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The fate of discs around massive stars in young clusters

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ABSTRACT

Aims. To understand whether there is a difference in the dispersion of discs around stars in high-density young stellar clusters like the Orion Nebula Cluster (ONC) according to the mass of the star.
Methods. Two types of simulations were combined – *N*-body simulations of the dynamics of the stars in the ONC and mass loss results from simulations of star-disc encounters, where the disc mass loss of all stars is determined as a function of time.
Results. We find that in the Trapezium, the discs around high-mass stars are dispersed much more quickly and to a larger degree by their gravitational interaction than for intermediate-mass stars. This is consistent with recent observations of IC 348, where a higher disc frequency was found around solar mass stars than for more massive stars, suggesting that this might be a general trend in large young stellar clusters.

Key words. stars: circumstellar matter – stars: planetary systems: protoplanetary disks – galaxies: star clusters

1. Introduction

Our current understanding is that planetary systems are formed from the material of the star-surrounding protoplanetary discs and that the existence of a disc is a prerequisite for the formation of a planetary system. Not surprisingly there has been an increasing number of observational studies investigating the frequency of discs in young stellar clusters to address this question (Hillenbrand et al. 1998; Lada et al. 2000; Haisch et al. 2001; Kenyon & Gomez 2001). The general trend seems to be that the disc frequency decreases with the cluster age, but how quickly the disc dispersal process occurs is still not certain because due to observational constraints, the disc frequencies are often only known within a relatively wide margin. It might be that apart from the cluster age, factors like the presence of massive stars contribute to the disc dispersal rate.

In a recent study of IC 348 by Lada et al. (2006) not was only the disc frequency investigated but also its dependence on the stellar mass. They found that the disc frequency is higher for intermediate-mass stars (47% ± 12%) than for massive stars (11% ± 8%) and low-mass stars (28% ± 5%).

At the moment several disc destruction mechanisms are under consideration, among them photevaporation (Störzer & Hollenbach 1999) and gravitational interactions. Although favoured, photoevaporation mechanisms tend to have difficulties matching the observed disc destruction timescales (Scally & Clarke 2001).

Here we will concentrate on modelling the effect of gravitational interactions. Our simulations of the disc mass loss in the ONC show that high-mass stars lose their discs to a larger degree and more rapidly than intermediate-mass stars due to the gravitational interactions of the cluster stars. This effect could be a general tendency in all young clusters containing a sufficiently high number of massive stars.

2. Model and numerical technique

We follow the idea of Scally & Clarke (2001), combining a simulation of the dynamics of the ONC to determine the interaction parameters of close encounters between stars in the cluster with results from studies of isolated star-disc encounter simulations. The main differences are slightly changed initial conditions of the cluster and a more detailed treatment of the disc mass loss. The details of the numerics can be found in Olczak et al. (2006). In contrast to the latter study the emphasis in the current investigation is on the differences in disc mass loss for stars of low, intermediate and high mass.

2.1. Cluster simulation

The dynamical model of the ONC presented here contains only stellar components without considering gas or 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. The masses were generated randomly according to the mass function given by Kroupa et al. (1993) in a range 50 $M_\odot \geq M^* \geq 0.08$ $M_\odot$, apart from θ^1C Ori, which was directly assigned a mass of 50 $M_\odot$ and placed at the cluster centre.

In an encounter list the information of all perturbing events of each stellar disc was recorded during the course of the simulation, i.e. both encounter masses, the relative velocity and the eccentricity. The ONC was simulated for 13 Myr – the assumed lifetime of θ^1C Ori. The cluster simulations were performed with NBODY6++ (Spurzem & Baumgardt 2002). The quality of the dynamical models was determined by comparison to the observational data at 1–2 Myr, which marks the range of the mean ONC age. The quantities of interest were: number of stars, half-mass radius, number densities, velocity dispersion and projected density profile. Here we chose the ONC to be in virial equilibrium; for more details of the selection process, see Olczak et al. (2006).

2.2. Mass loss

In the event of a close encounter between young cluster stars, the discs surrounding them can be severely disturbed and either partially or completely destroyed. From parameter studies for the disc mass loss in such encounters, Pfalzner et al. (2005) determined a fit formula. If one has to deal with penetrating encounters and high mass ratios M_2^*/M_1^*, like in the ONC, the following more complex Eq. (1)

$$\frac{\Delta M_\mathrm{d}}{M_\mathrm{d}} = \left(\frac{M_2^*}{M_2^*+0.5M_1^*}\right)^{1.2} \ln\left[2.8\left(\frac{r_\mathrm{p}}{r_\mathrm{d}}\right)^{0.1}\right] \times \exp\left\{-\sqrt{\frac{M_1^*}{M_2^*+0.5M_1^*}}\left[\left(\frac{r_\mathrm{p}}{r_\mathrm{d}}\right)^{3/2}-0.5\right]\right\}. \quad (1)$$

is more suitable.

However, a number of assumptions were made in these parameter studies: only two-body encounters were considered, the discs were assumed to be of low mass (i.e., $M_\mathrm{d}/M^* \ll 0.1$) and the surface density to have a $1/r$-dependence initially. In addition, Eq. (1) is for coplanar, prograde encounters only. According to studies on inclined and retrograde star-disc encounters (Clarke & Pringle 1993; Ostriker 1994; Heller 1995; Pfalzner et al. 2005), these approximations mean that Eq. (1) can only be interpreted as an upper limit of the disc mass loss. However, the degree to which it overestimates the disc mass loss should be the same independent of the mass of the star, so that the quantitative numbers could be reduced, but this should not change the qualitative results presented here.

As the cluster consists of a wide spectrum of stellar masses, the simulation results, valid for $M_1^* = 1\ M_\odot$, are generalized by scaling the disc radius according to

$$r_\mathrm{d} = 150\,\mathrm{AU}\sqrt{M_1^*[M_\odot]}, \quad (2)$$

which is equivalent to the assumption of a fixed force at the disc boundary. We will see in Sect. 3 what happens if we assume the disc radius to be uncorrelated with the mass of the star.

3. Results

Applying Eq. (1) to the results of the encounter tracking in 20 cluster simulations, we obtain the average disc mass loss as a function of time. Looking at the temporal development of the disc mass of low-($M_1^* \leq 1\ M_\odot$), intermediate-($M_1^* = 1$–$10\ M_\odot$) and high-mass stars ($M_1^* > 10\ M_\odot$) separately, Fig. 1 shows that massive stars have much more disc mass loss than stars of lower mass, which manifests itself very early on in the cluster development. This is valid for the entire ONC but even more so for the central Trapezium cluster.

Taking a snapshot at 2 Myr (the ONC age is estimated to be 1–2 Myr and the IC 348 age to be 2–3 Myr), the solid line in Fig. 2 shows the average relative disc mass loss as a function of the mass of the star for the Trapezium region. At 2 Myr the disc mass loss is ~30% for intermediate-mass stars whereas for stars with $M^* = 20\ M_\odot$ it is ~60% and for higher mass stars close to 100%. This last value has to be taken with some care because of the poor mass loss statistics in this case.

Scaling the disc size with the star mass (Eq. (2)) seems intuitively right, but observational results do not give such a clear

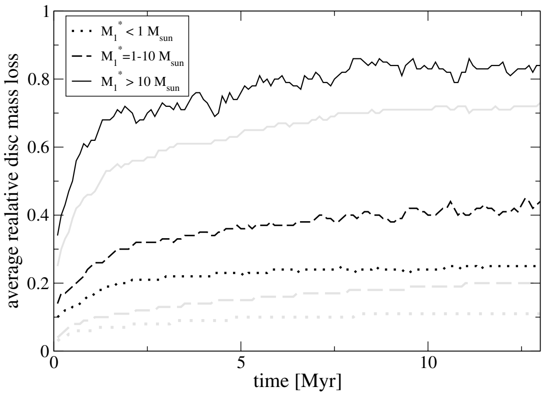

Fig. 1. Temporal dependence of the average relative disc mass loss for stars of different mass (black lines – Trapezium, grey lines – entire ONC).

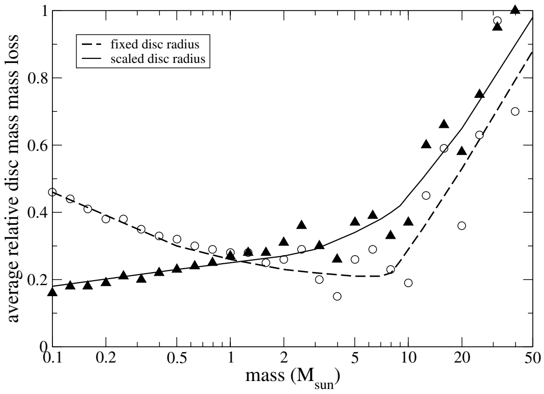

Fig. 2. The average relative disc mass loss at 2 Myr for the Trapezium as a function of the stellar mass. The triangles show the results assuming the disc radius to scale as in Eq. (2) whereas the circles indicate the data for a constant disc radius (150 AU).

picture: Although Vicente & Alves (2005) derive a clear correlation between disc diameters and stellar masses using a sample of proplyds from Luhman et al. (2000), they see no indication for such a dependence in the data of Hillenbrand (1997). However, as Vicente & Alves (2005) pointed out, the present Trapezium is probably not in its primordial state and various disc destruction processes have most likely altered the disc sizes considerably.

If we assume that the disc size does not depend on the stellar mass as in Eq. (2) but is instead 150 AU for all stars, this results in a somewhat lower relative disc mass loss for the massive stars and an increase for the low-mass stars (see dashed line in Fig. 2). Nevertheless, it still holds that the disc mass loss is considerably greater for massive stars than for intermediate-mass stars. For the low-mass stars the relative disc mass loss is now higher than for intermediate-mass stars, leaving the stars with masses in the range 1–10 $M_\odot$ as the ones with the lowest disc mass loss in the cluster at 2 Myr. This is consistent with the observational results of Lada et al. (2006).

To illustrate the underlying reason for this difference in relative disc mass loss, Fig. 3 shows the average number of encounters and average relative disc mass loss in a single collision as a function of the stellar mass. It can be seen that the number of collisions is nearly constant for low- and intermediate-mass stars but increases considerably for high-mass stars. So for low-mass stars the mass-loss occurs through a few strong encounter events, whereas the disc of high-mass stars is removed via a steady nibbling by many encounters with stars of lower mass.

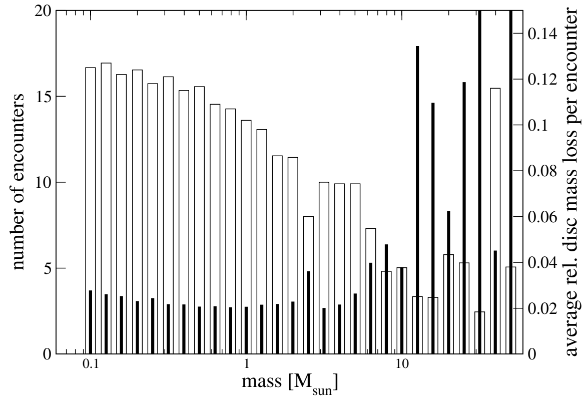

Fig. 3. The average number of collisions that each star experienced up to 2 Myr is shown as black bars as a function of the stellar mass for the Trapezium. For comparison the average relative disc mass loss per encounter is shown for the case of all discs initially being the same size.

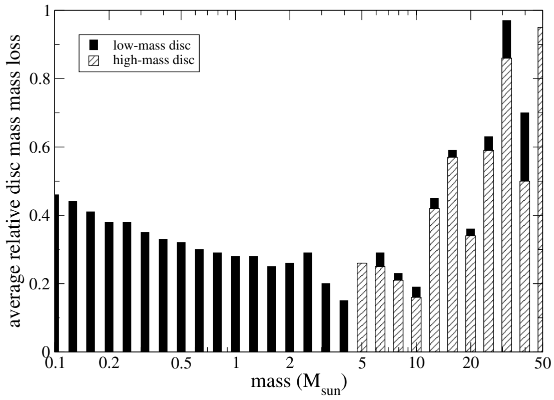

Fig. 5. Average relative disc mass loss as a function of the stellar mass assuming constant disc radius. Comparison between the case where all discs are of low mass and with the situation where all high-mass stars are surrounded by massive discs.

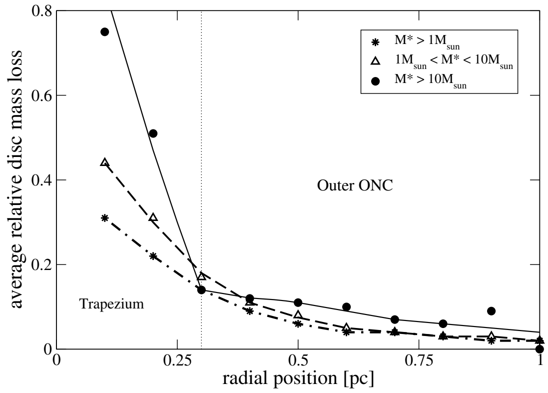

Fig. 4. The average relative disc mass loss as a function of the radial distance from the cluster center for low-mass, intermediate-mass and massive stars at 2 Myr. Here the disc size was assumed to be scaled. The dotted line indicates the extent of the Trapezium region.

Figure 4 shows the average relative disc mass loss as a function of the distance from the cluster center for low-, intermediate- and high-mass stars for the entire ONC. For distances $r > 0.25$ pc the massive stars do not exhibit greater disc mass loss than the low-mass stars, but the number of massive stars at such radii is in any case small (3 stars with $M^* > 10\ M_\odot$, 20 simulations), so that the statistics in this region is poor.

During the last few years a number of massive stars surrounded by high-mass discs ($M_\mathrm{d} > 0.1\ M^*$) have been detected (Zhang 2005, and references therein). The question is how would the above results change if all massive stars had initially massive discs? As the interaction dynamics of high-mass discs is much less well understood than for low-mass discs, only an estimate can be given here. To do so, we repeated the simulations with the assumption that all stars of $M^* > 5\ M_\odot$ are surrounded by a disc of $M_\mathrm{d} = 1\ M^*$ by simply assuming that the disc particles are all twice as strongly bound to their star, i.e. when Eq. (1) is applied, M_1^* is replaced by $M_1^* + M_\mathrm{d}$. This is obviously a strong simplification and more detailed investigations would be necessary in the future. However, Fig. 5 shows that although the stronger binding naturally leads to less disc mass loss for the massive stars than before, they still lose a significantly higher proportion of their disc mass than intermediate-mass stars. In this case the described effect is thus only slightly weaker.

4. Summary and discussion

In this article the relative disc mass loss induced by encounters between stars in a cluster has been studied for the example of the ONC. The main result is that discs around massive stars can be disrupted by close passages of stars with far greater efficiency than discs around intermediate-mass stars. If we assume that the disc size scales with the stellar mass, the relative disc mass loss is even lower for low-mass stars. However, if the disc size is independent of the stellar mass then low-mass stars have as well a higher relative disc mass loss than intermediate-mass stars in accordance with Lada et al. (2006). In this case we found the minimum disc mass loss for stars with $3\ M_\odot < M^* < 10\ M_\odot$.

The reason for greater disc mass loss for massive stars is twofold: first, high-mass stars are found preferentially in the cluster core (due to dynamical mass segregation) where the stellar densities are higher and second the more massive stars suffer greater disc mass loss than low-mass stars in the same region (as Fig. 4 shows), a result that can be traced (from Fig. 3) to the larger number of encounters suffered by these more massive stars. The gravitational focusing of low-mass stellar orbits by massive stars enhances the encounter rate between the massive star and other cluster members for any particular periastron separation. So not only for the IC 348 as observed by Lada et al. (2006) and the ONC investigated here, but generally there should be more intermediate-mass stars than massive stars surrounded by discs in the inner regions of high-density clusters, provided they contain a sufficient number of massive stars.

In the inner cluster regions, discs around massive stars are much more rapidly destroyed than around intermediate-mass stars, so planetary systems should be less likely to develop around massive stars. There the same should hold for low-mass stars if the disc size is independent of the stellar mass.

The result that regardless of the stellar mass, fewer discs are destroyed at larger distances from the center does not necessarily mean a higher formation rate of planetary systems there. It rather depends on the dominating planet formation mechanism. If coagulation is the driving force, this would hold. If, on the other hand, planet formation predominantly occurs via gravitational instabilities, then the higher encounter rate close to the cluster center might even promote planet formation in the cluster core and possibly even dominate. However, this effect has not been demonstrated to date.

In this paper we have concentrated on the destruction of discs caused by gravitational interactions of the cluster stars. Another disc destruction mechanism is photoevaporation (Johnstone et al. 1998; Störzer & Hollenbach 1999). At the moment it is not entirely clear which mechanism dominates the disc destruction at a given cluster age. Most likely gravitational interactions are more important during the first Myr and photoevaporation later on. However, as the disc mass loss is in both cases dependent on distance, qualitatively similar results – i.e. more disc mass loss for the massive stars – should be obtained in the photoevaporation process as well.

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