Interrelation Between the Physical Properties and the Orbital Evolution of Near Earth Asteroids: A New Numerical Approach

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ABSTRACT

Possible connections between the physical properties of Near-Earth Asteroids and their orbital evolution were explored, with emphasis on binary asteroids. The main hypothesis, suggested from the observations, is that the Near-Earth population contains considerably higher percent of binaries compared to the Main Belt. Typical evolution paths for different types (in the sense of physical properties) of binary Near-Earth Asteroids were also explored, as well as the distribution of these types among different areas in the space of orbital elements. The simulation covered simultaneously both orbital evolution and evolution of physical properties, which is the main improvement in comparison to the previous researches of this kind. Orbital evolution was simulated with a second-order symplectic integrator based on the concept of mixed variables (MVS) and optimized for close approaches. Physical evolution due to tidal forces and collision/disruption events was described with TREESPH hydrocode, which combines N-body integration and Smoothed Particle Hydrodynamics equations. The results show typical evolution paths of some Near-Earth Asteroids: contact binaries, separated binaries, asteroids with a satellite, fast rotators. Slow rotators (like 4179 Toutatis) have not been detected. Possible explanations lie in the specific (possibly cometary) cosmogonic origin of these objects and strong non-gravitational influences but other explanations also cannot be written off. Of course, larger ensemble and longer interval of integration would make the results of this simulation more certain.

1. Introduction

The population of Near-Earth Asteroids (NEA) is generally considered to be an especially interesting group of asteroids, in part because of their complicated origin, and in part because of their accessibility for observations. Physical properties and physical evolution of these objects are relatively poorly known[1]. The basic concept of most models is the "rubble-pile" structure: an aggregate of loosely (gravitationally) bond blocks. The algorithm for simulations of this kind can be based either on an N-body code (e. g. Leinhardt et al 2000; Solem & Hills 1996) or on a hydrocode (e. g. Love & Ahrens 1996a; Richardson 2001; Richardson et al 1998; Richardson & Bottke 1996). Some recent papers take into consideration both gravity and cohesive forces (Michel et al 2002). The initial conditions of events like collision or close approach to the Earth are usually estimated from coarse (and occasionally quite non-physical) empirical distributions. Therefore, despite some progress in understanding tidal and collisional processes among the NEA, we still lack a consistent model of the physical evolution of NEA and formation of binary systems. The laboratory experiments of collisional processes can also yield some information but their validity is questioned by the problems of scaling.

On the other hand, the orbital evolution of NEA is known in much more detail. A particular form of chaos is especially notable in this population: although it is strongly affected by numerous close approaches, the whole population seems to remain in an approximately steady state. Despite the lack of long-scale predictability for particular objects, some detailed models of NEA population have been published (Rabinowitz 1997; Morbidelli et al 2002). According to the mentioned papers, the $3:1$ and ν_6 resonances seem to be the most important source of NEA although the Mars crosser (MC) population also has some importance.

In this paper, we give some results of our numerical simulation of NEA orbital and physical evolution, with special emphasis on the formation and properties of binary systems. The main contribution of this paper is the simultaneous simulation of orbital motion and collision/disruption events, which is, as far as we know, carried out for the first time. One of the primary objectives of this research is the explanation of observational evidences that the NEA population has substantially larger percent of binary asteroids than the Main Belt (e. g. Margot et al 2002). Tidal deformations (and disruptions) during close approaches, collisions among the NEA, as well as mutual tidal influences in binary systems, cause very complicated perturbations of both orbital elements and physical properties. Many of the mentioned processes are probably interrelated. Therefore, we expect this simultaneous treatment to resolve some previously unknown mechanisms and to explain evolution paths of some typical NEA objects, e. g. contact binaries or fast rotators.

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[1]Under "physical properties" we assume any properties which are not orbital elements and are not explicitely dependent upon the orbital motion, e. g. shape, binarity, rotation state, ellastic properties, internal structure, existence of precession, etc.

Of course, the most significant drawback of this approach is the large amount of calculations that have to be done since many processes are being simulated at the same time. This limits the number of objects involved as well as the time span of the simulation. In addition, some of the initial conditions are not known very well, which also affects the validity of the results. Therefore, this research should only be considered as a qualitative picture of some processes among the NEA, given on a fictitious representative ensemble of objects — it is not a model of NEA population nor does it give valid predictions for the evolution of any particular object.

The second section gives a short review of the methodology, including the orbital integrator, the treatment of non-gravitational influences, the dynamical model of binary systems and the hydrodynamical model adopted for the description of physical evolution. The third section describes the implementation of the simulation and the simulated system. Results are given in the fourth section. Some theoretical implications of the results, as well as some comparisons to the previous research are discussed in the fifth section. The sixth section sums up the conclusions.

2. Methodology

2.1. Orbital integrator

Basic request for the orbital integrator was efficiency rather than precision. As it is mentioned in the first section, we were seeking only for a qualitative description of the orbital movement, not for the exact orbital elements. We adopted a second-order symplectic[2] integrator, proposed by Wisdom & Holman (1992), usually known as the "Mixed-Variable Symplectic" integrator (MVS). Its efficiency is usually considerably higher than that of ordinary integrators (e. g. Bulirsch-Stoer), while the precision remains valid for many purposes, despite the (typically) low order of MVS integrators.

In our integrator, we used a second-order algorithm. The integration included four planets (Earth, Mars, Jupiter, and Saturn). The Mercury's mass was added to that of the Sun, while the Moon's mass was added to the Earth's mass. Asteroids were included as test particles. The Hamiltonian of the system was mapped as:

[2] "Symplectic" integrator of a Hamiltonian system is an integrator which preserves all the Hamiltonian properties of the system (e. g. Liouville's theorem, conservation of energy, etc). Therefore, symplectic integrators identically (in fact, up to the roundoff error) conserve the total energy of the system and the volume of a cell in the phase space.

$$H_{Map} = H_{Kep} + \Phi\left(t\right) H_{Pert} \quad (1)$$

where H_{Kep} represents the Keplerian motion and H_{Pert} represents the perturbations of the former, originated by the interaction among the planets. The $\Phi\left(t\right)$ function is a periodical function of time, which can formally be written as a sequence of Dirac delta functions. In practice, this is equivalent to periodically adding finite corrections to the momenta of the bodies. Therefore, the integration consists of moving the particles on Keplerian orbits and correcting their momenta periodically. A more detailed description of these topics can be found in the aforementioned reference.

Our integration scheme is somewhat different from the original concept of Wisdom & Holman, since it includes some improvements, proposed by Saha & Tremaine (1992, 1994). On the start of the integration the so-called "warm-up" of the integrator, a specific starting procedure for minimization of the truncation error, was performed. In addition, a kind of multi-step scheme was adopted, which improves efficiency. Due to the request for preservation of the symplectic nature of the integrator, all the time steps have to be a simple multiple of some unit time step. This version of the MVS integrator gives the error of the order $\mathcal{O}\left(\varepsilon^2\tau^2\right)$, where ε denotes the planets to Sun mass ratio, and τ stands for the average time step.

The non-gravitational forces (the Poynting-Robertson drag and the Yarkovsky force) could not be included directly since they make it impossible to write the Hamiltonian of the system in the form (1). As it is well known, these effects are largely negligible for objects that exceed about 100 m. However, some recent results (Vokrouhlický 1999, and references therein) show that the Yarkovsky effect could significantly influence evolution of some objects by putting them into mean motion resonances. Therefore, we decided to include this effect by applying periodical corrections to the semimajor axes of the asteroids' orbits, using the linear approximation derived by Vokrouhlický (1999). His equations do not separate the seasonal part (dependent on the orbital period) and the diurnal part (dependent on the rotation period) of the effect but treat them together. We omit them here for the sake of conciseness; they are very complicated and can be found in the aforementioned reference. It is enough to mention that the only parameters that correspond to particular asteroid are density, mean radius, thermal capacity, and thermal conductivity. The former two characterized each asteroid in the simulation (for details see the third section) while the latter two were fixed, calculated from the parameters of the equation of state (see the third subsection of this section).

2.2. Dynamical model of binary systems

As it is well known, binary systems undergo mutual tidal perturbations, which affect their motion around the mutual center of mass. Close approaches to the Earth are also expected to change their dynamical nature. A simple dynamical model was used to describe these events, based on some analytical and semi-analytical results.

Dynamic state of each binary system was characterized by spin vectors, eccentricity and semimajor axes of the components (the latter two, together with the masses, determine the orbital frequency around the center of mass)[3]. The tidal influence was calculated as a series of periodical changes in orbital frequency, eccentricity, and rotational periods, using the analytical expressions of classical tide theory (Peale 1999). Since these expressions are complicated and can be found in many classical references, we shall, as for the Yarkovsky drift, omit them.

The close approaches were treated in a semi-analytical way, following the idea of Farinella & Chauvineau (1993). The relative changes of energy and angular momentum of the system can be expressed as:

$$\frac{\Delta E}{E} = \frac{G^2 m_A m_P}{V b^2} \left(-2E\right)^{-\frac{3}{2}} I \tag{2}$$

$$\frac{\Delta L}{L} = \frac{1}{2} \frac{\Delta E}{E} \tag{3}$$

where m_P and m_A denote masses of the planet (in this case Earth) and the asteroid (the whole binary system), while V and b represent the velocity of the planet in the reference frame of the asteroid and the impact parameter, respectively. The dependence of the perturbation upon the geometry of the approach (parameterized with three angles, see Farinella & Chauvineau 1993 for details) is contained in the non-dimensional integral I. Analytical solution of this integral does not exist in the general case. Farinella & Chauvineau approximate it with a Gaussian random variable, starting from the rectilinear approximation. We, however, calculated (numerically) and tabulated the value of I for different geometries of the encounter, which allowed us to adopt a more realistic, hyperbolic approximation. During the simulation, the actual value for each close approach was calculated as a linear interpolation from the table with respect to the independent parameters, which allowed better efficiency than immediate integration.

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[3]We mention here only those parameters which are included in the dynamical model; others are mentioned in the next subsection, and all the parameters are listed in the third section.

2.3. The hydrodynamical model of asteroids

The core of our hydrodynamical model is the hydrocode usually known as TREESPH, given by Hernquist & Katz (1989). It is a combination of the Smoothed Particle Hydrodynamics code (SPH), and the Hierarchical Tree Method (HTM), an algorithm developed for hierarchical work with clusters of objects. The latter gives to TREESPH also some good features of N body algorithms. All the details of our model and its specific properties are not of interest here and will be published elsewhere. In this subsection, we shall mention only some basic ideas and differences from the published models.

First, we shall briefly revisit the SPH formalism. This method was given by Gingold and Monaghan (1977; according to Hernquist & Katz 1989) and it has become widely accepted for applications that require high efficiency and modest precision. It is a Lagrangian particle code, which is mathematically based on the integral interpolation. The interactions among the particles are described via an interpolation function. Value of a physical field $f(\mathbf{r})$ in a given location (i. e. for a given particle) is calculated as:

$$f_{SPH}(\mathbf{r}) = \int W\left(\mathbf{r}-\mathbf{r}'; \mathbf{h}\left(\mathbf{r},\mathbf{r}'\right)\right) f\left(\mathbf{r}\right) \mathrm{d}\mathbf{r} \tag{4}$$

where W denotes the kernel, and the integration is performed over the whole volume of the system (in this case asteroid). The h parameter is the smoothing length, which roughly corresponds to the resolution of the hydrocode. The kernel characterizes the strength of the interaction, so it typically drops very quickly when $r - r'$ becomes large. Its integral is normalized to unity. As it can be seen from (4), the smoothing length is spatially variable, and it changes both locally and globally. This spatially adaptive smoothing length is a peculiarity of TREESPH; the original SPH uses constant smoothing length. In practice, of course, the integration turns into summation over a set of discrete particles. For the kernel, we adopted the cubic spline proposed by Monaghan and Lattanzio and given by Hernquist & Katz (1989). Its value drops to zero for $r - r' > h$. The evolution of the system is described, as usually, by continuity equation, momentum equation, energy equation and equation of state (EOS). The procedure for discretization of these equations can be found in the aforementioned reference and will be omitted here. The well-known fourth-order adaptive step Runge-Kutta algorithm (e. g. Press et al 1997) was used for the integration.

For the EOS were adopted the Tillotson equations (Benz & Asphaug 1999). Since they are somewhat less known, we will describe them here. The basic idea is to consider analytically only two extreme cases (concerning the energy of the system); otherwise, the resulting EOS is calculated via linear interpolation. If the volume density of energy is less then the energy of incipient vaporization ($E < E_{iv}$) the pressure is given by:

$$P = \left[a + \frac{b}{1 + \frac{E}{E_0 \eta^2}} \right] \rho E + A\mu + B\mu^2 \tag{5}$$

If the volume density of energy grows larger than the energy of complete vaporization ($E > E_{cv}$) the previous equation becomes:

$$P = a\rho E + \left[\frac{b\rho E}{1 + \frac{E}{E_0 \eta^2}} + A\mu \exp\left(\beta - \beta \frac{\rho_0}{\rho} \right) \right] \exp\left[-\alpha \left(\frac{\rho}{\rho_0} - 1 \right)^2 \right] \tag{6}$$

The parameters A, B, a, b, α, β, E_0, E_{iv}, E_{cv}, ρ_0, μ are dependent on the material. Following Love & Ahrens (1996a), we adopted their values for basalt from Benz & Asphaug (1999). Density of each particle was also taken to be equal to the density of basalt ($\rho = 2.7$ g/cm^3). Initially, the particles were distributed in a face-centered cubic array, which gives the average density about 1.8 g/cm^3 (less than the theoretical value because of finite dimensions of asteroids).

The role of HTM is to make the calculations of interactions among the particles more efficient. It has been used for several decades in various problems (e. g. Appel 1981; according to: Hernquist & Katz 1989). Summation of interactions between each two particles in general case requires an $\mathcal{O}(N^2)$ algorithm. In HTM, particles are formally arranged in clusters, which may replace single particles in hydrodynamical calculations. During the force evaluation, the algorithm creates a tree with clusters (which have the physical meaning of three-dimensional cells in space) at the nodes. Therefore, distant particles contribute to the resulting force only as clusters while near ones contribute to it directly. Of course, some empirical criterion for clustering has to be adopted; we have used a polynomial law derived from numerical experiments. The whole procedure (tree construction and the force evaluation) is now performed in $\mathcal{O}(N \log N)$ time, and it makes the model plausible also for the ballistic phase of an impact (unlike the traditional SPH code).

As it has already become clear, the model asteroid is simply a set of gravitationally interacting particles in an external gravitational field (originated from some other body, see next section for details). We completely neglect material strength, so this is a purely "rubble-pile" model. Friction and fractures are also neglected. Particles are represented as non-elastic spheres of finite radius. The reference frame is always the center of mass of the system. We used this model to simulate collisions and tidal disruptions.

Criterion for escaping particles was one of the most problematic issues since the safest solution – direct integration long enough for all the escaping particles to actually escape – was not possible due to computational reasons. Speed criterions are not plausible because of the non-sphericity of the asteroid. We implemented a criterion suggested by William F. Bottke (e-mail communication): simply to look for the particles with the absolute value of potential energy larger than the kinetic energy. Although somewhat dangerous because of artificial energy oscillations, which are sometimes produced by SPH, this criterion generally seemed realistic. The second major issue was the detection of satellites that may form during a collision/disruption event. Since the satellites of asteroids are among the main objectives of our research this criterion had to be imposed more exactly, also because we had to calculate its starting orbital elements (to be used by the dynamical model, see the previous subsection). We decided to use the semianalytical results based on Hill's equations (Hasegawa & Nakazawa 1990), which allowed us to calculate the orbital elements and mark the fragment as a satellite if its orbit turns out to be stable (i. e. orbit which does not include the collision with the main body; hyperbolic orbits are eliminated by the previous test, since they are equivalent to the escape). Finally, the simulation of a particular event was considered complete when all the non-escaping particles either fall back to the asteroid, or start moving on elliptical orbits as satellites.

3. Model and simulation

The simulated system was designed as a representative ensemble of objects that are in source regions for NEA population and therefore can be expected to become NEA relatively quickly. Since we supposed that most of the interesting events (e. g. collisions) happen during the transit to the NEA region, we decided to start with objects in the source regions, and not with objects which have already become NEA. We also decided to work with fictitious objects, since any selection of known objects could result in a biased ensemble and, on the other side, as we have already mentioned, the precision of the simulation does not give valid predictions for any particular object. Therefore, our simulation was intended to follow the migration processes in general and to allow the analysis of typical NEA after they pass through the transition mechanisms and, possibly, collision/disruption events.

The simulated system contained 160 objects – one sixth of the estimated current NEA population (Morbidelli et al 2002). The interval of the simulation was 10 Myr. The initial orbital elements were calculated from distributions given in the aforementioned reference. The mentioned paper considers the following source regions: the 3 : 1 resonance, the ν_6 resonance, the MC population, the comets of Jupiter family (JFC), and the outer belt (OB). We omitted the last two sources (from which come 14% of NEA, according to Morbidelli et al 2002) since their transition mechanisms tend to be very complicated and beyond the scope of our research. Relative populations of 3 : 1, ν_6 and MC regions were, respectively

44%, 29%, and 27% (the mentioned 14% of JFC and OB were proportionally distributed among the first three regions). For exact distributions of orbital elements, see Morbidelli et al (2002).

Each object was characterized by orbital elements, mass, spin vector and hydrodynamical model (i. e. coordinates and momenta of each particle, which determine also the density, dimensions and shape). To make the comparison with the observational data easier, we also introduced the mean radius. All the binary systems were marked with a flag since they required two additional parameters — semimajor axis and eccentricity of the orbit around the mutual center of mass. We supposed that the starting population contains no binaries.

The starting distribution of spin vectors (concerning both orientation and intensity) is generally an unexplored subject. Most authors (e. g. Chauvineau et al 1995; Vokrouhlický 1999) assume an isotropic distribution of spin vectors, so we followed them, largely to make comparison with Chauvineau et al easier. Possible problematic consequences of this decision are discussed in the fifth section. For the periods of rotation, we adopted the Maxwellian distribution obtained by Farinella et al (1981). Size distribution (distribution of radiuses) was taken from Gomes (1997); this is an exponential distribution, a widely accepted form for various objects. Finally, the starting shapes were triaxial ellipsoids, with axial ratios distribution taken from observational data given in Uppsala Photometric Catalogue of Asteroids (Lagerkvist et al 2002).

The organizational base of the simulation was the orbit integrator, which was programmed to "turn on" the hydrodynamical simulator if a collision/disruption event is likely to happen. At the end of each time step, a test was performed to check if the asteroid enters the sphere of influence of some other object (an asteroid or a planet). If a direct collision with a planet happened, the asteroid was discarded from the simulation. Otherwise, the hydrocode was activated, which performed the calculations during the collision or close approach (the latter results in deformation and, in the extreme case, disruption). The Yarkovsky drift and, for binaries, the tidal drift were added periodically, as it was described in the previous section. If an asteroid breaks into fragments, at the end of the hydrodynamical simulation each fragment becomes a separate asteroid and continues its evolution separately; its spin vector is calculated from the equation of angular momentum. Bodies with mean radius less than 100 m were discarded since such small bodies require a much more detailed treatment of cohesive forces and non-gravitational influences. Objects that cross the Jupiter's orbit were also discarded.

The implementation of the simulation cannot treat encounters of three or more bodies nor can it treat more than one collision/disruption event at the same time step; bearing in mind the probability of these events, we did not take this for a serious disadvantage. The code was written in MATLAB 6.0 package.

4. Results

We have to emphasize once again the qualitative and somewhat uncertain character of the results. It is also clear that a simulation with so many parameters gives a large amount of numerical results; their detailed analysis is not of interest for this research (although it could be interesting in general). We shall focus only on some characteristic results, which are important for the objective of this paper.

Evolution of the simulated system generally corresponds with current theoretical knowledge about NEA migration and evolution. Processes of transition follow the usual path; the most efficient mechanisms are, as expected, close encounters of the planets, and the most efficient source is, again expected, the 3 : 1 resonance. The MC region was somewhat more efficient than expected. After about 2 Myr the system became relatively stable and the number of bodies in the NEA region was nearly constant. Most of the particles survived until the end of the integration, despite largely chaotic nature of their evolution.

Collisions of asteroids also seem to fit well into current models (e. g. Benz & Asphaug 1999). The outcome depends on the mass ratio and impact angle, while the relative speed tends to be less important. It seems that the reaccumulation of collisional fragments has a more prominent role than in previous researches (e. g. Leinhardt et al 2000), which may be a consequence of partially N-body nature of TREESPH. The bottom size limit for formation of stable rubble-pile objects seems to be about 100 m-200m. Of course, these remarks should be treated carefully, as they are only our general notes about the collisions; they are not a result of systematic analysis.

The tidal forces act relatively slowly but in long intervals they can become key factors for an object's evolution. Low-speed approaches tend to be the most efficient disruption mechanisms while the fast ones usually only slightly deform the asteroid. Still, the outcome largely depends on the initial physical properties of an asteroid. Only in two cases, we detected a complete disruption into many fragments.

One of the most interesting aspects is, of course, the dynamical evolution of binary systems. Fig. 1 shows the dependence of the final rotational period upon the initial orbital elements of the binary system — eccentricity and semimajor axis (compare with figures 2-3 in Chauvineau et al 1995). In a few cases, objects with very similar initial conditions had very different evolution paths; in these cases, we included in the figure the system that had lasted for the longest time. One should bear in mind that this is just a rough visualization

— it gives only global properties of the period-eccentricity-semimajor axis distribution.

Fig. 1.— Contour plot of the period of rotation (for binary systems which are not synchronized, period of the larger component is given) upon the initial values of the semimajor axis (in units of the primary's radius R) and the eccentricity of the components. The darkest area ($P < 2.5$h) in fact corresponds to the pericentric distances smaller than the primary's radius.

The general trend is slowdown of rotation with increase of semimajor axis and eccentricity. A rather strong correlation with the initial conditions can be seen. However, we could not detect any significant influence of the spin vector orientation. This is in clear contradiction with Chauvineau et al (1995) which emphasize strong instabilities of retrograde rotators. A possible cause is that in our, hydrodynamical model asteroids gradually lose most of the rotational energy on internal "heating" (random motion of particles of the asteroid) so the additional tidal action which appears in the case of retrograde rotation does not have sufficient energy to cause the collision of components (which happens in model of Chauvineau et al). Other aspects of the dynamical evolution of binary systems are qualitatively similar to the results of the mentioned authors: close approaches and tidal forces make asteroids lose energy, which causes either collision or ejection of one component. In the latter case, the larger component loses most of its angular momentum. However, decceleration of rotation is much less prominent for the contact systems (which, of course, form by gradual decrease of the semimajor axis). Finally, it may be worth noting that the fast rotating asteroids undergo most drastic changes in collision/disruption events.

Now we shall briefly describe four types of objects that could be clearly distinguished at the end of simulation. Their most important characteristics are summed in 1. As before, given numerical values should be treated only as rough estimates. Of course, besides these "tidally/collisionally evolved" objects, there were many "non-evolved" objects — single asteroids with no peculiar features; we focus only on those, which had been subject to intense evolution processes.

The first type in the table, separated binaries, denotes the binary objects with non-

Table 1: Basic properties of typical collisionally and/or tidally evolved objects: physical origin, number of detected objects of that type during the simulation, lifetime (in Myr), periods of rotation and revolution around the center of mass, semimajor axis of the secondary's orbit in units of primary's radii, eccentricity of the secondary's orbit and ratio of the components' radii. Types: 1 — separated binaries, 2 — contact binaries, 3 — asteroids with a satellite, 4 — fast rotators.

synchronized rotation (revolution around the mutual centre of mass with period different from the rotation period). Under contact binaries, we assume synchronized systems, i.e. systems that rotate as a rigid body (their components are very near but not necessarily in physical contact). To the third type – asteroids with a satellite – belong objects with the mass ratio less than 1/10, i. e. systems in which one component clearly dominates the other, but only if they are not synchronized – we always classified synchronized systems as contact binaries. Under fast rotators we assume simply asteroids (single) with period of rotation shorter than 4 hours. We did not detect the fifth type that occurs in practice — slow rotators; we shall consider this problem in more detail later. The separated binaries and the fast rotators are well known from observational practice (e. g. Harris 1996; Margot et al 2002), so we can say we have reproduced some typical objects. Asteroids with a satellite and contact binaries have not been noticed among NEA. The reasons for this probably lie partly in selection effects of observational techniques, and partly in the possibility that these objects tend to evolve into separated binaries (as given in Chauvineau et al 1995), due to some sophisticated mechanisms (e. g. non-gravitational effects) not included in our simulation.

Separated binaries were detected mostly as outcomes of tidal disruption. Of course, tidal effects influence primarily the Earth crossers; however, these objects occasionally become ejected from the region of the Earth crossers so we could detect them in the whole NEA belt. Mutual tidal perturbations may lead to collision, ejection, or formation of contact binaries. However, many systems of this kind were remarkably stable and were able to survive until the end of the simulation.

For contact binaries, we have noticed two formation scenarios. The first is tidal evolution of the previous type. The second is tidal disruption during close encounters. Speed during the encounters is typically lower than in the previous case, so the tidal forces become less efficient. Rotation of contact binaries is usually slower than for single asteroids, which is expected.

Asteroids with a satellite seem to be a typical outcome of collisional evolution. According to our simulation, they can be formed only in collisions. Satellite usually forms from ejected material of both components. For colliding objects of similar masses, the most probable outcome is the fast rotator (the next type) while for larger mass ratios the usual outcome is the asteroid with a satellite. In extreme cases, the only outcome is ejection of many small particles, which do not form a satellite. It is interesting that collisions cannot produce (at least in our simulation) separated binaries which appear as a natural "transient" form between contact binaries and asteroids with a satellite. However, we have to emphasize the instability of asteroids with a satellite. As it can be seen in Table 1, only one such object survived for a considerably long time. Satellite usually becomes lost very soon after its formation.

Fast rotators were also formed mostly during collisions if the mass ratio of the colliding bodies is of the order of unity. One object of this type was also formed as a consequence of collision of components in a binary system. The latter case, however, seems to be very improbable in practice, as it requires very exact alignment of angular momenta, in order to produce a large enough resulting momentum. During formation of fast rotators, asteroids usually suffer significant mass loss, which is certainly due to many small fragments that become ejected.

Therefore, we can say we have succeeded to give possible explanations of some typical evolution paths among NEA although we failed to reproduce the slow rotators and also did detect some thus far unobserved objects. In the following section, we shall try to give theoretical interpretation of these results.

5. Discussion

Results of our research, although speculative and tentative in nature, do somewhat explain formation of some types of NEA. Our basic concept — simultaneous simulation of both orbital motion and collision/disruption events — seems to have shed some light on the interrelations between these aspects of NEA evolution. Namely, collision and disruption events, which lead to formation of NEA, are strongly associated with transition mechanisms so it seems unnecessary to introduce cosmogonic influences. Of course, disadvantages of this concept are also clear — large amount of calculations, somewhat difficult precise interpretation of results due to many factors and processes involved and, most important of all, uncertain initial conditions for some parameters (e. g. spin vectors, shapes, etc). Propagation of errors is nearly unpredictable. So, we wish to emphasize the value of our concept but we also stress that the “traditional” collision/disruption simulations remain the basic means of numerical research of NEA.

Relatively long lifetimes of NEA in our simulation contrast to the widespread belief in the very low stability of these objects but agree with other numerical simulations (e. g. Duncan & Quinn 1993, and references therein). This simulation also confirms some conclusions by Murison et al (1994) concerning the “event time” (expected lifetime of an object, in contrast to formal Lyapunov time) but we have to stress that we do not agree with their interpretation of this effect (log-log relation between the Lyapunov time and the event as a consequence of the peculiar topology of the stable region in the phase space) which is, in our opinion, too pretentious.

Dynamical evolution of binaries shows some similarity with the research of Chauvineau et al (1995) although, as already mentioned, we have not noticed importance of spin vector orientation. Detailed treatment of internal heating in our model (Tillotson EOS) has probably allowed us to get a more realistic picture of where the energy of tides in retrograde systems goes: it becomes lost in internal "geological activity". However, we have to admit that the mentioned authors used a more precise dynamical model, which strengthens their results.

Continual ejection of small fragments during collisions may be an explanation for the overabundance of small Earth crossers, noticed by some authors (Michel & Froeschlé 2000; Rabinowitz 1997). Again, cosmogonic influences seem to be unnecessary if these fragments are taken into account. This could also be a source of some meteor streams (e. g. Geminids). The latter idea is, clearly, only a speculation.

Nature and role of collisions seem somewhat different than in other simulations. While Leinhardt, Richardson and Quinn (2000) notice strong dependence of the outcome on the initial relative speed, we have not noticed that. Also, the main source of stable binary systems in our simulations are tidal breakups, while Michel et al (2002) detect a very wide spectrum of objects, including binaries, which may be formed in collisions.

Overall, tidal forces seem to play a more prominent role than collisions. This is in part a consequence of more realistic initial conditions for close approaches but it also seems that our model treats tides better than collisions — the latter require better resolution, taking into account effects of fractures, etc. It seems hard to estimate the consequences of the neglecting of friction. Absence of friction limits the deformation an asteroid can withstand with no disruption and therefore lessens the magnitude of large deformations but, on the other side, it makes small deformations easier. This is qualitatively similar to the conclusions of Solem & Hills (1996) and Love & Ahrens (1996b).

The most intriguing result may be the lack of single slow rotators. We also cannot give any firm explanation for this. Previous researches of this topic (Chauvineau et al 1995; Richardson 2001) also do not state any definite conclusion. Spectrum of possible explanations is very diverse: from inadequate simulation, inadequate initial conditions and short interval of integration to more complicated, theoretical reasons concerning the early evolution of asteroid belt and cosmogonic influences. Theoretically, very slow rotators can also form in collisions but we think this is not a very probable mechanism. There are some speculations (Brunini 1998) that various groups of asteroids may have different cosmogonic origin. We have also been suggested (Milan Ćirković, personal communication) that slow rotators might be of cometary origin. In that case, their former cometary activity might greatly influence their present dynamical and physical state. Finally, bearing in mind the specific optical properties of some observed slow rotators (e. g. 4179 Toutatis), we think that non-gravitational forces may also have some influence on their spin vectors. This can account also for the overabundance of contact binaries in our simulation: they are probably likely to evolve into separated binaries on very long time scales, influenced also by non-gravitational forces (see Vokrouhlický 1999, for a discussion). For the asteroids with a satellite, we think the most important reason why they have not been observed is the inability of observational techniques to detect very small companions (Merline et al. 2002).

Many questions remain open. A more detailed physical model of asteroids would allow a more refined treatment of collision/disruption events. The primary task would be to include friction and fractures. More realistic treatment of non-gravitational forces (primarily their influence on the spin vectors) could also give some new explanations. A better description of chemical and elastic properties of the asteroid material (basalt is only a phenomenological approximation) is also one of possible enhancements for this kind of research.

6. Conclusions

We have carried out a simultaneous numerical simulation of migration and short-term evolution of NEA. This has allowed us to investigate the interrelation of orbital and physical evolution in a more realistic way than in previous, isolated numerical researches. We have confirmed a strong correlation between the formation of binary systems and events typical for the transition process which makes it unnecessary to introduce cosmogonic influences in order to explain the hypothesis, suggested by the observations, that an overabundance of binaries among NEA exists in comparison to the Main Belt.

We have detected formation of four typical products of tidal and/or collisional evolution: separated binary systems, contact binary systems, asteroids with a satellite and fast rotators. The simulation gives, in our opinion, sufficiently robust and realistic models for their formation. Asteroids with a satellite and fast rotators are formed in collisions, the primary difference being the mass ratio of the colliding bodies: the formation of the latter requires colliding bodies to be of the same order of magnitude, and also some other conditions (e. g. impact angle, spin axis alignment, etc). Asteroids with a satellite, however, seem to be very unstable, for unknown reasons. Separated binaries are a product of tidal evolution. Contact binaries form either from the previous type, or by tidal evolution. We failed to reproduce extremely slow-rotating bodies, which could be due to their peculiar cosmogonic origin or due to the disadvantages of our simulation. We conjecture that this issue is connected to the overabundance of contact systems in our simulation (in comparison to the observations), which are probably likely to eventually evolve back into separated binaries, when the non-gravitational forces act for long enough to become significant.

Generally speaking, tidal forces have proven to be more important than collisions but this could also be a consequence of some systematic errors of the simulation. We noticed the continual formation of small fragments in collision/disruption events, which can explain the overabundance of these objects in the NEA belt and allow a mechanism for keeping their population in a stationary state.

Of course, some results remain unexplained. Among them are the origin of slow rotators, fate of contact systems, influences of friction and fractures, importance of non-gravitational forces, etc. These problems require further numerical and theoretical investigations.

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Type	Origin	N	T [Myr]	P_0 [h]	P [h]	a [R_p]	e	R_s/R_p
1	tides	18	1.1–4.9	2–11	14–36	2.1–7.1	0.02–0.58	0.11–0.82
2	type 1 and tides	25	1.4–7.3	9–21	$P \equiv P_0$	0.0-7.9	0.02–0.72	0.19-0.89
3	collision	3	0.0–1.2	6–12	17–33	5.3–12.2	0.15–0.48	0.02-0.08
4	collision	9	0.9–3.2	2–4	—	—	—	—