Runaways from the ONC in Simulations and Observations

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The Dynamical Evolution of Young Star Clusters

Most stars form in **clustered/grouped** environments and we observe star-forming regions at different stages of their evolution in the night sky. Stars are often found on the periphery of star clusters but it is unclear if they originate from the cluster, or are background/foreground stars in the galaxy.

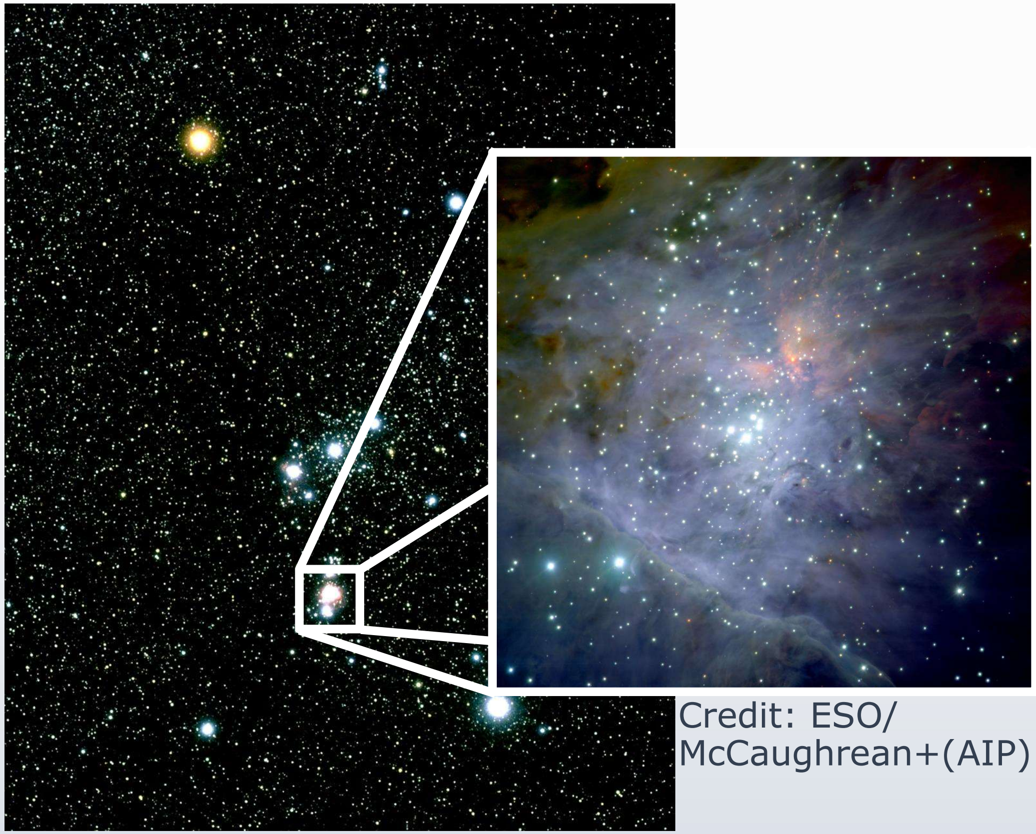
The next generation of telescopes will enable us to distinguish **stars that have been ejected** from the clusters and such ejected stars can be used to test models of star formation.

Simulating the evolution of star clusters with different initial conditions and then comparing the number and velocities of ejected stars with observations will allow us **to place constraints** on the initial density, spatial and velocity structure of star-forming regions.

What is a Young Star Cluster?

Young star clusters are regions in space that are actively forming new stars from giant clouds of molecular gas.

The **Orion Nebula Cluster** (ONC, right image) in the Orion constellation (left image) is an example of such a cluster. It is located ~400 pc (~1350 light years) away from the Solar System and is thought to be about 1-4 million years old (Da Rio+ 2010).



Credit: ESO/
McCaughrean+(AIP)

Credit: A. Fujii

What are Runaways?

Runaways (and slower walkaways) are stars that are ejected from a cluster after a dynamical interaction with another stellar system or when one component of a binary star system explodes as a supernova.

These ejected stars travel with velocities faster than the cluster's escape velocity and can reach velocities of several hundred km/s. During their life, they can travel large distances (several pc) and are observed on the outskirts of star-forming regions (Blaauw 1961, Poveda+ 1967).

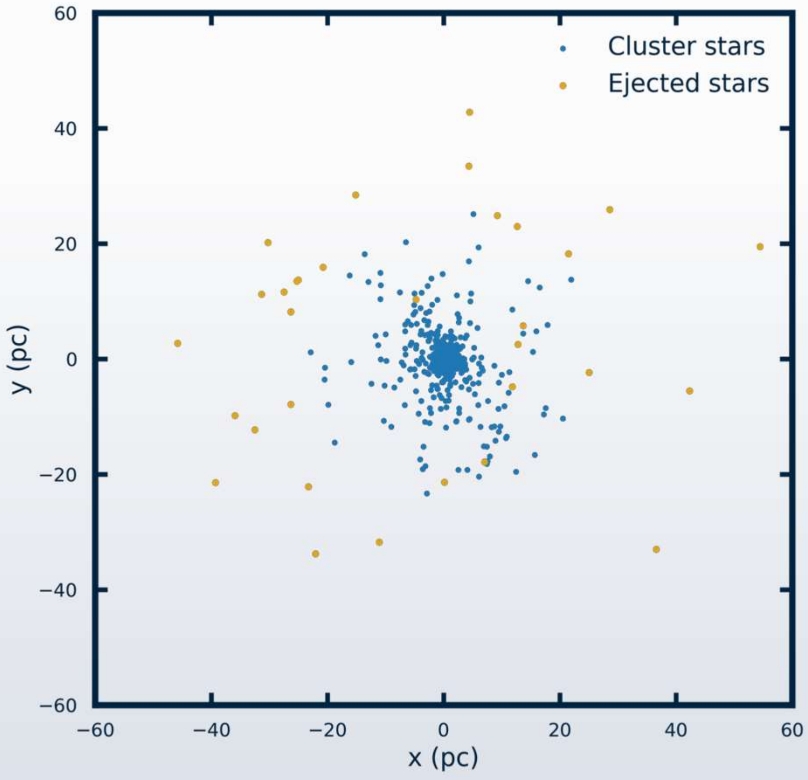


Fig. 2: 2D-positions of cluster (blue) and ejected (yellow) stars at a cluster age of 10 Myr, showing that some stars have travelled a distance of ~50 pc (160 ly) during this time.

Using N-body simulations

We use N-body simulations to study the gravitational interactions of stars in dense, dynamical systems such as **young star clusters**, over a defined time period.

Different **initial conditions** are run using specialised software producing data on the position, velocity and close encounters for every star (Hut 2003).

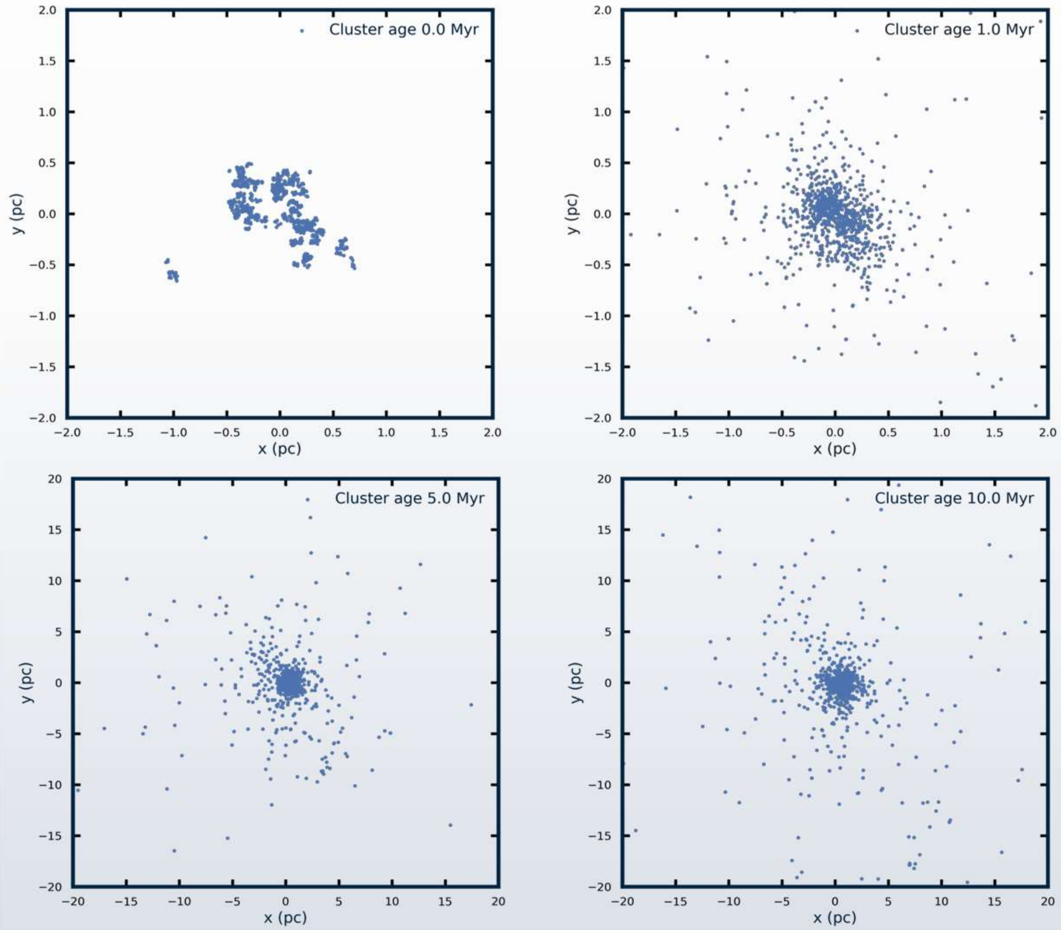


Fig. 1: 2D-positions of the central stars of a cluster at four different times, showing the spatial evolution of this cluster.

Runaways from the ONC in simulations

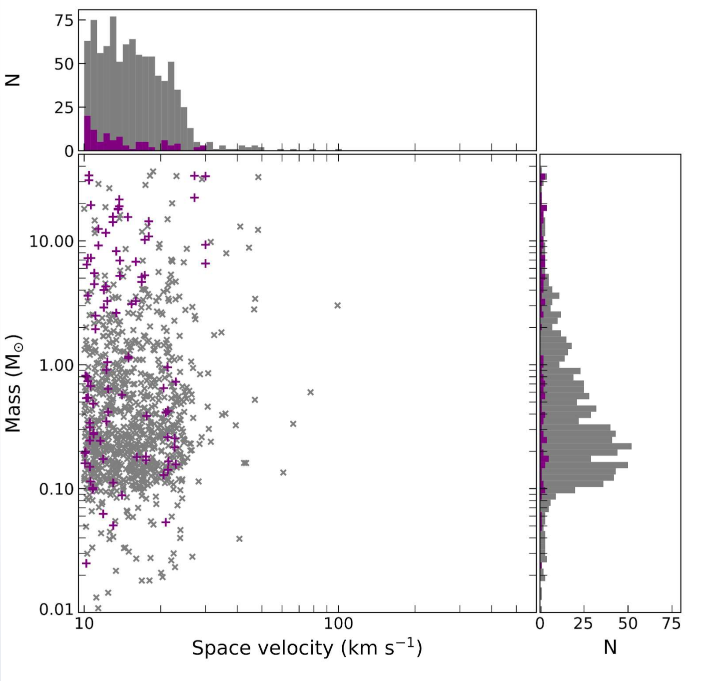
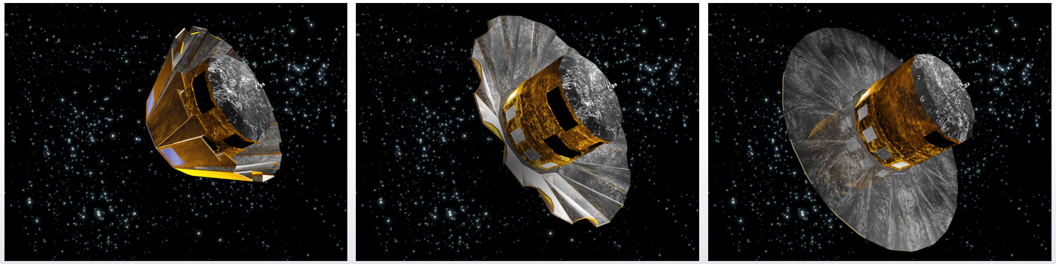


Fig. 3: From **Schoettler+ 2020.** Masses and velocities of all runaway/walkaway stars from 20 simulations within 100 pc after 4 Myr. Stars with masses m<0.1 $M_\odot$ are current or previous brown-dwarf binary companion stars. Ejected binaries are marked with a purple "+", whereas single stars are marked with a grey "x".

Ejected stars within 100 pc after 2, 3 & 4 Myr

Cluster age	Runaways	Walkaways
2 Myr	10	29
3 Myr	5	32
4 Myr	3	30



Gaia satellite - Credit: ESA

Comparing simulation results to observations using *Gaia*

Gaia is a space-based telescope launched in 2013 by ESA (European Space Agency) with the main scientific aim of mapping the Milky Way. Its second data release in April 2018 provided three-dimensional spatial and velocity information for over a billion stars. Its high-resolution astrometry results should make it possible to find many runaways from young star clusters, both high-mass and low-mass (Gaia Collaboration 2018).

Running **simulations with initial conditions similar to those expected for the ONC**, we see that the maximum number of runaway stars within 100 pc of the simulated cluster decreases the older the cluster is (table on left).

Using observations of proper motion and locations of stars within 100 pc of the ONC, we trace back these stars to find runaways and walkaways from the ONC. We then compare these results to our simulations, drawing conclusions about the initial conditions that were present when the stars formed in these regions.

Runaways from the ONC in *Gaia* DR2

We trace back stars to the ONC using their 3-dimensional space motion. However not all stars that are traced back originate in the ONC. Some stars are older visitors that have passed through the cluster.

We use a Colour-Magnitude Diagram to estimate ages for our trace-back stars and use a 4 Myr isochrone (yellow line) as the upper age limit for the ONC - stars above it are young enough to have been born in the cluster.

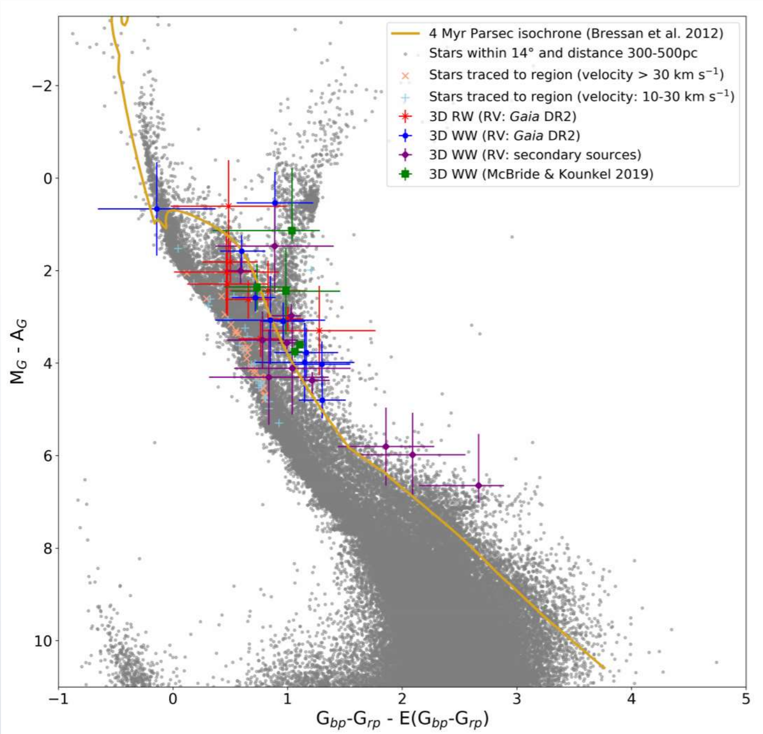


Fig. 4: From **Schoettler+ 2020.** 3D RW stars are shown with red "x". 3D WW stars are shown with blue squares and purple dots and green squares, depending on the origin of the radial velocity used.

Observation vs. Simulations

We find nine runaways and 24 walkaway stars that are young enough in *Gaia* DR2.

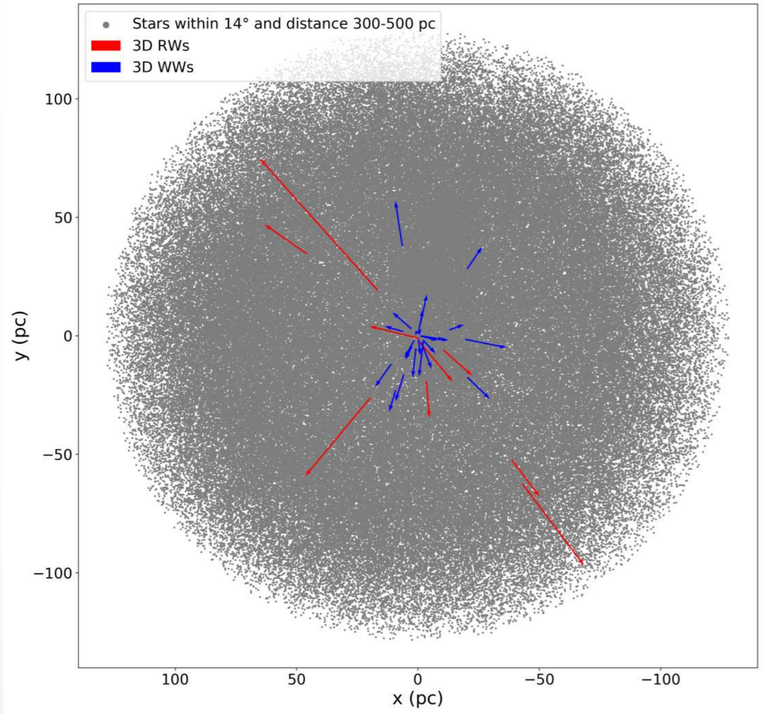


Fig. 5: From **Schoettler+ 2020.** 3D runaways (RWs) are shown with red. 3D walkaways (WWs) are shown with blue. The grey points show the stars within 100 pc of the ONC, which is located at the centre of the figure.

Comparing these numbers to our simulations shows that the ONC is likely younger than 3 Myr, as there would only be 5 RWs within 100 pc at this age.

The number of RWs in *Gaia* is consistent with those at **an upper age of ~2.4 Myr** and we show that ejected stars can be used to estimate/confirm ages of young star clusters.