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Mass segregation in star clusters is not energy equipartition

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ABSTRACT

Mass segregation in star clusters is often thought to indicate the onset of energy equipartition, where the most massive stars impart kinetic energy to the lower-mass stars and brown dwarfs/free floating planets. The predicted net result of this is that the centrally concentrated massive stars should have significantly lower velocities than fast-moving low-mass objects on the periphery of the cluster. We search for energy equipartition in initially spatially and kinematically substructured N-body simulations of star clusters with $N = 1500$ stars, evolved for 100 Myr. In clusters that show significant mass segregation we find no differences in the proper motions or radial velocities as a function of mass. The kinetic energies of all stars decrease as the clusters relax, but the kinetic energies of the most massive stars do not decrease faster than those of lower-mass stars. These results suggest that dynamical mass segregation – which is observed in many star clusters – is not a signature of energy equipartition from two-body relaxation.

Key words: stars: formation – kinematics and dynamics – open clusters and associations: general – methods: numerical

1 INTRODUCTION

The majority of star formation occurs in regions that exceed the mean density of the Galactic disc by several orders of magnitude (Blaauw 1964; Lada & Lada 2003; Porras et al. 2003; Bressert et al. 2010). A fraction of these star-forming regions subsequently form bound, centrally concentrated star clusters (Kruijssen 2012; Parker et al. 2014), whose occurrence rate depends on their Galactic environment (Adamo et al. 2015). Understanding the subsequent dynamical evolution of clusters can place constraints on the initial conditions of star formation, and the likely birth environment of the majority of stars in the Galaxy.

One observed characteristic of star clusters is the relative spatial distribution of the most massive stars compared to low-mass stars. The over-concentration of massive stars in the cluster centre, referred to as 'mass segregation', is either a primordial outcome of the star formation process (e.g. Zinnecker 1982; Bonnell et al. 1997) or a later dynamical effect (Allison et al. 2009b).

In either scenario, mass segregation is often assumed to be the first signature of energy equipartition in clusters, in which all stars have the same kinetic energy. In this picture, the most massive stars exchange kinetic energy with low-mass stars as they move to the centre of the cluster and slow down, and the low-mass stars (and/or brown dwarfs and free floating planets) gain kinetic energy and are ejected to the outskirts.

When full energy equipartition occurs the velocity dispersion, σ of every subset of stars is proportional to the average stellar mass m in the subset,

$$\sigma \propto m^{-0.5}. \quad (1)$$

Before this occurs, a cluster is expected to attain partial energy equipartition where the more massive stars have lower velocities than average-mass stars.

The timescale for energy equipartition is many relaxation times, $t_{\rm relax}$ (Spitzer 1969) where

$$t_{\rm relax} = \frac{N}{8 {\rm ln} N} t_{\rm cross}, \quad (2)$$

and N is the number of stars and $t_{\rm cross}$ is the crossing time. For a typical crossing time in a dense cluster of 0.1 Myr, $t_{\rm relax} \sim 100$ Myr for $N = 1000$ stars and as a consequence would only be expected in the oldest clusters

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(globular and old open clusters). Several studies (Spitzer 1969; Vishniac 1978; Khalisi et al. 2007) have shown that full energy equipartition never occurs in globular clusters, but these systems sometimes reach partial energy equipartition (Trenti & van der Marel 2013; Sollima et al. 2015; Bianchini et al. 2016).

It is currently unclear whether younger, less massive clusters exhibit energy equipartition. Their lower masses (and hence number of stars) relative to globular clusters means that their relaxation times will be much shorter, and many of them display prominent mass segregation of the most massive stars (e.g. Hillenbrand & Hartmann 1998; Gouliermis et al. 2009). Furthermore, Allison et al. (2009b, 2010); Parker et al. (2014) show that more realistic spatially and kinematically substructured initial conditions accelerate mass segregation in clusters, but it is unclear if these initial conditions also lead to (partial) energy equipartition.

In this Letter, we follow the dynamical evolution of clusters to an age of 100 Myr using N-body simulations to investigate whether any mass segregation that occurs can be attributed to energy equipartition. We describe the simulations in Section 2, we present our results in Section 3, we provide a discussion in Seection 4 and we conclude in Section 5.

2 METHOD

We follow the formation and evolution of our model clusters using N-body simulations. Observations of young star-forming regions, and the giant molecular clouds from which they form have a hierarchical and substructured morphology irrespective of their mass (Cartwright & Whitworth 2004; Sánchez & Alfaro 2009; Walker et al. 2015). Furthermore, the velocity dispersions of star-forming cores within filaments are sub-virial (Peretto et al. 2006; Kauffmann et al. 2013), and kinematic substructure is observed in young star-forming regions (Hacar et al. 2013; Alfaro & González 2016).

We therefore set up our N-body clusters with both spatial and kinematic substructure, using the fractal generator from Goodwin & Whitworth (2004). This determines the amount of spatial and kinematic substructure from one parameter, the fractal dimension D. We then scale the velocities of the stars so that the whole region is subvirial with a virial ratio $\alpha_{\rm vir} = 0.3$ (virial equilibrium is $\alpha_{\rm vir} = 0.5$) – i.e. it will collapse to form a cluster (Allison et al. 2010; Parker et al. 2014; Parker & Wright 2016).

The fractal clusters have 1500 stars (similar to the lowest-mass open clusters – i.e. those with the shortest relaxation times) with masses drawn from a Maschberger (2013) IMF between 0.01 $M_\odot$ and 50 $M_\odot$ and an initial radius of 1 pc. The fractal dimension is $D = 1.6$, which gives a very substructured initial distribution (and leads to the most pronounced dynamical mass segregation, Allison et al. 2010). We also ran a set of simulations containing primordial binaries with properties similar to systems in the Galactic field (Raghavan et al. 2010; Reggiani & Meyer 2011).

We ran 20 versions of the initial conditions, identical apart from the random number seed used to initialise the stellar masses, positions and velocities. The N-body simulations were evolved for 100 Myr (the typical relaxation time of these clusters) using the `kira` integrator within the Starlab environment (Portegies Zwart et al. 1999, 2001). We implement stellar evolution using the `SeBa` look-up tables (Portegies Zwart & Verbunt 1996), which are also part of Starlab.

3 RESULTS

3.1 Cluster definition

The fractal simulations initially erase their substructure and collapse to form a smooth, centrally concentrated cluster. The presence of substructure, in tandem with correlated velocities on local scales, has been shown to facilitiate dynamical mass segregation at very early times ($\sim$ 1 Myr) (Allison et al. 2009b, 2010). During this violent relaxation process, unstable multiple systems consisting of the most massive stars form in the centre of clusters (Allison & Goodwin 2011). However, these Trapezium-like systems are unstable and can lead to the ejection of one or more massive stars.

Furthermore, as the clusters evolve over the 100 Myr, the process of two-body relaxation leads to further ejections of both massive (Oh et al. 2015) and lower-mass stars. When stars are ejected at high velocities (>10 km s^{-1}) they can travel several tens of pc during the simulation and are unlikely to be observationally associated with the star cluster.

For this reason, we consider the star cluster boundary to be twice the half-mass radius, $r_{1/2}$ of all stars; this encompasses most of the stars in the cluster but disregards the ejected stars that have travelled beyond the periphery of the cluster. Defining the cluster boundary using the position of the furthest energetically bound star from the cluster centre gives very similar results to using $2r_{1/2}$ (Parker & Quanz 2012). In the example simulation we present here, of the 1500 stars in the cluster initially, 1039 remain at the end of this simulation.

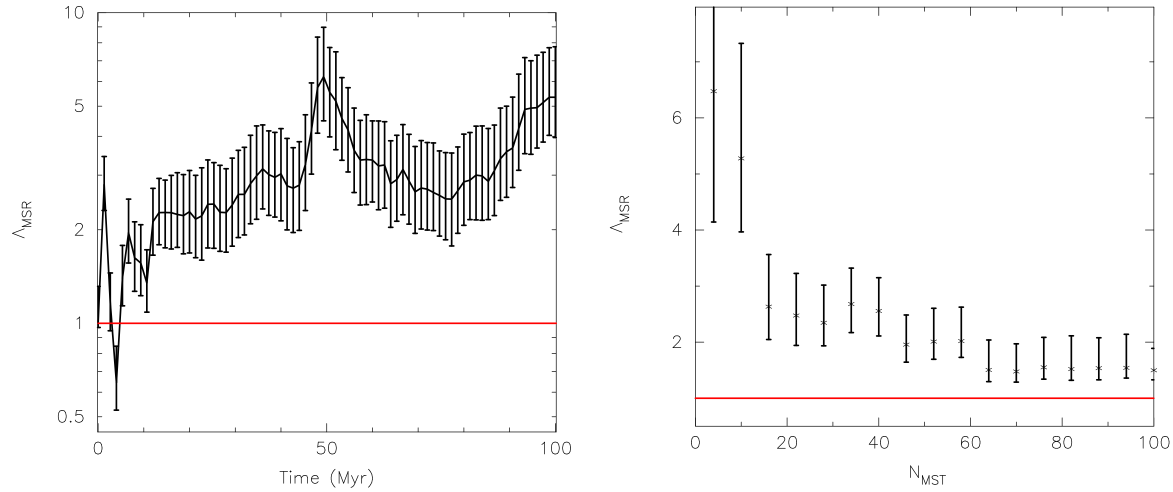
3.2 Mass segregation

We define mass segregation in two different ways. First, we use the $\Lambda_{\rm MSR}$ mass segregation ratio from Allison et al. (2009a), which compares the relative spatial distributions of a chosen subset of stars (e.g. the 10 most massive) to randomly chosen subsets. A minimum spanning tree (MST) is used to quantify the typical length between the most massive stars $l_{\rm sub}$, and this is compared to the mean MST length of many realisations of randomly chosen stars $\langle l_{\rm average}\rangle$ (which may or may not include members of the most massive subset):

$$\Lambda_{\rm MSR} = \frac{\langle l_{\rm average}\rangle}{l_{\rm sub}}^{+\sigma_{5/6}/l_{\rm sub}}_{-\sigma_{1/6}/l_{\rm sub}}. \quad (3)$$

$\Lambda_{\rm MSR} = 1$ indicates no mass segregation, whereas $\Lambda_{\rm MSR} >> 1$ indicates strong segregation. The lower (upper) uncertainty is defined as the MST length which lies 1/6 (5/6) of the way through an ordered list of all the random lengths (corresponding to a 66 per cent deviation from the median value, $\langle l_{\rm average}\rangle$).

In Fig. 1(a) we show the evolution of $\Lambda_{\rm MSR}$ for the ten most massive stars (3.4 – 5.2 $M_\odot$) in a cluster that



(a) Evolution of $\Lambda_{\rm MSR}$

(b) $\Lambda_{\rm MSR}$; 100 Myr

Figure 1. Mass segregation in the simulations as defined by the $\Lambda_{\rm MSR}$ ratio, with uncertainties defined by Eqn. 3. In panel (a) we show the evolution of $\Lambda_{\rm MSR}$ for the 10 most massive stars in the simulation. The cluster rapidly dynamically mass segregates, before ejecting some of the most massive stars at around 5 Myr. Once these stars have travelled beyond twice the half-mass radius they are excluded from the determination of $\Lambda_{\rm MSR}$, and the cluster remains mass segregated until 100 Myr. In panel (b) we show $\Lambda_{\rm MSR}$ as a function of the $N_{\rm MST}$ most massive stars at 100 Myr. The cluster is mass segregated down to the $\sim$50$^{\rm th}$ most massive star.

shows behaviour typical of the full suite of simulations. As in Allison et al. (2010); Parker et al. (2014) dynamical mass segregation occurs early in the simulation, but ejections of the most massive stars cause the signal to decay, before the ejected massive stars move beyond the cluster limits and are not included in the determination. A strong mass segregation signal returns, which is maintained even as the most massive stars lose mass due to stellar evolution[1].

We show the level of mass segregation at 100 Myr in Fig. 1(b). The plot shows $\Lambda_{\rm MSR}$ as a function of the $N_{\rm MST}$ most massive stars, and the cluster is clearly mass segregated down to the 50$^{\rm th}$ most massive star which has a mass 1.05 $\rm M_{\odot}$, although stochastic differences in evolution mean that other clusters can be mass segregated to fewer, or more stars.

In a cluster that no longer has primordial substructure and is mass segregated, we would expect a clear difference in the cumulative distributions of the positions of the most massive stars compared to the cluster average. If the cluster has also undergone energy equipartition, we might expect that the lowest mass objects (free floating planets and brown dwarfs) to be further out than the stars.

In Fig. 2 we show the cumulative radial distribution of the massive stars by the red dashed line, all objects by the solid black line, and the brown dwarfs ($m < 0.08 \rm M_{\odot}$) by the dotted orange line. Whilst the most massive stars are more centrally concentrated than the cluster average, the brown dwarfs are not further from the cluster centre than the average objects.

[1] We also ran a control simulation with no stellar evolution and found very similar results.

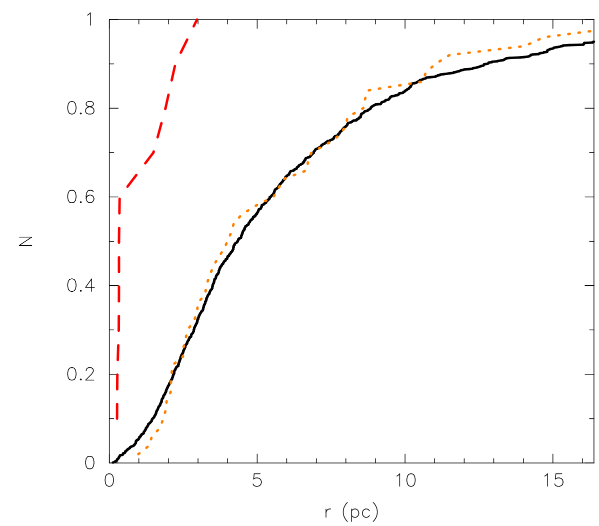


Figure 2. The radial distribution of the ten most massive stars (shown by the red dashed line), all stars (the solid black line) and the brown dwarfs (dotted orange line) at 100 Myr. The most massive stars are clearly more centrally concentrated, but the brown dwarfs are not more distributed than the average star.

3.3 Proper motions

If energy equipartition has occurred in a star cluster, we would expect the most massive objects to be moving more slowly than the average cluster stars, and that the lowest mass objects (brown dwarfs and free-floating planets) would be moving faster. In Fig. 3 we show the cumulative distribution of the proper motions of stars in the cluster. We mimic an observational determination by comparing the change in positions in the x-y plane between timesteps ($\Delta t = 0.1$ Myr)

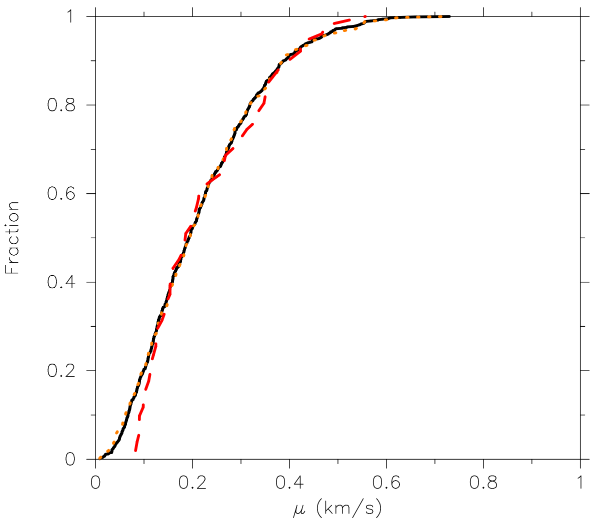


Figure 3. The proper motions of the ten most massive stars (red dashed line), all stars (solid black line) and the brown dwarfs (orange dotted line) at 100 Myr. All objects have the same proper motion velocity distribution.

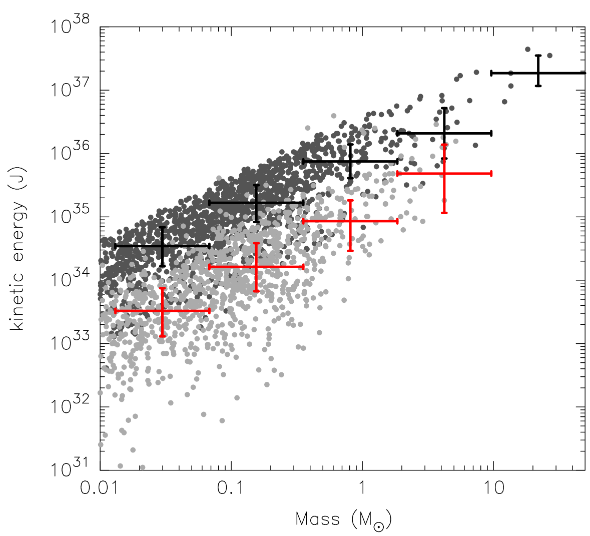


Figure 4. Kinetic energy as a function of stellar mass for the initial conditions (dark grey points) and at 100 Myr (light grey points). The median kinetic energies for equally-spaced mass intervals are shown by the error bars, where the horizontal error bars indicate the mass range, and the vertical error bars are the interquartile range of kinetic energies. The black error bars are for the initial conditions; the red error bars are the values at 100 Myr.

in the simulation. We also checked that we obtain the same result using the respective v_x and v_y velocities.

Fig. 3 clearly shows that the most massive stars are not moving more slowly, nor are the brown dwarfs moving faster than the average stars in the cluster. We note that Zapatero Osorio et al. (2014) find evidence that the proper motions of objects in the Plaiedes cluster increase with decreasing mass. We suggest that this result is probably due to the stochastic nature of cluster dynamics; Parker & Andersen (2014) find that dynamical evolution can cause brown dwarfs to be less spatially concentrated than higher-mass objects, but this is a stochastic effect that only occurs in 20% of their simulations.

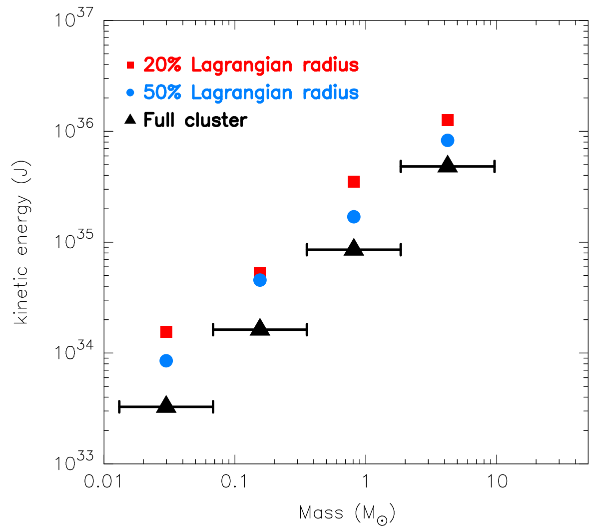


Figure 5. The median kinetic energies for equally spaced mass intervals (indicated by the horizontal error bars) at 100 Myr for different Lagrangian radii.

3.4 Kinetic energies

In order to directly look for energy equipartition, we plot the kinetic energies of individual stars as a function of their mass in Fig. 4. We show the individual kinetic energies for the stars before dynamical evolution ($t = 0$ Myr, the dark grey points) and at the end of the simulation ($t = 100$ Myr, the light grey points). We also show the median kinetic energy in a series of mass bins, where the vertical error bar is the interquartile range of kinetic energies. Black error bars are for the initial values, red are the values at 100 Myr. Due to stellar evolution, the rightmost bin is not present after 100 Myr.

As the cluster relaxes and expands, each star slows down and hence loses kinetic energy on average, but the rate at which energy is lost is independent of stellar mass. There is no indication of energy equipartition, and the stars that are mass segregated are not distinct in this plot. In Fig. 5 we show the median binned kinetic energies at 100 Myr for different Lagrangian radii. There is no radial dependence on the kinetic energy distribution. We also determined the velocity dispersion as a function of mass for the mass bins in this plot (as is more commonly done for globular cluster simulations). We find that at all ages the velocity dispersions remain constant (within a few per cent) as a function of mass, and at different Lagrangian radii.

4 DISCUSSION

Our N-body simulations show that where mass segregation is pronounced in low-mass, intermediate age star clusters, there is no indication of the onset of energy equipartition. If mass segregation was indicative of energy equipartition, we would expect the most massive stars to be moving more slowly, as their kinetic energies would be the same as those of lower-mass stars. We find that the most massive stars do not slow down faster than the average stars during mass segregation. In some ways this is not surprising; as the massive stars move towards the cluster centre, they fall deeper into the gravitational potential and would be expected to speed up. Once in the cluster centre, they often behave as a separate sub-system (Allison & Goodwin 2011), which relaxes by ejecting one or more of the massive stars from the centre.

This is a somewhat continuous or self-regulating process. The level of mass segregation is generally constant throughout the simulation (Fig. 1(a)); if a star is ejected or loses mass through stellar evolution, it is replaced in the potential well by the next most massive star such that the highest mass member in the subset of the ten most massive stars that are significantly mass segregated decreases from 30 $M_\odot$ to 7 $M_\odot$ during the lifetime of the simulation.

Spitzer (1969) and Vishniac (1978) show analytically that the formation of a sub-system of the most massive stars in the core leads to the suppression of energy equipartition in clusters. Our initial conditions, which contain spatial and kinematic substructure, are informed by observations of young star-forming regions and lead to mass segregation and the formation of massive star sub-systems (Allison & Goodwin 2011) on faster timescales than for more commonly adopted Plummer (1911) or King (1966) profiles. If open clusters formed from initial conditions similar to observed star-forming regions, we therefore would not expect any energy equipartition to occur through dynamical evolution.

We repeated the simulations without stellar evolution and find similar results; the most massive stars sink to the centre more rapidly than the average star and form an unstable higher-order multiple system, which decays by ejecting one or more massive stars. This suggests that mass-loss via stellar evolution is not a strong influence on our results.

In the simulations that included primordial binaries, their presence suppresses the level of mass segregation measured by $\Lambda_{\rm MSR}$, and it occurs only half as often as in clusters containing all single stars. In the clusters where it does occur, we find no evidence for energy equipartition.

We do not find any clear evidence in the simulations that the massive stars are imparting energy to lower-mass objects. Several observations have shown that lower-mass objects (brown dwarfs and free-floating planets) appear to be more sparsely concentrated, and are moving at faster velocities, than the average stars in a cluster (Andersen et al. 2011; Kumar & Schmeja 2007; Caballero 2008; Zapatero Osorio et al. 2014). We suggest that this could be a stochastic effect from dynamical evolution of a dense cluster which occasionally preferentially ejects the lowest mass objects to the outskirts of the cluster (Parker & Andersen 2014). However, this happens in only 20 per cent of simulated clusters, and free-floating planets have also been shown to tend to move with similar velocities to the stellar members of the cluster (Parker & Quanz 2012).

5 CONCLUSIONS

We perform N-body simulations of the evolution of $N = 1500$ clusters with stellar evolution for the first 100 Myr of their lifetimes. We look for mass segregation (an over concentration of the most massive stars with respect to the average stars) and when it occurs, look for evidence for energy equipartition. Our conclusions are as follows.

(i) Most clusters reach mass segregation on timescales of 10 Myr (100 crossing times), and maintain the level of mass segregation for the duration of the simulation.

(ii) The clusters are significantly mass segregated down to the $\sim 50^{\rm th}$ most massive star (out of 1039 stars which remain in the cluster). Stellar evolution and dynamical ejections can change the identities of the stars that are mass segregated, but only occasionally cause the mass segregation signature to disappear. The presence of primordial binaries suppresses mass segregation and we will explore this in a future paper.

(iii) The stars that are mass segregated are not moving with slower velocities than the average stars, which would be expected if they were attaining (partial) energy equipartition.

(iv) When we look at the individual kinetic energies of stars as a function of stellar mass, we see no evidence that the most mass segregated stars have kinetic energies that are equal to, or even tend towards those of average-mass, or low-mass stars, and the kinetic energy decreases for all stars as the clusters relax.

In summary, we suggest that any mass segregation observed in young (<10 Myr) and intermediate age (10 – 500 Myr) clusters is not a signature of energy equipartition. Rather, it is simply either primordial mass segregation from the outcome of star formation, or dynamical mass segregation due to violent, and/or two-body relaxation.

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