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THE SYSTEM OF HD169142 SEEN BY SPHERE/VLT

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Abstract. Young stellar objects are perfect targets to unveil the mechanisms of planetary formation. We present new observations of HD169142, a young Herbig Ae star surrounded by a succession of rings. Interestingly, several previous direct imaging observations showed two point-like structures that were interpreted as substellar companions, one of 28 to 80 M_{Jup} at a separation of 110-156 mas, and the other of 8-15 M_{Jup} at 180 mas from the star. We used the high-contrast capabilities of SPHERE/VLT to investigate the nature of these detected companions. Our new observations reveal a bright ring at 180-200 mas, that is confirmed by polarised images. We also show that the companion detected at 180 mas is actually a part of this ring and follows the disk in a Keplerian movement. Finally, we marginally detect a structure at 93 mas from the star that could also correspond to an undiscovered ring in the innermost part of the system.

Keywords: Stars: individual: HD169142, Planets and satellites: detection and formation, Techniques: high angular resolution, Protoplanetary disc

1 Introduction: a complex disc structure

Young stellar objects are adequate laboratories to study planetary formation processes. In particular, transitional discs are interesting because they constitute the intermediate step between gas-rich protoplanetary discs and dusty debris discs. HD169142 is a Herbig Ae star surrounded by a nearly face-on pre-transitional disc. A succession of rings have been detected in this disc with polarimetric observations with NaCo (Quanz et al. 2013), later confirmed by Monnier et al. (2017) with GPI: a ring stands at 20 au*, followed by an annular gap at 32-56 au, the surface brightness smoothly decreasing after 66 au. More interestingly, Biller et al. (2014) detected with NaCo in the L' band a point-like structure of Δmag=6.4$\pm$0.2 at a positional angle (PA) of 0$\pm$14^{o} and a separation ρ=110$\pm$30 mas, that could correspond to a 60-80 M_{Jup} substellar companion. In turn, Reggiani et al. (2014) discovered with the same instrument an emission source of Δmag=6.5$\pm$0.5 at ρ=156$\pm$32 mas and PA=7.4$\pm$1.3^{o}, compatible with a 28-32 M_{Jup} companion. However, none of these detections were confirmed by/in follow-up observations. Biller et al. (2014) detected another point-like structure around HD169142 using the MagAO/MCT in 2013. It is located at ρ=180 mas and PA=33^{o}, and would correspond to a 8-15 M_{Jup} substellar companion, although it was not initially detected in the L' band with NaCo.

We tried to investigate the nature of these point-like detections using SPHERE/VLT instrument. SPHERE has primarily been designed to image and characterise exoplanets, but it is also a powerful instrument for probing the dusty surface of protoplanetary discs. These new observations aim at bringing light to the complex disc structure of HD169142, and are fully described in Ligi et al. (2018).

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*the separations in mas have been converted to au using the Gaia distance, 117 pc (Gaia Collaboration 2016).

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Table 1. Observing log of SPHERE SHINE data for HD169142. A more detailed table is given in Ligi et al. (2018).

UT Date	MJD [day]	Coro-nagraph	Instr. & Band	Exposure time [s]	Field rotation [deg]	Mean seeing ["]
2015-06-07	57180.17	Y	IFS YJ IRDIS $H2H3$	91.7 102.4	45.82	1.57
2015-06-28	57201.12	Y	IFS YJH IRDIS $K1K2$	69.3 85.33	36.42	1.00
2016-04-21	57499.34	Y	IFS YJ IRDIS $H2H3$	82.1 90.67	145.0	1.88
2016-06-27	57566.15	N	IFS YJH IRDIS $K1K2$	64.8 64.22	149.9	0.67
2017-04-30	57873.30	N	IFS YJH IRDIS $K1K2$	61.2 78.10	98.82	0.62

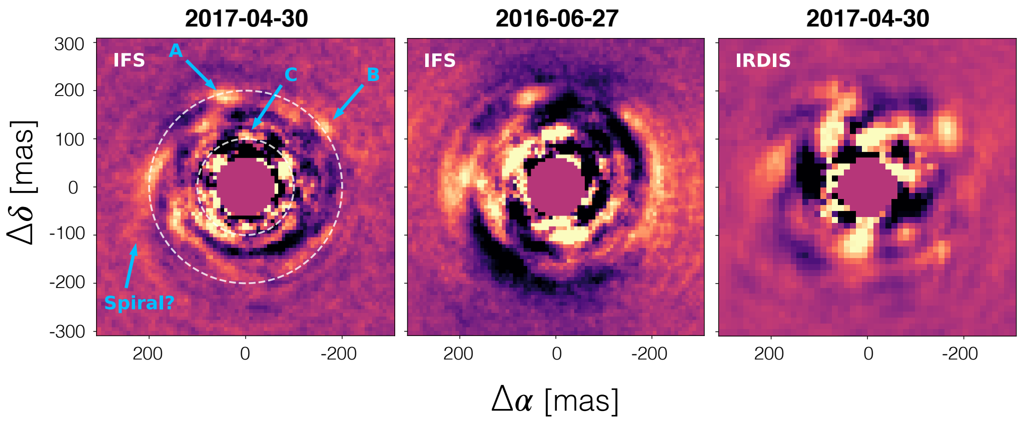

Fig. 1. Results of the PCA analysis in the YJ (left), H (middle) and K (right) bands. For the IFS and IRDIS data, 50 modes were subtracted. The bright structures which we are particularly interested in are indicated with the blue arrows. North is up and East is left.

2 SPHERE/VLT observations and data analysis

2.1 Observations

We performed observations of HD169142 from 2015 to 2017 using SPHERE/VLT with IRDIS and IFS instruments in pupil-stabilised mode in order to enable angular differential imaging (ADI, Marois et al. 2006). These observations were part of the GTO program aimed at detecting and characterising exoplanets using the direct imaging technique. The observations made use of either the `IRDIS` or the `IRDIS_EXT` modes, both with the dual-band imaging mode. For the first observations, a coronagraph was used but not for the two recent ones, in order to image the very inner part of the system of HD169142. A summary of the observations is given in Tab. 1. The data reductions were made using several pipelines in order to check the consistency of the results. We used the LAM-ADI pipeline (Vigan et al. 2015), the SPHERE Data Center pipeline, the `PYPOINT` pipeline (Amara & Quanz 2012) for the IRDIS data only, and the pipeline described in Mesa et al. (2015) (ASDI-PCA algorithm) for the IFS data only.

2.2 Data analysis: PCA and RDI reductions

We analysed the data using the Principal Component Analysis (PCA) and the Reference Differential Imaging (RDI). The first method is based on the formalism described by Soummer et al. (2012). The modes are calculated over the full sequence at separations up to 500 mas, and are subtracted to the total number of modes. The images are then rotated to a common orientation and averaged. The RDI method (Soummer et al. 2014) consists in subtracting one or several reference images to the target image. This allows to subtract speckle patterns

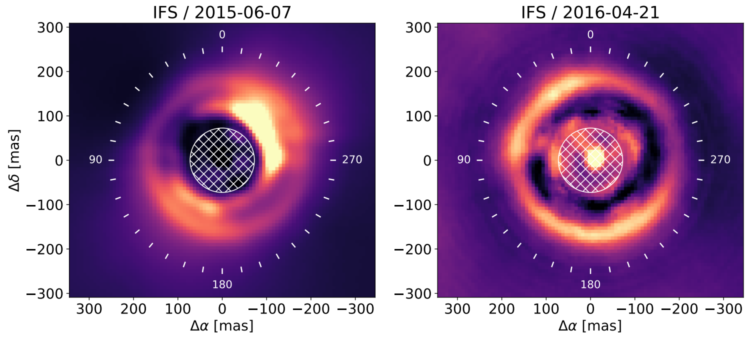

Fig. 2. Results of the RDI analysis of the IFS data. We clearly see en inhomogeneous bright ring at ∼180 mas, and possibly another inner ring. North is up and East is left.

while limiting the self-subtraction effects usually affecting ADI data, in particular for extended structures like discs (e.g. Milli et al. 2012).

With the PCA reduction (Fig. 1), point-like (in particular in the YJ and K bands) and extended (especially in the H band) bright structures appear at 180-200 mas, particularly at PA=20° (structure A), 90° and 310° (structure B). Other structures appear at ∼150 mas (PA=320°) and 100 mas (PA=355°, structure C). In the YJ band, we also see an arm-like structure that looks like a faint spiral in the IFS data. Structures A, B and C are detected at positions close to previous detections of point-like structures (see Sec. 1). We thus try to investigate if the previous and our detections are the same objects.

The RDI reduction (Fig. 2) shows a possible double-ring structure, with one located at ∼180 mas and the other one at ∼100 mas separation. The ring at 180 mas has an inhomogeneous brightness: it is darker at PA∼20°, while several brightness enhancements are visible in the north-west and south-west directions. The inner ring also is homogeneous, with a brighter region in the north-west direction. However, this ring is not detected in each reduction.

3 An inhomogeneous ring at 180 mas

3.1 *Simulationof cADI reduction with PDI data*

Observations of Polarimetric Differential Imaging (PDI) data from 2015 show a bright inhomogeneous ring at ∼180 mas (Fig. 3; see Pohl et al. 2017, for a complete analysis of these data), that is very similar to our detection. Brightness enhancements are particularly obvious at 20°, 90°, 180°, and at a lesser extent at 310°. Interestingly, these are the locations were we find regions of enhanced brightness structures in our IRDIFS PCA images. We also clearly see a cavity inside the ring thanks to the small coronagraph used. We thus try to understand if there is a link between this ring, in one hand, and the point-like detections from our IRDIFS data and the previous NaCo detections, in another hand.

We perform a simulation of ADI reduction using the IRDIS PDI intensity image. First, we create a copy of 1709 images[†] of the PDI image, with each of the images being rotated to match the pupil offset rotation and the PA of the observations. We apply the classical ADI (cADI) reduction to these images, and rotate them back to a common orientation and mean-combine them. We see a strong correlation between the main structures seen in the IRDIFS images using PCA, and the result of this simulation, where 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.

This result shows that the main structures in the IRDIFS reductions and in the simulation have been spatially filtered by the ADI processing. This effect has already been encountered in the study of several objects (HD100456, T Cha, e.g.), and studied by Milli et al. (2012) who show that ADI has a strong impact on the flux and morphology of discs, up to the point of creating artificial features. Moreover, planets are not supposed to emit polarised light, in particular when embedded in a disc because their emission would be too low (Berdyugina et al. 2008, 2011). The consistency between the ring seen in polarized light and our non-

[†]which corresponds to the number of frames after selection using the LAM-ADI pipeline.

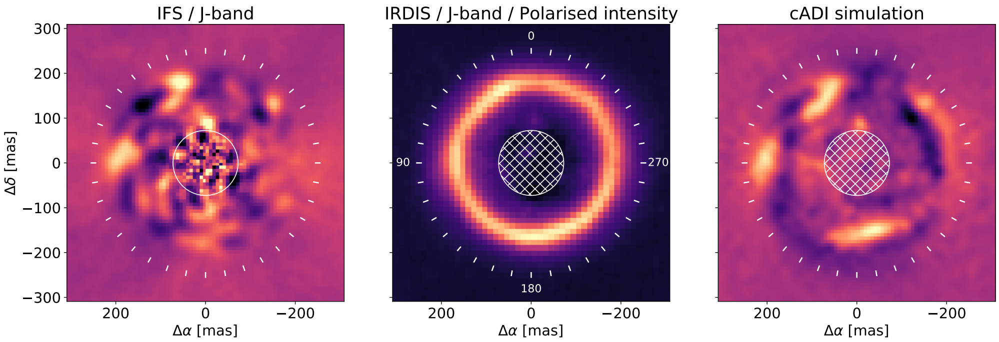

Fig. 3. Left: IFS image in the J band with 50 PCA modes subtracted. Middle: IRDIS PDI polarised intensity image in the J band, which shows a bright irregular ring. Right: Result of a cADI simulation using the polarised intensity image as input. The circular grid at the centre represents the centre star covered by coronagraphic mask in the PDI data. North is up and east is left. See Ligi et al. (2018) for details.

polarised ring indicates that we are observing bright structure tracing a ring and not substellar companions as first suggested by Biller et al. (2014) and Reggiani et al. (2014).

3.2 Keplerian anaysis

To confirm ou statement, we analyse the positions of structures A and B according to the observing period. The object detected by Biller et al. (2014) was at PA=33° and ρ=180 mas. Considering the stellar distance (117 pc, Gaia Collaboration 2016), mass (1.65 $M_\odot$ Blondel & Djie 2006) and inclination of the disc (13±1°, Panić et al. 2008), this object should have an orbital period of 78.5 years if in the disc plane. It should have moved of 13.7° from 2013 June to 2016 June which would bring it to PA=19.3° with a clockwise motion, that is, at a position similar to structure A. Besides, the position of structures A and B as a function of the MJD is consistent with a Keplerian motion in a clockwise direction, while the separation to the parent star remains constant. Thus, the blobs trace the bright ring in the disc, and they rotate in a clockwise direction with a Keplerian velocity. Combining our result with ALMA data (Fedele et al. 2017), we see that the northern part of the disc is moving faster toward us while the southern part is moving slower, with the western side closer to the observer.

3.3 Origins of the blobs

The nature of the detected blobs remains to be investigated. However, two hypothesis seem compatible with our observations. The first possibility invokes intrinsic disc variations in density and temperature. The dust concentration might trace the maximum density in the gas profile, that could trigger the formation of vortices by the Rossby wave instability. Since these vortices could be favourable places to initiate planet formation (Barge & Sommeria 1995), HD169142 could be the site of on-going planet formation at an earlier stage than previously expected. However, SPHERE images only show the surface of discs, thus we cannot confirm that our blobs have the spatial extend of vortices. Moreover, ALMA data, that trace the mid-plane layer of the disc, would not be able to resolve the structures we detect at this scale.

The second hypothesis concerns illumination variations because of azimuthally asymmetric optical depth variations through an inner disc closer to the star. Pohl et al. (2017) found azimuthal variations of 25% at 180 mas that could be caused by such effects. Moreover, the inner disc at ∼0.3 present a variable SED. However, this hypothesis would be difficult to prove since the Keplerian movement that we found is not consistent with an origin from the inner structure of the disc.

4 A point-like structure at 100 mas?

Another structure in the disc draws attention: structure C, located at PA≈ 4° and ρ=105±6 mas. Indeed, its locations is close to that of the object detected by Biller et al. (2014) and is slightly offset but consistent with that of the object detected by Reggiani et al. (2014). While our detection seems robust when using the ASDI-PCA algorithm and the LAM-ADI pipeline, it is only marginally detected using the `PYNPOINT` pipeline.

Structure C appears quite extended in the H and K bands, whereas it appears point-like in the NaCo images. It also is detected in the PDI images, which means that it is light scattered by dust rather than emission from a planet photosphere. When considering the effect of a cADI reduction to a disc (see Sec. 3.1), we can consider that our detection is actually a yet undiscovered ring whose azimuthal component has been spatially filtered. The RDI images seem consistent with this assumption, althought we cannot verify it. Additional observations in polarised light without a coronagraph would bring a precious assess to understand this structure.

5 Conclusion

We used the SPHERE/VLT instrument to investigate the innermost parts of the system of HD169142. We found several interesting results:

- we detected several blobs at 180-200 mas separation from the star using the PCA algorithm. Comparing these detections to RDI and PDI images, that both show a bright ring at 180 mas, we find that these blobs are part of this ring. It is confirmed by the fact that we detect polarised (PDI) and scattered (IRDIFS) light from the dust at the surface of the disc, which is more compatible to disc structure than to planetary companions in formation. These blobs could be precursors of Rossby vortices, or (even if less plausible), the results of illumination variations from an inner disc.
- Analysing the movement of several blobs (structures A and B), we show that they follow a Keplerian motion, and thus trace the bright ring in the disc. Combining this result with ALMA data results leads to a better comprehension of its position, that is, the western-side is closer to us and the northern part is moving faster toward us.
- We also marginally detect a bright structure at PA$\approx 4^\circ$ and ρ=105$\pm$6 mas, which is also visible in the polarised data. This structure could be a part of a yet undetected disc, that would have been filtered out by the ADI reduction.

Additional observations of HD169142 would certainly help better understanding the system of HD169142.

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References

Amara, A. & Quanz, S. P. 2012, MNRAS, 427, 948
Barge, P. & Sommeria, J. 1995, A&A, 295, L1
Berdyugina, S. V., Berdyugin, A. V., Fluri, D. M., & Piirola, V. 2008, ApJ, 673, L83
Berdyugina, S. V., Berdyugin, A. V., Fluri, D. M., & Piirola, V. 2011, ApJ, 728, L6
Biller, B. A., Males, J., Rodigas, T., et al. 2014, ApJ, 792, L22
Blondel, P. F. C. & Djie, H. R. E. T. A. 2006, A&A, 456, 1045
Fedele, D., Carney, M., Hogerheijde, M. R., et al. 2017, A&A, 600, A72
Gaia Collaboration. 2016, VizieR Online Data Catalog, 1337
Ligi, R., Vigan, A., Gratton, R., et al. 2018, MNRAS, 473, 1774
Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, ApJ, 641, 556
Mesa, D., Gratton, R., Zurlo, A., et al. 2015, A&A, 576, A121
Milli, J., Mouillet, D., Lagrange, A.-M., et al. 2012, A&A, 545, A111
Monnier, J. D., Harries, T. J., Aarnio, A., et al. 2017, ApJ, 838, 20
Panić, O., Hogerheijde, M. R., Wilner, D., & Qi, C. 2008, A&A, 491, 219
Pohl, A., Benisty, M., Pinilla, P., et al. 2017, ApJ, 850, 52
Quanz, S. P., Avenhaus, H., Buenzli, E., et al. 2013, ApJ, 766, L2
Reggiani, M., Quanz, S. P., Meyer, M. R., et al. 2014, ApJ, 792, L23
Soummer, R., Perrin, M. D., Pueyo, L., et al. 2014, ApJ, 786, L23
Soummer, R., Pueyo, L., & Larkin, J. 2012, ApJ, 755, L28
Vigan, A., Gry, C., Salter, G., et al. 2015, MNRAS, 454, 129