Influence of the cluster environment on the disc properties

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Influence of the cluster environment on the disc properties

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Abstract. Most stars are not born in isolation, but in a cluster environment. This means that gravitational interactions might lead to changes in the disc properties. Numerically modelling the Orion Nebula Cluster, as an example, we investigate how the cluster environment influences through gravitational interactions disc properties like disc frequency, disc mass, angular momentum transport and accretion. We show that the massive stars in the cluster center are the engines driving these processes and that their discs are most affected.

1. Introduction
Observations show that most (if not all) young stars are initially surrounded by discs. Our knowledge of these discs has hugely increased through observations during the last 10 years. Here observations at infrared wavelength mainly probed the inner disc area (up to a few AU) and submillimeter observations investigated the outer disc regions down to ∼ 50 AU. For a state-of-the-art picture of this knowledge see, for example, the talks by R. Akeson and A. Dutrey covered in this volume.

Understanding protoplanetary discs is so important, because they are directly linked to the question of how stars and planets form. This question is still far from being completely answered. We know now that discs disappear on time scales of 3-10 Myrs. But how can giant planets then form, if in our standard coagulation picture they need more than 10 Myrs to do so?

What has so far often been neglected, is, that most stars form in a cluster environment. Cluster environments can differ very much, most obviously in their density. For example, the stars in σ Ori cluster are so far apart that they will barely interact with each other, so that our picture of a star forming in isolation is most probably true in such environments. However, in dense clusters like the Trapezium in the Orion Nebula Cluster (ONC) or the Arches cluster interactions most probably will have some effect on the discs. Due to the high density and the presence of (many) O stars, not only dust growth will be a dominating evolutionary effects but also photoevaporation and gravitational interactions. Here we will concentrate on the latter.

We have chosen the ONC as model cluster because it has several advantages: It is one of the best observed star forming regions and therefore many physical parameters are well known. The number of stars N is ∼ 4000, which makes it numerically manageable. In addition, is the ONC one of the densest near-by star forming regions in the Galaxy. This in turn means that there is a high probability of encounters. Finally, it is believed to be a typical star forming region, so
one can be optimistic that results obtained for the ONC are probably applicable to other star forming regions.

To study the effects of the cluster environment on the discs around the young stars, we combine two types of simulations: (i) simulations of the dynamics of the stars in the cluster and (ii) simulations that model the effect that the fly-by of another star has on the star-disc system (see Fig. 1).

In the cluster simulation particles are set up to initially represent a $r^{-2}$-density profile and the simulations that reproduce the observed density profile at 1 Myr are selected. Our model of the ONC contains only stars, the gas dynamics is so far not included and the stellar dynamics is simulated using the NBODY6++ code. During these simulations lists of encounter informations (encounter partners, orbits, etc.) of all stars are collected.

In the encounter simulations we model the disc by 10 000 particles and study properties like the mass and angular momentum loss in coplanar, prograde encounters using a hierarchical tree code. We performed a parameter study of star-disc encounters which covers all cases necessary for the interactions in the cluster development. Eventually we combine the results from the cluster and encounter simulations to obtain the average encounter-effect on protoplanetary discs in the ONC.

Gravitational interactions influence star-disc system in several ways: The mass distribution in the disc changes, often leading to disc mass loss which in turn means a different disc size. After several such encounters the star can loose its disc completely leading to a change in the disc frequency of the cluster. At the same time the angular momentum change in the discs induce spiral arm patterns and the loss of angular momentum eases accretion onto the star. The accreted disc matter increases the mass of the star.

We will look at these processes now separately in more detail.
2. Disc Mass Loss

We find that at \(1-2\) Myr, the age of the ONC, up to \(\sim 5\%\) of stars in the entire ONC (\(R = 2.5\) pc) have lost their discs due to encounters, if looking only at the inner denser Trapezium region (\(R = 0.3\) pc) this increases to \(10 - 15\%\) [2]. This is in accordance with the observations of Lada et. al (2001), who found that \(80-85\%\) of stars in the Trapezium Cluster possess discs.

If we have a look at the most massive stars of the cluster the situation becomes more dramatic. The massive stars are mostly found near the cluster center - the densest part of the cluster. There the massive stars function as gravitational foci, being more or less the engines for the cluster dynamics. This means for the massive stars themselves that they undergo many encounters and loose their discs much faster and to a higher degree than low-mass stars [3]. This can be seen as well in Fig. 2.

This is in agreement with observations of disc frequencies in various cluster that show that the disc frequency is lower for massive stars than for intermediate mass stars [4].

Obviously this has consequences for planet formation. As the disc around massive stars are destroyed after a short time (typically a few 100 000 years) planets around massive stars are quite unlikely to form.

3. Observational Evidence for Encounters

One observational evidence for encounters would be spiral arms in discs. This have been found in a number of discs [5, 6, for example], but the problem is that companions, massive planets in the discs and instabilities would result in similar spiral structures. However, we want to find a unique identifier of encounters. We look for that in the velocity distribution: 3-body encounters in a cluster environment are thought to produce a stronger bound binary plus a high-velocity star (usually of lower mass).

C. Olczak explains the technique in detail in his contribution in these proceedings. He uses the velocity observations by Jones and Walker (1988) to determine the number and position of high velocity stars in the ONC and IR excess observations of Hillenbrand et al. (1998) to determine whether the stars are likely to be surrounded by discs.

Performing numerical simulations one obtains velocity distributions with a similar fraction of stars with high-velocities as in the observations. In the simulations one can trace them back as
resulting from encounters. There are actually two dynamically distinct groups of ejected stars: i) one as result form scattering in the inner cluster regions and ii) another obtained by scattering of a star originally positioned further out at the cluster center. This latter group forms a kind of ring (see Fig. 3), which possibly could be used to determine the cluster age.

4. Angular Momentum Loss
One long-standing problem in the understanding of disc development is, how the star can accrete disc matter despite the fact that the disc angular momentum is far too big for the star to accrete. Obviously the disc matter has to loose its angular momentum in some way. One possibility would be through interactions with other cluster members. As mass transport is always coupled to angular momentum transport, this should be a common effect to occur in the ONC. Even more so as actually the interaction region for angular momentum loss is larger than for mass loss.

![Figure 3](image-url)  
*Figure 3.* Position of high-velocity stars in the ONC relative to the cluster center (black circle). Red indicates stars with infrared excess, blue without infra-red excess.

![Figure 4](image-url)  
*Figure 4.* Specific angular momentum loss per disc as a function of primary mass for the Trapezium region (red) and the entire ONC(green) for different cluster ages.
We investigated whether encounters in a cluster environment are destructive enough to reduce angular momentum in discs. We found that indeed the angular momentum in the discs is reduced, but by far not enough to solve the angular momentum problem. The reduction is 3-5% in the ONC and 15-20% in the Trapezium region.

However, this angular momentum loss might nevertheless be essential: If we look at discs with a 3-5% angular momentum loss this is coupled to the formation of spiral arm patterns. The formation of spiral arms is an important prerequisite in gravitational instability scenario of giant planets [9].

Like for the mass loss it is the massive stars that loose the most specific angular momentum (see Fig. 4). As the loss of angular momentum eases the accretion of disc matter onto the star, there exist an additional growth mechanism: in the final phases of formation of massive stars: cluster-assisted accretion [10].

5. Accretion

Angular momentum loss is only an indirect indicator of accretion, so we try to model accretion directly. As we can not resolve the accretion process as such, we use the in these circumstances often used method [6] to define accretion as matter that enters within a certain radius (here we used 0.5AU).

Like expected from the angular momentum results, we find the highest cluster induced accretion for massive stars. The cluster-assisted accretion consists of short phases (100 to 10 000 years) of high accretion (from $10^{-7}$ up to $10^{-4} \, M_\odot/\text{yr}$).

It is quite likely that similar processes happen as well in the earlier star forming history not covered here. If so, this could possibly be a reason for a top-heavy IMF especially in massive clusters like the Arches cluster.

Most accretion events happen early on in the cluster development, meaning in the first few 100 000 years. So it is most likely to observe cluster-induced accretion in very young clusters. However, even at the age of ONC ( 1-2 Myr ) at least 1-8 stars in the Trapezium region will
show high accretion due to cluster-assisted accretion at any given time. However, this will be predominantly low-mass stars (see Fig. 5) because of their relative abundance and the short disc-destruction times of the most massive stars.

Figure 6. Number of encounters per $10^4$ yrs as a function of cluster age for massive (black), intermediate-mass (red) and low-mass stars (green).

6. Summary
In summary, the cluster environment in the ONC influences star and planet formation in several ways:

- The cluster environment has a considerable effect on star-disc systems. Up to 10-15% of the stars in the Trapezium loose their discs completely due to encounters. Spiral arm are excited in most discs at some point in their development and these could be strong enough to trigger giant planet formation.
- Massive stars function on the one hand as engines of the cluster dynamics but are on the other hand as well most affected. They loose as well mass as angular momentum faster and to a higher degree than lower mass stars. So that planets around high-mass stars are unlikely to form.
- The cluster environment triggers short bursts of accretion.

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