ON THE ORIGIN OF HIGH-ALTITUDE OPEN CLUSTERS IN THE MILKY WAY

L. A. MARTINEZ-MEDINA1, B. PICHARDO1, E. MORENO1, A. PEIMBERT1, and H. VELAZUEZ2

1 Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, 04510, México, D.F., México; lamartinez@astro.unam.mx
2 Instituto de Astronomía, Universidad Nacional Autónoma de México, Apartado Postal 877, 22860 Ensenada, B.C., México

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ABSTRACT

We present a dynamical study of the effect of the bar and spiral arms on the simulated orbits of open clusters in the Galaxy. Specifically, this work is devoted to the puzzling presence of high-altitude open clusters in the Galaxy. For this purpose we employ a very detailed observationally motivated potential model for the Milky Way and a careful set of initial conditions representing the newly born open clusters in the thin disk. We find that the spiral arms are able to raise an important percentage of open clusters (about one-sixth of the total employed in our simulations, depending on the structural parameters of the arms) above the Galactic plane to heights beyond 200 pc, producing a bulge-shaped structure toward the center of the Galaxy. Contrary to what was expected, the spiral arms produce a much greater vertical effect on the clusters than the bar, both in quantity and height; this is due to the sharper concentration of the mass on the spiral arms, when compared to the bar. When a bar and spiral arms are included, spiral arms are still capable of raising an important percentage of the simulated open clusters through chaotic diffusion (as tested from classification analysis of the resultant high-z orbits), but the bar seems to restrain them, diminishing the elevation above the plane by a factor of about two.

Key words: galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure – open clusters and associations: general

1. INTRODUCTION

The total number of open clusters in the Galaxy is estimated to be up to 100,000 (Piskunov et al. 2006; Portegies Zwart et al. 2010); due to large amounts of reddening, crowding, and disruption, we only know a few thousand of them toward the Galactic Center (Freeman 1970; van der Kruit 2002). The ones we observe are mostly located between 5 and 20 kpc from the Galactic center, with ages ranging from a few Myr to approximately 10 Gyr. From the total, only about 10% survive their embedded stage as gravitationally bound systems (Lada & Lada 2003). Orbital elements of open clusters show that the majority were formed within a galactocentric radius of 10.5 kpc and are closer than 180 pc from the Galactic plane (Dias et al. 2002; Gozha et al. 2012). The most massive open clusters can reach lifetimes comparable to the age of the universe, probably even becoming the seeds of some globular clusters (Friel 1995; Portegies Zwart et al. 2010).

Open clusters are thought to form from dense molecular gas clouds. In the Galaxy the molecular gas is at an extremely short scale-height of the disk plane, approximately 50–75 pc (Malhotra 1994; Vergely et al. 1998; Weiß et al. 1999), and moves in dynamically cold orbits (almost circular and with low inclination), therefore it is naturally expected that open clusters will follow these types of orbits. Although some molecular gas is known to exist above the Galactic plane, these high-latitude clouds are orders of magnitude smaller than giant molecular clouds and they are frequently not self-gravitating (Blitz & Williams 1999, p. 3). However, there is a non-negligible fraction (13%) of open clusters at heights greater than 200 pc over the plane of the Galaxy, far beyond where the molecular clouds reside (de la Fuente Marcos & de la Fuente Marcos 2008), which might be an indication either of an unusual origin (Wu et al. 2009; Vande Putte et al. 2010), or of some dynamical effect produced by the Galaxy, as discussed in this letter.

Open clusters older than 1 Gyr seem to be part of a separate structure that is gravitationally trapped by the main body of the Galaxy known as the “cluster thick disk” (van den Bergh 2006; Gozha et al. 2012).

Explaining how open clusters reach such altitudes over the Galactic plane poses a difficult challenge since no universally accepted explanation has been found for their existence. The preferred scenarios that have been proposed to address this problem postulate that clusters are captured from satellite galaxies or formed through star formation events in situ of high Galactic altitude gas clouds (Williams et al. 1977; Martos et al. 1999; de la Fuente Marcos & de la Fuente Marcos 2008; de la Fuente Marcos et al. 2013). However, the Galaxy seems to be dominated by smooth and well-mixed vertical age and metallicity gradients, meaning that for a long time the main mechanisms governing its evolution have been internal dynamical processes (Casagrande et al. 2015); this provides us with hints for the present work, a deeper study on the non-axisymmetric large-scale structures as the drivers for the presence of a fraction of the high-altitude open clusters. This mechanism has been already proposed and disregarded in the past on the basis of theoretical simplifications such as direct (and of low probability) close encounters of clusters, with compact molecular clouds employing the impulse approximation, or with the spiral arms as a potential well using idealized models (Spitzer 1958; Wielen 1977). However, with three-dimensional extensions, Quillen (2002) and Quillen et al. (2014) found that vertical resonance capture might be a mechanism to lift particles above the plane.

2. METHODOLOGY AND NUMERICAL IMPLEMENTATION

To carry out this study, a careful construction of the initial conditions was a key ingredient, in addition to a very detailed, observationally motivated Milky Way galactic potential. The open clusters are represented as test particles in the multi-
component galactic field. In this approximation we are interested only in the destiny of clusters, each as a unit, from an orbital point of view.

2.1. Milky Way’s Gravitational Potential

The model includes an axisymmetric potential, formed by a Miyamoto & Nagai (1975) disk and bulge, and a massive halo (Allen & Santillán 1991). For the spiral arms we employ the PERLAS model (Pichardo et al. 2003) that consists of a bisymmetric self-gravitating three-dimensional density distribution. For the Galactic bar we use a non-homogeneous triaxial ellipsoid that reproduces the density law of the COBE/DIRBE triaxial central structure of the Galaxy. For further details on the model see Pichardo et al. (2003, 2004).

To fit our model we make use of observational/theoretical parameters in literature. The triaxial length of the bar is set to 3.5 kpc, with scale-lengths of 1.7, 0.64, and 0.44 kpc. The total mass is $1.4 \times 10^{10} M_\odot$, with a pattern speed of $\Omega_\text{b} = 45$ km s$^{-1}$ kpc$^{-1}$. For the spiral arms, we consider a pitch angle of $i = 15^\circ.5$ and a mass ratio of $M_{\text{arms}}/M_{\text{disc}} = 0.05$ at a pattern speed of $\Omega_\text{c} = 20$ km s$^{-1}$ kpc$^{-1}$. Further details on the parameters of the model and restrictions were introduced in Pichardo et al. (2012).

2.2. Cluster’s Initial Conditions

The initial conditions for the particle distribution are setup by following the Miyamoto–Nagai density profile for the disk.

To discretize the Miyamoto–Nagai density profile and distribute particles, we used the Von Neumann accept/reject algorithm (Press et al. 1992). Particle velocities are assigned with the strategy proposed by Hernquist (1993), approximated by the second moment of the Boltzmann equation assuming the epicyclic approximation.

We ran control simulations with the axisymmetric components of the model to check that the initial velocity dispersion of the particle distribution does not evolve significantly over 5 Gyrs; this ensures that the initial stellar disk particle distribution is relaxed within the background potential.

2.3. Introducing Adiabatically the Spiral Arms and the Bar

We now introduce the spiral arms and the bar to the potential. Both components are grown adiabatically into the simulation, during a period of time long enough to avoid artificial effects in the particle kinematics. The mass of each component will be zero at time $t = 0$ and will increase with time until they reach their maximum value at a given time $t_i$; once $t = t_i$ the mass of each component remains fixed. The functional form to model the mass increment with time is taken from (Dehnen 2000). This particular temporal dependence allows a smooth variation for the value of the mass within the time interval $0 < t < t_i$. The mass of the spiral arms is given as a fraction of the mass of the disk and the mass of the bar is taken from the mass of the bulge.

Following this procedure we made some tests using different growing periods for the non-axisymmetric structures $t_i = 0.5$, 1, 2 Gyrs. For each case all measurements start after the non-axisymmetric components have been fully grown. We found no significant differences in the final results. Nonetheless we took the value $t_i = 2$ Gyr, which will guarantee the absence of artificial effects in the measurements.

3. RESULTS

3.1. The Contribution of the Spiral Arms to the Origin of High-altitude Open Clusters

We first isolate the spiral arms effect. We start with $10^5$ particles, representing the open clusters, distributed on a cold disk, with $\sigma_z \ll 10 \text{ km s}^{-1}$ for $R \gtrsim 4 \text{ kpc}$; we follow the evolution of the system for 5 Gyrs after the arms have grown completely.

Figure 1 shows how particles in the cold disk move away from the midplane due to the gravitational interaction with the spiral arms. The plot is a comparison with the axisymmetric case (top panels), along 1 Gyr (from left to right), where no particles are scattered in the vertical direction. On the bottom, the galactic model with spiral arms, from the point where arms reach their total mass at $t_i$ (bottom left panel), to 1 Gyr after, at $t_i$ (bottom right panel). In this case, lots of particles are scattered to large distances above and below the midplane. By comparing both models, we can establish that the collective gravitational effect of the spiral arms induces long vertical excursions of open clusters. Note the bulge-like structure that the model predicts would be formed by a number of these clusters.

To quantify the number of particles departing from the initial cold disk, first we divide the disk into radial bins of width 0.1 kpc and count the number of particles with $|z| > 200$ pc. The top left panel in Figure 2 shows the number of particles with $|z| > 200$ pc for each radial bin; the initial measure (blue) is taken once the arms have reached their total mass, and from there the count is followed for another 5 Gyrs. More and more particles raise at all radii, although it is more efficient toward the galactic bulge.

The bottom left panel in Figure 2 shows the difference $N - N_0$ measured every 1 Gyr within each radial bin. Although there are some negative values for the quantity $N - N_0$, these are small, and the overall trend is clear and indicates that as an
outcome of the interaction with the spiral arms, the number of particles that move away from the galactic plane ($|z| > 200$ pc) increases with time.

### 3.1.1. Alternative Numerical Approach

With the previous procedure to introduce the spiral arms, the count of uprising particles might be underestimated; namely, we are letting the arms grow adiabatically for 2 Gyr and we are not measuring any quantity during this period. Although starting the analysis from the time the arms have grown completely avoids any transient effect appearing in the results, this procedure leave us without knowledge of the true initial time from which the kinematics of the particles starts being affected by the spiral arms. This means that we are losing some information because aside from possible relaxation effects, the particles are already interacting with the arms while these are growing.

With the aim of recovering the physical information lost during the growing period, we apply the following numerical procedure.

a. We distribute $10^5$ particles in density and velocity space as in Section 2.2, but initially setting $z = 0$ and $v_z = 0$, i.e., we start with a two-dimensional particle distribution. Then the simulation starts running with the arms introduced adiabatically within the first 2 Gyr.

b. Once the arms have reached their total mass, the numerical integration goes for another 3 Gyr to allow the particles to relax with the spiral background potential. At this point the arms are totally formed and the stellar disk is relaxed.

c. Now for each particle at a given radial coordinate $R$, a $z$ coordinate and $v_z$ velocity are assigned following the usual procedure (Section 2.2). At this stage we have recovered our three-dimensional disk but with the particles already relaxed in the radial direction. This point is closer to what we call an “initial time” since at the end of this new procedure, we have gotten rid of most of the spurious reaction, providing us with a better starting point for the calculations.

Finally, the integration restarts from here for another 5 Gyr, which includes all the periods of interest. Measurements made from here will capture as many of the particles that undergo large vertical excursions above and below the midplane as possible.

For this alternative numerical implementation we repeated the counts as described above for particles with $|z| > 200$ pc (right panels in Figure 2). We see the same behavior found before, that the number of particles with high $|z|$ increase with time due to their interaction with the spiral arms. But a first comparison of the top panels in Figure 2 shows that for the second procedure, the number of particles at the starting point with high $|z|$ is smaller than in the previous procedure, mainly toward the Galactic Center. The relaxation strategy of the disk avoids the loss of information that is inherent to the growing period of the arms. This has direct consequences for the effective number of particles scattered away from the midplane at the end of the simulation, as seen by comparing bottom panels in Figure 2. We see that the count of uprising particles is slightly larger for the second numerical procedure, as expected.

### 3.2. The Contribution of the Bar and the Bar+Arms to the Origin of High-altitude Open Clusters

We have shown that particles in a cold disk can be scattered away from the midplane of the disk in an effective fashion by gravitational interaction with the spiral arms. Now, in order to study the effect of the galactic bar, we introduce a triaxial potential, observationally motivated (see Section 2). After the bar is totally formed, we follow the time evolution of the particle disk for another 5 Gyr.

In the third row of Figure 3, we show the initial and final stages for the 5 Gyr evolution. Contrary to the result in the previous experiment with only spiral arms, the bar does not drive particles away from the midplane of the disk. This is because the bar, compared to the arms, is efficient for capturing particles in orbits mostly confined within the triaxial structure, rather than crossing the potential well of the bar periodically, as it seems to be occurring with the spiral arms. Therefore, the massive bar acts more as an attractor that confines the clusters, spreading them radially instead of scattering them away from the plane of the disk. The spiral arms, on the other hand, are capable of imprinting vertical accelerations to the particles due to the concentration, but they do not seem to be massive
enough to retain them, resulting in particles moved away from the plane.

The most realistic case for the Milky Way is when the bar and spiral arms are present. To study this case, both are introduced adiabatically during the simulation (as described in Section 2.3). Figure 3 (fourth row) shows the result of the 5 Gyr evolution. Lots of particles in this case are again scattered away from the plane, even in the presence of the bar. The vertical response of the disk is a combination of the previous two experiments: the arms scatter particles to large vertical distances, although these new distances are slightly diminished by the presence of the bar toward the Galactic Center.

Quantifying the effect with particle counts, we noticed they can reach altitudes larger than 1 kpc. By dividing the disk into radial bins of width 0.1 kpc we count the number $N$ of particles with $|z| > 1$ kpc every 1 Gyr, as shown in Figure 4 for the simulations with spiral arms (left) and bar+arms (right). At the initial time the number of particles with $|z| > 1$ Gyr is almost zero for the two experiments, and from there the number $N$ of these particles increases with time in both cases. As we saw earlier, when comparing the third and fourth rows in Figure 3, Figure 4 shows that the number $N$ of particles with $|z| > 1$ kpc is always greater for the case with the spiral arms alone than with the combination of bar+arms. In either case, particles are still being scattered to high altitudes, 1 kpc or more above the plane.

3.3. Orbital Analysis

The collective effect of the spiral arms produces a chaotic diffusion of a number of the very cold open cluster orbits that drives them very high over the disk plane. In Figure 5 we show one example of those orbits. At early times the particle moves mainly on the plane, then at 1.3 Gyr the orbit is deflected upwards. After this point the orbit is no longer confined to the plane; further interactions with the spiral arms move it to even higher altitudes.

Chaotic stellar orbits are very common, and in some cases, they may even outnumber the regular orbits in a stellar system. To see if this is the case for the particles with high altitudes in our simulations we used the classification code by Carpintero & Aguilar (1998), based on the method of spectral dynamics introduced by Binney & Spergel (1982, 1984). We applied the orbital classifier to the total sample of orbits that ended up the simulation with high $z$. In the specific case of high-reaching orbits, we found that: one-third of the orbits that go above 200 pc are chaotic orbits, with the rest being tube orbits; for the orbits that go above 500 pc, this fraction has gone up to about one-half; by the time the orbits go beyond 1 kpc, slightly over one-half are chaotic. Chaos seems to be the dominant mechanism to explain the highest reaching orbits. As for the tube high-reaching orbits, the mechanism might be associated with resonances.
4. CONCLUSIONS

With the use of a detailed observationally motivated model of the Milky Way Galaxy and a set of carefully constructed cold initial conditions for the newly born open clusters, we study the effect of the spiral arms and bar on the orbits of open clusters. Particularly, we are interested in the contribution of the large-scale non-axisymmetric structures to the high elevation of open clusters over the galactic plane.

We find that spiral arms are able to induce large excursions of clusters’ orbits up to 3 kpc heights over the plane of the disk, depending on their specific parameters. All results in this work were computed assuming a spiral arm mass of 5% of the disk (corresponding to a relative torque \( Q_{\max} \sim 0.1 \)) and a pitch angle of 15°.5. We performed a second simulation with a mass of 3% (\( Q_{\max} \sim 0.06 \)). For the second case, the behavior is similar but diminished by a factor of \( \sim 0.7 \) by number, and a factor of \( \sim 0.75 \) by height, with respect to the 5% mass case of the spiral arms (in a future paper we will present this study). This means that for spiral arms with larger pitch angles than the 15°.5 usually assumed for the Milky Way, or higher masses of the spiral arms for instance, the quantity of these clusters could be even larger.

On the other hand, the bar, despite its total mass, has a much smaller effect. The difference in this behavior is due to the density, which allows the spiral arms to give stronger kicks to the clusters. The net effect of the bar is to concentrate the orbits toward the galactic plane and to produce a radially outward diffusion of cluster orbits.

In the full model that includes both spiral arms and the bar, despite the presence of the more massive bar, spiral arms are readily able to raise up an important percentage of the simulated open clusters through chaotic diffusion, as tested from a spectral classification analysis of the resultant high-z orbits; while the bar produces the same radial diffusion and at the same time seems to concentrate the orbits toward the Galactic plane, slightly reducing the effect of the arms.

The cluster system forms a bulge-like structure. Although the bar shrinks the cluster system, it is still half (or more) of the size of the case with only spiral arms. In an extended ongoing paper (L. A. Martinez-Medina et al. 2015, in preparation), we will present a detailed study based both on an analytical approximation to destruction rates and tidal radii of known clusters and also a second order analytical approximation and N-body simulations with clusters to ponder their survival rates in the plane and off the plane in a Milky Way detailed model.

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