The Kilo-Degree Survey

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The Kilo-Degree Survey (KiDS), a 1500-square-degree optical imaging survey with the recently commissioned OmegaCAM wide-field imager on the VLT Survey Telescope (VST), is described. KiDS will image two fields in *u*-,*g*-,*r*- and *i*-bands and, together with the VIKING survey, produce nine-band (*u*- to *K*-band) coverage over two fields. For the foreseeable future the KiDS/VIKING combination of superb image quality with wide wavelength coverage will be unique for surveys of its size and depth. The survey has been designed to tackle some of the most fundamental questions of cosmology and galaxy formation of today. The main science driver is mapping the dark matter distribution in the Universe and putting constraints on the expansion of the Universe and the equation of state of dark energy, all through weak gravitational lensing. However, the deep and wide imaging data will facilitate a wide variety of science cases.

Survey design

KiDS is part of a long heritage of ever improving wide-field optical sky surveys, starting with the historical photographic plate surveys. The KiDS survey targets two areas of extragalactic sky, some 750 square degrees each, to ensure that observations can be done all year. While KiDS observes in four filters (*u,g,r,i*), the companion VIKING project on the neighbouring Visible and Infrared Survey Telescope for Astronomy (VISTA) is already covering the same area in five near-infrared bands: *z*, *Y*, *J*, *H* and *Ks*. The two fields (Figure 1) are chosen to overlap with previous and ongoing galaxy redshift surveys, which means that the foreground galaxy distribution is already mapped out, and that spectral diagnostics for several 100 000 galaxies are already available. One of the central aims of KiDS is to "weigh" these galaxies systematically as function of their type and environment.

The exposure times of KiDS (see Table 1) are chosen such that the survey will reach a median galaxy redshift of 0.7. They are also well-matched to the natural exposure times for efficient VST operations, and balanced over the astro-climate conditions on Paranal (seeing and Moon phase, see Table 1) so that all bands can be observed at the same average rate. This strategy takes advantage of the Paranal queue-scheduling system, which makes it possible to use the best seeing time for deep *r*-band exposures, for example, and the worst seeing for *u*-band. After completion of the survey, repeat observations of the full area in the *g* filter with a minimum time difference of two years are planned, allowing proper motion measurements.

Half of the KiDS area overlaps with the Sloan Digital Sky Survey (SDSS; Abazajian et al., 2009), and, since very similar filter bands are used, the KiDS photometric calibration can be checked thoroughly. All VST observations are observed in the context of a nightly calibration plan that relies on a number of large standard star fields established as part of the OmegaCAM instrument development (Verdoes Kleijn et al., 2013). As the survey grows and information from overlapping pointings is incorporated, the overall photometric accuracy will continue to improve.

Filter	Exposure time	FWHM	Moon phase
u	900 s	< 1.1″	< 0.4
g	900 s	< 0.9″	< 0.4
r	1800 s	< 0.8″	< 0.4
i	1080 s	< 1.1″	any

Table 1. KiDS exposure times, maximum point spread function size (full width at half maximum [FWHM]) and Moon phase per filter.

Science drivers

The central science case for KiDS is mapping the matter distribution in the Universe through weak gravitational lensing and photometric

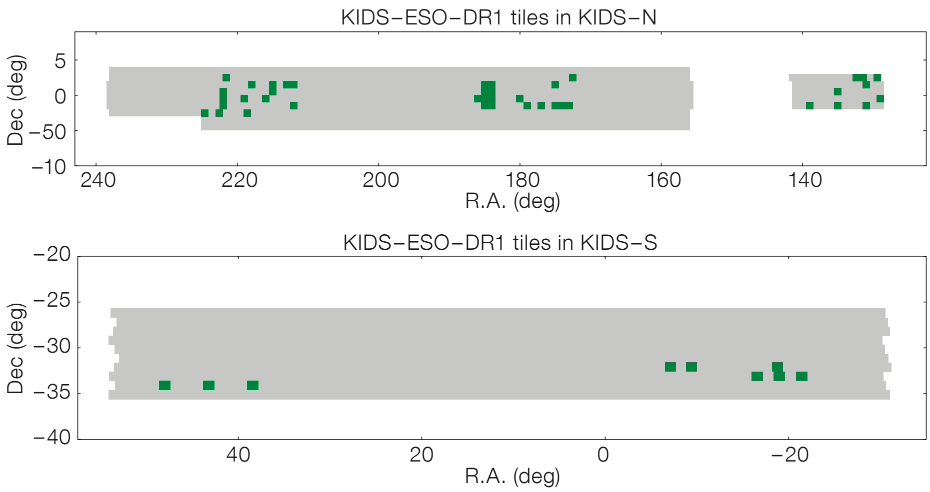

Figure 1. Layout of the two KiDS fields. The KiDS-North (upper) and KiDS-South (lower) fields are indicated in grey. Green rectangles show the pointings that are included in the first KiDS data release (KiDS-ESO-DR1).

redshift measurements. The power of using weak gravitational lensing as a cosmological probe relies on two facts: it is a very geometric phenomenon; and, it is sensitive to mass inhomogeneities along the line of sight (see e.g., Peacock et al., 2006). This makes gravitational lensing both a good probe of the growth of structure with time (redshift), as well as a purely geometrical distance measure. Both the distance–redshift relation and the rate of growth of overdensities with cosmic time depend directly on the expansion history of the Universe, and thus form the most fundamental measures of the energy content of the Universe. Weak lensing is an excellent method for making such a measurement, although the requirements on the systematics of shape measurements and photometric redshifts are challenging.

With the combination of KiDS and VIKING we have put ourselves in the optimal position to attempt this, by ensuring the best image quality in our instrument, and having a wide wavelength coverage that maximises the accuracy of the photometric redshifts. An independent measurement of the expansion history of the Universe can be made using baryon acoustic oscillations (BAO), utilising the high-precision photometric redshift measurements that will be provided by KiDS and VIKING.

However, the KiDS dataset will have many more possible applications, and the main science interests pursued by the KiDS team are briefly discussed below. Note that the primary gravitational lensing science case sets tight requirements on the astrometric and photometric calibration of the data, which is of direct benefit to other analyses as well.

Numerical simulations provide a detailed picture of the assembly and structure of dark matter haloes at large scales. At smaller scales complex baryonic physics starts to play an important role, and this is not represented realistically in current models (e.g., van Daalen et al., 2011). The relation between dark matter and baryons is crucial to our understanding of galaxy formation and evolution. Galaxy–galaxy lensing (GGL) can provide observational constraints on the relation between mass and light at scales ranging from 10 kpc to several Mpc. Since the gravitational lensing effect from single galaxies is very weak, it can only be detected statistically, by averaging over large numbers of galaxies. The size of KiDS will afford an enormous sample of galaxies, allowing the GGL effect to be studied as function of galaxy type and redshift.

Several ramifications of the current cosmological paradigm for the formation and evolution of galaxies have, until now, eluded rigorous observational testing. For example, the influence of galaxy mergers is poorly determined, and the number of known galaxy clusters at $z > 1$ is too small to constrain the models. Also here, KiDS can make an important contribution. The survey is expected to yield 10^8 galaxies with a median redshift of 0.7, and 1–2 × 10^4 galaxy clusters, 5% of which are at redshifts greater than 1. Since KiDS also overlaps with two nearby superclusters (Pisces–Cetus and Fornax–Eridanus), the relation between galaxy properties and environment can be studied from cluster cores to the cosmic web.

To study the stellar halo of the Milky Way, photometry of faint stars over large areas of sky is required. The SDSS proved to be a milestone in Milky Way science, unveiling many previously unknown stellar streams and faint dwarf spheroidal galaxies (e.g., Belokurov et al., 2006). Although it has a smaller footprint than SDSS, KiDS is more sensitive and will provide a view of more distant parts of the halo. Because the KiDS-S area is still uncharted at the KiDS depth, new substructures may still be uncovered.

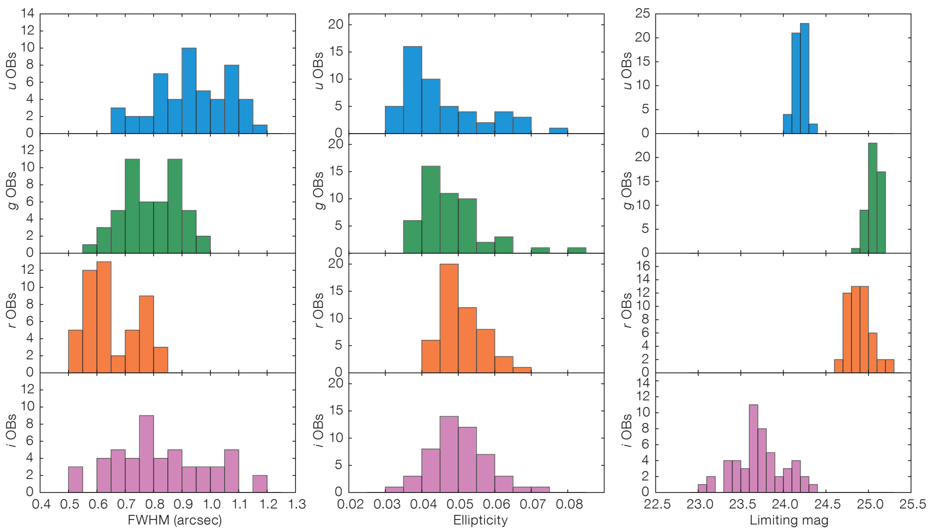

Figure 2. Histograms showing the data quality of KiDS-ESO-DR1. Left: PSF FWHM distribution. Middle: average ellipticity distribution. Right: limiting magnitude (5σ in a 2-arcsecond aperture) distribution. In all columns the panels show from top to bottom *u* (blue), *g* (green), *r* (red), and *i* (magenta) bands respectively.

Finally, the deep, multicolour object catalogues that KiDS will produce are also ideal hunting grounds for rare objects. In particular, the combination with VIKING data is ideal for detecting high-redshift quasars (see Mieske et al. p.12 and Venemans et al., 2013), while the good optical image quality benefits the search for strongly lensed systems. When the planned repeat-pass in *g*-band is completed, the proper motion information will allow the identification of nearby objects, for example brown dwarfs or ultra-cool white dwarfs.

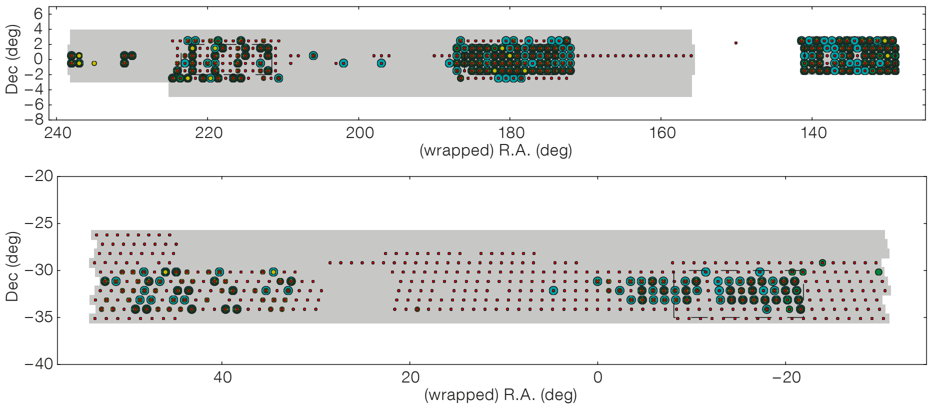

Figure 3. Status of KiDS observations at 1 October 2013. The grey areas correspond to the survey fields KiDS-North (upper panel) and KiDS-South (lower panel). Coloured circles indicate which data has been obtained successfully at each position in a specific filter: *u* = cyan, *g* = green, *r* = yellow, *i* = red. The GAMA spectroscopic survey fields are outlined with black dashed lines.

KiDS-ESO-DR1

The first public data release (DR) of the KiDS survey, dubbed KiDS-ESO-DR1, was made available through the ESO Science Archive in July 2013[1]. Since colour information is important for verifying the photometric accuracy of the data, each DR will only contain pointings that have been observed in all four filters. KiDS-ESO-DR1 comprises the 50 pointings that were completed during the first year of VST operations (15 October 2011 to 1 October 2012) and the preceding Early Science Time period. For these 50 square degrees, DR1 includes the following data products: i) photometrically and astrometrically calibrated stacked images; ii) their associated weight frames; iii) masking flag maps; and iv) single-band source lists. Data products can also be accessed via the KiDS consortium's Astro-WISE information system, which allows the full data lineage to be traced. Note that since the first year of observations, the data rate has increased substantially!

Figure 2 illustrates the data quality of KiDS-ESO-DR1. The image quality (IQ) distribution, expressed as the full width at half maximum of the point spread function, reflects the seeing constraints in Table 1. In *i*-band this distribution is very broad, because most of the bright time with seeing < 1.1 arcseconds is used for KiDS. Designed specifically to deliver good, constant image quality over the full one square degree field of view, the VST/OmegaCAM system generally performs very well, producing images with very low point spread function (PSF) ellipticity. The limiting magnitudes (5σ measured in a 2-arcsecond aperture) obtained are around 25th mag for *g* and *r*, while *u*-band is 0.8 mag shallower. In *i*-band the limiting magnitudes span a wide range due to the larger range in sky brightness.

All data products in KiDS-ESO-DR1 have been produced by the KiDS production team, using a pipeline based on the Astro-WISE astronomical data processing system (de Jong et al., 2013; McFarland et al., 2013). The pipeline version used for this release includes electronic crosstalk correction, satellite track removal, and illumination correction. By tying stellar photometry between the dithers and overlapping CCDs together, pointings are photometrically homogenised, resulting in photometry that is flat within typically 2 % over the full field of view. Absolute photometry is based on nightly calibration field observations. Due to the scattered on-sky distribution of the observations (see Figure 1), the photometry is not homogenised over the whole survey; this will be possible for future DRs encompassing more homogeneous sky coverage.

Automated masking software, dubbed Pulecenella (Huang et al., in prep), was developed for KiDS. This software produces "flag maps" that distinguish between different types of masked areas, such as saturated pixels, readout spikes, diffraction spikes, and reflection haloes. Certain other defects, for example reflections introduced by the open structure of the telescope, have been masked as well. Another stand-alone procedure was developed to produce single-band source lists, relying on SExtractor for source detection and extraction. The source lists provided in this release include star/galaxy separation and a large set of source parameters[2].

Current status

Apart from continuing to prepare and process the ongoing observations in preparation for DR2 next year, the KiDS team is also engaged in scientific analysis of the data. Much of this analysis is focussed on the opportunities that the synergy of KiDS with the Galaxy and Mass Assembly (GAMA; Driver et al., 2011) project offers. The fields of the GAMA survey, a dense spectroscopic survey on the Australian Astronomical Telescope (AAT), lie inside the KiDS areas, and they have been prioritised in the KiDS observations (see Figure 3, which shows the distribution of all data in hand at the time of writing). Combining the large-scale structure (as mapped by GAMA) with the detailed KiDS imaging of the galaxies is enabling an unprecedented study of the relation between galaxy structure, environment and, via lensing, the dark matter distribution.

To extract the cleanest possible lensing signal from the data, the team is also performing a dedicated, lensing-optimised, reduction of the data using the Bonn THELI pipeline (Erben et al., 2013) that was also used for the weak lensing analysis of the Canada France Hawaii Telescope (CFHT) Legacy Survey (e.g., Heymans et al., 2012). Initial indications are that the KiDS data are very well suited to this type of analysis.

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Links

[1] Access to KiDS ESO DR1: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?phase3_collection=KiDS&release_tag=1
[2] For more details on the KiDS-ESO-DR1 pipeline see: http://kids.strw.leidenuniv.nl/DR1