

1 Title: The VISTA Hemisphere Survey(VHS)

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1.1 Abstract:(10 lines max)

We propose to carry out a panoramic Infra-Red survey in Z, Y, J and K_s over the whole southern celestial hemisphere ($\sim 20,000\text{deg}^2$) to a depth ~ 4 magnitudes fainter than 2MASS/DENIS. We have made the scientific case for this survey in terms of both legacy value and medium-term science, which promises very large returns. However, we suspect even these will be dwarfed by the science from projects we cannot yet anticipate. The medium term scientific goals include: a huge expansion in our knowledge of the lowest-mass stars and possibly the discovery of the nearest star to the Solar System; knowledge of large-scale structure out to $z \simeq 1$ and measuring the properties of Dark Energy; discovery of the first quasar with $z > 7$ and determining the baryonic content of the Universe during the Era of Reionization; deciphering the merger history and Genesis of our own Galaxy. In addition the survey will provide essential support for the ESA Cornerstone missions; XMM-Newton, Planck, Herschel and GAIA.

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

2.1 Scientific rationale:

The primary aim of the VISTA Hemisphere Survey(VHS) is to provide a fundamental resource for European astronomers, which will be a springboard for research for many years to come. VISTA is the very first facility to make a deep IR sky survey plausible. This is therefore a key 21st century opportunity for astronomy. However, we can also anticipate several strands of direct scientific benefit, which we have used to determine the flux limits of the VHS. The sensitivity of the VHS in the proposed survey bands(Z, Y, J and K_s) are given in Table 1.

We include the sensitivity limits for H but currently consider the case for the inclusion of H a lower priority except in the case of specific high value targets. We have also considered the case for a 2nd epoch in one or more wavebands to provide proper motions. The case for the inclusion of BOTH Z and Y is driven primarily

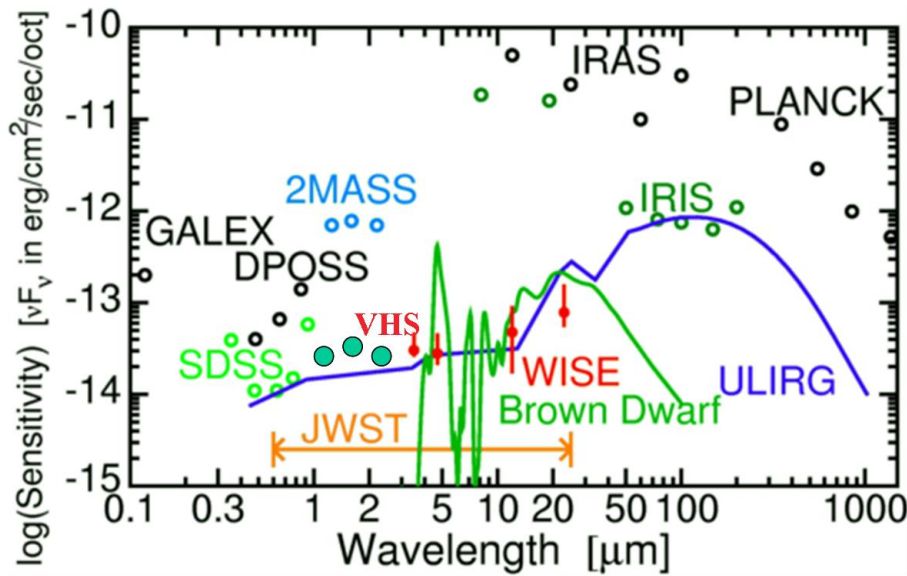


Figure 1: Sensitivity of various existing and planned sky surveys versus wavelength. This figure has been adapted (with permission) from that on the WISE web page at <http://www.astro.ucla.edu/~wright/WISE/>. Note that "IRIS" here refers to AKARI, i.e. Astro-F, and are not the most up to date sensitivity figures. The vertical axis is νF_ν in units of energy per second per $d(\ln)$. The Brown dwarf is a model from Burrows et al of a 200K BD at a distance of 1.3 pc. VHS limits are large green circles.

by the high redshift quasar and low mass stars science. We suggest that a smaller area ($\sim 7500\text{deg}^2$) could be initially surveyed with these filters.

2.1.1 The case for a 21st century IR sky atlas

Sky surveys are the core of astronomy. They represent a basic resource, are the main engine of discovery, are an efficient use of resources, and provide the very large statistical samples needed to address many problems. These strengths apply to any large survey project, but apply *a fortiori* to a **complete sky atlas**, and especially so as the age of the Virtual Observatory becomes a reality. The survey we propose has wider wavelength coverage than 2MASS and is also fifty times deeper. It is therefore the true IR equivalent of the historic Palomar-UK-ESO Schmidt visible light sky surveys of the second half of the 20th century, and we would expect it, like those surveys, to be a fundamental reference source for several decades. The following are the general advantages of a complete hemisphere survey :

(i) Any astronomical object or event found elsewhere can be searched for in the IR, regardless of location. (ii) In Euclidean space, time spent on increasing area increases *sample volume* much faster than spending time going deeper. The same argument applies to large statistical samples. (iii) Some rare but very important objects (eg $z=7$ QSOs, very nearby free floating planetary mass objects) may be present in only a handful of cases over the whole sky (iv) The chance of completely serendipitous discoveries is maximised, as is the realisation of new classes of object. (v) Some key scientific goals require intrinsically large angular area. The first key example is the structure of the Milky Way; the second is the large scale structure of the Universe, where we wish to minimise "cosmic shot noise". (vi) The same dataset can be used many times for many different projects. This is true at the design stage, as we demonstrate in the following sections, but will continue to be true for many years. This advantage of surveys in general is maximised for a hemispheric survey.

A true IR sky survey is clearly very desirable, but is plausible? The minimum sensible depth is essentially set by when overheads began to dominate. For a combination of overheads and science reasons we adopted four

bands with the baseline sensitivity limits given in Table 1. The 20,000 square degree VISTA hemisphere survey to these depths can be completed within seven years on the schedule given in Table 3. This is ambitious but not unreasonable. This is therefore the first opportunity in history to construct a genuine deep IR sky atlas.

2.2 Selected Science Highlights

We highlight some of the key science goals that highlight the power of the VHS:

1. Legacy value, serendipity, curiosity and new classes of object, 21st century Infra-Red equivalent of the Palomar-UK-ESO Schmidt Surveys.
2. Knowledge of large-scale structure out to $z \simeq 1$ and measuring the properties of dark Energy via the Integrated Sachs-Wolfe effect.
3. Galactic structure and Galaxy Genesis; deciphering the accretion and formation history of our Galaxy.
4. The nearest star and lowest mass stars; the bottom of the stellar main sequence and the brown dwarf planet transition zone
5. Physics of the epoch of Reionization; Luminous high redshift($z > 6.5$) quasars as probes of the epoch of reionization and the baryonic content of the high redshift Universe; The first $z > 7$ quasar.
6. Galactic Cluster Survey; Find planetary-mass objects with masses as little as a few Jupiter masses to investigate the fragmentation limit problem, a major unanswered question in star formation.
7. Synergy with VST Atlas, AKARI(Astro-F), WISE, SDSS-II, eROSITA
8. Supporting the ESA cornerstones, XMM-Newton, Planck, Herschel, and GAIA.

2.2.1 Legacy value

We have primarily made the scientific case for this survey in terms of medium-term science, which promises very large returns. However, we hope that these will be dwarfed by the science from projects we cannot yet anticipate. We expect the VHS to have a very long lifetime as a scientific tool. A replacement will only be created when one can obtain significantly deeper data, which means large amounts of 8-m telescope time. Since no such surveys are even in the planning stages, VHS is likely to be the premier near IR resource for 10 to 20 years.

We have kept this in mind when designing the survey. A survey of the entire hemisphere means that astronomers will always be able to find their objects, or upper limits in the survey. In the medium term, we focus some of the survey time on known lower surface density 'high value' objects such as galactic stellar clusters, nearby clusters of galaxies, nearby resolved large($>5'$) galaxies and also ~ 200 of the deepest XMM-Newton pointings. When the Herschel survey regions become known they could be added to VHS survey observing schedule. In addition we include an annual scan of the SDSS-II SGC equatorial strip(270deg^2). Finally, we have maintained, and will continue to maintain close contact with both the Galactic Plane Survey and the Magellanic Clouds Survey to ensure all three can act in concert where they can be used to study similar classes of objects and objectives.

2.2.2 Large-scale structure out to $z \simeq 1$ and the properties of dark Energy via the Integrated Sachs-Wolfe effect

One of the principal results of VHS will be a catalogue of close to 100 million galaxies, reaching out to approximately $z=1$. The multicolour data will permit photometric redshift estimates for most of these, giving a wonderful resource for measuring the 3D density field within a substantial fraction of our horizon volume. Information derived from this (e.g. detecting of order 100,000 clusters) will be of the widest application in

innumerable follow-up programmes. Perhaps the most exciting direct application of the data will be the chance to probe the nature of the Dark Energy, which is currently causing the expansion of the universe to accelerate. One key signature of this is the late-time Integrated Sachs-Wolfe (ISW) effect, which is which is the gravitational redshift of Cosmic Microwave Background (CMB) photons as they pass through an evolving gravitational potential well. Interest in the ISW effect has been sparked by the realisation that in a matter-dominated flat universe, the ISW should be zero, as all large-scale gravitational potentials (in the linear regime) should be not evolve in co-moving coordinates. This is no longer true in the presence of Dark Energy, which will effect the rate of growth of large-scale structures thus causing an ISW effect. Therefore, the detection of an ISW effect either means $\Omega_{matter} < 1$, or provides direct physical evidence for the existence of dark energy, assuming $\Omega_{total} = 1$ from observations of the CMB (Spergel et al. 2003). Scranton et al. (2003) have used Luminous Red Galaxies (LRGs) from the Sloan Digital Sky Survey (SDSS) to cross-correlate with the WMAP first year data, and have detected a positive correlation between the over-density of LRGs and the temperature of the CMB, ie., the CMB is (on average) hotter behind superclusters of LRGs. Unfortunately, the ISW signal is weak (a few micro-Kelvin) and the measurement error is dominated by cosmic variance causing by false large-scale correlations, e.g., Scranton et al. have a 5σ detection of the ISW effect using $\simeq 6000\text{deg}^2$ of SDSS data.

In this proposal, we plan to make a definitive measurement of the ISW by making the measurement over the largest possible area of the sky: this is the only way to beat cosmic variance. We plan to use the IR data to select high redshift ($z=0.4-0.8$) galaxies to provide a measure of the ISW effect using WMAP and Planck data at redshifts greater than achieved by present galaxy surveys. We may also be able to measure the ISW in several photo- z shells, and when combined with the low redshift ISW measurements, we will constrain the time evolution of the equation of state of dark energy well in advance of the next generation of DE experiments (SNAP, WFMOS, LSST).

2.2.3 Galactic structure and Galaxy genesis

The origin and evolution of our own Galaxy is among the key unanswered questions in astrophysics. The Local Group of galaxies is thought to be typical of the general field population of the Universe and hence provides a unique opportunity to study the genesis of one galaxy in great detail. Although significant observational progress has been made recently we are still a long way from answering these questions.

Λ CDM cosmologies demonstrate the ubiquity of hierarchical merging as the main driver in galaxy formation and evolution, and the discovery of the tidally disrupting Sagittarius dwarf (Ibata et al. 1994) provided the first compelling nearby evidence of this. However, the detailed process by which large galaxies such as the Milky Way arrive at their current state is still largely speculative (eg. Abadi et al. 2003, 2006; Bullock and Johnston 2005; Font et al. 2006) despite recent observational and theoretical progress.

Existing large area surveys such as 2MASS and SDSS illustrate the crucial importance of all-sky coverage in deciphering the complex merger history of local structure in the outer disk and halo of our Galaxy (see Figure 2. However, 2MASS, although providing a new impetus to this subject (eg. Majewski et al. 2003; Martin et al. 2004), is limited in depth to relatively nearby structures in the Galaxy, particularly those seen in projection close to the Galactic Plane; while SDSS (and even the SEGUE extension) lack both the extinction penetration and areal coverage necessary to deliver a complete census of nearby substructure.

The combination of large area and NIR photometric coverage provided by the VHS provides enormous leverage in attacking these problems by enabling a range of structural probes in a multi-parameter space sensitive to both density and spectral types of objects. With the VHS we will be able to probe a factor of ~ 40 fainter than 2MASS or a factor of 6 further in distance out to 50kpc for the stellar streams remnants of merger events associated with the formation and genesis of our Galaxy.

2.2.4 The lowest mass stars and the nearest star

SDSS and 2MASS have revolutionised studies of ultra-cool stars and brown dwarfs in the field, with the discovery of numerous L and T dwarfs in the solar neighbourhood. These surveys however, could only detect objects down

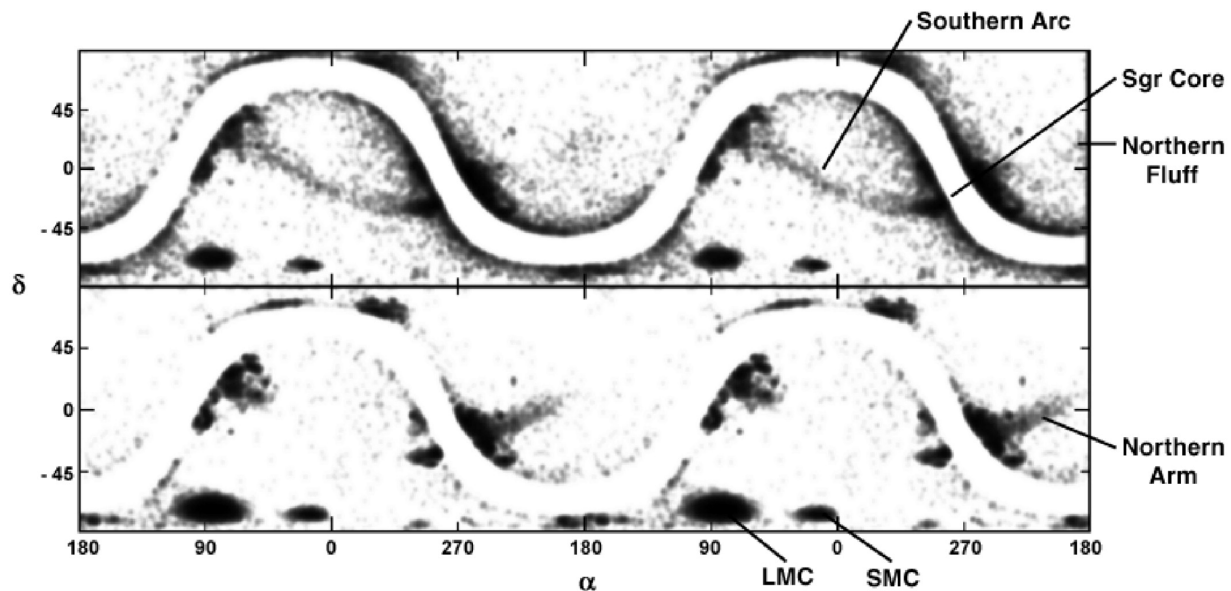


Figure 2: From Majewski et al. 2003; Smoothed maps of the sky in equatorial coordinates for two color-magnitude windows of the (nonreddened) 2MASS point-source catalog filtered optimally to show the Sagittarius dwarf (Ibata, Gimre & Irwin, 1994) southern arc (top) and the Sagittarius dwarf northern arm (bottom): $11 < K_s < 12$ and $1.00 < J-K_s < 1.05$ (top), and $12 < K_s < 13$ and $1.05 < J-K_s < 1.15$ (bottom). Two cycles around the sky to demonstrate the continuity of features.

to $\sim 1000\text{K}$ within 10pc of the Sun. Most of the late-L and T dwarfs discovered to date appear to be relatively young, relatively high-mass brown dwarfs (Burgasser et al 2003, 2006). Older, lower-mass objects are cooler, and remain as yet undiscovered, though they should exist in large numbers. To identify the coolest stars we need a survey in ZYJK bands to select objects which are red in ZYJ and blue in J-K due to methane. The main science goals are:

1. To identify the nearest and coolest brown dwarf to the Sun
2. To discover objects cooler than the T-dwarfs and define the new ‘Y’ spectral class.
3. To measure the field brown dwarf luminosity function down to objects cooler than 400K , and thus derive the field substellar mass function down to the lowest mass objects that can form as stars.
4. To investigate the birth rate, galactic distribution and kinematics of cool field brown dwarfs.
5. To search for population II brown dwarfs.

Survey Volume

The VISTA Hemisphere Survey has been carefully designed to detect objects as faint as 400K , corresponding to a $10M_J$ brown dwarf at an age of 1GYr (or a $20M_J$ brown dwarf at 5GYrs). Objects this cool have spectra dominated by H_2 , H_2O , CH_4 and NH_3 opacities and are brightest in the J-band, and are detectable in both the Y and J filters out to at least 20 parsecs. In 20000 square degrees, the volume surveyed for 400K Y-dwarfs is $> 18000\text{pc}^3$, which is larger than the volume ($\sim 4000\text{pc}^3$) surveyed for T-dwarfs in the 2MASS all-sky survey. We also note that the VHS survey is more sensitive to Y-dwarfs than the proposed NASA WISE $3.5\text{-}23\ \mu\text{m}$ all-sky survey, which can only detect 450K Y-dwarfs out to 9pc in two passbands (Kirkpatrick 2003).

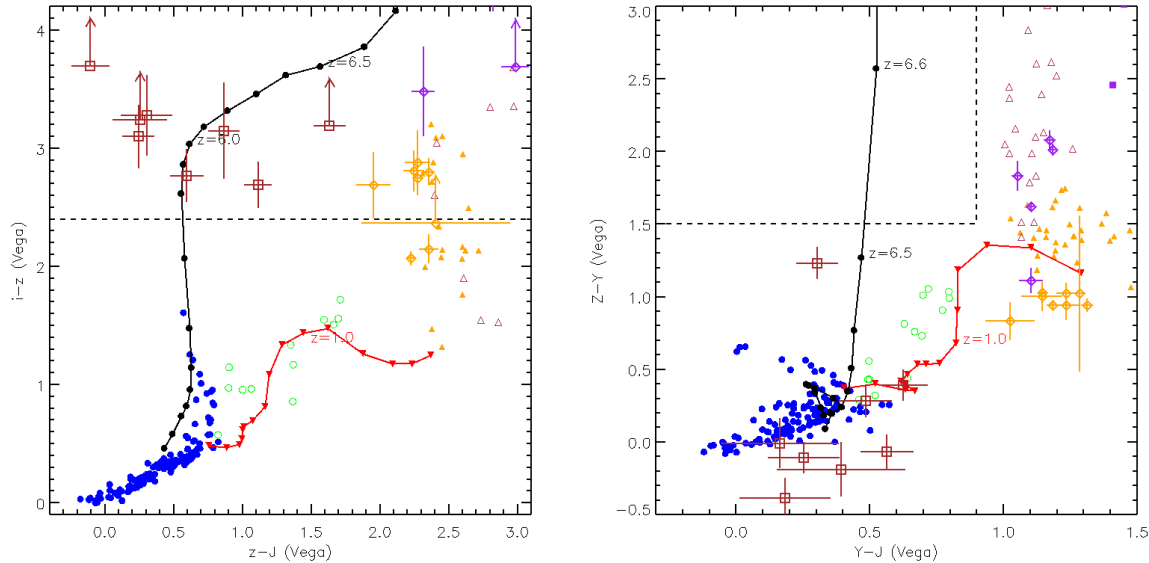


Figure 3: Left(a) $i-z$ vs $z-J$ diagram in Vega system illustrating colours of simulated stars, elliptical galaxies and quasars. The simulated objects colour coded as follows: BPGS O-K main sequence stars blue circles; M dwarfs green circles; L dwarfs orange circles; T dwarfs purple circles; Burrows model cool brown dwarfs maroon circles; elliptical galaxies $0.0 < z < 1.5$, $\Delta z = 0.1$ red open circles; quasars $5.0 < z < 6.7$, $\Delta z = 0.1$ black circles with redshifts $z = 6.5$ and $z = 6.6$ marked. Quasar with redshifts $z > 6.5$ can be distinguished from cool stars by their red Z-Y colour and blue Y-J colour. The region in colour-colour space occupied by high redshift quasars is outlined by the dashed lines. The measured colours from the UKIDSS LAS of eight known L stars (orange diamonds), five known T stars (purple diamonds) and eight quasars with $5.8 < z < 6.4$ (brown squares). Right(b) $z > 6.5$ quasar selection diagram; Z-Y vs Y-J diagram in Vega system with symbols as in (a). Note the isolated quasar near the $z > 6.5$ selection boundary. This is the highest redshift quasar known ($z = 6.4$).

We will detect the coolest T dwarfs (e.g. Gliese 570D, T7.5, $T \sim 800\text{K}$) out to ~ 60 parsecs increasing their known population by a factor 40. Combining the new L, T and Y-dwarf luminosity functions will enable us to make a meaningful measurement of the substellar field mass function down to the minimum mass for a brown dwarf (e.g. Burgasser 2003).

The Nearest Coolest Brown Dwarfs

Our nearest neighbour is Proxima Centauri, at $d = 1.3$ parsecs. The VHS is sensitive to an object as cool as 300K ($M = 5M_{\text{Jup}}$ at 1 Gyr) out to 4 parsecs. The VHS will be used to search for our nearest neighbours down to the planetary mass regime.

Object Identification

Y-dwarfs are predicted to be unusually red in Z/Y-J, and should be largely distinguishable from their Y-J colours alone. L, T and Y dwarfs can be further discriminated on the basis of their J-K colours (see Figs 3, 4 and 5). Ultimately, a VHS proper motion survey (repeating one band, probably J, after ~ 5 years) will be an additional efficient way to detect the nearest and coolest stars (Hambly & Deacon 2006), whilst also providing kinematic information.

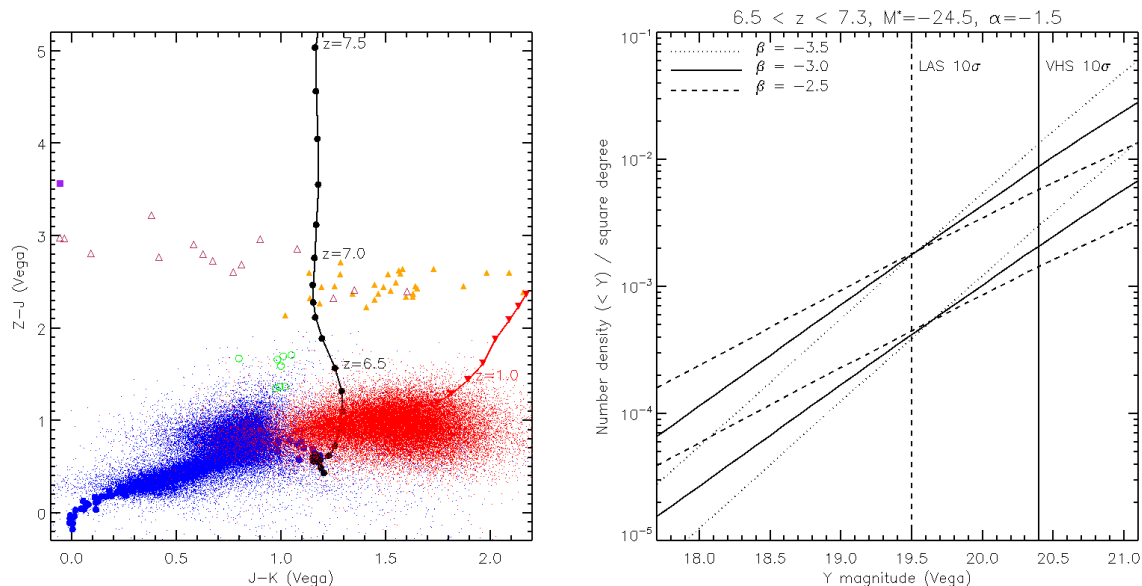


Figure 4: [left(a)] Z–J vs J–K diagram in Vega system. Symbols are the same as in Figure 3. We have also plotted 'real' data from 20deg² from the UKIDSS Early Data Release(EDR). Blue points are objects classified as stars, Red points are objects classified as galaxies. This shows how Z-J vs J-K CANNOT be used to distinguish $z > 6.5$ quasars from cool low mass stars. [right(b)]: Predicted surface density of $z > 6.5$ quasars for VHS is the upper set of lines; the different linestyles are different bright end slopes as indicated. The lower set of lines shows the expected surface density of $z > 7$ quasars. The predictions use the Fan etal(2004) space density at $z \sim 6$ and the Schmidt, Schneider, Gunn(1995) density evolution, decreasing with redshift, in the quasar space density. The two vertical lines indicate the 10σ Y[Vega] limits for the UKIDSS LAS and VISTA VHS respectively

2.2.5 Probing the end of the dark ages; The first $z > 7$ quasar and the baryonic state of the Universe during the era of reionization

After the epoch of recombination at $z \sim 1000$, the Universe remained almost neutral until the first generation of luminous sources (massive stars, galaxies, accreting black holes) formed. Quasars are the most luminous objects in the Universe and have been discovered out to a maximum redshift of $z \sim 6.4$ by the SDSS. A single quasar at a redshift of above 7 or even 8 would be of immense value and would allow us to determine the metal content, and ionization state of the IGM at these redshifts.

However, the SDSS is unlikely to find any quasars beyond $z \sim 6.5$ since the z waveband which is the reddest band in the SDSS survey is absorbed away by the Lyman- α forest. The technique used by the SDSS group is shown in Figure 3a. The VHS has been designed with the goal of extending surveys beyond $z = 6.5$. Figure 3b shows how the VHS will use the Z-Y versus Y-J to identify higher redshift ($z > 6.5$) quasars. The Y-J colour is ESSENTIAL since the so called 'rare' L and T dwarfs outnumber the quasars by a factor of 200:1 based on the well established space densities of the foreground L and T dwarfs. We have verified that this is practical using the UKIDSS EDR data for the known objects shown in Figure 3.

The proposed VHS survey will have a 10σ limit in Y of 20.4[Vega]; see Table 1. We set the limit as 10σ in Y since this band contributes to both colour selection criteria. To distinguish quasars with $z > 6.5$ from the more numerous galactic foreground L and T dwarfs requires $Y-J < 0.9$. The $Y-Z > 1.5$ constraint for $Y = 20.4$ corresponds to a Z limit of 21.5(5σ). A 5σ rather than a 3σ limit is required to minimise Gaussian scattering of false positives. The proposed VHS survey goes a magnitude fainter than the UKIDSS LAS in Y and 1.6mags deeper in Z than SDSS. The expected surface densities as a function of redshift is shown in Figure 4b.

Table 1: Baseline VHS Survey median sensitivity limits

Band	λ_{eff} (μm)	Exp (secs)	Seeing "	Vega(AB) 10 σ	Vega(AB) 5 σ	Vega(AB) 3 σ	$\Delta(\text{Vega} - \text{AB})$	μJy 5 σ
Z	0.88	180	1.0	21.1(21.6)	21.9(22.4)	22.4(22.9)	0.53	6.9
Y	1.03	180	1.0	20.4(21.0)	21.2(21.8)	21.7(22.3)	0.63	7.6
J	1.25	60	1.0	19.4(20.3)	20.2(21.1)	20.7(21.6)	0.94	10.0
H \dagger	1.63	60	1.0	18.4(19.8)	19.2(20.6)	19.7(21.1)	1.38	19.0
K _s	2.20	60	1.0	17.3(19.2)	18.1(20.0)	18.6(20.5)	1.90	36.3

Notes: \dagger H band is not included in the baseline VHS survey but the sensitivity is included here for convenience. (i) Limiting magnitude is for point sources in seeing of 1.0" and a software aperture with diameter 2.0". (ii) The AB=0 normalisation in Jy is 3630Jy (iii) For 180sec add 0.6mags to 60sec depth and vice versa (iv) For 10 σ limits subtract 0.75mags from 5 σ limits. (iv) For 3 σ limits add 0.50mags to 5 σ limits. (v) For 1.4" seeing in 3.0" diameter aperture, exposures time to reach the same limits are 50 % longer ie. 90secs in J/K. (vi) might expect nominal K seeing to be better than Z seeing by 20% since seeing varies as $\lambda^{-1/5}$. (viii) ETC using default 'Dark Sky Brightness' of Z = 18.2 Y = 17.2 J = 16.0 H = 14.1 KS = 13.0 and airmass 1.2. (ix) λ_{eff} and AB to Vega normalisation from Hewett, Warren, Leggett, Hodgkin etal, 2006.

Both Z and Y are required as show by Figure 4a. Without the Y band one cannot distinguish the $z>6.5$ quasars from the more numerous L and T dwarfs which outnumber the expected number of quasars $>100:1$. A more speculative goal would be the discovery of $z>7.5$ quasars with $Y-J>1.5$ (i.e. Y-drops) on the basis of selection using the YJK bands. The expected surface density of $z>7.5$ is 3 per 10,000deg² at the VHS 10 σ J limit.

2.2.6 Galactic Cluster Survey

The Initial Mass Function (IMF) is a key issue to address in the context of the formation of very-low-mass stars and brown dwarfs because it represents the outcome of star formation processes. Major questions remain to be answered, including (1) what is the shape of the IMF below 50 Jupiter masses? (2) is the IMF universal or does it depend on the galactic environment and/or on metallicity? (3) is the spatial distribution of stars and brown dwarfs similar (4) is there a lower-mass cut-off in the process of star formation?

The main aim of the VISTA Galactic Cluster Survey are:

1. Derive the IMF down to 20 Jupiter masses or lower depending on the age and distance of the region
2. Investigate the dependence of the IMF with environment and metallicity by studying a large number of open clusters and star-forming regions at different ages, distances, and galactic environments
3. Study the distribution of stars and brown dwarfs over the entire cluster area to test current theories on the formation of brown dwarfs
4. Find planetary-mass objects with masses as little as a few Jupiter masses to investigate the fragmentation limit problem, a major question in star formation

We plan to observe those clusters and regions early in the survey in order to obtain proper motion from a second epoch observations about 5 years later. Several clusters harbour significant proper motions, including Blanco 1, IC 2391, NGC 2516, IC 2602, and Upper Sco.

2.2.7 Synergy with other survey projects

The VISTA Hemisphere surveys is an excellent match with several other ongoing or imminent projects. Several of the key opportunities are with ESA missions - XMM-Newton, GAIA, Herschel, and Planck. These are discussed in Section 2.2.7 Other key opportunities are :

(i) *VST Atlas*. The VHS will be a useful resource for all VST surveys, but the best match is with the "VST Atlas" programme. This aims to cover 4500 sq. deg at $u g r i z$ to the same depth as SDSS. VHS will of course detect redder and higher-redshift objects than ATLAS.

ii) *AKARI (Astro-F)*. AKARI is a Japanese mission with some UK, ESA and Dutch involvement. It will make an all-sky FIR survey with resolution 30". Amongst other things it will produce a sample of 10^6 luminous IR galaxies to $z \sim 1$. The match to VHS depth is excellent, yielding the prospects of photometric redshifts for more or less the whole of this key sample.

(iii) *WISE*. This is a NASA Midex mission, committed to making a public all-sky MIR survey from 3.5 to 23 microns. WISE is currently under construction and should be launched in 2009, part-way through the VHS programme. The match to VHS is excellent.

(iv) *eROSITA* This an MPE hard X-ray imaging survey (timescale about 2010-2012) which will discover some 10000 clusters of galaxies by means of their X-ray emission.

VST-ATLAS+SDSS together with VHS, WISE, and AKARI make a fantastic atlas dataset covering two decades of wavelengths. Figure 1 shows the expected survey depths.

2.2.8 Support for ESA missions; XMM-Newton, Herschel, Planck and GAIA

Europe has invested in a remarkable series of space astronomy missions. The VISTA Hemisphere Survey will help to extract the maximum value from these world-leading facilities.

(i) *XMM-Newton*. We are currently in a new golden age of X-ray astronomy, with *Chandra* and *Newton* between them representing unprecedented sensitivity and resolution. All XMM-Newton observations are being systematically processed and a serendipitous catalogue is being generated. The soon to be released 2XMM catalogue covers 600 square degrees (spread over the whole sky) and almost 10^5 X-ray sources, and this resource will continue to grow until 2010. A significant fraction of counterparts will be invisible in VST surveys - for example reddened quasars, and many stellar X-ray sources in the Milky Way - and other objects, such as distant clusters of galaxies, are more efficiently found in the IR, where the contrast is better.

(ii) *Herschel-Planck*. Planck and Herschel will be launched together in 2007 and represent a huge advance in FIR-submm astronomy. Herschel is a pointed mission operating from 60um to 670um. A significant fraction of sources found will have no counterparts at visible wavelengths. Of course many will require deeper K-band data to identify, but the VHS will be the first port of call before applying for deep observations. Planck will survey the sky at mm wavelengths. It will also produce the first ever all-sky catalogue of mm-wave sources. Cross-matching with VHS will be a very high priority. Furthermore a key project will be cross-correlating the CMB with the galaxy clustering foreground measured by VHS, to measure the ISW effect.

(iii) *GAIA*. When launched in 2011, GAIA will make a revolutionary three dimensional map of the Milky Way. As well as astrometry of unprecedented accuracy for a huge number of stars, it will produce a photometric catalogue which VHS will extend into the IR. This can for example yield a three dimensional map of the extinction in the Milky Way - the parallaxes from GAIA give a distance, but the spectral type will often be unclear because of reddening; the visible-IR colour combination then gives spectral type, reddening, and absolute magnitude. VHS of course can also see things that GAIA can't - such as L, T and Y dwarfs, and their proper motions, and luminous objects such as Miras clean through the Galaxy. Adding VHS to GAIA then gives a more complete picture of the Milky Way. The NIR bands of the VHS will help to determine the extinction and to determine intrinsic stellar parameters, in particular the effective temperature and ultimately the intrinsic luminosity (the larger wavelength coverage also provides a more accurate bolometric correction). In addition, the VHS data, when combined with Gaia optical photometry and astrometry, will increase significantly the number of cluster brown dwarfs and field ultra cool dwarfs discovered by either survey.

2.3 Immediate objective:

The prime objective for the VHS is to provide targets for follow-up with the VLT. By surveying a large area one can identify the brightest objects in any class of astrophysical object. Area is better than depth in the Euclidian regime since it maximises the survey volume.

Immediate goals(3 year plan): The survey area for the first three years could include the following strands:

- SGP VST Atlas area
- The two southern SDSS SGP strips (600 deg²)
- Deeper in dec=0 strip; with one VHS epoch every year(300deg² per year).
- NGP VST Atlas
- Highest priority Galactic clusters in ZYJK.
- Execute tiles that overlap with nearest 200 galaxies.
- Execute tiles that overlap with nearest 200 galaxy clusters.
- Execute tiles that overlap with 200 deepest XMM pointings.
- Fornax galaxy cluster(50deg²)

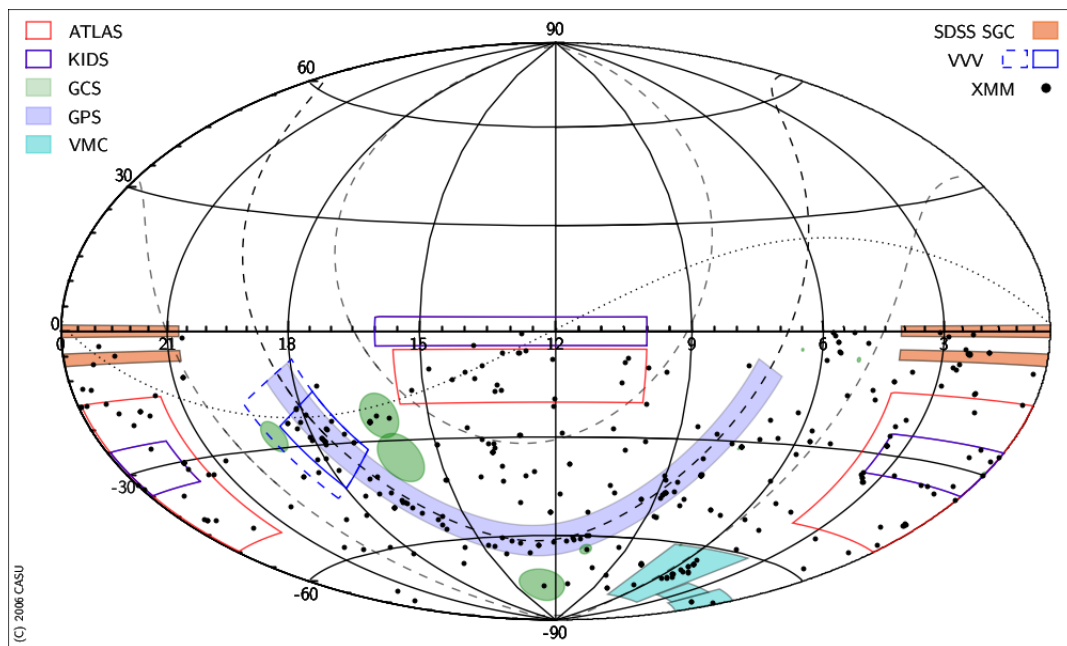


Figure 5: Overview of the VISTA surveys that relate to the VHS. Also shown are some of the Galactic clusters that are contained within VHS. The black filled circles are ~ 200 deep public XMM pointings from the 2XMM catalogue.

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

3.1 UKIDSS Large Area Survey(LAS)

Table 2: UKIDSS LAS Survey; Median limits(5sigma in 2arcsec aperture)

band	sec	seeing median	Sky Brightness	Vega	AB	μ Jy	comments
				5σ			
<i>i'</i>	55	1.4	-	22.1	22.4	4.0	SDSS
<i>z'</i>	55	1.4	-	20.3	20.9	15.8	SDSS
<i>Y</i>	40	0.84	17.3	20.2	20.8	17.4	
<i>J</i>	2x40	0.83	16.0	20.0	20.9	15.8	
<i>H</i>	40	0.80	14.1	18.8	20.2	30.2	
<i>K_s</i>	40	0.74	13.5	18.2	20.1	33.1	

Notes: (i) UKIDSS limiting magnitudes are Median values are derived from data taken during the period May 2006 to Jan 2007. (ii) The J limit is an extrapolation from the current limits for the 40sec single epoch observations. (iii) SDSS limits are derived from actual data and are median limits for region covered by UKIDSS EDR. Also SDSS magnitudes are PSF magnitudes.

The UKIRT Infra-Red Deep Sky Survey(UKIDSS) started in May, 2005. UKIDSS is a multi-survey project and the element of UKIDSS that most closely relates to the VHS is the UKIDSS Large Area Survey(LAS). The LAS has already covered around $\sim 300\text{deg}^2$ in YJHK of which $\sim 25\text{deg}^2$ is public.

Our proposed VHS differs from the UKIDSS LAS in a number of different ways:

- UKIDSS LAS uses SDSS *z'* with a median 5σ limit(Vega) of 20.3. The VHS survey will have a Z(Vega) limit of 21.9 which is 1.6 magnitudes deeper. The extra depth comes from higher QE, and longer exposure times.
- The VHS Y band limit(5σ) is 21.2 compared with the UKIDSS LAS limit(5σ) of 20.2. The extra depth comes from higher QE and longer exposure times.
- The K limit for VHS is 0.1mag brighter than the LAS limit. This is a due to a combination of the brighter sky at Paranal and the poorer seeing assumed for the VHS(1.0 versus 0.8)

Overall, VISTA can survey sky faster than WFCAM by a factor of 3 neglecting weather so even for the same survey depth parameters the VHS could overtake the UKIDSS LAS in survey area.

3.2 VST ATLAS

The VST Atlas survey is aimed at surveying 4500deg^2 of the Southern Sky at comparable depths to the Sloan Digital Sky Survey (SDSS). This would be the first step at surveying the entire Southern Sky in the optical bands. VHS is a natural complement to the ATLAS survey.

3.3 Other VISTA surveys

The total survey requirements outlined in Table 4, assumes that no other VISTA survey is carried out. We are aware of a number of large area survey that each cover $>100\text{deg}^2$; VVV(PI:Minuti), GPS(PI: Lucas) and VMC(PI: Cioni) surveys, VIKING(PI: Sutherland).

The boundaries of these surveys are shown on Figure 5 Whilst VHS does not need to cover the areas that are covered by these surveys there may to be some observing time scheduled, if the different surveys use different filter combinations to ensure that colour-magnitude diagrams can be cross-calibrated for each survey.

4 Observing strategy: (1 page max)

The science goals require that we cover the whole southern sky in at four wavebands to the depths above. We assume 1.0" seeing in each filter and 5sigma detection limits in a 2arcsec diameter aperture. Exposure times of 60 seconds in J and K_s , and 180 sec in Z and Y are proposed over the whole area of the survey. Even with these shortish times it will take many observing periods to complete the hemisphere survey. We take a reasonable amount of time to be 14 observing periods which would give completion around the time of launch of GAIA and data release for WISE.

Because of potential variables we ideally wish to get at least two (ideally more) filters observed within 20 minutes of each other by having them in the same OB. For example studies of the variability in a 4Myr-old OB association by Naylor (priv comm) finds that more than 1 percent of the stars have varied by more than 0.05 mags within 2 hours. So if you are looking for rare objects, say if you expect 1 in a hundred stars to deviate from some colour relationship by 0.05 mags, a time separation of 2 hours destroys such a study because 1% will have varied by that amount in 2 hours. So in fact you want to take the two different colours within about 20 minutes, to avoid variability confusing the finding of rare objects. Of course other types of object /region vary more or less but this argument is indicative of the importance of quasi simultaneous filters. [The SDSS and 2MASS observing strategies ensured this in their cases]

But for the increased Z and Y background in bright time we would do a tile in all 4 filters which would fit within a one hour OB. However experience with WFCAM on UKIRT suggests the increased sky background at bright in Z and Y is significant so we content ourselves with getting at least two filter in the same OB. OBs containing Z and Y will be carried out away from bright time. OBs containing J and K_s can be carried out even in bright time

There is little speed to be gained in shortening exposure times much below 60secs since overheads such as read out, disk i/o and telescope motion start to dominate.

We make standard 6 pawprint tiles without microstepping. In the longer exposures (Z and Y) we jitter between 2 positions, but to avoid extra overhead do not jitter in J and K_s relying on the 2nd pawprint of the tile to cover any bad pixels on the first.

The distribution of observing time request with period over the first 6 Periods is given in Table 3 assuming a 14 period length of the whole survey. It includes steps towards the 20,000 sq deg single coverage and additionally each Period 41 hrs in Z and Y and 17 hrs in J and K_s for the repeats on the 300 sq deg dec=0 strip for variability and proper motions.

5 Estimated observing time:

5.1 Time justification: (1 page max)

Table 4 gives the parameters of the survey and the elapsed hours required to complete it.

In practise (see strategy above) we will use OBs each containing 2 filters and allowing for the 25 sec filter change each will take $2*710+25$ elapsed time, so that 13,333 tiles in Z and Y will take 5,333 hours.

Similarly for J and K_s allowing for the 25 sec filter change each would take $2*284+25$ elapsed time, so that 13,333 tiles in J and K_s will take 2,222hours.

If this is spread over 14 observing periods we require 381 hours in Z and Y and 159 hours in J and K_s in each period. We shall need no time for photometric calibration since we shall use the general VISTA calibrations

Table 3: VHS Observing Time Request by Observing Period

Period	Time (h)	Mean RA	Moon	Seeing	Transparency	Comment
P79(Apr'07 - Sep'07)	422 (ZY)	18h	dark	0.8-1.4	THIN, CLEAR	Planck, Herchel launch
P79(Apr'07 - Sep'07)	176 (JKs)	18h	bright	0.8-1.4	THIN, CLEAR	
P80(Oct'07 - Mar'08)	422 (ZY)	06h	dark	0.8-1.4	THIN, CLEAR	Planck, Herchel reach L2
P80(Oct'07 - Mar'08)	176 (JKs)	06h	bright	0.8-1.4	THIN, CLEAR	
P81(Apr'08 - Sep'08)	422 (ZY)	18h	dark	0.8-1.4	THIN, CLEAR	
P81(Apr'08 - Sep'08)	176 (JKs)	18h	bright	0.8-1.4	THIN, CLEAR	
P82(Oct'08 - Mar'09)	422 (ZY)	06h	dark	0.8-1.4	THIN, CLEAR	
P82(Oct'08 - Mar'09)	176 (JKs)	06h	bright	0.8-1.4	THIN, CLEAR	
P83(Apr'09 - Sep'09)	422 (ZY)	18h	dark	0.8-1.4	THIN, CLEAR	WISE launch
P83(Apr'09 - Sep'09)	176 (JKs)	18h	bright	0.8-1.4	THIN, CLEAR	
P84(Oct'09 - Mar'10)	422 (ZY)	06h	dark	0.8-1.4	THIN, CLEAR	
P84(Oct'09 - Mar'10)	176 (JKs)	06h	bright	0.8-1.4	THIN, CLEAR	
End of first 3 year plan	N.B. We will choose VST-ATLAS fields early to match it					

Table 4: VHS Survey parameters

	Z	Y	J	H	K _s
Detector Integration Time (DIT) s	45	45	10	-	10
Exposure co-adds (Ndit)	1	1	3	-	3
Exposure loops (Nexp)	1	1	1	-	1
Jitter pattern (Njitter)	2	2	1	-	1
Microsteps pawprints	none 6				
Time per object s	180	180	60	-	60
Depth (5 σ) Vega	21.9	21.2	20.2	-	18.1
Total exposure time per tile s	540	540	180	-	180
Total Elapsed time per tile s	710	710	284	-	284
Observing efficiency % per tile	76.1	76.1	63.4	-	63.4
Time for 20,000 sq deg = 13,333 tiles of 1.5 sq deg					
Total Elapsed Hours	2,667	2,667	1,111	-	1,111

and use 2MASS for the photometric calibration.

Clearly there may be other VISTA Public surveys of significant parts of the hemisphere, for example the galactic plane, the VST-KIDS area, the VST-ATLAS area, the bulge, the Magellanic clouds etc and it will be necessary for efficiency to share data between the various surveys covering the same areas to different depths. The details of how to do this will be discussed with other surveys as directed by the PSP in due course, and the areas required to be covered in the VHS here could be reduced in the observational sense, though still included in the released survey to a uniform depth.

6 Data management plan: (3 pages max) [Based on VDFS DMP v3.0]

6.1 Team members:

Table 5: Responsibilities and Group Leaders

Name	Function	Affiliation	Country
R. McMahon	PI	University of Cambridge	UK
A. Lawrence	Deputy/Co-PI	University of Edinburgh	UK
J. Emerson	VDFS Coordinator	Queen Mary University of London	UK
CASU (VDFS) team†	Pipeline processing	University of Cambridge	UK
CASU (VDFS) team†	Data Quality Control-I	University of Cambridge	UK
WFAU (VDFS) team‡	Science Archive	University of Edinburgh	UK
WFAU (VDFS) team‡	Data Quality Control-II	University of Edinburgh	UK
N. Walton	VO Standards	University of Cambridge	UK
VHS Survey specific tasks			
TBD	OB Preparation Working Group		
TBD	Survey Progress Working Group		
T. Naylor	VISTA Surveys cross-calibration Working Group	University of Exeter	UK
R. McMahon	Data Quality control and validation Group	University of Cambridge	UK
TBD	Astrometry Working Group		
TBD	Galaxy Photometry Working Group		
TBD	Stellar Photometry Working Group		
J. Emerson	Photometric Calibration Working Group		
F. Carrera	XMM-Newton Working Group	Santander	Spain
C. Bailer-Jones	GAIA Working Group	MPIA	De
S. Oliver	Herschel Working Group	Sussex	UK
G. Lagache	Planck Working Group	IAS, Paris	Fr
H. Rottgering	LOFAR and radio surveys Working Group	Leiden	NL
N. Lodieu	Galactic Cluster Working Group	Leicester	UK
TBD	Nearby Galaxy Working Group		
TBD	Galaxy Cluster Working Group		
TBD	Solar System Working Group		

Notes: † The CASU (VDFS) team consists of Irwin, Lewis, Hodgkin, Evans, Bunclark, Gonzales-Solares, Riello. ‡ The WFAU (VDFS) team consists of Hambly, Bryant, Collins, Cross, Read, Sutorius, Williams.

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 copies remaining at the point of origin.

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. We emphasise the track record over the last decade of both the Cambridge and Edinburgh survey units in processing and delivering large-scale imaging datasets to the community as exemplified by the WFCAM Early Data release (EDR, (<http://surveys.roe.ac.uk/wsa/dboverview.html>) Lawrence et al 2006, Dye et al 2006).

The observation planning team is a sub-set of the Data Processing and Quality control teams. 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 Scientific Working groups (following the themes of the goals listed in the Objectives). Any problems found by these teams will be addressed by the appropriate Functional Working Groups.

6.3 Data reduction plan:

The data reduction will be using the VDFS, operated by the VDFS team, and augmented by individuals from the VHS co-Is, especially for product definition and product Quality Control. We divide the plan into two distinct but intimately related parts: pipeline processing and science archiving. Much greater detail can be found in the SPIE papers cited previously,

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 wide range of CCD mosaic camera data.

The pipeline is a modular design allowing straightforward addition or removal of processing stages and will have been tested on a range of input VISTA datasets. The standard processing includes: instrumental signature removal – bias, non-linearity, dark, flat, fringe, cross-talk; sky background tracking and homogenisation during image stacking and mosaicing – possible extras may include removal of other 2D systematic effects from imperfect multi-sector operation of detectors; assessing and dealing with image persistence from preceding exposures if necessary; combining frames if part of an observed dither sequence or tile pattern; producing a consistent internal photometric calibration to put observations on an approximately uniform system; standard catalogue generation including astrometric, photometric, shape and Data Quality Control (DQC) information; final astrometric calibration based on the catalogue with an appropriate World Coordinate System (WCS) placed in all FITS headers; photometric calibration for each generated catalogue augmented by monitoring of suitable pre-selected standard areas covering the entire field-of-view to measure and control systematics; frames 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 headers.

The pipeline processing centre hosts a data quality database that is updated daily with the data quality control information for pipeline processed products.

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. Archive curation includes quality control procedures, as required and led by the public survey consortium, and supported by archive team members. 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 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/>

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 image 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 available bands in any one field

6.5 General schedule of the project:

T0: Start of survey observations

T0+4months; ESO-wide release of science products from first month of survey observations

T0+6month; ESO-wide release of science products from first 3 months of survey observations

Thereafter we would hope that science products can be released within 1-2 months of raw data arriving in the UK.

Optional reprocessing of data based on improved knowledge of instrument would also be considered

7 Envisaged follow-up: (1 page max)

We summarise below the types of follow-up observation that are envisaged for the science highlights identified in section 2.

7.1 Large scale structure and Integrated Sachs-Wolfe

Much of the core science in this area can be performed with photo-z estimates alone. It will be important to have an extensive set of spectroscopy to calibrate these. At the brighter level, this exists via the 2MASS-selected 6dF Galaxy Survey. For fainter objects, a variety of large Southern galaxy redshift surveys are currently being proposed using AAOmega on the AAT. These may be expected to provide spectroscopic datasets at an appropriate depth for VHS (roughly $r=20-21$) of order a few times 100,000 objects over the next five years. In the longer term, as VHS progresses, there will be a case for seeking to use AAOmega to carry out larger-scale VHS-selected surveys, which will be deeper analogues of the 6dFGS.

7.2 Galactic structure and Galaxy Genesis

Deeper imaging may be required to corroborate any streams that are identified. The main follow-up will be velocity dispersion work which could use FLAMES or FORS1/2.

7.3 HZQs

Will require candidate screening with ISAAC imaging and spectroscopy. Also X-Shooter for detailed follow-up; 1night per object; upto 10nights for 'best' objects.

7.4 Cool and low mass stars

Additional deep H, and possibly deeper K, imaging will be used to confirm Y dwarfs candidates, before proceeding to NIR spectroscopy with e.g. ISAAC.

7.5 Galactic Cluster Survey

The surveys conducted in each cluster will provide hundreds of candidates to be followed up spectroscopically. Many contaminants will be rejected on the basis of their Z-K, and J-K colours. Second epoch observations will provide proper motions for several clusters and weed out field dwarfs. Follow-up observations include multi-fibre optical spectroscopy with AAOmega on the AAT, Flames on the VLT, as well as near-infrared spectroscopy of the faintest and coolest members. Low-resolution optical spectroscopy will provide $H\alpha$ equivalent width measurements to infer chromospheric activity, equivalent widths for gravity-sensitive doublets, and lithium measurements. Higher resolution optical spectroscopy will determine the radial velocities, yielding another criterion for membership assessment. The main goal is to obtain complete population of spectroscopically confirmed stellar and substellar members in open clusters and star-forming regions. We can also derive lithium age for open clusters with ages between 30 and 100 Myr.

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

Our team is large as befits such an undertaking. We have a broad range of science experience from cosmology, weak lensing, large surveys, high-redshift quasars, galaxy properties to Galactic science. The VISTA PI, VISTA Project Scientist, and VISTA Camera Scientist, and the leaders of the VDFS Pipeline and Archive are co-Is and so we have extensive experience with the technical issues for VISTA and its data handling. We are well equipped to deliver a high-quality science product and believe that the VHS survey will have lasting long-term value to the whole ESO, and indeed world, community.

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