Mem. S.A.It. Suppl. Vol. 26, 57

Memorie della
Supplementi

Collisional evolution of binary asteroid systems

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Abstract. Impacts among asteroids is one of the main mechanisms affecting both the physical characteristics of single bodies and the properties of the overall population. The statistics and the outcomes of catastrophic and non-catastrophic collisions among asteroids has been studied by several authors. The effects of the collisions on the evolution of binary asteroids are, however, less investigated. Only recently some papers have dealt with this topic. We present the results of a recent theoretical study which shows how non-destructive collisions would be important for the orbital stability of binary asteroids in the Main Belt on timescales shorter than the collisional lifetime of the members. Such kind of processes are important not only for the study of the population of the binary asteroids but also for the origin of the recently discovered asteroid pairs.

Key words. binary asteroids – collisional evolution

1. Introduction

The number of known systems composed by two or more asteroids gravitationally bound and orbiting around each other has grown dramatically during the last decade. In 2002 Merline et al. (2002) reported a list of a little more than a dozen systems in their review about asteroids with satellites. Presently the Binary Minor Planets data set of Johnston (2013) list more than two hundreds systems, among double and multiple asteroids.

Several techniques have been used to detect those systems. About 40 % of the systems have been discovered by means of photometric lightcurve observations. More or less the same number of binaries have been detected using direct imaging, mainly with the Hubble Space Telescope (HST). About 10 % of binaries has been detected using adaptive optics technique, and finally another 10 % with radar observations. Only one system has been revealed after a spacecraft mission (Ida/Dactyl). Different techniques have different efficiencies in revealing binary systems among different minor body populations. While lightcurves allow to discover binary minor bodies throughout the whole Solar System, radar technique is more suitable for searching them among Near Earth Asteroids (NEA), adaptive optics among Main Belt Asteroids (MBA) and HST among trans-Neptunian Objects (TNO).

It is currently estimated that about 2 % of main belt asteroids larger than 20 km have satellites (Merline et al. 2002), a rather small fraction compared with the much larger incidence of binaries among NEAs. Different discovery techniques and formation mechanisms are likely both responsible for the differences between observed binaries among MBAs and NEAs. More than half of binary MBAs have been discovered with adaptive optics, which preferentially finds distant companions outside of the point spread function of the brighter primary. All techniques (but particularly adaptive optics) are sensitive to primary size. HST and lightcurves have found most of the small binary MBAs, but they are still larger than all binary NEAs. Generally, a binary with primary diameter of 1 km and a small companion is extremely difficult to observe in the Main Belt with present techniques. For what concerns TNOs, current estimates suggest the frequency of TNO binaries is about 4 % (Petit & Mousis 2004).

Three main mechanisms have been invoked for justifying the existence of binary asteroids. Impacts among asteroids can disrupt partially or totally the bodies involved and produce fragments that can form satellites orbiting around the largest remnant. Numerical simulation have been shown how formation of binary asteroids can be a natural by-product of the formation of the asteroid families (Durda et al. 2004). Being dynamical lifetimes of NEAs shorter than their collisional lifetime, this kind of mechanism should be more effective in the Main Belt. Another formation mechanism consist in the fission due to large rotational motion. Recently YORP effect (Rubincam 2000) has been proposed as the main mechanism of spin-up able to lead the asteroid to the breakup limit. Due to their vicinity to Sun, NEAs should be more affected by YORP spin-up (and spin-down), making rotational fission the most likely mechanism of binary formation among those bodies. One last mechanism of binary formation consists in the gravitational capture of one body by another one. Mutual capture is considered the most favored mechanism for forming the binary TNOs observed to date.

Different physical mechanisms can drive the post-formation evolution of asteroid binary systems. Tidal interaction among the members of the systems can produce modification of size and shape of the orbit of the system. The efficiency and the final outcome of this mechanism strongly dependent on the spin and shape of the members, and it can produce, depending on the circumstances, a collapse, separation or stabilization of the system (Scheeres 2000; Jacobson & Scheeres 2011a,b). Encounters with planets could produce modification of the system orbit among NEAs, justifying the existence of double crater retrieved on the planetary surfaces (Bottke & Melosh 1996a,b). More recently again non-gravitational forces like thermal effects have been studied as mechanism of evolution of binary asteroids. Yarkovsky and YORP effects have been suggested to have a significant role in perturbing already formed binary asteroid systems or stabilize them (Fahnestock & Scheeres 2009; Steinberg & Sari 2011). Finally impacts certainly have a role in the evolution of binary asteroids, only for the fact that collisional lifetimes of the single members of a system corresponds to the collisional lifetime of the whole system. Apart this, separation of members due to linear momentum transfer of non catastrophic collisions has been preliminary investigated by some authors in the context of study of trans-Neptunian Objects (Petit & Mousis 2004; Nesvorny et al. 2011).

Here we show a systematic analysis of the effects of non-destructive impacts on the evolution of the orbits of asteroid binary systems. We focus on the evolution of binary systems among Main Belt Asteroids, where collisional evolution is more intense. Both the role of a single enough energetic collision able to produce a direct separation of the members and the cumulative contribution of numerous gentle collisions with smaller or less energetic projectiles have been taken into account.

2. Destruction threshold and lifetimes

The final outcome of an impact between a third body and a member of a binary asteroid depends on many factors. In general an impact can modify the physical properties of the target (internal fragmentation, destruction and dispersion of the fragments, simple surface craterization and mass erosion...) and the parameter of the mutual orbit. For what concerns the effect on the physical properties, a common approach is to assume a threshold of the specific impact energy, namely the projectile's kinetic energy per mass unit of the target body, which is needed to shatter the target and disperse its fragments (Dell'Oro & Cellino 2007;

Dell'Oro et al. 2012). This threshold, commonly denoted with Q^*, depends on the physical characteristics of the target, and mainly on its composition and size (Benz & Asphaug 1999). In a simplified framework in which the mean impact velocity of the projectiles population is statistically representative, the existence of an energy threshold corresponds to a limit of the size of the projectile dividing the catastrophic collision regime from the regime of gentle collision producing only transfer of linear and angular momentum. By definition of Q^* it follows that the projectile limit size is $D_* = (2Q^*/U^2)^{1/3} D_T$, where U is the mean relative impact velocity and D_T the diameter of the target.

In a asteroid binary system, each member is characterized by a own value of Q^*. This means that each members has a different resistance to the collisional environment, or in other words its collisional lifetime is different. The mean number per unit of time of catastrophic events consisting in a collision between a given target and a projectile able to destroy it is $\mathrm{d}N_{destr}/\mathrm{d}t = (1/4)D_T^2 P_i N(> D_*)$, where P_i is the so-called mean intrinsic probability of collision (Wetherill 1967) and $N(> D_*)$ is the number of existing projectiles with diameter larger than the critic value D_*. The quantities P_i and $N(> D_*)$ are characteristic of the orbital and size distributions of the projectiles. The inverse of $\mathrm{d}N_{destr}/\mathrm{d}t$ is the mean collisional lifetime τ_{destr} of the target.

Each member of a binary system, due to its own value of Q^* and its size from which its cross-section depends on and therefore the rate of impacts with other bodies, has a given lifetime. The total rate of catastrophic events able to put an end to the existence of the binary system is the sum of the rates of similar events for each member. It turns out that the collisional lifetime of the whole system is:

$$\frac{1}{\tau_{destr}} = \frac{1}{\tau_{1,destr}} + \frac{1}{\tau_{2,destr}}$$

where $\tau_{1,destr}$ and $\tau_{2,destr}$ are the collisional lifetimes of each member.

3. Collisional orbital instability

Dell'Oro & Cellino (2007) discussed the effects of non-catastrophic collisions on the orbital motion of the Main Belt Asteroids around the Sun. They showed that, under some conditions, the transfer of the linear momentum due to the flux of gentle collisions produces a secular modification of the orbits of the asteroids. The same mechanism can produce a modification of the mutual orbit of the members of a binary system. An impact between a member of the system and a projectile the size of which is below the destruction threshold, produces an impulsive variation of the instantaneous velocity. This entails a variation of the mechanical energy of the system. The impact can occur in any point of the member's orbit, causing a more or less large variation $\delta\mathcal{E}$ of the total energy $\mathcal{E}$. Dell'Oro et al. (2012) pointed out that in mean this variation is positive and equal to $(\delta\mathbf{v})^2/2$, where $\delta\mathbf{v}$ is the total impulsive variation of the relative velocity between the members. Following the conservative approach of Dell'Oro & Cellino (2007) about the amount of the transferred linear momentum, and assuming that the mass of the projectile is much smaller that the mass of the target, it results that the energy variation is $\delta\mathcal{E} = (1/2)(D_T/D_p)^6 U^2$, where D_p is the diameter of the projectile and U is the relative velocity between the projectile and the barycenter of the binary system. It is worthwhile to stress that we are talking about collisions for which $D_p < D_*$, that is impacts in non-catastrophic regime.

The evolution of the binary system due to non-catastrophic collisions can be described as a random walk in the space of the total mechanical energy $\mathcal{E}$. In this space the value $\mathcal{E} = 0$ is the boundary beyond which the binary system no longer exists. The overcoming of this boundary happens when $\delta\mathcal{E} > -\mathcal{E}$. This can happens in a single collision and/or after a progressive increase of the energy by a large number of small impacts producing perturbations $\delta\mathcal{E} \ll -\mathcal{E}$. Dell'Oro et al. (2012) call the former mechanism "emission" and the second "inflation". Both mechanism act at the same time, and the combination of the two produce sooner or later the "evaporation" of the binary system.

4. Final fate of a binary system

Collisional evaporation puts an end to the existence of a binary system breaking off the gravitational link between the members. It can occurs before or after the collisional lifetime of the members, that is when one of them is destroyed by a catastrophic collision. Dell'Oro et al. (2012) classify the binary systems between smashed and evaporating systems. A smashed system disappears as a binary asteroid for the destruction of one of the two members (typically the smaller one), while an evaporating system disappear because the members stop to be gravitationally bound but they continue to survive as independent bodies. In the second case characteristic time of the evaporation process is less that the collisional lifetimes.

Collisional lifetime for impact destruction depends on the size and the impact strength of the target, and the slope of the size distribution of the projectiles whose orbit cross the orbit of the target. Evaporation time also depends on the structure of the binary system, that is the ratio between the size of the companion and the size of the primary member (the largest one), and the ratio between the semimajor axis of the mutual orbit and the size of the primary. Dell'Oro et al. (2012) has performed extensive numerical simulations taking into account different types of binary systems and different slope of the asteroids size distributions. The assumed impact strength is that one provided by Benz & Asphaug (1999). A significant result is that in the range of the diameters of the primary between 0.1 km and 1000 km, the frequencies of smashed and evaporating systems are more or less the same. On the other hand, evaporating systems dominate for small primary size (less than few kilometers) and, to a lesser extent, for large primary sizes (larger than 100 km). The maximum frequency of smashed systems is in the range of primary size from 10 to 100 km, increasing with the slope of the size distribution of the projectiles. The collisional evaporation is only one of the mechanism able to alter the population of the binary systems. A comprehensive model of the evolution of the population of the binary systems should include together the mechanisms of their formation and destruction at the same time. This result is yet to come and it will the topic of future studies. Last but not least, the discovery of the possibility that some binary asteroids can evaporate sheds new light on the problem of the origin of the so-called asteroid pairs (Vokrouhlicky & Nesvorny 2008; Pravec at al. 2010), couples of asteroids with very similar orbital elements but not gravitationally bound, recently discovered among Main Belt asteroids. The collisional instability of binary asteroids among other populations of minor bodies, like Trojan asteroids and TNOs, is also a very interesting topic to be investigated in future. For what concerns Near Earth Asteroids, the short dynamical lifetimes of the members of that population probably makes the collisional instability irrelevant for the evolution of their binary systems.

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