SPHERE Science Verification

Bruno Leibundgut[1]
Jean-Luc Beuzit[2]
Neale Gibson[1]
Julien Girard[1]
Markus Kasper[1]
Florian Kerber[1]
Lars Lundin[1]
Dimitri Mawet[1]
Melissa McClure[1]
Julien Milli[1]
Monika Petr-Gotzens[1]
Ralf Siebenmorgen[1]
Mario van den Ancker[1]
Zahed Wahhaj[1]

[1] ESO
[2] Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), France

Science Verification (SV) for the latest instrument to arrive on Paranal, the high-contrast and spectro-polarimetric extreme adaptive optics instrument SPHERE, is described. The process through which the SV proposals were solicited and evaluated is briefly outlined; the resulting observations took place in December 2014 and February 2015. A wide range of targets was observed, ranging from the Solar System, young stars with planets and discs, circumstellar environments of evolved stars to a galaxy nucleus. Some of the first results are previewed.

The Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) is the new Very Large Telescope (VLT) extreme adaptive optics instrument (Beuzit et al., 2006; Kasper et al., 2012). SPHERE provides on-axis diffraction-limited observations (imaging, spectroscopy and polarimetry) from optical to near-infrared wavelengths in combination with various coronagraphic facilities. The common path and infrastructure (CPI) of SPHERE provides an adaptive optics (AO) corrected and coronagraphic beam to the three sub-instruments: the near-infrared integral field spectrograph (IFS); the infrared dual-beam imager and spectrograph (IRDIS); and the visible light Zurich Imaging Polarimeter (ZIMPOL).

Following the commissioning activities, as part of the transition to operations, all Paranal instruments undergo a Science Verification phase where scientific observations are carried out by a dedicated ESO team to test the end-to-end operations of a new instrument. The SPHERE SV took place from 4–11 December 2014 (eight full nights) and 9–12 February 2015 (four half nights). The SV runs were very successful, with some spectacular results, and one has already appeared in print (on the lack of a brown dwarf around V471 Tau, by Hardy et al. [2015]) We could complete 24 programmes and declared a further four programmes finished with sufficient data for a scientific analysis. Eight programmes received partial data — in several cases complete datasets on individual objects — although we could not obtain data for all the requested targets. The remaining four programmes were not observed. The total observed time expended for the approved programmes was 68 hours.

Proposal solicitation and submission

The call for SPHERE Science Verification proposals was issued on 19 September 2014[1] and was advertised through the ESO Science Newsletter issued on 22 September 2014[2]. With the call, the SPHERE SV web page[3] was launched. The deadline for observing proposals was 15 October 2014 and a total of 67 proposals was received.

The SPHERE SV team evaluated all proposals and the selection was discussed at a video conference. Care was taken to clarify any possible overlap with Guaranteed Time Observations (GTO) and proposed Period 95 (P95) observing programmes. For the latter, it was decided to reject all SV proposals which requested the same targets and observing modes as a P95 proposal, removing seven SV proposals. The cut-off line was defined at 88 hours of allocated time, which meant that 40 programmes received a time allocation. The approval of the selected proposals (announced 11 November 2014) was followed by a short and intensive Phase 2 period during which all principal investigators (PIs) had to prepare their observations in detail and submit them to the ESO User Support Department for final review. By 3 December 2014 all 40 programmes were ready to go, awaiting their execution during the following week.

A wide range of science topics was proposed, including the imaging and spectroscopy of Solar System objects (companions of asteroids, shapes of asteroids, moons of Jupiter), exoplanetary systems, protoplanetary and debris discs around young stars, the binarity of brown dwarfs, the environment of evolved stars, SN 1987A and the nearby active galactic nucleus NGC 1068.

Observations

The observations were executed in service mode, giving priority to the programmes with the highest scientific ranking among those matching the required weather conditions. The target distribution was heavily concentrated in the right ascension (RA) range from 4 hours < RA < 6 hours with only few targets at the end of the night (see Figure 1). Modifications to the scientific ranking were necessary in regions where there were only a few Observing Blocks (OBs) available and hence lower ranked proposals were observed. Conversely, in RA regions with a high pressure, some higher ranked proposals could not be observed in the available time.

The weather conditions during the SV run were mostly good to excellent. Out of the eight nights in December 2014, there were two nights with cirrus and parts of two nights with wind restrictions. During the February 2015 run, two nights were lost to clouds and high humidity. The instrument worked without major faults and we experienced no major loss for technical reasons. The resulting data are of excellent quality and in almost all cases we were able to obtain unique high-contrast observations. All SPHERE modes were used during SV and all worked to expectation.

The complex SPHERE extreme AO (SAXO) / Standard Platform for Adaptive optics Real Time Applications (SPARTA) adaptive optics system proved to be reliable in operations and observational issues could be easily solved. Based on our SV experience, we can confirm that

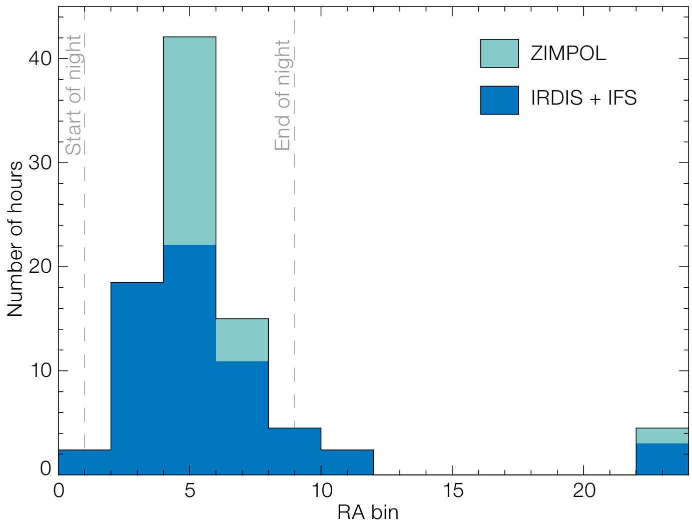


Figure 1. (Left) The distribution of the allocated SV targets in RA.

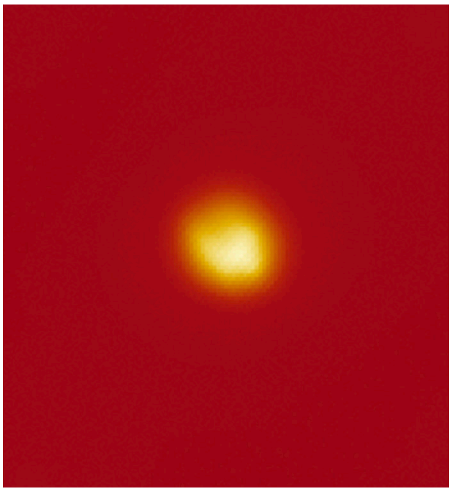


Figure 2. (Right) A SPHERE image of R Doradus — the largest star in the sky after the Sun. This *V*-band image taken with ZIMPOL shows R Dor, which has a diameter of 57 milliarcseconds. The surface is clearly not smooth and shows large star spots.

the guide probe "seeing" is a good indicator for performance prediction and quality control (QC0). Above a full width half maximum (FWHM) of 1.2 arcseconds on the guide probe the AO system struggles. On the other hand, we managed to operate in photon-counting mode on rather faint natural guide stars, although with significantly degraded AO performance.

Archive and data processing

All raw data have been archived and are publicly available. The SPHERE SV web page[3] contains direct links to the SV raw data. A link to a pre-release of the SPHERE pipeline is also provided on the SV webpage. The pipeline is mostly functional.

First scientific results

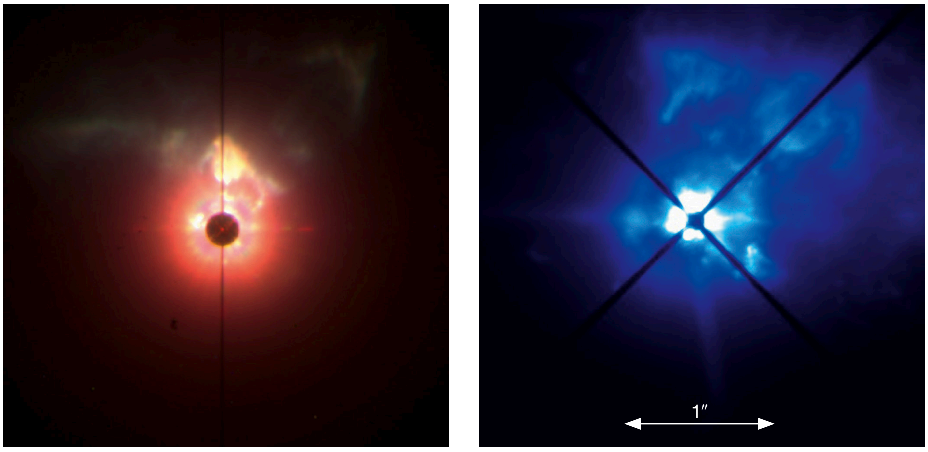
The following provides a sample of some preliminary results obtained during SPHERE SV and demonstrates the scientific promise of SPHERE.

Resolving the surfaces of stars has not so far been possible with direct imaging. During SPHERE SV, the largest apparent diameter star in the sky after the Sun, R Doradus (diameter 57 milliarcseconds), was observed with ZIMPOL (Figure 2) and the *V*-band image displays large structures on the stellar surface. R-Dor is a Mira variable and one can easily imagine that monitoring the surface features on R Dor, and similar giants, will yield further information on such evolved stars.

VY CMa, a red hypergiant star at a distance of 1.3 kpc, is one of the most massive (18 $M_\odot$) and most luminous ($2.7 \times 10^5\ L_\odot$) nearby stars. VY CMa is losing the equivalent of 30 Earth masses per year. The ejected matter now constitutes the nebula seen in the high-contrast images of SPHERE (Figure 3; Scicluna & Siebenmorgen [2015] in prep.). The observations are key to understanding mass-loss phenomena in evolved stars. Mass loss in massive stars is thought to provide the interstellar medium with building blocks that have, are, and will eventually be, seeds of life in the Universe.

Figure 3 shows two images of VY CMa: on the left is an infrared multi-colour image obtained with IRDIS (field of view, 11 arcseconds on a side); the right-hand image was obtained with ZIMPOL, the visible camera providing diffraction-limited images at scales as fine as 15 milliarcseconds. Each feature in the image comes from a distinct mass-loss episode, similar to the Sun's own coronal mass ejections, but on a much larger scale. The material visible in the images was ejected within the last 1000 years. Emission is only visible on the upper half of the image because dense matter blocks the rest. VY CMa is a candidate for a supernova: if the explosion occurs before the current nebula disperses a strong interaction between the supernova shock

Figure 3. Left: Colour-composite image of the outflow around the evolved star VY CMa in the *JHK* filters. The image displays the full IRDIS field of view of 11 by 11 arcseconds. Right: Optical *V*-band image of VY CMa obtained with ZIMPOL. Note that the field of view is a fraction of the near-infrared image size (left) and shows nebular structure much closer to the star.



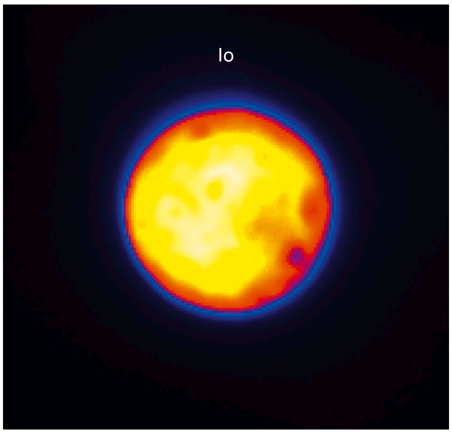
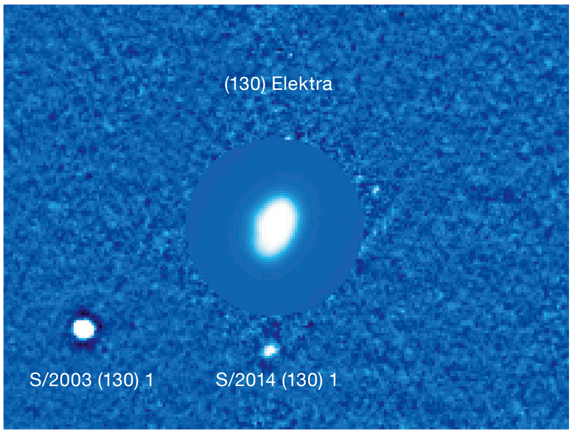


Figure 4. (Left) IRDIS *K* filter image of Jupiter's moon Io. The surface structure is clearly noticeable, with silica-rich hot spots attributed to geological activity. Using the IFS's capabilities, spectral mapping of these regions could be carried out.

Figure 5. (Right) The asteroid (130) Elektra with its satellites, observed with SPHERE IFS. The second (inner) satellite is a new discovery with SPHERE and received the preliminary designation S/2014 (130) S1. This represents the fifth known multiple system in the asteroid main belt.



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wave and the circumstellar material is expected, leading to a very bright supernova due to the kinetic energy liberated in the shocks.

Within the Solar System, SPHERE can be used to map the surfaces of planets, moons or smaller bodies. Several Jovian moons were observed during SPHERE Science Verification at different times to obtain a full map of the surface of these objects. As an example, an image of Io is shown in Figure 4 and surface structures are easily visible. The full map of Io is being produced from a series of images at different rotational phases of the satellite (the rotational period is 1.77 days).

Two main belt asteroids with known satellites were observed in order to characterise the orbits. The observations of (130) Elektra yielded a new, second satellite to this asteroid, named S/2014 (130) S1 (Yang et al., 2014; see Figure 5). The image illustrates SPHERE's capability to observe faint objects close to bright sources. The adaptive optics correction was performed on the asteroids themselves, which are resolved at SPHERE's angular resolution, validating the effectiveness of the AO system for extended objects.

One of SPHERE's main goals is the direct observation of exoplanets. During SV this was demonstrated by observing the well-known planetary system around HR 8799. The planetary images could even be seen on the real-time display during the observations in the control room! The processed SPHERE *H*-band image displayed here (Figure 6) shows the power of the instrument for high-contrast imaging. The removal of the fixed speckles reveals sources very close to the central (masked) star.

SPHERE also provides the option of high-contrast spectroscopy using a coronagraphic mask with IRDIS, covering in this case the *Y*- and *J*-bands. This capability was demonstrated by obtaining a spectrum of the brown dwarf companion to an M star (2MASS J01225093-2439505). The separation of the spectra is critical to allow the emission from the fainter source to be cleanly extracted without being swamped by the light of the bright primary star. The spectrum of the brown dwarf is displayed as the two-dimensional spectrum (wavelength runs vertically and the spatial direction is horizontal in the picture) in Figure 7.

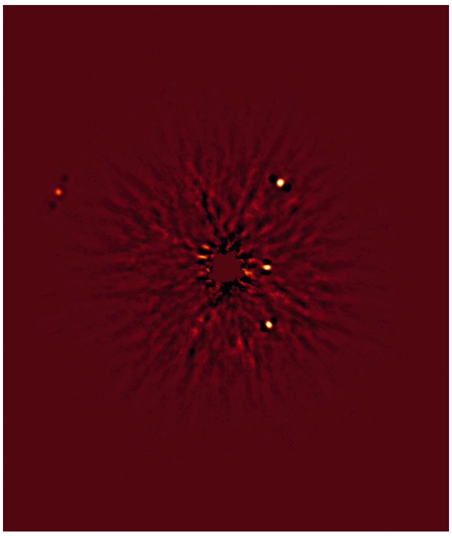


Figure 6. Four planets imaged with SPHERE around HR 8799. This is a processed image (in *H*-band), but the planets were also visible on the real-time display.

Another popular application of SPHERE will be the direct imaging of discs around stars. We show here two very prominent examples of such discs. One is a face-on disc around the star MWC 758 where a strong spiral structure is detected in polarised light in the *Y* filter from the protoplanetary disc. The starlight has been suppressed by the coronagraph and the emission visible in Figure 8 stems from

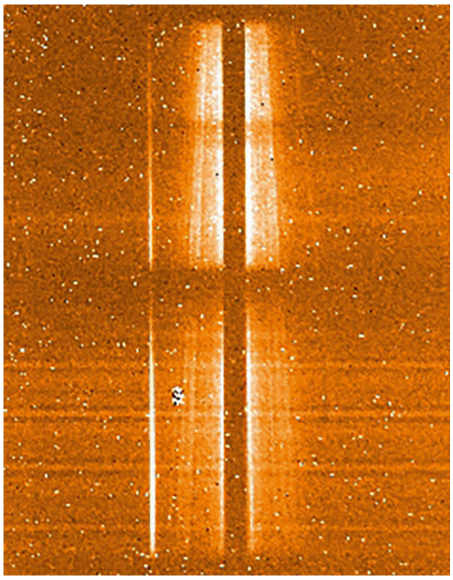
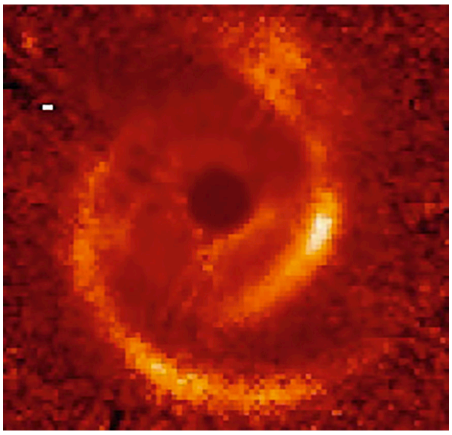


Figure 7. Spectrum display of a brown dwarf companion to the M star 2MASS J01225093-2439505 is shown. The spectrum is the bright, narrow, vertical line to the left of the M star spectrum. The coronagraph is the dark line covering the brightest parts of the M star spectrum.



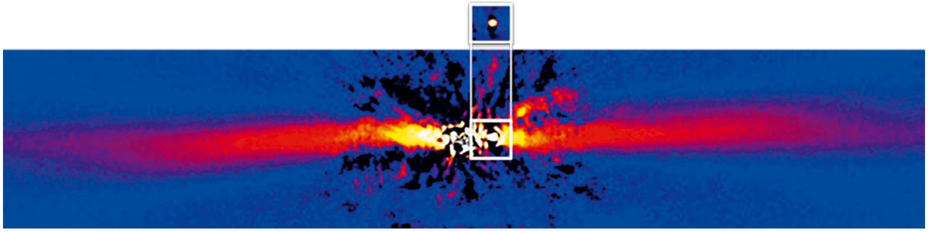


Figure 8. (Left) Spectacular spiral structure revealed around the star MWC758. This image shows the dust in the protoplanetary disc in polarised light, obtained with IRDIS in the *Y* filter.

Figure 9. (Above) The famous planetary system around β Pictoris imaged by SPHERE in a narrow *K* filter. The system harbours an edge-on debris disc with many asymmetries and distortions and a 10 Jupiter-mass planet currently at a projected separation of about 350 milliarcseconds from the star (shown by the different colour scale above). This image shows the full IRDIS field of view.

dust in the disc. The disc surface brightness is not uniform and probably indicates structure forming within the disc. The second example is the well-known massive disc around β Pictoris, shown in Figure 9. The detailed structure of the inner disc has been imaged with SPHERE and the (known) planet could be clearly observed. The narrowband *K* filter image of the debris disc reveals the warp and distortions in the inner disc.

Prospects

The above examples give only a small foretaste of the science we can expect from SPHERE observations. The main topics will be exoplanet imaging and characterisation of planetary atmospheres. Circumstellar discs will also be favourite targets. But there are many other applications of high angular resolution and high-contrast imaging and spectroscopy that we can look forward to from SPHERE in the near future.

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Hardy, A. et al. 2015, ApJ, 800, L24
Kasper, M. et al. 2012, The Messenger, 149, 17
Yang, B. et al. 2014, CBET, 4035

Links

[1] Science announcement of SPHERE SV: http://www.eso.org/sci/publications/announcements/sciann14047.html
[2] SV announcement in Science Newsletter: http://www.eso.org/sci/publications/newsletter/sep2014.html
[3] SPHERE SV webpage: http://www.eso.org/sci/activities/vltsv/spheresv.html

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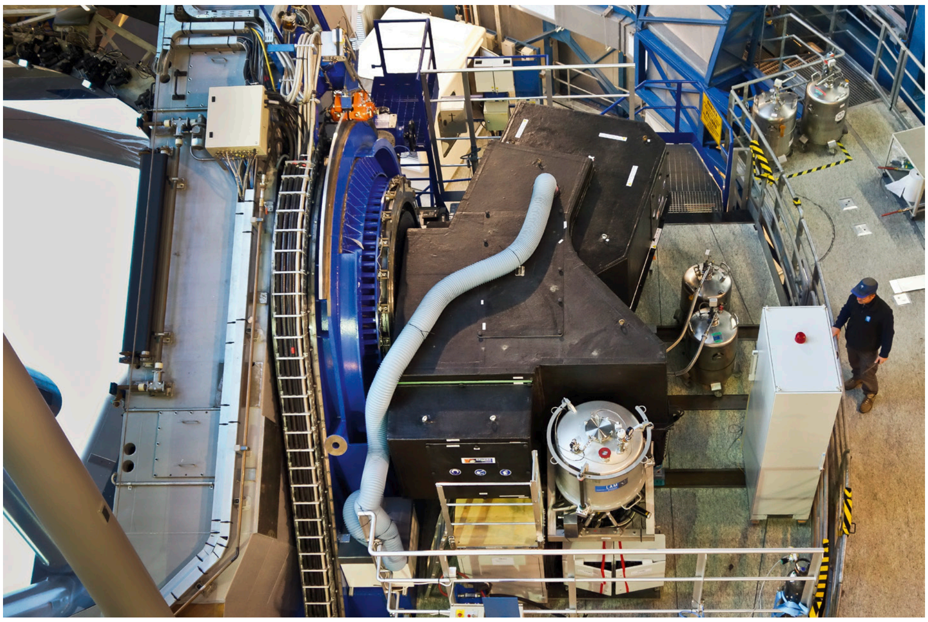

The SPHERE instrument is shown shortly after it was installed on the VLT Unit Telescope 3 Nasmyth platform in May 2014. See Releases eso1417 and eso1506 for more detail.