CLUSTER-ASSISTED ACCRETION FOR MASSIVE STARS

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ABSTRACT

Gravitational interactions in very young high-density stellar clusters can to some degree change the angular momentum in the circumstellar disks initially surrounding the majority of stars. However, for most stars, the cluster environment alters the angular momentum only slightly. For example, in simulations of the Orion Nebula cluster (ONC), encounters reduce the angular momentum of the disks by 3%–5%, on average, and in the higher density region of the Trapezium by 15%–20%—still a minor loss process. However, in this Letter, it is demonstrated that the situation is very different if one considers high-mass stars only ($M > 10 M_\odot$). Assuming an age of 2 Myr for the ONC, their disks have, on average, a 50%–90% lower angular momentum than primordially. This enormous loss in angular momentum in the disk should result in an equivalent increase in accretion, implying that the cluster environment boosts accretion for high-mass stars, thus making them even more massive.

Subject headings: accretion, accretion disks — circumstellar matter — galaxies: star clusters — planetary systems: protoplanetary disks

1. INTRODUCTION

Observational evidence is mounting that most, if not all, stars are initially surrounded by disks. For example, Lada et al. (2000) found that 80%–85% of all stars in the Orion Nebula cluster (ONC) possess a disk. In most cases, young stars are not isolated but part of a cluster. This immediately poses the question as to the relevance of interactions between the cluster members. Back-of-the-envelope estimates indicate that it is very unlikely that these cluster stars themselves collide, and although the cross section for star-disk systems is a lot larger (with disk sizes of approximately a few hundred AU), gravitational interactions between such star-disk systems should play only a minor role. This view is supported by the simulations of Scally & Clarke (2001). However, initial substructuring or gas in the cluster could change the dynamics of encounters in the early stages (Scally & Clarke 2002; Bonnell et al. 1998).

As already noted by Mestel (1965) and Spitzer (1968), the temporal development of the angular momentum in the disk is of vital importance for our understanding of the late stages of star formation. The typical observed angular momentum of the cloud cores from which the stars develop is about 3 orders of magnitude larger than the maximum that can be contained in a single star (Bodenheimer 1995). For the formation of stars and planetary systems, it is essential that angular momentum be transported outward from the inner regions of the disk in some way for accretion to be at all possible. Many different processes have been suggested for this angular momentum transport (see review by Larson 2002). One possible mechanism for accretion-enabling angular momentum transport is gravitational interaction. However, it was demonstrated in Pfalzner & Olczak (2006) that in the ONC, the specific angular momentum loss (AML) averaged over all stars (low-mass to massive) is at most 3%–5%, increasing to 15%–20% in the Trapezium region (the region within 0.3 pc from the cluster center). Therefore, gravitational interactions of single stars seem, at first sight, to be of minor importance for accretion (although possibly not for planet formation).

However, recent detailed simulations (Olczak et al. 2006) of the effect of encounters showed that although the average disk mass loss does not exceed 10%–15% of the disk mass, even in the Trapezium region, the situation is altered remarkably if one considers the massive stars by themselves. The massive stars are predominantly situated close to the cluster center, functioning as gravitational foci for the other cluster stars, and resulting in an ∼60%–100% relative disk mass loss for massive stars (Pfalzner et al. 2006) in the first 2 Myr of the cluster development.

This raises the question as to whether the same can be said for the AML of the massive stars. In the following, it will be shown that indeed the average relative AML is extraordinarily higher for massive stars than for lower mass stars.

2. CLUSTER AND ENCOUNTER SIMULATIONS

As in Pfalzner & Olczak (2006), the ONC was chosen as the model cluster because its high density suggests that stellar encounters might be relevant for the evolution of circumstellar disks. In addition, it is one of the best-studied regions in our Galaxy, so that observational constraints significantly reduce the range of modeling parameters. Combining results of the dynamics of the ONC with those of isolated star-disk encounters allows us to determine the AML of the disks. The procedure is described in detail in Pfalzner & Olczak (2006); here only a short summary of the simulation method is given since the main purpose of this investigation is to reanalyze the data with special emphasis on massive stars.

The dynamical model of the ONC contains only stellar components (~4000 stars, with ~700 of them in the Trapezium region), neglecting gas and the potential of the background molecular cloud OMC-1. Cluster models were set up with a spherical density distribution $\rho(r) \propto r^{-2}$ and a Maxwell-Boltzmann velocity distribution. Some observations indicate a uniform density core of approximately 0.032 pc radius (McCaughrean et al. 2002), but our simulation results are not sensitive to this difference in initial conditions. The masses were generated randomly according to the mass function given by Kroupa et al. (1993) in the range $50 M_\odot \leq M \leq 0.8 M_\odot$, apart from $\theta^1$ Ori C, which was directly assigned a mass of $50 M_\odot$ and placed at the cluster center. The ONC was simulated for 13 Myr—the assumed lifetime of $\theta^1$ Ori C.

The cluster simulations were performed with NBODY6++ (Spurzem 1999), and the quality of the dynamical models were determined by comparing them to the observational data at the
approximate age of the ONC (1–2 Myr). The quantities of interest were the number of stars, the half-mass radius, the number densities, the velocity dispersion, and the projected density profile. Most investigations were performed for the ONC in virial equilibrium. Information concerning all perturbing events of each stellar disk was recorded in an encounter list. It was assumed that only two-body encounters occur and that higher order encounters are negligible, so that the effect of an encounter was investigated by considering it to be isolated from the rest of the cluster.

Earlier angular momentum transport investigations of star-disk encounters (Ostriker 1994; Hall et al. 1996; Pfalzner et al. 2005b) were extended in Pfalzner & Olczak (2006) to cover the parameter range necessary for modeling the ONC. The disk surrounding the star was assumed to extend to \(r_p = 100~\text{AU}\), and the surface density to have a 1/\(r\)-dependence initially. For a star of mass \(M^* = 1~M_\odot\), the angular momentum loss \(\Delta J / J\) induced by the flyby of a star of mass \(M_2^*\) was determined for parabolic, prograde, coplanar encounters for low-mass disks and fitted by

\[
\frac{\Delta J}{J} = 1.02 \left(\frac{M^*_2}{M^*_1 + M^*_2}\right)^{0.5 r_p} \exp \left[-\frac{M^*_2 (r - 0.7 r_p^{0.5})^3}{M^*_2}\right],
\]

where \(r_p\) is the periastron in units of the disk radius. The low-mass assumption matches the observational evidence in the ONC that for most disk masses, \(m_d / M^* \ll 0.1\). This reduces the complexity since low-mass disks do not significantly influence the encounter orbit, self-gravitation and viscosity can be neglected, and the results are scalable to other star masses. Considering only parabolic coplanar, prograde encounters means that the results can only be interpreted as upper limits (Heller 1995; Hall et al. 1996; Pfalzner et al. 2005b).

The wide spectrum of star masses in the cluster requires the simulation results for \(M^*_1 = 1~M_\odot\) to be generalized. Here the disk radius is scaled with the stellar mass according to \(r_p = r_p(1~M_\odot) (M^*_1 / M_\odot)^{0.2}\). This seems intuitively right, but observational results are ambiguous: Although Vicente & Alves (2005) see a correlation between disk diameters and stellar masses using a sample of proplyds from Luhman et al. (2000), they detect no dependence in the data from Hillenbrand (1997).

The relative AML \(\Delta J / J\) given by equation (1) is always larger than the relative mass loss \(\Delta m / m\) and affects the disk at much larger distances. Given a sufficiently large perturber mass, even encounters at \(r_p = 20 r_p\) as distant as 20 times the disk radius can reduce the angular momentum in the disk by \(\leq 10\%\) or more without disk mass loss.

### 3. RESULTS

Combining the cluster dynamics with the encounter results, in the following the dependence on the stellar mass of the outer mass of the encounter-induced AML of the disks in the ONC is investigated. For the Trapezium region as well as the entire ONC, the AML (according to eq. [1] in Pfalzner & Olczak 2006) is larger than the mass loss for all stellar masses \(M^*_1\). More importantly, both increase considerably for massive stars. The largest difference between the mass and angular momentum loss is found in the mass range of \(5-15 M_\odot\). As the high-mass stars are also the ones that have the highest mass loss, this could simply reflect that this lost mass carries with it a high angular momentum. However, what one is really interested in is whether the specific angular momentum in the remaining disk is lowered, as only this can eventually facilitate accretion of matter onto the star. The specific angular momentum \((\Delta J / J)_{\text{mass}}\) is defined by the ratio of the relative angular momentum to the relative disk mass \(\Delta m / m\) of the remaining disk:

\[
\left(\frac{\Delta J}{J}\right)_{\text{mass}} = \left(1 - \frac{\Delta J}{J}\right) \left(1 - \frac{\Delta m}{m}\right).
\]

From here onward, it is always this specific angular momentum that is considered. Pfalzner & Olczak (2006) showed that for a single encounter, there exists an upper limit of 60% AML in the remaining disk. However, as Pfalzner (2004) and Moeckel & Bally (2006) showed, consecutive encounters can lead to a significant angular momentum transport.

Therefore, when determining the specific AML (SAML) as defined in equation (2), it rises from about 3%–8% for low-mass stars to \(\sim 40\%–70\%\) for high-mass stars in the ONC and from 15%–20% to \(\sim 60\%–95\%\) in the Trapezium region (see Fig. 1).

How can a reduction to 5% of the initial angular momentum occur? Clearly not in a single encounter, where only up to 60% can be lost at a time (see Pfalzner & Olczak 2006). Figure 2 demonstrates that the massive stars experience, on average, a much larger number of encounters than lower mass stars and that the AML in a single encounter is not as sensitive to the stellar mass as the mass loss is. The reason for the higher number of encounters is that massive stars act as gravitational foci for lower mass stars, which eventually leads to more pronounced SAML in the disks of massive stars.

As the age of the ONC is not precisely known, with most estimates in the range of 1–2 Myr, the question is how sensitive is this result to the ONC age. Figure 1 also shows the SAML for the case of a 1 Myr old ONC. It can be seen that the overall result of a much higher SAML for massive stars still holds.

The scaling of the disk size with the mass, although intuitively right, is not really observationally proven (Hillenbrand 1997; Luhman et al. 2000; Vicente & Alves 2005). Comparing the above results to those obtained by assuming an equal constant disk size (150 AU) for all stars, we find that the now larger disk size for the low-mass stars leads to an increase in
the SAML there, whereas the smaller size for massive stars has the opposite effect. However, these are minor changes, leaving the overall result of the much higher SAML for massive stars untouched.

Recent observations (see Zhang 2005 and references therein) suggest that massive stars can be surrounded by high-mass disks $m_d > 0.1 M^*$. Since the interaction dynamics involving high-mass disks is still poorly understood, we resolve to the crude method of setting $m_d = M^*_1$ for all stars with $M^*_1 > 5 M_\odot$ and simply add their disk mass to the stellar mass when determining the AML using equation (1) from Pfalzner & Olczak (2006). This leads to an $\sim 5\%$--$12\%$ reduction of the relative SAML, but again the general trend that massive stars lose more angular momentum than lower mass stars is unaffected.

Up to now, the ONC was treated as being in virial equilibrium. If the cluster is allowed to expand ($Q_{\mathrm{vir}} = 1$), we find that the SAML is larger for all masses, with the largest differences in the Trapezium region. The additional SAML happens early on in the cluster development, where the density in the expanding cluster is initially higher in the center.

4. DISCUSSION AND CONCLUSIONS

In this Letter the dependence of the encounter-induced angular momentum loss in circumstellar disks has been investigated for the example of the ONC. This has been done by combining simulations of the cluster dynamics with investigations of SAML in isolated encounter events. The main outcome is that although most stars experience only an average specific angular momentum loss of 3\%--5\%, massive stars suffer much higher losses ($\sim 70\%$--$95\%)$. The reason is that the massive stars act as gravitational foci, experiencing many more encounters than lower mass stars. Although the actual percentages might vary, the general trend of much higher SAML for massive stars is not very sensitive to modeling parameters like the disk size scaling with stellar mass, the age of the ONC, or the virial coefficient of the cluster.

The SAML was obtained assuming parabolic prograde, co-planar encounters, which as such can only be regarded as upper limits. Since stars of all masses are equally affected by this, the actual percentages might be somewhat lower, but it will still hold that massive stars have a much higher SAML than lower mass stars.

What are the consequences of such higher SAML for massive stars? The SAML is connected to many particles moving on highly eccentric orbits around the central star after the encounter. This does not in itself ease accretion straight away. However, viscosity-driven processes may cause the angular momentum to be redistributed in the disk, eventually easing accretion. The correlation between angular momentum and accretion means that the enormous loss in disk angular momentum for massive stars induced by the cluster environment should result in an equivalent increase in accretion. This happens predominantly in the cluster center, but to a lesser degree it also happens farther out. The interaction with the other cluster members thus triggers the accretion in the massive stars, a process that could be described as cluster-assisted accretion.

In § 2, the SAML was deduced by assuming that only one of the stars is surrounded by a disk, contradicting the initial configuration where all stars are initially surrounded by a disk. If both stars are surrounded by a disk, the disk material can be captured from the passing star, but the angular momentum of this captured matter is actually extremely low (Pfalzner et al. 2005a). Therefore, including this captured matter would probably result in an even lower specific angular momentum. In this way, the disk can be replenished with matter while at the same time lowering its average specific angular momentum. However, this increase in accretion cannot become a runaway process because, in this case, accretion is directly coupled to disk mass loss, thus setting a natural limit on the material that can be accreted.

In the simulations herein, the starting point is a set of more or less fully formed stars describing the accretion process in the late stages of stellar formation. However, a similar mechanism could be at work earlier on in the star formation process, too. There the dominate process for the formation of massive stars is still an open question. Competitive accretion (Bonnell & Bate 2006), mergers (Bonnell et al. 1998; Bally & Zinnecker 2005), and accretion-easing processes (Krumholz 2006) are the main mechanisms currently discussed. The present study suggests that cluster-assisted accretion should also be considered as a formation process for massive stars.

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