SPHERE: a 'Planet Finder' Instrument for the VLT

Jean-Luc Beuzit[1]
Markus Feldt[2]
Kjetil Dohlen[3]
David Mouillet[1]
Pascal Puget[1]
Jacopo Antici[5]
Andrea Baruffolo[5]
Pierre Baudoz[4]
Alessandro Berton[2]
Anthony Boccaletti[4]
Marcel Carbillet[6]
Julien Charton[1]
Riccardo Claudi[5]
Mark Downing[7]
Philippe Feautrier[1]
Enrico Fedrigo[7]
Thierry Fusco[8]
Raffaele Gratton[5]
Norbert Hubin[7]
Markus Kasper[7]
Maud Langlois[3]
Claire Moutou[3]
Laurent Mugnier[8]
Johan Pragt[9]
Patrick Rabou[1]
Michel Saisse[3]
Hans Martin Schmid[10]
Eric Stadler[1]
Massimo Turrato[5]
Stéphane Udry[11]
Rens Waters[12]
François Wildi[11]

[1] Laboratoire d'Astrophysique de Grenoble, France
[2] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[3] Laboratoire d'Astrophysique de Marseille, France
[4] Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Paris, France
[5] INAF – Osservatorio Astronomico di Padova, Italy
[6] Laboratoire Universitaire d'Astrophysique de Nice, France
[7] ESO
[8] Office National d'Etudes et de Recherches Aérospatiales, Chatillon, France
[9] Stichting ASTRonomisch Onderzoek in Nederland, the Netherlands
[10] Eidgenössische Technische Hochschule Zürich, Switzerland
[11] Observatoire de Genève, Switzerland
[12] Universiteit van Amsterdam, the Netherlands

Direct detection and spectral characterisation of extrasolar planets is one of the most exciting but also one of the most challenging areas in modern astronomy. For its second-generation instrumentation on the VLT, ESO has supported two phase A studies for a so-called 'Planet Finder' dedicated instrument. Based on the results of these two studies, a unique instrument, SPHERE, is now considered for first light in 2010, including a powerful extreme adaptive optics system (SAXO), various coronagraphs, an infrared differential imaging camera (IRDIS), an infrared integral field spectrograph (IFS) and a visible differential polarimeter (ZIMPOL).

The prime objective of the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument for the VLT is the discovery and study of new extrasolar giant planets orbiting nearby stars by direct imaging of their circumstellar environment. The challenge consists in the very large contrast between the host star and the planet, larger than 12.5 magnitudes (or 10^5 in flux ratio), at very small angular separations, typically inside the seeing halo. The whole design of such an instrument is therefore optimised towards reaching the highest contrast in a limited field of view and at short distances from the central star (Mouillet et al., 2001). Both evolved and young planetary systems will be detected, respectively through their reflected light (mostly by visible differential polarimetry) and through the intrinsic planet emission (using IR differential imaging and integral field spectroscopy). Both components of the near-infrared arm of SPHERE will provide complementary detection capabilities and characterisation potential, in terms of field of view, contrast, and spectral domain.

SPHERE will greatly contribute to the field of extrasolar planet studies, already very active, particularly by offering direct detections of planets more massive than Jupiter at various stages of their evolution, in the key separation regime 1 to 100 AU. Migration mechanisms will then be better understood. The complementarities of direct imaging with other detection methods such as radial velocities and photometric transits, in terms of targets, detection biases and measured planetary parameters, and more specifically the combination with results from other projects like HARPS, COROT, VLTI/PRIMA, JWST and Kepler, will offer promising avenues. The present indications that massive distant planets could be numerous will be firmly confirmed or denied by SPHERE, if the number of observed targets with relevant detection limits is statistically acceptable, i.e. of the order of 300 to 400.

This would in particular fully justify a large effort in an extended observational survey of several hundred nights concentrating on the following classes of targets:
- *Nearby young associations* will offer the best chance of detecting low-mass planets, since they will have brighter substellar companions, and therefore the greatest number of planets per star observed.
- *Stars with known planets*, especially any that exhibit long-term residuals in their radial-velocity curves, indicating the possible presence of a more distant planet.
- *Nearest stars:* measuring these targets will probe the smallest orbits and will thus provide the only opportunities for detecting planets by directly reflected light.
- *Stars aged from 100 Myr to 1 Gyr:* The planets will still be over-luminous as compared to Solar System planets, so the mass limit will be lower than for old systems.

With such a prime objective, it is obvious that many other research fields will benefit from the large contrast performance of SPHERE: protoplanetary discs, brown dwarfs, evolved massive stars and marginally, Solar System and extragalactic science. These domains will nicely enrich the scientific impact of the instrument. Their instrumental needs should however not be in conflict with the high-contrast requirements.

Science requirements and observing modes

The key scientific requirements deriving from the science analysis and driving

the design of the instrument are summarised below:
- High contrast to reach giant planets 14 to 16 magnitudes fainter than their host star.
- Access to very small angular separations, 0.1″ to 3″ from the host star.
- Sensitivity and optimal performance for targets up to visible magnitude ~ 10, for building a potential target list in which the sample volume is consistent with the objectives (more than 400 targets in total, with 100 high-priority targets).
- Sensitivity to faint companions down to magnitude H ~ 24.
- Access to an extended spectral domain at low resolution, for the characterisation of the detected objects, at a resolving power ~ 30.
- Sensitivity to extended sources down to ~ 17 magnitudes per square arcseconds at less than 0.2″ from the host star.

Three main observing modes have been defined in order to draw the maximum benefit of the unique instrumental capabilities of SPHERE.

The *NIR survey mode* is the main observing mode which will be used for ~ 80% of the observing time. It combines IRDIS dual imaging in *H* band with imaging spectroscopy using the IFS in the *Y*+*J*-bands by the aid of dichroic beam separation after the coronagraph. This configuration permits to benefit simultaneously from the optimal capabilities of both dual imaging over a large field (out to ~ 5″ radius) and spectral imaging in the inner region (out to at least 0.7″). In particular, it allows to reduce the number of false alarms and to confirm potential detections obtained in one channel by data from the other channel. This will be a definitive advantage in case of detections very close to the limits of the system.

The *NIR characterisation mode*, in which IRDIS is used alone in its various modes, will allow obtaining observations with a wider FOV in all bands from Y to short-K, either in dual imaging or in broad and narrow-band filters. This will be especially interesting in order to obtain complementary information on already detected and relatively bright targets (follow-up and/or characterisation). Spectroscopic characterisation at low or medium resolution will be possible in long-slit mode.

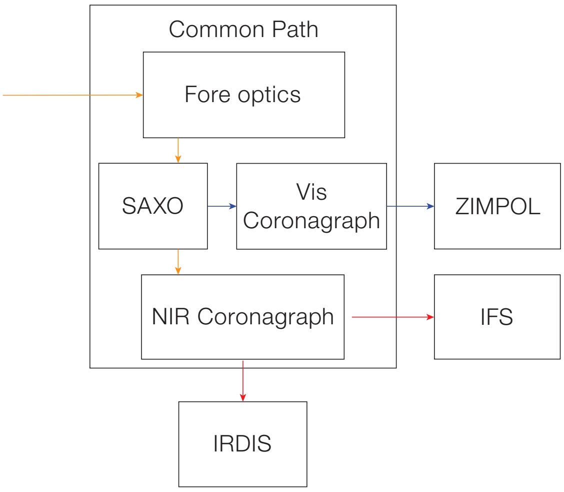


Figure 1: Global concept of the SPHERE instrument, indicating its four sub-systems: Common Path Optics, IRDIS, IFS, and ZIMPOL. It also includes the main functionalities within the Common Path sub-system. Optical beams are indicated in red for NIR, blue for visible and orange for Common Path.

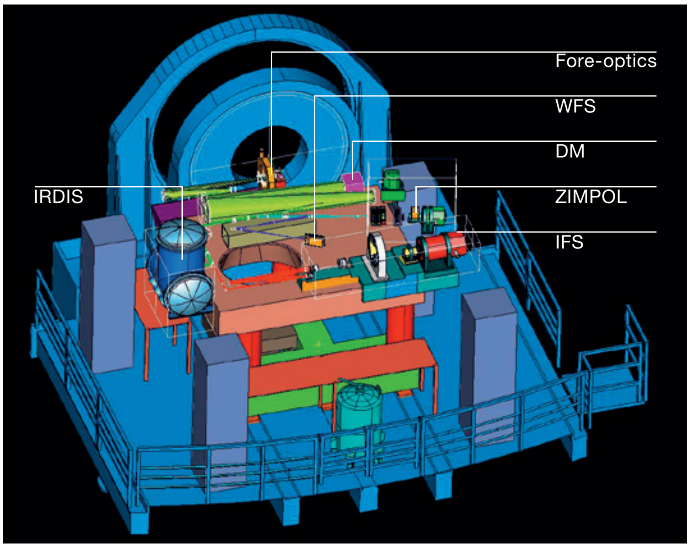


Figure 2: Implementation of SPHERE on the Nasmyth platform.

Additional science cases will also benefit from these observing modes (discs, brown dwarfs, etc.). This will be a very useful capability for the ESO community at a time when NACO will most likely no longer be offered.

The *visible search and characterisation mode*, will benefit from ZIMPOL polarimetric capacities to provide unique performance in reflected light very close to the star, down to the level required for the first direct detection in the visible of old close-in planets, even if on a relatively small number of targets. ZIMPOL also provides classical imaging in the visible, offering unique high-Strehl performance in an era when the Hubble Space Telescope (HST) will probably have been decommissioned.

Instrument concept

To fulfil these requirements, the proposed SPHERE instrument is divided into four sub-systems as illustrated by Figure 1.

Common Path Optics

The Common Path Optics, transmitting the telescope beam via the various correcting elements of the adaptive optics system (pupil tip-tilt and pupil de-rotator, deformable mirror, image tip-tilt mirror, atmospheric dispersion compensator ...) and via the coronagraphic unit (apodizer, coronagraphic mask, Lyot stop) to the adaptive optics wavefront sensor and to the science channels. The proposed implementation of SPHERE on the VLT Nasmyth platform is presented in Figure 2.

Extreme adaptive optics

The design of the SPHERE Adaptive optics for eXoplanet Observation (SAXO), resulting from a global trade-off combining optical design, technological aspects, cost and risk issues, leads to the use of a 41 × 41 actuator DM of 180 mm diameter with inter-actuator stroke > ±1 μm and maximum stroke > ± 3.5 μm, and a two-axis tip-tilt mirror (TTM) with ± 0.5 mas resolution (Fusco et al. 2006). The wavefront sensor is a 40 × 40 lenslet Shack-Hartmann sensor, with a spectral range between 0.45 and 0.95 μm equipped with a focal plane filtering device of variable size (from λ/d to 3λ/d at 0.7 μm, where d is the projected microlens diameter) for aliasing control. A temporal sampling frequency of 1.2 kHz is achieved using a 240 × 240 pixel electron multiplying CCD detector (CCD220 from EEV) with a read-out noise < 1 electron and a 1.4 excess photon noise factor. The global AO loop delay is maintained below 1 ms.

Image and pupil stability are essential in high-contrast instruments. Differential image movements due to thermo-mechanical effects and ADC mechanism precision are therefore measured in real time using an auxiliary NIR tip-tilt sensor located close to the coronagraphic focus and corrected via a differential tip-tilt mirror in the WFS arm. Likewise, pupil runout is measured by analysis of the WFS sub-pupil intensity along the pupil edge and corrected by a pupil tip-tilt mirror close to the telescope focal plane at the entrance of the instrument. Non-common path aberrations are measured offline using a phase diversity algorithm and compensated on-line by reference slope adjustments.

Coronagraphs

Efficient coronagraphy is important for reaching the science goals of SPHERE. Its action is twofold: reduce the intensity of the stellar peak by a factor of at least 100 and eliminate the diffraction features due to the pupil edges. Stellar coronagraphy is a quickly evolving research field and it is important to leave the instrument open for future evolution by allowing exchangeable masks both in the coronagraphic focus and in its entrance and exit pupil planes.

The baseline coronagraph suite will include an achromatic four-quadrant phase mask coronagraph (A4Q) based on precision mounting of four half-wave plates (HWP), and both a classical Lyot coronagraph (CLC) and an apodised Lyot coronagraph (ALC). The A4Q has recently been demonstrated in the visible, where the main difficulties of precision edge-polishing and mounting of the HWPs have been addressed and excellent performance has been demonstrated (Mawet et al., 2006). Extension of these techniques to the NIR is ongoing. While the CLC option, with mask diameter of about 10 λ/D, is within the realm of classical manufacturing, the ALC option requires an apodiser in the coronagraph entrance pupil. Prototyping is ongoing, and a promising technology using graded metal deposition has been identified. An alternative technology based on ion implantation is also considered, but this technology gives discrete steps in the apodization profile. The effects of this are being quantified by simulations.

Infra-Red Dual-beam Imaging and Spectroscopy

The Infra-Red Dual-beam Imaging and Spectroscopy (IRDIS) sub-system constitutes the main science module of SPHERE. The main specifications for IRDIS include a spectral range from 950 to 2320 nm and an image scale of 12.25 mas per pixel consistent with Nyquist sampling at 950 nm. A FOV greater than 11″ square is required for both direct and dual imaging, leaving a slight margin for system optimisation when using two ‘quadrants’ of a 2k × 2k detector. The main mode of IRDIS is the dual imaging, providing images in two neighbouring spectral channels with minimised (< 10 nm rms) differential aberrations. Ten different filter couples are defined corresponding to different spectral features in modelled exoplanet spectra. In the direct imaging mode, 12 broad, medium and narrow-band filters are defined. In addition to direct and dual imaging, long-slit spectroscopy at resolving powers of 50 and 500 is provided, as well as a dual polarimetric imaging mode. A pupil-imaging mode for system diagnosis is also implemented.

Dual imaging separation is done using a beam-splitter combined with a mirror, producing two beams in parallel. Each beam has its own camera doublet and band-limiting filter. The main challenge is to achieve the required 10 nm differential aberrations requirement, but an error budget based on high-quality classical polishing technology is found to satisfy the requirement. This option has been favoured over the alternative Wollaston-based option used for example in the NACO SDI camera (Lenzen et al., 2004) because it eliminates spectral blurring problems, which would limit the useful FOV, and allows the use of high-quality materials with high homogeneity.

The proposed opto-mechanical design of IRDIS is shown in Figure 3.

Integral Field Spectroscopy

While an integral field spectrograph (IFS) for planet imaging is conceptually challenging, it is widely recognised as a potentially extremely useful science module for a planet-searching instrument. The reasons for this are twofold: Firstly the IFS can be built with virtually zero differential aberrations, and secondly the multiple spectral channels allow for better correction of speckle chromaticity and even data-analysis strategies that do not rely on the presence of *a priori* assumed features in the planet’s spectrum.

For SPHERE we are pursuing a microlens-based IFS concept related to the classical TIGER concept, modified for the case of high-contrast diffraction-limited observations. The required 5σ detectivity at 0.5″ is 10^{-7} with a goal of 10^{-8} with respect to the un-occulted PSF peak, and the spectral range of the IFS is limited to the *Y-J* bands (0.95–1.35 μm), allowing the use of a single detection channel and parallel operation of IRDIS and IFS. A resolving power per pixel of 30 is maintained, with a minimum FOV of 1.35″ square and a strong goal of 3″ square. Nyquist-limited spatial sampling at 0.95 μm is imposed as for IRDIS. Optimised commonality between IFS and IRDIS in terms of detector and associated equipment is seen as an important system goal. The same 2k × 2k detector format is therefore adopted, and it is highly likely that the long-wavelength cut-off defined for IRDIS will also be acceptable for IFS. The opto-mechanical concept including micro-lens array, collimation optics, an Amici Prism providing zero beam deviation and constant resolution within the entire wavelength range, camera optics, and the detector cryostat is illustrated in Figure 4.

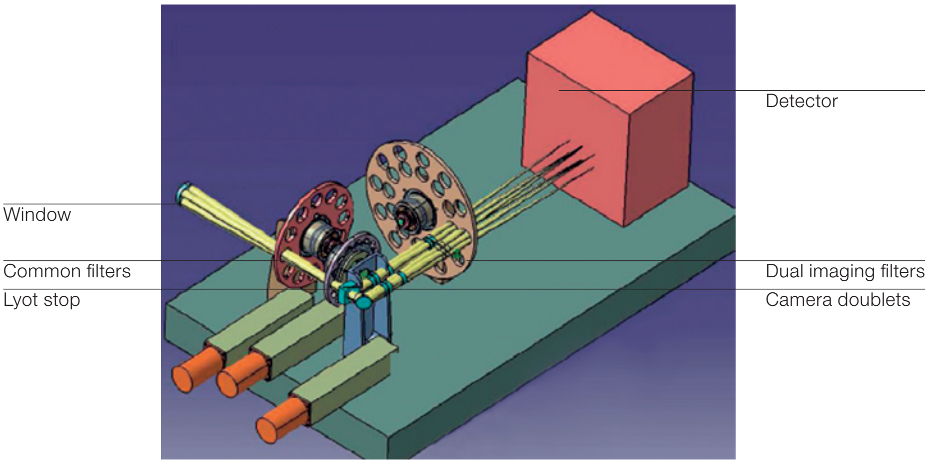
Imaging Polarimeter

The Zurich Imaging Polarimeter (ZIMPOL) sub-system is a high-precision imaging polarimeter working in the visual range, covering at least 600 to 900 nm. The instrument principle (Gisler et al., 2004) is based on fast modulation, using a ferro-electric retarder, and demodulation of the polarisation signal, using a modified CCD array, as illustrated in Figure 5. Key advantages of this technique are the simultaneous detection of two perpendicular polarisations (the modulation is faster than seeing variations), and the recording of both images on the same pixel. Thanks to this approach, a polarimetric precision of 10^{-5} or even better should be achieved. The CCD will cover a Nyquist sampled field of 3″ × 3″ square and it is foreseen that the FOV can be moved around the bright star so that a field with a radius of 4″ can be covered. In addition to polarimetric imaging, ZIMPOL provides the possibility for high-resolution imaging in the visual range using a set of broad and narrow-band filters. This capability will be unique in the post-HST era.

Expected performances

Various numerical simulation approaches have been developed by different groups during the Phase A studies of the SPHERE instrument. All these efforts are being gathered into a single instrument simulator developed on the CAOS platform in order to provide the technical and scientific community with a tool to predict the instrument performance. We present here the basic approach and key results of the AO/IRDIS simulator developed in Phase A, invoking a double subtraction, dual imaging approach.

Figure 3: IRDIS opto-mechanical implementation.



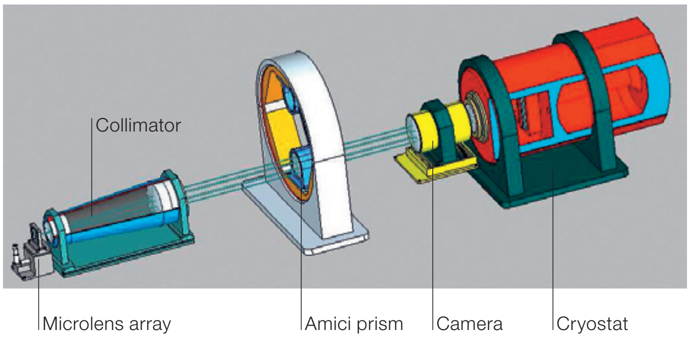


Figure 4: Opto-mechanical design of the IFS.

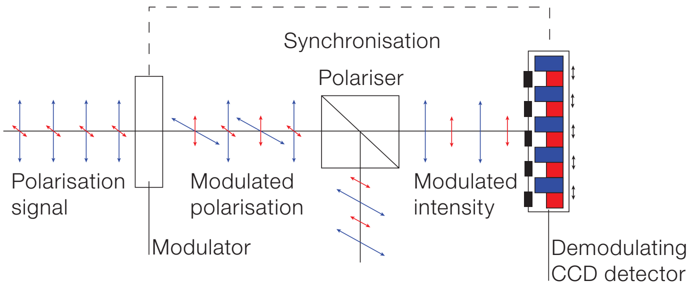


Figure 5: Basic polarimetric principle.

Figure 6: Basic structure of the dual-imaging performance model.

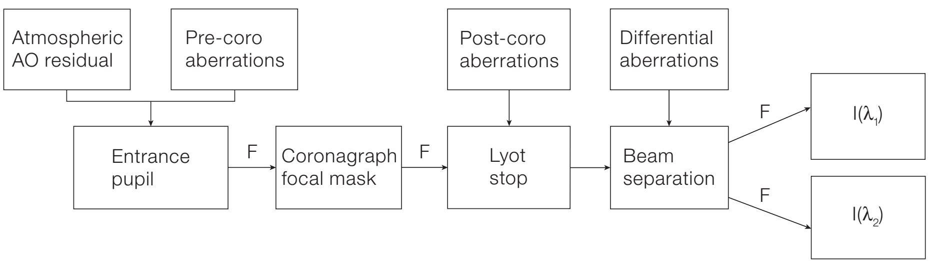


Figure 6 shows the structure of the dual imaging performance simulator. Through a series of three Fourier transforms (denoted F in the figure), the coronagraphic action on a perturbed wavefront and the influence of post-coronagraphic aberrations are simulated. The coronagraphic entrance wavefront is affected by time-variable residuals of the AO correction of atmospheric turbulence, as well as quasi-static instrumental aberrations. Instrumental aberrations include actual phase maps representing the VLT mirrors, and estimated phase maps of instrument optics generated using a power spectral density (PSD) with an inverse square-law radial profile, assumed to represent typical high-quality optical surfaces. All the optics upstream of the dichroic beam-splitter is high-pass filtered with a cut-off at the AO cut-off spatial frequency (20c, denoting cycles per pupil diameter). All optics downstream of the dichroic is high-pass filtered with a cut-off at 4c, representing the expected limit of instrumental calibration based on phase-diversity techniques. Post coronagraphic aberrations represent aberrations within the IRDIS science module. While common aberrations, as predicted by theoretical studies, are of little influence on the speckle reduction process, differential aberrations are extremely important. This leads to the strict differential aberrations budget imposed upon the IRDIS design. Other factors included in the simulations include image decentring on the focal plane mask, both dynamic (jitter), chromatic (ADC residual) and fixed offset, coronagraph defaults (e.g. deviation from π phase shifts in the 4QPM mask), etc.

In the complete double difference simulation, this simulation is performed twice, once for the object star and once for a reference star, using uncorrelated atmospheric screens and introducing small differences, in particular in terms of fixed offset of the star on the coronagraph and transverse and rotational alignment error between telescope phase screens and instrument phase screens. A sensitivity analysis has confirmed the great importance of controlling these parameters to great precision (image centring < 0.5 mas, pupil shift < 0.2 %, pupil rotation < 0.1°), imposing the pupil and image stabilisation optics and control loops described above.

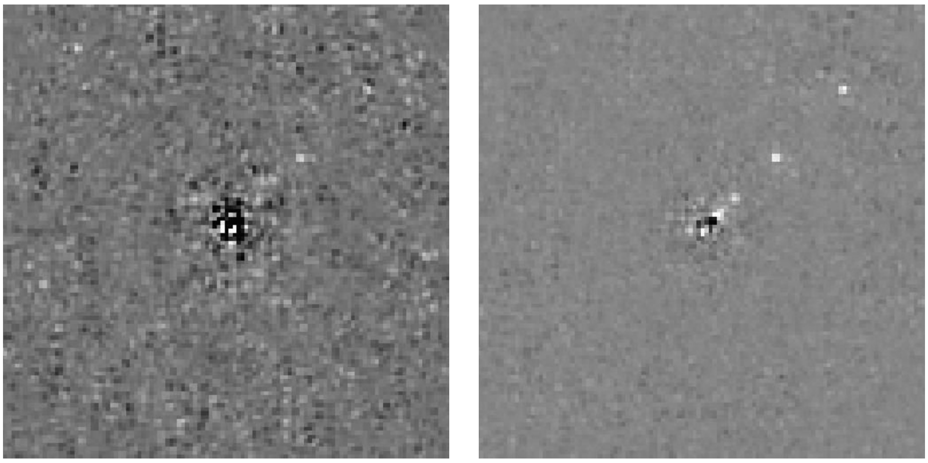


Figure 7: Residuals after simple dual-band subtraction (left) and double subtraction (right). Gray scale is linear between +/– $5\ 10^{-6}$ of the non-coronagraphic PSF maximum. Residual noise is subtracted down to a level much lower than companion flux.

Figure 7 shows the resulting processed image after dual wavelength subtraction (left) and the complete double difference subtraction involving a reference star. The object here is a young (10 Myr) M0 star at 10 pc, with 1 MJ companions located at 0.1 to 0.4 arcsec from the star. These companions have a difference in magnitude of 12 with respect to their host star, representing a contrast of $1.3\ 10^{-5}$. Through an extensive simulation of test cases involving various stellar ages and distances and a series of different-sized companions at different orbital separations, we find in particular that 1 MJ planets are detectable down to angular separations of 0.2″ for a young (10 Myr) M0 star at 40 pc, and that 10 MJ planets are detectable down to angular separations of 0.1″ for an older (1 Gyr) M0 star at 10 pc.

Project organisation

Following two concurrent phase A studies, the ESO Scientific and Technical Committee recommended in April 2005 to investigate the feasibility and interest of benefitting from both studies by proposing an optimised instrument including the XAO system, coronagraphic devices and differential imaging camera proposed by one consortium as well as the Integral Field Spectrograph and ZIMPOL visible dual imaging polarimeter proposed by the other consortium. A post-phase A study has validated the interest of such an approach in terms of scientific return and its feasibility in terms of system analysis and project management.

The new consortium includes several European institutes, namely: Laboratoire d'Astrophysique de Grenoble (P.I. institute), Max-Planck-Institut für Astronomie in Heidelberg (co-P.I. institute), Laboratoire d'Astrophysique de Marseille, Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique de l'Observatoire de Paris, Laboratoire Universitaire d'Astrophysique de Nice, ONERA, Observatoire de Genève, Osservatorio Astronomico di Padova, Institute of Astronomy of the Zurich College of Technology, Astronomical Institute of the University of Amsterdam, ASTRON and ESO.

The kick-off meeting took place in March 2006 and the current development plan, foresees first light for SPHERE in late 2010.

Conclusion

The SPHERE instrument, optimised for very high-contrast imaging around an extensive sample of stars, and its operation model including in particular a large survey strongly supported by the building consortium, will allow the direct detection of a sample of giant planets in a variety of conditions. Such a return in the proposed schedule (first light in 2010) will provide a timely and critical contribution to the highly competitive research field of extrasolar planets: formation, evolution and characterisation. This observational approach will provide specific information, complementary to other observational techniques (radial velocities, photometric transits, thermal IR imaging, etc.) and absolutely necessary to prepare for the foreseen next-generation challenges, from the ground with Extremely Large Telescopes or from space with coronagraphic imaging telescopes (TPF-C) and interferometric instruments (DARWIN, TPF-I).

The science return of SPHERE will be optimised through the observation of a large enough number of targets in survey(s). Large homogeneous data sets allow for the derivation of statistically significant data on the incidence and properties of planets, from both detection and non-detection, and for a better discussion of the false alarms. The SPHERE consortium proposes to dedicate most of its GTO allocation to such a moderately large survey, covering a few of the identified science goals on a sub-set of the possible SPHERE targets, and endorses the proposal to have a broader community involved in a much wider and more complete survey. ESO and the consortium are currently exploring the possibility to promote such a SPHERE large survey.

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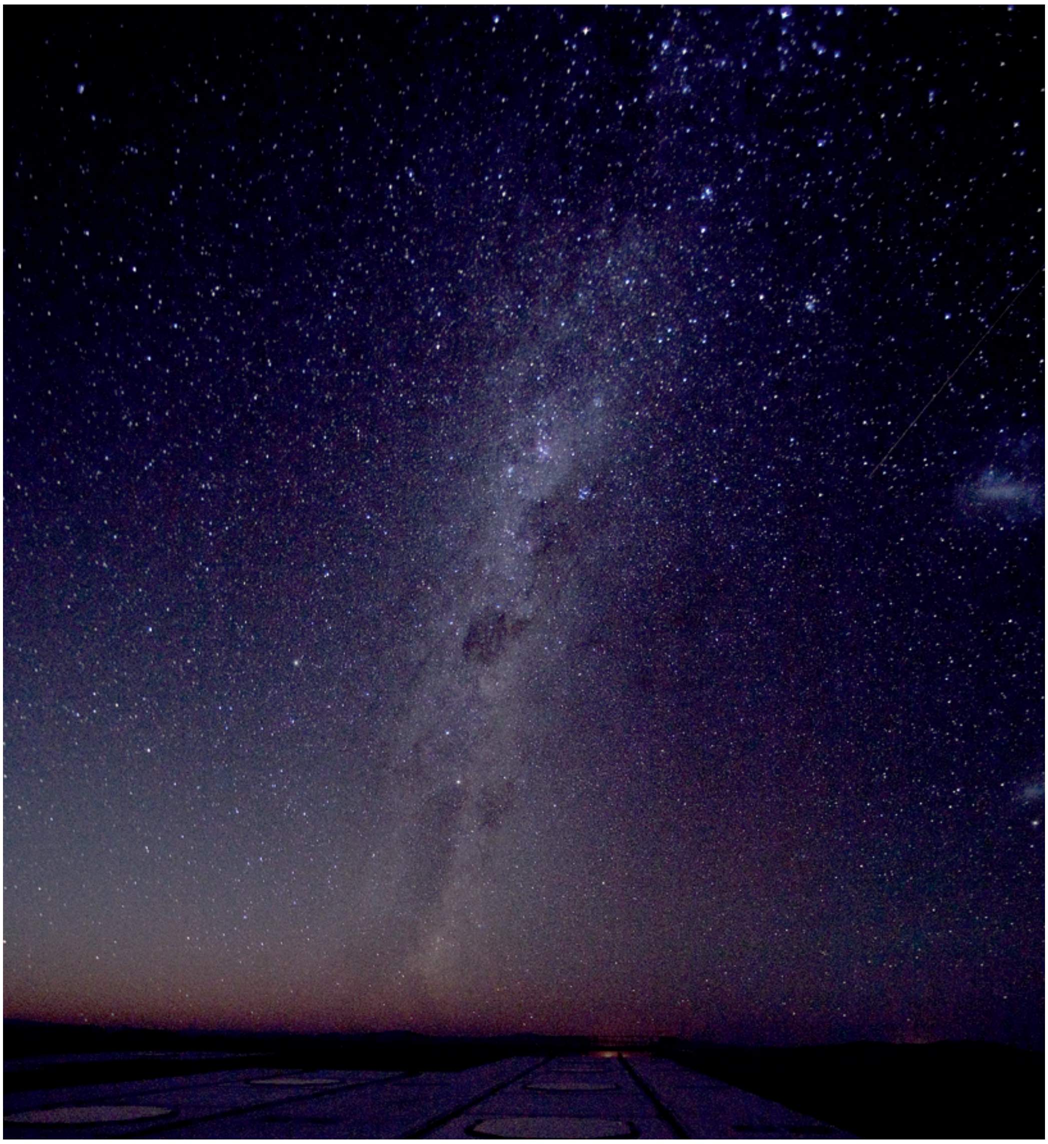

The sky above Paranal. The Milky Way is clearly visible in all its majesty, as well as the Magellanic Clouds on the right. This image was obtained on 11 December 2005 by Hans Hermann Heyer (ESO) with a Canon EOS 5D.