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Characterizing the youngest protostellar disks with the IRAM-PdBI and ALMA interferometers

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Abstract. I present our observations and modeling of the 1.3 mm and 3.18 mm dust continuum emission in Class 0 protostars, from the IRAM-PdBI CALYPSO survey. We show that most protostars are better reproduced by models including a disk-like dust continuum component contributing to the flux at small scales, but less than 25% of these candidate protostellar disks are resolved at radii > 60 au, which favors magnetized models of rotating protostellar collapse for disk formation (Maury *et al.* 2019). I also present new ALMA observations of the molecular line emission in the IRAM04191 protostar, suggesting a small counter-rotating disk is detected in this young low-luminosity solar-type protostar. Finally, I show our ALMA observations of the magnetic field topology in the B335 protostar, which when compared to the typical output from protostellar collapse models, suggest the magnetic field might be responsible for constraining the disk size to remain very small in this protostar (Maury *et al.* 2018).

Keywords. stars: formation, ISM: individual (L1448, NGC1333, Serpens South, Serpens Main, L1157, GF9-2, L1527, IRAM04191, B335), ISM: magnetic fields

1. Introduction

Understanding the first steps in the formation of protostars and protoplanetary disks is a great unsolved problem of modern astrophysics. At the simplest level, the formation of circumstellar disks is a natural consequence of the conservation of angular momentum during the collapse of rotating protostellar envelopes in the course of the main accretion phase (Cassen & Moosman 1981, Terebey *et al.* 1984). Hydrodynamic simulations show that in the absence of magnetic fields, rotationally supported disks form and quickly grow to reach large radii > 100 au after a few thousand years (Yorke & Bodenheimer 1999). On the other hand, magnetohydrodynamics (MHD) numerical simulations of magnetized protostellar collapse form much smaller disks, at scales $r \sim 20$ au because of strong magnetic braking (for a review, see Li *et al.* 2014). Observationally, the key to constraining theoretical models for the formation of protostars and disks lies in high-resolution studies of the youngest protostars. Class 0 protostars are representative of the main accretion phase of protostellar evolution: they are observed only $t \lesssim 4 - 9 \times 10^4$ yr after the formation of a central hydrostatic protostellar object (Evans *et al.* 2009; Maury *et al.* 2011) while most of their mass is still in the form of a dense core/envelope. Only the recent advent of powerful interferometric facilities at (sub) millimeter wavelengths has allowed the inner envelopes of Class 0 protostars to be explored with sufficient sensitivities to distinguish envelope emission from resolved disk emission at the relevant scales (20–200 au). The characteristics of Class 0 disks, and the exact ingredients responsible for early disk properties during the main accretion phase, hence remain strongly debated.

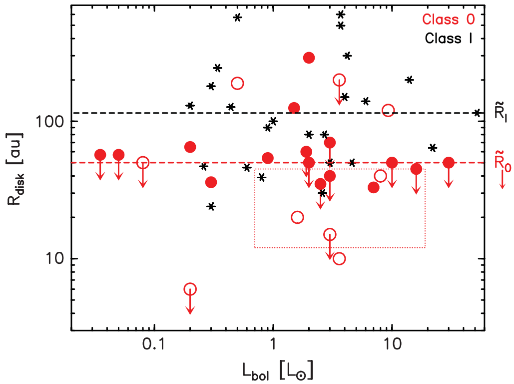

Figure 1. Protostellar disk radii $R_{\rm disk}$ in function of the protostellar bolometric luminosity $L_{\rm bol}$, for all Class 0 (red circles) and Class I (black stars) protostars observed between 0.7 mm and 2.7 mm with a spatial resolution better than 50 au, from both the CALYPSO sample and the literature. See Maury *et al.* (2019) for source names and references. The dashed lines show the median disk radii: in red from the sample of 25 Class 0 disks where $\tilde{R_0}$ <50 au (including upper limit radii), and in black the median radius from the sample of 25 Class I disks is $\tilde{R}_I = 115$ au.

2. Class 0 disks in the CALYPSO sample

Only a survey providing high angular resolution observations for a large sample of Class 0 protostars can shed light on the controversy about the pristine characteristics of protostellar disks and ultimately on the importance of magnetic fields in regulating disk formation during protostellar formation. CALYPSO (see `http://irfu.cea.fr/Projets/Calypso/`) is a survey of 16 Class 0 protostars, carried out with the IRAM Plateau de Bure (PdBI) interferometer at high angular resolution ($\sim 0.3''$). The 16 Class 0 objects of the CALYPSO sample are among the youngest known solar-type protostars (André *et al.* 2000), with $M_{\rm env} \sim 0.5$–$10\ M_\odot$, and internal luminosities $L_{\rm int} \sim 0.03$–$30\ L_\odot$ (see Table 1 in Maury *et al.* 2019). We analyzed the dust continuum emission datasets, obtained at both 1.37 mm and 3.18 mm: our analysis shows that less than 25% of the CALYPSO Class 0 disk candidates are resolved at radii > 60 au. When taking into account all available literature on resolved Class 0 disks (or upper limit sizes obtained with interferometers), we also show that a similar fraction ($< 28\%$) of Class 0 protostars studied so far may harbor large disks with radii > 60 au. Our results suggest that the formation of disks during the Class 0 phase could occur at smaller scales than predicted by hydrodynamical models of rotating protostellar collapse (Maury *et al.* 2010, Maury *et al.* 2019). At the current state of our knowledge, this may either point to (i) the extreme youth of these objects (which may not yet have developed a disk), (ii) an overestimate of the initial angular momentum of the cores in hydrodynamical collapse models, or (iii) a magnetically regulated disk formation scenario. I discussed these scenari and conclude that, because they reduce the centrifugal radius and produce a disk size distribution that peaks at radii < 100 au during the main accretion phase (Li *et al.* 2014, Hennebelle *et al.* 2016), magnetized models of rotating protostellar collapse are favored by our CALYPSO observations.

3. A counter-rotating disk in IRAM 04191 ?

IRAM 04191+1522 is a Class 0 protostar in the Taurus molecular cloud (André *et al.* 1999). Its large envelope mass (1.5 $M_\odot$), low-luminosity (0.1 $L_\odot$) and temperature suggest an age of 1-3 $\times$ 10^4 yr and a stellar mass $\sim$0.05 $M_\odot$, making it one of the youngest protostars in Taurus. Single-dish observations of molecular lines, combined with radiative

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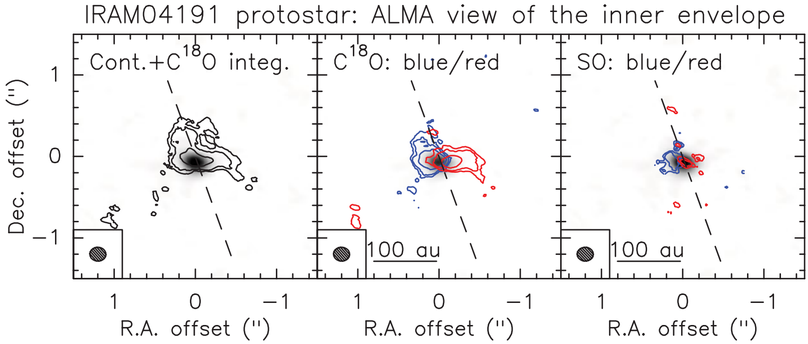

Figure 2. In all panels, the background map shows the ALMA 1.29 mm dust continuum emission. Left: The black superimposed contours show the levels of $C^{18}O(2–1)$ integrated emission. Center: The blue and red contours show the levels of respectively blue-shifted and red-shifted $C^{18}O(2–1)$ emission (integrated over $\pm$ 1.5 km s^{-1}with respect to the systemic velocity 6.6 ± 0.1 km s^{-1}). Right: Same for the SO(65–54) emission.

transfer modeling of the IRAM 04191 envelope, enabled to constrain the outer envelope kinematics: a steep velocity gradient of ~40 km s^{-1} pc^{-1} was detected along the NW-SE direction, i.e., perpendicular to the axis of the outflow, in the envelope at scales r~4000 au (see Fig. 2 in Belloche *et al.* 2002). This velocity gradient is consistent with differential rotation of the envelope, with the blueshifted emission to the northwest and the redshifted emission to the southeast (Belloche *et al.* 2002, Takakuwa *et al.* 2003, Lee *et al.* 2005). We have observed the dust continuum emission and molecular line emission from IRAM 04191, using ALMA to obtain a synthesized beam $0.18'' \times 0.15''$ ($\sim$ 23au). Our ALMA molecular emission maps reveal an organized velocity gradient at scales $r \lesssim 50$ au. Considering a systemic velocity of the IRAM 04191 core 6.6 ± 0.1 km s^{-1}, the $C^{18}O(2-1)$ and $SO(6_5 - 5_4)$ emission are tracing a velocity gradient perpendicular to the axis of the large-scale outflow (blue to the east and red to the east, see Fig. 2), but in a direction opposite to the one observed at the envelope large-scales. This reversal between the large- and small-scale velocity gradients suggests a counter-rotating disk is forming within the IRAM 04191 protostar (Maury *et al.* in prep). Investigations of the envelope kinematics at intermediate scales are crucially needed to propose a formation scenario for this young disk, and polarimetric observations could shed light on a possible scenario where magnetic braking would be responsible for the kinematics reversal in this pristine protostellar envelope.

4. A magnetically-regulated disk formation scenario in B335

The role of the magnetic field during protostellar collapse is still poorly constrained from an observational point of view, and only few constraints exist that shed light on the magnetic braking efficiency during the main accretion phase. I presented our ALMA polarimetric observations of the thermal dust continuum emission at 1.3 mm, towards the B335 Class 0 protostar (Maury *et al.* 2018). Linearly polarized dust emission is detected at all scales probed by our observations (50 to 1000 au). The magnetic field structure has a very ordered topology in the inner envelope, with a transition from a large-scale poloidal magnetic field, in the outflow direction, to strongly pinched in the equatorial direction. We compared our data to a family of magnetized protostellar collapse models. We show that only models with an initial core mass-to-flux ratio $\mu \sim 5 - 6$ are able to reproduce the observed properties of B335, especially the upper-limits on its disk size, its large-scale envelope rotation β and the pronounced magnetic field lines pinching observed in our ALMA data. In these MHD models, the magnetic field is dynamically relevant to regulate the typical outcome of protostellar collapse, suggesting a magnetically-regulated disk formation scenarios is at work in B335.

5. Conclusions

Observational studies of large Class 0 protostar samples with PdBI, ALMA and VLA found only few large disks at scales r>100 au, while pure hydrodynamic models routinely form rotationally-supported protostellar disks with typical radius ∼150-500 au, as a result of the conservation of the initial core's angular momentum during protostellar collapse. Contrasting with this simple picture, the inclusion of magnetic fields in models of protostellar collapse reduce the disk sizes drastically at the beginning of the main accretion phase, producing a disk size distribution consistent with our observational findings in Class 0 protostars. Our observations of small disks, counter-rotating disks and organized magnetic fields in the youngest star-forming cores question the established paradigm of disk formation as a simple consequence of angular momentum conservation during the main accretion phase: they instead highlight the need to investigate magnetized models in order to unveil the mechanisms responsible for protostellar disk properties. In the future, obtaining accurate disk size and mass distributions, as well as detailed maps of the magnetic field topology in star forming cores, will be of paramount importance to make progress in our understanding of the formation and early evolution of both stars and protoplanetary disks.

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Discussion

DWARKADAS: You started by mentioning that the angular momentum in the solar system is mostly locked in Jupiter. Could MHD instabilities in viscous disks be partly responsible for most of the angular momentum being at large radii?

MAURY: Transport of angular momentum in disks is indeed an unsolved problem. The point I wanted to make is that during the formation process of the star, most of the core angular momentum is not transferred to the star and part is found later on in the more evolved protoplanetary disks, in which planets like Jupiter form. Jupiter is the most massive planet so it seems all right that it took most of the disk's angular momentum.

JOHNSTONE: Beautiful observations. What importance do you believe the jet/outflow plays?

MAURY: Probably part of angular momentum is being carried away by jets during the main accretion phase. But from observations of angular momentum in protoplanetary disks, it seems the bulk of the angular momentum must remain in the system to be transferred to the disk later on, so magnetic braking is a prime suspect.

CUNTZ: Can you comment on the role of the central star (especially its mass) regarding the disk structure, in particular the attained distribution of angular momentum.

MAURY: We have no good constraints on the stellar mass yet, because this requires to characterize the Keplerian pattern of these small disks, mostly unresolved with existing molecular line observations.