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Collisional evolution of trans-neptunian populations in a Nice model enviroment

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Abstract

The TNO region can be inserted in the global frame of the dynamical evolution of the giant planets, as described by the Nice model [18]. We have developed ALICANDEP, a collisional evolution package that includes statistical elimination of objects by dynamical effects within the frame of a disc migrating and gradually dynamically exciting, as well as the dynamical migration of objects between regions. The possibility to distinguish between dynamically cold and hot bodies in the Inner and Main Classical Belt and to keep track of primordial bodies in those regions has been included in the model. ALICANDEP manages to match the current observables under the dynamical conditions of the Nice model. This allows to constrain the fragmentation physics and some of the initial conditions of the disk.

1 Introduction

The trans-neptunian region (or Edgeworth-Kuiper belt) is a large population of objects that orbit the Sun with semimajor axes beyond that of Neptune. After two decades of observations we begin to understand the overall structure of the TNO (trans-neptunian objects) populations in terms of dynamical features and absolute magnitudes number distributions. The TNOs can be dynamically classified as: a) *Classical*, that can be divided into an Inner belt, with semimajor axes below the 3:2 mean motion resonances with Neptune and a *Main* belt, in between 3:2 an 2:1 mean motion resonances with Neptune. Main belt objects can be further classified as *hot*, responding to high inclinations and eccentricities, and *cold*. b) *Resonant* objects, trapped in the 3:2 resonance (called *Plutinos*). And c) *Scattered* Disk objects (SDOs) [13].

The current mass of the whole trans-neptunian region is estimated to be in the range 0.01 to 0.2 $M_\oplus$ (Earth masses) [12, 3, 11]. This mass is insufficient to allow the formation of 500 km or larger TNOs on timescales of $\sim$ 5 Gyr [21, 22]. Therefore a much larger mass should have been present in the region and TNOs are suspected of retaining the most pristine solar system material.

The current knowledge about TNOs populations is generated by a number of observables:

a) There are at least 3 objects larger than 1500 km, the dwarf planets Pluto, Makemake and Haumea (Eris, with a semimanor axis of 76 AU is off the considered region).

b) The size distribution of TNOs. The TNO differential size distribution is estimated to be a power law of the form: $dN(D) \propto D^{-q}dD$, where q is the slope of the distribution. The most recent measurements of the trans-neptunian region size distribution have estimated q between 4.5 and 5.0 [11, 10, 9].

c) The change in the slope of the size distribution between 50 and 150 km.

d) The bias-free Canada-France Ecliptic Plane Survey (CFEPS, [16]) strongly constrains the number of the cold classical belt objects larger than 70 km in the cold classical population and also gives some constraints on the number of inner and main belt objects. For the main classical trans-neptunian region population they estimated $\sim (120^{+50}_{-46}) \times 10^3$ objects bigger than 70 km. The cold main classical belt population is estimated a population of $N(> 70 \text{ km}) = 50 \pm 5 \times 10^3$ and the hot component of the main classical belt represents $\sim$ 60 % of the total population.

The Nice model is based on the idea that the gas giants formed much closer together, surrounded by a disk of planetesimals stretching between 16 and 30 AU. Due to interactions with the planetesimal disk, Saturn, Neptune and Uranus migrated outwards and Jupiter migrated slightly inwards. After some $\sim$ 800 Myr, Jupiter and Saturn crossed their 2:1 mean motion resonance and the system became temporarily destabilized, affecting the orbital elements of the outer planets. A constraint to the evolution of TNOs is set on the mass of the region just before the onset of the LHB period, $\sim 25\ M_\oplus$. As Neptune moved out into the trans-neptunian region, its secular resonances excited the orbits of many of the TNOs [14]. After that, Neptune has continued to erode the trans-neptunian region by gravitational scattering [15, 8].

The Nice model offers an explanation to the Late Heavy Bombardment (LHB) and to the main features of the current dynamical structure observed in the trans-neptunina region. Therefore, any reliable collisional evolution model should include the main features of the Nice model and should produce results within the constraints imposed by current observables.

A number of collisional evolution models for TNOs have been proposed in the past. Most of them simply consider the collisional evolution of the trans-neptunian region as a whole, ignoring dynamical effects and different populations [6, 17, 20, 5]. [5] proposed the first model that combines collisional evolution and dynamics to study the population of TNOs. [7] analyzed the collisional and dynamical evolution only for the population of Plutinos.

2 ALICANDEP

Based on our previous collisional evolution model [1] (hereinafter, BCB09), we have developed a numerical model of the collisional evolution of small body populations, applying it specifically to the case of the TNOs populations (Asteroid-LIke Collisional ANd Dynamical Evolution Package: ALICANDEP). The model includes statistical elimination of objects by dynamical effects within a frame of a disc migrating and gradually dynamically exciting, as well as the dynamical migration of objects between regions. Moreover, we implemented the possibility to distinguish between dynamically cold and hot bodies in the main belt and to keep track of primordial bodies in those regions. Size distribution slopes and eventual break sizes can be also calculated. All the features included in our former model are described and explained in BCB09 and are present in ALICANDEP as well, as are the computation of the number of gravitational aggregates in any given size interval and the possibility to use different sets of parameters involved in the collisional physics and different sets of parameters regarding boundary conditions (initial overall mass, mass distribution in different regions, initial size distribution).

Contrarily to most models dealing with the collisional evolution of TNOs, the fact that relative velocities of impacts are widely dispersed is suitably taken into account by assuming maxwellian distributions around the most probable values corresponding to each dynamical period (pre-LHB, LHB, post-LHB). Collisional probabilities are calculated, for each zone at each period, accordingly.

The model evolves in time the collisional interactions of numbers of objects in discrete logarithmic size bins, whose central values span the range from 35 cm to 3000 km in diameter, in such way that there is always a factor 2 in mass between any two neighbouring bins.

Schematically, the model consists of two parts:

1. Handling of collisions.

   Simulation of the collisional outcomes of every impact between objects belonging to any pair of size bins is performed. The outcome of a collision depends on the ratio of kinetic energy of the impactor to the mass of the impacted body, and on the specific energy of the collision, Q^*. The threshold for a shattering event is defined by $Q^*_{\rm S}$, that is the specific energy required to break a body so that the largest fragment produced is half the mass of the parent body. Bodies can be characterized by any of the scaling laws proposed in the literature for $Q^*_{\rm S}$. Our nominal case follows [2] scaling law for ice bodies.

   The collisional algorithm is based on the fragmentation and reaccumulation model of [19], including improvements based on recent available experimental data, numerical and theoretical studies. This part of the package computes the number of fragments produced in any possible collision between objects belonging to different size (mass) bins. Different algorithms consider shattering or cratering events. The energy of the created fragments is compared to the binding gravitational energy in order to decide what fraction of ejected mass is gravitationally reaccumulated on the largest remnant of the collision.

2. Time evolution.

   ALICANDEP considers three concentric toroidal zones around the Sun where the orbits of objects from different zones can cross each other and stay in common regions during a fraction of –or all– their periods, as a consequence of their eccentricity and semimajor axes. Therefore, the number of objects from each zone that interacts with objects from other zones depend on their mean anomaly and the range of semi-major axis that define the corresponding common zone in each case (see BCB09 for a detailed description of interactions between dynamical zones). Time integration of the evolution equations for all size bins must be then performed taking into account those interactions.

At the beginning of the evolution, the total mass, M_0, was shared between two contiguous zones, namely Zone 1 (20 to 29 AU) and Zone 2 (29 to 34 AU). Zone 3 is initially empty. Consistently with the Nice model, we consider an initially cold disk, located between 20 and 34 AU.

After 100 Myr of collisional evolution, dynamical excitation of eccentricities and inclinations of objects in Zones 1 and 2 begins, and dynamical effects start depleting mass in three different dynamical phases, each one characterized by different depletion rates and values for eccentricities, inclinations and semimajor axes, as summarized below:

• *PHASE 0*: From 0 until 100 Myr. No excitation nor depletion of mass happens. Semimajor axis intervals (in AU) for Zone 1 and 2: $(20, 29)$ and $(29, 34)$ respectively.

• *PHASE 1*: From 100 Myr until $t_{\rm LHB}$. The disk excites its eccentricity from 0.01 to 0.15 in Zone 1 and from 0.01 to 0.08 in Zone 2. Inclinations grow from 3° to 6° in Zone 1. Mass loss starts due to dynamical interactions.

• *PHASE 2 (Late heavy bombardmente –LHB– phase)*: From $t_{\rm LHB}$ until $t_{\rm LHB+100}$. In this period the disk is strongly excited dynamically. Eccentricities and inclinations grow respectively to 0.18 and 17° in Zone 1, and to 0.10 and 7° in Zone 2. Migration of bodies from Zone 1 to Zones 2 and 3 takes place and very strong mass depletion happens due to dynamical effects.

• *PHASE 3*: From $t_{\rm LHB+100}$ until the end of the evolution (4500 Myr). Dynamical excitation and migration stop, while mass loss is reduced to interactions with Neptune. The disk enters a quiet phase with little collisional and dynamical evolution.

At the same time that zones are translated by migration and expanded by excitation, their corresponding volumes, average relative velocities and collisional probabilities are updated accordingly at each time step.

In order to avoid undesired wavy effects due to an abrupt truncation of the size distribution at small sizes [4], a number of the smallest size intervals (from 35 cm to 30 m) have been used to produce a low–end "tail" according to the size distribution for $D > 30$ m.

3 Results and conclusions

In order to match current observables and the dynamical conditions of the Nice model, we performed a large number of numerical simulations varying physical parameters (namely, the scaling-law for fragmentation), initial conditions (mass, initial distribution in regions, slopes of initial size distribution of objects and corresponding transition size) and the parameters that drive dynamical depletion and migration. This allows to constrain the fragmentation physics and some of the initial conditions, like the initial mass, the distribution in different zones and the size distribution of objects.

Table 1 shows excellent agreement with CFEPS-L3 release [16]. Table 2 shows that ALICANDEP also matches current estimates of the slope of the overall differential size distribution for large bodies and the current break in size distribution.

Best fits to current observables are obtained under the following set of collisional and initial conditions: a) Initial mass, 60–72 $M_\oplus$ (Earth masses). b) Initial surface density $\Sigma^{-3/2}$ for the TNO region. c) Initial size distribution slope for $D > 50$ km: 4.8–5.0 (differential); very shallow (< 4.0) for $D < 50$ km. d) Scaling law for fragmentation as of [2]. "Weaker" scaling laws –with high *strain-rate* effect contributions– imply excessive collisional mass depletion and no set of boundary conditions and evolution parameters may be found to match observables.

Some predictions can be drawn from these results: a) Present mass in the TNO region may be up to $0.17 - 0.18$ M_E. b) The number of bodies larger than 1500 km found in simulations allows speculations about 50% Poisson probability of existence of at least one more large body in the TNOs populations. c) Primordial (never shattered) bodies should be 2–5 % in the Inner Main Belt and 18–24 % in the Classical Main Belt.

Table 1: Number of objects in each population (1–σ intervals) (surface density $\Sigma \sim r^{-3/2}$). N_MB and N_IB stand for number of objects in the Main and Inner Classical Belt, respectively. c_1 and c_2 denote two different initial conditions, as specified in the note, where numbers in parentheses are the initial slopes of the size distributions for sizes smaller and laerger than the break size. M_0 is the initial total mass of the belt.

	Classical Belt			Primordial (%)		
	N_MB(cold)	N_MB(cold)/N_MB	$N_\mathrm{IB}/N_\mathrm{MB}$	I.B.	M.B.	$N(> 1500$ km)
c_1[a]	48000–55300	0.32–0.38	0.20–0.23	2–3	19–26	2–5
c_2[b]	49200–54100	0.31–0.37	0.21–0.23	2–3	16–24	2–6

[a] c_1 = (3.0, 4.8–5.0); M_0 = 120–160 $M_\oplus$
[b] c_2 = (none, 4.8–5.0); M_0 = 60–70 $M_\oplus$

Table 2: Final distribution slopes and transition size D_tr (1–σ intervals).

	Slope q_2 ($D > 70$ km)				D_tr (km)
	Inner Belt	Main Belt	Scattered Disk	TOTAL	TOTAL
c_1	4.5–4.9	3.9–4.2	4.6–5.1	4.4–4.7	130–170
c_2	4.4–4.6	4.0–4.2	4.4–4.7	4.2–4.4	60–90

Further improvements to ALICANDEP are under way to better match the mass of the belt as predicted by the Nice model at the end of the LHB phase, and to check the effect of different inital distributions for the primordial Inner and Main Classical Belt populations on the corresponding current distributions.

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