Disks and planetary forming regions as seen by mm/submm interferometers

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Abstract.
Until the last fifteen years, the origin of planetary systems was mostly investigated from observations and modelling of our own Solar System. However, the new generation of large interferometers, is slowly but surely changing this. In particular, observations of circumstellar gas and dust around young stars similar to the Sun in its infancy are now routinely provided by millimeter and submillimeter arrays with angular resolution corresponding to \( \text{fbYcbb} \) at the distance of the nearest star forming regions (e.g. Taurus-Auriga). Waiting for ALMA, these upgraded instruments provide invaluable information inside the regions of young disks where planets should form. I briefly discuss here their contribution to this scientific domain which is quickly evolving. I will present several well-known objects such as HH30 or AB Auriga in order to emphasize the input of mm/submm arrays but also to demonstrate that multi-wavelength approaches remain necessary to trace the dust and gas material from the inner disk to the outer disk.

1. Introduction
Disks orbiting young Pre-Main-Sequence (PMS) low mass stars are dust and gas residual from the molecular core which has formed the central young star. With total masses (gas + dust) ranging from \( \sim 0.001 \) to a few 0.1 \( M_\odot \), most of these disks contain enough gas (H\(_2\)) to allow, in theory, the formation of a giant planet and they are often called “protoplanetary disks”. Large optical telescopes provide images of the disk where the small dust grains scatter the impinging stellar light, the dust opacity in the IR and optical being very high, only the disk surface is visible. However, for edge-on disks, these images reveal that the disks are flaring, as expected from the theory of disks in hydrostatic equilibrium. Contrary to the optical/IR, the dust emission in the millimetre/submillimetre domain is mostly optically thin, providing constraints on the dust mass. Molecular hydrogen is, by far, the major constituent of disk (the dust-to-gas ratio is usually assumed to be \( \sim 100 \)) but remains difficult to observe essentially because it does not possess a dipolar rotational spectrum. Its quadrupolar rotational lines, in the MID-IR domain, mostly trace material at hot/warm temperature at the disk surface close to the star and do not sample the bulk of the cold gas located along the mid-plane. After H\(_2\), carbon monoxide is the most abundant molecule (with abundance CO/H\(_2\) of order \( \sim 10^{-4} - 10^{-6} \)). Spectro-imaging of the CO gas provided by mm/submm arrays has shown that protoplanetary disks are in Keplerian rotation around their central star and that disks can be as large as 500-800 AU, in radius. At the distance of the closest star forming regions (D~ 150 pc), the angular radii of these disks are

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usually within the range $1 - 3''$ or 150-450 AU. However, being mostly heated by the central star, their spectral energy distribution is such that the apparent angular size drops very fast when the observing wavelength goes from the millimeter domain to the optical one. Typically the apparent radius of the thermal emission of a hot dust disk at 10$\mu$m would not exceed a few AU or $\sim 0.1''$ while it would be around $1 - 2''$ at $\lambda = 1$ mm.

One can observationally distinguish three parts in disks. The very inner disk, located close to its inner radius, is extending up to radius of $\sim 1 - 3$ AU and is only resolved by optical and IR interferometry. The inner disk is extending up to a radius of $\sim 30$ AU and would somewhat correspond in our system to the inner solar system, located up to the first Kuiper Belt objects. The outer disk extending from $\sim 30$ AU to the outer radius corresponds to the relatively cold ($\sim 10 - 50$ K) large dust and gas disk usually traced by CO rotation line emission and observed by current millimeter and sub-millimeter interferometers such as the IRAM array, the SMA or CARMA. Thanks to its large collecting area, the submm array ALMA which is currently in construction in Chili will allow observers to image inner disks up to a few AUs from the central stars.

In this talk, I will mostly review recent results obtained with the IRAM array. Section 2 is dedicated to observations of cold gas and Section 3 deals with the dust disk properties traced by observations from mm/submm arrays. Section 4 presents several detailed studies of the AB Aurigae circumstellar dust and gas, a prototype of the Herbig Ae stars. I will then conclude in Section 5.

2. Observing Molecular Lines in Disks

The lowest rotation lines of CO are observable with current mm/submm arrays allowing to trace the outer gas disk properties. Moreover, since the density in disks is very high ($n(\text{H}_2) > 10^6$ cm$^{-3}$), the $J=1-0$ and $J=2-1$ CO lines are thermalized by collisions with $\text{H}_2$ in almost the whole disk. In most cases, a simple model of rotating disk assuming LTE conditions is sufficient to retrieve the CO disk properties (Dutrey et al 1994). There also exists some studies of other molecules than CO but these are sensitivity limited.

2.1. CO lines

CO maps not only reveal that disks are in Keplerian rotation around TTauri (Koerner et al 1993) and Herbig Ae stars (Piétu et al 2003), they also allow us to retrieve the physical conditions in outer disks.

Fig.1, from Simon et al 2000, shows examples of channel maps from the CO emission ($J=2-1$ transition) of disks orbiting young TTauri and Herbig Ae stars. In all cases, the CO velocity gradients are compatible with rotation since the observed velocity gradients (bottom panels) are along the major axis of the disks. These data can be modeled in order to determine the radial and vertical distributions of the density and of the temperature. This is possible provided the analysis properly takes into account the transfer function of the interferometer (Guilloteau & Dutrey 98, Dutrey et al 2007). The comparison between the CO data and the disk model is then performed inside the visibility plane (by $\chi^2$ minimization of the disk physical parameters).

Since the $^{12}\text{CO}$ and $^{13}\text{CO}$ $J=1-0$ and $J=2-1$ lines have different opacities, they sample different disk layers and allow us to probe the existence of a vertical temperature gradient. This is illustrated in Dartois et al (2003) who showed that the “CO disk surface”, traced by $^{12}\text{CO}$, is significantly warmer than the mid-plane characterized by the optically thinner $^{13}\text{CO}$ $J=1-0$ transition, in the DM Tau disk (DM Tau is a TTauri star of about 0.5 $M_\odot$). This effect appears in the region of the disk where the dust is still optically thick in absorption to the stellar radiation while it is already optically thin to its own emission, around $r \sim 50 - 200$ AU in the DM Tau case. Beyond $r \geq 200$ AU where the dust becomes optically thin to both processes, the temperature profile appears vertically isothermal. These observations of DM Tau (Dartois
Figure 1. From Simon et al 2000. This figure presents several CO velocity channel maps of disks orbiting around MWC480 (Herbig Ae star), DM Tau, LkCa15 and GM Aur (TTauri stars). The $^{12}$CO J=2→1 data have been obtained with the IRAM array. The angular resolution is about 1″. The last box (bottom) shows the observed velocity gradient which is in agreement with rotation since the velocity gradient appears to be along the major disk axis.
et al 2003) were the first direct evidence of the vertical thermal gradients in disks which were predicted by models (e.g. models by Chiang & Goldreich 1997, d’Alessio et al 1998, d’Alessio et al 1999).

More recently, (Piétu et al 2007) have analyzed several objects, confirming in most cases the existence of vertical and radial temperature gradients. Fig. 2 presents the results obtained on DM Tau. The top row shows the temperature derived from the CO isotopologues and HCO$^+$ J=1-0 while the bottom one presents the surface density derived from the same molecular transitions. In both cases, the S/N ratio versus radius is given in red on the right scale. As expected, the peak in sensitivity (or in S/N) with radius does not appear at the same location for the temperature and for the surface density. In fact, the inner part of the disk being optically thick, the brightness distribution directly traces the temperature while in the outer optically thinner part, the brightness distribution is a function of the density and temperature which depends on the observed transition (see Dutrey et al 2007 for details).

It is also important to mention that CO in the gas phase has been observed in all TTauri disks at a temperature which is well below the CO freeze out point (17 K). This suggests that the vertical turbulence should play an important role by providing chemical mixing between the vertical molecular layers.

2.2. Towards molecular Chemistry

Several groups (e.g. Dutrey et al 1997, Kastner et al 1997, Van Zadelhoff et al 2001, Dutrey et al 2007) have searched for other molecules than CO. So far, molecular surveys remain sensitivity limited to the most abundant molecules found in molecular clouds. In addition to CO, $^{13}$CO and C$^{18}$O, only HCO$^+$, H$^{13}$CO$^+$, DCO$^+$, CS, HCN, HNC, DCN, CN, H$_2$CO, N$_2$H$^+$ and C$_2$H have been detected. This domain will clearly benefit from the forthcoming submm array ALMA.
3. Dust Disks at mm/submm wavelengths

It is now clearly established that a significant fraction of the dust grains has grown in protoplanetary disks, with particles having at least centimeter size (Testi et al 2003). In the submm regime, the dust emission is mostly optically thin. Following the standard prescription of the dust absorption coefficient used for disks from Beckwith et al 1990 ($\kappa(\nu) = 0.1(\nu/1000\text{GHz})^\beta$ cm$^2$/g, per gram of dust+gas), the typical radius for an optically thick core is about 10 − 50 AU at 1.3mm. This depends on the value of $\beta$ and the surface density law. The observed values of $\beta$ are within the range 0.5-1.5, corresponding to dust more evolved than in the interstellar medium where $\beta \simeq 2$ (Draine 2006).

3.1. Studies of the Dust Disks

As in the case of the CO lines, modelling the dust emission provides constraints on the dust temperature and surface density. As soon as the optically thick core is resolved, the temperature can be estimated in the inner part while the surface density is derived from the optically thinner outer part.

This can be illustrated through the analysis of the PdBI data of LkCa15 and MWC480 performed by Piétu et al 2006. These data were obtained using the extension of the IRAM array baselines providing an angular resolution of 0.3″ or ~ 40 AU at the Taurus distance. MWC480 and LkCa15 are two young stars of a few million years old and masses of ~ 2 (Spec.Type A4) and 1 $M_{\odot}$ (Spec.Type K5), respectively. Fig.3 presents the images of the thermal emission of the dust at 2.8 and 1.3mm around the two stars. The emission from the dust disk of MWC480 is strongly centrally peaked, as expected from a standard density distribution while the central part...
of the LkCa15 disk appears partly devoid of emission. This is confirmed by the best modeling of the data.

For the dust disk of MWC480, the size of the optically thick core is about 35 AU and the dust temperature is of the order of ~ 20 K at 20-30 AU. This temperature has to be compared with measurements from CO data. Piétu et al 2007 found ~ 50 K from the $^{13}$CO analysis and ~ 135 K from the $^{12}$CO data. Such a discrepancy between the dust and gas temperature confirms the existence of a relatively strong vertical gradient. The layer where the dust reaches an opacity around one is likely located deeper in the disk than that where the same opacity is found in $^{13}$CO J=2-1. Note that the dust emission in the mm range being optically thin, the temperature derived from the mm data also appears significantly lower than the temperature derived from the IR SED (the optically thick IR observations only probe the surface of the dust disk). As a consequence, the temperature derived from the IR SED cannot be simply used to analyze mm/submm data. Using them underestimates the disk masses, as the mm emitting dust temperature is overestimated.

For LkCa15, Piétu et al 2006 found that the mm image is best explained by a disk exhibiting a central cavity of radius 46 ± 3 AU. Such a cavity is not detected at NIR wavelengths because, contrary to the mm/submm range, the high opacity of the dust in the NIR precludes the detection of cavities corresponding to low or moderate density contrast (~ 10-100). The most probable explanation for such a hole is the presence of a massive planet of Jupiter mass orbiting at ~ 30 AU from the star or a low-mass companion (< 0.2 $M_\odot$).

3.2. The HH 30 case study

**Figure 4.** From Guilloteau et al 2008. The emission of the dust disk observed at 1.3mm with the IRAM array (contours) is superimposed to the HST image from Burrows et al 1996. The angular resolution of the millimeter data is about 0.5″. The disk is well resolved and the two bright peaks correspond to the maximum of column density at the inner edge of the disk. The central depression traces the cavity of radius 45 AU.

HH 30, revealed by the HST, is the most beautiful example of an edge-on dust disk orbiting a TTauri star (Burrows et al 1996). It is the case study of the flared disk with an on-axis optical jet. Peté et al 2006 have observed this object in CO J=2-1 and $^{13}$CO J=2-1 and J=1-0 with the IRAM array. The $^{13}$CO data reveal that the disk is in Keplerian rotation and is orbiting a 0.45$M_\odot$ star. The derived temperature of 12 K (at 100 AU), is much lower than the 35 K derived from the scale height of the scattering dust, again indicating significant vertical temperature gradient. More recently, Anglada and collaborators (2007) analyzed the existing optical data of the jet in order to study the jet kinematics and proper motions on a period of about 10 years. Their study has definitely changed the interpretation of the HH 30 dust disk because they found that the jet is wiggling. The regular pattern of the wiggles is most simply explained as the composition of ballistic ejection with the orbital velocity of a star in a binary system. The binary is expected to excavate a central cavity, like in the GG Tau case (Dutrey et al 1994). In NIR, since the disk is seen edge-on, the star and possible inner cavity are completely
hidden by the highly optically thick dust lane of the disk, but such a cavity can be detected at mm/submm wavelengths where the dust emission is optically thin. This is indeed what was recently revealed by new PdBI observations performed at 0.3" resolution by Guilloteau et al 2008. Fig.4 is a superimposition of the image of the dust disk obtained by Burrows et al 1996 with the HST and the high angular resolution image from the IRAM array. Guilloteau et al 2008 found an inner cavity of 45 AU, in reasonable agreement with one of the two solutions proposed by Anglada et al 2007. The size of the hole implies a binary semi-major axis of about 18-20 AU.

The three examples we have presented above not only show the impact of the high angular resolution on the interpretation of the physical structure of circumstellar disks, but also illustrate the wide variety of disks found.

4. Illustration of a multi-λ Study: the AB Aurigae Case
So far, AB Auriga is considered as the proto-type of the Herbig Ae star surrounded by a complex circumstellar environment which has been observed at almost all wavelengths. It is therefore interesting to use the recent high angular data to characterize at best the physical properties of
its surroundings within the 1000 central AU down to scales of tens of AU. The inclination angle from the plane of sky has been derived at several wavelengths (from NIR interferometric data tracing the small scales up to the mm domain tracing the larger scales). The values found are within the range $i \sim 20\text{--}35^\circ$, indicating that the object is seen close to face-on.

At large scale, this object is surrounded by an envelope of at least 10000 AU seen in the NIR (e.g., Grady et al 1999) but also revealed by ISO. The left panel of Fig. 6 shows in false color the HST image with the 1.3mm continuum emission from the dust disk (Piétu et al 2005) superimposed. Fukagawa et al 2004 used the Subaru telescope to make a deep image in the NIR which reveals a spiral pattern at intermediate scale ($\sim 100\text{--}500$ AU) in the envelope.

4.1. AB Aurigae seen with mm arrays

At intermediate scale ($\sim 500\text{--}100$ AU) observations of the $^{12}$CO gas trace the envelope and the disk while the optically thinner isotopes ($^{13}$CO and C$^{18}$O) mostly characterize the disk, see Fig. 5. Both the CO and mm continuum emissions reveal that the disk displays a large inner cavity, of about 100 AU in radius. The cavity is not totally devoid of gas (and dust): the apparent inner radius increases from the most optically thick tracer, CO $J=2-1$, to the most optically thin one, dust emission. Surprisingly, the CO disk displays clear evidence of non-Keplerian rotation (Piétu et al 2005, Lin et al 2006), although the non-circularity of the structure affects the interpretation of the projected velocities. This is observed both in the SMA and PdBI CO data. The disk mass is too low to be the cause of the spiral structure. The cavity may be due to a low mass companion ($<0.3 M_\odot$) orbiting around 40 AU, companion whose trace may have been found since (Rodriguez et al 2006). However, it is unclear if such a companion can sustain the large spiral structure. An alternative (not necessarily exclusive) possibility may be that the disk is much younger than anticipated, so that the Keplerian rotation is not yet fully established. The existence of a still massive envelope is an argument in this direction.

The mm dust emission also presents asymmetries which are likely the inner continuation of the “spiral-like” structure found at larger scale by Fukagawa et al 2004 (Piétu et al 2005, Lin et al 2006).

4.2. AB Aurigae seen with IR Interferometers

Going to smaller scales ($\sim 0.5\text{--}10$ AU) by observing with NIR interferometers, several observations reveal the existence of very close circumstellar material around AB Auriga (Eisner et al 2004, Millan-Gabet et al 2006). The very inner disk appears truncated at an inner radius $\sim 0.3$ AU, consistent with the expected location of the dust sublimation radius for an A0 star (Millan-Gabet et al 2006).

Using the MIDI interferometer, Di Folco et al 2008 (submitted) have studied the properties of the dust inner disk (see Fig. 6, middle and right panels). At first sight, the analysis of the MIDI data of the Silicates bands at $\sim 10\mu m$ suggest the presence of amorphous Silicates, as it is also observed at larger scales with ISO (Bouwman et al 2000), in agreement with a relatively young stellar object. At scales of a few AU, a detailed study of the interferometric MIDI data and of the SED in the same frequency range has been made using the Monte-Carlo code MC3D. The disk is seen close to face-on and most of the visibilities have been obtained along the disk major axis. This allows Di Folco and collaborators to measure not only the scale-height but also its flaring index. Both appear to be compatible with those measured at larger scales from the mm observations (Piétu et al 2005). So far, this is the most complete study of a disk from small to large scales ($\sim 1\text{--}300$ AU).
5. Summary

High angular resolution has started to really become available with mm/submm arrays. Thanks to simultaneous upgrades in sensitivity, this gives the first quantitative studies of the close circumstellar environment in a regime where the optical depth of the material is reasonable enough to unveil the inner structure. This is illustrated through several examples where inner cavities hidden in the IR have been revealed by new mm or submm observations. In many cases, these observations also imply a new physical interpretation (binarity, existence of a very-low-mass companion...). In the meantime, the new generation of IR interferometers provide more accurate measurements in the very close vicinity of young stars, a necessary complement to study disk properties from large to small scales.

ALMA will soon have the potential of providing much higher angular resolution on images of the emission of molecular lines, allowing investigators to perform detailed modelling. For the nearest star forming regions, ALMA will have the capability of reaching AU-scale angular resolution at wavelengths where dust has a moderate opacity. It is expected to be the premium instrument to image planetary forming regions in the earlier phases. In synergy with IR interferometers, it would allow astronomers to constrain the models of planet formation.

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Figure 6. Left: from Piétu *et al* 2005, continuum emission from the dust disk at 1.3mm superimposed to the HST image from Grady *et al* 1999. Middle and right panels: from Di Folco *et al* 2008, MIDI observations of the inner disk (the angular resolution traces material down to scales of 1-2 AU). The central panel shows the normalized visibility obtained on the 5 baselines, the disk is clearly resolved. On the right panel, the UV coverage is presented, most of the visibilities were obtained along the major axis of the disk, allowing the observers to resolved out the radial disk structure.
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