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Stirring up a embedded star cluster with a moving gas filament

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Resumen / Realizamos simulaciones para probar los efectos de un filamento de gas en movimiento sobre un cúmulo estelar joven (i.e. el modelo *Slignshot*). Modelamos un *Orion Nebula Cluster* como una esfera de Plummer, y el Filamento con Forma de Integral como un potencial cilíndrico, donde su posición viene dada por una función sinusoidal. Observamos que en un filamento estático, un cúmulo inicialmente esférico evoluciona de forma natural hacia una distribución elongada de estrellas. Para un filamento en movimiento, observamos distintos remanentes y los clasificamos en 4 categorías. Cúmulos "saludables", donde casi todas las estrellas permanecen dentro del filamento y del cúmulo; cúmulos "destruidos" son el caso opuesto, casi sin estrellas en el filamento o cerca del centro de densidad del cúmulo; cúmulos "ejectados", donde una fracción mayor de estrellas permanecen unidas al cúmulo, pero casi ninguna se mantiene dentro del filamento; y cúmulos de "transición", donde aproximadamente el mismo número de partículas es eyectado del cúmulo y del filamento. Un cúmulo con las características de *Orion Nebula Cluster* podría permanecer dentro del filamento o ser eyectado, pero no será destruido.

Abstract / We perform simulations to test the effects of a moving gas filament on a young star cluster (i.e. the "Slingshot" Model). We model Orion Nebula Cluster-like clusters as Plummer spheres and the Integral Shaped Filament gas as a cylindrical potential. We observe that in a static filament, an initially spherical cluster evolves naturally into an elongated distribution of stars. For sinusoidal moving filaments, we observe different remnants, and classify them into 4 categories. "Healthy" clusters, where almost all the stars stay inside the filament and the cluster; "destroyed" clusters are the opposite case, with almost no particles in the filament or near the centre of density of the clusters; "ejected" clusters, where a large fraction of stars are close to the centre of density of the stars , but almost none of them in the filament; and "transition" clusters, where roughly the same number of particles are ejected from the cluster and from the filament. A cluster similar to an Orion Nebula Cluster might stay inside the filament or be ejected, but it will not be destroyed.

Keywords / methods: numerical — Galaxy: open clusters and associations: individual: ONC

1. Introduction

The Orion nebula is the nearest site of massive star formation. One of its predominant features is the Integral Shaped Filament (ISF, Bally et al., 1987), a filament of gas in where the Orion Nebula Cluster (ONC, Hillenbrand & Hartmann, 1998) is forming.

Observations of the protostars in the ONC show that they are distributed in different ways in space: protostars are located right on top of the ridgeline of the filament, meanwhile pre-main-sequence stars are symmetrically distributed around the filament (Stutz & Gould, 2016; Kainulainen et al., 2017; Stutz, 2018). A similar behavior is observed for the radial velocity of the stars, where protostars have radial velocities close to the velocity of the gas, with a low velocity dispersion, and the pre-main-sequence stars have a larger velocity dispersion of the order or larger than the velocity of the gas (Stutz & Gould, 2016).

To explain these observations, Stutz & Gould (2016) proposed a scenario where the gas of the ISF oscillates. The protostars are formed from this gas and move with the oscillating filament. Once they accrete enough mass, they are ejected from their birthplace and start moving with the transverse velocity of the oscillation at the moment of decoupling. Stutz & Gould (2016) named this scenario "the Slingshot".

To test this hypothesis, Boekholt et al. (2017) showed that an initially narrow distribution of stars can be dynamically heated to produce a broad distribution with a net relative velocity when the filament oscillates with a certain amplitude and period. Moreover, Gaia data of the protostars plus the radial velocities of the gas confirm that the gas of the ISF moves like a standing wave (Stutz et al., 2018).

In this work we continue the exploration of the Slingshot via simulations, this time replacing the string of stars with spherical star clusters of different masses.

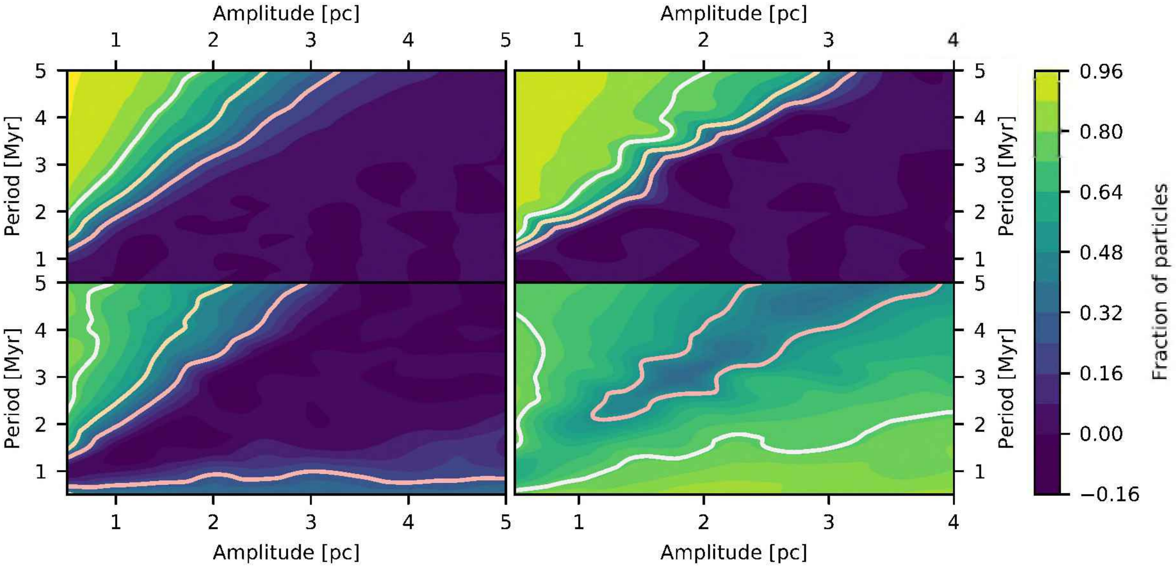

Figure 1: Fraction of particles inside the filament (top) and inside the cluster (bottom) after one oscillation for a cluster with $R_{\rm pl} = 0.1$ pc, $M_{\rm pl} = 250$ $M_\odot$ (left) and $R_{\rm pl} = 0.1$ pc, $M_{\rm pl} = 1000$ $M_\odot$ (right). The contours indicate 75%, 50% and 25% of the initial number of particles. Notice that the number of particles inside the filament drops drastically after it reaches $\sim 50\%$ for the more massive cluster, but decreases smoothly for the less massive cluster.

2. Method

2.1. The gas filament

To study the effect of the ISF on a young star cluster, we build a cylindrical potential as in Boekholt et al. (2017), using the observed line density of the gas at the position of the ONC (Stutz, 2018) as a constraint to obtain the relevant parameters of the model in the region of interest.

The ISF likely moves due to the interplay of gravitational and magnetic forces (Stutz & Gould, 2016; Schleicher & Stutz, 2018), but in this work we assume that the gas potential is moving along the x-axis like an harmonic oscillator:

$$x(t) = A \sin\left(\frac{2\pi}{P} t\right), \tag{1}$$

where A is the amplitude of the oscillation and P is the period.

2.2. The star cluster

We use a cluster of equal-mass point particles to represent the ONC. The particles are distributed following a Plummer profile (Plummer, 1911) and located inside the cylindrical potential.

The presence of an external potential means that there is an extra component to the net force that acts on the particles, but due to the symmetry of the filament, that extra acceleration can be non-zero only in the x-y plane. Therefore, a standard Plummer sphere will collapse due to the extra mass of the filament along those axes. We avoid that initial contraction by increasing the x-y velocity of the particles so that the cylindrical Lagrangian radii of the cluster inside the filament remains roughly constant.

2.3. The code

The system of particles is evolved using the PH4 N-body code (McMillan et al., 2012). To account for the gas filament, we implement the background potential using AMUSE (Pelupessy et al., 2013). We couple this potential with the N-body solver using the BRIDGE (Fujii et al., 2007) method, in which the velocities of the stars are periodically updated using the acceleration due to the filament.

3. Results

Due to the cylindrical symmetry of the potential used to represent the filament, the embedded clusters tend to elongate along the z axis. Particles moving throughout the length of the gas filament, will do so following corkscrew orbits around the center of the potential.

We determine the state of the cluster by counting the stars inside the filament, measured as the number of stars that never move beyond $5R_{\rm pl}$ from the centre of the filament. Inside the cluster, we define the evolution in a similar fashion using the centre of density of the particle system instead.

If the filament moves slowly, a large fraction of particles stays inside the filament and the cluster. As the amplitude of the oscillation increases, or the period decreases, a larger fraction of stars are ejected from the system, up to the moment where no stars are inside the filament (Fig. 1, top left) or close to the centre of density of the stars (Fig. 1, bottom left). If the filament moves too quickly, it will not spend enough time inside the cluster to perturb the particles and a large fraction

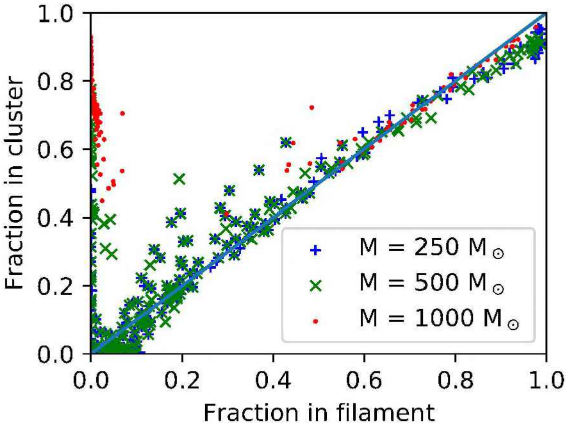

Figure 2: Fractions of particles inside cluster and filament for models with $R = 0.1$ pc after one full oscillation. The blue line is a reference for a 1:1 ratio.

of stars (but not all of them, so we can still identify an over-density of particles) will be ejected from the cluster.

A more massive cluster will have a similar behavior. However, being more tightly bound, it will not be destroyed (Fig. 1, bottom right). The fraction of particles in the filament will have a sharper transition from the high values characteristic of the slow filaments to the empty filament state (Fig. 1, top right).

Fig. 2 shows the fraction of stars inside the filament, versus the fraction of stars inside the cluster, for clusters with $R_{\rm pl} = 0.1$ pc. This shows us a sequence of remnants after one full oscillation of the filament that can be cataloged into 4 groups:

- Slow filaments (i.e. large period and/or small amplitudes) will keep a large number of particles inside the cluster and filament, and in this case, it behaves like a cluster inside a static filament. Some stars are ejected from these "healthy" clusters, since the filament is still injecting energy into the cluster.
- Some combinations of period and amplitude will produce remnants that are completely destroyed, where only a small (< 20 %) fraction of stars will stay inside the filament and move with it.
- A high fraction of stars in the cluster, but almost none in the filament is observed when the cluster is ejected from the filament. There is negligible mass loss when the cluster is outside the filament.
- The last kind of objects are those where the same number of particles are ejected from the filament and cluster. Most of the mass loss happens between the beginning of the simulation and by the time the filament reaches its maximum amplitude. After that, there are small losses each time the filament reaches the maximum distance from the origin.

Not all the models will produce remnants in every category. As can be seen in Fig. 2, none of the clusters with $M_{\rm pl} = 1000$ M$_\odot$ are destroyed. Moreover there is a gap where none of the cluster remnants end with < 40 % of the particles inside the filament, with the exception of the ejected clusters. This means that the cluster can stay inside the filament or it can be ejected after losing less than half of its mass, but it is not destroyed by the filament.

4. Conclusions

We present results of the first simulations of the effects of an oscillating cylindrical potential in the early evolution of a young star cluster. We explore the space of oscillation parameters with star clusters of different densities and masses.

We find 3 possible evolution trends:

- Small, low-mass clusters stay bound and move with the filament, if the filament is moving slowly.
- Fast-moving filaments can eject and destroy star clusters
- Large, high-mass clusters stay bound and the filament just moves through, pumping energy into the cluster.

The fate of the cluster in an oscillating potential is decided quickly. By the time the filament reaches its maximum amplitude, any star that manages to stay inside the cluster or the gas filament will likely stay there for the rest of the simulation time. A cluster like the ONC might be ejected or stay inside the filament, but these simulations suggest that it will endure the stirring by the filament and it will not be destroyed.

The physics behind the origin of the sharp transition, shown in Figure 1 (top right panel) is still under investigation, but we believe that it might be related to the mass ratio between the cluster and the gas filament.

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