The impact of an evolving bar on the kinematics of a primordial hot population of star clusters in the bulge

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ABSTRACT
We present a numerical study of the effect of an evolving bar on the kinematics of a primordial hot star cluster population in the bulge, as well as on bulge field stars originating within dissolved star clusters. We confirm that an evolving bar is able to transfer a small amount of angular momentum to the star cluster system, in good agreement with observations for Galactic bulge clusters. In the case of a realistic mass model, in which the bar slows down and grows in size, the star cluster escapers evolve in a configuration consistent with that expected for a classical bulge and share comparable kinematic properties with the spheroidal metal-poor component identified within the bulge of the Milky Way. Our results are consistent with a scenario in which the bulge of the Milky Way has a composite nature, with the star clusters belonging and contributing to a primordial pressure-supported component.

Key words: methods: numerical – Galaxy: bulge – globular clusters: general.

1 INTRODUCTION
The Galactic bulge exhibits the presence of two distinct populations characterized by different kinematical signatures: a young, metal-rich component showing cylindrical rotation and an old, spheroidal metal-poor component with small rotation and roughly constant velocity dispersion (for a review see Babusiaux 2016). Such evidence has been used to constrain formation models of the bulge. The metal-rich population shows the kinematics expected for a pseudo-bulge, formed in situ as a consequence of a disc instability in the inner regions of the Galaxy which lead to the formation of a bar. In this scenario, the bar heats the disc perpendicular to the galactic plane and gives rise to a boxy-peanut-shaped bulge. The metal-poor component appears instead to be more spherically distributed and pressure-supported with velocity dispersion of about 120 km s−1. The current estimates of the percentage of the mass of the metal-poor population that is not part of a continuum with the pseudo-bulge are low, ranging from about 1 per cent (Kunder et al. 2016; Debattista et al. 2017) to 8 per cent (Shen et al. 2010) of the stellar mass. The old component is therefore only a small fraction of the bulge’s overall mass. Kunder et al. (2016) showed that old RR Lyrae variable stars from the BRAVA-RR survey present the characteristics of a hot population with null or negligible rotation formed before the development of the bar, suggesting a composite nature of the bulge (see also Di Matteo et al. 2015). On the other hand, Debattista et al. (2017) showed that an evolving bar can indeed be responsible for the observed separation of stellar populations that originated within the disc, supporting the scenario in which the bulge formed largely in situ. More recently Gomez et al. (2018) showed that the results of N-body simulations indicate that the metal-poor stars in the bulge can be part of a thick disc rather than an old pressure-supported system.

Assuming that the old and hot component is indeed a stellar population separated from the disc and which formed before the development of the bar, a question is how can it remain stationary under the development of a bar. It has been shown that the development of a bar can indeed transfer angular momentum to a pre-existing low-mass (Saha, Martinez-Valpuesta & Gerhard 2012; Saha 2015) and a massive (Saha, Gerhard & Martinez-Valpuesta 2016) classical bulge through resonances, where the process is more efficient for smaller classical bulge masses. Furthermore, the results of Minchev et al. (2012) suggest that a hot, pre-existing spherical component is only mildly affected kinematically by the development of a bar.

The Galactic bulge hosts another important stellar population: star clusters. The Galactic bulge cluster system numbers about 50 objects with metallicities within the −1.5 < [Fe/H] < 0 range and peaked around [Fe/H] ≈ −1.0. They are very old (e.g. Ortolani et al. 2011) and most likely formed before the bar developed. By comparing the metallicity and kinematics of star clusters and field stars in the inner 3 kpc of the Galaxy, Minniti (1995) already concluded that these clusters are likely associated with the Galactic bulge, rather than the Galactic disc/bar. Furthermore, star clusters evolve in time, losing stars which end up populating the field, and the population

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of star clusters in the bulge was originally composed of more objects than the present-day count, with previous members that are now mixed with the field stars. In light of these considerations, the suspicion of a possible connection between the pressure-supported metal-poor component and the bulge clusters naturally arises. In more recent years the proper motions of several clusters in the bulge region have also been derived. Having information on the six-dimensional state vector (position and velocity) of the clusters allows us to obtain information on the total angular momentum of the bulge cluster system. The information from the proper motions, in combination with the radial velocities, is fundamental in order to obtain a more accurate picture of the kinematical state of the bulge star clusters.

The primary goal of this work is to verify how a primordial hot population of star clusters is expected to respond to a developing bar and evaluate any transfer of angular momentum between the bar and the star cluster system. As a second step, we aim to evaluate the present-day spatial distribution and kinematic properties of a stellar population originating within dissolved star clusters in the presence of an evolving bar and compare the results with observational evidence for the Milky Way.

The paper is structured as follows. In Section 2, we present our analytic time-dependent mass model. Section 3 includes an analysis of the effect of the development of the bar on the angular momentum components of a primordial kinematically hot population of star clusters. In Section 4, we follow the spatial and kinematic evolution of a population of stars that originated within dissolved star clusters. Section 5, presents the observational data for the Galactic bulge cluster system and how it compares to our predictions and in Section 6 we summarize the results of our analysis.

## 2 The Galactic Model

We modelled the mass distribution of a disc galaxy calibrated to the observations of the Milky Way in terms of analytic functions representing the different galactic components. The disc and the halo are described as a Miyamoto–Nagai (Miyamoto & Nagai 1975) potential and as a logarithmic potential (Aarseth 2003), respectively. In Cartesian right-handed galactocentric coordinates these components can be expressed as

\[
\Phi_d = -\frac{GM_d}{\sqrt{x^2 + y^2 + \left[a_d + \left(b_d^2 + z^2\right)^{1/2}\right]^{1/2}},}
\]

\[
\Phi_h = \frac{\nu_0^2}{2} \log \left(a_h^2 + x^2 + y^2 + z^2\right),
\]

where \(\Phi_d\) and \(\Phi_h\) are the gravitational potentials associated with the disc and halo, respectively. In the present notation, \(M_d = 7.2 \times 10^{10} M_\odot\) (Irrgang et al. 2013) is the mass of the disc component, \(a_d = 0.29\) kpc, \(b_d = 3.26\) kpc (Irrgang et al. 2013), and \(a_h = 9.03\) kpc are scale lengths, \(\nu_0 = 239.7\) km s\(^{-1}\) (Irrgang et al. 2013) is the asymptotic value of the circular velocity curve, and \(G\) is the gravitational constant.

The bar is modelled as a triaxial rotating Ferrers ellipsoid following the density profile (Pfenniger 1984)

\[
\rho(x, y, z) = \begin{cases} 
\rho_0(1 - m^2)^n, & m < 1 \\
0, & m \geq 1
\end{cases}
\]

where \(n\) is a positive integer and

\[
m^2 = \frac{x^2}{a_b^2} + \frac{y^2}{b_b^2} + \frac{z^2}{c_b^2}.
\]

\(a_b, b_b\), and \(c_b\) are the semi-axes of the ellipsoid with \(a_b > b_b > c_b\), and \(n = 2\) is the density profile parameter.

In our model we allow the bar to evolve with cosmic time. Given that there is no conclusive picture capturing the details of the evolution of the bar of the Milky Way, at this point most of our ideas about the evolution of bars come from numerical simulations. It has been shown in several works (e.g. Athanassoula 1984, for a review) that bars arise from a disc instability. They usually form and grow in mass quite rapidly, on time-scales varying between a few rotations (few 100 Myr) to about 1 Gyr. This growth can be interpreted as the mass of the disc rearranging from an axisymmetric to a barred configuration in the inner regions. Once they form, bars transfer angular momentum to the disc and halo and decrease their pattern speed, slowly growing in size (e.g. Weinberg 1985; Debattista & Sellwood 2000; Athanassoula 2002, 2003; O’Neill & Dubinski 2003). In simulations without gas this evolution can be very rapid but gas may help regulate the process (Machado, Athanassoula & Rodionov 2012). Bar slowdown can be reasonably approximated as a linear function (Athanassoula 2003). Generally, bars are observed to extend to about their corotation radii (Aguerri, Beckman & Prieto 1998), which serves as a constraint on how rapidly a bar grows in size as it slows down.

In our experiment, we used as a reference the bar evolution model presented in Cole et al. (2014), in combination with the observed present-day properties of the Galactic bar. Before expanding on the details of our model, we emphasize that the model can be considered an approximation of the true evolution of a bar, but does present a plausible picture that allows insight into the dynamics of the bulge. In our model the bar forms at \(t = 3\) Gyr (see also Debattista et al. 2017) and grows exponentially in mass up to \(t = 4\) Gyr, when the mass reaches \(M_{bar} = 1 \times 10^9 M_\odot\) (Gardner & Flynn 2010). In agreement with observational evidence for the Galaxy, we assumed that the present-day pattern speed of the bar is \(\Omega_b \approx 55\) km s\(^{-1}\) kpc and we approximate a constant circular velocity curve to 200 km s\(^{-1}\). Under this assumption the semimajor axis of the bar is \(a_b \approx 3.6\) kpc, in good agreement with observations (Bissantz & Gerhard 2002). Following Cole et al. (2014), we assumed that the semimajor axis of the bar at 6 Gyr is 2 kpc. If we adopt as a first approximation a constant velocity curve (see also Athanassoula 2013), this corresponds to a pattern speed of about \(\Omega_b \approx 100\) km s\(^{-1}\) kpc. By extrapolating this result backwards, under the assumption of a linear decrease of the pattern speed, we find that at 3 Gyr, which is the time at which the bar starts forming, the pattern speed is \(\Omega_b \approx 120\) km s\(^{-1}\) and the semimajor axis is \(a_{bar} \approx 1.7\) kpc. The axial ratios of the bar are assumed to be \(b_{bar}/a_{bar} = 0.5\) (Shen et al. 2010) and \(c_{bar}/a_{bar} = 0.3\) (Bissantz & Gerhard 2002), which are conserved in cosmic time. Fig. 1 shows the evolution of the mass, pattern speed, and semimajor axis of the bar with time in our simple evolutionary model. The total mass of the galaxy is conserved and we simulated the development of a bar from the disc by accordingly decreasing the total mass of the disc as the bar grows exponentially in mass. As a comparison, in order to evaluate the impact of a growing bar we also implemented a simpler model in which the bar does not grow in size. In this model the bar forms at \(t = 3\) Gyr, exponentially increases in mass until \(t = 4\) Gyr but does not slow down and does not grow in size with time, maintaining its present-day size and pattern speed since its initial development. We refer to this model as the non-growing bar.
3 IMPACT OF A BAR ON THE KINEMATICS OF A PRE-EXISTING HOT POPULATION OF STAR CLUSTERS

In the present section, we evaluate to what extent a bar can spin-up a pre-existing pressure-supported population of star clusters. It has been already demonstrated that a small isotropic, non-rotating bulge can absorb angular momentum emitted by the bar by angular momentum exchange through resonances (e.g. Saha et al. 2012). Here, we repeat a similar exercise, focusing on an initially kinematically hot population of star clusters.

We started by creating a system of $10^3$ test particles tracing the orbits of the clusters assuming they are initially following a homogeneous distribution within a sphere with radius equal to 4 kpc. The values of the three velocity components are drawn from a normal distribution peaked at zero and with velocity dispersion equal to 100 km s$^{-1}$, in good agreement with the observed distribution of radial velocities of the bulge globular clusters (see Section 5.1 and Fig. 13). The orbits of the test particles have been integrated with the code NIGO (Rossi 2015). The code is based on a Shampine–Gordon integration scheme (Shampine & Gordon 1975) for differential equation solution, and we refer to the original publication for further details. We integrated the orbits until 13 Gyr, requiring a maximum relative variation of total specific energy $E$ and angular momentum $L_z$ (in the axisymmetric potential before the development of the bar) equal to $10^{-12}$. In order to take into account stochastic effects we averaged the results of 10 different realizations of the hot population and assigned to the results a statistical 3$\sigma$ error derived from the Monte Carlo scheme.

Fig. 2 shows the time evolution of the mean angular momentum components ($L_x$, $L_y$, and $L_z$) of the hot population of $10^3$ test particles (each representing a star cluster), both in the case of a growing and a non-growing bar. The plots also include the components of the average specific angular momentum derived from the proper motion of the Galactic bulge clusters, which is discussed in more detail in Section 5.1. The evolution of the $L_x$ and $L_y$ angular momentum...
components of the system of test particles is shown in the top and middle panels of Fig. 2. The average values of $L_x$ and $L_y$ of the system remain roughly constant and close to zero in both the cases of a growing and non-growing bar. In other words there is no transfer of angular momentum from the bar to the cluster system along the $x$ and $y$ directions, as naturally expected. The results are different for the $L_z$ component. Since the system is initially non-rotating, the average value of $L_z$ is zero and remains constant until the development of the bar at $t = 3$ Gyr. At this time the newly formed bar starts transferring angular momentum to the system of clusters, to an extent that strongly depends on the evolutionary model adopted. In the case of a bar that slows down and grows in size the angular momentum of the system is observed to progressively decrease in value. On the other hand, in the model in which we do not take into account the slow-down of the bar the average angular momentum of the test particles decreases until the bar is fully formed, after which it remains roughly constant in time. The slowing down of the bar itself appears to be a dominant effect in the transfer of angular momentum to the pressure-supported system. Considering the $3\sigma$ uncertainty of the Monte Carlo scheme and the uncertainty on the age of the Galactic bulge cluster system, the data point of $L_z$ for the Galactic bulge cluster system is well matched by the simulations. On a side note, we also recall that the $z$ component of the bar is negative as it shows a clock-wise rotation, as seen from the North Galactic Pole.

The predictions for the rotation curve of the system and the velocity dispersion profile as function of the galactic longitude in the case of a growing bar are shown by the black triangles in Fig. 3. Even though the system is expected to gain a small amount of angular momentum, we did not observe any obvious rotation of the system in the average radial velocity curve, with maximum values lower than $50$ km s$^{-1}$.

We refer to Section 5.1 for a comparison of these results with the observations for the Milky Way.

Considerable uncertainty exists in the determination of the present-day properties of the Galactic bar so for the sake of completeness we have tested our results for a different set of properties, namely the recent estimates by Wegg, Gerhard & Portail (2015) that put the semimajor axis of the bar at $5$ kpc and pattern speed at $\sim 33$–$40$ km s$^{-1}$ kpc. The prediction of the average $L_z$ component for these alternative present-day semimajor axis and pattern speed are shown in Fig. 4. In this case the predicted average value for the simulated cluster system at $t = 13$ Gyr is roughly $-270$ km s$^{-1}$ kpc, which is almost a factor of 2 higher than the value observed for the Galactic bulge cluster system (see Section 5).

4 CONTRIBUTION OF DISSOLVED STAR CLUSTERS TO THE BULGE POPULATION

The results above confirm that the development of a bar can indeed transfer angular momentum to a pre-existing pressure-supported population of star clusters. A further consideration is that star clusters themselves evolve in time, losing stars mostly owing to two-body relaxation effects and tidal shocks (e.g. Rossi, Bekki & Hurley 2016), which end up populating the field. As already discussed in Section 1, given the old nature and the low metallicity of globular clusters in the bulge, together with the detection of a spheroidal metal-poor bulge component formed before the development of the bar, the question that naturally arises is whether there could be any connection between these two systems.

As a next step of our numerical experiment, we evaluated the long-term evolution of a population of stars originating within star clusters dissolved before the formation of the bar, using as initial conditions for the escapers the self-consistent results of direct N-body simulations of star clusters. In Section 4.1, we introduce the $N$-body simulations, while the results are presented Section 4.2.

4.1 Numerical simulations

The simulations of the clusters are performed with NBODY6 (Aarseth 2003), a state-of-the-art collisional code designed to follow in great detail the dynamical and internal evolution of stars within an $N$-body system. The clusters are assumed to be initially in virial equilibrium and with a spatial distribution of the stars described by a Plummer sphere (Plummer 1911). The initial distribution of the stellar masses follows a Kroupa mass function (Kroupa 2001) with a metallicity $Z = 0.002$ (corresponding to $[\text{Fe/H}] = -1.0$). We adopted a 5 per cent fraction of primordial binaries, with binary orbital set up chosen as
Figure 5. Face-on view (left column) and edge-on view (right column) of the snapshots of the evolution of the tidal tails of dissolved clusters at $t = 1, 5, 9,$ and 13 Gyr in the model that implements a growing bar. The black ellipse in the face-on projections shows the contour of the bar.
described in Geller, Hurley & Mathieu (2013). The code allows us to simulate the evolution of multiple systems as well as close encounters and collisions. The effects of single stellar evolution (Hurley, Pols & Tout 2000) and binary stellar evolution (Hurley, Tout & Pols 2002) are also included. All the simulated clusters are initially composed of $N = 10k$ stars and a half-mass radius equal to $r_{\text{hm}} = 1.15$ pc, neglecting any dependence of the size on the initial location of the clusters within the bulge.
We simulated a total of 20 clusters, with initial position and velocity in the galaxy randomly chosen from one of the realizations of the pressure-supported cluster population described in the previous section. All the simulations typically finished (i.e. the cluster dissolved) before 1 Gyr of evolution had elapsed, which is well before the development of the bar. We also note that in order to avoid small number effects we defined a cluster to be ‘dissolved’ when only 300 stars remain gravitationally bound. Once the clusters have evaporated, we recorded the position and velocities of the escapers and continued the integration of their orbits until 13 Gyr with NIGo.

The choice of simulating clusters originally composed of 10k stars is dictated by the choice of focussing on clusters dissolved before the development of the bar in this particular study. For comparison purposes, we again evaluated the results obtained both in the case of models implementing a growing and a non-growing bar.

4.2 Evolution of the cluster escapers

Some snapshots of the spatial evolution of the cluster escapers in the bulge, seen both face-on (left column) and edge-on (right column), are shown in Figs 5 and 6. At 1 Gyr, before the development of the bar, the tidal tails are well defined both in the (x, y) and in the (x, z) plane. As soon as the bar develops the tidal tails start to progressively mix in space until the end of the simulation at \( t = 13 \) Gyr. By visually comparing the two models, the spatial mixing of the tidal tails is quite efficient in the case of a growing bar. On the other hand, in the case of a non-growing bar several tidal tails tend to
occupy well-defined regions of space both in the \((x, y)\) and in the \((x, z)\) plane (examples are the blue and red points in Fig. 6). This effect is clearly visible in the contour plots of the final configuration at 13 Gyr, particularly in the \((x, z)\) plane, as shown in Figs 7 and 8. The contour plots shown in Fig. 8 seem to suggest that there is a ‘two-component’ shape to the resulting debris. However, this feature is due to only a few clusters for which the debris tends to follow more regular orbits. As is visible in Fig. 6, we found stars following retrograde \(x^4\) orbits perpendicular to the semimajor axis of the bar (for a review see Contopoulos & Papayannopoulos 1980). We already identified such orbital families in the present mass model of the bar in Rossi & Hurley (2015). As shown in that work (see Fig. 6, black points) these orbits occupy a well-defined region in the Poincaré diagram but they are not exactly resonant. Interestingly, the dissolved cluster population in the growing bar model represents an overall geometry of an oblate ellipsoid with an axial ratio of about 0.6 (see Fig. 9). The impact of the choice of the bar evolutionary model on the spatial distribution of dissolved individual clusters is also shown in Fig. 10.

The bar is then expected to be quite efficient at spatially mixing the initially well-defined tidal tails of star clusters dissolved before its development, where this effect is more important in the growing-bar model. As a further test, we evaluated the evolution of the bar model. As a further test, we evaluated the evolution of the bar model on the spatial distribution of dissolved stars following retrograde \(x^4\) orbits perpendicular to the semimajor axis of the bar (for a review see Contopoulos & Papayannopoulos 1980). We already identified such orbital families in the present mass model of the bar in Rossi & Hurley (2015). As shown in that work (see Fig. 6, black points) these orbits occupy a well-defined region in the Poincaré diagram but they are not exactly resonant. Interestingly, the dissolved cluster population in the growing bar model represents an overall geometry of an oblate ellipsoid with an axial ratio of about 0.6 (see Fig. 9). The impact of the choice of the bar evolutionary model on the spatial distribution of dissolved individual clusters is also shown in Fig. 10.

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5 COMPARISON OF THE SIMULATIONS WITH THE GALACTIC BULGE GLOBULAR CLUSTER SYSTEM

Even though an accurate match with the observations is beyond the main scope of this work, we have analysed how the predictions of our models compare with the data for the Galactic bulge star cluster systems, aiming mainly to obtain some constraints on the model describing the evolution of the bar.

5.1 The data

The catalogue compiled by Harris (Harris 1996, 2010 edition) contains data on the kinematic, photometric, and dynamical properties of 157 objects classified as globular clusters in the Galaxy. More recently Bica, Ortolani & Barbuy (2016) presented a catalogue of candidate genuine bulge clusters. In this work, we consider the sample of candidate bulge clusters included within the inner 4.5 kpc of the Galaxy, excluding the probable halo intruders identified by the authors. The selected bulge cluster system contains 50 objects with known distance and radial velocity. We searched in the literature for information regarding the proper motions of the identified bulge cluster system, finding data for 22 objects. Having information on the 3D components of the velocity vector is fundamental not only to integrate the orbit of a cluster, but also to determine the value of its specific angular momentum. Namely, we found information regarding the state vectors of NGC 6266, NGC 6304, NGC 6553, NGC 6723 (Dinescu et al. 2003), NGC 6316, NGC 6342, NGC 6388, NGC 6441 (Casetti-Dinescu et al. 2010), NGC 6626 (Casetti-Dinescu et al. 2013), Terzan 1, Terzan 2, Terzan 4, Terzan 9, Palomar 6, NGC 6522, NGC 6540, NGC 6558, NGC 6652 (Rossi et al. 2015), NGC 6717 (Cudworth, Smetanka & Majewski 1992), NGC 6528 (Feltzing & Johnson 2002), HP 1 (Ortolani et al. 2011), and Terzan 5 (Massari et al. 2015).

As displayed in Fig. 12 (see red dots), the bulge cluster system does not show a clear overall rotation, but rather seems to be pressure supported as already concluded by Minniti (1995). However, it could also be argued that the bulge cluster system shows a very
Figure 10. Examples of tidal tails of dissolved star clusters at 13 Gyr projected on the \((x, y)\) plane in the case of a growing (left-hand panels) and a non-growing (right-hand panels) bar.

small degree of rotation at higher longitudes \((l > 10 \text{ deg})\). Fig. 13 shows the distribution of radial velocities of the bulge cluster sample, which is reproduced well by a normal distribution with velocity dispersion \(\sigma_r \sim 100 \text{ km s}^{-1}\).

With the available information on the proper motions of some of the clusters in the bulge sample we derived the average value of the component of the specific angular momentum projected on the rotation axis of the Milky Way \((z\text{-axis})\), finding \(L_z = -150.5 \pm 5.6 \text{ km s}^{-1} \text{ kpc}\). In other words, the proper motions of the bulge clusters suggest that the bulge cluster system is actually slightly rotating. We note that the average angular momentum of the system is quite small. As a comparison, the specific angular momentum of a particle on a circular planar orbit with a 4 kpc radius and with tangential velocity of 200 km s\(^{-1}\) is \(L_z = 800 \text{ km s}^{-1} \text{ kpc}\), which is about a factor 5 higher than the average angular momentum found for the bulge cluster system. In Fig. 2, we compare the observed values of the \(x, y,\) and \(z\) components of the specific angular momentum of the bulge cluster system with the prediction of the simulations for the growing and non-growing bar. In order to take into account differences in the age of the bulge clusters we assumed an uncertainty of 1 Gyr in the age of the system. A static model of the bar is not able to explain the observed mild rotation of the system of bulge clusters, which is instead better matched in the simulation with a bar that slows down and grows in size. This is particularly evident in the evolution of the average \(L_z\) component (bottom panel of Fig. 2). If taking into account the stochastic error of the Monte Carlo scheme and the error associated with the measure of the proper motions, the result of the simulation implementing a model of a bar that slows down and grows in time is in good agreement with the data points from observations.

We also compared the observed radial velocity profile and velocity dispersion of the bulge star cluster sample with the results obtained at 13 Gyr for both the initially pressure-supported population of star clusters described in Section 3 and the population of stars originating within dissolved primordial star clusters. In this case, we only present the results for the simulations with a growing
Figure 11. Evolution of the cluster escapers in energy–angular momentum space at $t = 1, 5, 9,$ and $13$ Gyr in the case of a growing bar (left column) and a non-growing bar (right column).
The radial velocity (top panel) and velocity dispersion (bottom panel) of star clusters and field stars originating within dissolved star clusters at 13 Gyr in the presence of a growing bar. The red dots show the data points for the Milky Way bulge clusters, the triangles show the predictions for a population of primordial star clusters after 13 Gyr of evolution while the open squares show the prediction for a population of field stars originating within dissolved star clusters.

6 SUMMARY AND CONCLUSIONS

We have quantified the impact of the development of a bar on the kinematics of an initially pressure-supported population of star clusters in the bulge, including information on the field stars that originated within dissolved star clusters belonging to such a population. The analysis is based on a numerical approach which employs NICO and NBODY6 for orbit integration and direct N-body simulations of the clusters, respectively. We implemented an analytic, yet time-dependent, model of a disc galaxy representative of the Milky Way, which would correspond to an initial bulge cluster system numbering about 420 clusters and would imply that roughly $2.5 \times 10^7$ M⊙ of bulge field stars originated in star clusters. Assuming a total mass of the central component of the Galaxy equal to $10^{10}$ M⊙, i.e., the mass of the bar, this number corresponds to about 25 per cent of the mass of the old spheroidal component identified by Kunder et al. (2016). We want to emphasize that this is a very rough estimate which would need to be supported by a more detailed dynamical study, as discussed in the next section. None the less, it also suggests that the contribution of dissolved star clusters to the hot population of stars in the inner Galaxy could be non-negligible.
good agreement with previous studies, our results suggest that a bar is able to transfer angular momentum to the hot system of star clusters, to an extent dependent on the evolutionary model implemented. In particular, a bar slowing down and growing in size is more efficient in transferring angular momentum across cosmic time. The maximum rotational velocity of the system is expected to be lower than 50 km s$^{-1}$, which is comparatively smaller than the value expected for a genuine disc population.

As a next step, we evaluated the spatial and kinematic properties of field stars generated within dissolved star clusters originally belonging to the pressure-supported population and evaporated before the development of the bar. We self-consistently simulated star clusters by employing direct $N$-body models and adopted as initial conditions for the orbit integration of the escapers the positions and velocities from the last snapshot of the $N$-body simulation. Also in this case the results are strongly influenced by the underlying assumption on the evolutionary model of the bar. In the simple model of a bar that does not slow down and does not grow in size each tidal tail of the various dissolved clusters is expected to occupy a well-defined region of space in the bulge at $t = 13$ Gyr and still trace the original orbit of the dissolved cluster. This behaviour is also observed in the energy–angular momentum space, where the various tidal tails are well recognizable. However, in the more realistic model with a bar slowing down and growing in size the cluster escapers are spatially well mixed and no clear residual stream structures are observed. Overall, the escapers occupy a region of space that closely resembles a classical bulge with semimajor axis of about $5\text{kpc}$ and semiminor axis of about $3\text{kpc}$, rather than a pseudo-bulge originating from a disc instability. Likewise, we observed a significant spread of the escapers within energy–angular momentum space. The population of field stars that originated within primordial star clusters shows an overall small rotation owing to transfer of angular momentum from the bar lower than $50\text{ km s}^{-1}$, which is consistent with the prediction for the population of surviving star clusters.

Finally, we compared our prediction for the primordial hot population of star clusters with observational evidence from the subset of the Galactic bulge star cluster population with available radial velocities and proper motions. We found the best agreement with the more realistic model implementing a growing bar, both for the average radial velocities and velocity dispersion profile and for the average angular momentum of the system. Furthermore, the bulge field population generated within star clusters shows a kinematic signature similar to that observed for the old spheroidal metal-poor bulge component identified in the bulge of the Milky Way, which suggests a possible connection between the two populations.

The major conclusions of this work can be summarized as follows:

(i) An evolving bar is expected to transfer angular momentum to a pre-existing pressure-supported population of star clusters in the bulge but not to such an extent as to show a clear overall rotation of the system, which is in good agreement with observations.

(ii) In our simple evolutionary model, the field stars that originated within primordial star clusters are expected to be efficiently mixed by an evolving bar and to occupy a region of space within an oblate ellipsoidal volume axial ratio of about 0.6. They are observed to absorb angular momentum from the bar and to show a mild rigid-body rotation with magnitude less than $50\text{ km s}^{-1}$ and velocity dispersion peaked at about $150\text{ km s}^{-1}$ towards the Galactic centre.

(iii) The spheroidal metal-poor component identified within the Galactic bulge and the bulge star clusters are observed to share similar kinematic properties. This same behaviour is observed in our numerical simulations, which suggests a possible connection between these stellar populations. This suspicion is reinforced after a first estimate of the contribution of a population of dissolved star clusters to the bulge field stars, with a mass contribution of the order of 25 per cent. A further dynamical investigation is required to study the details of the mass-loss rates of star clusters in the bulge to obtain stronger constraints on the field contamination.

(iv) Our results support the scenario in which the bulge has a composite nature, consisting of a pseudo-bulge and a primordial classic bulge, which the star clusters belong to. This is further confirmed by the study of the orbits of individual star clusters (Pérez-Villegas et al. 2018), which suggest that the bulge clusters belong to a population supported by random motion rather than to a disc population.

(v) The observations are better matched in the case of a more realistic mass model taking into account angular momentum transfer between the bar and the dark matter halo in which the bar forms early. We also note that the details of the model of the bar (such as mass, pattern speed, size, and age) are expected to influence the amount of angular momentum transferred to the star clusters and an accurate model is required for a more precise comparison with the observational data.

According to the results presented here it would be hard to identify tidal debris of evaporated clusters in the bulge by studying the spatial distribution of field stars. However, we predicted that the debris should be more easily identifiable in the energy–angular momentum space. Having access to precise proper motion measurements of the stars belonging to the old spheroidal component, and hence to their angular momentum, would allow us to test the presence of structures in the $(E, L_z)$ space. A natural continuation of this work is to investigate the details of the mass-loss rates of clusters in the presence of an evolving bar. Such a dynamical study would allow us to more accurately constrain the expected contribution of the bulge cluster system to the field population, taking into account information on metallicity and stellar evolution as well. Direct $N$-body simulations of star clusters are an ideal tool to tackle such a problem, which will be addressed in a forthcoming paper.

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