Disks around Young O-B (Proto)Stars: Observations and Theory

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Disks are a natural outcome of the star formation process in which they play a crucial role. Luminous, massive stars of spectral type earlier than B4 are likely to be those that benefit most from the existence of accretion disks, which may significantly reduce the effect of radiation pressure on the accreting material. The scope of the present contribution is to review the current knowledge about disks in young high-mass (proto)stars and discuss their implications. The issues of disk stability and lifetime are also discussed. We conclude that for protostars of less than ∼20 $M_\odot$, disks with mass comparable to that of the central star are common. Above this limit the situation is unclear and there are no good examples of proto O4–O8 stars surrounded by accretion disks: in these objects only huge, massive, toroidal, non-equilibrium rotating structures are seen. It is clear on the other hand that the observed disks in stars of 10–20 $M_\odot$ are likely to be unstable and with short lifetimes.

1. INTRODUCTION

Disk formation seems to be the natural consequence of star formation. For low-mass stars, this is attested to by the existence of pre-main sequence (PMS) star disks as shown by a number of publications including several reviews in Protostars and Planets IV (see, e.g., *Mathieu et al.*, 2000; *O'Dell and Wen*, 1994; *O'Dell*, 2001; *Guilloteau et al.*, 1999; *Simon et al.*, 2000; *Mundy et al.*, 2000; *Calvet et al.*, 2000; *Hollenbach et al.*, 2000; *Wilner and Lay*, 2000). Noticeably, all of these refer only to disks in low- to intermediate-mass protostars, while the topic of disks in O-B stars is reviewed for the first time in the present contribution. Millimeter observations of disks around young early B stars (*Natta et al.*, 2000; *Fuente et al.*, 2003) give upper limits (or in one case a detection) less than 0.001 times the mass of the star, in contrast to PMS stars of B5 and later. Thus the evidence is that O and early B stars lose any disks they may originally have had prior to becoming optically visible after roughly 10^6 yr. This article aims at discussing the question of what happened in those first million years. That in turn depends on understanding what happens in the embedded phase where we depend on millimeter and infrared measurements to detect disks. Before getting to this, it is worth noting that there is evidence for disks around what one presumes to be embedded young O-B stars with characteristics similar to those of the BN object in Orion (e.g., *Scoville et al.*, 1983; *Bik and Thi*, 2004). This comes from high resolution spectra of the CO overtone bands and suggests that the lines are emitted in a disk a few AU from the star at temperatures above 1500 K. Note that disks of this size would not be detectable by the mm observations mentioned earlier. Nevertheless, it seems likely that also disks on AU scales disappear rapidly. *Hollenbach et al.* (2000) summarize disk dispersal mechanisms and many of these are more effective in the high pressure cores where O-B stars form. Stellar wind stripping and photo-evaporation occurs naturally in the neighbourhood of hot massive stars whereas disks on AU scales dissipate rapidly due to viscous accretion.

On the other hand, massive stars have to form and one may need to accrete through a disk in order to form them. This is mainly because the most obvious barrier to massive star formation is the action of radiation pressure on infalling gas and dust (e.g., *Kahn*, 1974; *Wolfire and Cassinelli*, 1987). Current models (*Jijina and Adams*, 1996; *Stahler et al.*, 2000; *Yorke and Sonnhalter*, 2002; *Yorke*, 2004a; *Krumholz et al.*, 2005) suggest that the most effective way of overcoming radiation pressure is to accrete via a disk. In this way, however, forming a star requires loss of angular momentum and one way of doing this is via an outflow which may be powered by a wind (*Shu et al.*, 2000; *Königl and Pudritz*, 2000). As discussed in Section 2.1, there is evidence for outflows from young massive (proto)stars (*Rich-*

er et al., 2000) and thus implicitly evidence for disks. Thus it seems likely that disks are an essential part of high-mass star formation but that they are short lived and hence, by inference, high-mass star formation is a rapid process. In fact, current models (*McKee and Tan*, 2003; see also the chapter by *Beuther et al.*) of the formation of high-mass stars in clusters suggest timescales of the order of 10^5 years and accretion rates upwards of $10^{-4}\ M_\odot \mathrm{yr}^{-1}$.

One difficulty in understanding the observations of massive protostars and their associated disks is our ignorance of the evolution of the central star itself. One can imagine scenarios where the accreting protostar evolves rapidly to the zero-age main sequence (ZAMS) and others where the protostellar radius remains larger than the ZAMS value (and thus the effective temperature smaller) for a protracted period of time (e.g., *Nakano et al.*, 2000). In this latter case, the accretion luminosity is a considerable fraction of the bolometric luminosity. This alleviates somewhat the radiation pressure problem and postpones the photo-evaporation of the disk. It also may explain why some luminous young stellar objects (YSOs) appear to have a very low Lyman-continuum output as measured by the observed radio free-free emission (e.g., *Molinari et al.*, 1998; *Sridharan et al.*, 2002). In any case, the uncertainty about the central star properties gives rise to an additional uncertainty in our discussion of the surrounding disk.

Since it is useful to be guided in the first place by the observations, we in Section 2 of this review summarize the observations of disks around massive protostars, where by massive we mean luminosities larger than $\sim 10^3\ L_\odot$, corresponding on the ZAMS to a B4 spectral type ($\sim$8 $M_\odot$). This is roughly the point where the accretion (free-fall) timescale equals the Kelvin-Helmholtz timescale (e.g., *Palla and Stahler*, 1993; *Stahler et al.*, 2000). Conversely, all stars below $\sim$8 $M_\odot$ will be called hereafter "low-mass", so that we will *not* use the expression "intermediate-mass", commonly adopted in the literature for stars in the range 2–8 $M_\odot$. It is worth noting that the threshold of 8 $M_\odot$ is not to be taken at face value: this corresponds to an accretion rate of $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$, while for higher or lower rates the critical mass may change significantly (*Palla and Stahler*, 1993). We will thus consider as massive also (proto)stars with slightly lower masses than 8 $M_\odot$.

In Section 3, we summarize the data for the well studied "disk" around the protostar IRAS 20126+4104, which we take to be our prototype. In Sections 4 to 6, we discuss the evolution, stability, and lifetime of massive disks around massive stars. We illustrate the difficulties with classical disk theory to explain the accretion rates needed to form massive stars on short timescales and that thus "unconventional approaches" (perhaps involving companions) might be required. In Section 7, we give a brief summary and draw our conclusions.

2. OBSERVATIONAL ASPECTS

In this section we illustrate the techniques adopted to search for disks in regions of high-mass star formation and the results obtained, with special attention to the physical properties of the disks. Eventually, we will draw some conclusions about the apparent scarcity of detections, in an attempt to decide whether this is due to instrumental limitations or instead related to the formation mechanism.

As already mentioned, the first step to undertake is the definition of "disk". Theoretically a disk may be defined as a long-lived, flat, rotating structure in centrifugal equilibrium. Although not easy to fulfill on an observational ground, this criterion may inspire a more "pragmatical" definition.

A morphological definition based on the disk geometry may not only be difficult but even ambiguous, given that massive YSOs (and hence their disks) are deeply embedded in the parental clumps. This makes the distinction between disk and surrounding envelope hard to establish, even at sub-arcsecond resolution. Disks could be identified from their spectral energy distributions (SEDs), but such an identification would be model dependent. The most reliable criterion is based on the velocity field of the rotating disk: an edge-on disk should be seen as a linear structure with a systematic velocity shift along it. However, velocity gradients may be determined also by infalling or outflowing gas, not only by rotation. To discriminate among the these, one possibility is to take profit of the fact that disks are probably always associated with large scale jets/outflows, ejected along their rotation axes: this is likely true also for disks in high-mass YSOs, as the disk-outflow association is well established in a large variety of environments ranging from disks in low-mass protostars (e.g., *Burrows et al.*, 1996) to those in active galactic nuclei (e.g., *Krolik*, 1999). One may hence compare the direction of the velocity gradient detected on a small scale ($\lesssim$0.1 pc), which traces the putative disk, to that of the molecular flow (seen over $\lesssim$1 pc): if the two are parallel, the disk hypothesis can be ruled out, whereas perpendicularity supports the disk interpretation.

In conclusion, one may use as indicative of the presence of a disk the existence of a small ($\lesssim$0.1 pc) molecular core, located at the geometrical center of a bipolar outflow, with a velocity gradient perpendicular to the outflow axis. This "observer's definition" is to be taken as a necessary condition: a satisfactory disk identification not only needs more robust observational evidence, but must satisfy theoretical constraints related to disk stability and life-time. These will be discussed in Sections 4 to 6.

The association between disks and outflows is very important. The fact that outflows turn out to be common in star forming regions of all masses (*Shepherd*, 2003) suggests indirectly that disks exist also in massive YSOs. The outflow detection rate also allows one to obtain a quantitative estimate of the disk number in such regions. This is discussed in the following section.

2.1 The outflow-disk connection and the expected number of disks

During the last decade a number of systematic searches for molecular outflows have been carried out towards a variety of candidate high-mass YSOs. After the work by *Shepherd and Churchwell* (1996a, 1996b) who searched for CO(1–0) line wings in a sample of ultracompact (UC) HII regions, subsequent surveys were made by *Osterloh et al.* (1997), *Beuther et al.* (2002a) and *Zhang et al.* (2001, 2005), towards IRAS selected sources, and *Codella et al.* (2004) in UC HII regions and maser sources. The estimated outflow detection rate ranges from 39% to 90%, demonstrating that the phenomenon is ubiquitous in massive star forming regions (SFRs). The parameters of these flows, such as mass, momentum, and mass loss rate are at least an order of magnitude greater than those of outflows from low-mass YSOs. Nevertheless, this fact by itself does not demonstrate that the massive outflows are powered by massive YSOs, but they might arise from a cluster of low-mass stars. Based on knowledge of the properties of outflows from low-mass YSOs and assuming a Salpeter initial mass function, *Zhang et al.* (2005) have actually shown that a collection of outflows from a cluster of low-mass stars may explain the total outflow mass observed. However, the same authors conclude that this scenario is unlikely, as a randomly oriented sample of outflows should not produce a clear bipolarity such as that observed in massive flows.

In conclusion, single-dish observations indicate that outflows from massive YSOs are common. This result is confirmed by high-angular resolution observations of a limited number of objects (see, e.g., *Martí et al.*, 1993; *Cesaroni et al.*, 1997, 1999a; *Hunter et al.*, 1999; *Shepherd et al.*, 2000; *Beuther et al.*, 2002b, 2003, 2004a; *Fontani et al.*, 2004; *Su et al.*, 2004) where interferometric observations have resolved the structure of several outflows, proving that their properties are indeed different from those of flows in low-mass SFRs.

An important consequence is that disks must also be widespread in massive SFRs, if the (somewhat arbitrary) assumption that disks and outflows are strictly associated is correct. Only direct observations of the circumstellar environment on a sub-arcsecond scale may prove this conclusion. In the next section we will illustrate the methods used to search for circumstellar disks in massive YSOs.

2.2 The search for disks in massive YSOs

Identifying candidate disks in massive (proto)stars requires careful selection of targets and tracers, to overcome the problems related to observations of massive YSOs. The most important of these are the large distance (a few kpc, i.e. $\sim$10 times those to low-mass objects) and richness of the environment (massive stars form in clusters), which often complicates the interpretation of the results. Consequently, sensitive and high angular resolution observations are needed. Albeit difficult to establish during the protostellar phase, the luminosities of massive YSOs must be significantly larger than those of low-mass stars, so that a reasonable lower limit to search for massive YSOs is $\sim 10^3\ L_\odot$. In an attempt to bias the search towards young sources, additional criteria may be applied, such as association with maser sources (mainly water and methanol), non-detection of free-free emission from associated HII regions, and/or constraints on the IRAS colours to filter out more evolved objects. Finally, the presence of molecular outflows may be used to identify sources which are potentially more suited to host disks, for the reason discussed in the previous section. Examples of catalogues of massive protostellar candidates selected according to the previous criteria are those by *Churchwell et al.* (1990), *Plume et al.* (1992), *Tofani et al.* (1995), *Molinari et al.* (1996), *Sridharan et al.* (2002).

As for the choice of tracers, disks are located in the densest and hottest part of the molecular clump. It is hence necessary to look for optically thin, high-temperature tracers, such as continuum emission at (sub)mm wavelengths and line emission from high-energy levels of low-abundance molecular species. In Table 1, we summarize the main techniques used to search for disks in massive YSOs and a number of relevant references. These may be classified in four categories depending on the tracer adopted.

2.2.1 Continuum emission. The dust in the disk is bound to emit as a grey body, characterized by temperatures from a few 10 K to several $\sim$100 K. This means that the continuum emission must peak at far-IR wavelengths. However, at present, (sub)arcsecond imaging is possible only in the (sub)millimeter and mid-IR regimes, due to instrumental limitations and poor atmospheric transparency which make (sub)arcsecond imaging impossible in the far-IR. Multi-wavelength information is nevertheless helpful to identify the possible contribution from ionized stellar winds to the continuum emission, which may be confused with dust (i.e. disk) emission especially at 7 mm (see, e.g., *Gibb et al.*, 2004a). The major problem with continuum imaging is related to the fact that massive young (proto)stars, unlike their low-mass counterparts, are still deeply embedded in their parental clumps: this makes it very difficult to decouple the disk from the surrounding envelope, even at sub-arcsecond resolutions. The problem may be less critical in the near-IR, where the large extinction in the plane of the disk makes it possible to see the disk (if close to edge on) as a dark silhouette against the bright background. Examples of this are found in M17 (*Chini et al.*, 2004), IRAS 20126+4104 (*Sridharan et al.*, 2005), and G5.89–0.39 (*Puga et al.*, submitted). Also, near-IR polarimetric imaging may be helpful in some cases (*Yao et al.*, 2000; *Jiang et al.*, 2005). Notwithstanding a few encouraging results, continuum observations alone can hardly achieve convincing evidence of the presence of disks: line observations are needed in addition and are necessary to study the rotation velocity field.

2.2.2 Maser lines. Maser emission is concentrated in narrow ($\lesssim$1 km s^{-1}), strong (up to 10^6 Jy) lines and arises from regions ("spots") which may be as small as a few AU (e.g., *Elitzur*, 1992). These characteristics make it suitable for milli-arcsecond resolution studies, which can investigate

TABLE 1

LIST OF TRACERS USED TO SEARCH FOR DISKS IN HIGH-MASS YSOS

Tracer	References
CH_3OH masers	*Norris et al.* (1998); *Phillips et al.* (1998); *Minier et al.* (1998, 2000); *Pestalozzi et al.* (2004) *Edris et al.* (2005)
OH masers	*Hutawarakorn and Cohen* (1999); *Edris et al.* (2005)
SiO masers	*Barvainis* (1984); *Wright et al.* (1995) *Greenhill et al.* (2004)
H_2O masers	*Torrelles et al.* (1998) ; *Shepherd and Kurtz* (1999)
IR, mm, cm continuum	*Yao et al.* (2000); *Shepherd et al.* (2001); *Preibisch et al.* (2003); *Gibb et al.* (2004a); *Chini et al.* (2004); *Sridharan et al.* (2005); *Jiang et al.* (2005); *Puga et al.* (submitted)
NH_3, $C^{18}O$, CS, $C^{34}S$, CH_3CN, $HCOOCH_3$	*Keto et al.* (1988); *Cesaroni et al.* (1994, 1997, 1998, 1999a, 2005); *Zhang et al.* (1998a, 1998b, 2002); *Shepherd and Kurtz* (1999); *Olmi et al.* (2003); *Sandell et al.* (2003); *Gibb et al.* (2004b); *Beltrán et al.* (2004, 2005); *Beuther et al.* (2004b, 2005)

the distribution, line of sight velocities, and even proper motions of the maser "spots". One may thus obtain a detailed picture of the kinematics of the circumstellar environment on scales (a few 10 AU) not accessible by any other means. The shortcoming of this technique is that the strength of maser lines is very sensitive to a variety of factors (amplification path, inversion conditions, velocity gradients, etc.), which make it very hard if not impossible to derive useful physical parameters (temperature, density) from the observables. As shown in Table 1, a large number of tentative disk detections are reported in the literature using maser observations. In all cases the authors find a linear distribution of maser spots with velocity changing systematically along it. This is taken as an indication of rotation in an edge-on disk. As discussed at the beginning of Section 2, such an evidence must be corroborated by the presence of a jet/outflow perpendicular to the maser distribution, which is not always the case. It hence remains unclear whether the velocity gradients observed are related to rotation, infall, or expanding motions. In fact, the interpretation of CH_3OH masers as disks rotating about massive YSOs (see, e.g., *Norris et al.*, 1998; *Pestalozzi et al.*, 2004), is questioned by the small stellar masses implied by the rotation curves ($\lesssim$1 $M_\odot$) and by the fact that in many cases the maser spots are aligned along the direction of a large scale H_2 jet (*De Buizer*, 2003), suggesting that the spots could be part of the jet. A similar conclusion is attained from mid-IR imaging observations of the putative disk in NGC 7538 IRS 1 (*De Buizer and Minier*, 2005). Nonetheless, interesting examples of convincing disks in massive YSOs have been found. Using SiO masers, *Greenhill et al.* (2004) have imaged an expanding and rotating disk in the Orion KL region, while hydroxyl masers have been observed to trace rotation in the disk associated with the massive source IRAS 20126+4104 (*Edris et al.*, 2005). Also, the putative disk detected towards Cep A HW2 in the H_2O maser, VLA study of *Torrelles et al.* (1998) has found recent confirmation in the SMA observations of *Patel et al.* (2005).

2.2.3 Thermal lines. As explained above, convincing evidence of a disk can be obtained by comparing its orientation to that of the associated jet/outflow. The latter may be revealed by mapping the wing emission of lines such as those of CO and its isotopomers, HCO^+, SiO, and other molecular species. A disk tracer to be observed simultaneously with one of these outflow tracers would hence be of great help for disk surveys. This must be searched among high-excitation transitions of rare molecular species, which are the most suitable to trace the high density, optically thick, hot gas in the plane of the disk. Experience has shown that species such as NH_3, CH_3CN, $HCOOCH_3$, $C^{34}S$ are very effective for this purpose. In particular, the proximity in frequency of CH_3CN to ^{13}CO makes the former an ideal tool to study the disk *and* the outflow, simultaneously. With this technique, interferometric observations at millimeter and (thanks to the advent of the SMA) sub-millimeter wavelengths have been carried out, leading to the detection of an ever growing number of disk candidates in massive YSOs. A handful of sources has been observed also at centimeter wavelengths, with the Very Large Array: the main advantage in this regime is the possibility to observe strong absorption lines against the bright continuum of background

UC HII regions. Although successful, thermal line observations must be complemented by diverse imaging and spectroscopy at various wavelengths to safely identify a disk: an illuminating demonstration of the effectiveness of this type of synergy is provided by the case of IRAS 20126+4104, which will be discussed in detail in Section 3.

2.3 Evidence for disks in high-mass YSOs

In recent years, the disk searches towards massive YSOs described in the previous section have detected an ever growing number of candidates. The main discriminating feature between these disks and those in pre-main sequence low-mass stars is the ratio between disk and stellar mass. While in the latter such a ratio is < 0.1, for massive YSOs the disk mass becomes comparable to or even greater than that of the star. This poses a question about the stability and lifetime of the disks, which will be discussed in detail in Section 4. Here, we note that candidate disks may be roughly divided into two types: those having mass M in excess of several 10 $M_\odot$, for which the ratio $M/M_\star \gg 1$, and those with $M \lesssim M_\star$. As noted by *Cesaroni* (2005a) and *Zhang* (2005), the former have in all cases luminosities typical of ZAMS O stars, whereas the latter are more likely associated with B-type stars.

Typically, the massive, rotating structures observed in YSOs with luminosities $\gtrsim 10^5\ L_\odot$ have radii of 4000–30000 AU, masses of 60–500 $M_\odot$, and observed rotation speeds of a few km s^{-1}. Examples are G10.62–0.38 (*Keto et al.*, 1988), G24.78+0.08 (*Beltrán et al.*, 2004, 2005), G28.20–0.05 (*Sollins et al.*, 2005b), G29.96–0.02 (*Olmi et al.*, 2003), G31.41+0.31 (*Cesaroni et al.*, 1994; *Beltrán et al.*, 2004, 2005), IRAS 18566+0408 (*Zhang et al.*, submitted), and NGC 7538 S (*Sandell et al.*, 2003). These objects transfer mass to the star at a rate of 2×10^{-3}–$2 \times 10^{-2}\ M_\odot \mathrm{yr}^{-1}$ (*Zhang*, 2005 and references therein): for the mass range quoted above, these correspond to time scales of $\sim 10^4$ yr. Noticeably, this is an order of magnitude less than the typical rotation period at the outer disk radius of $\sim 10^5$ yr. This fact indicates that these massive rotating structures cannot be centrifugally supported, and should be considered as transient, non-equilibrium evolving structures. These objects might be observational examples of either the "pseudo-disks" discussed by *Galli and Shu* (1993a, 1993b; in which however the flattening is induced by magnetic pinching forces) or the transient structures seen in numerical simulations of competitive accretion (*Bonnell and Bate*, 2005; see also the chapter by *Bonnell et al.*). On the other hand, "true disks", which extend on much smaller scales, are more likely to be close to an equilibrium state where gravity from the central star (and the disk itself) is balanced by rotation, and, possibly, by radiative forces. Clearly, a stability analysis makes sense only for this class of objects. In Section 4, we will therefore discuss the stability of massive disks, with the aim of providing some insight into the properties of these objects.

It is advisable to use a different terminology for non-equilibrium massive rotating structures: following *Cesaroni* (2005a), we will call them "toroids". What is the role of toroids in the process of high-mass star formation? Given the large masses and luminosities involved, they likely host a stellar cluster rather then a single star. That is why some authors have used the term "circumcluster" toroids, as opposed to "circumstellar" disks (*Beltrán et al.*, 2005). Since their size is several times the centrifugal radius (i.e. the radius at which a centrifugal barrier occurs; see, e.g., *Terebey et al.*, 1984), one may speculate that eventually toroids will fragment into smaller accretion disks rotating about single stars or binary systems (*Cesaroni*, 2005b). In the following we will not consider toroids but only "true" circumstellar (or circumbinary) disks in massive YSOs.

Table 2 lists disk candidates associated with high-mass YSOs. The columns are: luminosity, disk mass, disk radius, mass of the central star, outflow mass loss rate, and outflow dynamical timescale. When considering this table, several caveats are in order. Although most of the entries are to be considered bona fide disks, in some cases the interpretation is challenged (e.g., Cep A HW2; Comito et al. in prep.). Also, some of the values given in the table are quite uncertain, in particular the mass of the star. While in a few cases (e.g., IRAS 20126+4104) this is obtained directly from the Keplerian rotation curve of the disk, in the majority of the objects the estimate comes from the luminosity or from the Lyman continuum of the YSO. The conversion from these quantities to stellar masses is very uncertain as it depends on the unknown evolutionary stage of the (proto)star, on the optical depth and origin of the radio emission (HII region or thermal jet), on the number of Lyman continuum photons absorbed by dust, and on the multiplicity of the system. Hence, the luminosities are affected by significant errors and the mass–luminosity relationship for this type of objects is unclear. We have thus decided to adopt the values quoted in the literature without any further analysis.

Despite the large uncertainties, one may conclude that all objects have luminosities typical of B-type ZAMS stars, i.e. below a few $10^4\ L_\odot$. Albeit very difficult to establish, accretion rates for disks seem to be $\sim 10^{-4}\ M_\odot \mathrm{yr}^{-1}$ (*Zhang*, 2005): this implies a time of $\sim 10^5$ yr to transfer the material from the disk to the star, significantly larger than the rotation period ($\sim 10^4$ yr), thus allowing the disk to reach centrifugal equilibrium. Whether this will be stable or not is a complicated issue that we will deal with in Section 4. Here, we just point out that the disk time scale is comparable to the typical free-fall time of molecular clumps hosting massive star formation, which in turn equals the star formation time scale predicted by recent theoretical models ($\sim 10^5$ yr; *Tan and McKee*, 2004). This seems to suggest that the material lost by the disk through infall onto the star and ejection in the jet/outflow, is continuously replaced by fresh gas accreted from the surrounding envelope.

Naïvely, one may thus conclude that disks fit very well in the high-mass star formation scenario. However, this seems to hold only for B-type stars, as the stellar masses quoted in Table 2 are never in excess of $\sim$20 $M_\odot$and the luminosities

TABLE 2
LIST OF CANDIDATE DISKS IN HIGH-MASS (PROTO)STARS

Name	$L(L_\odot)$	$M(M_\odot)$	R(AU)	$M_\star(M_\odot)$	$\dot{M}_{\rm out}(M_\odot{\rm yr}^{-1})$	$t_{\rm out}(10^4$ yr)	Ref.[a]
AFGL 490	2.2–4 $\times 10^3$	3–6	$\lesssim$500	8–10	6.2×10^{-4}	0.95	1,2
G192.16–3.82	3×10^3	15	500	6–10	5.6×10^{-4}	17	3,4
AFGL 5142	4×10^3	4	1800	12	1.6×10^{-3}	2	5,6
G92.67+3.07	5×10^3	12	14400	4–7.5	1.7×10^{-4}	0.35	7
Orion BN	2.5×10^3–10^4	?	500	7–20[b]	10^{-6}	?	8,9
Orion I	4×10^3–10^5	?	500	$\gtrsim 6$	10^{-3}	?	10,11
IRAS 20126+4104	10^4	4	1600	7	8.1×10^{-4}	6.4	12,13,14,15,16
G35.2–0.74N	10^4	0.15	1500	4–7	3×10^{-3}	2	17,18,19
Cep A HW2	$\sim 10^4$	1–8	400–600	15	3×10^{-5}	3	20,21; but see 22
AFGL 2591	2×10^4	0.4–1.8	500	16	5.8×10^{-4}	6	23,24,25
IRAS 18089–1732	6×10^4	12–45	1000	<25	?	4	26,27
M17	?	4–>110	7500–20000	<8–20	?	?	28,29

[a] 1: *Schreyer et al.* (2002, 2006); 2: *Mitchell et al.* (1992); 3: *Shepherd and Kurtz* (1999); 4: *Shepherd et al.* (2001);
5: *Zhang et al.* (2002); 6: *Hunter et al.* (1999); 7: *Bernard et al.* (1999); 8: *Jiang et al.* (2005); 9: *Scoville et al.* (1983);
10: *Greenhill et al.* (2004); 11: *Genzel and Stutzki* (1989); 12: *Cesaroni et al.* (1997); 13: *Zhang et al.* (1998b);
14: *Cesaroni et al.* (1999a); 15: *Cesaroni et al.* (2005); 16: *Shepherd et al.* (2000); 17: *Hutawarakorn and Cohen* (1999);
18: *Fuller et al.* (2001); 19: *Dent et al.* (1985); 20: *Gómez et al.* (1999); 21: *Patel et al.* (2005);
22: *Comito et al.* (in prep.) challenge the disk interpretation; 23: *Hasegawa and Mitchell* (1995); 24: *van der Tak and Menten* (2005);
25: *van der Tak et al.* (2006); 26: *Beuther et al.* (2004b); 27: *Beuther et al.* (2005); 28: *Chini et al.* (2004); 29: *Sako et al.* (2005);
[b] see *Hillenbrand et al.* (2001) and references therein; values depend on adopted mass-luminosity conversion.

on the order of $\sim 10^4\ L_\odot$, typical of stars later than B0. What about disks in more luminous/massive objects? Disk searches performed in sources with luminosities typical of O-type stars (i.e. above $\sim 10^5\ L_\odot$) resulted in negative detections: in all cases, as already discussed, massive rotating toroids were found. One possibility is that the latter "hide" true disks in their interiors, still not detectable due to insufficient angular resolution and sensitivity. It must be taken into account that objects that luminous are mostly located at significantly larger distances than B stars. A noticeable exception is Orion, the closest high-mass star forming region (450 pc), whose total luminosity is $\sim 10^5\ L_\odot$. The presence of a disk rotating about source I has been clearly established by VLBI observations of the SiO masers (see Table 2). However, it remains unclear which fraction of the total luminosity is to be attributed to this object. Thanks to their recent high-frequency observations with the SMA, *Beuther et al.* (2006) have interpreted the continuum spectrum of source I as the combination of free-free emission from a uniform HII region plus thermal emission from dust. According to their fit, one expects an optically thin flux of ∼45 mJy at ∼200 GHz, corresponding to a B1 ZAMS star. On the other hand, proper motion measurements of source I and BN (*Rodríguez*, 2005) have demonstrated that the two are receding from each other with speeds respectively of 12 and 27 km s^{-1}. Since the estimated mass of BN lies in the range ∼7–20 $M_\odot$ (see Table 2), the ratio between the two velocities suggests a mass for source I of 16–45 $M_\odot$. While the upper limit is larger than expected for a ZAMS star of $\sim 10^5\ L_\odot$, the lower seems roughly consistent with the estimate from the free-free emission. It is hence possible that Orion I is an early B or late O star. In this case, we would be still missing an example of a disk in an early O-type star.

Is such a lack of evidence for disks in O-type stars due to an observational bias? The absence of disks in O stars could have important theoretical implications, as disks are believed to play a key role in favouring accretion onto the star through angular momentum dissipation. If no disks are present in stars more massive than ∼20 $M_\odot$, alternative models of massive star formation may be needed, such as, e.g., those involving coalescence of lower mass stars (*Bonnell and Bate*, 2005). It is hence in order to discuss all possible technical limitations which may have hindered detection of disks in O-type stars.

2.4 Are disks in O-type stars detectable?

As noted above, no clear evidence for circumstellar disk in early O-type stars has been presented to date. But even disks in B-type stars do not seem to be easy to detect. It is difficult to draw any statistically reliable conclusion on the real number of high-mass YSOs with disks, as most studies have been conducted towards selected candidates. Only one systematic search for disks is known to date: this is the recent survey by *Zhang et al.* (pers. comm.). These authors used the VLA to survey 50 YSOs with luminosities between 10^3 to 10^5 $L_\odot$ in NH_3 inversion transitions, and detected 10 possible disks. Is a detection rate of 20% the one expected if all B-type stars form through disk accretion? And are disks in O-type stars really elusive?

We consider the possibility of an observational bias in disk searches, due to limited sensitivity, angular, and spectral resolution (in the case of line observations). Let us discuss separately the sensitivity and resolution issues.

2.4.1 Spectral and angular resolution. As explained in Section 2.2, most disk searches attempt to detect the velocity gradient due to rotation about the star. To achieve such a detection, the observations must disentangle the emission of the red- and blue-shifted parts of the disk, not only in space but also in velocity. One constraint is hence the angular resolution achieved by current interferometers. As for the spectral resolution, at radio wavelengths one may easily attain 0.1 km s^{-1}, sufficient to resolve lines as broad as a few km s^{-1}. The limitation is due to the line width, of the same order as the expected rotation velocity. Therefore, to detect rotation with velocity V at radius R, two conditions must be fulfilled: the separation between two diametrically opposite points must be greater than the instrumental half power beam width (HPBW); and the corresponding velocity difference must be greater than the line full width at half maximum (FWHM). These may be expressed as:

$$2\,R \;>\; \Theta\,d \qquad (1)$$

$$2\,V(R)\,\sin i \;>\; W \qquad (2)$$

where i is the inclination angle with respect to the line of sight ($i = 0$ for a face-on disk), Θ the HPBW, d the distance to the source, and W the line FWHM. For a star with mass $M_\star$, $V = \sqrt{G\,M_\star/R}$, so that one obtains

$$d(\mathrm{kpc}) < 7\frac{M_\star(M_\odot)\,\sin^2 i}{\Theta('')\,W^2(\mathrm{km\ s^{-1}})}. \qquad (3)$$

A conservative estimate of this expression may be obtained for $\Theta = 1''$ (the HPBW of millimeter interferometer), $W = 5$ km s^{-1}(the typical line FWHM of a hot molecular core – to be taken as an upper limit, as the intrinsic line width is less than the observed one), and a mean value of $\langle\sin^2 i\rangle = 2/3$ assuming random orientation for the disk axes. The result is $d(\mathrm{kpc}) < 0.19 M_\star(M_\odot)$ which implies that the maximum distance at which a disk can be detected in, e.g., a 50 $M_\odot$ star is 9.5 kpc. This shows that disks in all massive stars should be seen up to the Galactic center.

The previous analysis does not take properly into account the effect of the inclination angle, as well as other effects which may complicate the picture: infall and outflow, disk flaring, and non-Keplerian rotation. Further complication is added by the presence of multiple (proto)stars, each of these possibly associated with and outflow/disk, and by the fact that molecular species believed to be "pure" disk tracers might instead exist also in the outflow.

Naïvely, infall and rotation speeds should both be $\propto R^{-0.5}$ and hence comparable, so that the Keplerian pattern should be only slightly affected. However, recent observations have revealed infall with no or little rotation, in the O-type (proto)stars, G10.62–0.38 (*Sollins et al.*, 2005a) and IRAS 18566+0408 (*Zhang* pers. comm.). This occurs on spatial scales of ~1000 AU, comparable to those over which pure rotation is seen in the B-type sources of Table 2. Possible explanations must involve angular momentum dissipation, perhaps due to magnetic field braking.

Deviation from Keplerian rotation is expected to occur at large radii, where the enclosed disk mass becomes comparable to the stellar mass (see the example in Section 3): in this case, though, the value of V is larger than in the Keplerian case and Eq. (2) is satisfied.

Outflows could "spoil" the detection of disks, because the ratio between expansion and rotation speeds may be as large as ~100. However, the molecular lines used for disk searches do not seem to trace also the outflow/jet: an illuminating example of this is given by the best studied disk-outflow/jet system to date, IRAS 20126+4104: here the Keplerian disk (rotating at a few km s^{-1}; *Cesaroni et al.*, 2005) is clearly seen in the CH_3CN lines, notwithstanding the presence of a jet with velocities in excess of 100 km s^{-1} (*Moscadelli et al.*, 2005) on the same scale as the disk. It is hence clear that the success of disk searches and the possibility to decouple them from the associated outflows/jets depend crucially on the molecular tracers used.

Finally, disk flaring may help revealing rotation. In fact, while Eq. (3) depends sensitively on the inclination angle i, this result is obtained for an infinitesimally thin disk. Real disks have a finite $H(R)$ and, considering as an example IRAS 20126+4104, we can assume $H = R/2$ (see Section 4.2). Under this assumption, the line of sight will lie in the plane of the disk as long as $76^\circ < i < 104^\circ$. For a random orientation of the disk axis, this implies that ~24% of the disks will satisfy this condition. Noticeably, such a number is very close to the 20% detection rate obtained in the previously mentioned NH_3 survey by *Zhang et al.* and suggests that disk inclination should not represent a serious limitation for disk searches.

2.4.2 Sensitivity. The continuum emission from disks in the (sub)millimeter regime (see also Section 2.2) should be easily detected by modern interferometers. This can be evaluated assuming a disk mass M proportional to the stellar mass $M_\star$, e.g., $M = M_\star/2$ (see Table 2) and a dust temperature of 100 K. The flux density measured at a distance d is equal to

$$S_\nu(\mathrm{mJy}) = 85.3\,\left[\frac{\nu(\mathrm{GHz})}{230.6}\right]^{2+\beta}\,M_\star(M_\odot)\,d^{-2}(\mathrm{kpc}) \qquad (4)$$

where a dust absorption coefficient equal to 0.005 $\mathrm{cm^2\,g^{-1}}$ $[\nu(\mathrm{GHz})/230.6]^\beta$ has been adopted (*Kramer et al.*, 1998). Very conservatively, one may assume a sensitivity of 30 mJy at 230.6 GHz, which sets the constraint $d(\mathrm{kpc}) < 1.7\sqrt{M_\star(M_\odot)}$. Disks associated with stars of 10 and 50 $M_\odot$ should be detectable up to 5.4 and 12 kpc, respectively. Therefore, the main limitation is not given by the sensitivity but by confusion with the circumstellar envelope, as illustrated in Section 2.2.

On the other hand, line observations are less affected by this problem, as the velocity information helps decoupling the rotating disk from the more quiescent envelope. The line intensity may be estimated under the assumption of optically thick emission. For $T \gtrsim 100$ K, the flux density from the disk surface within a radius R must be at least

$$S_\nu = \frac{R^2\,\pi B_\nu(T)}{4\,\pi\,d^2} \qquad (5)$$

with B_ν black-body brightness. Here, we have assumed R^2 as a lower limit to the surface: this relies upon the fact that the disk thickness is $\sim R/2$, so that the effective surface ranges from R^2 (edge on) to πR^2 (face on). In order to detect the line emission from the disk with an instrumental noise σ, one must have $S_\nu > 3\,\sigma$, which using Eq. (5) turns into $R > \sqrt{12\sigma/B_\nu(T)}d$. The radius within which the flux is measured must satisfy also Eq. (2). For the sake of simplicity, we assume a temperature $T = 100$ K independent of R and a noise $\sigma \simeq 0.1$ Jy at 230 GHz, thus obtaining

$$d(\mathrm{kpc}) < 6.2\frac{M_\star(M_\odot)\sin^2 i}{W^2(\mathrm{km\ s^{-1}})} \qquad (6)$$

For the same fiducial values adopted for Eq. (3), this condition takes the form $d(\mathrm{kpc}) < 0.16\,M_\star(M_\odot)$. Once more, all stars of a few 10 $M_\odot$ should be detectable up to the Galactic center.

In conclusion, albeit very rough, the previous discussion suggests that the currently available instruments should be sufficient to detect circumstellar disks around all massive stars, if the disk mass is non-negligible with respect to the stellar mass. One must hence look for an astronomical explanation to justify the lack of detections for disks in O-type stars. As illustrated in the following, this might be found in the stability and/or lifetime of massive disks.

3. IRAS 20126+4104: THE PROTOTYPE DISK

Among the disk candidates listed in Table 2, one stands unique as the best studied and probably most convincing example of a Keplerian disk rotating about a massive YSO. This is IRAS 20126+4104, an IRAS point source believed to be associated with the Cyg X region (*Wilking et al.*, 1989 and references therein). First recognized by *Cohen et al.* (1988) as an OH maser emitter, it was then observed in the continuum, at millimeter wavelengths (*Wilking et al.*, 1989; *Walker et al.*, 1990), and in the CO(2–1) line by *Wilking et al.* (1990), who detected a powerful, parsec-scale molecular outflow. Later on, association with H_2O and CH_3OH masers was also established (*Palla et al.*, 1991; *MacLeod and Gaylard*, 1992) and the molecular emission from high-density tracers was detected (*Estalella et al.*, 1993). These pioneering works provided evidence that the source is associated with a luminous, embedded star still in a very early stage of the evolution. The fact that no free-free continuum was detected (*Tofani et al.*, 1995) indicated that although luminous, the source had not yet developed an HII region, while the presence of a molecular outflow suggested that the YSO could be actively accreting material from the parental cloud. Eventually, observations at 3 mm with the Plateau de Bure interferometer (*Cesaroni et al.*, 1997) achieved the angular resolution needed to dissect the outflow and analyse the velocity field in the associated molecular core. Thanks to these observations, it was first recognized that the core was rotating about the outflow axis.

This finding triggered a burst of observations towards IRAS 20126+4104, thus shedding light on its properties and allowing us to draw a detailed picture which is best summarized in Fig. 1. The main features of this object may be summarized as follows.

(1) The spectral energy distribution, well sampled at (sub)millimeter and mid-IR wavelengths (*Cesaroni et al.*, 1999a and references therein) supplies us with a luminosity of $\sim 10^4\ L_\odot$ for a distance of 1.7 kpc. Although near-IR observations of the 2.2 μm continuum reveal an embedded cluster spread over 0.5 pc (*Cesaroni et al.*, 1997), arcsecond resolution mid-IR images (*Cesaroni et al.*, 1999a; *Shepherd et al.*, 2000; *Sridharan et al.*, 2005) prove that most of the luminosity arises from the inner 1000 AU.

(2) A bipolar molecular outflow is seen in various tracers, including CO and HCO^+ (*Wilking et al.*, 1990; *Cesaroni et al.*, 1997, 1999b; *Shepherd et al.*, 2000). The kinematical outflow age is $t_{\rm out} \simeq 6\times10^4$ yr, which may be taken as a lower limit to the age of the YSO powering the flow. The momentum (400 $M_\odot$ km s^{-1}) and mass loss rate ($8\times10^{-4}\ M_\odot$yr^{-1}), as well as the other parameters of the flow, are typical of outflows in high-mass YSOs.

(3) The orientation of the outflow axis changes by $\sim 45°$ from the large (1 pc) to the small (0.1 pc) scale. A similar behaviour is observed in H_2 knots which are distributed along the outflow axis and thus describe an S-shaped pattern centred on the YSO powering the flow (*Shepherd et al.*, 2000). These features supply evidence that one is observing a precessing jet feeding the outflow, the former outlined by the shocked H_2 emission, the latter by the CO and HCO^+ line emission. *Cesaroni et al.* (2005) estimate a precession period of 2×10^4 yr, which implies that the jet/outflow has undergone at least 3 full precessions.

(4) The collimated jet traced by the H_2 knots is also seen on the same scale in other molecular tracers such as SiO (*Cesaroni et al.*, 1999a; *Liu et al.*, 2005), NH_3 (*Zhang et al.*, 1999) and CH_3OH (*Cesaroni et al.*, 2005), although the morphology and kinematics of the gas may vary significantly from molecules tracing the pre-shock and those arising from the post-shock material (*Cesaroni et al.*, 2005). The expansion speed of the jet over 0.5 pc is estimated $\sim$100 km s^{-1} (*Cesaroni et al.*, 1999a), while the component along the line of sight is relatively small, of order $\pm$20 km s^{-1}. This finding and the fact that both blueand red-shifted emission overlap in space prove that the jet/outflow axis inside ≤ 0.5 pc from the YSO lies very close to the plane of the sky, at an angle $\lesssim 9^\circ$. Proper motion measurements of the H_2O masers indicate a jet expansion speed in excess of ~ 100 km s^{-1} at a distance of ~ 250 AU from the powering source (*Moscadelli et al.*, 2005), while on an intermediate scale between the one traced by H_2 (and other molecular lines) and that sampled by the H_2O masers, free-free emission from the thermal component of the jet is seen at 3.6 cm (*Hofner et al.*, 1999). All these results indicate that the jet/outflow system extends almost continuously from the neighbourhoods of the YSO powering it, to the outer borders of the parental molecular clump.

(5) At the geometrical center of the bipolar jet/outflow, a hot molecular core is detected, of ~ 200 K. When observed at high angular resolution in the CH_3CN transitions, this core presents a velocity gradient roughly perpendicular to the jet. *Cesaroni et al.* (1997) interpreted this result as rotation about the YSO powering the outflow, while subsequent imaging in CH_3CN(12–11) (*Cesaroni et al.*, 1999a), NH_3(1,1) and (2,2) (*Zhang et al.*, 1998b) and $C^{34}S$(2–1) and (5–4) (*Cesaroni et al.*, 2005) has established that the rotation is Keplerian. However, the estimate of the stellar mass seems to differ depending on the tracer used to measure the rotation curve. In fact, going from a few 10^3 AU to 10^4 AU, such an estimate changes from 7 $M_\odot$ (*Cesaroni et al.*, 2005) to 24 $M_\odot$ (*Zhang et al.*, 1998b). This effect may be due to the disk mass enclosed inside the radius at which the velocity is measured (*Bertin and Lodato*, 1999): for small radii, the disk mass inside that radius ($\sim 4\ M_\odot$) is less than that of the star, whereas at large radii the two become comparable, thus mimicking Keplerian rotation about a bigger star. *Cesaroni et al.* (2005) have also estimated the temperature profile as a function of radius, which seems to be compatible with the "classical" law expected for geometrically thin disks heated externally by the star or internally by viscosity: $T \propto R^{-3/4}$. The mean disk temperature is of order ~ 170 K. Additional evidence of a circumstellar or possibly circumbinary disk in IRAS 20126+4104 comes also from OH and CH_3OH maser studies (*Edris et al.*, 2005), as well as from recent near and mid-IR continuum images obtained by *Sridharan et al.* (2005). In particular, at 2.2 μm the disk is seen in absorption as a dark silhouette similar to those observed in the optical towards the proplyds in the Orion nebula (e.g., *O'Dell and Wen*, 1994).

In conclusion, the observational results obtained for IRAS 20126+4104 provide robust evidence for the existence of a Keplerian disk associated with a precessing jet/outflow powered by a massive YSO of $\sim 10^4\ L_\odot$. One possibility is that one is dealing with a binary system, as suggested by the jet precession which may be caused by interaction with a companion. Indeed, the latter seems to appear as a secondary peak, close to the disk border, in the mid-IR images by *Sridharan et al.* (2005). However, it is unlikely that the mass of the companion is comparable to that of the YSO at the center of the disk, because the Keplerian pattern does not seem to be significantly perturbed by the presence of the second star. Better angular resolution and sensitivity are required to settle the binary issue.

4. FORMATION AND STABILITY OF MASSIVE DISKS

In this section, we consider some theoretical problems posed by the existence of massive (few solar masses) disks around massive protostars as in the cases listed in Table 2. One obvious question is that of their stability particularly if, as seems likely, the disk mass in some cases is comparable to the stellar mass. A second problem is posed by the high accretion rates needed both to form the massive stars on a reasonable timescale (typically 10^5 years, according to *Tan and McKee*, 2004) and to account for the observed large outflow rates. We ask the question of whether classical "α-disk models" can account for such high accretion rates and conclude it is unlikely. Thirdly, following the approach of *Hollenbach et al.* (2000), we consider briefly effects which might limit massive disk lifetimes in the phase just subsequent to the cessation of accretion. We commence however by a brief discussion of what one might naively expect to be the properties of disks associated with massive protostars.

4.1 From clouds to disks

From a theoretical point of view, the presence of disks around massive protostars is expected on the same physical grounds as in the case of solar mass protostars. In a simple inside-out collapse with constant accretion rate (*Terebey et al.*, 1984), the mass of the disk increases linearly with time, $M \propto t$, whereas the disk radius increases much faster, $R \propto t^3$, or $R \propto M^3$. Thus, in principle, we expect massive, centrifugally supported disks to have much larger sizes than the low-mass disks observed around T Tauri stars.

In particular, the sizes and masses of the disks observed around young massive stars can be used to set constraints on the physical characteristics of the clouds from which they formed. It is a good approximation to express the disk angular velocity at a radius R as $\Omega(R) \approx (GM_{\rm t}/R^3)^{1/2}$ (*Mestel*, 1963), where $M_{\rm t}$ is the total (star plus disk) mass of the system (the relation holds exactly only for a surface density $\Sigma \propto R^{-1}$). The specific angular momentum of the system is then $J/M_{\rm t} \approx \Omega R^2 \approx (GM_{\rm t}R)^{1/2} \approx 10^{-2}$ km s^{-1} pc with the values listed in Table 2 for IRAS 20126+4104. This is within the range of observed values of the specific angular momentum of molecular cloud cores in low-mass star forming regions ($J_{\rm c}/M_{\rm c} \approx 10^{-3}$–$10^{-1}$ km s^{-1} pc; *Goodman et al.*, 1993), although it is unclear if similar values pertain to massive star-forming regions too.

In any case, the formation of disks like IRAS 20126+4104 from the collapse of slowly rotating clumps appears physically possible, and seems to imply that the clump's angular momentum is not much reduced during the formation of a massive disk. It is possible to obtain the radius $R_{\rm i}$ within which the mass $M_{\rm t}$ of the star plus disk system was originally contained in

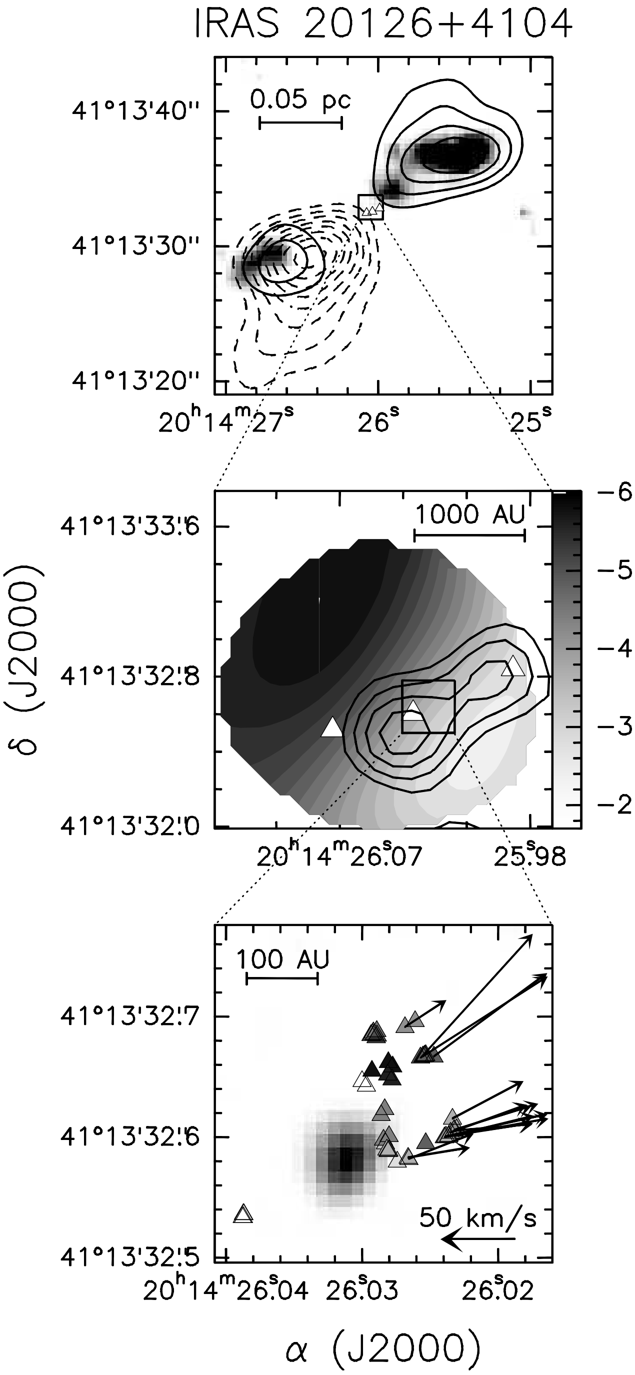

Fig. 1.— Disk/outflow system in the high-mass (proto)star IRAS 20126+4104. Top: Overlay of the H_2 lime emission at 2.2 μm (grey scale) and the bipolar outflow traced by the HCO^+(1–0) line (*Cesaroni et al.*, 1997). Solid and dashed contours correspond respectively to blue- and red-shifted gas. The triangles mark the positions of the H_2O maser spots detected by *Tofani et al.* (1995). Middle: 3.6 cm continuum map (contours; *Hofner et al.*, 1999) overlaied on a map of the velocity measured in the $C^{34}S$(5–4) line by *Cesaroni et al.* (2005). Bottom: Distribution of the H_2O maser spots (*Moscadelli et al.*, 2000, 2005) compared to a VLA map (image) of the 7 mm continuum emission (*Hofner*, pers. comm.). The grey scale of the spots ranges from white, for the most red-shifted spots, to black, for the most blue-shifted. The arrows denote the absolute proper motions of the spots, measured by *Moscadelli et al.* (2005).

the parental cloud, $R_\mathrm{i} \gtrsim (GM_\mathrm{t}R/\Omega_\mathrm{c}^2)^{1/4}$, where Ω_c is the cloud's angular rotation. This imposes a severe constraint on the effective sound speed in the cloud $c_\mathrm{eff} \approx GM_\mathrm{t}/2R_\mathrm{i} \lesssim (G^3M_\mathrm{t}^3\Omega_\mathrm{c}^2/2R)^{1/8} \approx$ 1–2 km s^{-1} for $\Omega_\mathrm{c} \approx 1$ km s^{-1} pc^{-1}. Notice that the resulting accretion rate $\dot{M} \approx c_\mathrm{eff}^3/G$ is $\dot{M} \approx 2 \times 10^{-4}\ M_\odot$ yr^{-1}, which implies a timescale of $\sim 6 \times 10^4$ yr for the formation of the IRAS 20126+4104 star plus disk system, in agreement with the inferred outflow kinematical age (see Table 2). Thus, the cloud cores where massive stars are formed must be characterized, at least in their central parts, by low or moderate levels of turbulence, similarly to their low-mass counterparts. The cold, massive ($M_\mathrm{c} \approx 10^2\ M_\odot$) molecular cloud cores with narrow linewidhts ($\Delta v \approx 1$ km s^{-1}) recently discovered by *Birkmann et al.* (2006) seem to present the required properties, and suggest that the initial conditions for the formation of massive stars should be similar to those observed in low-mass star forming regions.

Numerical calculations of the collapse of massive molecular cores have been performed by *Yorke and Sonnhalter* (2002), who also included a detailed treatment of continuum radiation transfer. The calculations start from cold, massive, slowly rotating clouds far from equilibrium that typically contain tens of Jeans masses. The resulting mass accretion rate is strongly time-dependent, peaking at a value $\dot{M} \approx 10^{-3}\ M_\odot$ yr^{-1} after $\sim 10^4$ yr from the onset of collapse and declining thereafter because of radiation pressure. In some cases, the infalling material flows onto a disklike feature appearing after $\sim 10^5$ yr from the onset of collapse, which rapidly extends up to 10^4 AU in radius. The calculated density in the outer disk is $\sim 10^{-18}$ g cm^{-3} and compares well with that inferred from the ratio of $C^{34}S$ (2–1) and (5–4) lines measured in IRAS 20126+4104 at radii $R \gtrsim 2000$ AU. The calculations suggest that for disks around stars above $\sim 20\ M_\odot$ stellar radiative forces may contribute as much as rotation to the radial support of the disk. The disk may also be short-lived disappearing after some 10^4 yr.

4.2 Local gravitational stability of massive disks

It is well known, since *Toomre* (1964), that a fluid, thin disk is unstable to axisymmetric gravitational disturbances if the stability parameter

$$Q = \frac{c_s\kappa}{\pi G\Sigma} < 1, \tag{7}$$

where c_s is the sound speed, Σ the disk surface density, and κ the epicyclic frequency. The angular velocity and the epicyclic frequency are related by $\kappa = f\Omega$, where f is a numerical factor dependent on the shape of the rotation curve: for Keplerian rotation $f = 1$, while for a flat rotation curve $f = \sqrt{2}$

The value of Q, the disk aspect ratio and the total disk mass can be easily related to one another in the following way. The disk thickness H is given by

$$H = \begin{cases} c_s/\Omega & \text{if } M/M_\mathrm{t} \ll H/R \\ c_s^2/\pi G\Sigma & \text{if } M/M_\mathrm{t} \gtrsim H/R. \end{cases} \tag{8}$$

If we assume a power-law behaviour for $\Sigma \propto R^{-1}$, so that $M(R) = 2\pi\Sigma R^2$, and we adopt the approximation $\Omega \approx (GM_{\rm t}/R^3)^{1/2}$, we can rewrite Q as

$$Q = \begin{cases} \frac{2H}{R}\frac{M_{\rm t}}{M} \gg 1 & \text{if } \frac{M}{M_{\rm t}} \ll \frac{H}{R} \\ \left(\frac{2H}{R}\frac{M_{\rm t}}{M}\right)^{1/2} \lesssim \sqrt{2} & \text{if } \frac{H}{R} \lesssim \frac{M}{M_{\rm t}} \ll 1 \\ \left(\frac{4H}{R}\frac{M_{\rm t}}{M}\right)^{1/2} \simeq 2\sqrt{\frac{H}{R}} & \text{if } \frac{M}{M_{\rm t}} \approx 1 \end{cases} \quad (9)$$

The relationship between cumulative disk mass, aspect ratio and stability parameter Q is also shown in Fig. 2, that shows a contour plot of Q, as a function of $M/M_{\rm t}$ and of H/R based on the equation above. We wish to stress that Q is only a measure of the local stability of a massive disk: the above relationship and the figure describe the stability of the disk at a radius R, where M is the disk mass enclosed within R and the aspect ratio H/R is computed at R. We then see that, in order for the disk to be gravitationally unstable, we need $M/M_{\rm t} \gtrsim 2\,H/R$.

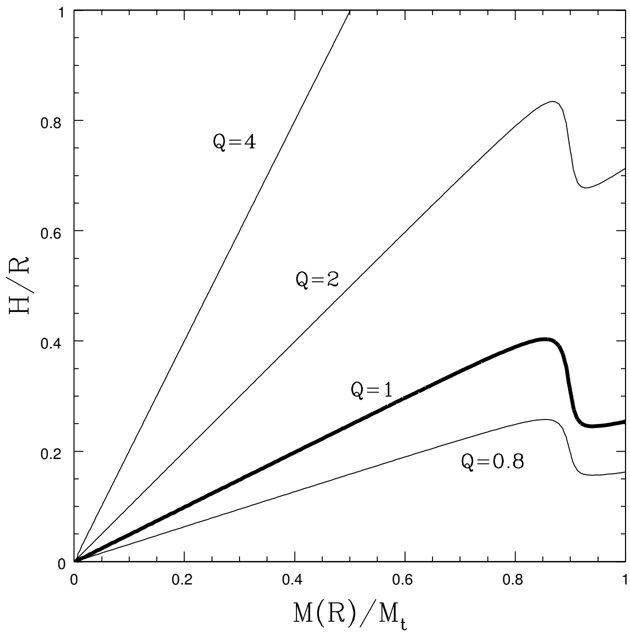

Fig. 2.— Contour plot of the relationship between stability parameter Q, enclosed disk mass $M(R)/M_{\rm t}$ and aspect ratio H/R. This plot describes local stability at radius R, and M has to be intended as the mass enclosed within R. The curves are computed under the assumption that $\Sigma \propto R^{-1}$. The wiggles at large disk mass indicate the transition from a Keplerian to a flat rotation curve. The thick contour corresponds to $Q = 1$, which marks the threshold between stability and instability.

Non-axisymmetric, spiral disturbances are generally more unstable, and thin disks can result unstable at considerably larger values of $Q \approx$ 3–4. On the other hand, it is also well known that a finite thickness is a strong stabilizing effect. The general problem of finding the marginal stability of a thick disk with respect to non-axisymmetric instabilities is however too complex to be treated analytically. Numerical simulations (*Lodato and Rice*, 2004, see below) seem to show that relatively thick and massive disks evolve in such a way to achieve $Q \approx 1$.

The simple estimate of Q outlined above and shown in Fig. 2 offers an easy tool to evaluate the local stability of the massive disks observed around massive stars. Let us take, as an example, the case of IRAS 20126+4104 and consider its properties at a radius $R \approx 1600$ AU. As we have seen before, the enclosed mass within 1600 AU is of the order of 4 $M_\odot$, while the central object mass is 7 $M_\odot$, so that $M(R)/M_{\rm t} \approx 0.4$. The average temperature at R is 170 K, so that $H/R \approx 0.4$. With these estimates, the value of Q turns out to be $Q \approx 2$ (see Fig. 2). The disk is therefore expected to be stable with respect to axisymmetric disturbances but unstable with respect to spiral instabilities.

4.3 Transport properties and evolution of massive disks

From theoretical models of massive star formation (*Yorke and Sonnhalter*, 2002) we know (see above) that in order to form massive stars, the disk has to be fed at high accretion rates (of the order of $10^{-3}\ M_\odot{\rm yr}^{-1}$). On the other hand, we also know from observations that this mass has to be transported at similar rates to small radii, in order to resupply the powerful outflows observed in these systems (with outflow rates in the range of $10^{-4} - 10^{-3}\ M_\odot{\rm yr}^{-1}$, see Table 2). The natural question that arises is therefore whether in the disk there are efficient mechanisms able to deliver the torques needed to redistribute the angular momentum within the disk at the required rates.

Torques in accretion disks are generally parametrized through the dimensionless parameter α, that measures the strength of the viscous torques relative to the local disk pressure. The most promising mechanism of transport in disks is usually considered to be related to MHD instabilities, and in particular to the magneto-rotational instability (*Balbus and Hawley*, 1992). This kind of instability is able to provide torques with $\alpha \approx 10^{-2}$ (see *Balbus*, 2003 for a review). It is not clear, however, how efficient such processes can be in the cold outer regions of the disk, where the ionization level is expected to be small.

On the other hand, we have just shown how the massive disks observed around massive stars are likely to be gravitationally unstable. This leads to another important source of angular momentum transport, in the form of gravitational instabilities. In this context, numerical simulations play a very important role, being the only way to follow the dynamics of gravitationally unstable disks to the non-linear regime. A detailed discussion of the role of gravitational instabilities is presented in the chapter by *Boss et al.*. Here, we will only summarize the main results on this issue, in consideration of the particular properties of disks around massive stars (taking, as a prototypical example, the case of IRAS 20126+4104).

Laughlin and Bodenheimer (1994), in a pioneering work, have shown for the first time through smoothed particle hydrodynamics simulations the effectiveness of gravitational instabilities in promoting the accretion process. They found that the redistribution of matter in the disk, due to the spiral structure, occurs over a few rotational periods. However, these early simulations were limited by the particular choice of the equation of state of the gas in the disk. *Laughling and Bodenheimer* (1994), in fact, assumed that the disk is isothermal, thus inhibiting the important feedback effect on the disk stability provided by the heating of the disk due to the instability itself.

A full treatment of the disk thermodynamics, including a detailed radiation transfer through the disk, is presently impossible to achieve with current numerical techniques (although progress is being made to include a more realistic cooling, see *Johnson and Gammie*, 2003). The approach that has been taken more recently is to adopt some simplified prescription for the cooling of the disk and constrain the evolution under such simplified conditions (*Laughlin and Korchagin*, 1996; *Pickett et al.*, 2000; *Gammie*, 2001; *Lodato and Rice*, 2004, 2005). *Gammie* (2001) assumed that $t_{\rm cool} = \beta\Omega^{-1}$ and found that for $\beta < 3$ the disk fragments into bound objects, whereas for $\beta > 3$ a quasi-steady unstable state is reached, in which efficient redistribution of angular momentum takes place. *Lodato and Rice* (2004, 2005) have extended the analysis of Gammie to a full 3-dimensional, global context. In this way they were able to study the effect of the development of global spiral structures on the disk evolution, which is precluded in the local simulations by Gammie. The general result of these simulations (either local or global) is that the gravitational instability saturates at an amplitude such that the dissipation provided by the instability is able to balance the imposed cooling. The typical values of α found in these simulations are in the range $0.01 - 0.06$. More recently, *Rice et al.* (2005) have elucidated the process of fragmentation in massive disks, finding that a self-gravitating disk can provide a stress no larger than $\alpha \approx 0.06$. If the cooling time is so short that the dissipation required to balance it is larger than this maximum, the response of the disk is to fragment.

We can now estimate the maximum accretion rate expected for a centrifugally supported accretion disk. Assuming a density profile $\Sigma \propto R^{-p}$, we have

$$\dot{M} = 3\pi\nu\Sigma \approx \frac{\alpha}{2-p}\left(\frac{H}{R}\right)^2 M(R)\Omega(R), \qquad (10)$$

where $\nu = \alpha H^2\Omega$ is the viscosity, expressed through the *Shakura-Sunyaev* (1973) prescription, and $M(R)$ is the disk mass enclosed within R. Let us consider, as an illustration, the case of IRAS 20126+4104, where the mass enclosed within $R = 1600$ AU is $M = 4\ M_\odot$, and the aspect ratio is $H/R \approx 0.4$ (see Section 4.2). With $\alpha = 0.06$ and $p = 1$ we find that the maximum accretion rate that can be delivered by gravitational instabilities is $\dot{M} \approx 10^{-5}\ M_\odot$ yr^{-1}, much smaller than the values required to power the outflow (the MRI instability can only provide lower accretion rates). It is important to stress that the above numerical estimate for the mass accretion rate depends on the specific radius at which we evaluate the enclosed mass and the angular velocity at that radius. The "problem" that we are referring to here refers to the difficulty of transferring to the star $\sim 4\ M_\odot$ from a distance of ~ 1600 AU through a standard accretion disk. The problem may be alleviated (or eliminated) if the density distribution in the disk is very steep ($p \approx 2$) and most of the disk mass is concentrated at small radii where the rotation period is shorter and therefore the disk's dynamical evolution is faster.

The required high accretion rates pose in general a serious challenge for theoretical models. However, we must keep in mind that the accretion rates predicted by hydrodynamical or magnetohydrodynamical disk simulations is highly variable in time, and may be temporarily enhanced by an order of magnitude above the average value. For example, *Lodato and Rice* (2004, 2005) have compared simulations of self-gravitating disks of low ($M \ll M_\star$) and high mass ($M \approx M_\star$), finding that low-and high-mass disks behave somewhat differently. In the low-mass case a self-regulated state is rapidly achieved and the evolution of the disk after the development of the gravitational instability is quasi-steady. On the other hand, as M approaches $M_\star$ the temporal behaviour of the disk becomes more complex and a series of recurrent episodes of spiral activity are often seen, lasting for roughly one rotation period, of the order of $\sim 10^4$ yr in IRAS 20126+4104 at a radius of ~ 1600 AU. During such episodes, the efficiency of angular momentum transport increases by at least one order of magnitude. In this way one might expect the inner disk to be episodically resupplied to power the outflow. Such episodes are observed to last for a few rotation periods, a timescale not inconsistent with the estimated outflow kinematic age (see Table 2). This recurrent behaviour is also observed in simulations of magnetized disks, as a consequence of the interaction between gravitational and magnetic instabilities (*Fromang et al.*, 2004a, 2004b), that can lead to a periodic variability of the accretion rate.

Finally, it should be remembered that the energy transport in self-gravitating disks might be dominated by wave transport, rather than by viscous diffusion (*Balbus and Papaloizou*, 1999). These non-local effects may affect significantly the rate of mass transfer through the disk and possibly lead to higher values of α. However, the evidence for these non-local phenomena remains controversial – see *Lodato and Rice* (2004, 2005), *Pickett et al.* (2003), and *Mejía et al.* (2005) for contrasting views.

5. DISK LIFETIME

The radiation emitted by the central star affects the structure and evolution of the surrounding disk in many ways. One of the most important effects is the possibility of photo-evaporative mass flows from the surface of the disk. These processes have been studied extensively in the past, starting from *Hollenbach et al.* (1993, 1994), who proposed that the process of photo-evaporation of a massive disk could lead to the formation of an ultracompact HII region.

The basic idea of the photo-evaporation is that the ionizing ultraviolet radiation from the central star can produce a thin, hot layer of ionized material at the surface of the disk. Far enough from the central star, this thin layer can be hot enough to become unbound from the star and leave the disk plane to form a photo-evaporative outflow. The radius outside which this outflow can be produced is obtained by equating the thermal energy of the hot gas to the gravitational binding energy – see Eq. (2.1) of *Hollenbach et al.* (1994). The photo-evaporation outflow rate depends sensitively on the magnitude of the ionizing flux Φ:

$$\dot{M}_{\rm ph} \approx 10^{-6} \left(\frac{\Phi}{10^{47}{\rm s}^{-1}} \right)^{1/2} \left(\frac{M_\star}{10\, M_\odot} \right)^{1/2} M_\odot\ {\rm yr}^{-1}, \quad (11)$$

where we have scaled the main parameters to values typical of a B0 star. The above estimates, based on a simple static model, neglect the effects of dust opacity. However, more realistic models (*Richling and Yorke*, 1997) confirm the estimate of an outflow rate of $\sim 10^{-6} M_\odot$ yr^{-1} for a typical B star, as in the case of IRAS 20126+4104.

Note that the photo-evaporation outflow rate estimated above is much smaller than the typical accretion rate estimated for these systems (see Sections. 2.3 and 4). However, the situation might be different for O stars, where the photo-evaporation lifetime becomes comparable to the accretion time-scale (*Yorke*, 2004b). In order to properly assess the interplay between viscous evolution and photo-evaporation (especially for very high-mass stars, where the two processes occur on comparable time-scales), we need models that incorporate both processes. Such models have been developed only in the context of low-mass young stars (*Clarke et al.*, 2001; *Matsuyama et al.*, 2003), but their extrapolation to higher masses is not straightforward.

6. THE EFFECTS OF STELLAR COMPANIONS

A process competing with photo-evaporation in the dispersal of disk material at distances $\sim 10^3$ AU from the central star is the tidal stripping due to encounters with binary or cluster companions. This process may result in the truncation of the disk at smaller radii, or in the complete dispersal of the disk material depending on the impact parameter of the collision. The following two limiting cases are easy to analyse.

(*a*) If the periastron of the companion is inside the primary's disk, the interaction is highly destructive, and results in removing all disk material external to the periastron in a single orbital transit. A smaller circumstellar disk of radius $\sim 1/3$ of the original periastron radius may survive or reform shortly after the interaction, as shown by *Clarke and Pringle* (1993) and *Hall et al.* (1996).

(*b*) For a wide binary system, the maximum size of a circumstellar accretion disk is smaller than the Roche lobe (*Paczynski*, 1977). For stars of comparable mass M_1 and M_2 this is a fraction $\sim 0.4 + 0.2 \log(M_1/M_2)$ of the semi-major axis (*Paczynski*, 1971). Under these assumptions, *Hollenbach et al.* (2000) estimated a time scale of $\sim 2 \times 10^5$ yr for dispersal of a 10^3 AU disk in a cluster with stellar density $\sim 10^4$ pc^{-3} and velocity dispersion ~ 1 km s^{-1}.

It is clear then that a higher frequency of wide binaries (separation $\sim 10^3$ AU) among O-type stars might help to explain the apparent scarcity of large circumstellar disks around these stars discussed in Section 2. There is in fact a possible indication of a trend for increasing degree of multiplicity among stars of the earliest spectral types (*Preibisch et al.*, 2001). For example, the binary frequency in O-type stars ranges from $\sim 40\%$ (*Garmany et al.*, 1980) to $\sim 60\%$ (*Mason et al.*, 1998), whereas the binary frequency of B-type stars is generally lower, of the order $\sim 14\%$ (*McAlister et al.*, 1993). Despite the large statistical uncertainties in these estimates, the possibility of efficient tidal truncation of circumstellar disks by binary companions among O-type stars is not completely negligible, especially for wide binary systems with separations comparable to the disk sizes listed in Table 2, of the order of $\sim 10^2$–10^3 AU. These systems, however, seem to be underrepresented in the Orion Trapezium cluster relative to the main sequence field star population (*McCaughrean et al.*, 2000).

In addition to interactions with an orbiting exterior companion, a circumstellar disk around a star in a dense cluster is also subject to significant tidal forces due to the cluster's gravitational field, that may limit the disk size and affect its evolution. Tidal effects are not important if the variation of the cluster's potential $\mathcal{V}_{\rm cl}$ over a distance of the order of the disk diameter is smaller than the gravitational potential of the star plus disk system itself, $2R{\rm d}\mathcal{V}_{\rm cl}/{\rm d}r < GM_{\rm t}/R$, implying $R^2 < GM_{\rm t}(2{\rm d}\mathcal{V}_{\rm cl}/{\rm d}r)^{-1}$.

For a cluster with central density ρ_0 and central velocity dispersion v_0, the gradient of the gravitational potential is maximum at a distance of the order of the cluster's scale radius $R_{\rm cl} = v_0(6/4\pi G\rho_0)^{1/2}$. For a Plummer's model (see *Spitzer*, 1987), this occurs at a distance $0.71 R_{\rm cl}$ from the cluster's centre, where the enclosed mass is 19% of the total cluster mass $M_{\rm cl} = (4/3)\pi R_{\rm cl}^3 \rho_0$. At this radius, $({\rm d}\mathcal{V}_{\rm cl}/{\rm d}r)_{\rm max} = 0.38\, GM_{\rm cl}/R_{\rm cl}^2$, and the condition on the disk radius becomes $R < 1.1\,(M_{\rm t}/M_{\rm cl})^{1/2} R_{\rm cl}$. Inserting appropriate numerical values, we obtain

$$R < 10^4 \left(\frac{M_{\rm t}}{10\, M_\odot} \right)^{\frac{1}{2}} \left(\frac{v_0}{1\ {\rm km\ s}^{-1}} \right)^{-\frac{1}{2}} \left(\frac{n_\star}{10^4\ {\rm pc}^{-3}} \right)^{-\frac{1}{4}} {\rm AU}, \quad (12)$$

where we have adopted a mean stellar mass in the cluster of 1 $M_\odot$. Tidal effects thus do not seem to be significant for disks of $\sim 10^3$ AU size. For clusters like the Orion Trapezium cluster, however, with $v_0 \approx 4.5$ km s^{-1} (*Jones and Walker*, 1988) and $n_\star \approx 4 \times 10^4$ pc^{-3} (*McCaughrean and Stauffer*, 1994), tidal effects become important for $R \approx$ 3500 AU, not an unrealistic value for massive circumstellar disks, and their contribution to the disk stability and lifetime must be properly taken into account.

7. SUMMARY AND CONCLUSIONS

The way high-mass stars form is matter of debate and observations of circumstellar disks may help to settle this issue. The existence of "disks" rotating about YSOs with masses $\leq 20\ M_\odot$ and luminosities $\leq 10^4\ L_\odot$ is well established, strongly supporting a common formation scenario across the stellar mass spectrum. To date about ten disks in massive stars have been found, among these IRAS 20126+4104 being the best studied. Here one sees a Keplerian disk about a $\sim$7 $M_\odot$ (proto)star associated with a precessing outflow. This suggests the presence of a binary system, with the dominant member lying at the center of the disk. Using IRAS 20126+4104 as a prototype, we have shown that the disk is likely to be gravitationally stable and is bound to develop spiral density waves. These effects may be invoked to solve the problem of transfer of material through the disk, which in a classical α-disk is much less than the expected accretion rate onto the star.

What is still missing is evidence of disks in more luminous objects, namely above $\sim 10^5\ L_\odot$, where only huge, massive, non-equilibrium rotating structures are detected: these we have named "toroids". However, absence of evidence does not imply evidence of absence and it is still possible that O (proto)stars are surrounded by circumstellar disks that remain undetected because of instrumental limitations. Indeed, the distance of these objects is significantly larger than for B-type stars, so that observational biases may play an important role. Also, more massive stars are expected to be associated with richer clusters: the presence of multiple outflows/disks in the same field may confuse the observations. A slightly different possibility is that disks are hidden inside the massive toroids, and one may speculate that the latter could eventually evolve into a sample of circumstellar disks. Alternatively, the formation of large disks might be inhibited in O stars: we have shown that tidal interaction with companions may be effective for this purpose, whereas disk photo-evaporation by the O star occurs over too long a time scale. Consequently, disks in O stars might be truncated at small radii and hence difficult to detect with current techniques.

In conclusion, it seems plausible that massive stars form through disk accretion as well as low-mass ones. However, one cannot neglect the possibility that really *no* disks are present in early O stars: in this case alternative formation scenarios (coalescence, competitive accretion) must be invoked. The advent of new generation instruments such as the Atacama Large Millimeter Array (ALMA) with their high sensitivity and resolution is bound to shed light on this important topic.

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