuming 9 hours per night, takes a total of 82 nights (86.5% observing efficiency). In order to facilitate OBs which are less than one hour in length, we intend to split the $Z-$band observations into OBs which observe a half-tile (Npaw=3).

For the $Y-$band observations we will use a 5-point jitter pattern, 2x2 micro-stepping and DIT=45 s with NDIT=1. Using this set-up, a single exposure loop (Npaw=6) takes 6794 s, and will reach a $5\sigma$ detection limit in a 2 arcsec diameter aperture of $Y = 23.3$ (AB). Therefore, to reach our desired final depth of $Y = 27.0$(AB) we require 950 exposure loops which, including overheads and assuming 9 hours per night, takes a total of 183 nights (86.5% observing efficiency). In order to facilitate OBs which are less than one hour in length, we intend to split the $Y-$band observations into OBs which observe a half-tile (Npaw=3).

For the $J-$band observations we will use a 5-point jitter pattern, 2x2 micro-stepping and DIT=20 s with NDIT=2. Using this set-up, a single exposure loop (Npaw=6) takes 6314 s, and will reach a $5\sigma$ detection limit in a 2 arcsec diameter aperture of $J = 22.9$ (AB). Therefore, to reach our desired final depth of $J = 26.5$(AB) we require 725 exposure loops which, including overheads and assuming 9 hours per night, takes a total of 129 nights (83.3% observing efficiency). In order to facilitate OBs which are less than one hour in length, we intend to split the $J-$band observations into OBs which observe a half-tile (Npaw=3).

In summary:

| Filter | Exp.Time | seeing |
|---|---|---|
| Z | 82 nights | 0.8 |
| Y | 183 nights | 0.8 |
| J | 129 nights | 0.8 |
| **Total** | **394 nights** | |

or, if Z replaced by $z'$-band observations at Subaru:

| Filter | Exp.Time | seeing |
|---|---|---|
| Y | 183 nights | 0.8 |
| J | 129 nights | 0.8 |
| **Total** | **312 nights** | |

# 6 Data management plan: (3 pages max)

## 6.1 Key roles of team members:

| Name | Function | Affiliation | Country |
|---|---|---|---|
| J. Dunlop | PI & OB Preparation | Edinburgh | UK |
| O. Almaini | OB Preparation | Nottingham | UK |
| M. Jarvis | OB Preparation | Oxford | UK |
| M. Page | OB Preparation | MSSL | UK |
| CASU | Pipeline processing | Cambridge | UK |
| CASU | Data Quality Control-I | Cambridge | UK |
| J. Emerson | VDFS Coordinator | QMUL | UK |
| WFAU | Science Archive | Edinburgh | UK |
| WFAU | Data Quality Control-II | Edinburgh | UK |
| N. Walton | VO Standards | Cambridge | UK |
| | **VUUDS Specific Tasks** | | |
| R. McLure | Data Quality Control-III | Edinburgh | UK |
| I. Smail | Data Quality Control-III | Durham | UK |
| S. Foucaud / C. Concelice | Data Quality Control-III | Nottingham | UK |
| J. Bergeron/ A. Omont | Data Quality Control-III | IAP | F |
| O. Almaini | Frame Stack | Nottingham | UK |
| S. Serjeant / S. Eales | Frame Stack | OU/Cardiff | UK |
| P. Hirst | Frame Stack | JAC | USA |
| R. McLure, M. Cirasuolo | Final Catalogue Production | Edinburgh | UK |
| I. Smail, A. Edge | Final Catalogue Production | Durham | UK |
| | **Other data products** | | |
| C. Simpson | Subaru-VISTA-WFCAM catalogue production | LJMU | UK |
| M. Franx | Subaru-VISTA-WFCAM catalogue production | Leiden | NL |
| M. Bremer | Subaru-VISTA-WFCAM catalogue production | Bristol | UK |
| R. Ivison / S. Rawlings | VUUDS-VLA-GMRT catalogue production | UK ATC/Oxford | UK |
| P. Best / G. Cotter | VUUDS-LOFAR strategy | Edinburgh/Oxford | UK |
| S. Serjeant | VUUDS-SWIRE/Herschel catalogue production | OU | UK |
| M. Watson / P. O'Brien | VUUDS-XMM catalogue production | Leicester | UK |
| G. Dalton | VUUDS-FMOS strategy | Oxford | UK |
| K. Sekiguchi | VUUDS-MOIRCS strategy | Subaru | Jap |
| A. Cimatti | VUUDS-VIMOS/FORS2 strategy | Arcetri | I |
| J. Dunlop | VUUDS-SCUBA2 strategy | Edinburgh | UK |

## 6.2 Detailed responsibilities of the team:

We will use the VISTA Data Flow System (VDFS; Emerson et al. 2004, Irwin et al. 2004, Hambly et al. 2004) for all aspects of data management, including: pipeline processing and management; delivery of agreed data products to the ESO Science Archive; production of a purpose-built IVOA compliant science archive with advanced datamining services; enhanced data products including federation of VISTA survey products with SDSS survey products. Standardised agreed data products produced by VDFS will be delivered to ESO, with a copy remaining at the point of origin (in the Science Archive in Edinburgh).

The VDFS is a collaboration between the UK Wide Field Astronomy Units at Edinburgh (WFAU) and Cambridge (CASU) coordinated by the VISTA PI (QMUL) and funded for VISTA by PPARC. The VDFS is a working systems-engineered system that is already being successfully employed for the UKIRT WFCAM surveys as a test bed for the VISTA infrared surveys, and which is sufficiently flexible as to be applicable to any imaging survey project requiring an end-to-end (instrument to end-user) data management system.

The observation planning team will be led by the PI (Dunlop) and include members of the VUUDS team from Edinburgh (Dunlop, McLure), Nottingham (Almaini, Foucaud), Durham (Smail, Edge) and MSSL (Page). They are responsible for generating the OBs using the Survey Area Definition Tool and P2PP and for revising these and monitoring survey progress using a local Data Quality Control database as necessary.

Experience shows that the a full scientific validation is only possible when people start trying to do science with the data. Thus we will also have a number of people from Edinburgh, Nottingham, Durham, Oxford, IAP and the OU carrying out the first checks on the pipeline reduced data.

## 6.3 Data reduction plan:

The data reduction will be carried out using the VDFS, operated by the VDFS team, and augmented by Dunlop, Smail, McLure, Serjeant, Foucaud and Cimatti, especially for product definition and product Quality Control.

### 6.3.1 Pipeline processing

The Cambridge Astronomy Survey Unit (CASU) are responsible for the VDFS pipeline processing component which has been designed for VISTA and scientifically verified by processing wide field mosaic imaging data from UKIRT's NIR mosaic camera WFCAM and is now routinely being used to process data from the WFCAM at a rate of up to 250GB/night. It has also been used to process ESO ISAAC data e.g. the FIRES survey data and a range of CCD mosaic cameras.

The pipeline includes the following processing steps but is a modular design so that extra steps are easily added. All the steps will have been tested on a range of input VISTA datasets. and include: instrumental signature removal – bias, non-linearity, dark, flat, fringe, cross-talk; sky background tracking and removal during image stacking – possible need to also remove other 2D background variations from imperfect multi-sector operation of detectors; define and produce a strategy for dealing with image persistence from preceding exposures; combine frames if part of an observed dither sequence or tile pattern; consistent internal photometric calibration to put observations on an approximately uniform system; basic catalogue generation including astrometric, photometric, shape and Data Quality Control (DQC) information; final astrometric calibration from the catalogue with an appropriate and World Coordinate System (WCS) in all FITS headers; basic photometric calibration from catalogue using suitable pre-selected standard areas covering entire field-of-view to monitor and control systematics; each frame and catalogue supplied with provisional calibration information and overall morphological classification embedded in FITS files; propagation of error arrays and use of confidence maps; realistic errors on selected derived parameters; nightly extinction measurements in relevant passbands; pipeline software version control – version used recorded in FITS header; processing history including calibration files recorded in FITS header

### 6.3.2 Science archiving

The concept of the science archive (SA, Hambly et al. 2004 and references therein) is key to the successful exploitation of wide field imaging survey datasets. The SA ingests the products of pipeline processing (instrumentally corrected images, derived source catalogues, and all associated metadata) into a database and then goes on to curate them to produce enhanced database-driven products. In the VDFS science archive, the curation process includes, but is not limited to, the following: individual passband frame association; source association to provide multi-colour, multi-epoch source lists; global photometric calibration; enhanced astrometry including derivation of stellar proper motions; consistent list-driven photometry across sets of frames in the same area; cross-association with external catalogues; and generation of new image products, e.g. stacks, mosaics and difference images etc., all according to prescriptions set up for a given survey programme. All these features are available in the context of a continually updating survey dataset from which periodic releases (as required by the community) can be made.

Moreover, end-user interfaces were catered for from the beginning in the VDFS design process, and the philosophy has always been to provide both simple and sophisticated interfaces for the data. The former is achieved via simple point-and-click web forms, while the latter is achieved via exposing the full power of the DBMS back-end to the user. To that end, full access to Structure Query Language and the relational organisation of all data are given to the user.

We have developed a generalised relational model for survey catalogue data in the VDFS. The key features to note are the normalised design with merged multi-waveband catalogue data (the table of most use for scientific queries) being part of a related set of tables that allow the user to track right back to the individual source images if they require to do so; and also that the merged source tables (as derived either from individually analysed images, or consistently across the full passband set available in any one field) are seamless, and present the user with a generally applicable science-ready dataset. Similar relational models describe the organisation of all data in the science archive (image, catalogue, calibration metadata, etc.) - see Hambly et al. (2004) and references therein. The relational model is applicable to any imaging survey project, and provides an easy-to-use science-ready data resource for the community scientist in the form of a seamless, merged multi-colour multi-epoch source catalogue. The science archive has a high-speed query interface, links to analysis tools such as TopCat, and advanced new VO services such as MySpace.

Data products are being successfully ingested into the WFCAM Science Archive (WSA) in Edinburgh, with the EDR in Feb 2006, and the WSA concept was also demonstrated on the SuperCOSMOS Science Archive (SSA). *http://surveys.roe.ac.uk/ssa/*

The multi-wavelength stacked catalogues will also be made available by the VUUDS team led by Dunlop.

## 6.4 Expected data products:

Instrumentally corrected frames (pawprints, tiles etc) along with header descriptors propagated from the instrument and processing steps (science frames and calibration frames)
Statistical confidence maps for each frame
Stacked data for dithered observations
Derived catalogues (source detections from science frames with standard isophotal parameters, model profile fitted parameters, image classification, etc.)
Data Quality Control database
Database-driven image products (stacks, mosaics, difference images, image cut-outs)
Frame associations yielding a survey field system; seamless, merged, multi-colour, multi-epoch source catalogues with global photometric calibration, proper motions (where appropriate)
Source remeasurement parameters from consistent list-driven photometry across all bands in any one field

## 6.5 General schedule of the project:

T0: Start of observations
T0+8months; Release of science products from first month of survey observations
T0+14month; Release of science products from first 6 months of survey observations
Thereafter we hope that science products can be released within 6 months of raw data arriving in the UK.
Optional reprocessing of data based on improved knowledge of instrument would also be considered

References:
Emerson J.P. et al., 2004, Proc. SPIE, vol. 5493, 401
Hambly N.C. et al., 2004, Proc. SPIE, vol. 5493, 423
Irwin M.J. et al., 2004, Proc. SPIE, vol. 5493, 411

# 7 Envisaged follow-up: (1 page max)

**Spectroscopic follow-up**

AAT 2dF spectra have been obtained for all the bright ($R < 20.5$) sources in the VUUDS field, and several masks of deep VLT VIMOS spectra have been taken (targetted primarily on X-ray, radio and sub-mm sources), with the data currently being reduced. For the red galaxies with $R < 25$ we aim to obtain deep spectra with FORS2 commencing in 2006. However, for the extreme redshift galaxies which are the focus of this proposal, it is clearly deep, near-infrared spectroscopy which is of most importance. Fortunately we are now entering the era of multi-object, near-infrared spectrographs on 8-m class telescopes with MOIRCS (Subaru), Flamingos-2 (Gemini) and FMOS (Subaru) all scheduled to be commissioned this year. Because VUUDS is targetted on an equatorial field it can be observed from both Hawaii and Chile, and Co-Is on this proposal provide access to all of these facilities. Ultimately VUUDS is expected to provide a short-list of potential very high-redshift candidates for deep near-infrared spectroscopy with KMOS on VLT, and NIRSpec on JWST.

**Radio and sub-mm follow-up**

The entire VUUDS field is covered to appropriately deep flux density limits at 240, 610 and 1400 MHz. The 1400-MHz observations were undertaken by Ivison, Simpson and Rawlings using the VLA during 2003. The data comprise a mixture of data from the A, B and C configurations with a 9:3:1 ratio of recorded visibilities to ensure sensitivity on essentially all angular scales, with the data evenly distributed in three pointings separated by 15 arcmin to minimise bandwidth smearing. The resulting noise level is around $6\,\mu$Jy beam$^{-1}$ with a 1.7-arcsec synthesised beam (FWHM). To supplement the 1400-MHz data, 240- and 610-MHz data were obtained in 2006 February from the GMRT, evenly distributed over the same three pointings, with the final image reaching unprecedented noise levels at these frequencies ($20\,\mu$Jy beam$^{-1}$ r.m.s. at 610 MHz, i.e. the confusion limit for a $\sim5''$ synthesised beam).

At sub-mm wavelengths, the central 500 sq arcmin of the VUUDS field has already been imaged at 850$\mu m$ by SCUBA as part of the SHADES survey (Mortier et al. 2005), yielding $\simeq 60$ sources with $S_{850} > 7$mJy. It is planned that the entire VUUDS field will be imaged by SCUBA2 to the confusion limit at both 450$\mu m$ and 850$\mu m$ as part of the SCUBA Cosmology Legacy Survey (P.I. Dunlop). These observations should be complete by 2011, a timescale well matched to that proposed here for the completion of VUUDS.

**Spitzer and Herschel mid/far-infrared follow-up**

The VUUDS field has already been observed with IRAC and MIPS on Spitzer as part of the SWIRE survey. The SWIRE survey is now complete (final public data release July 2006). A public proposal for deeper IRAC data in the field was submitted in Feb 2006 (P.I. Franx). The field will also be observed with Herschel, by the Open Time Consortium, providing confusion-limited mid-to-far infrared photometry.

**X-ray follow-up**

A 100-ksec XMM image of the VUUDS field has already been taken (P.I. Watson) as illustrated in Fig. 2b. Still deeper XMM and Chandra imaging is planned in support of VUUDS.

# 8 Other remarks, if any: (1 page max)