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# HAWK-I/GRAAL Science Verification

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Science Verification observations with the High Acuity Wide field *K*-band Imager (HAWK-I) instrument enhanced by the ground-layer adaptive optics module (GRAAL) were obtained during 4.5 nights from 2 to 6 January 2018. Fourteen projects were selected from a total of 19 submitted proposals. The total time scheduled for these 14 projects was 35.5 hours, which represents a slight oversubscription for the four allocated summer nights. The seven top-ranked projects were completed, three more programmes received some data, one was observed outside the requested constraints, and three projects were not started. The Science Verification nights were affected by various technical problems, mostly unrelated to GRAAL, which resulted in a total loss of 10 hours. Half a night was allocated on 6 January to compensate for some of the lost time. The atmospheric conditions were rather variable with occasionally excellent natural seeing (0.3 arcseconds). The ground layer turbulence fraction varied from 40% to 85% during these nights. The best performance in terms of improved image quality was observed when the ground layer fraction was above 70%, as expected for the system. The image quality in the *K* filter ranged between 0.2 arcseconds (in excellent conditions) to about 0.5 arcseconds (with mediocre seeing, > 0.8 arcseconds), and a small fraction of ground-layer turbulence. The delivered image quality was very stable, but in some cases an asymmetric point spread function was observed.

## Proposal solicitation and submission

The call for HAWK-I/GRAAL Science Verification proposals and the corresponding web page were published on 2 October 2017[1]. The call was announced through the ESO Science Newsletter on 17 October 2017[2] with a deadline for proposal submission of 31 October 2017. Nineteen proposals were received by the deadline and evaluated by the Science Verification team over the following 2.5 weeks. A total allocation of 35.5 hours was chosen, a slight oversubscription compared to the available observing time (30 hours in total over four summer nights). This resulted in 14 projects being selected for scheduling. All Principal Investigators (PIs) were informed of the outcome of this selection process on 27 November, and the successful applicants were given a deadline for submission of the Phase 2 material of 14 December 2017. All PIs complied with this deadline and the submitted material was verified by the User Support Department before 22 December, so the HAWK-I/GRAAL Science Verification queue was ready by 31 December.

The scheduled projects covered a range of topics, including: the characterisation of a Solar System binary object — the dwarf planet Eris and its moon Dysnomia; observations of the mass function and dynamics of young clusters; pairs of stellar clusters and their origins; and a massive embedded cluster. Star formation projects included an investigation into the infrared excess emission of pre-main-sequence stars in the Large Magellanic Cloud (LMC) and observations of molecular hydrogen in a Herbig Haro object. Extragalactic topics included a potentially binary active galactic nucleus in a merging galaxy system, and multi-epoch observations of luminous infrared galaxies to search for core-collapse supernovae.

## Observations

All observations were made without tip-tilt stars and using only the four laser beacons provided by the Adaptive Optics Facility (AOF). Various technical problems led to a loss of several hours during the Science Verification nights. At the same time some very good seeing conditions were encountered (down to 0.3 arcseconds). The image quality throughout was quite good (0.5 arcseconds), and nearly independent of the outside seeing with occasionally spectacular image quality in the fast photometry mode (0.2 arcseconds in *K*). In rare cases, an elongation of the images was observed, which was probably not related to the adaptive optics, as it has also been observed with other instruments on UT4. The only noticeable instrument issue during the run was a systematic instrument configuration tool error, revealed for non-zero position angles and corrected during the run.

The observations essentially followed the priority given by the ranking of the proposals. The seven top-ranked projects were completed fully within the requested constraints. Some data were obtained for three programmes, and for one project, the data did not comply within the requested constraints. The lowest-ranked three projects could not be started.

## Archive and data processing

All raw and pipeline-reduced data are publicly available through the ESO science archive. The ESO data quality control group reduced all Science Verification data and the resulting products are available from the ESO Phase 3 data product form[3]. A new version of the HAWK-I/GRAAL data reduction pipeline has been released. The HAWK-I/GRAAL Science Verification web page also contains direct links to the Science Verification data in the archive[1].

## Some early science results

### Solar System objects: Eris and Dysnomia

Trans-Neptunian objects (TNOs) are icy/rocky bodies located beyond the orbit of Neptune, which are believed to be remnants of the building blocks from which planets formed. The dwarf planet (136199) Eris is one of the largest TNOs known in the Solar System, with a size similar to that of Pluto. During the HAWK-I/GRAAL Science Verification, high-precision photometric observations of Eris were obtained at near-infrared wavelengths. The aim of the observations was to characterise the surface heterogeneity

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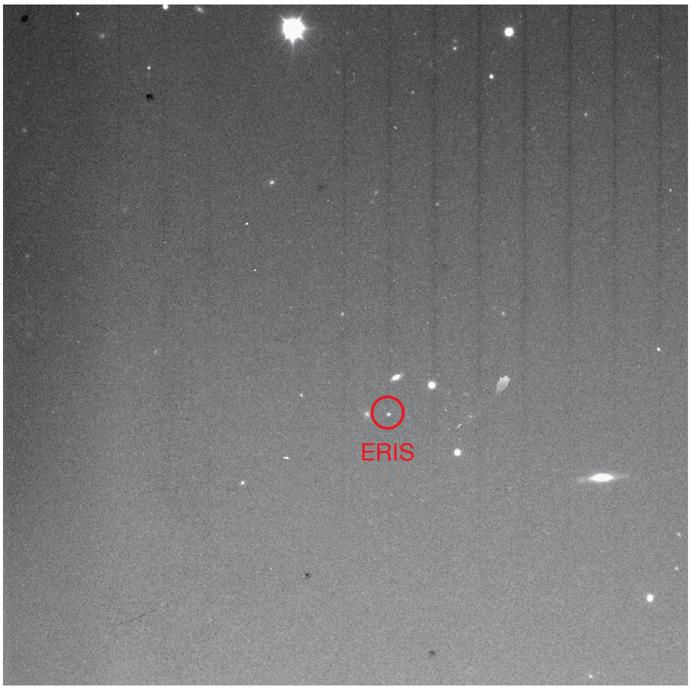


Figure 1. One of several images of Eris in one HAWK-I quadrant with a 3.6 × 3.6 arcminute field of view.

of this large TNO and detect photometric variations due to its rotation. Thanks to the performance of the GRAAL AO module (Figure 1), the team should be able to resolve Eris and its moon Dysnomia, whose separation varies between 0.3 and 0.5 arcseconds. A total of 18 high-quality images were obtained, spread over three consecutive nights. If photometric variations are detected in these observations, it will provide a way to definitively determine the rotation period of the dwarf planet Eris.

## Probing the cores of nearby stellar clusters

The mass function and the dynamics of young clusters are among the most important observational constraints to the study of star formation. The presence of extremely bright, massive stars has prevented the analysis of environments in the cores of stellar associations. The γ Velorum cluster, which has an age of ~ 7 Myr and is at a distance of 350 pc, was targeted with HAWK-I/GRAAL specifically to observe the region around the naked-eye star γ Velorum ($V$ = 1.8 mag). The star itself was carefully positioned outside the HAWK-I field of view and observations were obtained in the fast-photometry mode (integration time ~ 3.3 seconds, see Figure 2). This resulted in 2000 individual frames in $K_s$ and 1040 frames in $Y$. A few frames with elongated images were discarded in the analysis. These data will ultimately provide a colour-magnitude diagram that will probe the stars down to about 5 Jupiter masses in the core of the cluster.

Figure 2. A comparison of HAWK-I/GRAAL images with archival VISTA observations around the star γ Velorum. The circles mark the sources detected in the HAWK-I frames.

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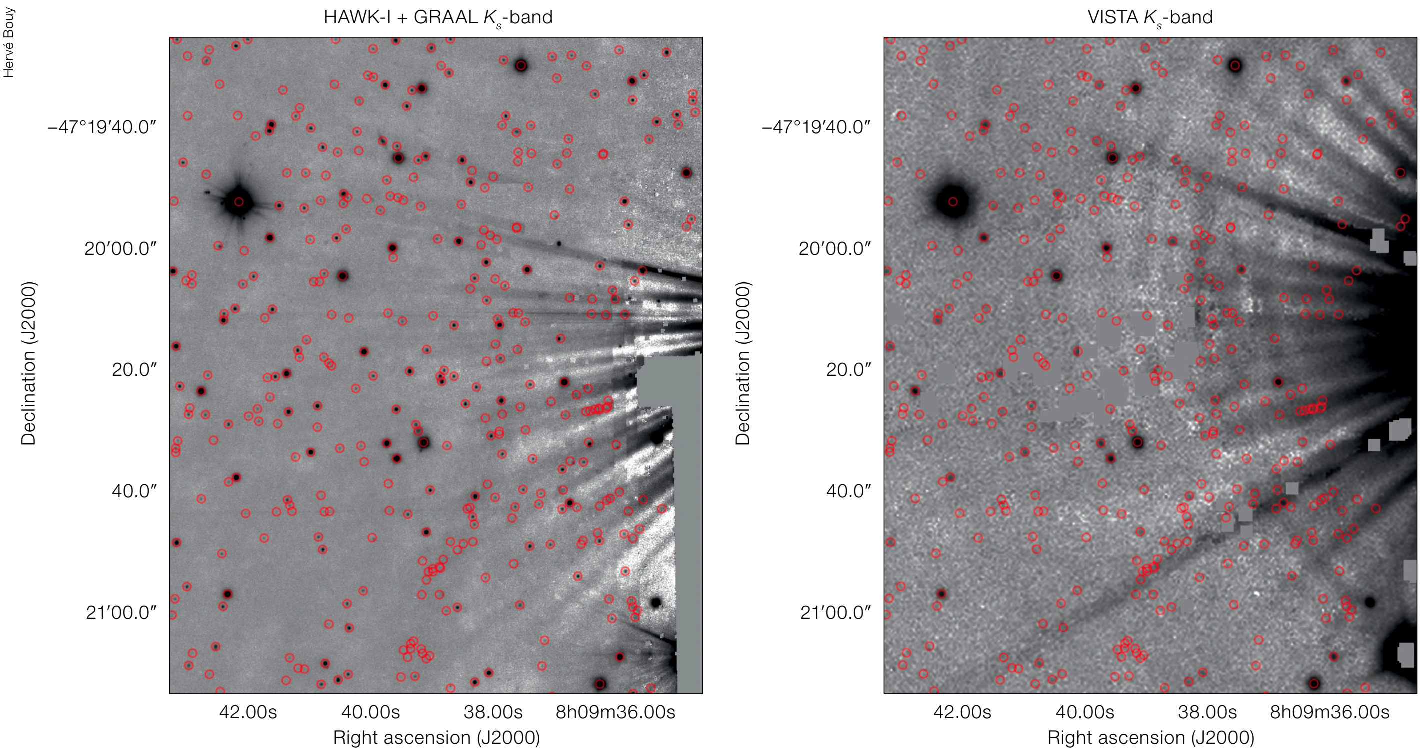

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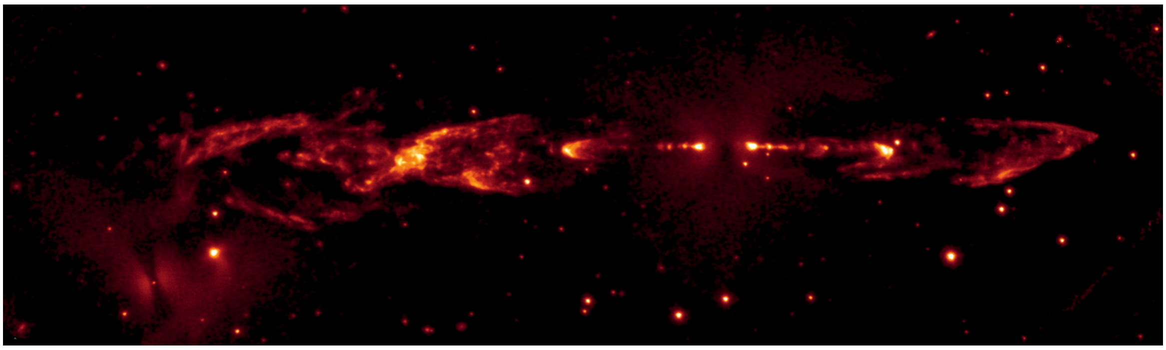

Figure 3. HH 212 in the $H_2$ filter at 2.12 µm with HAWK-I/GRAAL. The image shown here is 5 by 1.5 arcminutes.

## Stellar outflows from young stars

Herbig-Haro objects are massive outflows driven by stellar systems in the making. They are large objects on the sky, extending over several arcminutes (~ 1 parsec), and appear mostly diffuse, although they also contain point-like substructures, which evolve on timescales of years. In fact, time evolution is key to understanding the physics of outflows, and in particular the link to their driving source: the planet-forming young stellar disc. Efficient mapping of Herbig-Haro objects requires wide-field, high-spatial-resolution data; this is exactly what HAWK-I provides in the near-infrared, where extinction effects are mitigated. Molecular hydrogen emission at 2.12 µm was observed in the Herbig-Haro object HH 212 using HAWK-I in 2007. The driving source of HH 212 is a low-mass protostar located in the Orion star-forming region at a distance of about 400 pc. The new HAWK-I/GRAAL Science Verification image of HH 212 shows all the characteristics of Herbig-Haro objects: well developed bow shocks, where the outflowing gas interacts with the ambient medium; jet-like features closer to the source, tracing the largely undisturbed flow originating in the star-disc system; and structure at essentially all scales. The new data (Figure 3) compared with the archival HAWK-I image will enable proper motions to be measured with high accuracy, i.e., down to 20 km $s^{-1}$, over the entire length of HH 212 — a fraction of the typical flow velocity of 300 km $s^{-1}$. A detailed comparison between the dynamics of the blue- and red-shifted lobes is especially interesting because, although HH 212 appears symmetrical, its lobes show substantially different space velocities, something that is challenging to explain with current jet launching models.

## Young star cluster RCW38

RCW 38 is the youngest (< 1 Myr) of the Milky Way's 13 super star clusters (Fukui et al., 2016), and the densest stellar system within 4 kpc of the Sun (Kuhn et al., 2015). The cluster contains hundreds of protostars, pre-main sequence stars, and OB-star candidates (Winston et al., 2011), along with a substantial substellar candidate population revealed in the cluster core (Muzic et al., 2017). With HAWK-I/GRAAL data (see the cover image), one can directly study several key aspects of star formation: massive star birth; low-mass star and brown dwarf formation in a dense environment and under the influence of photoionisation fronts from massive stars; the initial mass function (IMF) on an unprecedented sample spanning three orders of magnitudes in mass; and mass segregation in young clusters.

## Star-forming complex in the LMC

Pre-main-sequence candidate stars in the LMC often show near-infrared excesses compared to theoretical model predictions. This was discovered using VISTA images from the VISTA Magellanic Cloud survey (VMC; Cioni et al., 2011). However, the VISTA images are affected by crowding and photometric uncertainties, which could also mimic this excess. The HAWK-I/GRAAL Science Verification observations targeted the central area of the star-forming complex N44 to obtain a colour-magnitude diagram to well below 1 solar mass. The increased angular resolution has resolved the crowding problem — almost 3 times as many stars were detected in the densest young star cluster areas (Figure 4) — and also helped with independent photometry. If the near-infrared excess persists in these HAWK-I/GRAAL data as well, then it may be that the low metallicity in the LMC is responsible for significant changes in the early evolution of stars in such an environment.

## Stellar cluster pairs in the LMC

The LMC possibly hosts the largest number of candidate stellar cluster pairs within the Local Group. These systems are extremely interesting as their study can provide a fresh look at the mechanisms of cluster formation and evolution. As part of a larger effort aimed at providing an independent characterisation of cluster pairs in the LMC (Dalessandro et al., 2018; Mucciarelli et al., 2012) this study exploited the wide field of view and the enhanced spatial resolution available with HAWK-I/GRAAL to observe the cluster pair NGC 2136 and NGC 2137 in the *J*- and *H*-bands. The high-quality colour-magnitude diagrams for the two clusters (Figure 5) will yield accurate cluster ages from the main-sequence turnoff luminosity, the structure of the systems from accurate star counts, and density profiles and the degree of mutual interaction. This information will, in turn, yield clues as to the origin and final fate of these stellar systems.

## Supernovae in the cores of galaxies

Luminous infrared galaxies are highly star-forming and dust-obscured galaxies. While relatively rare in the local Universe, they start to dominate the total core-collapse supernova rates at $z$ ~ 1. Two luminous infrared galaxies were observed during HAWK-I/GRAAL Science Verification. This resulted in the discovery of a new supernova, SN 2018ec (Kankare et al., 2018; Figure 6), in NGC 3256, which is only the second reported supernova in this luminous infrared galaxy, with an expected intrinsic core-collapse supernova rate of about one per year. Optical transient surveys did not discover this nearby supernova — at a distance of only 37 Mpc — owing to a combination of

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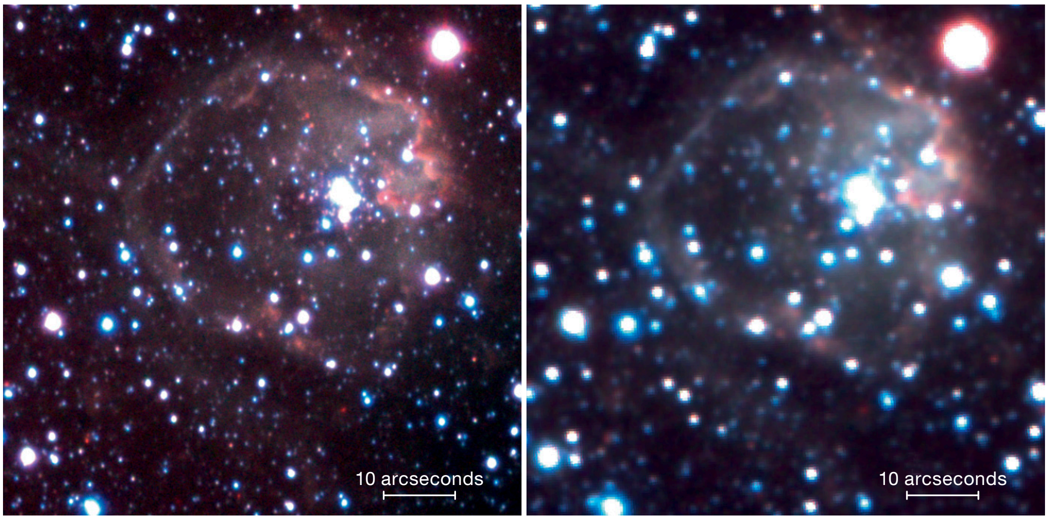


Figure 4. Comparison of HAWK-I/GRAAL (left) and VISTA (right) images of a region in the N44 star forming complex in the LMC.

Emanuele Dalessandro

Figure 5. *J* and *H* colour-composite image of the binary cluster pair NGC 2136 and NGC 2137. The image size is 210 × 160 arcseconds.

the high extinction ($A_V$ ~ 2 magnitudes) along the line of sight of the host galaxy and the high background. SN 2018ec was classified as a Type Ic supernova by the survey "extended-Public ESO Spectroscopic Survey for Transient Objects" (ePESSTO; Berton et al., 2018). The study of SN 2018ec will contribute to the long-term aim of deriving missing fractions for core-collapse supernovae from the local to the high-redshift Universe.

## A dual active galactic nucleus?

Recent observations using the VLT instrument Multi Unit Spectroscopic Explorer (MUSE) uncovered a potential dual active galactic nucleus candidate at redshift $z$ = 3.3 with a separation of only 20 kpc. The merging of supermassive black holes in galaxy mergers is expected in the hierarchical formation of galaxies. HAWK-I/GRAAL follow-up observations of this high-redshift dual active galactic nucleus system are crucial to characterising the coordinated assembly of the galaxies and the supermassive black holes. The goal of obtaining the $K_s$-band image (Figure 7) was to detect the host galaxy of the obscured active galactic nucleus. Indeed, the host galaxy was detected at the expected location (thanks to the exquisite image quality, of 0.4 arcseconds, and depth delivered by the adaptive optics system). After de-blending

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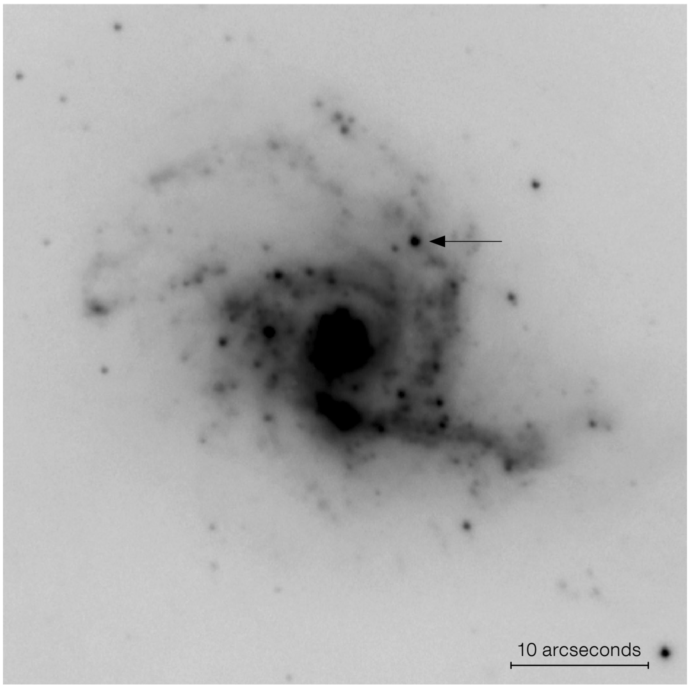


Figure 6. Discovery image of supernova SN 2018ec in NGC 3256 in a $K_s$ image.

Bernd Husemann

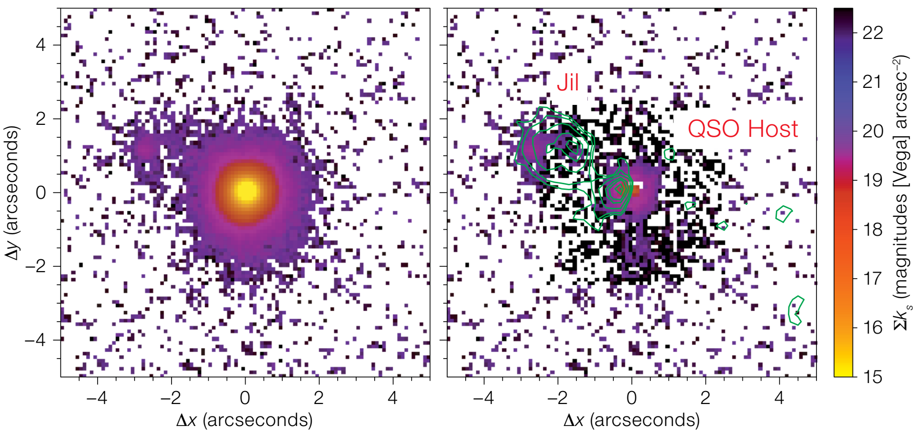


Figure 7. Left panel: VLT/HAWK-I/GRAAL $K_s$-band image of the LBQS 0302-0019 dual AGN system. Right panel: Same as left, but the quasar light has been subtracted based on the PSF obtained froma nearby star. Significant extended emission is detected for the companion galaxy well above the surface brightness limit. The distribution of VLT/MUSE He II emission is shown by green contours. The emission peaks exactly at the location of the companion galaxy (dubbed "Jil") with a slight preference towards the fainter asymmetric part of the continuum distribution.

the quasar plus companion galaxy system using the software package GALFIT3 (Peng et al., 2010), $K_s$-band magnitudes of 19.2 (Vega magnitudes) for the quasar host galaxy and 20.6 magnitudes for the companion galaxy were derived. At $z$ = 3.3 the $K_s$-band corresponds nearly to the rest-frame velocity, and stellar masses of $\log(M_*/M_\odot)$ ~ 11.4 and ~ 10.9 were derived for the quasar host and the companion, respectively (adopting a mass-to-light ratio of ~ 0.1 for a 200 Myr-old stellar population). The host galaxies are both very massive and probably trace one of the most massive dark matter halos at that epoch of the Universe (Husemann et al., 2018).

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## Links

[1] HAWK-I/GRAAL Science Verification web page: http://www.eso.org/sci/activities/vltsv/hawkigraalsv.html
[2] ESO Science Newsletter dated 17 October 2017: http://www.eso.org/sci/publications/newsletter/oct2017.html
[3] ESO Phase 3 data product query form for HAWK-I: http://archive.eso.org/wdb/wdb/adp/phase3_imaging/form?ins_id=HAWKI