High-contrast imaging of protoplanetary disks

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Chapter 8

English summary

8.1 The formation of solar systems

To study how planetary systems such as our Solar system come into existence we can choose to study the current state of our Solar system and derive theories on its history; or we can study much younger systems still in formation. The 18th century German philosopher Immanuel Kant did the former and devised his "Nebular Theory" based only on two simple observations: 1) The planets orbit the Sun within a single plane and in a single direction; 2) The space between the planets is predominantly empty. Since the latter observation of empty space apparently excludes a currently existing mechanism causing the alignment of the orbits, such a mechanism must have acted in the past. Kant suggests that during the early stages of our Solar system, space must have been filled with gas and dust, initially in a three-dimensional nebula. The gas and dust in this cloud, which form the building blocks for the current bodies (e.g., planets, comets) in our Solar system quickly flatten to form a disk around a dense core. This core will grow in mass by attracting (or *accreting*) matter from the disk to eventually grow into our Sun, while in other parts of the disk clumps grow to form the current planets.

It is surprising to see how closely Kant's Nebular Theory agrees with our current understanding of the formation of planetary systems, although the latter is mainly based on observations of stars (of mass similar to our Sun) in the early stages of their formation. Giant molecular clouds comprised of gas and dust collapse to grow globules, within which dense cores contract to become protostars. While disks form around these protostars, the latter become so luminous that their radiation clears the surrounding cloud near the poles of the protostars (perpendicular to the disks). As soon as the surrounding nebula is completely dispersed or accreted onto the disk, the star becomes visible at optical wavelengths and is now called a *pre-main sequence star*. Initially, the disk surrounding the young star is filled with gas and small dust grains. It is during this phase when we expect the giant planets (e.g., Jupiter, Saturn, Neptune, Uranus) to form because they are thought to accrete their massive gaseous envelopes at the final stages of their formation. Therefore, these gas-rich disks are called *protoplanetary disks*.

While the dust grains within protoplanetary disks grow to ever-larger sizes, the large-scale shape of these disks will be altered by various processes such as the disturbance caused by the presence of forming planets, inside out clearing (*photoevaporation*) due to radiation coming from the central star, and trapping of large dust particles at pressure maxima in the gas disk. Eventually, the original small dust grains and the gas will be completely cleared by the stellar radiation and small dust will only exist as debris, resulting from collisions of larger bodies. Therefore disks in the final stage of their evolution are called *debris disks*. During the time remaining for the star to reach "adulthood" (*main-sequence*, where nuclear fusion of hydrogen into helium at the stellar core becomes the star's dominant source of energy) most of the debris clears and a planetary system remains.

In this thesis, I study large-scale structures in protoplanetary disks through *high-contrast imaging* of the scattering surfaces of these disks. To observe these disks at optical wavelengths, we need to take into account that the central star is much brighter than the (star)light reflected by the disk surface: there is a high contrast between light originating from the star and that from the disk. Additionally, light coming from the star & disk is disturbed by the Earth's atmosphere. Therefore, specialized high-contrast imaging instruments are required to correct for atmospheric disturbance of the stellar light (using *adaptive optics*) in order to allow the highest possible spatial resolution and contrast between the star and its nearby surroundings. Improving the understanding of high-contrast imagers will allow for a better interpretation of the data recorded with these instruments. The interpretation of disk structures detected at high spatial resolution forms a crucial step in our understanding of the general principles that govern disk evolution and planet formation. My contribution to the field of planet formation is twofold: I determined specific key disk properties by directly imaging disks, and I calibrated two high-contrast imagers. The resulting enhancement in our understanding of the instrumentation is a crucial step to perform high-accuracy measurements required to constrain the more degenerate disk properties, such as the dust grain size distribution.

Chapters 2, 3 & 4 of this thesis describe VLT/SPHERE observations of protoplanetary disks around the stars BP Psc, J1604, and RX J1615, respectively. In these chapters, I determine disk properties (such as variability, the large-scale disk shape and the height of the scattering surface) and have discovered new features (e.g., disk rings and companion candidates) that are instrumental to further our understanding of protoplanetary disk evolution. Chapters 5 & 6 discuss the calibration of the polarimetric modes of two high-contrast imagers installed at the Very Large Telescope (VLT) at Cerro Paranal in Chile: The NAOS/CONICA (VLT/NACO) instrument and the Spectro-Polarimetric High-Contrast Exoplanet REsearch (VLT/SPHERE) instrument.

8.2 This thesis: High-contrast imaging of protoplanetary disks

BP Piscium: its flaring disk imaged with SPHERE/ZIMPOL. Although initially classified as a young (pre-main sequence) star surrounded by a protoplanetary disk, the age and evolutionary stage of BP Piscium (BP Psc) have been a topic of debate. It is either one of the nearest young stars of low-mass (T Tauri star of 10 million years old at ~ 80 parsec = 260 light-year) or it is an old (few billion years) post-main sequence star that has just finished burning hydrogen at its core and started expanding its envelope to become a *red giant*. If it is indeed an old star, which would be much brighter and therefore at a larger distance (~ 300 parsec), it would be the first at this evolutionary stage for which a surrounding disk is detected.

We have observed this system with SPHERE/ZIMPOL and succeeded at directly imaging the circumstellar disk. Because the disk is seen nearly edge-on, we detect clear signs of a strong flaring (rapidly expanding disk height for increasing radius). Our radiative transfer modeling of the system confirm an exceptionally large amount of flaring for the small (micron-sized) grains, while the disk made of larger (~ mm-sized) grains must be much flatter. These characteristics are so a-typical for a disk around a young star that we conclude that the star is most likely an old (hydrogen-shell burning) giant.

Variability and dust filtration in the transition disk J160421.7-213028 observed in optical scattered light. Transition disks are protoplanetary disks that show signs of large cavities in their innermost regions (i.e., close to the star). They derive their name from the assumption that they are in transition between the gas-rich protoplanetary and gas-depleted debris disk phase. The best-studied members of the small sample of transition disks are all rich in large-scale disk features, such as spiral arms, rings and large cavities.

We observed J160421.7-213028 (J1604) in visible light with SPHERE/ZIMPOL to search for previously undetected disk structures and to compare our observations with images recorded at different wavelengths. We detect a single ring in the disk with a large inner cavity of ~ 40 astronomical units (au = distance between Earth and the Sun).

We detected the disk surface brightness peak at 61 au from the star, which is 20 au closer than previous sub-mm observations have shown. We interpret this discrepancy as dust filtration: a spatial separation between the mm-sized grains (residing near a maximum in the gas-pressure) and the micron-sized grains (following the general distribution of the gas). Previous near-infrared images observed three years earlier displayed a strong dip (local decrease in surface brightness) at the eastern side of the disk, while our images contain a similar dip in the north-east. Such rapid variation cannot be explained with the orbital motion of a locally decreased surface density in the outer disk. Therefore, we conclude that the dip is caused by an object closer to the star that casts a shadow on the outer disk. This shadow-casting object could be a warp in a yet unresolved inner disk or a planet surrounded by circumplanetary material, in either case residing within ~ 9.6 au from the star.

Multiple rings in the transition disk and companion candidates around RX J1615.3-3255. Due to the massive gaseous envelopes of giant planets we expect these planets to form while the circumstellar disk still contains enough gas to accrete. Because disk only contain enough gas for this process until the end of the protoplanetary phase, we are most likely to find traces of interactions between massive planets and their native disk during the final stages of this phase, i.e., in transition disks.

To search for such traces of planet-disk interaction we imaged the transition disk around RX J1615.3-3255 (RX J1615) with multiple observing modes of SPHERE, using ZIMPOL, IRDIS & IFS. This disk, which had not previously been imaged in the optical regime, was clearly detected in all observing modes and displayed multiple elliptical rings. Furthermore, we have detected nine point sources near the star, outside the disk, which we consider as companion candidates. In archival NACO data we also find four of the nine point sources and determine that these are not co-moving with the central star. Therefore these four point sources are considered to be background objects, not associated with the RX J1615 system.

Compared to the position of the star, the elliptical rings in the disk are offset along the minor axes of the ellipses. We explain the ellipticity and the offset as a consequence of the inclination (47°) with which we observe the disk. The ellipticity is caused by the projection of circular structures seen at this inclination, while the offsets of the ellipses with respect to the star-center can be explained with a significant disk-height above the disk mid-plane (the same plane in which the star resides), because we detect the scattering surface of the disk. Our images allowed to perform the first-ever model-independent determination of the height of the disk's scattering surface, which does not appear to be increasing more rapidly than the disk radius (i.e., no flaring). Furthermore, we propose two explanations for the presence of the outermost arc: it is either part of a full new ring or it is the bottom side of the ring detected directly inward of the arc. To allow for the bottom of a ring to be detected requires truncation of the disk outside this ring, otherwise it would block the light coming from the bottom side of the ring. We speculate that this truncation can be due to the presence of a (planetary) companion orbiting close to the outer edge of the disk. The innermost companion candidate, for which we do not yet know whether it is gravitationally bound to the RX J1615 system, could be responsible for this truncation of the disk.

Characterizing instrumental effects on polarization at a Nasmyth focus using NACO. To better understand the polarimetric behavior of high-contrast imagers, I devised a calibration scheme for the polarimetric imaging mode of VLT/NACO. Using Sunlight reflected in the Earth's atmosphere at zenith as a polarized calibration source, I have determined the change in the measured degree of polarization due to changing telescope and instrument setup. Rotating a component of the instrument with 90° allows us to disentangle the various undesired instrumental contributions to the measured polarization downstream of this component. By subsequently rotating the half-wave retarder plate (HWP) inside NACO, the entire instrument itself on the derotator flange with which it is attached to the telescope, and finally the full telescope in azimuthal direction, we can distinguish between instrumental contributions of the optical components in-between these rotating segments.

Characterizing the polarimetric imaging mode of SPHERE/IRDIS. After the commissioning of VLT/SPHERE, we have used the experience gained with the NACO calibrations to characterize the polarimetric imaging mode of SPHERE's near-infrared imager: the InfraRed Dual-beam Imager and Spectrograph (SPHERE/IRDIS). We have used the internal calibration light-source and an unpolarized standard star to separately characterize the polarization properties of the telescope mirrors (mainly the third: M3), the first mirror in SPHERE (M4), the HWP, and the "K"-shaped mirror used for derotating the images (derotator). For the four available broad-band filters we determined the full (4x4) Mueller matrices, describing the polarimetric response of each of these telescope/instrument components. Particularly striking is that the polarimetric efficiency can get below 10 % in the H and K-band filters when the derotator is oriented in an unfavorable position. Therefore, this study allows us to make strong recommendations for the observing strategy to be used in these filters. By inverting the combined Mueller matrices for the entire telescope & instrument we can correct for the instrumental contribution to on-sky polarimetric observations, which we illustrate by correcting the protoplanetary disk observations of TW Hya. These instrument-model corrections are necessary to determine the true polarization angle and polarized surface brightness of the disk.

8.3 Final notes

In this thesis, I illustrate the capacity of VLT/SPHERE to study protoplanetary disks at high spatial resolution. Detailed knowledge of the scattering surfaces of disks has proven to be instrumental in our general understanding of these disks. Our work on the calibration of the polarimetric mode of SPHERE/IRDIS has opened a new window of highly accurate polarimetric measurements. From this high accuracy, not only the study of protoplanetary disks will benefit, but any field that requires spatially resolved polarimetric measurements, such as studying the dusty surroundings of evolved stars, Solar system bodies (e.g., comets and moons) and the characterization of the atmospheres of exoplanets and their circumplanetary disks.