Hawk-I – First Results from Science Verification

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The VLT wide-field near-infrared imager HAWK-I was commissioned in 2007 and Science Verification (SV) programmes were conducted in August 2007. A selection of results from among the twelve Science Verfication proposals are summarised.

HAWK-I is the new wide-field infrared imager on the VLT. We reported previously in The Messenger on its capabilities (Casali et al., 2005) and refer to Kissler-Patig et al. (2008) for a recent description of the instrument. Here we briefly describe a selection among the twelve accepted Science Verification programmes and highlight some of the first spectacular results in the areas of distant galaxies, clusters of galaxies, star clusters and star formation.

The science verification (SV) for HAWK-I was interleaved with the commissioning activities that took place in three runs between October 2007 and February 2008. The goal of SV was to demonstrate the capabilities of the new instrument in a wide variety of research fields. More details on SV, the selected programmes and all the data, together with a description of how they were acquired, can be found on the HAWK-I SV web pages *(http://www.eso.org/sci/activities/vltsv/hawkisv/)*. HAWK-I was offered to the community in Period 81 for regular service and visitor mode observing.

Distant galaxies

HAWK-I observations in the GOODS-S field were designed to obtain a self-consistent sample of galaxies at redshift about 7, providing a new view on the Universe at the end of the epoch of re-ionisation. The extraordinary efficiency of HAWK-I was used to detect $z > 6.5$ candidates in the *Y*-filter (centred at 1.021 μm) through an appropriate recasting of the Lyman-break technique: candidates are selected as "Z-drop", i.e. their colours satisfy the following criteria: (Z–Y) > 1.0 mag. and (Y–K) < 1.5 mag. 333 frames were obtained, for a grand total of 27 hours of integration. The final mosaic provides the deepest image ever obtained in the *Y*-band. Thanks also to the excellent image quality (< 0.5″), it enables the detection of galaxies as faint as m(AB) = 26.8. The preliminary photometric analysis has identified a set of 25 high-redshift candidates. Extensive simulations are underway to assess the completeness and reliability of the selected sample.

This programme was complemented by HAWK-I observations in the NB1060 filter as an alternative method to search for star-forming galaxies at $z = 7.7$, thus demonstrating the potential of HAWK-I in directly probing the epoch of re-ionisation. The SV observations alone will form a sufficiently complete dataset to put a constraint on the number of luminous star-forming galaxies at $z = 7.7$. Preliminary analysis of 8.3 hours of narrowband data indicates that HAWK-I is capable of reaching a limiting depth of 7.5×10^{-18} erg s^{-1} cm^{-2} $arcsec^{-2}$ (5 sigma). By measuring the colours of the candidate line emitters in the available HST/ACS images of the field, the line which has caused the narrowband excess can be determined. Figure 1 shows a colour-magnitude diagram of detected sources and an example image of a low-redshift emission-line galaxy.

A programme with similar aims, but using a different technique, aimed at detecting high-redshift ($z \sim 7.7$) Ly-α emitters amplified by the strong lensing of a massive

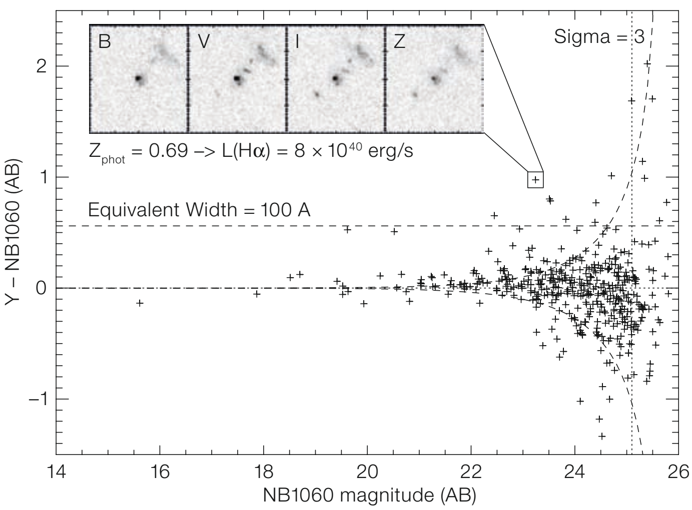

Figure 1. Colour-magnitude diagram showing objects detected in one of the four HAWK-I chips. Candidate emission-line galaxies are objects with a significant flux excess in the narrow-band filter. The inset shows ACS images of an example low-redshift line emitter, detected through Hα redshifted to $z = 0.69$.

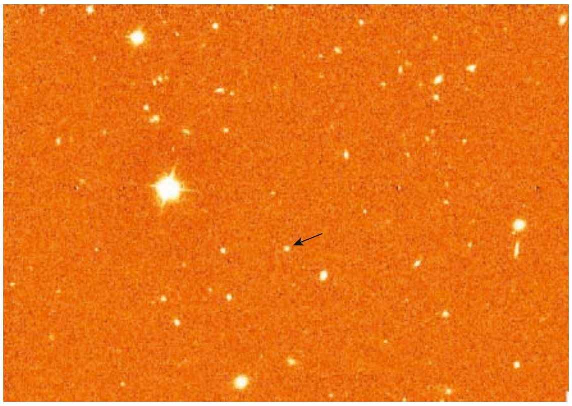

Figure 2. A ~ 2.5′ × 2′ section of a HAWK-I *Ks*-band image containing the radio galaxy MRC0030-219, which is marked with an arrow.

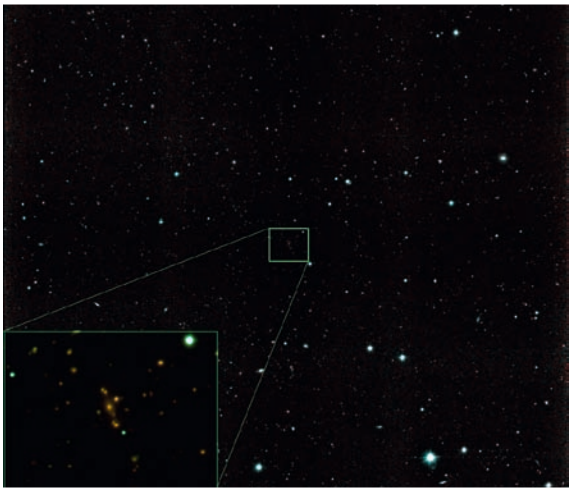

Figure 3. Colour composite of four HAWK-I pointings in both *J* and *Ks*, covering 13.5′ on a side, of the galaxy cluster XMMU J2235.3-2557. The cluster is in the middle of the frame and a blow-up centred on the cluster is shown in the inset. The centre of XMMU J2235.3-2557 is dominated by red galaxies with very similar colours.

cluster. The massive cluster MS0451-03 was observed with the NB1060 filter of HAWK-I. The magnification of background galaxies ranges from 0.3 to 3 mag. The NB image provides an effective test for the presence of gravitationally lensed z ~ 7.7 galaxies. Many interloping $z < 7$ galaxies are detected in this image and will be of wider interest for follow-up studies.

Galaxy clusters

There is now strong evidence that galaxy evolution is closely linked to environment and that the oldest, reddest galaxies locally are found in large clusters. Hence to study the early stages of galaxy evolution we need to study the highest redshift (proto-)clusters. The number of these currently known is small but one of the most promising ways to locate them is by characterising the environment of high-redshift radio galaxies which lie at the centres of proto-clusters. HAWK-I was used to image the radio galaxy MRC0030-219 at $z = 2.168$ in the *J*-, *K*- and NB1190-filters (see Figure 2 for the *K*-band image). At this redshift the narrowband filter traces [O II] 3727 Å emission: the aim is to search for an overdensity of star-forming galaxies and at the same time for redder, evolved galaxies using *J*–*K* colours. Initial analysis seems to indicate no evidence for an over-density but this is still to be verified. If true, it will allow interesting limits to be placed on the properties of a radio galaxy required for a forming proto-cluster.

A ubiquitous feature in rich galaxy clusters at all redshifts is the tight sequence of red, passively-evolving early-type galaxies in the colour-magnitude diagram. HAWK-I is well suited for studying the formation of the red sequence and of rich galaxy clusters in general, since such clusters form over regions that are several Mpc in size. In the concordance cosmology, 5 Mpc corresponds to 10′ on the sky at a redshift of 1.5. The aim of this SV programme was to image the galaxy cluster XMMU J2235.3-2557 at $z = 1.39$, one of the most distant X-ray luminous clusters known. The resulting images were superb (see Figure 3). In *Ks*, the image quality of the final stack reached 0.32″, and, in some of the individual images, the image quality reached 0.2″, which approaches that obtainable with NICMOS on HST, but with the advantage of a much larger field of view.

Star clusters

Globular clusters provide important tools to distinguish between competing models for the formation of their host galaxies. The combination of optical and IR photometry is a very powerful tool to investigate the age distribution of globular clusters in a given system. However, currently available samples are severely limited by the spatial coverage of the IR data. With HAWK-I, wide field *J*-, *H*-, *Ks*-band imaging was obtained of the nearest S0 galaxy NGC 3115. A preliminary colour-colour plot, obtained using archival FORS2 imaging and the HAWK-I SV data (filled black circles), is shown in Figure 4, and compared with previous measurements (open blue circles) by Puzia et al. (2002) who used ISAAC and HST/WFPC2 imaging. Overplotted are Maraston et al. (2003) SSP models for ages 3–15 Gyr and [Z/H] −2.25 to 0.67. The depth of the HAWK-I data allows exploration of the interesting blue end (intermediate ages?) of the colour distribution in *V*–*Ks*.

In a similar programme HAWK-I was used to study the star cluster system of the intermediate-age (~ 3 Gyr) merger remnant NGC 1316. This galaxy has a substantial number of star clusters, some of which have ages corresponding to the merger. However, it is not clear what fraction were formed during this most recent merger event. The new, deep *Ks*-band imaging (Figure 5) has already revealed an extensive system of star clusters and, along with archival VIMOS optical imaging and spectroscopy, will allow the various cluster populations in NGC 1316 to be clearly separated and their ages and metallicities to be constrained.

The spiral galaxy NGC 7793 was also observed with HAWK-I to complement

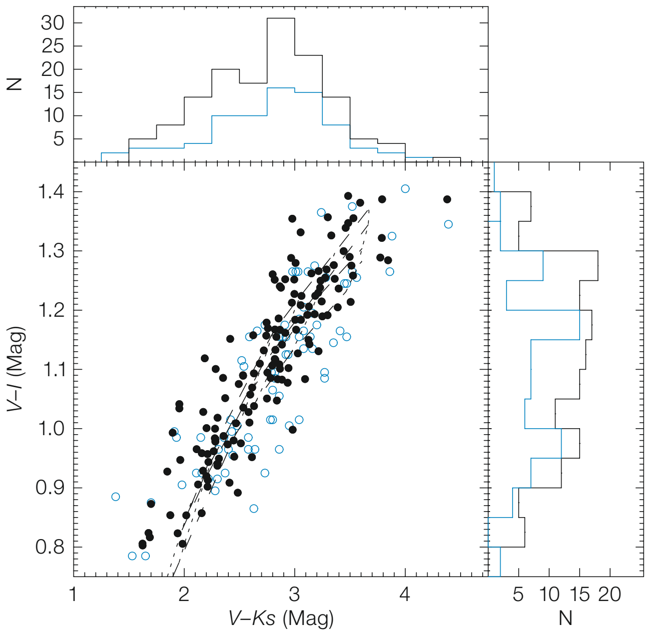

Figure 4. *V–I versus V–Ks* colour-colour diagram, with associated projections of the axes, of globular clusters in NGC 3115. The black points refer to data taken with FORS2 and HAWK-I, the blue points to data from HST WF/PC2 and ISAAC.

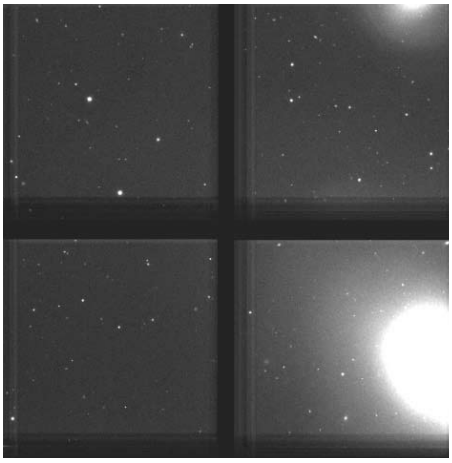

Figure 5. A deep HAWK-I *Ks*-band image of NGC 1316 showing many star clusters. The inter-chip gaps are apparent on this combined image.

existing wide-field optical HST/ACS data and to study its star cluster population. The combination of NIR and optical data and the large field of view of HAWK-I allow construction of the cluster luminosity function, the cluster initial mass function and the cluster age distribution of the entire cluster population, and for different environments within the disc. This will shed light into how cluster masses depend on the star formation rate of the host galaxy and how the early disruption due to the removal of natal gas, or 'infant mortality' of clusters, depends on local variables.

Star formation

NGC 602/N 90 in the Small Magellanic Cloud (SMC) hosts a cluster of Young Stellar Objects (YSOs) including pre-main-sequence (PMS) stars detected by HST/ACS and Class 0-I protostars detected by Spitzer/IRAC. Some protostellar objects are apparently related to optical PMS stars. Since the Spitzer/IRAC beam is relatively large and such associations are surprising, NGC 602 was observed with HAWK-I, taking advantage of its high spatial resolution and sensitivity, in order to analyse the association of IRAC protostars and their suggested optical counterparts. Figure 6 shows the spectacular HAWK-I composite *JHKs* image of the young stellar population and the nebulosity in NGC 602/N 90. The 0.5–8 μm SED was computed, using the preliminary HAWK-I fluxes, of three previously suggested Class I protostellar objects in the region (see Figure 7). It is apparent that the near-IR data are essential to determine the true nature of these objects.

High spatial resolution H_2 2.122 micron images of the highly symmetric protostellar jet HH 212 were made with HAWK-I. Since the jet fits within a single quadrant of the HAWK-I field of view, these data provide a stable, precision astrometric template to which the archival mosaiced ISAAC images of HH 212, taken from 2001–2006, can be aligned. The scientific aim is to measure transverse motions in the outflow down to 20 km/s to trace the dynamical history of the jet and thus the accretion history of the underlying protostar. The HAWK-I observations also extend the proper-motion monitoring baseline from five to seven years, further improving the velocity resolution.

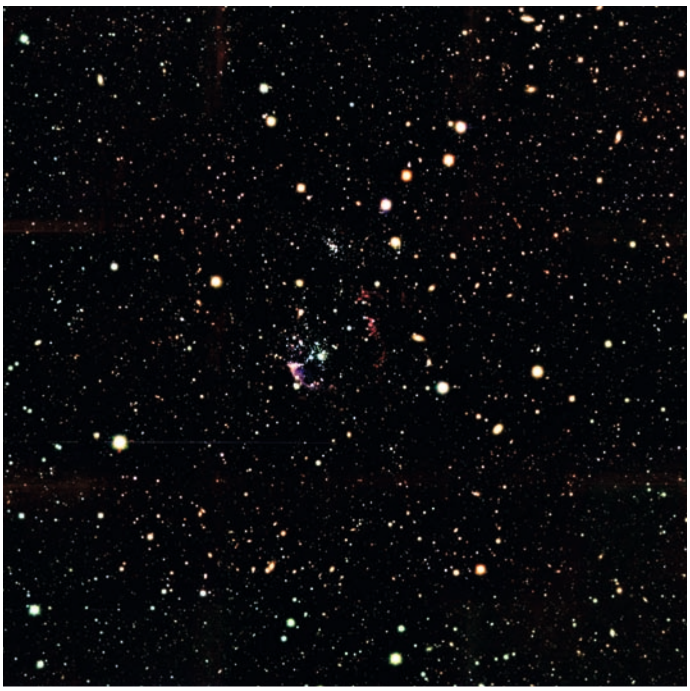

Figure 6. *JHKs* colour composite of the central region of NGC 602/N90. Reflection nebulae and a rich stellar population, mainly grouped in clusters, are distinguished, together with many background galaxies.

A deep wide-field near-IR survey of the Carina Nebula was performed with HAWK-I, in order to study the physics of violent massive star formation and the resulting feedback effects, including cloud dispersal and triggered star formation. The survey reveals all young stars in the region through extinction of up to A_V < 25 mag and brown dwarfs down to 35 Jupiter masses through 10 mag of extinction. In combination with recent observations at other wavelengths, the survey will allow mass, age, and circumstellar disc fraction distributions to be ascertained for the entire young stellar population as a function of environment within the Carina Nebula.

Deep HAWK-I images (5 sigma *K*-band limit approx. 19.5 mag in 12-min on-sky) were collected in two sub-fields of the Chamaeleon I star-forming region. The observations are complete down to at least 5 Jupiter masses, according to theoretical isochrones for the typical distance and age of Chamaeleon I. The internal astrometric precision is better than 25 mas (root-mean-squared error – see Figure 8). Given the typical proper motions of Chamaeleon members, a second epoch after three years will reveal all members of this region down to the free-floating planetary mass objects (planemos) regime. The astrometric performance is further backed up by the high number of background galaxies identified in the deep HAWK-I frames. These galaxies form the astrometric reference frame of the planned second epoch. The current data of this programme will be made accessible as an Advanced Data Product.

Prospects

HAWK-I is currently the most performant near-infrared imager on an 8-m-class telescope. It has proven its very high throughput and exceptional image quality during the SV observations. In period 81, HAWK-I has been scheduled for 21 runs and will, without doubt, deliver further stunning images. Given its performance, it is on the path to becoming a workhorse instrument at the VLT. We are looking forward to seeing many more spectacular HAWK-I results reported in the Messenger and elsewhere.

Acknowledgements

Many thanks to the SV team who enabled all these first science results: Nancy Ageorges, Mark Casali, Yves Jung, Jorge Melnick, Alan Moorwood, Monika Petr-Gotzens, John Pritchard and Masayuki Tanaka.

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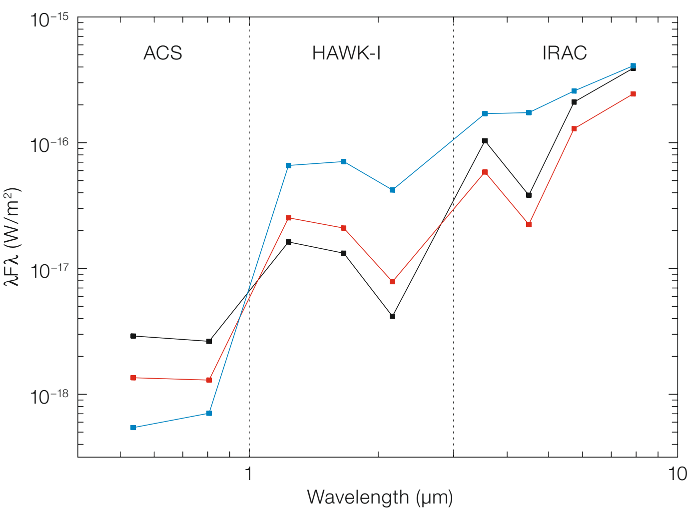

Figure 7. Spectral energy distribution for selected objects identified as protostars in Spitzer/IRAC images of NGC 602/N 90 having tentative optical counterparts observed with HST/ACS.

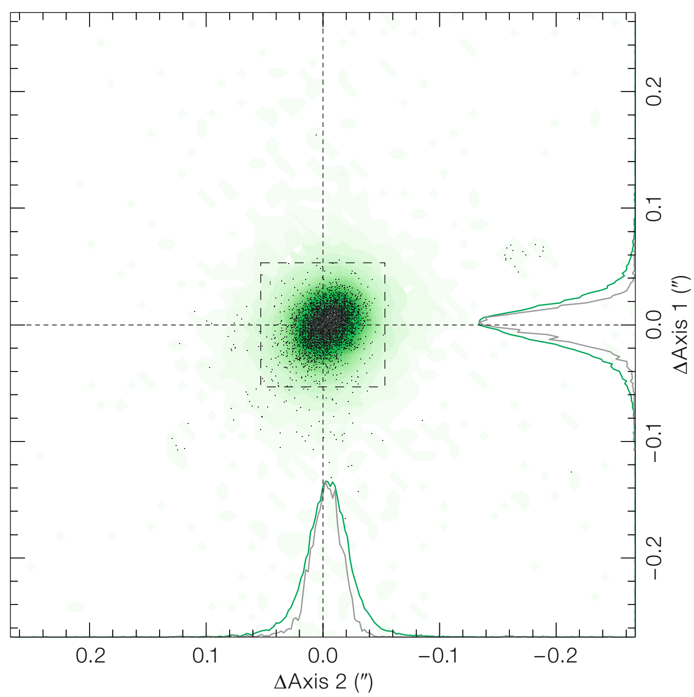

Figure 8. The X and Y astrometric errors corresponding to the HAWK-I astrometry in the Chamaeleon I star-forming region.