Could 67P/Churyumov-Gerasimenko and (486958) Arrokoth be primordial bodies evolved in an early giant planet instability environment?

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Introduction

It is widely accepted that the dynamical mechanism that governed the planet formation process, giving place to an early or late instability, would imprint some feature on the trans-Neptunian populations. They did not only undergo dynamical evolution but were affected by collisional evolution, which was responsible for shaping the size-frequency distribution (SFD) of the TNO population at small sizes. Dynamical effects (as population depletion) are not size-dependent and just uniformly deplete populations. Inspired by the state of the art of recent dynamical models \cite{1,2,3}, we update our former model to ALICANDEP-21 to consider an early excitation scenario in which Neptune begins its migration between 10 to 100 My of the start of Solar System evolution. We apply our model to the problem of the origin of comet 67P/Churyumov-Gerasimenko, visited by the Rosetta (ESA) spacecraft in the past decade and of the TNO 486958 Arrokoth, flown-by in early 2019 by the New Horizons (NASA) spacecraft. A debate rose about their primordial or evolutionary genesis \cite{4,5} to which we contribute with this research. We study the collisional and dynamical evolution of the trans-Neptunian populations using numerical simulations based on the package ALICANDEP-21. This model includes the statistical elimination of bodies from a migrating disk imitating dynamical effects present in the Nice model.

Methodology

The model evolves in time -under the mentioned boundary conditions- the collisional interaction and dynamical depletion of objects in discrete logarithmic size bins, whose central value generally span in the range of 35 cm to 3000 km in diameter so that any two adjacent bins central values scale a factor 2 in mass. Evolution takes place starting from populations abundance of objects with initial size distributions such that the overall results of the evolution accomplish with current observables in the TNO populations.

We improved our model to study in detail the evolution of populations corresponding to objects of particular interest, as in the case of comet 67P/C-G and TNO 486958 and Arrokoth.
We consider different kind of bodies depending on collisional outcome. We define as primordial body an object that remains forever — unshattered— in the zone where it began its evolution and only suffered cratering collisions. After each collision, a body is classified as gravitational aggregate (GA) if the mass of the largest fragment produced in the fragmentation is less than half the mass of the whole re-accumulated object after the collision [6]. Instead, we consider it as a fragment, a body that is not a GA (nor primordial). It is worth mentioning that this includes all products of shattering or cratering collisions.

In many cases, the result of shattering is a re-accumulated aggregate for which the largest component mass is larger than half the whole body's mass and therefore does not accomplish the definition of GA. The volume fraction of the largest component of comet 67P/C-G as of today is about 73% of the overall comet volume. In the case of Arrokoth, it is about 65%. According to our definition, 67P/C-G and Arrokoth are classified as "fragments" as they do not accomplish our GA definition.

In order to follow the evolution of the potential populations related to such bodies, we set their size range and keep track of the primordial, re-accumulated (gravitational aggregate, GA) and fragments history. We consider 67P/C-G and Arrokoth belonging to the inner belt and the main classical belt, respectively. The corresponding size ranges are 2.4 to 5 km for 67P/C-G and the equivalent diameter corresponding to a size range from 15 to 23 km for Arrokoth [5]. At the beginning of simulations, both bodies belong to the "primordial" category.

Results

No initial mass assumption for evolution or size distribution is compatible with primordial bodies survival beyond 100 My of evolution.

Instead, all bodies of equivalent size to 67P/C-G were created as fragments during the short period of collisional evolution. The fraction of re-accumulated bodies remains practically negligible in any scenario. If we look at the situation at 70 My (the start of the dynamical instability), only in the case of shallow initial population distributions of small bodies the primordial fraction is non-zero but is, however, smaller than 5%. In an early dynamical instability scenario, a massive disk grinds almost all bodies down in the size range of 67P/C-G sooner than □40My. In contrasts, a low mass disk tends to delay such evolution state doubling the time needed to grind almost □100% of bodies in such size range in the inner belt.

On the other hand, a late dynamical instability scenario delays the complete grinding of bodies in size range of 67P/C-G until about 100 My in the most conservative case (A1). Primordial bodies in the size range of Arrokoth can generally survive longer than the ones in 67P/C-G size range. However, the corresponding fraction strongly depends on initial mass and distribution. Our model finds that up to 55% of primordial bodies may survive in the case of an early dynamical excitation scenario with low initial mass provided the initial belt had not an initial shallow distribution of bodies below 100 km. The fraction of primordial bodies is between 20 and 30% in a massive disk under specific scaling law. The rest of the initial configurations constrain the fraction of primordial bodies to 10% at most. In summary, our results indicate that it is plausible to conserve a significant fraction of primordial bodies larger than 10 km, even if only under specific boundary conditions. On the contrary, primordial smaller bodies are quickly converted into fragments in the first tens of My.
