The Evolution of Circumstellar Disks: Lessons from the VLT and ISO

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Abstract. There is strong evidence that the planets in the solar system evolved from a disk-shaped solar nebula \(\approx 4.56\) Gyr ago. By studying young stars in various evolutionary stages, one aims at tracing back the early history of the solar system, in particular the timescales for disk dissipation and for the formation of planetary systems. We used the VLT & ISAAC, and ESA’s Infrared Space Observatory & ISOCA M to study the circumstellar environment of young low-mass stars.

1 Disk-Origin of the Solar System

The coplanarity of planetary orbits and their moons, and the preferentially prograde rotation direction led\textsuperscript{[14,17]} to the conclusion that the solar system evolved out of a flattened disk. Meteoritic evidence from Carbonaceous Chondrites suggests that the Solar System formed 4.56 Gyr ago within a time span of \(\leq 10\) Myr. Studies of circumstellar disks around young stars aim at establishing the initial conditions and the exact sequence of events leading to the formation of giant and terrestrial planets in the solar system.

2 How to find Circumstellar Disks?

Until the late 20th century, the existence of circumstellar disks around young stars could only be deduced indirectly. IR and UV excess from young stars were interpreted as disk and accretion signatures\textsuperscript{[19,1]}. Submm and mm measurements provided the first estimates on disk masses and disk lifetimes\textsuperscript{[2,13]}. Measurements of the frequency of IR excess, in particular L-band excess of stars in young clusters reveal that up to 100\% of all young (\(\leq 1\) Myr) stars show evidence for circumstellar disks\textsuperscript{[12]}. Physical Parameters of star-disk systems were determined from their spectral energy distribution (SED) and the comparison to models\textsuperscript{[8]}. Unfortunately, solutions derived from this SED fitting turned out to be not necessarily unique\textsuperscript{[15]}. This highlights the need for spatially resolved observations. The size of the
solar system is $\approx 100$ A.U., which corresponds to $\leq 1''$ at the distance of the nearest star forming regions. Thus high-spatial resolution observations are required. We used VLT/ISAAC [21], complemented by high-sensitivity ISO/ISOCAM [10] observations for our studies.

3 High-resolution ANTU/ISAAC survey for edge-on disks

The main observational difficulty in identifying circumstellar disks in the visual and near-infrared is that they are typically $10^6$ times fainter than the central star. Circumstellar disks have been detected and spatially resolved in the Orion HII region as dark silhouettes seen against the bright background [20]. Another possibility to detect disks is if they are oriented close to edge-on (within $5^\circ$ to $10^\circ$) and hence act as natural occulting bars, which block out star light [28, 25].

![Fig. 1. Top: Edge-on circumstellar disk sources in Ophiuchus detected with VLT/ISAAC. In comparison to isolated disks in Taurus (bottom, shown as observed with HST/NICMOS), the Ophiuchus disks and their reflection nebulosities are more compact. For the disk sources in the Ophiuchus region, North is up and East is to the left.](image)
With the aim to establish a sample of edge-on circumstellar disk sources, which is suitable for detailed follow-up studies with VLT, VLTI and ALMA, we employed VLT & ISAAC to observe southern Class I IRAS sources associated with faint nebulosities in the optical or NIR.

16 sources were observed with ANTU & ISAAC in JHKs in April 1999 under 0.35″ seeing conditions, which corresponds to a spatial resolution of 50 A.U. at a distance of 140 pc, i.e., comparable to the radius of the Kuiper Belt. The central dark lane in the Chamaeleon IR Nebula is for the first time nicely resolved [29]. Furthermore, two disks seen close to edge-on could be identified in the ρ Oph star forming region (Figure 1, [6]). Disk 1 (OphE-MM3) was previously classified as a starless core or isothermal protostar [22]. It is located 50″ west and north 10″ of Elias 2-29 – one of the most prominent and most luminous IR sources in Oph. Disk 2 (CRBR 2422.8−3423), which was originally identified as an IR source by [11], is located 30″ west and 10″ south of WLY 2-43.

**Fig. 2.** Spectral energy distribution of CRBR 2422.8−3423 (disk 2) and HH 30. Both sources exhibit about the same flux at 2.2 μm and 1.3 mm. The slightly larger inclination of CRBR 2422.8−3423’s disk allows the warm, inner disk to become detectable at NIR to MIR wavelengths. The dip at 9.6 μm can be explained by absorption due to the silicate feature. The spectral energy distribution of HH 30, whose disk is seen closer to edge-on than in the case of CRBR 2422.8−3423, is dominated by scattered light out to wavelengths of 10 μm.

The mm measurements by [22] yield disk masses of ≈0.01 M⊙, which is also the mass of the “minimum solar nebula” [9]. The disks in the ρ Oph region
appear to be more compact (100 A.U. × 40 A.U.) than the majority of edge-on disks in Taurus. Due to the prevalence of forward scattering, the brightness ratio of the two parts of the bipolar reflection nebulosity in each disk directly yields information on the disk inclination. Disk 1, which in the NIR is also the fainter of the two disks, is seen closer to edge-on than disk 2 (inclination angle 85° vs. 75°).

ISOCAM observations between 3 µm and 12 µm of disk 2 (inclination ≈ 75°), and of the edge-on disk source HH 30 (inclination ≥ 80°) confirm theoretical predictions that a slight change in the viewing angle of a disk leads to a dramatic difference in the spectral energy distribution of YSOs [4,26]. HH 30 and disk 2 have about the same integrated brightness in K and exhibit the same 1.3 mm continuum flux. The SED of disk 2 is steeply rising between 2.2 µm and 6.0 µm, and a silicate absorption feature is visible at 9.6 µm. The SED of HH 30 is rather flat, and appears to be dominated by scattered light out to a wavelength of 10 µm [27].

4 How long do disks survive?

Disk survival times and the sequence of events leading to the formation of planetary systems are closely linked. Giant planets in the solar system possess a core of higher density material surrounded by a shell of metallic hydrogen and an outer atmosphere. According to one model, a higher density (rocky) core with a mass of ≈10 M⊕ has to form first, before noticeable amounts of nebular gas can be accreted by the proto-giant planet. Simulations indicate that at least 10⁶ yr are necessary to form a 10 M⊕ rocky core [18], and that another 10⁷ yr are required for the 10 M⊕ core to accrete 300 M⊕ of nebular gas. It is still unknown if massive circumstellar disks can indeed survive for such an extended period. A second model, recently reinstated by [5], suggests that gravitational instability of a protoplanetary disk leads directly to the formation of a giant gaseous protoplanet on time scales as short as 10³ yr. The rocky core then forms due to the settling of dust grains initially acquired, and by further accretion of solid bodies in the course of the subsequential 10⁵ yr. The difference in timescales for the formation of giant planets in the two models provides observational means to decide for or against either model by studying the circumstellar environment of stars with ages ≤ 15 Myr.

A sub-mm study of Lindroos binaries with ages between 3 and 150 Myr indicates that dust depletion in circumstellar disks occurs within the first 10 Myr [13]. Similarly, the percentage of sources with near-infrared and L-band excess in young clusters drops sharply within the first ~ 6 Myr (e.g., [12]).

Is this the same period, which defines the “birth” of the Solar System 4.56 Gyr ago? Do dust and gaseous disk components vanish within 5 to 10 Myr? This would imply a potential timescale problem for the formation of giant planets.

ISO studies of nearby star forming regions with ages of the order of 1 Myr to 10 Myr also suggest a gradual decrease of the amount of circumstellar material
Fig. 3. Color-magnitude diagram based on ISOCAM observations of young stars in Chamaeleon (circles) and Scorpius-Centaurus (squares). Black filled circles indicate previously known Young Stellar Objects and classical T Tauri stars (CTTS), circles with a central dot previously known weak-line T Tauri stars (WTTS), and open circles new sources detected with ISO by [23]. The dashed line indicates the location of pure stellar photospheres, the dotted and solid line the location of flat and flared circumstellar disks, respectively, as predicted by the models from [16]. Post-T Tauri stars in Scorpius-Centaurus show a spectral index intermediate between main-sequence stars and CTTS and WTTS in Chamaeleon [7].

(Figure 3), in particular a depletion of smaller size dust grains, as stars evolve towards the main-sequence [23, 24, 7]. The diminished infrared excess can be explained by disk dissipation or by changes in the global dust opacities due to, e.g., grain growth on timescales of 5 to 15 Myr.

5 Outlook

Detailed images of the distribution of scattered light and polarization maps can now be obtained with adaptive optics systems at 8m class telescopes (e.g., Hokup'a & QUIRC at Gemini, and NAOS & CONICA at VLT). The diffraction limit of 50mas in the H-band corresponds to <8 A.U. at a distance of 150 pc, thus the inner regions of circumstellar disks (and potential “protoplanetary systems”) become resolvable. In particular dual imaging methods using a Wollaston
prism (in order to eliminate speckle noise from unpolarized light) appear to be predestinated for these kinds of studies. Detailed polarization maps combined with refined theoretical models will enable us to determine physical properties of young disks, such as disk geometry, density structure, or dust properties.

High-spectral resolution studies in the infrared (e.g., with CRIRES at VLT), CRIRES, could probe and (weigh in) the gaseous disks around the post-T Tauri stars by searching for H$_2$ features seen in absorption against the stellar photosphere. This should provide additional information on the dispersal time scales for (gaseous) disks and the formation time scales of giant planets.

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