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Accretion disks in luminous young stellar objects

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Abstract. Spatially resolved molecular line observations have revealed circumstellar disks in Keplerian rotation around young stellar objects with masses up to 30 $M_{\odot}$. In this contribution, we will provide an observational review of the properties and evolution of accretion disks around young stars and compare them to those of circumstellar structures around lower mass counterparts. Particularly, we will discuss the mass accretion of disks as a function of stellar mass and time to get insights into the universality of star-formation models.

Key words. Accretion: accretion disks – Techniques: high angular resolution – Techniques: interferometric – Stars: formation

1. Introduction

Circumstellar disks are a natural outcome of the process of star formation and are the result of the redistribution of the specific angular momentum of the collapsing material. The disks around nearby solar-type stars have been studied to great extent and detail, but the number of disk studies of more distant, massive stars (of equivalent spectral type A and earlier) is comparatively small. Our knowledge of the physical properties of massive star disks has significantly improved thanks to the powerful new capabilities of optical/infrared (optical/IR) instruments, such as the very large telescope interferometer (VLTI), and radio/(sub)millimeter (radio/mm) ones, such as the Atacama Large Millimeter Array (ALMA). These technical improvements have led us, pushed by Francesco Palla, to review the properties, kinematics, and dynamics of accretion disks around young luminous stars, that is, the primordial disks of intermediate- and high-mass young stellar objects, and compare them to those of well-studied lower mass young stellar objects (Beltrán & de Wit 2016).

2. Disks around intermediate-mass stars

Accretion disks around A-type stars have been observed in both, embedded protostars and optically revealed Herbig Ae/Be stars. The velocity field of such disks has been studied in detail and the motions appear to be consistent with Keplerian rotation (e.g., HD 163296: de Gregorio-Monsalvo et al. 2013). Recent mm and IR observations have revealed that these disks show discontinuous radial and azimuthal dust distributions, with large cavities, as seen in the Herbig Ae HD169142 by Fedele et al. (2017), with gas and dust not always tracing the same regions. This has been interpreted as the signature of planet formation, which resembles the scenario depicted by ALMA towards the low-mass protostar HL Tau (Partnership ALMA 2015).

3. Disks around high-mass stars

3.1. Disks around early B-type and late O-type (proto)stars

Circumstellar disks have been detected around stars with masses up to 25–30 $M_\odot$ by means of NIR and MIR (e.g., IRAS 13481-6214: Kraus et al. 2010; CRL 2136: de Wit et al. 2011), and (sub)millimeter (e.g., IRAS 20126+4104: Cesaroni et al. 2014) interferometric observations. ALMA high-angular resolution observations have allowed us to study in detail the velocity field of these circumstellar disks. The observed velocity gradients have been modeled and are consistent with Keplerian rotation (e.g., G35.20−0.74N: Sánchez-Monge et al. 2013; G35.03+0.35: Beltrán et al. 2014; AFGL 4176: Johnston et al. 2015). The radii of these disks are approximately a few 1000 au, although for some sources observed at very high-angular resolution, the radii can be as small as 300–400 au (Beltrán & de Wit 2016, and references therein). Their masses are of a few $M_\odot$. For true accretion disks candidates, the mass of the disk is always smaller than (or similar to) the mass of the central star, $M_\star$. This suggests that these structures could be rotationally supported.

3.2. Disks around early O-type (proto)stars

For higher mass stars, with luminosities $>10^5\,L_\odot$ and spectral types earlier than O6–O7, the situation is different. What has been found around these objects are huge and massive rotating structures called toroids. These toroids have masses of a few 100 $M_\odot$ and sizes of several 1000 au, which suggests that they are probably surrounding protoclusters. The mass of these toroids is much higher than that of the central star, and therefore, Keplerian rotation is not possible (on scales of 10^4 au) because the gravitational potential of the system is dominated by the toroid and not by the central star. In addition, the mass of the toroid is higher than the dynamical mass, which suggests that these structures might be undergoing fragmentation and collapse.

In a recent study carried out with ALMA, Cesaroni et al. (2017) have observed six early O-type star-forming regions looking for circumstellar disks. The 1.4 mm dust continuum emission has revealed that some of the cores fragment in few sources, while others, like G31.41+0.31, do not fragment at all. The CH_3CN observations with an angular resolution of $0\farcs2$ have revealed that:

i) three of the cores show signatures of Keplerian rotation, with the position-velocity (PV) plots showing the typical butterfly pattern;
ii) three of the cores show velocity gradients that suggest rotation, but the PV plots are not consistent with Keplerian motions;
iii) G17.64+0.16 shows no hints of rotation.

Cesaroni et al. (2017) have plotted the luminosity-to-mass ratio, which is an evolution stage indicator, as a function of the distance to these sources, and have included also the O-type star AFGL 4176 (Johnston et al. 2015). The plot shows that true accretion disks are found for sources with an intermediate evolutionary stage, while those with questionable disk evidence are the younger sources. The explanation for the non-detection of Keplerian disks around these young sources could be that their disks are so embedded that their emission is difficult to disentangle from that of the envelopes. Alternatively, disks might start small and grow up with time. On the other hand, for the most evolved source in the sample, G17.64+0.16, the molecular gas might have dispersed and therefore, no disk is found.

4. Disks versus toroids

Disks and toroids are different from a point of view of stability. While accretion disks around Herbig Ae stars and bona-fide Keplerian disks around early B- and late O-type (proto)stars have masses $<0.3M_\star$ and a stability Toomre's Q parameter >1, suggesting that they are stable, toroids have all masses $>0.3M_\star$ and Q<1.

Disks and toroids are also dynamically different. Disks around Herbig Ae and those in Keplerian rotation around high-mass stars have dynamical masses higher than those of the central star, while toroids around O-type stars have dynamical masses much smaller, and therefore cannot be centrifugally supported and could be susceptible to gravitational collapse and fragmentation. The same result is obtained if one compares the ratio of the free-fall time, $t_{\rm ff}$, that should be proportional to the dynamical timescale needed to refresh the material of the rotating structure, and the rotational period at the outer radius, $t_{\rm rot}$, which is basically the time scale needed for the structure to re-adjust its internal structure to the newly accreted material, versus the mass of disks and toroids. Disks have a $t_{\rm ff}/t_{\rm rot}$ ratio higher than that of massive toroids. This suggests that if the structure rotates fast, the infalling material has enough time to settle into a centrifugally supported disk. Vice versa, if the structure rotates slowly, the infalling material does not have enough time to reach centrifugal equilibrium and the rotating structure is a transient toroid. In this case, rotation plays a little role in their support. The higher the $t_{\rm ff}/t_{\rm rot}$ ratio of the rotating structure, the more similar to a circumstellar disk is.

Typical infall rates, $\dot{M}_{\rm inf}$, in intermediate- and high-mass (proto)stars are of the order of 10^{-3}–$10^{-2}\,M_\odot$/yr, while typical accretion rates, $\dot{M}_{\rm acc}$, estimated from the mass loss rate of the associated outflow, are of the order of 10^{-4}–$10^{-3}\,M_\odot$/yr (Beltrán & de Wit 2016). $\dot{M}_{\rm inf}$ are always higher than $\dot{M}_{\rm acc}$, and in some cases up to a factor 1000. A possible explanation for this could be stellar multiplicity: the infalling material is not accreted onto the single star that is responsible for the molecular outflow, but onto a cluster of stars. This explanation seems plausible for the most massive O-type (proto)stars, because as already explained, the sizes and masses of the rotating toroids suggest that they are enshrouding stellar (proto)clusters. However, this explanation cannot solve the problem for the intermediate-mass protostars and probably neither for the B-type (proto)stars. For intermediate-mass protostars with $M_\star \simeq 2$–$3\,M_\odot$, the $\dot{M}_{\rm inf}/\dot{M}_{\rm acc}$ ratio is still 20–300, with mass of the structure of $\sim$0.3–1.4 $M_\odot$. Therefore, although these disks could be circumbinary disks, it seems unlikely that they are circumcluster structures surrounding several members. The apparent implication of this is that the infalling material needs to pile up in the disk and results in disk masses that are tens to hundreds of solar masses given the observed rates. This is massive and suggests a gravitationally unstable disk inducing variable, "FUOri-like" accretion events onto the central object. And this is what has been recently discovered in the high-mass regime by Caratti o Garatti et al. (2016). These authors have discovered the first disk-mediated accretion burst from a young stellar object of $\sim$15 $M_\odot$, S255 NIR 3. The NIR photometry reveals an increase in brightness of 2.5–3.5 magnitudes and NIR spectroscopy reveals emission lines typical of accretion bursts in low-mass protostars, but orders of magnitude more luminous, confirming our prediction.

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