Sparse Aperture Masking on Paranal

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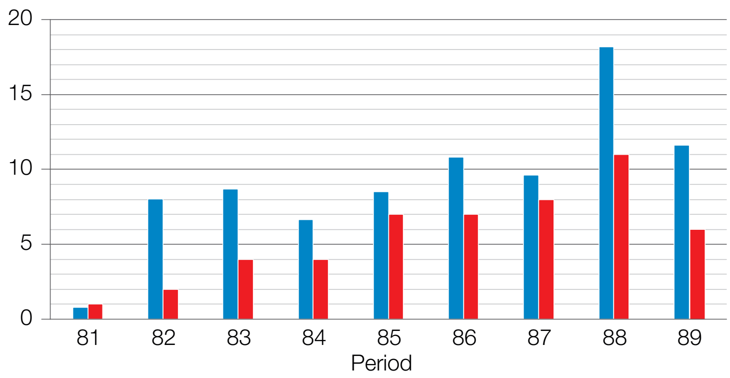


Figure 1. In blue, the percentage of SAM proposals with respect to the total number of NACO proposals submitted. Over the last two periods, 224 NACO proposals have been submitted, of which 33 required the use of SAM (approx 15%). In red, the number of SAM PIs for proposals that were accepted by the Observing Programmes Committee and eligible for technical feasibility. This is one of the major successes of recent years: the aperture masking community is getting wider.

The new operational mode of aperture-masking interferometry was added to the CONICA camera four years ago. Over the years, the masks — pieces of metal only two centimetres wide — have opened an unprecedented observational window for the NACO instrument. In comparison to the full aperture, they deliver superior point source function calibration, rejection of atmospheric noise and robust recovery of phase information through the use of closure phases. In the resolution range from about half to several resolution elements, masking interferometry sets the benchmark for the present state of the art worldwide in delivering high fidelity imaging and direct detection of faint companions. The technique and observational applications to imaging of circumstellar discs and exoplanets are outlined.

As its name suggests, aperture masking consists of putting a mask at the entrance pupil of a telescope. We could have placed a mask with the physical size of the primary (M1) mirror on the VLT Unit Telescope 4 (UT4). Instead, we have placed a precision fabricated sheet of thin steel inside the CONICA camera in a plane conjugate to the telescope's aperture. On NAOS–CONICA (NACO), there are four masks available. Each one completely blocks the incoming light except for a number of small circular holes. One mask has seven holes, two have nine holes, and one has 18 holes. For example, the 7-hole mask transforms the 8-metre VLT primary into an array of small telescopes each 1.2 metres in diameter. Instead of 49 m^2 of light-collecting power, only seven times 1.13 m^2 of the reflective surface of UT4 is used – this is only 16%. At first thought, discarding 80% of the valuable stellar photons seems pure madness, and it is true that on faint targets, when observations are limited by photon noise, aperture masking is detrimental. However, it is in the speckle-dominated domain, where atmospheric turbulence and instrumental defects limit the signal-to-noise, that the real power of sparse aperture masking (SAM) is manifest. The steady increase in popularity of this mode is a clear indication of its relevance in this domain, as demonstrated by the histogram of VLT SAM proposals and Principal Investigator (PI) statistics of over nine semesters shown in Figure 1.

The simplest way to explain the principle of aperture masking is to consider the wavelike nature of light. In order to form a perfect image, the incoming starlight must be perfectly coherent, with flat wavefronts spanning the area of the aperture. With an 8-metre-class telescope, attaining perfect correction becomes difficult, even with a functioning adaptive optics (AO) system. With SAM, the requirement is less stringent, because the wavefront has to be flattened only within the size of a hole. Even though the image of a star looks like a "snowflake" on the detector (see Figure 2), the high frequency information from interference between the hole pairs can be recovered through techniques involving computation of the bispectrum and closure phases. In other words, SAM makes an instrument more robust to any large optical aberration over the pupil, such as atmospheric noise or instrumental non-common path errors. Figure 2 shows the application of SAM to resolving the close separation binary star HD9129Aab, itself part of a wide separation binary.

A second advantage of SAM is that it exploits Fourier transform techniques to dramatic effect. To many astronomers, Fourier techniques are sometimes regarded as an arcane and difficult way to perform science. However here they provide one of the best ways to increase the resolution of a telescope. Images can be thought of as an ensemble of multiple spatial frequencies: the highest ones give the image its sharp edges, and the lowest ones give the broad distribution. Observationally, the recovered information from a filled telescope pupil is weighted towards recovery of the lower spatial frequencies resulting in the well-known Rayleigh resolution limit of $1.2\,\lambda/D$, where λ is the wavelength of the light and D the imaging aperture. With Fourier analysis, the information contained in the highest frequencies can be extracted, giving access to resolutions down to $\lambda/2D$. This process is called Fourier deconvolution, a difficult technique when working on full-aperture images (but not impossible, i.e. as in speckle interferometry). The superiority of aperture masking comes from the fact that non-redundant masks make an image with only a few unique spatial frequencies. The complex amplitudes of

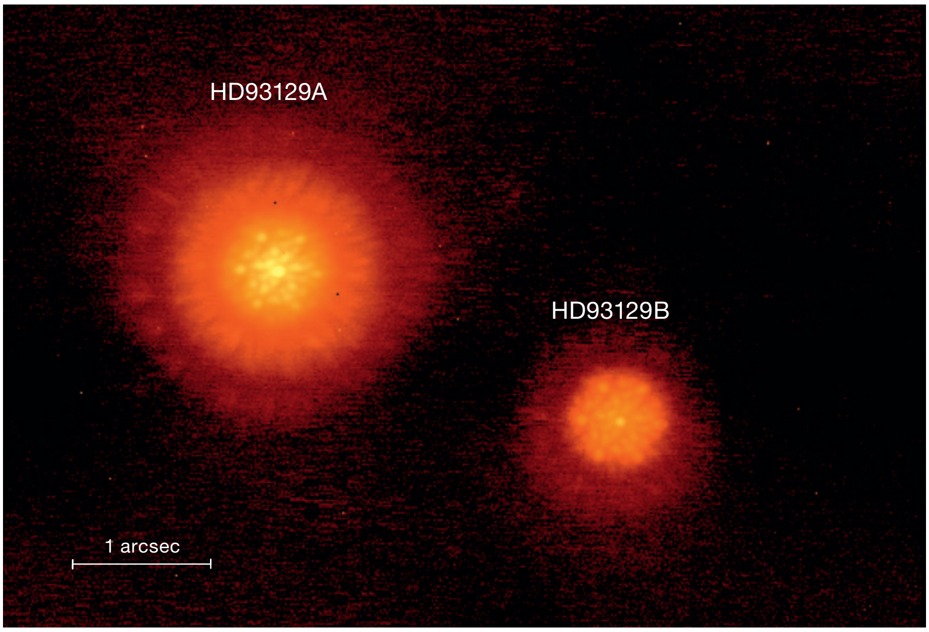


Figure 2. NACO–SAM observations of the HD93129A and B visual binary (angular separation 2.76 arcseconds). SAM is not needed to split the AB pair; classical imaging would have served better here. But SAM is able to resolve the HD93129Aab pair with 0.034 arcsecond separation — almost one hundredth of the separation of the binary depicted. The Aab pair is embedded within the diffraction pattern of HD93129A. HD93129A appears as an Airy pattern (of size given by the diffraction of the 1.2-metre holes — thus 800 mas in *K* band), interlaced with high frequency fringes. Only through careful Fourier processing can the phase of the fringes be determined to reveal the presence of the third component (Sana et al., 2011).

each frequency are accurately measured thanks to the fact that each one is produced by a single pair of holes. Amplitudes are more stable to seeing fluctuations, and phase aberrations can be subtracted thanks to the use of closure phase (see Figure 3). The use of closure phase is one of the key strengths of aperture masking as it yields an observable that is only affected by the astronomical object, and is robust to any residual optical phase aberration. By recording as many low frequencies as high frequencies, the detection limit of aperture masking is constant at any separation down to an inner working angle of $\lambda/2D$, more than twice that commonly expected for a single-dish telescope.

The point to remember about aperture masking is that its key discovery space, when compared to other imaging methods, lies at scales close to the diffraction limit of the telescope. Here we present notable scientific and instrumental successes, which give a broad view of the capabilities and potential of the SAM observational modes.

Imaging with unprecedented details

The proof of the pudding is in the eating: to test the capability to recover full images at diffraction-limited resolutions of relatively complex targets, we observed VY CMa with the 18-hole mask. With respect to the other masks, this mask gives the best Fourier coverage, but restricts observations to relatively bright systems. An alternate mask geometry which has proved to be very

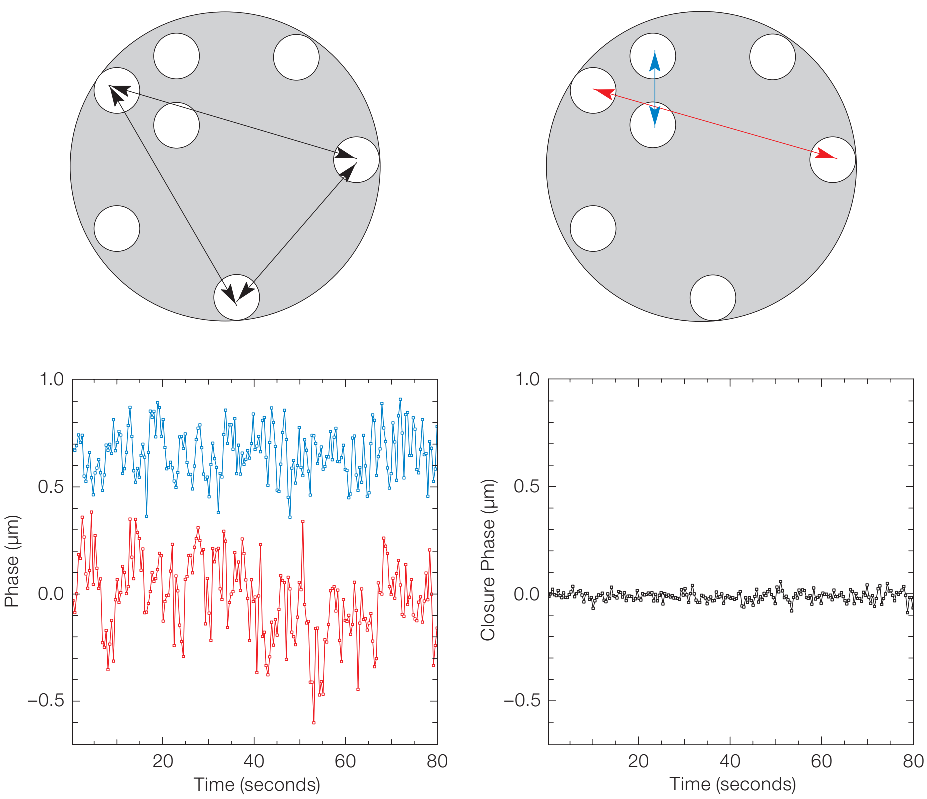


Figure 3. For each pair of apertures in the 7-hole mask, a set of fringes of a given spatial frequency is observed on the detector. The ensemble image created by many such overlapping fringe packets is illustrated in Figure 2. The phase of the fringes, which for a perfect optical system would be zero everywhere, corresponds to residual aberrations in the pupil. Actual NACO phase data are shown in the lower left panel for two different pairs of holes (red and blue baselines, marked by arrows on the pupil image), exhibiting phase residuals of the order of 300 nm. On the lower right panel, instead of the phase we plot the closure phase. This is the sum of three phases of three baselines formed by three separate holes (the triangle is given by black arrows in the pupil image). For the example dataset, most of the phase noise coming from uncorrected seeing disappears, leaving a closure phase residual of 10 nm; an improvement by a factor of 30.

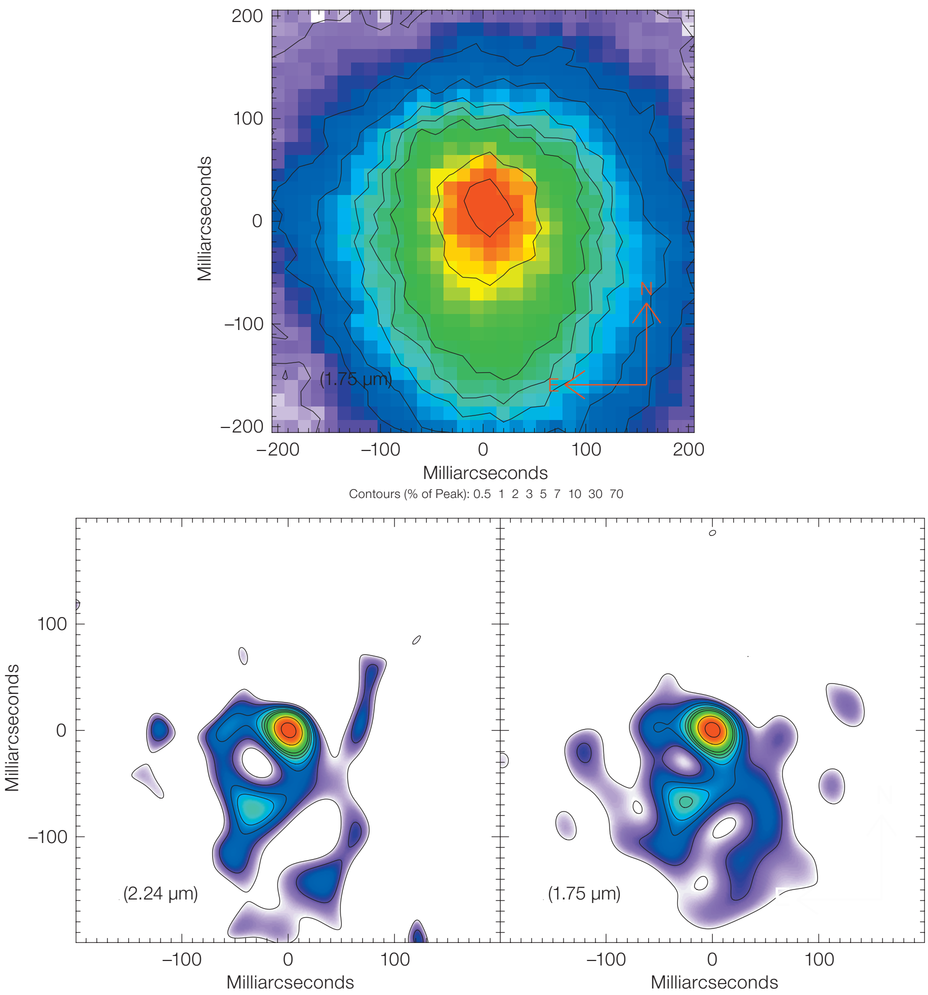


Figure 4. Images of the extreme mass-losing supergiant VY CMa. Upper panel: *K*-band image with the full telescope pupil of UT4 and adaptive optics system correction. Lower panels: *K*- and *H*-band images recovered with NACO–SAM data. There is some correspondence between the AO-only and SAM, but the fine detail and diffraction-limited structures appearing in the masking data cannot be seen in the AO image. (Data taken in March 2008).

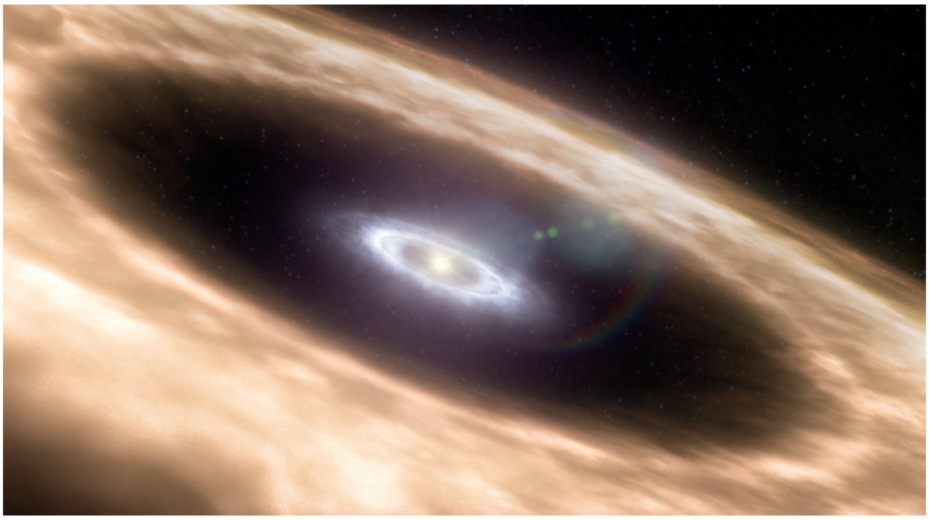
successful for the imaging of fainter complex targets is an annular geometry: this forms one possible upgrade path now being explored with ESO staff.

For comparison, we obtained imaging observations using the full telescope pupil taken only minutes apart from the SAM data. We used the shift-and-add algorithm to stack these data into a final resultant best image. The images are shown in Figure 4. There is some correspondence between the AO-only and SAM images, in that there is evidence for a similarly skewed centre of brightness in the AO image. However, the fine detail and diffraction-limited structures appearing in the masking data cannot be seen in the AO-only image. It is possible that more real structure may be recovered with deconvolution using a carefully recorded point spread function (PSF) frame, but this procedure has proved to be controversial in the past, and can lead to spurious structures. Note that the asymmetric structures reproduced in the SAM images are nearly identical to those found by the Keck telescope over a decade ago (also with aperture masking, Monnier et al., 1999).

Hunting for exoplanets

Although the exoplanet hunting season has been declared open for quite a while, the field of direct imaging is just beginning to get exciting. With the discovery of Beta Pictoris b (Lagrange et al., 2010), a new race has commenced, towards the detection of ever younger planets. We hope new discoveries will provide clues about the formation of the Earth, that existing observations (including 2M1207b [Chauvin et al., 2004] or HR8799bcd [Marois et al., 2008]) have not been able to provide. But the problem is that planets which formed like the Earth are faint and close to their parent stars, requiring imaging at very small angular separations. Techniques like angular differential imaging (ADI), spectral differential imaging (SDI) or coronagraphy all gain in power as the planet-to-star separation increases. On the other hand, SAM is able to perform well in the region from several λ/D down to separations as small as 0.5 λ/D (Lacour et al., 2011). It turns out that this separation range is a particularly valuable one. When imaging the nearest populations of young stars, AO surveys to date can be criticised for doing little more than proving that planets are rare in wide orbits, where they are not expected to form anyway. (Beta Pictoris is an exception because of its extreme proximity to the Sun). SAM on the other hand has demonstrated the ability to probe Solar System scales (Evans et al., 2011), successfully revealing companions and brown dwarfs at resolutions commensurate with the diffraction-limited core.

At the vanguard of the revolution in high-contrast imaging was the discovery of T Cha b. T Cha is a young star (only ~ 7 million years old) with a transition disc (Huélamo et al., 2011). Transition discs are so named because they mark the transition between protostellar discs (formed with the star) and a debris disc (created by subsequent planetary collision — see illustration in Figure 5, upper). Transitions discs are protoplanetary discs with gaps, or put another way, transition discs are made of at least two discs: an inner disc and an outer disc separated by a region which has been cleared of material. Most transition discs have only recently come to scientific attention particularly due to the work of the Spitzer telescope. Astronomers have observed these discs with intense interest in the hope of finding a gravitating body responsible for the creation of the



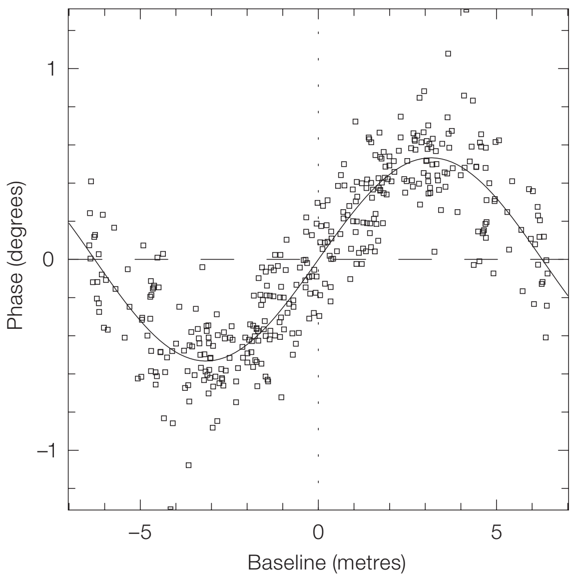


Figure 5. Artist's impression of a transition disc is shown (upper). In the case of T Cha, the inner disc is 0.1 AU in radius, and the outer disc 7.5 AU (according to modelling by Olofsson et al. [2011]). Inside the gap, at a distance of 6.7 AU from the central star, aperture masking revealed a young orbiting body (Huélamo et al., 2011). The closure phase values are plotted as a function of the spatial frequency in the lower panel. The flux ratio in the *L*-band is below 1/100, and the separation is 60 mas (while λ/D is equal to 100 mas).

gap, a scenario that would constitute the youngest sign of planet formation. The problem lies in the fact that the gap is at a few astronomical units (AU), and the closest of the star formation associations (like ρ Ophiucus or η Cha association) are at at least 100 pc distant, which implies that an angular resolution of ~ 50 milliarcseconds (mas) is needed to probe the gap. This resolution corresponds to λ/D for the VLT telescopes in the near-infrared (NIR), a regime which is problematic for most classical high dynamic range imaging techniques.

Exploiting the SAM mode on NACO, we have probed within the gap of T Cha, and, for the first time, managed to discover the presence of such a body through closure phase (see Figure 5, lower). At 6 AU from the central star (slightly above $\lambda/2D$), this object is right within the gap. But as is often the case with a new breakthrough in observational capability, new discoveries generate more questions than they answer and the nature of the T Cha system is an enigma. Currently the true nature of the body (planet, brown dwarf, low-mass star?) is not known, but its existence is likely to be linked to the presence of the gap. The object is profoundly red, relatively easy to detect in the *L*- and *M*-bands (3–5 μm), but almost invisible at 2 μm. It does not compare well with any contemporary models of planet formation. This object is thus likely to open a new window on planet formation. To add to the mystery, a second similar object has been observed in the gap of LkCa 15 (Kraus & Ireland, 2011), also thanks to aperture masking — but on the Keck telescope this time.

SAMPol

In the optical/infrared, celestial targets usually exhibit a polarised signal due to scattering or reflection of light. Common astronomical objects studied through polarimetry include young stellar objects, evolved mass-losing stars and Solar System bodies. The polarised signature is very difficult to observe where such scattering occurs in the immediate vicinity of a star (as opposed to an extended nebula), as can often be the case. This is because light from different spatial regions, each of which may be highly polarised, often adds together with polarisation vectors to cancel out any net signal when the final stellar image is formed. The integrated polarisation from even highly polarised stellar targets is therefore rarely more than a few percent, despite the fact that parts of their circumstellar environments probably emit nearly completely polarised light.

What is needed to overcome this problem is an observing method capable of preserving polarised signals which arise from regions which may be only milliarcseconds apart on the sky. Utilising SAM mode with the polarising Wollaston prisms and halfwave plates already installed as part of the CONICA optics complement, we have commissioned a powerful new observing mode, christened SAMPol. Calibration precision is dramatically enhanced thanks to differential techniques (the camera records both polarisations simultaneously). The halfwave plate can be used to exchange the polarisation states of the two images produced by the Wollaston, allowing for a high degree of resilience against instrumental and seeing-induced sources of measurement error.

In order to test the ability of SAMPol to recover signals from high resolution polarised sources, several late-type giants including L2 Pup were observed utilising the differential interferometric polarimetry method. The masking diffraction pattern

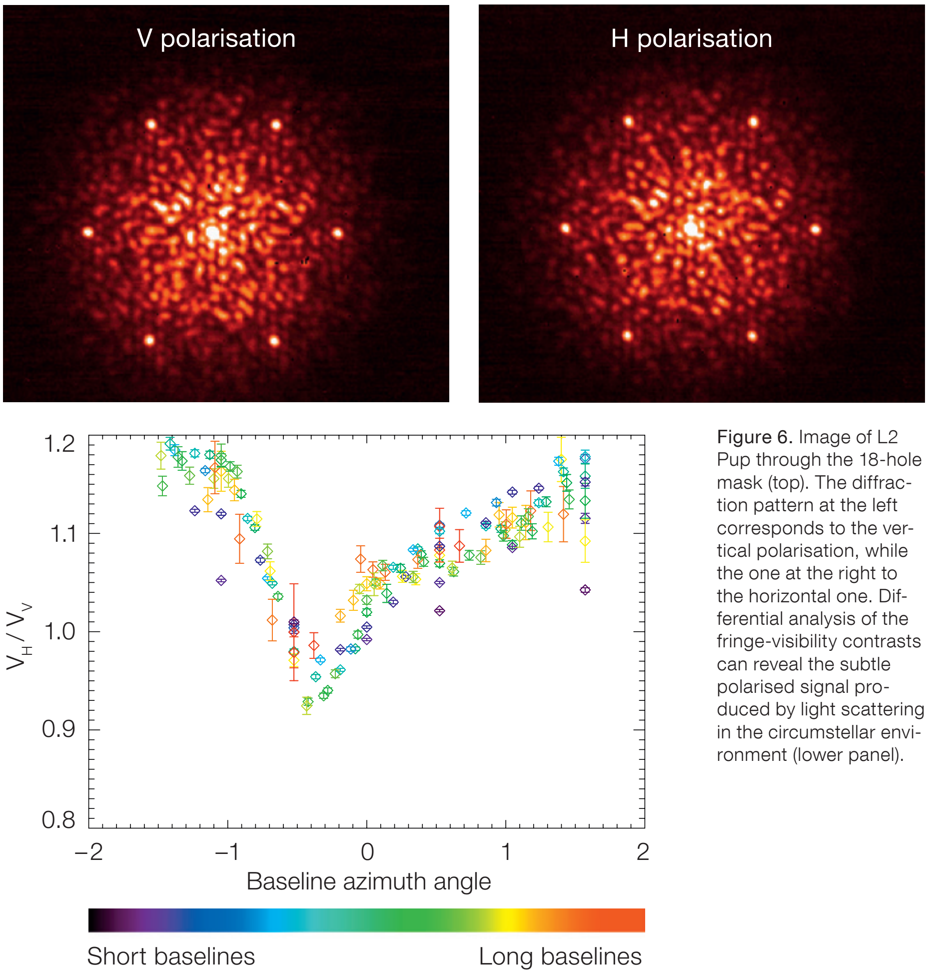


Figure 6. Image of L2 Pup through the 18-hole mask (top). The diffraction pattern at the left corresponds to the vertical polarisation, while the one at the right to the horizontal one. Differential analysis of the fringe-visibility contrasts can reveal the subtle polarised signal produced by light scattering in the circumstellar environment (lower panel).

produced by the star appears twice on the detector thanks to the use of the Wollaston prism (see Figure 6, top). After reduction of the raw data, the final observables can be obtained as ratios of visibilities in different polarisation states (Figure 6, lower; and Norris et al., 2011). The data can be compared with models of scattering to understand the features of the polarisation data.

Prospects for aperture masking at the VLT

Aperture masking allows imaging with a formal resolution limit twice as good as a full telescope pupil, while simultaneously delivering observables such as closure phase, which are very resilient to instrumental aberrations. For these reasons, SAM has a future at long wavelengths, as well as in the field of extreme AO.

A SAM mode for the VISIR instrument recently passed the final design review. No schedule for implementation has been yet agreed, but most of the implementation task is software development (another advantage of SAM mode is the simplicity of the hardware). The utility of aperture masking at 10 μm is sometimes debated, because it is a common — although false — view that the telescopes deliver a nearly perfect beam at mid-infrared wavelengths. It is correct that if the full optical chain were perfect, there would be no need for aperture masking. But the truth is that whatever the wavelength, there are still aberrations which will limit the dynamic range at very small separations. Aperture masking will always bring an additional level of robustness compared to full aperture imaging. Moreover, the mask will be cold, and as such, will decrease both the stellar light and sky background in proportion, thus preserving this particular signal-to-noise term.

A second project is an upgrade of the SPHERE instrument. SAXO, the SPHERE extreme AO system, will produce an extremely well-corrected wavefront from infrared to visible wavelengths. SAM would double the resolution capabilities of the instrument. At short wavelengths, thanks to an angular resolution of 10 mas at 600 nm, the SAM mode on ZIMPOL would probe the structures of polarisation in young discs or circumstellar shells to unprecedented fine angular scales. The mode is not yet officially accepted by the SPHERE consortium; but such an implementation could happen through an upgrade, or as a visitor instrument mode. It is amazing to think that these new capabilities can be obtained with such a modest hardware investment (a photo of the mask is shown in Figure 7). At longer wavelengths, a mask in front of the SPHERE integral field spectrometer (IFS) would enable a method to characterise companions detected at offsets around λ/D for wavelengths from 0.9 to 1.7 μm. Moreover, the IFS will offer new possibilities with SAM for phase calibration, which could be used to provide even higher dynamic range.

Presently, the main challenge facing aperture masking is the issue of calibration. On NACO, the current dynamic range of the SAM mode is currently limited to 500 (Δ mag 6.7) at λ/D for stars down to magnitudes 7 or 8. For brighter

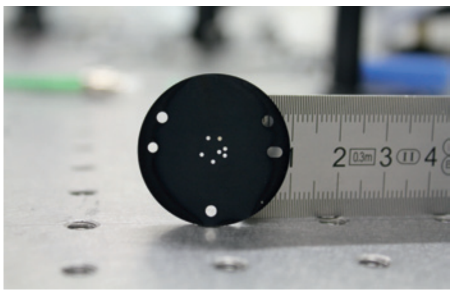


Figure 7. ZIMPOL 7-hole mask for the SPHERE instrument. The mask is 3 cm in diameter for a pupil of 6 mm. Each hole is 825 μm in diameter, which, scaled to M1, corresponds to 1.1 metres projected onto the primary mirror. Combined with the extreme AO system of SPHERE, this mask should allow polarisation structures to be characterised down to a resolution of 10 mas.

stars we are limited by our capacity to calibrate the closure phase (~ 0.3 degrees). On a star of the magnitude of Fomalhaut, aperture masking is capable of delivering closure phases with a scatter below 0.03 degrees, but calibration still dominates the error, preventing us from reaching the theoretical limit of 10 magnitudes in contrast. An important step forward for a new generation of aperture masking instruments would be to understand theses calibration errors, and invent an instrument that can overcome them.

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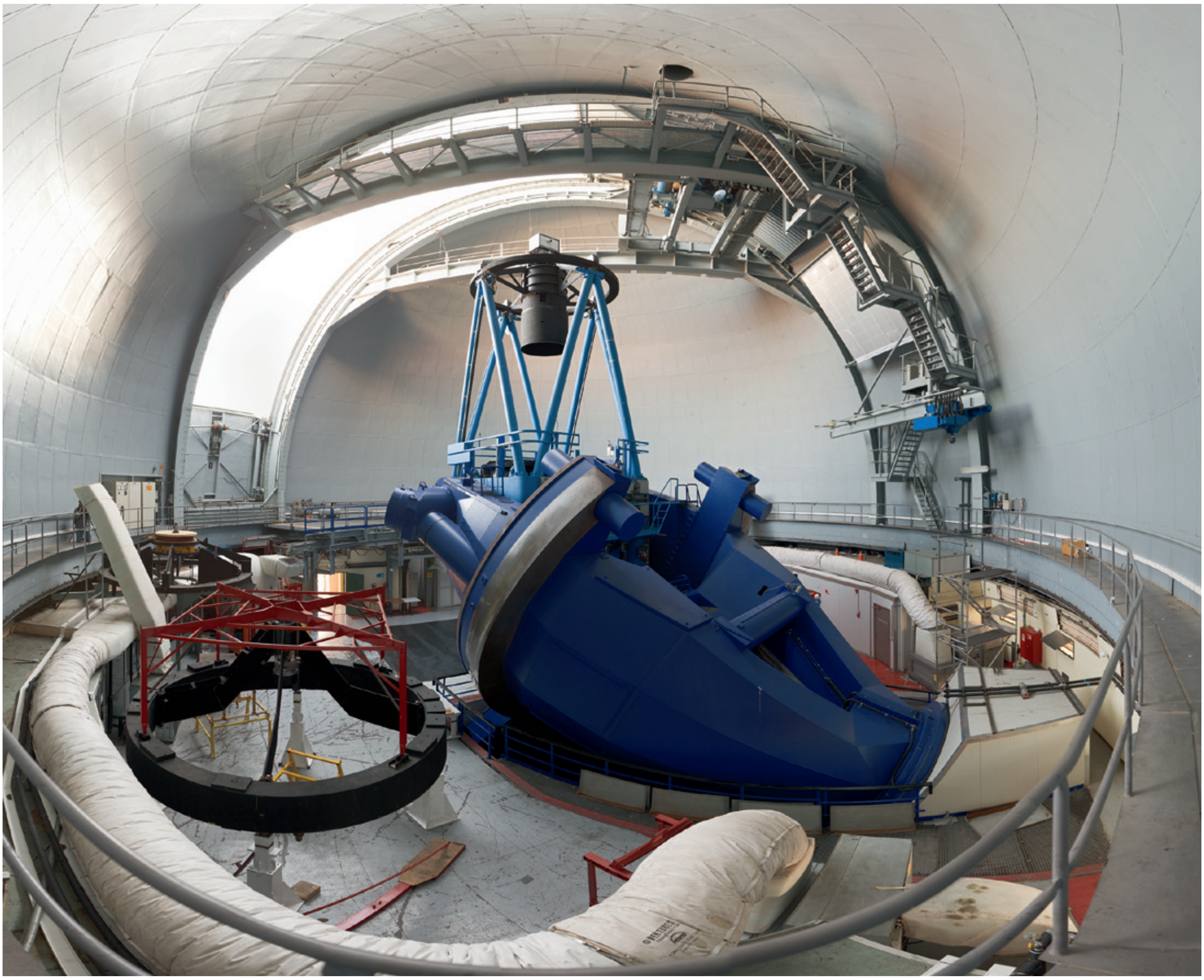

Wide-angle view of the inside of the dome of the ESO 3.6-metre telescope at the La Silla Observatory. The white tubes around the perimeter are part of the dome air-conditioning system.