Origins: From the Protosun to the First Steps of Life
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Planet-disk interactions in HD 169142? Tracing ellipticity, structures, and offsets

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Abstract. In Bertrang *et al.* (2018), we present new data of the protoplanetary disk surrounding the Herbig Ae/Be star HD 169142 obtained in the very broad-band (VBB) with the Zurich imaging polarimeter (ZIMPOL), a subsystem of the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) at the Very Large Telescope (VLT). Our Polarimetric Differential Imaging (PDI) observations probe the disk as close as $0.''03$ (3.5 au) to the star and are able to trace the disk out to $\sim 1.''08$ (~ 126 au). We find an inner hole, a bright ring bearing substructures around $0.''18$ (21 au), and an elliptically shaped gap stretching from $0.''25$ to $0.''47$ ($29 - 55$ au). Outside of $0.''47$, the surface brightness drops off, discontinued only by a narrow annular brightness minimum at $\sim 0.''63 - 0.''74$ ($74 - 87$ au). These observations confirm features found in less-well resolved data as well as reveal yet undetected indications for planet-disk interactions, such as small-scale structures, star-disk offsets, and potentially moving shadows.

Keywords. (stars:) planetary systems: protoplanetary disks, hydrodynamics, polarization, radiative transfer, scattering, methods: numerical, techniques: high angular resolution, techniques: polarimetric, magnetic fields

1. Introduction

Circumstellar disks around young stars are the key to understand star and planet formation (e.g., Williams & Cieza 2011). However, due to new high-contrast and high-sensitivity instruments, the study of star and planet formation is undergoing a rapid change with new spectacular observations of structures in protoplanetary disks such as gaps (e.g., Quanz *et al.* 2013), spirals, and sub-structures that appear in the scattered light (e.g., Avenhaus *et al.* 2017, 2018), where observations at long wavelengths reveal signs of dust traps (e.g., Long *et al.* 2018). These recent observations provide a glimpse at a sophisticated picture of disk evolution and dispersal, which in turn regulates the origin of planetary systems. In this work, we present new observations at unprecedented spatial resolution observed as well as a new model of the protoplanetary disks HD 169142.

2. Overview

We present PDI observations on unprecedented spatial resolution of the circumstellar disks around the Herbig Ae/Be star HD 169142 obtained with SPHERE/ZIMPOL (Fig. 1). Our analysis of the data reveal an intrinsically elliptical geometry (Fig. 2), small-scale substructures (Fig. 3), and potentially moving shadows in this disk (Fig. 3). We deepen our analysis by applying radiative transfer simulations and find a new model description for HD 169142: a flat disk. The features we detect in this object are indicative for planet-disk interactions and consistent with a set of 3 planets as shown by our hydrodynamical simulations (Fig. 4).

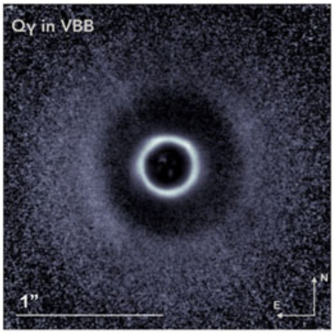

Figure 1. The gap which separates the bright inner ring from the outer disk is of elliptical shape [and not annular, as it was described before in Quanz *et al.* (2013)]. It can be explained by a circular outer disk which is observed under an inclination of 13°. We find that both the inner ring and the outer disk are offset relative to the central star. Our radiative transfer model shows that the residual scattered light detected inside the gap is indeed a consequence of the convolution with the PSF. Our model supports a gap devoid of any dust (Bertrang *et al.* 2018).

3. Implications

Intrinsically elliptical disk geometry.

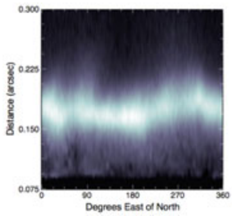

Figure 2. Surface brightness distribution of the inner ring. **Puzzling about the inner ring is the inclination of the disk of 13° - why is the ring appearing as a ring?** In an in-depth analysis, we find that the double-dip structure of the surface brightness distribution strongly indicates an intrinsically elliptical shape of the inner "ring", to our knowledge, the first of its kind - an actual ring would dip only once (Bertrang *et al.* 2018). A later finding in MWC758 (Dong *et al.* 2013) presents another case of this dust geometry which generally points strongly towards planet-disk interactions.

Moving shadows and substructures in the inner ring.

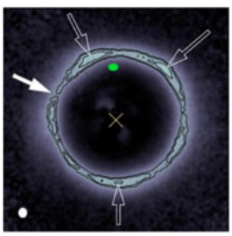

Figure 3. The bright inner ring reveals clear substructures, indicative of interactions with the (proto)planetary candidate (green ellipse). Additionally, observations with SPHERE/ZIMPOL in P95 (Bertrang *et al.* 2018) and with NACO in P89 (Quanz *et al.* 2013) reveal a dip in the surface brightness in the inner ring of HD 169142, at 50° (filled white arrow; P95) and 80° (P89), respectively. If this is the same dip then its angular velocity is ∼ 16 km/s. A likely explanation is a giant planet or a brown dwarf which is surrounded by a small accretion disk, located at 6 au from the central star.

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The new model: Flat disk with intrinsically elliptical shape and three planets.

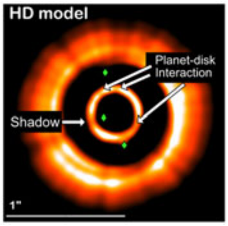

Figure 4. The new model, a flat disk, fits all, the SED, as well as the spatially resolved SPHERE/ZIMPOL and ALMA data very well (Bertrang *et al.* 2018). Our model contains one planet (10 M_J) at 15 au, and two planets (each 1 M_J) at 35 au, resp. 45 au (green diamonds). We find that the innermost planet casts a shadow on the inner ring, while the two outer planets create density bumps in the inner ring due to gravitational interaction. Also the offsets and the intrinsically elliptical shape we find in the data are explained by the planet-disk interactions in our model.

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