OmegaCAM Science Operations

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The science operations process of the VLT Survey Telescope (VST) camera, OmegaCAM, is described. OmegaCAM is a 267-megapixel CCD camera imaging a 1 × 1 degree field of view with a pixel scale of 0.21 arcseconds. It began operations in October 2011. The telescope and camera provide a survey speed that is five times greater than the now-decommissioned Wide Field Imager on the MPG/ESO 2.2-metre telescope at La Silla. OmegaCAM is currently used for three public surveys, guaranteed time observations for the OmegaCAM and VST consortia, and Chilean programmes. The execution of OmegaCAM observations, real-time quality control and the calibration plan are outlined.

General description of the facility

The VST resulted from a collaboration between the Italian National Institute of Astrophysics (INAF) under the Principal Investigator (PI) Massimo Capaccioli and ESO (see Capaccioli & Schipani [2011] for a description). OmegaCAM[1] was built in a collaboration between ESO and the OmegaCAM consortium (PI, Konrad Kuijken) with contributions from the Netherlands, Germany and Italy and is described by Kuijken et al. (2002) and Kuijken (2011). With OmegaCAM ESO fulfilled its mandate from the ESO Council to provide an optical wide-field imaging capability at Paranal Observatory.

OmegaCAM is the wide-field imager for the Cassegrain focus of the VST on Paranal. The VST is a 2.6-metre modified Ritchey–Chretien alt-azimuth telescope (F/5.5) designed specifically for wide-field imaging, to exploit the good image quality at the Paranal Observatory. OmegaCAM observes from 330–950 nm within a corrected field of view of 1 × 1 degree, four times the size of the full Moon. OmegaCAM samples the VST field of view with a 32-CCD, 16k × 16k detector mosaic with 0.21-arcsecond pixel scale (Figure 2). The CCDs are thinned, blue-sensitive, three-edge buttable CCD44-82 devices from e2v of high (but not perfect) cosmetic quality. In addition to the 32 CCDs making up the science array, OmegaCAM also contains four auxiliary CCDs around the edges of the field that are used for autoguiding and image analysis. Since both guiding and image analysis are performed on the instrument side, the telescope "only" tracks, but does so very well. Outside a zenith-centric circle of about 10 degrees diameter, image quality remains acceptable for up to ~ 2–3 minutes without guiding.

Most data are taken in the five Sloan-like bands *u′*, *g′*, *r′*, *i′* and *z′*, and a narrow-band Hα filter provided by the VPHAS+ consortium. Service mode operations for OmegaCAM started on 15 October 2011. The median full width at half maximum (FWHM) of OmegaCAM images, as measured during the first half year of operation, was about 0.80 arcseconds in *i′*-band, and 0.95 arcseconds in *g′*-band (including the instrumental resolution of 0.4 arcseconds). In the first two years of operations, the sky was clear or photometric 77 % of the time.

Three public surveys are being executed at OmegaCAM (see Figure 3): the Kilo-Degree Survey (KiDS; 1500 square degrees), ATLAS (4500 square degrees), and the VST Photometric Hα Survey (VPHAS+; 2000 square degrees). For their detailed setup and science goals, see the public survey web pages[2] and

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Figure 1. Left: The VST on the VLT platform. Right: OmegaCAM (the yellow volume) mounted on the VST.

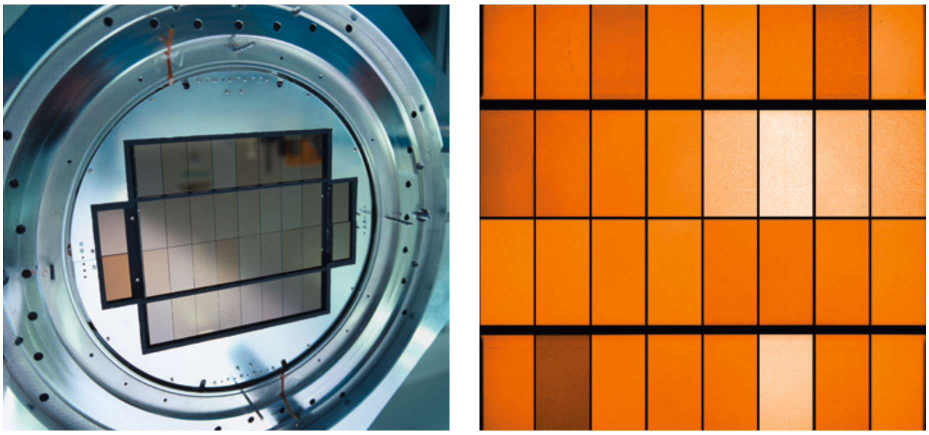


Figure 2. Left: An image showing the 32 (4 × 8) CCD array of OmegaCAM and the four auxiliary CCDs used for guiding and wavefront analysis. Right: OmegaCAM dome flat illustrating individual chip sensitivities, which have a root mean square chip-to-chip variation of ± 6%. The 32 science CCDs cover 92 % of the 1 × 1 degree field of view with only small inter-chip gaps. Dither patterns of a few arcminutes total amplitude are used to image the full field of view.

the dedicated articles in this *Messenger* edition. Releases of data from these surveys are available through Phase 3[3]. The execution of these three surveys takes up 50–60 % of the available service mode time. The remaining 40–50 % is shared between guaranteed time observations (GTO) for the OmegaCAM and VST consortia, Chilean programmes, and calibration observations. The respective shares may evolve over time as a function of programme completion rates.

The survey speed of OmegaCAM is about five times higher than the Wide Field Imager (WFI) at the MPG/ESO 2.2-metre telescope in La Silla (Baade et al., 1999). The good image quality and high blue sensitivity provide a unique window in observational parameter space. Furthermore, it complements very well the near-infrared survey telescope VISTA at Paranal (Emerson & Sutherland, 2010), which is operated at the neighbouring console in the VLT control room. VST and VISTA together cover the entire near-ultraviolet to near-infrared range 0.33–2.35 μm: VST from 0.33–0.95 μm, and VISTA from 0.85–2.35 μm, with an overlap at the z'-band that is used by both facilities.

Execution of observations

All observations on the VST are carried out in service mode. The two surveys with short integration times, VPHAS+ and ATLAS, observe most of the time in open loop (no guiding, no image analysis). Due to the high cadence of ~ 1–2 minutes between images taken at different positions on the sky in these two surveys, there is no time to acquire image analysis stars and perform active optics correction at each new position. A new correction is enforced after, at most, half an hour in such open loop observations. The KiDS survey spends more time on a single pointing due to the science requirement of providing a deep and accurate weak lensing map. KiDS observations are, therefore, performed with guiding and closed loop image analysis.

The telescope and instrument are operated at night by one telescope operator, without a night-time astronomer. The short-term scheduling of observations is done by a program called the Observing Tool (OT; see also Bierwirth et al. [2010]). The basic observation unit containing the full description of the observation sequence (acquisition and science exposures), information about the target and the required observing constraints necessary to achieve the scientific objective, is called an Observation Block (OB). At any given time, the OT filters out all OBs that are not observable in the current conditions (due to seeing, airmass, Moon illumination, sky transparency), and then ranks the observable OBs to match, as well as possible, the observing conditions requested by the users, while

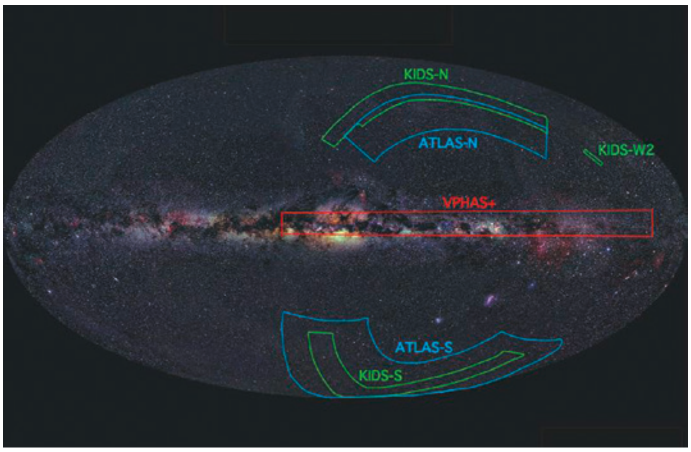


Figure 3. The on-sky footprint of the three public surveys executed with OmegaCAM: KiDS (1500 square degrees), ATLAS (4500 square degrees), VPHAS+ (2000 square degrees).

Figure 4. Distinguished visitors at the VST OmegaCAM console: Chilean president Sebastian Piñera and his wife. Also present in the picture is Paranal staff astronomer Fernando Selman.

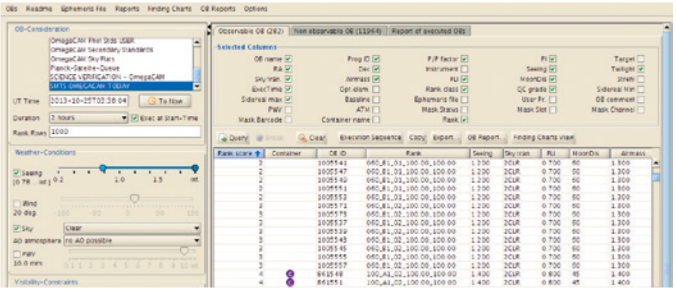


Figure 5. Example screenshot of Observing Block ranking as performed by the Observing Tool.

suggests quality control grades for each OB to the night-time operator (see Figure 6). Specifically, the script calculates, for each frame across the field of view, the mean FWHM, the mean ellipticity and the IQ variation, which is the variation in the FWHM in the centre of the field *vs.* the FWHM at the edge of the field of view. The script also measures the number of single CCD images affected by ellipticities greater than 0.2. These numbers are then appropriately averaged across an OB, or concatenation of OBs, and the script suggests to the operator the zero-level quality control (QC0) grades (fully/almost/not within constraints). The general QC0 acceptance criteria for an OB are: average seeing ≤ 1.1 × requested seeing; average ellipticity ≤ 0.15; and IQ variation ≤ 25 %.

In addition to these criteria for a single OB, the QC0 script includes a number of nested criteria regarding single images, concatenations of OBs, special cases like GTO and agreements with consortia about deviations from the general QC0 acceptance criteria per OB. The script also contains a number of warning flags which highlight image quality and calibration plan issues to the operator. The full set of these criteria is quite complex and could not realistically be tracked manually by an operator during the night. Therefore the QC0 script is a crucial part of OmegaCAM science operations. It allows fully reproducible quality control according to criteria agreed between ESO and the users that is as independent as possible from variations in human habits. An example output is indicated in Figure 6, left panel.

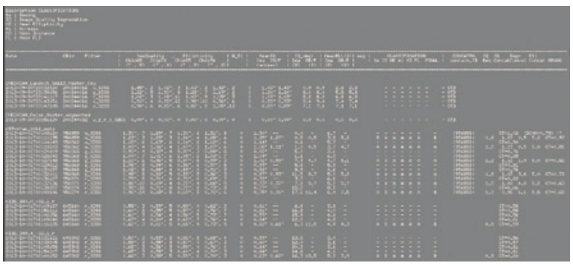
taking into account relative programme priorities (see Figure 5 for an example of the OT ranking). Users prepare their OBs using the P2PP[4] software which includes the option to define relations between OBs (groups, concatenations and time series). Those higher level constraints are also included in the ranking made by the OT.

It is worth noting that around full Moon there is a scarcity of observable OBs due to the bright sky background, which most of the science cases for optical imaging cannot tolerate. Also, only a few programmes accept the presence of thin clouds. The combination of those two issues has led to a comparably high fraction of 8–10 % idle time at the VST. ESO is taking measures to improve the baffling of the VST which, in turn, will reduce the effect of scattered moonlight on the science images. More detail is provided in the section on challenges and outlook.

Real-time quality control during night-time observations

The high cadence of observations and large number of 32 CCDs (267 megapixels) requires reliable automated quality control. With one person operating both the telescope and the instrument at night, it is not possible to measure manually image quality parameters across the field for all those images, which can amount to several hundred per night. Real-time quality control is performed by using the output log of the OmegaCAM data reduction pipeline, which was assembled by ESO from algorithmic modules provided by the OmegaCAM consortium. There is a 1–2 minute delay between the completion of an image and the availability of the pipeline output log. This allows near real-time assessment of data quality, enables fast decisions to be taken to re-adjust the input parameters for the OT ranking engine, and hence optimise the observation plan for the next hour(s). The pipeline provides measurements of mean point spread function (PSF) FWHM and ellipticities for detected sources in each single chip.

The core of the automated quality control is a dedicated script with some 800 lines of code which reads in the pipeline output log, calculates the specific parameters that are used for quality control assessment (called QC0 at ESO), and



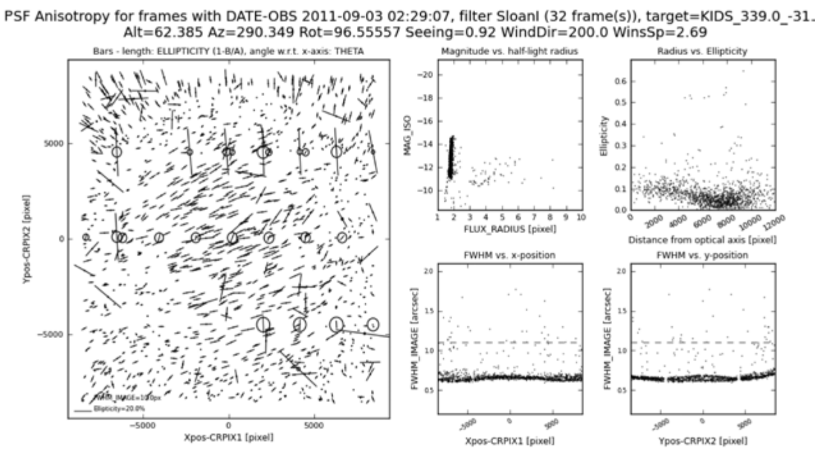


Figure 6. Left: Example output of the real-time quality control script used for OmegaCAM. Each line corresponds to one image. The grouped sets of images correspond to one OB or a concatenation of OBs. Right: PSF anisotropy distribution for a single image of average FWHM 0.65 arcseconds, taken in Early Science.

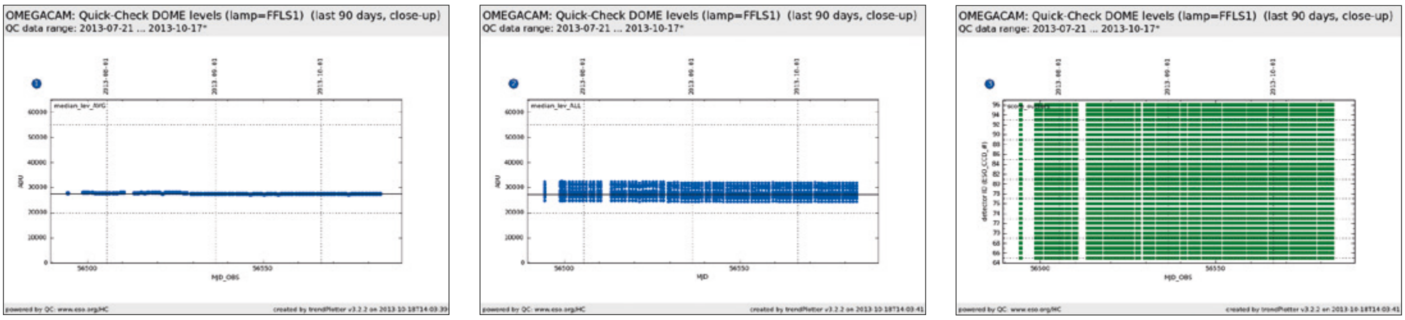


Figure 7. An example of an OmegaCAM health-check scoring performed by the QC group in ESO Garching. The left panel shows the dome flat level averaged over all 32 detectors, while the middle panel shows the median level for each detector. The panel on the right plots the score status of each detector (labelled with their names: ESO_CCD_#65 to ESO_CCD_#96) as a function of time. If the dome flat level falls below or exceeds levels defined for each detector, then the square at that date will turn red.

The set of QC0 criteria applied to OmegaCAM night-time observations ensures that we fulfil our mission statement of providing data of excellent image quality to the users. This very strict adherence to a combination of criteria leads to a slightly larger rate of OB repetitions than for other instruments: for OmegaCAM, about 20% of time in service mode is spent on repeating OBs (note that all data, whether in or out of constraints, is immediately transferred to the ESO archive). The typical fraction for other non-adaptive optics instruments at Paranal is 10–15%. Paranal instruments using adaptive optics, and VLT interferometer instruments, have a greater than 20% fraction of time spent on repeating observations since they very often push out to the instrumental and atmospheric limits. For OmegaCAM, the balance between strict QC0 and quick observing progress is constantly reviewed by the operations team in consultation with the survey consortia.

Calibration plan

The calibration plan of OmegaCAM ensures continuous monitoring of the system throughput in the *u′*, *g′*, *r′*, *i′* and *z′*-bands. Sky flats are taken in two to three filters during each clear evening twilight. Equatorial Landolt photometric standard star fields in *u′* to *z′*-bands are observed at the beginning and in the middle of the night. Furthermore, a short observation close to the southern celestial pole is performed three times per night in a segmented filter with simultaneous *u′*, *g′*, *r′* and *i′* coverage. These high airmass observations guarantee continuous monitoring of the extinction, complementing the low-airmass Landolt field observations. Other filters like Johnson *B* and *V* or Hα are calibrated with Landolt standards only if science data are taken in these filters. Based on dedicated dither observations of the Landolt fields in all chips and under photometric conditions, the OmegaCAM consortium has built up secondary standard star catalogues (currently with more than 315 000 stars) in the key bands for the full 1 × 1 degree field of view.

Daytime calibrations consist of daily bias and dome flats, and weekly gain/linearity measurements. Quality control during the day focuses on monitoring the chip sensitivities, bias levels, dark current levels, readout noise, gain and linearity, flat lamp intensities, twilight flat levels, magnitude zeropoints and image quality (FWHM and ellipticity). A description of the OmegaCAM health checks[5] and the resulting scores and plots[6] is maintained. This follows the classic ESO approach of scored health checks maintained by the QC group in Garching (Hanuschik et al., 2008). An example of the detector-monitoring health check is shown in Figure 7.

Challenges and outlook

VST operations have non-negligible overheads, impacting the completion progress of the public surveys, which were planned before the telescope and camera performance parameters were measured. Most notably, the time used to bring and keep the telescope focal plane to its best shape is higher than originally expected. In the first two years of OmegaCAM operations, about 30% of the available science time was used for acquisition, mainly image analysis. This can be compared to 10% for VISTA. Related to this, OmegaCAM has a larger fraction of direct interaction with the system for the telescope operator when compared to VISTA.

Work is ongoing, in collaboration with the instrument and telescope consortia, to improve the control procedures of the VST main and secondary mirrors, and to optimise image analysis algorithms on the OmegaCAM side. The aim is to move closer towards fully automated operations, including automatic acquisition of guide and image analysis stars.

Another area of improvement is the sky concentration effect that produces rotationally asymmetric features of 5% amplitude in the sky flats (see the OmegaCAM user manual[7]), and reflection/scattering features in images close to the Moon (within a few tens of degrees). Calibrating out the sky flat variations requires great care in data reduction (see the consortium report on sky concentration correction[7]). Additional baffling for the VST will be tested at the end of 2013; this will improve the reproducibility of the sky concentrations in sky flats, and permit observations closer to the Moon, thus reducing idle time.

Survey progress and first results

In Figure 8 the progress of the VST public surveys during the first two years of operations is shown. In total, about 1000 hours of observing time per year have been spent on executing public survey OBs within user constraints.

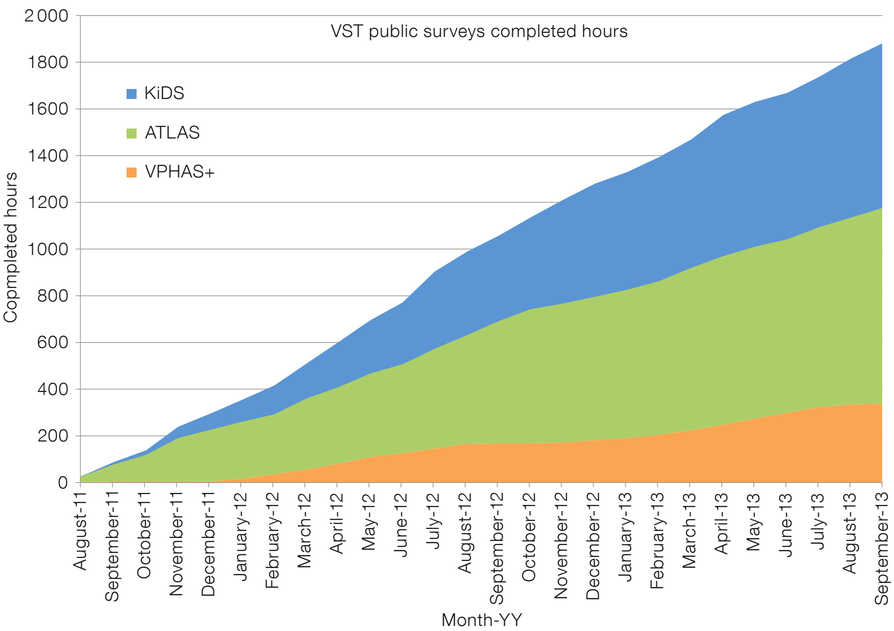


Figure 8. Cumulative number of hours, since start of operations, spent on completed OBs for the three VST OmegaCAM public surveys. About 50–60% of the available service mode time at VST is spent on public surveys. The rest is shared between GTO and Chilean programmes.

In Figure 9, a few first science results from VPHAS+ and KiDS, kindly provided by the survey teams, are illustrated. In the VPHAS+ example (left), an ionised nebula surrounding the extreme red supergiant, W26, begins to be resolved (from Wright et al., 2013). As the only known example of a compact ionised nebula around a red supergiant, this represents a unique opportunity to study the mass loss of red supergiants, using the tools of nebula astrophysics. The right panel shows one example of the nine-band *u′* to *Ks* photometry of KiDS (OmegaCAM) and VIKING (VISTA Kilo-Degree Infrared Galaxy Survey) being used to hunt for high-redshift quasi-stellar object (QSO) candidates which drop-out in the KiDS *i′*-band ($z > 5.7$) and VIKING *z*-band ($z > 6.5$); from Venemans et al. (2013). The histogram shows the redshift distribution of all published quasars at $z > 5.7$ (in grey). Currently, more than 50 quasars at $z > 5.7$ have been discovered in various surveys. The red histogram bars show the redshift distribution of the quasars found in the combined KiDS/VIKING survey thus far. The number of quasars expected in the total KiDS/VIKING area of 1500 square degrees is about 40, with > 10 above $z = 6.5$.

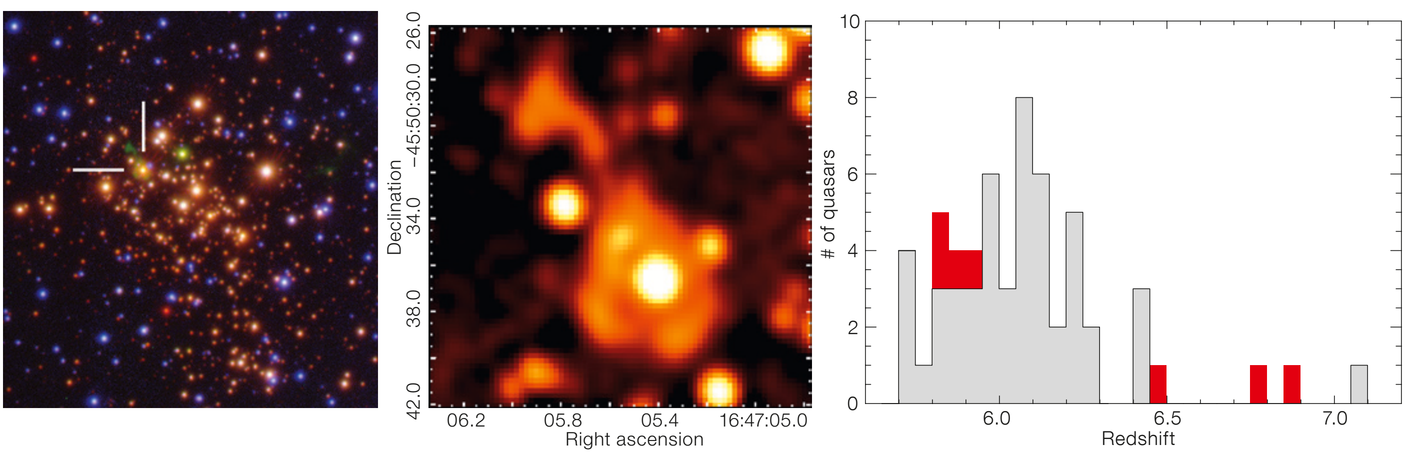


Figure 9. Left: A composite *g′*-Hα-*i′* image of the dense, very massive cluster Westerlund 1, taken as part of VPHAS+, is shown. This image allows the study of the ionised nebula surrounding the extreme red supergiant, W26 (Wright et al., 2013). The zoomed part of the image (centre), shown in orange, is Hα only. Right: High-redshift QSOs detected by combining KiDS (OmegaCAM) and VIKING (VISTA) data (Venemans et al., 2013), indicated as red in the histogram. See text for more details.

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Links

1 ESO OmegaCAM webpage: http://www.eso.org/sci/facilities/paranal/instruments/omegacam
2 Setup and goals of the VST public surveys: http://www.eso.org/sci/observing/PublicSurveys/sciencePublicSurveys.html
3 ESO Phase 3 page: http://www.eso.org/sci/observing/phase3.html
4 Phase 2 P2PP software: https://www.eso.org/sci/observing/phase2/P2PP3.html
5 OmegaCAM quality control pages: http://www.eso.org/observing/dfo/quality/OMEGACAM/qc/qc1.html
6 Health check scores and plots: http://www.eso.org/observing/dfo/quality/OMEGACAM/common/score_overview.html
7 OmegaCAM user manual and consortium report on sky concentration correction: http://www.eso.org/sci/facilities/paranal/instruments/omegacam/doc/