Resolving the Inner Regions of Circumstellar Discs with VLT/NACO Polarimetric Differential Imaging

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Planets originate from circumstellar discs of gas and dust around young stars. A better knowledge of the physical and chemical conditions in these discs is necessary in order to understand the planet formation process. As most planets form in the inner few tens of astronomical units these disc regions are of particular interest. However, the overwhelming brightness of the central star makes it very challenging to image directly those disc regions. Polarimetric Differential Imaging (PDI) is a powerful technique that overcomes these challenges. Without using a coronagraph, which would block not only the central star, but also part of the interesting inner disc region, PDI allows high-contrast imaging observations at small inner working angles.

The rapidly increasing number of known exoplanets reveals an unexpected diversity in properties, which in part challenges fundamentally our understanding of the planet formation process. Many exoplanets orbit their stars at separations where no counterparts exist in the Solar System, e.g., gas giant planets orbiting at very small or very large separations from their host stars. In order to understand how planets form one needs to understand the physical and chemical conditions in the natal circumstellar discs surrounding the young stars. Furthermore, the conditions in these discs will also dictate whether, and to what extent, a newly-formed planet might interact with the disc and thereby perhaps change its orbital separation.

Recent direct-imaging surveys suggest that gas giant planets around solar-type stars are in general rare at orbital separations in excess of ~ 50 astronomical units (AU; e.g., Chauvin et al., 2010). At least some early-type stars, on the other hand, are able to form gas giant planets even beyond this limit, as the remarkable examples of the HR8799 system (Marois et al., 2010) and Fomalhaut b (Kalas et al., 2008) have demonstrated. Still, as suggested already by the Solar System, most planet formation appears to take place in the inner few tens of AU, and it is exactly those regions of a circumstellar disc that one needs to study to learn about the relevant processes.

The classical direct-imaging approach to observe circumstellar discs at optical or near-infrared (NIR) wavelengths is to use a coronagraph and/or a reference star that is subtracted from the science target, thus subtracting the bright light from the central star and revealing the much fainter disc emission. This approach suffers from two significant limitations: (1) the coronagraph blocks out not only the central star, but also a significant fraction of the inner disc region; and (2) the reference star never matches the science target perfectly so that disturbing subtraction residuals remain, rendering the inner disc region often useless for scientific analyses.

Polarimetric differential imaging

One elegant way to overcome these limitations is PDI, a technique that allows high-contrast imaging of circumstellar discs at very small inner working angles, i.e., very close to the star. PDI takes advantage of the fact that direct stellar light is essentially unpolarised, while stellar photons that undergo single scattering from the dust grains on the surface layer of a circumstellar disc are polarised. The VLT's high-resolution NIR imager NAOS–CONICA (NACO), installed at Unit Telescope 4 (UT4), offers a PDI mode. A Wollaston prism splits the incoming light into two orthogonal, linearly polarised beams (the ordinary and extraordinary beam, I_{ord} and I_{ext}, respectively), which are simultaneously imaged onto the detector. A half-wave plate enables the observer to change the orientation of the polarisation direction with respect to the detector without rotating the Wollaston prism and without changing the field of view. Measurements are typically carried out for at least four angles (0°, 45°, 90° and 135°). The Stokes *Q* image can then be obtained from the differences of the I_{ord} and I_{ext} images at angles of 0° and 90° while the Stokes *U* image is computed correspondingly from the images taken at the other two angular positions (45° and 135°). To obtain the final image showing the polarised flux *P*, one combines the square root of the quadratic sum of the *Q* and *U* Stokes parameter images.

Inspection of the formula for the computation of *Q* reveals why PDI is so powerful: by subtracting the ordinary and extraordinary beams from each other, the unpolarised contribution from the central star cancels out almost perfectly because both beams have been imaged simultaneously. The result is the spatially resolved polarisation signal from the disc. For completeness we mention that one can also compute the fractional polarisation, i.e., images that show what fraction of the light at a given pixel is polarised, and also the position angle on the sky of the polarisation vector.

NACO PDI observations

We used NACO in PDI mode to image the circumstellar discs around the young, early-type stars HD100546 and HD97048 in the *H* and *Ks* filters, i.e., at wavelengths ~ 1.7 and 2.2 μm (Quanz et al., 2011a; Quanz et al., 2011b). The final polarised flux images are shown in Figure 1. For the first time we were able to image directly the scattered light coming from the surface layer of these discs from regions as close as ~ 0.15 arcseconds to the central stars. As mentioned above, these regions are typically not accessible with any other direct-imaging technique. To put our results in a broader perspective, we show, in Figure 2, a sketch comparing

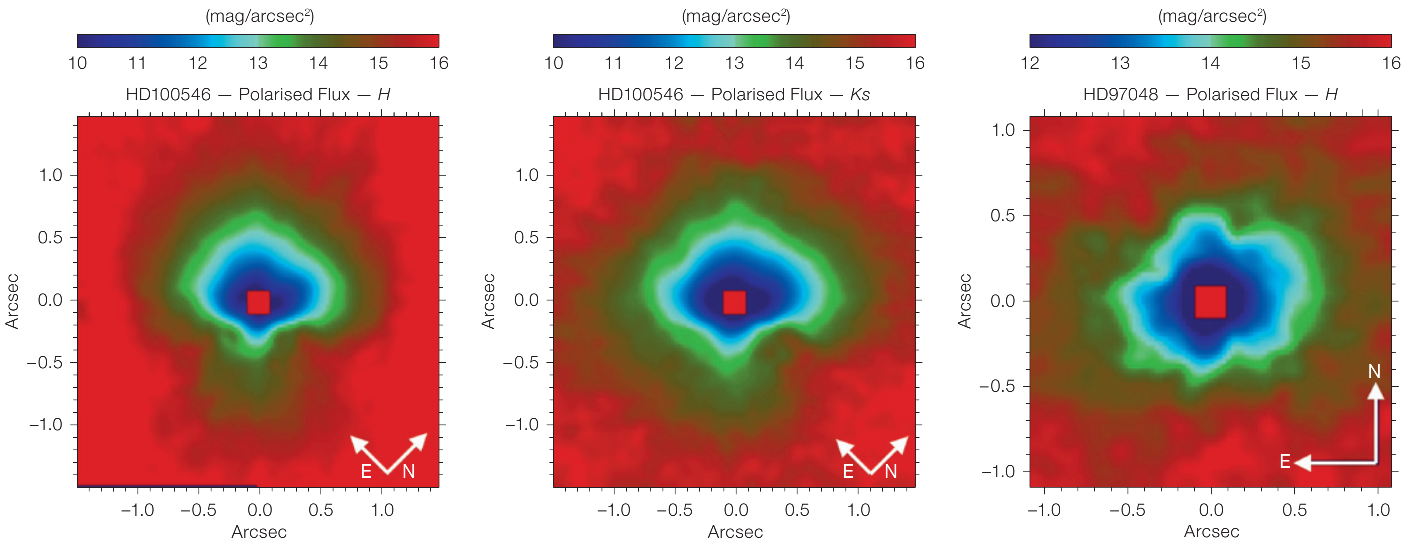

Figure 1. Polarised flux images of the circumstellar discs surrounding HD100546 (left: *H*-band; middle: *Ks*-band) and HD97048 (right: *H*-band). Note that 0.5 arcseconds correspond to ~ 50 AU projected separation in the case of HD100546 and ~ 80 AU in case of HD97048. The central region in each image has been masked out as the core of the PSF was saturated. Adapted from Quanz et al. (2011a, 2011b).

the two circumstellar discs as we have observed them with NACO/PDI, with the dimensions of the Solar System and the two extrasolar planetary systems HR8799 and Fomalhaut. It shows that our data probe those regions of the circumstellar discs where planetary bodies might form.

Analysis of circumstellar discs

But what exactly can we infer from our images? The most obvious information is certainly the spatial extent and geometric orientation, i.e., inclination and position angle, of the disc emission and its apparent brightness. From our images we can also measure how the disc brightness changes as a function of the disc radius r and derive disc surface brightness profiles. These profiles indicate whether the disc surface is "flared", i.e., the disc scale height increases with radius, or rather "flat". In case of HD97048 the measured profiles drop off roughly as r^{-2}, but there are indications of distinct "breaks" in surface brightness that appear roughly at 50 AU and 110 AU. Such breaks could

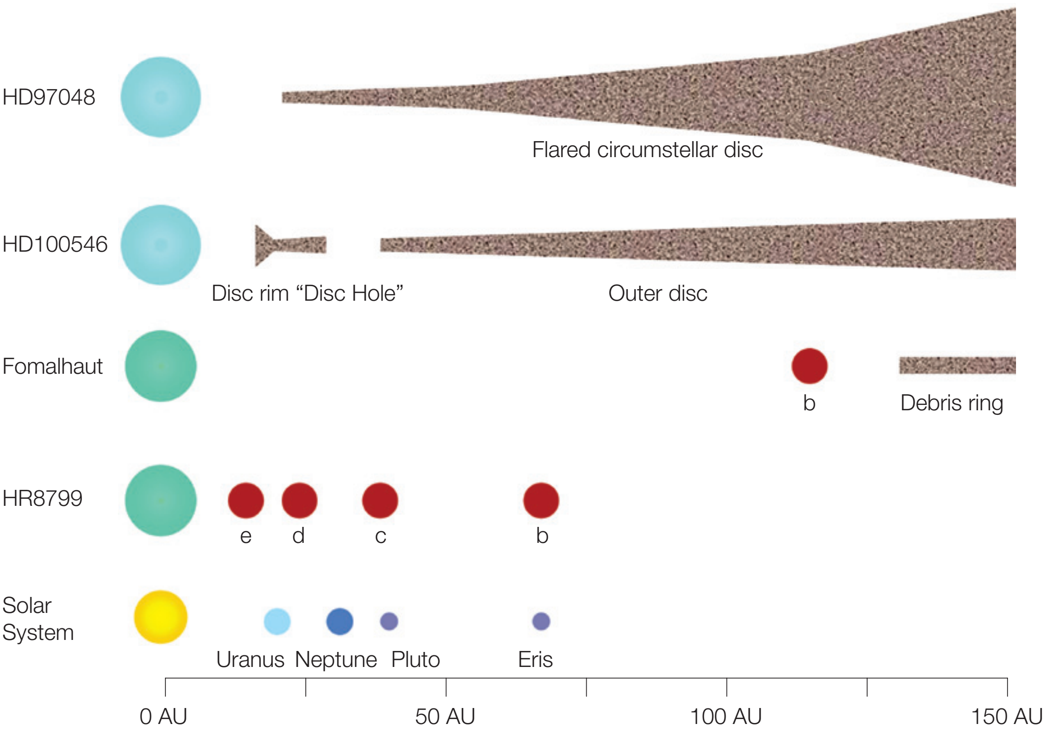

Figure 2. Schematic comparing the circumstellar disc regions of HD100546 and HD97048 resolved with NACO/PDI to the dimensions of the Solar System and the planetary systems around the A-type stars HR8799 and Fomalhaut. The sizes of the objects are not to scale. The inner six Solar System planets (Mercury to Saturn) are not shown.

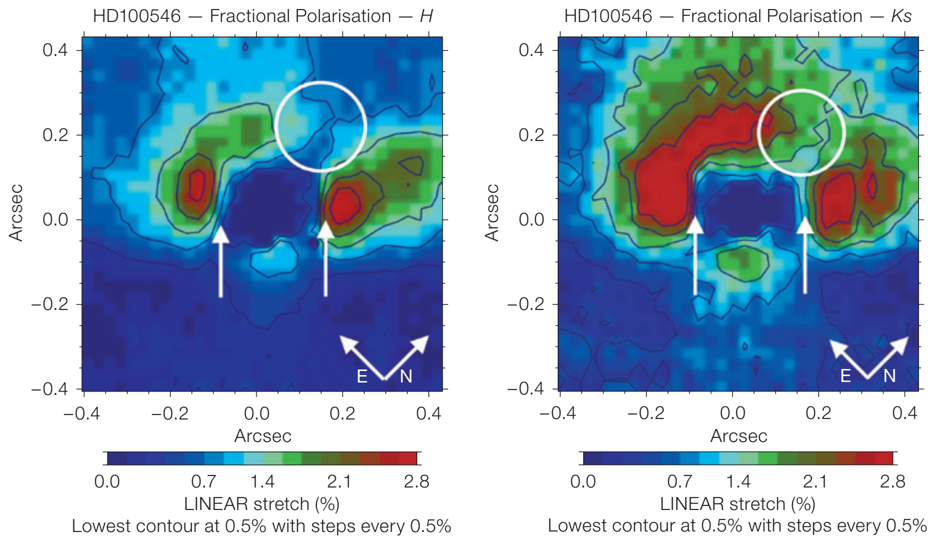

Figure 3. Images showing the fractional polarisation of the inner disc regions of HD100546 (*H*-band left, *Ks*-band right). Note that 0.4 arcseconds corresponds to ~ 40 AU projected separation. The circles show the position of the "disc hole", while the arrows indicate the position of the "disc rim". Adapted from Quanz et al. (2011a).

be signs that the disc is somehow perturbed at these separations or that the properties of the dust grains are suddenly changing. For comparison, the radial profile of HD100546 is steeper and drops off roughly with r^{-3}, but does not show any signs for discontinuities.

Furthermore, our images allow us to search for structures in the inner regions of the circumstellar discs. An example for the HD100546 disc is shown in Figure 3 and is also depicted in the cartoon in Figure 2. First, we find indications for a "hole" in the north-eastern part of the disc at a projected separation of ~ 30 AU. In both filters the amount of polarised flux shows a local minimum here. The reason for this hole is unknown, but signatures of ongoing planet formation are a tempting interpretation. Secondly, closer inspection of the images reveals that very close to the central star the amount of polarised flux rapidly decreases from its maximum. Previous studies (e.g., Benisty et al. 2010) suggested that HD100546 disc has a gap roughly between 4–15 AU and that a giant planet might be orbiting within this gap. While our images cannot reveal the planet itself they support the idea that the disc has a rim at 15 AU (the maximum in our images) and is relatively low in scattering dust particles close to the star.

Finally, polarisation measurements of circumstellar discs allow us to constrain the properties of the dust grains — size and composition — that we are probing. As we are observing the surface layer of circumstellar discs and as the dust grains on this layer are the dominant opacity source, the properties of the dust grains will determine how much stellar light is scattered, absorbed or transported in deeper disc layers. Hence, the surface grains strongly affect the energy budget of the discs, which in turn impacts on the physical conditions for planet formation. Knowing also the inclination of the disc and the disc-flaring angle we can compute how the intensity of the polarised flux changes as a function of the scattering angle. These scattering functions depend on the dust grain properties. If we have images in more than one filter we can furthermore see how the colour of the polarised light changes as a function of the disc radius. This is an additional probe to obtain information about the dust grain properties.

Potential and future of PDI

Despite the huge amount of information that PDI can offer for the inner regions of circumstellar discs, it has not yet been fully exploited with VLT/NACO. In addition to HD100546 and HD97048 there is only one additional circumstellar disc studied with NACO/PDI, TW Hya, which also shows signs of breaks in its radial surface brightness profile (Apai et al., 2004). However, NACO, as a Nasmyth focus instrument, is not perfect for PDI studies as it suffers from instrumental polarisation effects that change with the parallactic angle of the source (Witzel et al., 2010).

Soon, a new second generation instrument will be installed at the VLT that also has PDI modes: SPHERE (Beuzit et al., 2006). With its high-performance adaptive optics (AO) system, SPHERE will not only provide much better Strehl ratios, but a more stable point spread function (PSF) than NACO. In particular, ZIMPOL — a high precision optical imaging polarimeter — will yield an unprecedented polarimetric accuracy and open a new pathway for studying circumstellar discs from the ground in the *V*-, *R*- and *I*-bands. Furthermore, IRDIS — the NIR double beam imager — has also a PDI mode and is well suited to complement the ZIMPOL data with images at longer wavelengths. The current suite of VLTI instruments resolve the innermost few AU at NIR and mid-infrared wavelengths, while the Atacama Large Millimeter/submillimeter Array (ALMA) will probe the (sub-)millimetre thermal emission from cool dust grains in the disc midplane and the molecular gas content of the disc with comparable spatial resolution. In combination with these instruments, SPHERE will allow us to refine our understanding of circumstellar discs and uncover part of the physical and chemical conditions under which planets are presumably forming.

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