SPHERE: a 'Planet Finder' instrument for the VLT

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SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is a second generation instrument for the VLT optimized for the very high-contrast imaging around bright stars[1]. The primary goal is the detection and characterization of new giant planets around a variety of nearby stars. Together with the observation of early planetary systems and disks, and in association with the results of other planet search techniques, SPHERE will be a primary contributor to get a complete picture of the variety of planetary systems and to better understand their mechanisms of formation and evolution. Such results will be obtained before even more ambitious projects for the direct imaging of planets either from the ground with ELTs or from space.

1 Scientific context and main instrument goals

1.1 Primary astrophysical issues

For essentially a dozen years now, various observation techniques (mainly radial velocity measurements and transits) have revealed a large number of planets around other stars. The demonstrated existence of such common planetary systems and also some impressive differences with respect to our system did provide essential inputs to re-visit our complete understanding and modeling of this fundamental issue of planets formation and evolution. Among the very exciting results was the quite unexpected variety of discovered systems, including for instance the hot Jupiters (massive planets very close to the stars), planets on very eccentric orbits, the frequency of multiple systems or planets in binary systems. Exo-planets studies are now enriched with a solid basis of planet detections making possible the statistical analysis of the variety of possible planet formation scenarios. Moreover, the combined use of radial velocity measurements with (primary or secondary) transit measurements allow further insights of the physics of the outer atmospheres or of the inner planetary structure in some particular cases.

However, the techniques mentionned here have some important limitations and suffer from strong observational biases. Direct imaging of planets should provide the required complementary information to obtain a comprehensive view of the composition, structure and evolution of the exo-planetary systems. In particular, for a better statistical analysis of extra-solar systems, direct imaging should be complementary to current techniques in terms of:

- detectable star-to-planet separation: current studies are limited to data up to a few astronomical units at most, i.e. at the very edge of the expected peak region of giant planet formation. On contrary, direct imaging is easier at large separation ; it should reveal the composition of outer planetary systems, which is essential to understand their overall dynamical structure, just like in our own Solar System.
- stellar types: here again the current techniques are strongly biased towards cool and quiet stars (most performing for G and K old stars) ; direct imaging should enlarge such a sample including massive stars and also, very importantly, the case of younger systems at earlier stages of dynamical evolution.

Direct imaging is not only needed to complete our view of extra-solar systems in a statistical approach, it also has the potential to characterize the physics and composition of extra-solar planet atmospheres, through the NIR spectral properties of the intrinsic emission, the spectral and polarization properties of the reflected light in case of close-in planets, and possibly their variability along the orbit.

The main challenge for such direct imaging of exoplanets consists in the very large contrast between the star and the planet at very small separations, typically inside the seeing halo. The achievement of astronomical adaptive optics in the 90's allowed to really enter the domain of high contrast imaging from the ground and the high angular imaging instruments installed on 8-m telescopes, such as VLT/NACO, demonstrated another step forward in performance. Large observing surveys, including in particular the favorable cases of young nearby stellar associations, are underway with the successful first detections of brown dwarfs and of planetary-mass companions. However, with typical contrast performance of Δm $\simeq$ 10 at 0.5", the current capabilities are only marginally opening the domain of planet detections, with the access to Jupiter-mass companions in the case of very young systems only (a few 10^6 yrs when the planet is still quite warm and not too faint) and at separations so large that the presence of planets is unlikely.

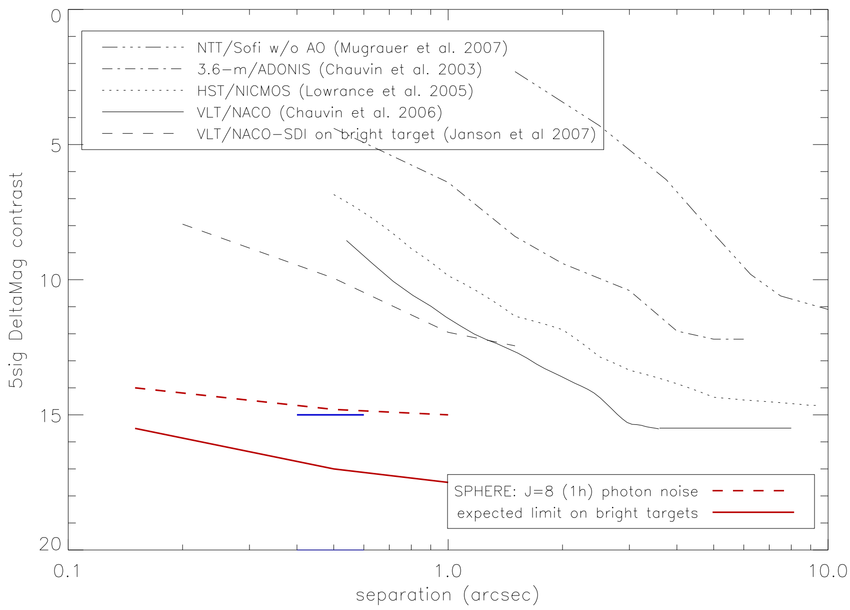

Fig. 1. Contrast performance as a function of separation: comparison between SPHERE and existing instruments. Upper black curves corresponds to the published results, obtained on existing instruments in NIR. Lower red curves indicate the estimated level of performance for SPHERE in NIR, in the photon noise-limited regime for a J=8 star in 1hr (dashed line) and in the ultimate calibration limit in the case of the brightest stars (full line). All curves correspond to a 5-σ detection of a point-like companion, and are expressed in terms of magnitude difference in the considered narrow band spectral channels.

1.2 Main instrument goals

As a second generation instrument on the VLT, dedicated to high contrast imaging, SPHERE will offer greatly enhanced capabilities (a gain of two orders of magnitudes in contrast with respect to existing instruments) to provide a clear view of the frequency of giant planets in wide orbits, searched for in a list of hundreds of potential stellar targets. Futhermore, for detected planets, SPHERE will provide information on NIR spectral properties of the atmosphere at low (R $\simeq$ 50) or medium (R $\simeq$ 500) resolution ; a few planets shining by reflecting stellar light might be detected, if present around very nearby stars, using the SPHERE polarimetric visible channel (ZIMPOL).

To achieve such astrophysical purposes, the main top level requirements of SPHERE include:

- very high contrast in NIR, in the stellar seeing halo: 10^{-6} to 10^{-8} at 0.5", down to inner working angles of 0.1"
- such contrast achievable in a typical observing time of 1 hr for a large number (hundreds to thousands) and a large variety (including various ages and various stellar types) of targets, corresponding to limiting magnitudes of V<$\sim$ 10 and J<$\sim$ 8
- spectral information covering the main planetary features from 0.95 to 1.7 μm at low resolution for first detection with possible extension to 2.32 μm or at medium resolution for further characterization
- operation plan compatible with a large survey of hundreds of stars: with small overheads, highly stable calibrations, and simultaneous covering of the complete 0.95 - 1.7 μm range with two complementary NIR instruments in parallel (an integral field spectrograph and a dual imager).
- high contrast dual polarization imager (ZIMPOL) for the detection of the planet reflected light at short separations and high angular resolution (diffraction-limited) in the visible (0.6 - 0.9 μm).

These instrumental capabilities will also allow to make great advances in related areas of study such as brown dwarfs and stellar and planetary formation processes (via imaging of inner disks at various evolutionary stages).

2 System overview

To fulfill these requirements, SPHERE is divided into 4 sub-systems[2]:

- the Common Path and Infrastructure (CPI) supports the other sub-systems and provide a very stable and accurate coronagraphic optical beam, in visible and NIR, to the other imaging sub-systems. A critical part is the high order adaptive optics correction stage, controlled at a temporal frequency of 1.2 kHz. The servo loop ensures very low turbulence residuals of the corrected modes ($<$ 3 mas jitter and $<$ 60 nm rms for other modes) but also the pupil stability. A de-rotator makes possible to control either the field orientation or the telescope pupil orientation as seen by the instrument at the Nasmyth focus. CPI also includes both visible and NIR coronagraphs, including four-quadrant phase devices or apodized-pupil coronagraphs to provide both a high stellar extinction and a very small inner working angle down to one or a few λ/D.

- the Integral Field Spectrograph (IFS) can be used either over the 0.95 - 1.35 μm spectral range with a resolution of 50 (simultaneously with the other NIR instrument in survey mode) or extended up to 1.7 μm. The number of independent spectral channels with essentially no differential wavefront errors will provide the deepest imaging performance over the central 1.7" field of view.
- the Infra-Red Dual-beam Imaging and Spectroscopy (IRDIS) sub-system complementarily covers a larger field of view (11") and a larger spectral domain up to 2.32 μm. When used simultaneously with IFS in planet detection survey mode, it will probe the main planetary methane absorption feature at 1.6 μm, in simultaneous dual imaging. A set of dual imaging filters are defined to cover the whole spectral domain and various types of expected planetary spectral features. Characterization of detected companions is possible through slit spectroscopy (R = 50, 500) ; a dual polarization imaging mode is also proposed for the detection and characterization of reflected light (on dust disks for instance).
- the Zurich Imaging Polarimeter (ZIMPOL) is a high-precision imaging polarimeter working in the visible (0.6 - 0.9 μm). Its principle is based on a fast polarization modulation (in the kHz range) with a ferro-electric retarder combined synchronously with charge transfer every second row of a modified CCD. Data processing extracts the images corresponding to two polarization states, obtained essentially simultaneously through the same optics and on the same detector pixels, leading to an extremely high differential polarization accuracy (better than 10^{-5}). The CCD will cover a Nyquist-sampled field of 3", with a possible offset up to 4" in radius.

SPHERE is an instrument designed and built by a consortium consisting of LAOG, MPIA, LAM, LESIA, LUAN, INAF, Observatoire de Genève, ETH, NOVA, ONERA and ASTRON, in collaboration with ESO. The preliminary design phase has been closed in late 2007 and the first light is foreseen in 2011.

References

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