DOI: 10.18727/0722-6691/5078

A Planet with a Disc? A Surprising Detection in Polarised Light with VLT/SPHERE

Christian Ginski[1,2]
Rob van Holstein[1]
Attila Juhász[3]
Myriam Benisty[4,5]
Tobias Schmidt[6]
Gaël Chauvin[4,5]
Jos de Boer[1]
Mike Wilby[1]
Carlo F. Manara[7]
Philippe Delorme[4]
Francois Ménard[4]
Gabriela Muro-Arena[2]
Paola Pinilla[8]
Til Birnstiel[9]
Mario Flock[10]
Christoph Keller[1]
Matthew Kenworthy[1]
Julien Milli[7]
Johan Olofsson[11,12]
Laura Pérez[13]
Frans Snik[1]
Nikolaus Vogt[11]

[1] Sterrewacht Leiden, the Netherlands
[2] Anton Pannekoek Institute for Astronomy, University of Amsterdam, the Netherlands
[3] Institute of Astronomy, University of Cambridge, UK
[4] Université de Grenoble Alpes, CNRS, IPAG, France
[5] Unidad Mixta Internacional Franco-Chilena de Astronomía, CNRS/INSU UMI 3386 and Departamento de Astronomía, Santiago, Chile
[6] LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Université Paris 06, Université Paris Diderot, Sorbonne Paris Cité, France
[7] ESO
[8] Department of Astronomy, Steward Observatory, The University of Arizona, Tucson, USA
[9] University Observatory Munich, Faculty of Physics, Ludwig-Maximilians-University, Munich, Germany
[10] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[11] Instituto de Física y Astronomía, Universidad de Valparaíso, Chile
[12] Núcleo Milenio Formación Planetaria – NPF, Universidad de Valparaíso, Chile
[13] Departamento de Astronomía, Universidad de Chile, Santiago, Chile

With the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument at ESO's Very Large Telescope (VLT) we can study the linear polarisation of directly detected planets and brown dwarfs, to learn about their atmospheres and immediate environments. We summarise here the recent discovery of a low-mass companion in polarised light by Ginski et al. (2018). The object shows an extreme degree of polarisation, indicating the presence of a circumplanetary disc.

High-resolution polarimetry of substellar companions

In the past 15 years, numerous substellar-mass companions to young nearby stars have been discovered with high-contrast and high-angular-resolution imaging. Using resolved photometry and spectroscopy we can study the atmospheres of these objects, which range from planetary to brown dwarf masses. This makes them especially interesting targets to test planet formation theories. At the same time, the formation of these objects at a few tens or hundreds of astronomical units is particularly challenging, given the limited spatial extent and lifetime of circumstellar discs.

High-spatial-resolution polarimetry is a powerful tool that can provide a plethora of information about these companions. While the thermal emission of substellar objects is not usually intrinsically polarised, scattering by patchy clouds or atmospheric haze can introduce an overall linear polarisation. Rotational flattening, the presence of orbiting moons, magnetic fields, or circumplanetary discs can also cause polarisation. By measuring the degree and angle of linear polarisation with high accuracy we can distinguish between these effects and extract atmospheric parameters as well as information about the circumplanetary environment.

Polarisation has been measured in the past for field brown dwarfs, but only the latest generation of extreme adaptive-optics imagers at large aperture telescopes are allowing us now to open the parameter space to detect these interesting low-mass companions to nearby stars.

The SPHERE instrument (Beuzit et al., 2008) is perfectly suited to this task. Recently van Holstein et al. (2017) were able to constrain the polarisation degree of the planets around HR 8799 to be lower than 1% and the companion to PZ Tel to be lower than 0.1% with measurements performed with the SPHERE Infra-Red Dual Imaging and Spectrograph (IRDIS). Here, we highlight another recent result: the first detection of a new substellar companion to a young nearby star in polarised light.

Observations of the CS Cha system

The CS Cha system contains a spectroscopic binary, both components of which appear to be solar-type pre-main-sequence stars (called T Tauri stars). The system is located in the nearby Chamaeleon I molecular cloud at a distance of 165 pc and was previously studied by means of unresolved photometric measurements, which revealed a large infrared excess. This suggests the presence of a circumstellar disc (see, for example, Espaillat et al., 2007). The observed spectral energy distribution shows a dip at 10 microns, which hints at the presence of a large cavity in the disc, a possible sign of ongoing evolution.

On 18 February 2017 we used SPHERE/IRDIS to observe the CS Cha system in near-infrared polarised light with the aim of resolving its surrounding disc for the first time. Our observation resolved a circumbinary disc with a diameter of ~ 110 astronomical units (au). We show this disc in Figure 1a.

However, the disc was not the only detection made that night. We noticed that a faint companion candidate was visible at approximately 1.3 arcseconds to the west of the primary stars. Remarkably, this companion is not only visible in intensity (see Figure 1c), but also in polarised light (see Figure 1a). It is extremely faint, with an apparent magnitude of 19.2 magnitudes in the *J*-band. Such flux levels are predicted by planetary atmosphere models for objects with a few times the mass of Jupiter. A particularly intriguing property of this companion is its high level of polarisation. In our *J*-band data we measured a degree of linear polarisation of ~ 14%. This value was later confirmed with a follow-up SPHERE/IRDIS observation in the *H*-band.

To prove that the companion is associated with the CS Cha system one needs to measure the common proper motion using archival data. CS Cha was observed with the Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph (NACO, Lenzen et al., 2003) at the VLT in the *K*-band 11 years prior to our SPHERE observations. Furthermore, we found *I*-band observations taken in February 1998 with the Hubble Space Telescope's Wide Field and Planetary Camera 2 (HST/WFPC2). Re-reducing these data sets, we were able to recover the companion (see Figures 1 b and e). With a 19-year baseline, we could then show that CS Cha and the companion have nearly the same proper motion on the sky (see Figure 2). The small differential motion that we found is consistent with the orbital motion that is expected for a low mass companion. This makes it very likely that this object is gravitationally bound to CS Cha.

The next step in our analysis was to investigate the possible causes for the high degree of polarisation. One possibility could be the presence of a large amount of interstellar dust between the Solar System and the CS Cha system. This would be especially likely if CS Cha is located deep within the Chamaeleon I molecular cloud. We measured the degree of polarisation of the unresolved primary stars in our *J*- and *H*-band SPHERE data sets and found that their light was polarised to less than 1%. This strongly suggests that the degree of polarisation of the companion is intrinsic and not caused by interstellar dust.

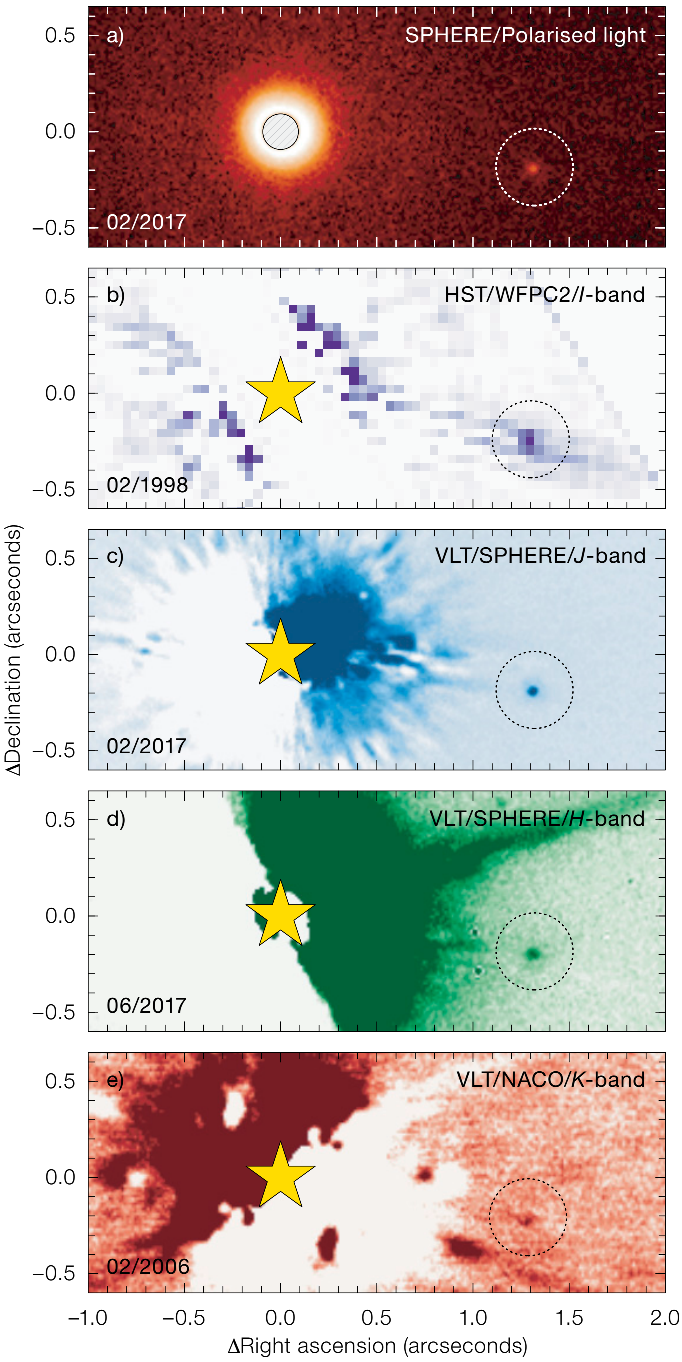


Figure 1. Observations of the CS Cha system at multiple wavelengths and with various instruments. The companion is always marked by a dashed circle.
(a) SPHERE polarised light image. The companion is seen in polarised light along with the disc around the central binary star. The coronagraph that was used is indicated by a grey hatched circle.
(b–e) Total intensity unpolarised images of the companion. The stellar PSF was partially subtracted to increase the companion contrast, also creating the dark-bright patterns visible. The position of the central binary is marked with a star symbol.

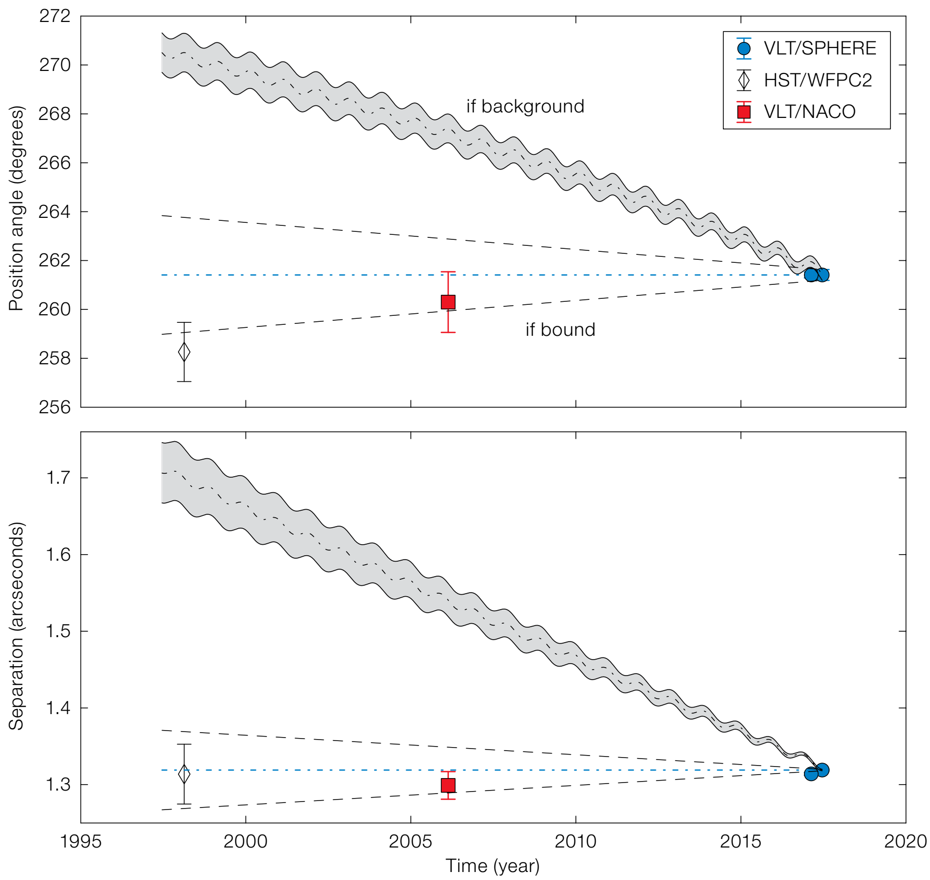
A planet with a disc?

Since we have multiple observations of the companion in various photometric bands we can attempt a characterisation. In particular, we are interested in constraining its mass and determining the causes of its high degree of polarisation.

In Figure 3 we show all the available photometric measurements along with upper limits for non-detections. We always measure the companion magnitude relative to the host star. We then use the known brightness of the host to translate these relative measurements into absolute fluxes. The SPHERE *H*-band photometry has larger uncertainties because the observations were taken in poor weather conditions.

We compared the companion photometry to PHOENIX (Helling et al., 2008) atmosphere models for substellar objects. In Figure 3, we show two model spectra, obtained for an object of 5 Jupiter masses (M_{Jup}) and one of 20 M_{Jup}. These model spectra include clouds in the atmosphere models, but do not include circumplanetary material.

We found that the *J*-*H* colour of the companion is somewhat consistent with a



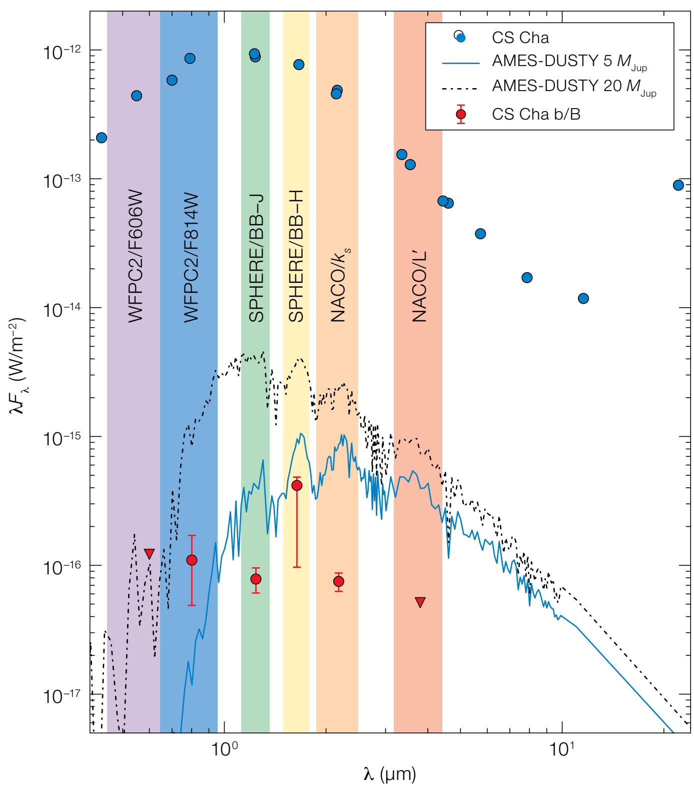


Figure 2. (Above) Astrometric measurements of the companion relative to the unresolved primary stars. The grey "wobbled" area is the area where background objects would be expected, while the area between the dashed lines is where gravitationally bound objects are expected.

Figure 3. (Left) Photometric measurements (circles) and upper limits (triangles) of the companion (red symbols) in different bands and with different instruments. For comparison we also plot the photometry of the unresolved primary stars (blue symbols), as well as theoretical models for a 5-M_{Jup} and a 20-M_{Jup} planet (solid and dashed lines).

5-M_{Jup} planet. However, the model spectrum overpredicts the flux in the NACO *K*- and *L*-bands and underpredicts it in the HST *I*-band. A 20-M_{Jup} planet, on the other hand, completely overpredicts the flux across all photometric bands. We conclude that no standard atmosphere model could reproduce these peculiar photometric measurements. Additionally, clouds in planetary atmospheres are not expected to cause linear polarisation of more than a few percent (Stolker et al., 2017).

The presence of a circumplanetary disc seen at a high inclination, i.e., close to edge-on, can produce a high degree of linear polarisation in the companion. Such a strongly inclined disc would then also block some of the light from the companion itself. This would naturally explain why "naked" planetary atmosphere models are a bad fit to the available photometry. We can put one further constraint on a potential circumplanetary disc. It needs to be small enough that we are not able to resolve it in our SPHERE images. This means that its diameter must be less than 4 au.

After some first attempts at modelling the observations we realised that an inclined disc alone still does not explain the high degree of polarisation. In fact, our models underpredict the degree of polarisation by a few percent and do not fit the photometry. However, if we include a very thin dusty halo, then we can nearly reproduce all of the measurements. This halo has a dust mass two orders of magnitude less than that of the disc itself. We show the best-fitting models in Figure 4. For simplicity, each model is computed for a single dust grain size only. The models with 0.1- and 1.0-micron particle sizes reproduce the companion photometry well. The smaller grains, on the other hand, lead to an overprediction of the degree of polarisation, while the larger grains slightly underpredict the polarisation, especially in the *J*-band. It is thus reasonable to assume that a more complex mixture of differently sized grains should be able to reproduce the measured polarisation.

Since the flux of the companion is attenuated by its surrounding disc, we need a higher-mass object to fit the photometry compared to the "naked" atmosphere models. In this case we use a 20-M_{Jup} planet.

These first models fit well with the measurements, but they still suffer a degeneracy between the mass of the central object, the inclination of the circumplanetary disc and the dust grain sizes. Therefore we caution that the solution we find is likely not the only one. However, since the modelled disc inclination of ~ 80° is rather high, we can be sure that the companion is not significantly more massive than our current estimates. More massive central objects would require a stronger attenuation to fit the photometry and thus a higher disc inclination.

We show a schematic of the full CS Cha system in Figure 5 as described in our model. The elevation of the companion along the line of sight is unknown, so we do not know if it is partially illuminated by the central binary, or completely shadowed by the circumbinary disc. We conducted tests to investigate the possibility of additional illumination of the companion by the central binary and found that this had only a marginal effect on our modelling.

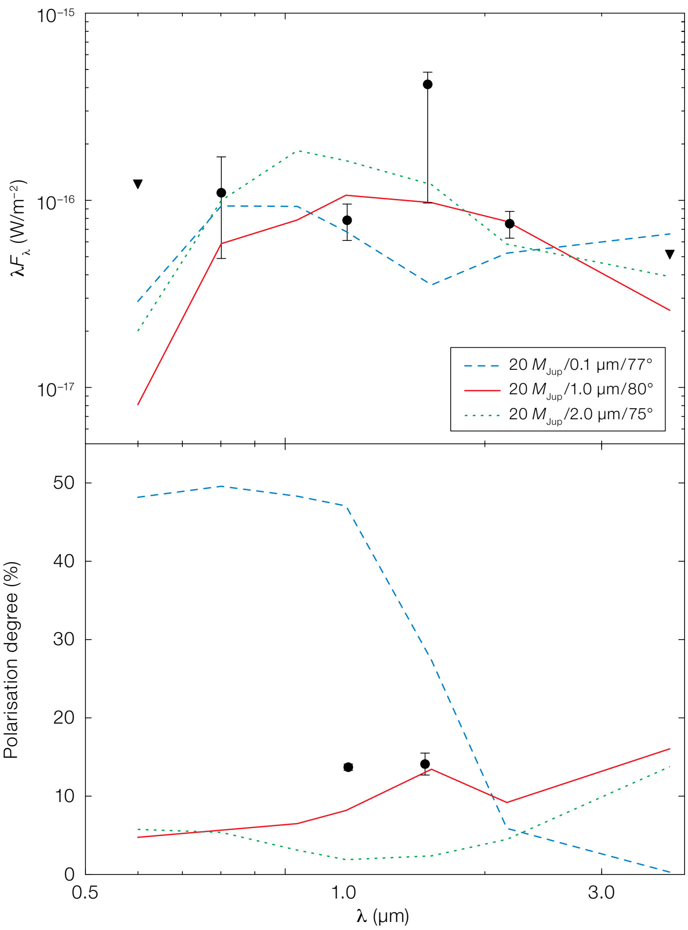


Figure 4. (Left) Companion photometry and degree of linear polarisation along with our best fitting models. Different colours and line styles denote different inclinations of the circum-companion disc as well as different dust grain sizes. Triangles show upper limits, while circles are current measurements.

Planet formation in the CS Cha system

Given what we know about the CS Cha system, we can speculate on how the companion may have formed. The circumstellar disc that we detected in polarised scattered light only extends out to ~ 55 au. It is possible that the disc extends further, but we do not see it in scattered light because it is partially self-shadowed. However, it seems unlikely that the disc extends out to the companion position at 214 au.

Given the available astrometry, we computed possible orbits of the companion. We found that orbits that are circular and co-planar with the circumstellar disc do not fit the available data. We further find that the companion's orbit must be at least slightly eccentric if the companion mass is indeed as low as our modelling work predicts. The orbital plane is likely misaligned with the plane of the circumstellar disc and thus with the spin axis of the primary stars. Furthermore, the circumplanetary disc may be misaligned with both the orbital plane and the stellar spin axis. Such misalignments would not be predicted if the companion formed in the disc around the primary stars. Thus we speculate that the companion may have formed as a component of a multiple stellar system. In multiple stellar systems such misalignments are quite common (see, for example, simulations by Bate, 2012).

In the future we will need follow-up observations with the Atacama Large Millimeter/submillimeter Array (ALMA),

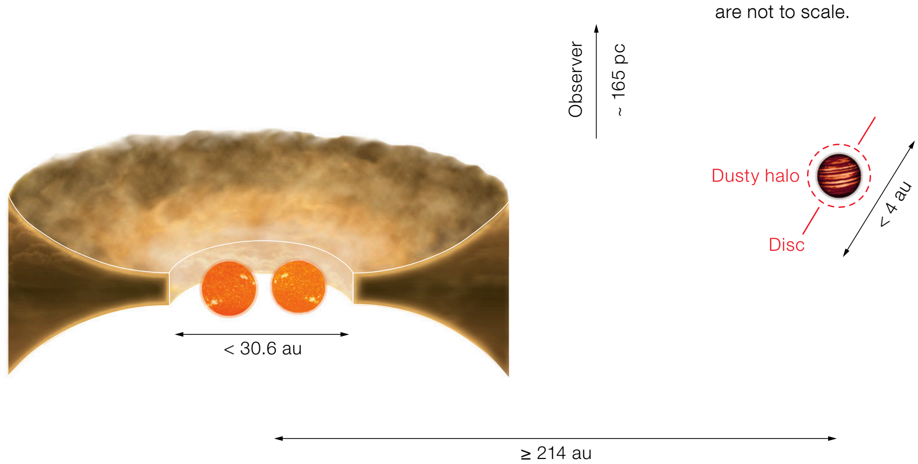


Figure 5. (Below) Schematic of the CS Cha system. Distances and sizes are not to scale.

to constrain the dust mass around the companion as well as the extent of the gas disc of the stellar spectroscopic binary. Also, spectral observations in the near-infrared are needed to better characterise the companion. In particular, we will need (HST/WFC3) observations as the limitations of current ground-based instruments do not allow us to detect the spectrum of the companion.

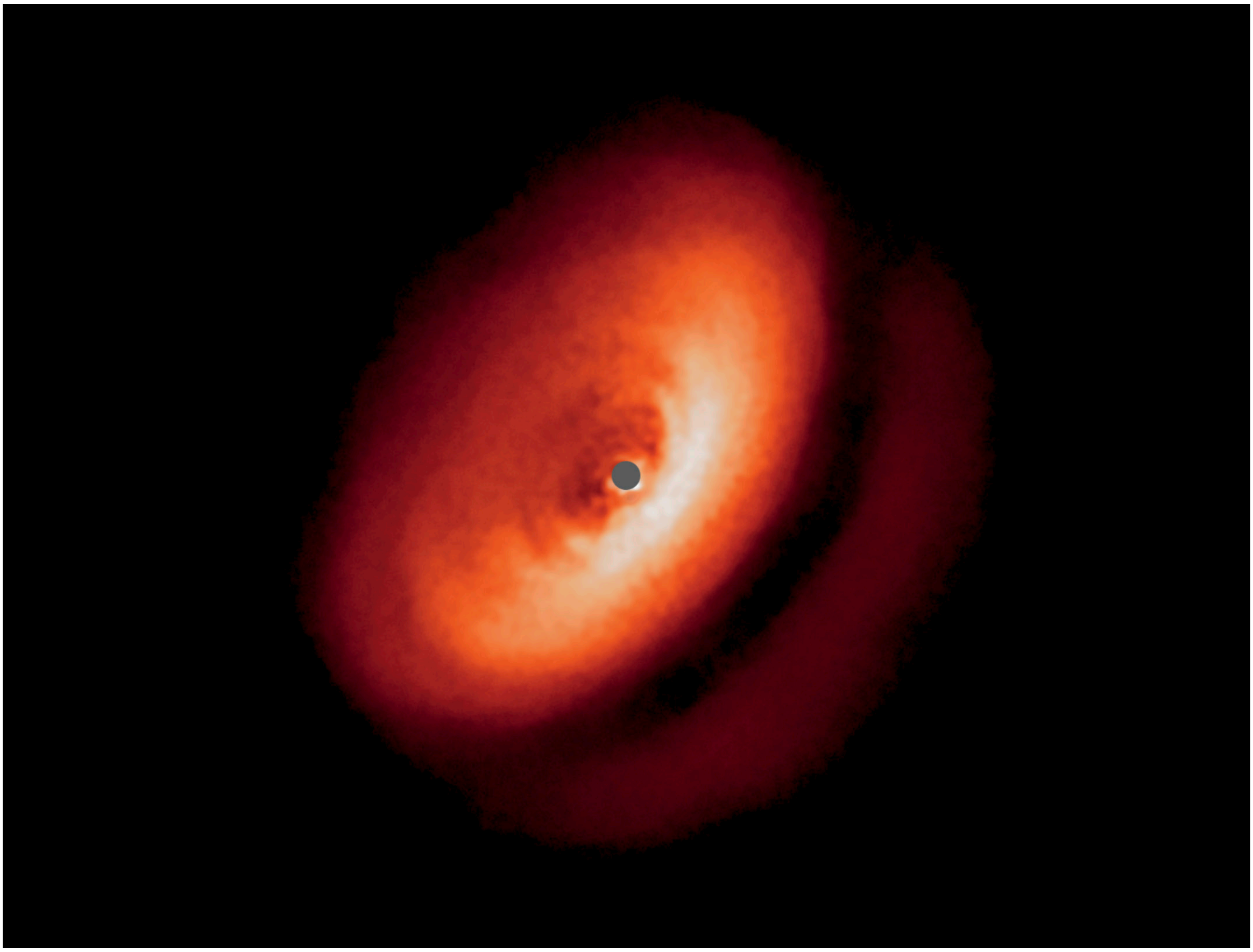
The CS Cha system offers concrete evidence of a formation pathway for wide planetary-mass companions and shows the power of polarimetry as a tool for planet characterisation.

Acknowledgements

Our new observations were performed with SPHERE at the VLT. SPHERE is an instrument that has been designed and built by a consortium consisting of IPAG (Grenoble, France), MPIA (Heidelberg, Germany), LAM (Marseille, France), LESIA (Paris, France), Laboratoire Lagrange (Nice, France), INAF–Osservatorio di Padova (Italy), Observatoire de Genève (Switzerland), ETH Zurich (Switzerland), NOVA (Netherlands), ONERA (France) and ASTRON (Netherlands) in collaboration with ESO. SPHERE was funded by ESO, with additional contributions from CNRS (France), MPIA (Germany), INAF (Italy), FINES (Switzerland) and NOVA (Netherlands). In addition, SPHERE received funding from the European Commission Sixth and Seventh Framework Programmes as part of the Optical Infrared Coordination Network for Astronomy (OPTICON) under grant number RII3-Ct-2004-001566 for FP6 (2004–2008), grant number 226604 for FP7 (2009–2012) and grant number 312430 for FP7 (2013–2016). Christian Ginski would like to thank Donna Keeley for language editing of the manuscript.

References

Bate, M. R. 2012, MNRAS, 419, 3115
Beuzit, J.-L. et al. 2008, SPIE, 7014, 18
Espaillat, C. et al. 2007, ApJ, 664, L111
Ginski, C. et al. 2018, A&A, submitted
Helling, C. et al. 2008, ApJ, 675, L105
van Holstein, R. G. et al. 2017, SPIE, 10400, 15
Lenzen, R. et al. 2003, SPIE, 4841, 944
Stolker, T. et al. 2017, A&A, 607, 42



ESO/H. Avenhaus et al./DARTT-S collaboration

SPHERE image of the enormous dust disc surrounding the T Tauri star IM Lup.