# 1 Title: The WFCAM Transit Survey (WTS)

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## 1.1 Abstract: (10 lines max)

This UKIRT Campaign Proposal is to carry out a survey to identify and study rocky planets using the transit technique, by targeting low mass M dwarfs in the near infrared. This is a ground breaking opportunity. While the survey data itself can reveal the size of the planets, radial velocity follow-up will provide planet mass and density. Planetary atmospheric properties will come from transmission spectra and secondary eclipse measurements. M dwarfs provide a particularly sensitive probe for small planet transits, will show larger Doppler wobbles than higher mass stars, and have lower planet/star brightness contrast ratios. Indeed, for the lowest mass M dwarfs this survey could find planets that could be habitable. Interestingly, since the transit technique is based on relative photometry, this survey can be conducted in poor weather conditions, thus maximising the efficiency of UKIRT/WFCAM observing. Other science products will include M dwarf variability, eclipsing low-mass binaries, new Plutinos and Kuiper Belt objects, and very faint high proper motion objects such as ultra-cool helium rich white dwarfs.

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

### 2.1 Scientific rationale:

It is of fundamental importance to understand the origins of life in the universe. A primary goal of modern science is to discover and characterise planets around other stars, where life might be able to take hold. A planet's habitability depends primarily on 2 factors; whether it is a rocky world or a gas giant, and whether it resides in the habitable zone around its host star, where liquid water may flow on its surface.

**Radial velocity planet searches:** The radial velocity (RV) technique has proved very successful in planet hunting, harvesting ~180 planets in the last decade (Marcy et al. 2005). However, nearly all the host stars lie in the range 0.7–1.4 $M_\odot$. Stars less massive than 0.7$M_\odot$ become increasingly faint in the green-visible where the iodine cell provide reference lines. RV surveys (e.g. Delfosse 1998, 1999) have tackled small samples of M dwarfs (~100). The Keck Doppler survey of the Berkeley group include 150 M dwarfs, while the Keck Hyades program of Cochran et al. (2002) contains a sample of 20 M dwarfs. Endl et al. (2003) have undertaken a dedicated M dwarf RV survey with HET. However, all of these surveys are limited to the earliest M dwarfs, and become rapidly incomplete beyond M2-M3. They are incapable of extending into the very late spectral types.

**Planets around low-mass stars:** Even with the difficulties of detecting planets around low-mass stars, some of the most interesting examples have been discovered around M dwarfs: GJ876 (Marcy et al. 2001) is a multiple planet system including a 7.5 $M_{Earth}$ planet with a 2 day period (Rivera et al. 2005), and GJ436 (Butler et al. 2004) hosts a Neptune mass planet at a separation of 0.028AU. Beaulieu et al. (2006) report the discovery of a 5.5 earth mass planet orbiting a 0.2 $M_\odot$ M dwarf, from the microlensing event OGLE 2005-BLG-390Lb. The best candidate so far for an image of an extra-solar planet is the putative 5 $M_{Jup}$ companion to the ~25 $M_{Jup}$ young M8 brown dwarf 2MASS J12073346-3932539 (Chauvin et al. 2005).

Recent theoretical predictions on the formation of planets around low-mass stars are of wide significance to the entire field of extrasolar and solar planetary science. Laughlin (2004) predict that the core accretion mechanism of planet formation results in only a few Jovian mass planets around low-mass stars, but instead many Neptune and terrestrial mass planets. The study of the frequency and distribution of planets around M dwarfs thus offers the possibility to discriminate between the two dominant theories of planet formation: core accretion (Pollack 1996) and gravitational instability (Boss 2004). In general, given that M dwarfs dominate the stellar population in number, it is clearly vital to fully probe their planet harbouring potential.

**Planets transiting M dwarfs:** The transit method is able to detect planets if the system is favourably aligned ($i$ ~90). Once per orbit the planet passes between the star and the observer, causing an occultation or transit that results in a dip in the light curve. RV measurements can yield precise planet masses, and detailed light curve measurements can determine planet radii. Planetary mass-radius measurements lead to constraints on its composition and atmospheric structure (e.g. Sato et al. 2005), and likely evolution and migration history. Transmission spectroscopy may also allow one to study the planetary atmosphere.

Searching for M dwarf transits is compelling for several reasons. There is a strong geometrical bias for transiting planets being close to their stellar hosts, which resulted in the identification of the transiting hot Jupiters discovered in optical transit surveys. However, the habitable zone around M dwarfs is much closer in (~0.02–0.4AU) than for solar type stars, and the likelihood of habitable transits is much higher. The smaller radii of M dwarfs results in much deeper dips in the light curve for giant planet transits, and makes it possible to detect smaller planet transits: an Earth radius planet orbiting a 0.08 $M_\odot$ star produces a transit of 1% depth as does a Jupiter radius planet orbiting a sun like star. Sensitivity to rocky planets could be particularly rewarding, since the IMF of the known exoplanets rises towards lower mass, and a continuation of this trend would result in at least one rocky planet around every star. Radial velocity confirmation is also aided by the larger reflex velocity of a low mass host star. Yielding accurate planetary mass, radius and separation, the discovery of rocky planet transits of M dwarfs could thus, for the first time, allow us to unambiguously identify warm rocky planets.

**The need for a VISTA transit survey:** Nearly all the emergent flux from M dwarfs is in the near infrared, and one can thus measure them out to the greatest distance at these wavelengths. Their intrinsic faintness requires a large scale survey to effectively probe for M dwarf planet transits. The wide field and sensitivity of VISTA make it ideal for the task. Some of us (led by Hodgkin & Pinfield) are conducting a "VISTA Pilot Survey" using the Wide Field Camera on UKIRT, and have demonstrated the capabilities of such a survey. We have shown that at low galactic latitudes (*b*), transits could be measured with just 2-3 mmag residuals (see Figure 1). This is in contrast to higher *b*, where we have found (using UKIDSS DXS data) that ∼10 mmag residuals are usual. This difference comes about largely due to the number of available comparison stars for construction of light curves. If one has to measure comparison stars over a large area of an array, systematic errors (e.g. flat field variations) increase. If VISTA is to effectively search for M dwarf planets, a dedicated public survey at low *b* is required, and will provide a rich dataset for coordinated international follow-up and interpretation of planetary populations, by an already strong exoplanet community in Europe.

### 2.2 Immediate objective:

We can begin the WFCAM Transit Survey (WTS) in P79, and observe in flexibly scheduled poor seeing conditions (>1 arcsecond) over a 4 year period. The WTS is undemanding in this respect, and can effectively make use of such time without compromising the science objectives. Light curve analysis will be done using relative photometry, which is not significantly affected by poor or moderately variable seeing. Also, a random timing of observation periods is quite acceptable (see Section 4), and is well served by this approach.

**The WFCAM planet catch:** To determine the sensitivity of the WTS to potential M dwarf planets, we have made a simulation of the survey. Precise predictions of the number of transits are difficult due to the relative novelty of the subject. The alignment probabilities as a function of separation are less good than around solar type stars because M dwarfs are smaller. However, we would recover this probability if M dwarf planets orbit their hosts closer in. This could be the case if the planetary system scales with primary mass – the inner edges of dust disks around young low-mass objects can be as close as ∼2 stellar radii (e.g. Luhman et al. 2005), and the known planet around the M dwarf GJ436 orbits at 14 $R_\star$. In light of this we consider separations from 0.006–0.06AU (or periods of ∼0.5–10 days).

For giant planets we have assumed that 1% of stars are hosts (the "planet fraction"; PF). This is the same as evinced by hot Jupiters around solar type stars, and is also reasonably consistent with the existence of the planets around GJ436 and GJ876. Small rocky planets could be much more common, and we thus model a range of PFs for these. We simulated a survey population of ∼20,000 M dwarfs ($M_J > 6$, J<16) which matches 2MASS star counts, using the luminosity function of Chabrier (2003) and the disk model of Zheng (2001). Stellar radii and masses were taken from the Lyon Group models. Companion planets were randomly assigned for 0.006-0.06AU separations to give a flat log(P) distribution. Planet radii were selected from 0.1 $R_{Jup}$ (1 $M_{Earth}$) up to 1 $R_{Jup}$ (1 $M_{Jup}$). Light curves of transits were modelled assuming random inclinations (Goldstein 1981), and *observed* (see Section 4) with VISTA sensitivities (employing the expected systematic errors shown in Figure 1), assuming average seeing of 1.3 arcseconds. A planet is detected if we measure ≥4 separate transits, and obtain a combined in-transit signal-to-noise greater than 10 (see Section 4 for details on these criteria).

The results from our simulations are summarised in Table 1 and an example planet catch is shown in Figure 2. Note that we have also used the code of Gillon et al. (2005) to carry out an independent simulation, and find consistent results for both. In brief, if 30% of M dwarfs have close large rocky planets, we would expect to detect ∼10 of them. Even for a 10% rocky PF we would still find ∼3. The close Neptune-like catch remains significant even for a PF of 1–2% due to increased transit depth, and would yield ∼5 Neptune-like planets around M dwarfs. Approximately 15 Jupiter-like and Saturn-like planets could be discovered, although the Jupiter-like PF may be less than 1% if such planets do not form easily around M dwarfs.

Figure 2 shows the separation–stellar mass plot for a WFCAM planet catch with PFs of 1% for Jupiter-like and Saturn-like planets, ∼2% for Neptune-like planets and 30% for large rocky planets. It can be seen that all the transiting planets are at smaller separations than the classical habitable zone (Kasting et al 1993; enclosed

Table 1: Simulated WFCAM M dwarf planet catch for different planet sizes and planet fractions (PFs).

| Planets | Radius ($R_{Jup}$) | Transits found (PF=planet fraction) | | |
|---|---|---|---|---|
| | | PF=30% | PF=10% | PF=1% |
| Large rocky planets | 0.10-0.25 | ∼10 | ∼3 | – |
| Neptune-like | 0.35 | – | – | ∼5 |
| Saturn-like | 0.8 | – | – | ∼15 |
| Jupiter-like | 1.0 | – | – | ∼15 |

by the dashed lines). However, these M dwarf planets will be tidally locked, and the habitable zone for such synchronously rotating systems is not simply a function of stellar mass. If a water trap forms on the dark side of such planets, then a low pressure atmosphere can maintain a dark side/terminator habitable region. Joshi Haberle & Reynolds (1997) have shown that for 100mb atmosphere, a habitable region could exists for orbits with 3 times the terrestrial insolation. This limit is indicated with a dotted line, and it is thus apparent that for a rocky planet PF≥30% the VTS could identify such potentially habitable planets around late M dwarfs.

**Complementary science drivers:** The general approach that we adopt for our transit survey is also extremely amenable to many other areas of time-domain astronomy. Since our observing strategy has some inherent flexibility, we have chosen to optimise the survey to facilitate the best science across a range of fields.

**Plutino discoveries and new realms of the Kuiper Belt:** The VTS also presents a remarkable opportunity to probe the Kuiper Belt region of our Solar system, and a fraction of the survey area has been chosen to be towards the Kuiper Belt (see Figure 3). So far only 931 Kuiper Belt Objects (KBOs) have been discovered out of a suspected $10^5$ objects (>100km in size) that are likely to inhabit the outer solar system. These icy KBOs retain a record of the earliest stages of solar system formation. Given the rate of motion of KBOs and the observing strategy employed by the VTS (see Section 4), we expect to be able to identify and follow KBOs for several months, providing orbit determination. We expect to find ≥400 new KBOs over the course of the 4 year survey. We will also be able to detect rotational signatures of elongated KBOs in VTS light curves, providing measurements of spin rate, shape and size. Currently, only 2% of the known KBO population have published rotational light curves, so the VTS could potentially increase this number by a factor of ∼20. Studies of the statistical properties of KBO rotation are suggestive but based on low numbers (e.g. Snodgrass et al. 2006). A well constrained KBO period cut-off, for instance, would have important implications for modelling their internal structure (cf. Weissman 2005).

There is also the exciting possibility of detecting objects that are larger than Pluto. Indeed, one such object was recently discovered (Bertoldi et al. 2006), provisionally designated 2003 UB313. With a limiting magnitude (for a typical nightly image stack) of J∼20.5-21, the VTS could easily detect new objects like 2003 UB313 out to ∼160AU, much further than the 92AU at which 2003 UB313 was discovered.

**Low-mass stars and brown dwarfs:** Our VTS light curve data will provide an unprecedented sample of field M dwarf rotation curves. Greatly increased numbers of measured M dwarf periods and spot covering fractions should significantly improve improve our understanding of the stellar dynamo for fully convective objects (e.g. Chabrier & Kuker 2006), with its implications for angular momentum evolution and disk-star interactions. A large variety of other types of stellar variability could also be studied using VTS data (e.g. Eyer 2006). There is a large potential for discovering low-mass eclipsing binaries in the VTS. Recent discoveries such as a young eclipsing brown dwarf binary (Stassun et al. 2005) allow us to empirically test our theoretical understanding of the physics of low mass objects. The VTS will monitor ∼6000 late M and early L dwarfs (see Reid et al. 2004) to J∼18, and it is likely that more very low-mass eclipsing binaries would be found.

**Searching for the faintest white dwarfs with high proper motion:** Since VTS observations of each region of sky will be spread across 2 years, deep high proper motion searches will be able to probe for interesting populations. For example, the MACHO survey (Alcock et al., 2000) and a proper motion survey for population II white dwarfs by Oppenheimer et al. (2001) sparked a lively debate whether white dwarfs contribute a large share of the (stellar) dark matter of the Milky Way. More recent results (e.g. Pauli et al. 2006) indicate that white dwarfs contribute more mass than previously thought, but not as much as suggested by the initial

MACHO and Oppenheimer et al. results. However, all systematic surveys for cool white dwarfs were performed in the optical. This imposes a strong bias for the detection of hydrogen-rich white dwarfs, whose optical fluxes are much enhanced compared to their redder counterparts with helium-rich envelopes (e.g. Hansen 1998).

However, it is possible that a high amount of stellar dark matter could be locked up in cool He-rich white dwarfs. The best chance to detect these objects is as high proper motion objects in a deep infrared survey. Although very faint, multi-band photometric follow-up will be capable of confirming the spectral morphology of helium rich white dwarfs. We simulated the local white dwarf population based on the results of Pauli et al. (2006). Our simulation predicts the detection of a few He-rich white dwarfs in the VTS, *if* their space density is that extrapolated from the observed white dwarf population. However, we will be able to put strong constraints on any excess population of cool He-rich white dwarfs that might contribute to galactic dark matter.

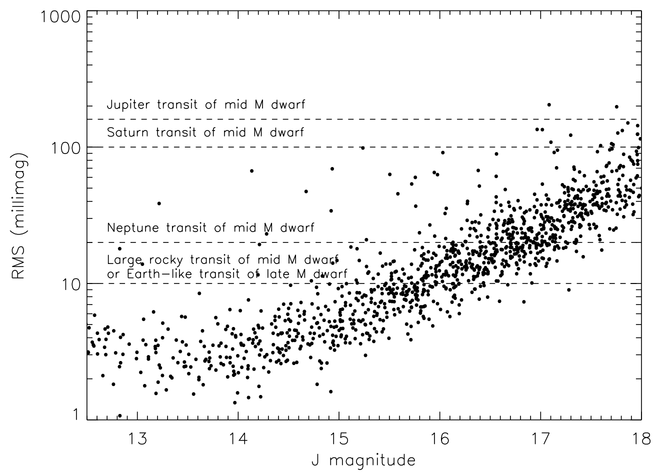


Figure 1: This RMS diagram is derived from 42 observations of one paw-print with WFCAM (from the pilot survey). Each observation comprises 90 seconds of integration (9-point dithers). The cadence of the observations is 12 minutes (8 pawprints are observed). We have averaged the data over 4 data points (the likely duration of a transit) to show our sensitivity. We achieve a precision of 2-3 mmags at the bright end, and ∼1% at J=16. The depth of various planetary eclipse dips are indicated with dashed lines.

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

Corot and Kepler will attempt to detect rocky planets around solar type stars from space, and Kepler will aim for Earth analogues in the habitable zone. A ground based M dwarf transit survey represents an extremely economical (by comparison) and yet complementary way to seek out habitable planets of a different ilk. The full extent of the habitable zone for different stellar populations needs to be properly investigated if we are to fully appreciate the scope of life bearing worlds.

There are a variety of ground-based optical transit surveys currently being made using telescopes with apertures from just a few centimetres up to 4m (see Horne 2003). However, it is an ongoing challenge for the very wide angle surveys to beat down the systematic errors in their measured light curves. The smaller optical surveys generally have less problems with systematic errors but are optimal for optically bright stars. The small pixels, large field of view, and infrared capability of VISTA make it an ideal choice to search for planets transiting M

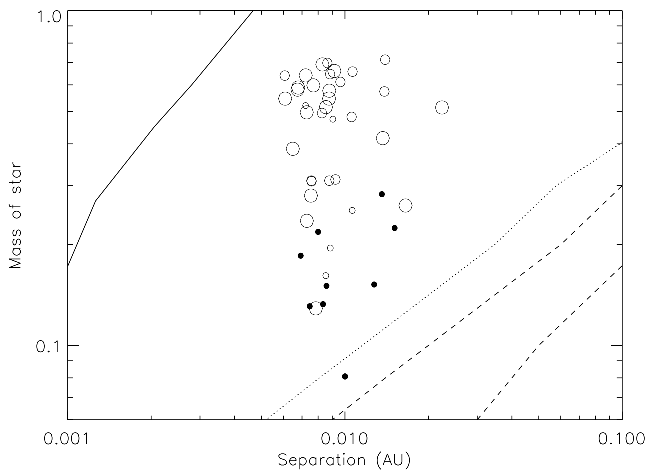


Figure 2: Simulated M dwarf planet catch for the WFCAM Transit Survey, with M dwarf PFs of 1% for Jupiter-like (large open circles) and Saturn-like (medium open circles) planets, 2% for Neptune-like planets (small open circles), and 30% for 2.5 $R_{Earth}$ large rocky planets (small filled circles). The simulated separation range is 0.006-0.06AU. The stellar surface is shown with a solid line. The classical habitable zone is indicated with dashed lines. A synchronously rotating inner habitable limit is indicated with a dotted line (see text).

dwarfs.

The benefits of moving into the near infrared to detect planet transits has been known for some time. Plavchan et al. (2005) are carrying out an M dwarf transit search using 2MASS calibration fields. These fields cover ∼4 sq degs, and were measured with 7.8s exposures by the 1.3m 2MASS telescopes. By comparison, the proposed VTS will cover ∼10 times the sky, with ∼4 magnitudes more sensitivity. It is most encouraging that even with the modest 2MASS transit survey parameters, two candidate M dwarf giant planet transits have been identified (Jura, private communication). But it is clear that the sensitivity and scope of this 2MASS survey is a long way short of providing the potential to detect populations of rocky planets, as VISTA could.

Several of us (led by Hodgkin & Pinfield) are carrying out a VISTA Pilot Survey to search for transits using the Wide Field Camera (WFCAM) on the UK Infrared Telescope. This survey has allowed us to test the use of near infrared technology for transit surveys of this type, and we succeeded in obtaining the required level of accuracy to potentially detect rocky planets around M dwarfs (see Figure 1). The WFCAM survey is scheduled to cover 3 sq degs of sky, with essentially the same cadence as the proposed VTS. The VTS could, however, monitor ∼13 times as many M dwarfs, with a lot more time coverage, and will thus be much more sensitive to transits, with a detection rate tens of times faster.

There are two ongoing surveys (UKIDSS UDS and DXS) and two proposed VISTA public surveys (VIDEO and V-UDS) that can provide a significant quantity of near infrared light curve data, with the potential to detect M dwarf transits. However, UDS and V-UDS are for small areas of sky, and DXS and VIDEO would provide only limited light curve coverage. Also, all these surveys are at high galactic latitude. This latter point is key, since the number density of stars at these galactic latitudes is insufficient to measure light curves with the accuracy to detect small planets. For instance, we have measured light curves using DXS data at $b$ =45, and find 10mmag systematic errors (this is the level of an eclipse dip when a large rocky planet transits a mid M dwarf). Giant planet and brown dwarf transits of mid-late M dwarfs could be detected by such surveys, if such systems are sufficiently common, but the detection of smaller planet transits will certainly be beyond their capability.

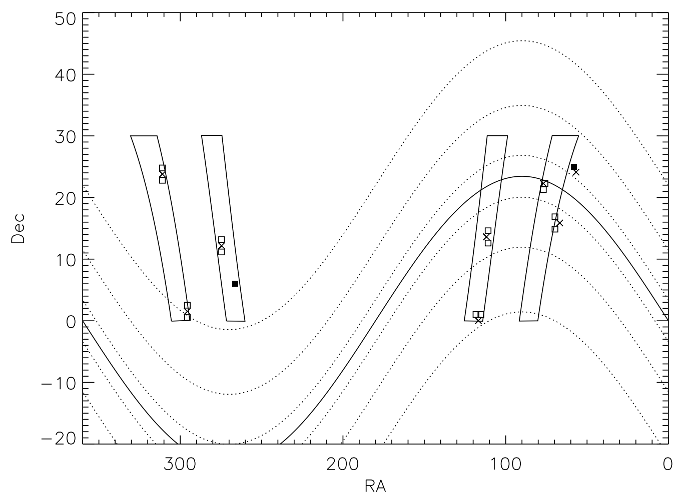


Figure 3: The location of the survey regions on the sky (shown as filled squares). Areas with $|b|$=10-20 and 0<Dec<30 are enclosed by solid lines (see Section 4). The following open clusters are indicated with triangles; Herschel 1, Alessi 44, Alessi 19, NGC 2395, Hyades, Platais 4, Alessi 4, Alessi 12, Pleiades. The ecliptic is shown as a solid line, with the extent of the classical Kuiper belt, the region in which Plutinos are found, and the scattered Kuiper belt (from Brown et al. 2001) shown as dotted lines.

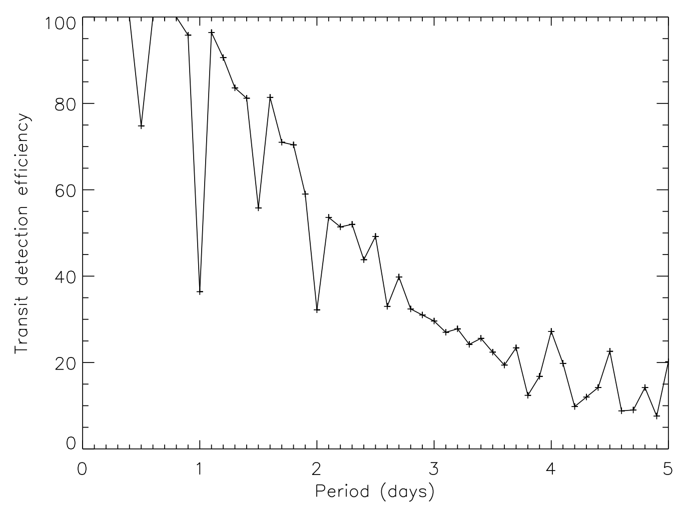


Figure 4: The simulated efficiency of the proposed WTS transit detection for 200 hrs on each region. A confirmed transit detection requires that at least 4 separate transits are measured, and a total in-transit signal-to-noise of at least 10 is obtained.

# 4 Observing strategy: (1 page max)

**Observing conditions:** The VTS will measure its light curve data in a series of observing blocks that can be queue scheduled on VISTA. We define our survey strategy to make use of randomly timed observation blocks, and this means that the VTS can take advantage of certain weather conditions. Our target stars are not faint, so we can make use of poor seeing conditions. About 28% of usable VISTA time is expected to have seeing worse than 1 arcsecond (by comparison with Paranal), with ∼10% worse than 1.3 arcseconds. This time is quite acceptable for the VTS, and will not compromise the science. Also, about 20% of usable VISTA time is likely to have thin cloud (∼20% photometric variation). This time might also be useful for the VTS, since our light curves will be measured using relative photometry. However, we would prefer clear poor seeing conditions to thin cloud, to avoid complex differential spatial transmission across the field (which can be difficult to calibrate out). We estimate that ∼41 of the 236 public survey nights will be clear with seeing worse than 1 arc second, and thus propose to carry out our survey in this time (except for a single $ZYJHK_s$ exposure; see below).

**Time per region:** We define our general observing strategy based on our VISTA Pilot Survey (using WFCAM). In this pilot survey we obtain 2–3 mmag accuracy within a transit time-scale (see Figure 4), and thus estimate that, for 1% eclipse dips of J≤14 M dwarfs, we will need to measure 4 separate transits to obtain a combined in-transit signal-to-noise of 10 (although note that large planets can cause much larger eclipse dips when transiting M dwarfs, and will be detected out to fainter magnitudes; see Figure 1). We have simulated the efficiency with which the VTS could achieve this 10-$\sigma$ detection requirement, and find that 200 hours on each region of sky is efficient for the short period (0.5–3 day) transits we seek. A plot of the predicted survey efficiency is shown as a function of a planet's orbital period in Figure 4.

**Light curve sampling:** Well sampled light curve data is important to both effectively sample the transits and allow for any non transit signatures to be identified. We note that M dwarfs can show enhanced chromospheric activity when young, and their light curves can show periodic quasi-sinusoidal modulations at the 1-2% level due to photospheric spots. However, it is relatively simple to distinguish and disentangle eclipse events from rotational modulation on the basis of shape and duty cycle provided one has well sampled light curves. Field M dwarfs do not show the kind of flickering/accretion phenomena that makes a transit survey in a star forming region so difficult (e.g. Caballero et al. 2004).

**Sky coverage and cadence in an observing block:** Although high cadence in an observing block is desirable, a balanced must be found that allows one to cover sufficient sky, and observe in an efficient manner. The VTS will use 12s DITS (Ndit=1, Nexp=1, NxM=1) in a jitter-pattern (Njitter=4) at each paw-print position. The sky coverage in an observing block will consist of 8 non over-lapping paw-prints (Npaw=8). These will consist of 4 pairs of offset paw-prints (each covering 2/3 of a tile), with pairs of paw-prints located next to eachother on the sky, within a 2x2 tile region − ie in a 2.4x3.0 degree region that is 66% covered. This maximises sky coverage efficiency, allowing 4.8 sq deg regions to be measured in ∼10 mins. This observing sequence will be repeated 6 times per hour for the length of the observing block, to provide well sampled light curve data.

**The length of observing blocks:** Observing blocks could last between 1 hour and 2 hours. 2 hours would be preferable for detecting complete transits in a single block, although we are conscious that ESO may prefer to flexibly schedule 1 hour blocks. In this case, back-to-back VTS block observations could be encouraged in the queue, and in any event, transits could be searched for in phase folded multiple block data.

**Filter choice:** We will observe our light curves in the $J$-band only, since M dwarf colours dictate that they are detectable out to the greatest distance in this filter. The only exception is a one-off single $ZYJHK_s$ image of each region in median seeing to allow both better identification of M dwarfs (photometrically) and the means to identify some sources that could be blended in the main survey images. This is only a small additional requirement (∼1 night), but will be very useful when creating an optimal list of transit candidates.

**Full survey coverage, and requested time allocation are discussed in Section 5.1.**

# 5 Estimated observing time:

| Period | Time (h) | Mean RA | Moon | Seeing | Transparency |
|---|---|---|---|---|---|
| P79 | 200 | 18h | any | >1” | clear⋆ |
| P80 | 200 | 6h | any | >1” | clear⋆ |
| P81 | 200 | 18h | any | >1” | clear⋆ |
| P82 | 200 | 6h | any | >1” | clear⋆ |
| P83 | 200 | 18h | any | >1” | clear⋆ |
| P84 | 200 | 6h | any | >1” | clear⋆ |
| P85 | 200 | 18h | any | >1” | clear⋆ |
| P86 | 200 | 6h | any | >1” | clear⋆ |

⋆ We prefer clear conditions (see Section 4), although some thin cloud conditions could be used.

## 5.1 Time justification: (1 page max)

**Total time request:** We chose to observe four 4.8 sq deg regions in any particular year, spread in R.A. to allow the VTS to have access to the poor seeing time all year round. In the expected ∼40 nights of poor seeing time per year, the VTS could thus observe each region for ∼100 hours. We can thus complete the 200 hours on each of these four regions in 2 years. To increase the number of M dwarfs monitored (to ∼20,000 down to J∼16), the VTS will repeat this process for an additional 2 years, on four new regions of sky. We will thus obtain 200 hours of light curve data per M dwarf in eight 4.8 sq deg regions. The total time request if thus 1600 hours of poor weather conditions across 4 years.

**Optimal coordinates for science and scheduling:** We avoid zenith distances < 5 degrees, since VISTA's alt-az axis moves unusually fast in this range. We thus chose fields in the declination ranges $0 > \delta > -20$ and $-30 > \delta > -45$. We chose 5 regions in the more southerly range and 3 regions in the more northerly range. This preference reflects our expectation that for declinations north of -20, 12-18m/s prevailing winds will cause a small fraction of time (10-15%) to be lost. However, it is clearly beneficial to be able to use northern facilities for follow-up of transits (see Section 6), so we include regions in both declination ranges. In order to meet the important requirement that the number density of background comparison stars is high (see Section 2.2), we chose fields with $|b|$=10-20. This is also beneficial because there are 2-3 times as many M dwarfs to J∼16 at these galactic latitudes compared to the galactic cap. However, we avoid $|b|$ <10 since high levels of contamination by reddened stars and giants make it difficult to select clean photometric M dwarf samples.

Within these constraints, and spread in RA, we chose 4 of our regions towards the Kuiper belt (to facilitate solar system science), and locate five fields close to open clusters (with ages from 100Myrs–2Gyrs), to provide the possibility of serendipitous cluster transits and more general cluster science (e.g. variable stars, the low-mass IMF). The survey fields are shown in Figure 3.

# 6 Data management plan: (3 pages max)

## 6.1 Team members:

| Name | Function | Affiliation | Country |
|---|---|---|---|
| CASU (VDFS) team | Pipeline processing | University of Cambridge | UK |
| CASU (VDFS) team | Data Quality Control-I | University of Cambridge | UK |
| J. Emerson | VDFS Coordinator | Queen Mary University of London | UK |
| WFAU (VDFS) team | Science Archive | University of Edinburgh | UK |
| WFAU (VDFS) team | Data Quality Control-II | University of Edinburgh | UK |
| | **The VTS Survey specific tasks** | | |
| D. Pinfield | PI | University of Hertfordshire | UK |
| C. Afonso | Light curve analysis | MPIA Heidelberg | Germany |
| S. Aigrain | Light curve optimisation and clean-up | University of Cambridge | UK |
| S. Hodgkin | High quality light curve generation | University of Cambridge | UK |
| R. West | Time domain archive at Leicester | University of Leicester | UK |
| P. Wheatley | Time domain archive data mining tools | University of Warwick | UK |

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:

**Survey coordination:** The PI will supervise the implementation and progress of the survey. This will include preparation of the observations (the observing blocks), and input and feedback on light curve generation, the form of the light curve database, and the light curve analysis tools. He will also set up a VTS candidate transit list to coordinate the followup of VISTA transits, and a public "Vista planet list" to provide "outreach" information about VISTA planets.

**The VDFS:** 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).

## 6.3 Data reduction plan:

The data reduction will be using the VDFS, operated by the VDFS team, 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,

**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 systematic errors; 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.

**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/*

**VTS software tools and archive:** Although the VDFS/VSA will development some basic VSA tools to facilitate a range of time domain physics with VTS data, we will also lead the development of some additional

VTS requirements. To facilitate optimised VTS light curves, Hodgkin will lead the development of software tools and the optimisation of analysis techniques to extract the most accurate milli-mag light curves from the VTS data (building on our experience with the VISTA Pilot Survey). These light curves will be placed in a VTS database in Leicester (UK) that will be set up by West. Afonso and Agrain have operational pipelines already constructed that will search the light curve data for transit signatures. Wheatley will also provide more general "Time domain data mining tools" for mining the light curve archive (making use of "WASP heritage").

### 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 re-measurement parameters from consistent list-driven photometry across all available bands in any one field.
- Light curve database with data-mining tools.

### 6.5 General schedule of the project:

**Year 1:** Data on the first four 4.8 sq deg regions will be taken throughout the year (totalling ∼40 nights of poor weather time). The release of science products (to the survey working group) from the first month of survey observations will happen 4 months after survey commencement. As the archival data grows, the light curve extraction/analysis tools will be optimised for the VISTA data. The first six months of data products will be released to the survey working group 8 months after survey commencement. Thereafter we would hope that science products can be released to the working group within 1-2 months of raw data arriving in the UK. The survey working group will perform science verification on the data, and public release will occur in the semester following the one in which the raw data arrived in the UK.

**Year 2:** Data on the first four 4.8 sq deg regions will continue to be taken (totalling another ∼40 nights). As the number of candidate transits grows, follow-up will begin in earnest (see Section 7).

**Year 3 and 4:** The first four sky regions will be replaced by the second four, and the survey will proceed as in years 1–2, with science products being released to the survey working group within 1-2 months of raw data arriving in the UK, and public release in the following semester. At the end of year 4 optional reprocessing of data, based on improved knowledge of the instrument would be considered, and a final data release made.

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

## 7.1 Identifying false positives

The "false positives" are a major concern for transit searches, and it is vital to diminish the need for time consuming radial velocity follow-up on 8m telescopes, by removing as much contamination as possible. The main contaminants are eclipsing binaries with grazing geometries, transits of a small star in front of a large star, (e.g. a K dwarf in front of a giant) and finally eclipsing binary systems blended with the light of another star along the line of sight. We will address possible blending to some degree with our "median seeing" images (see Section 4), and carry out analysis on the photometric morphology of the light curves to search for evidence of blends and stellar companions (e.g. Drake 2003; Sirko & Paczynski 2003; Seager & Mállen-Ornelas 2003). However, results from OGLE follow-up indicate that the number of contaminants at the 1% eclipse dip level can largely outweight the planetary transits, and we will thus employ an efficient and thorough follow-up strategy.

**Spectral typing:** Low resolution optical or near infrared spectroscopy will confirm the spectral type of candidate transit sources. This will identify any giant star contaminants, and will also allow the mass and radius of candidate transits to be estimated, by placing tight constraints on the size of the stellar host. This task can be done quickly using a variety of 2–4m class telescopes. The spectral types will feed back into the VTS candidate transit list, allowing for the removal of contamination and the flagging of particularly interesting candidates.

**Medium resolution RV studies:** Medium resolution spectroscopy will be capable of rapidly identifying eclipsing binaries with grazing geometries using 4m telescopes, since the expected amplitudes are generally several tens of $\mathrm{kms}^{-1}$, compared to a few hundred $\mathrm{ms}^{-1}$ caused by, for example, a Jupiter-mass planet orbiting an M dwarf.

**Multi-band light curves:** For blends however, the main star may show little or no velocity variation, suggesting the presence of a very low-mass companion. Multi-band photometric followup can be used to search for colour changes that will indicate a blended source where a transiting stellar companion is mimicking a planet. We will carry out multi-band photometric follow-up of candidates on a variety of facilities. In particular, we have guaranteed time (GT) on a range of facilities available for this program. We will use OmegaCam/VST GT of the Observatory of the Ludwig Maximillian University in Munich and the Max-Planck Institute for extraterrestrial physics (Saglia, Bender). We also plan to use GT of the Max-Planck Institute fuer Astronomie, Heidelberg, with the Wide Field Imager (WFI) on the 2.2m telescope on La Silla (Henning).

**High resolution RV studies:** We will carry out radial velocity follow up of our decontaminated transit candidates using several facilities world wide. The most challenging radial velocity measurements will be for potential rocky planet transits. However, we are aided by the relatively high reflex velocity of the low-mass M dwarfs around which such transits can be detected. For a $10\,\mathrm{M_{Earth}}$ rocky planet transiting a $0.1$–$0.25\,\mathrm{M_\odot}$ M dwarf at 0.01AU, we expect an M dwarf reflex velocity of $\sim$20-30 $\mathrm{ms}^{-1}$. We know from our simulation that VTS can detect such transits around stars with $J<14$ (for which we will achieve the 2-3 mmag uncertainties necessary to measure 1% eclipses). Gemini and GranTeCan are gearing up with new high performance high resolution (e.g. R$\sim$42,000) near infrared spectrographs, whose science drivers are strongly motivated by the prospects of detecting low-mass planets around M dwarfs. These instruments will meet the challenge of measuring the radial velocity signatures of VTS rocky planet transits. Jones is leading the bid for the near infrared PRVS spectrograph on Gemini. Martín is PI of the proposed NAHUAL spectrograph for GranTeCan.

More massive Jupiter- and Saturn-like transits will produce M dwarf reflex velocities of $>100\mathrm{ms}^{-1}$. We will measure such RVs with instruments like CRIRES on the VLT and NIRSPEC on Keck (for the more northerly transits – we will have access to NIRSPEC through Martín for instance). We can also use UVES on the VLT to measure radial velocity signatures in the optical of giant planets around many of our early or brighter M dwarfs (e.g. Joergens, 2006). Some of us (Saglia, Bender) have a 7.5% share of the Hobby Ebberly Telescope (the HRS provides capabilities similar to UVES), and part of this time would be used to follow up the more northerly transit candidates.

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

## 8.1 Follow-up of confirmed planets

Once confirmed, the VISTA planets will be a focus for a large variety of giant and rocky planet science. Detailed radius measurements (e.g. Wittenmyer et al. 2005) will reveal the planet density. Reflected light studies (e.g. Leigh et al. 2003) and emitted light measurements (Deming et al. 2005; Charbonneau et al. 2005) will constrain the physics of the planetary atmospheres. These studies will benefit greatly from reduced star/planet brightness contrast ratios. Also, transmission spectra (e.g. Ehrenreich et al. 2006; Narita et al. 2005) and the Rossiter effect (see Snellen 2004) can be brought to bear on the chemical composition of the planetary atmospheres. Such studies will make use of the latest instrumentation on large ground based telescopes and space based facilities such as Spitzer. They can also drive the development of future 20-30m class telescopes and the JWST, which could for e.g. measure secondary eclipses with un-precedented accuracy.

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