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Investigation of the inner structures around HD 169142 with VLT/SPHERE

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ABSTRACT

We present observations of the Herbig Ae star HD 169142 with the VLT/SPHERE instruments InfraRed Dual-band Imager and Spectrograph (IRDIS) ($K1K2$ and $H2H3$ bands) and the Integral Field Spectrograph (IFS) (Y, J and H bands). We detect several bright blobs at ∼180 mas separation from the star, and a faint arc-like structure in the IFS data. Our reference differential imaging (RDI) data analysis also finds a bright ring at the same separation. We show, using a simulation based on polarized light data, that these blobs are actually part of the ring at 180 mas. These results demonstrate that the earlier detections of blobs in the H and K_S bands at these separations in Biller et al. as potential planet/substellar companions are actually tracing a bright ring with a Keplerian motion. Moreover, we detect in the images an additional bright structure at ∼93 mas separation and position angle of 355°, at a location very close to previous detections. It appears point-like in the YJ and K bands but is more extended in the H band. We also marginally detect an inner ring in the RDI data at ∼100 mas. Follow-up observations are necessary to confirm the detection and the nature of this source and structure.

Key words: Stars: individual: HD169142 – Planets and satellites: detection, formation – Techniques: high angular resolution – Protoplanetary disc.

1 INTRODUCTION

Young stellar objects are surrounded by circumstellar material, making them ideal targets for studying planetary formation. Transitional discs are particularly interesting as they may constitute the intermediate step between gas-rich protoplanetary discs where planets are supposed to form and dusty debris discs.

Direct observations of companions and disc structures are necessary to set constraints on planetary formation. A few targets have already been identified as interesting cases to study this phenomenon, such as HD 100546 (Brittain et al. 2013; Quanz et al. 2013, 2015; Currie et al. 2015), HD 142527 (Biller et al. 2012) and LkCa 15 (Kraus & Ireland 2012; Sallum et al. 2015). These examples show that determining the origin of disc structures is difficult, and overall, the risk of confusing them with forming planets is quite high (see e.g. Follette et al. 2017).

HD 169142 is a well-studied Herbig Ae star (Meeus et al. 2010) at 117 pc (Michalik, Lindegren & Hobbs 2015; Gaia Collaboration 2016, see Table 1), hosting a nearly face-on disc often categorized as pre-transitional since it shows dust emissions at both close and large separations from the star, which are separated by several gaps (Osorio et al. 2014; Wagner et al. 2015). The disc was first spatially resolved by Kuhn, Potter & Parise (2001, H band) with polarimetry and studied by Meeus et al. (2001, 2–45 µm) with spectroscopy, and later confirmed by Hales et al. (2006, JHK bands). Quanz et al. (2013) reported polarimetric observations with NaCo (Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph) in the H band, revealing a bright irregular ring at

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Table 1. Parameters of HD 169142.

Parameter	Value	Ref.
RA (J2000)	$18^{\mathrm{h}}24^{\mathrm{m}}29\overset{\mathrm{s}}{.}787$	(1)
Dec (J2000)	$-29^{\circ}46'49\overset{''}{.}22$	(1)
Parallax [mas]	8.526 ± 0.288	(2)
Distance [pc]	$117.288^{+3.832}_{-4.101}$	(3)
J [mag]	7.31 ± 0.02	(1)
H [mag]	6.91 ± 0.04	(1)
K_S [mag]	6.41 ± 0.02	(1)
L' [mag]	5.66 ± 0.03	(4)
G [mag]	8.060	(2)
Age [Myr]	1–5; 6^{+6}_{-3}; 12	(5), (6), (7)
M [$\mathrm{M}_{\odot}$]	1.65	(7)
R [$\mathrm{R}_{\odot}$]	1.59; ∼1.6	(7), (8)
L [$\mathrm{L}_{\odot}$]	8.55	(7)
T_{eff} [K]	7500 ± 200; 6464; 7500–7800	(5), (7), (8)
Spectral type	A9III/IVe; A7V	(5), (7)
Fe/H	-0.5 ± 0.1; -0.5–0.25	(5), (8)
log (g)	3.7 ± 0.1; 4–4.1	(5), (8)

References. (1) 2MASS catalog (Cutri et al. 2003), (2) Gaia Catalog (Michalik et al. 2015; Gaia Collaboration 2016), (3) adapted from Gaia catalog (Gaia Collaboration 2016), (4) Malfait, Bogaert & Waelkens (1998), (5) Guimarães et al. (2006), (6) Grady et al. (2007), (7) Blondel & Djie (2006), (8) Meeus et al. (2010).

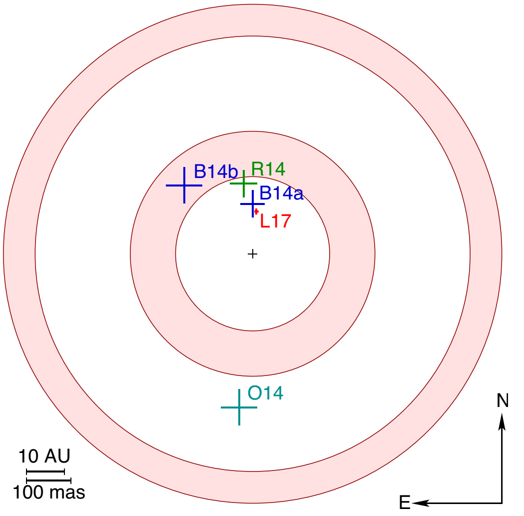


Figure 1. Diagram of the HD 169142 system. The red parts represent the two rings and the white parts are the gaps. The crosses represent the positions of the point-like structures discovered by Biller et al. (2014, B14b for the structure discovered with MagAO and B14a for the one detected with NaCo), Reggiani et al. (2014, R14) and Osorio et al. (2014, O14). We also show the structure around 100 mas detected with SPHERE in this work (L17, see Section 5). The dimension of the crosses represents the error bars (on scale), except for B14b and O14, where the error bars are given arbitrarily. The inclination of the disc is not shown in this diagram.

170 milliarcseconds (mas), that is 20 au, and an annular gap from 270 to 480 mas (32–56 au). The surface brightness smoothly decreases after 550 mas (66 au). Monnier et al. (2017) confirmed a double-ring structure using the Gemini Planet Imager (GPI) in the H band, showing a surface brightness enhancement at 180 mas (21 au) and one at 510 mas. Interestingly, Atacama Large Millimetre/Submillimeter Array (ALMA) observations revealed two rings at 170–300 mas and 479–709 mas, and an empty cavity ($R < 171$ mas) at the centre of the dust disc, which was filled with gas (Fedele et al. 2017). This might indicate the presence of multiple planets carving out the gaps and cavities (Zhu et al. 2012; Dong, Zhu & Whitney 2015), or alternatively that magneto-rotational instability effects combined with magnetohydrodynamic winds (Pinilla et al. 2016) shape the disc density structure.

Additional hints of planet formation have been identified around HD 169142. Biller et al. (2014) and Reggiani et al. (2014) observed HD 169142 with NaCo in the L' band. Biller et al. (2014) detected a faint marginally resolved point-like feature in the data from 2013 July, located at a position angle (PA) of $0 \pm 14^{\circ}$ and a separation of $\rho = 110 \pm 30$ mas (13 ± 3.5 au), with $\Delta\mathrm{mag} = 6.4 \pm 0.2$. If this emission was photospheric, it would correspond to a 60–80 $\mathrm{M_{Jup}}$ brown dwarf companion. However, this companion was not confirmed by shorter wavelength follow-up observations performed with the adaptive optics system at the Magellan Clay Telescope (MagAO/MCT) in the H, K_S and z_p bands (where it should have been easily detected if it was a 60–80 $\mathrm{M_{Jup}}$ companion), nor at 3.9 µm, though at lower sensitivity. This suggests that the object found in 2013 might be a part of the disc possibly showing planetary formation with an unknown heating source. Reggiani et al. (2014) also detected a point source in NaCo data from 2013 June. This emission source was at $\rho = 156 \pm 32$ mas (18 ± 3.8 au) and PA = $7.4 \pm 1.3^{\circ}$. It has $\Delta\mathrm{mag} = 6.5 \pm 0.5$, and an apparent magnitude of 12.2 ± 0.5 mag. They suggest that this could come from the photosphere of a 28–32 $\mathrm{M_{Jup}}$ companion, or from an accreting lower-mass forming planet in the gap. Additional observations were carried out with the GPI instrument (Macintosh et al. 2014) in the J band in 2014 April, where this hypothetical companion was not retrieved, again suggesting that it was not a 28–32 $\mathrm{M_{Jup}}$ object, as this should have been relatively easily detected in the J band. Finally, Osorio et al. (2014) additionally found with Atacama Large Millimetre/Submillimeter Array (EVLA) 7-mm observations a knot of emission at 350 mas (41 au at 117 pc), which could correspond to an object of 0.6 M_{Jup}.

The follow-up MagAO/MCT observations performed by Biller et al. (2014) led to another low signal-to-noise ratio (S/N) detection at $\rho = 180$ mas (21 au) and PA = 33°. If real, this structure would correspond to a 8–15 $\mathrm{M_{Jup}}$ substellar companion, but it was not found in the initial 2013 NaCo data in the L' band. All these results demonstrate the complexity of this system, which is even more critical given the lack of consistency between the results (possibly because of observational limitations). Fig. 1 summarizes the different point-like structures identified around HD 169142 so far.

In this paper, we investigate the innermost structures (<300 mas) previously detected around HD 169142 to confirm the presence of the candidate companions detected by Biller et al. (2014) and Reggiani et al. (2014) and investigate their nature. We present new near-infrared (NIR) observations of HD 169142 obtained with SPHERE/VLT (Spectro-Polarimetric High-contrast Exoplanet Research, Beuzit et al. 2008), as part of the Guaranteed Time Observations (GTO) dedicated to exoplanet searches (Sphere Infrared survey for Exoplanets or SHINE, Chauvin et al., in preparation). SPHERE has primarily been designed to image and characterize exoplanets, but it is also a powerful instrument for probing the dusty surface of protoplanetary discs.

The observations are described in Section 2 and the data analysis in Section 3. We report in Section 4 the detection of bright blobs at 180 mas, which are actually part of the inner ring, and we show in Section 5 the marginal detection of a bright structure located at a similar position to the object found by Biller et al. (2014) and Reggiani et al. (2014). We conclude in Section 6.

Table 2. Observing log of SPHERE SHINE data for HD 169142. Plate scale values for IRDIS are given for the *K*1*K*2 filters or *H*2*H*3 filters.

UT date	MJD [day]	Coronagraph	Instrument and band	DIT × NDITs	Exposure time [s]	Field rotation [deg]	Mean seeing [arcsecond]	Plate scale [mas]
2015 June 7	57180.17	Y	IFS *YJ*	64.0 × 86	91.7	45.82	1.57	7.46 ± 0.02
			IRDIS *H*2*H*3	64.0 × 4 or 2	102.4			12.255/12.250 ± 0.009
2015 June 28	57201.12	Y	IFS *YJH*	64.0 × 65	69.3	36.42	1.00	7.46 ± 0.02
			IRDIS *K*1*K*2	64.0 × 5	85.33			12.267/12.263 ± 0.009
2016 April 21	57499.34	Y	IFS *YJ*	64.0 × 77	82.1	145.0	1.88	7.46 ± 0.02
			IRDIS *H*2*H*3	64.0 × 17	90.67			12.255/12.250 ± 0.009
2016 June 27	57566.15	N	IFS *YJH*	2.0 × 1610	64.8	149.9	0.67	7.46 ± 0.02
			IRDIS *K*1*K*2	0.84 × 38	64.22			12.249/12.245 ± 0.009
2017 April 30	57873.30	N	IFS *YJH*	2.0 × 1152	61.2	98.82	0.62	7.46 ± 0.02
			IRDIS *K*1*K*2	0.84 × 561	78.10			12.249/12.245 ± 0.009

Note. The DIT values refer to the integration time and the NDIT values to the number of integrations per data cube.

2 OBSERVATIONS AND DATA REDUCTION

Observations of HD 169142 were performed from 2015 to 2017 (see Table 2). The data were obtained in the `IRDIFS` or in the `IRDIFS_EXT` modes, simultaneously using the dual-band imaging mode (Vigan et al. 2010). For the `IRDIFS` mode, the Integral Field Spectrograph (IFS; Claudi et al. 2008) was operating in the wavelength range between 0.95 and 1.35 µm (*YJ*) at a spectral resolution of $R = 50$, and the InfraRed Dual-band Imager and Spectrograph (IRDIS; Dohlen et al. 2008) in the *H* band with the *H*23 filter pair ($\lambda_{H2} = 0.055$ µm, $\lambda_{H3} = 1.667$ µm). For the `IRDIFS_EXT` mode, the IFS was used between 0.95 and 1.65 µm (*YJH*) ($R = 30$) and IRDIS in the *K* band with the *K*12 filter pair ($\lambda_{K1} = 2.110$ µm, $\lambda_{K2} = 2.251$ µm). Due to the very small angular separation of the previously reported detections, the two most recent observations were done without a coronagraph, but the core of the stellar point-spread function was saturated over a radius of $\sim 1\lambda/D$ and observations were performed in pupil-stabilized mode to enable angular differential imaging (ADI; Marois et al. 2006).

To check the consistency of the results, different pipelines were used to reduce and analyse the IFS and IRDIS data. We used the LAM-ADI pipeline (Vigan et al. 2015, 2016) and the SPHERE data reduction and handling automated pipeline (Pavlov et al. 2008) for IRDIFS data, and the pipeline described in (Mesa et al. 2015, ASDI-PCA algorithm) for the IFS data. Even though the observing conditions were good, there were some temporal variations, so we performed a frame selection on the data sets. We used the SORTFRAME routine developed by the SPHERE Data Center (DC) to select the good frames when using the DC and Mesa et al. (2015) pipelines. The minimum fraction of selected frames is about 80 per cent and the maximum is near 100 per cent, depending on weather conditions. For the LAM-ADI pipeline, we calculated the moving average of the flux in an annulus centred on the star. We then excluded frames presenting a flux above or below 1.5σ of the mean flux. This method follows a Gaussian behaviour and corresponds to ∼14 per cent of the frames removed using the 1.5σ criterion. This allows us to keep enough frames to get a correct S/N while removing very bad frames that could induce artefacts in the images (this applies only to the images shown in Fig. 4). Finally, the SHINE data were astrometrically calibrated following the analysis in Maire et al. (2016). To improve the S/N and to show the different structures in the images, the selected IFS and IRDIS data were collapsed to broad-band images equivalent to the *K*, *H* and *YJ* bands.

3 DATA ANALYSIS

3.1 Principal component analysis reduction

The data were first analysed using principal component analysis (PCA) based on the formalism described in Soummer, Pueyo & Larkin (2012). The modes were calculated over the full sequence at separations up to 500 mas. A variable number of modes were subtracted, up to ∼10 per cent of the total number of modes for IRDIS (∼50) and up to 50 modes for IFS, before rotating the images to a common orientation and combining them with an average. The resulting images obtained in the *YJ*, *K* and *H* bands for 2015 June 7 (best quality image for 2015), 2016 June 27 and 2017 April 30 (best quality images for 2016 and 2017) are presented in Fig. 2.

Fig. 2 shows extended and point-like surface brightness enhancements depending on the band, and a faint arc-like feature appears in the IFS data on the eastern part of the disc, in particular in the *YJ* band (referred to as a spiral). The bright structures are at separations of ∼180–200 mas, especially at PA = 20° (structure A), and 90° and 310° (structure B). Other structures are detected at ∼150 mas (PA = 320°) and at ∼100 mas (PA = 355°; structure C) from the central star. In the IRDIS data, the bright structures are still visible but appear fainter. The structures appear point-like in the *YJ* and *K* bands and more extended in the *H* band. They are persistent whatever the number of subtracted modes in the IFS and IRDIS data. In Appendix, we show S/N maps of epochs 2017 April 30 and 2016 June 27. The maps show bright and dark structures with positive and negative values of S/N, which is calculated as the normalized difference in intensity between a considered feature and two neighbouring areas at the same separation (following the method described in Zurlo et al. 2014). Thus, bright peaks are significant features, just as much as dark peaks, since they indicate darker features than the surrounding background. It is important to note that the calculation of the S/N can be modulated by the background, which is inhomogeneous. In particular, the dark peak at ∼40° in the S/N map is not dark in Fig. 5, but is surrounded by two bright structures. The positions of the structures showing a high signal (S/N ∼ 3) are consistent with the structures appearing in Fig. 2, in particular structures A and B. Structure C has a lower S/N.

Several features have already been discovered at the separations of structures A, B and C (a bright ring and candidate companions, see Section 1), but they appeared point-like. Since we detect bright spots at similar positions in our images, we try to investigate whether

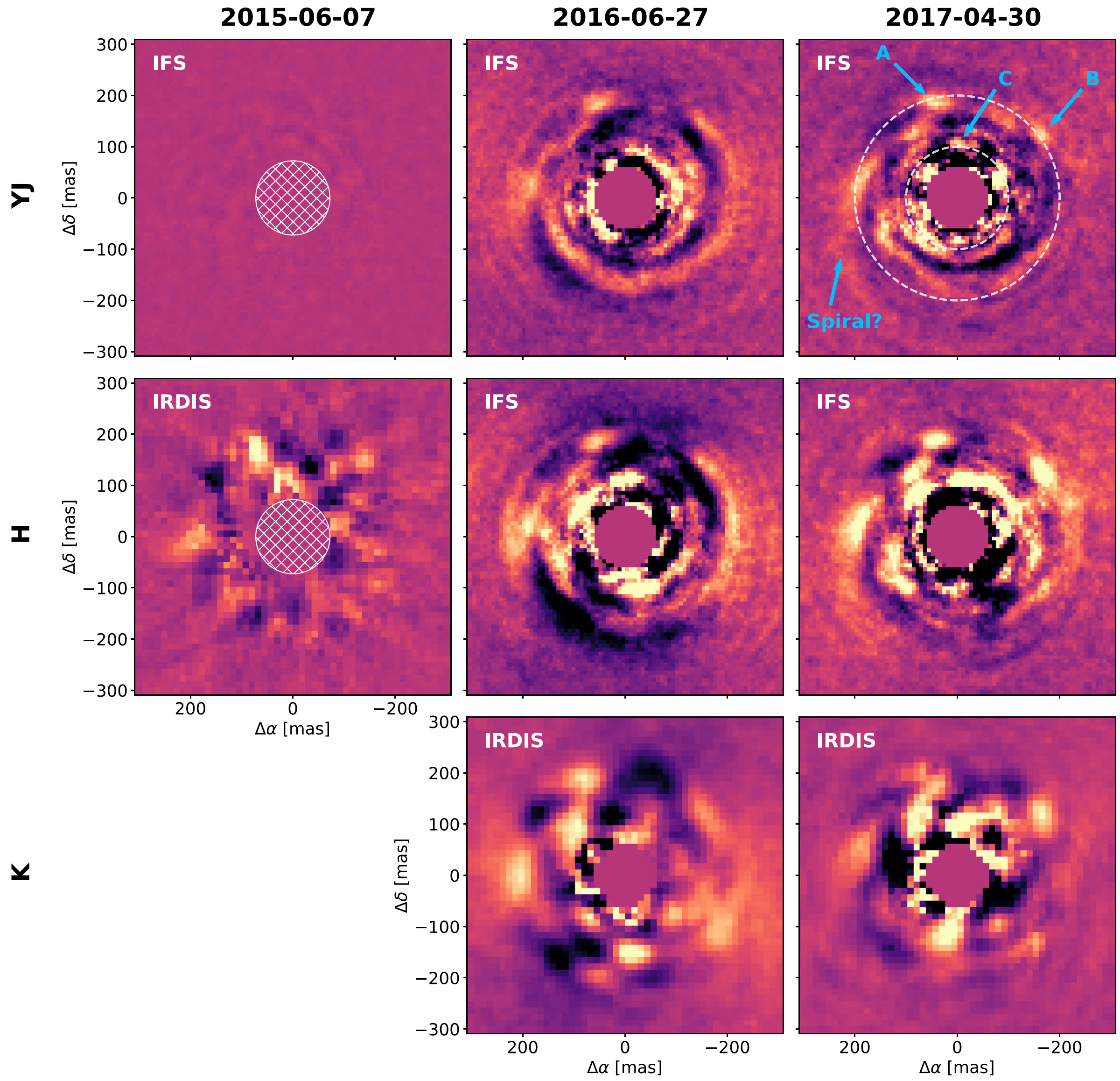


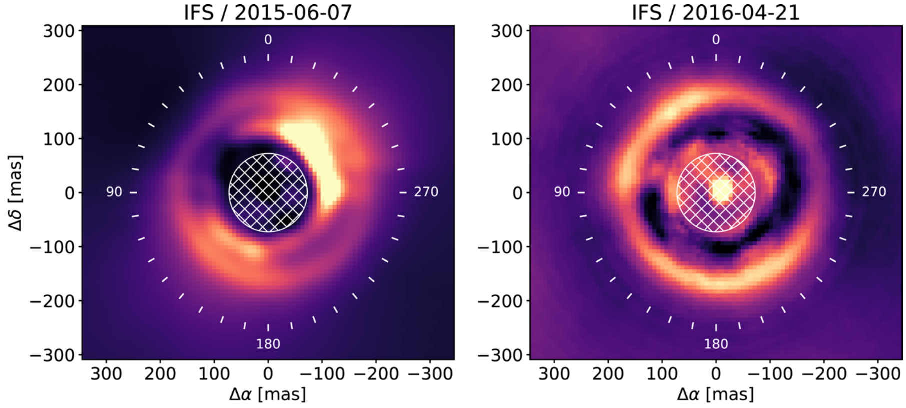
Figure 2. Result of PCA for IFS (pipeline from Mesa et al. 2015) with 50 subtracted modes, and IRDIS (pipeline from Vigan et al. 2015) with 6, 50 and 20 subtracted modes for the 2015, 2016 and 2017 data, respectively. The central circular grid shows the position of the coronagraph in the 2015 data set; the star is at the centre. The bright structures are indicated with blue arrows. Letter A indicates the structure at PA = 20° and letter B indicates the one at 310°, both being at separation ∼180 mas. Letter C shows the structure at ∼100 mas and PA = 355°. The two white dashed circles have a radius of 100 and 180 mas, respectively. North is up and east is left.

or not these detections are the same as the previous ones. In the next section, we analyse the structures found around ∼180–200 mas, and in Section 5, we focus on the detection at ∼100 mas.

3.2 Reference differential imaging reduction

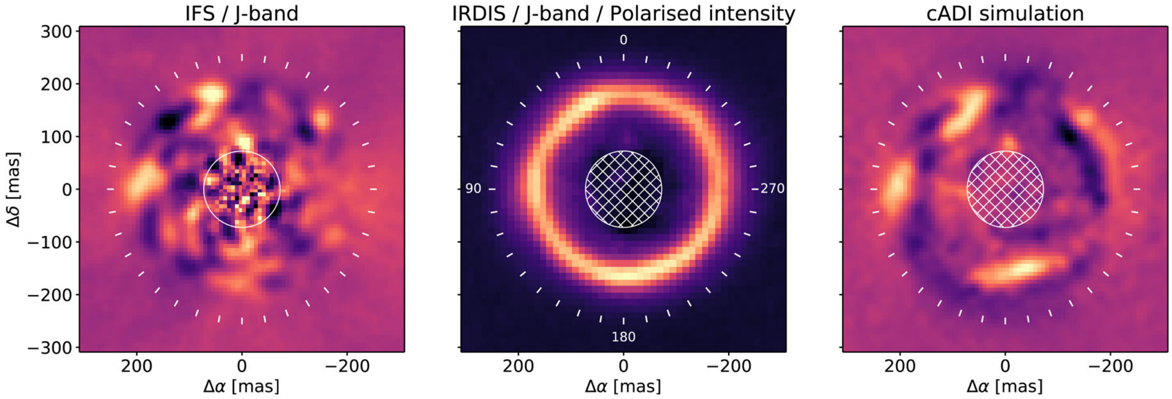
We performed reference differential imaging (RDI; Soummer et al. 2014), which consists of subtracting the reference image of one or several stars from the target image. This technique is used to subtract the speckle pattern, while it limits the self-subtraction effects usually affecting ADI data, in particular for extended structures like discs (e.g. Milli et al. 2012). To select the reference images, we searched the complete data base of SPHERE GTO observations for the reduced images that have the best correlation with our target images. This means that we calculated the correlation coefficient between the data sets taken in a similar band as the considered target observation, and the considered data set of our target. The best correlation coefficient (which is >0.90, in general) designates the data set that is used as the reference image. For images taken without a coronagraph, the correlation coefficient is lower (around 0.50) than with a coronagraph because there are fewer images taken without the coronagraph in the SPHERE data base. Similarly, there are many more $Y-J$ images than $Y-H$ images, leading to lower coefficients for the latter mode.

Fig. 3 shows the RDI IFS images of HD 169142 from 2015 June and 2016 April with a subtracted image of the same night each time. We see a possible double-ring structure, with one being located at ∼180 mas, and possibly another one at ∼100 mas, that is, close to the bright blobs detected with PCA. Both rings are inhomogeneous. In particular, the one at 180 mas shows a decrease in the brightness around PA = 45° compared to the surrounding ring signal (at 20° and 80°), and there are several brightness enhancements in the


IFS / 2015-06-07

IFS / 2016-04-21

Figure 3. Result of the RDI analysis of the IFS data from 2015 June and 2016 April. We clearly see an inhomogeneous bright ring at ∼180 mas, and possibly another inner ring, although its position close to the star makes it less trustable. North is up and east is left.


IFS / J-band

IRDIS / J-band / Polarised intensity

cADI simulation

Figure 4. Left: IFS image in the *J* band with 50 PCA modes subtracted. Middle: IRDIS PDI polarized intensity image in the *J* band, which shows a bright irregular ring. Right: Result of a cADI simulation using the polarized intensity image as input (see text for details). The circular grid at the centre represents the centre star covered by coronagraphic mask in the PDI data. The corresponding position in the IFS data is also represented in the IFS *J* band image, although these data were obtained without a coronagraph (empty circle). Tick marks placed every 10° of PA are plotted outside the area of interest. North is up and east is left.

north-west and south-west directions. The ring appears more clearly in the 2016 April image, possibly due to the better quality of the data and a larger rotation field. The inner ring at 100 mas is quite bright with a brighter region in the north-west direction in the 2015 image. However, it is not detected in each reduction (in particular, it is hardly seen in the RDI data without a coronagraph), and its appearance depends on the scale used (see Section 5). It appears much less bright in the 2016 April image, although we still detect a signal.

4 AN INHOMOGENEOUS RING AT 180 MAS

4.1 Simulation of classical ADI reduction with polarimetric differential imaging data

To understand the nature of the detected structures, it is important to know if the scattered light is polarized. Indeed, planets are usually considered not to emit polarized light, unlike protoplanetary discs (see however, Stolker et al. 2017, who suggest that a very small amount of polarization is possible in some cases). Polarized light due to reflection from hot Jupiter planets could also be detected in the optical (UBV bands). However, the signal produced would be low (Berdyugina et al. 2008, 2011), which might be impossible to detect when the planet is embedded in a disc that produces polarized scattered light.

To investigate the nature of the blobs at ∼180 mas, we use IRDIS polarimetric differential imaging (PDI) data that were acquired on 2015 May 2 with the `ALC_YJ_S` apodized-pupil Lyot coronagraph (145 mas in diameter) in the *J* band and reduced following de Boer et al. (2016). A full analysis and modelling of the PDI data will be presented in a forthcoming paper (Pohl et al., accepted).

The left-hand and middle panels of Fig. 4 compare the IFS *J*-band data and the IRDIS PDI data of the very central region around the star (±300 mas). The ring at 180 mas in the IRDIS polarized intensity image is detected at extremely high significance and a small coronagraphic mask allows us to confirm unambiguously the existence of the cavity inside the ring. The polarized intensity image also clearly shows a variation of the ring brightness as a function of PA, with an increase of the brightness at PAs of ∼20°, ∼90°, ∼180° and to a lesser extent at ∼310°. The brightness of the structure has been measured by Pohl et al. (accepted; Fig. 3), and higher signals at these same PAs are clearly visible. Interestingly, these regions of increased brightness seem to correspond to PAs where the IFS *J*-band image shows extended bright structures

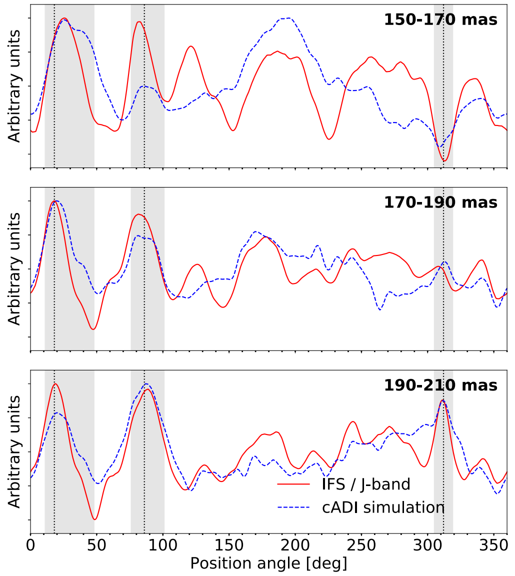


Figure 5. Azimuthal cuts at three different separations in the IFS *J*-band data with 50 PCA modes subtracted (plain red line) and in the cADI simulation (dashed blue line). The separation is indicated in the top right corner of each plot. The signal is measured every 0.5° and averaged in slices of 20 mas along the radial dimension. The curves are normalized to arbitrary units allowing a comparison between them. Grey areas highlight the structures that show the strongest correlation, with the dashed lines indicating the position of the highest signal for a given separation.

at a significance of 2.5–3σ above the surrounding residuals.[1] In particular, the bright structures at PA $\approx$ 20° and 310° in the PDI data seem to correspond to the structures shown by the blue arrows in Fig. 2 (structures A and B), and a structure at PA =380° and ρ = 100 mas seems to correspond to structure C. A bright extended structure also appears between 180° and 210° in the classical ADI (cADI) simulation images, which is clearly visible in the PDI image but appears fainter in the IFS *J*-band image. Finally, we notice the strong similarity between the rings in the PDI data and in the RDI data from 2016 April (Fig. 3).

To confirm that the residual structures seen in the IRDIS and IFS data are in fact ring structures filtered by the ADI processing, we perform a simulation of ADI reduction using the IRDIS PDI polarized intensity image. First, we create a data cube with 1709 copies of the PDI image (because this is the number of frames after selection using the LAM-ADI pipeline, see Section 3.1), corresponding to each of the IFS images, with each of the images being rotated to match the pupil offset rotation and the PA of the observations. Then, the median image of the cube along the temporal dimension is calculated and subtracted from each of the images in the cube (cADI). Finally, all the images are rotated back to a common orientation and mean-combined. The result of this simulation is presented in the right-hand panel of Fig. 4.

Visually, we see a strong correlation between the main structures identified in the IFS *J*-band image and the bright ring in the disc, which have been spatially filtered by the ADI analysis. The effect of ADI processing on discs has already been studied by Milli et al. (2012). They identified that ADI can have a strong impact on the flux and morphology of discs, up to the point of creating artificial features. This effect has also been encountered for HD 100546 (Garufi et al. 2016) and T Cha (Pohl et al. 2017). The ring of HD 169142, which is seen almost face-on, is an extreme case. All the azimuthally symmetric structures of the ring are completely filtered out by ADI, leaving only the signature of the features brighter or fainter than average. In the simulation, the shapes of the features at ~20° and ~90° are almost identical to those in the IFS image. The same bright spot at a PA of ~310° is also clearly visible.

For a more quantitative assessment, we compare in Fig. 5 azimuthal cuts of the IFS *J*-band data with 50 PCA modes and the cADI reduction simulation, measured at different separations from the star. The signal is averaged in annuli of 20 mas of radial extension to smooth the small pixel-to-pixel variations in the data. These cuts show a very strong correlation between some of the main features seen in the IFS data and the cADI reduction simulation. The Pearson correlation coefficients between the two data sets are 0.47, 0.64 and 0.80 for the 150–170 mas, 170–190 mas and 190–210 mas azimuthal cuts, respectively. This correlation is calculated on the full ring, but it would be even higher if we considered more local correlations centered on the main features.

4.2 Interpretation of the results

In the NIR, we are sensitive not only to the thermal emission from point sources but also to stellar light scattering off the protoplanetary dust. The detected point source at 180 mas (Biller et al. 2014) lies on the surface of the ring, which is optically thick in the NIR (as the whole disc). Thus, the signal from a point source in the mid-plane of the disc will be dominated by scattered light and the planetary emission would be strongly absorbed by the dust, making its detection impossible. It would be possible to detect a very massive companion at that location, but in that case we would expect it to have opened a deep and broad gap. Instead, we find a ring. Since the detection of polarized light from a planet is not expected, we conclude that the blobs that we detect both in PDI and unpolarized data are part of the same structure: the ring. Hence, we can conclude with a high confidence level that our images show disc features rather than planetary companions for the structures A and B. We can, thus, exclude the thermal emission from giant planets being consistent with the blob signals, but we cannot exclude clumps in an early stage of planet formation.

Multiple blobs are found on the same orbit at $\rho \approx 180$ mas. Of particular interest is the structure at PA $\approx$ 20° (structure A in Fig. 2), because it is bright and appears both in the PDI and unpolarized data. We investigate if it corresponds to an object candidate, and in particular, to the one detected by Biller et al. (2014) at PA = 33° and $\rho = 180$ mas (see Section 1) because it is close to our current detection's position. Considering the stellar distance ($117.3^{+3.8}_{-4.1}$ pc) and mass (1.65 $\mathrm{M}_\odot$) of HD 169142 (see Table 1), and the inclination of the disc (13 ± 1°), Biller et al. (2014)'s candidate should have an orbit of ~78.5 yr if it is in the disc plane with no eccentricity, and therefore, it should have moved ~13.7° from 2013 June to 2016 June. This would bring it to PA = 19.3° if it moved clockwise, which is in very good agreement with the measured PA of our structure (20°).

The movement of the blobs (structures A and B) according to the different epochs of observation are shown in Fig. 6. We also include the separation and PA obtained by Biller et al. (2014) (Fig. 6, green triangles). For each structure, we calculate the average separation over all the epochs (including the position of Biller et al. 2014, for

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[1] Note that the S/N maps were calculated for our images assuming that we were looking for point sources, which does not translate directly when considering extended structures such as discs. However, the structures visible in the data are clearly identifiable above the surrounding background.

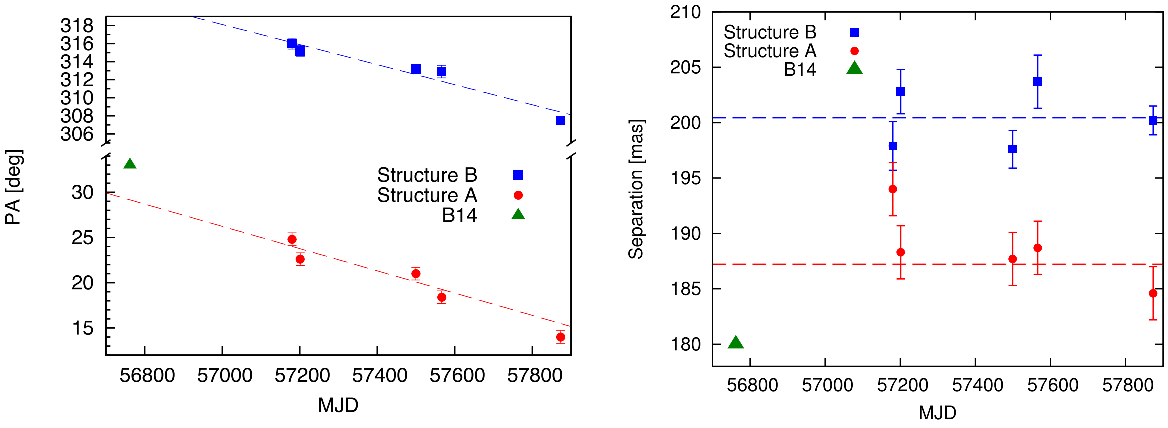

Figure 6. Left: PAs of the structures A (red circles) and B (blue squares) as a function of MJD. Right: Separation of the blobs. The dashed lines show the average separation and the corresponding Keplerian speed. The green triangle is the position given by Biller et al. (2014).

the calculation of the separation of structure A), and the Keplerian speed corresponding to this average separation. We then plot the Keplerian speed on the PA figure. We can see that the motion of the structures is compatible with Keplerian speeds. We note that Biller et al. (2014)'s positions are indicated without error bars, but they give a rough estimation of the position in their paper. We have already shown that our detections could be related to blobs in the disc. We, thus, conclude that the PA and separation evolution of the blob are consistent with a Keplerian motion. The blobs trace the bright ring in the disc, and they rotate in a clockwise direction with a Keplerian velocity. Moreover, ALMA data (Fedele et al. 2017) provide the direction of rotation of the disc (the northern part of the disc is moving faster towards us than the local rest frame, while the southern part is moving slower) and its closest side to the observer (the western side), which are compatible with the clockwise motion of the blobs.

The exact nature of the blobs and the origin of the bright disc rings and gaps, in general, remain to be investigated. We make here only a hypothesis about which scenarios could be compatible with our observations. We also refer the reader to the upcoming work by Pohl et al. (accepted) for a detailed modelling study of the disc around HD 169142 including planet–disc interaction processes and dust evolution dynamics.

The first possibility invokes intrinsic disc variations in density and temperature. Indeed, the dust concentration in the ring might be a tracer of the maximum density in the gas profile. This jump in the surface density could trigger the formation of vortices by the Rossby wave instability, which concentrates dust azimuthally. Our observations look like figs 3 and 5 of Meheut et al. (2012), who display simulations of Rossby vortices with several irregular blobs of enhanced dust density on the same orbit. Barge & Sommeria (1995) show that these vortices could be favourable places to initiate planet formation. If this is the case, HD 169142 could be the site of ongoing planet formation at an earlier stage than previously expected. Although multiple vortices are non-permanent states, the mass ratio between the disc and star (0.03, considering the refined estimate of the disc mass by Monnier et al. 2017) does not make the disc gravitationally unstable, and would allow self-gravity to improve the stability of multiple vortices (Lin & Papaloizou 2011). If the blobs in our image indeed trace vortices, we would observe only their signatures in the upper disc layers in our SPHERE observations. While ALMA observations, which trace the mid-plane layers, have already been interpreted as vortices in the protoplanetary disc (see e.g. van der Marel et al. 2013), recent observations of HD 169142 with this instrument (Fedele et al. 2017) did not show any asymmetrical features at a resolution of 0.2–0.3 arcsec. In addition, the spatial distribution of particles inside a vortex depends on their size (see e.g. Lyra et al. 2009; Gonzalez et al. 2012) and such structures would, thus, appear differently in the sub-millimetre regime. However, the currently available ALMA observations would not be able to resolve the various structures shown in this paper if they have the same or smaller spatial extent.

The second scenario involves illumination variations because of azimuthally asymmetric optical depth variations through an inner disc closer to the star. Even if much less plausible, this scenario has already been raised in previous studies concerning HD 169142 (Quanz et al. 2013; Pohl et al., accepted). The observed brightness variations at 180 mas are relatively small [Pohl et al. (accepted) suggest an azimuthal brightness variation of 25 per cent in the PDI data] and could be caused by such variations. Besides, the inner disc at ∼0.3 au is known to present a variable spectral energy distribution (SED) in the NIR. Wagner et al. (2015) propose several scenarios to explain the variations of the SED of HD 169142, but they invoke the stable shadowing effect, otherwise an anti-correlated variability in the emission of the inner and outer discs should be observed in the SED, which is not the case. If additional material exists within our inner working angle at high altitude, it could shadow the ring at 180 mas, but this remains to be investigated. In any case, our discovery of the Keplerian movement of the structures at 180 mas strongly suggests that the origin of their intensity variation is not from an inner structure.

5 A POINT-LIKE STRUCTURE AT 100 MAS

In the data, we also detect a point-like structure north of (PA $\approx 4^\circ$) and close to ($\rho = 105 \pm 6$ mas) the star (structure C in Fig. 2). This position was determined using the ASDI-PCA algorithm (Mesa et al. 2015, see Section 3.1). This structure is persistent in both the IRDIS and IFS data, and is visible with a large range of PCA reductions subtracting 12 to 200 modes. The separation of this structure from the star is like the separation of the object detected by Biller et al. (2014) with NaCo in the L' band, and is slightly offset but consistent with Reggiani et al. (2014)'s detection.

To confirm the robustness of our detection, we first split the IRDIS and IFS data into two subsets using the LAM-ADI pipeline, which were analysed following the same procedure described in

Section 3.1. In each of the resulting images, the structure was still visible at a S/N higher than that of the surrounding background. This reduction shows a structure at PA = 355 ± 3° and $\rho = 93 \pm 6$ mas in average over all wavelengths (S/N of 3.3 in the H band), which is consistent with the estimate provided with the ASDI-PCA pipeline. The IRDIS data were also analysed with the PYNPOINT pipeline (Amara & Quanz 2012). In this analysis, the structure is marginally detected, as it appears only between 8 and 15 PCA modes (over 50).

The structure at ∼100 mas appears in most data set as a somewhat extended structure (see Fig. 2), in particular, in the H and K bands. This was not detected previously in the analyses of Biller et al. (2014) and Reggiani et al. (2014), where it appeared point-like in the L' band and was not detected in lower-sensitivity short-wavelength observations.

The structure is partially visible in the PDI image and in the simulated image of the cADI reduction of the PDI data (Fig. 4). This means that its signal is polarized, which indicates light scattered by dust rather than the emission from a planet photosphere. The position of this structure in the simulation of the cADI reduction is $\rho = 82 \pm 3$ mas at PA = 355 ± 2°, which is very much like the PA estimate from the LAM-ADI pipeline. The separation measured in the simulation remains within the error bars of the estimated position in the IFS J band ($\rho = 90.5 \pm 2.5$ mas, PA = 357.9 ± 3.0°), but the separation is smaller than the estimate obtained with the ASDI-PCA algorithm. This could be explained by the measured positions on the real images, which are made on average over all wavelengths, as for the LAM-ADI pipeline.

As seen in Section 4, the average brightness of a disc can be filtered out by the cADI reduction. It is, thus, possible that this structure from the simulation of the cADI reduction of the PDI data actually traces a yet undiscovered ring, and that this structure is a bright part of this ring. Moreover, the structure lies close to the edge of the mask, so it is likely attenuated in the PDI image. This may explain why this hypothetical ring is not detected in the PDI image. The RDI image also shows a ring at ∼100 mas, that is, very close to the coronagraph (Fig. 3). Moreover, the ring is not retrieved in each detection, appearing sometimes in mean-scaled images, other times in median-scaled images. These results tend towards a marginal detection of a bright ring at a separation of ∼100 mas, which our current observations unfortunately cannot confirm. Additional PDI observations closer to the star without a coronagraph would certainly bring precious information.

6 SUMMARY AND CONCLUSION

We performed observations of the Herbig Ae star HD 169142 using SPHERE/VLT in the NIR domain with and without a coronagraph to investigate the inner parts of the system (<300 mas). We observed this star at five different epochs, leading to several new results:

(i) The ADI analysis shows bright structures in both the IRDIS ans IFS data. These structures appear more extended in the H band than in the YJ and K bands. They are mainly located at separations of ∼180–200 mas and ∼100 mas.

(ii) The RDI reduction clearly shows a bright ring at 180–200 mas. It also shows a hint of another inner ring located at ∼100 mas. However, it is very close to the edge of the coronagraph and does not appear identical in every data treatment. Thus, it cannot be confirmed.

(iii) To assess the origin of the structures seen in ADI reductions, we performed a cADI simulation using the image of the ring detected in PDI at 180 mas. While the main component of the ring is filtered out, we still observed residual structures that appear to be common to both PDI and ADI reductions. We, therefore, conclude that these structures are actually bright parts of the disc.

(iv) Given that (a) the bright blobs seen in PCA, in particular structures A and B, and the ring detected with the RDI analysis are located at the same separation (180 mas), and that (b) these blobs and the polarized data are actually part of the same structure (the ring), we conclude that the bright blobs trace this bright ring in the disc.

(v) From the previous result and considering the stellar parameters, we demonstrate that structure A follows a Keplerian motion along the ring. Considering this movement, structure A is very likely to be the same structure as the one detected by Biller et al. (2014) at PA = 33° and $\rho = 180$ mas. It is likely that Biller et al. (2014) actually detected a bright structure in this ring and that the ring brightness was averaged following the same process as for our PCA treatment. Structure B also shows a Keplerian movement and also traces the bright ring in the disc. The latter, thus, rotates in a clockwise direction with a Keplerian velocity, with the western side closer to us and the eastern farther.

(vi) The ring at 180 mas shows an inhomogeneous brightness. One explanation could involve Rossby vortices before they merge into one bigger vortex. These vortices are ideal places to trigger planetary formation at an early stage. If the inner ring is real, another explanation could be illumination effects from it. The irregularity of this ring could produce azimuthally optical depth variations of the ring at 180 mas, but the angular velocity does not match this hypothesis.

(vii) The structure located at 100 mas (structure C) appears to be point-like at shorter and longer wavelengths but extended in the H band, and its position is consistent with previous L'-band detections. The RDI images show a possible inner ring at the same separation. Thus, although marginally detected, it could also trace a yet undetected ring that is even closer to the star. The PCA treatment could easily make it appear point-like, as it does for structures A and B.

HD 169142 is very interesting for studying planet formation as it is a pre-transitional disc showing a succession of bright rings, gaps and a ring/gap alternation. To confirm the inner ring, additional observations would be needed, but the resolution of actual (and even future) direct-imaging instruments would hardly allow such a discovery.

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APPENDIX: SIGNAL-TO-NOISE MAPS

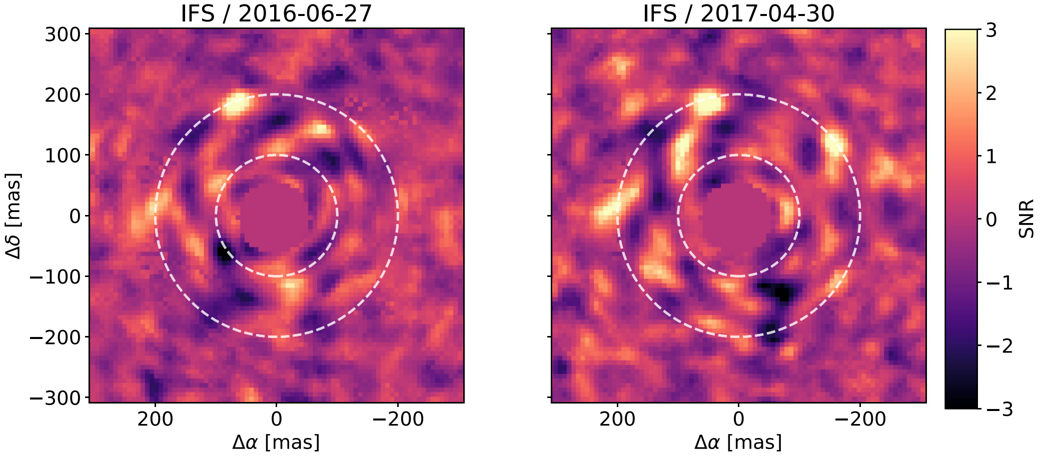

Figure A1. Maps of the S/N of the IFS data from 2016 June 27 (left) and 2017 April 30 (right). The S/N was calculated following the method described in Zurlo et al. (2014). The rings have radii of 100 and 200 mas. The highest signals appear at the same locations as the ones in Fig. 2. North is up and east is left.

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