Mem. S.A.It. Vol. 90, 669

Memorie della

Impact rate and water delivery to the terrestrial planets from a dwindling asteroid belt

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Abstract. We have computed the loss rate of bodies from the asteroid belt by means of numerical integrations of the population of observed asteroids (near-Earth asteroids and Jupiter-crossers or approachers) that are in their way of leaving the asteroid belt. From these computations, we derive the current impact rate of asteroids with Venus, the Earth and Mars. The frequency of collisions with the Earth is found to be about one asteroid with diameter $D > 1$ km every 0.4 Myr, with a similar frequency for Venus, and about a half for Mars. We also find that the asteroid belt is currently losing a fraction of about 5.3×10^{-5} Myr^{-1} of its mass. At this loss rate, the asteroid belt would have been only about 20% more massive 3 Gyr ago. However, at the beginning the asteroid belt might have been three orders of magnitude more massive than at present, but it was quickly depleted as the most dynamically unstable bodies were scattered to planet-crossing orbits causing a heavy bombardment on the surfaces of the terrestrial planets. Colliding water-rich bodies provided a outer veneer of water and organic material. Early Venus might have had an outer veneer of water and habitable conditions similar to the Earth, but its water was entirely lost as its climate evolved to an extremely hot one.

Key words. Minor planets – asteroids: general – Methods: numerical

1. Introduction

The asteroid belt has been the main source of extraterrestrial material that reached the Earth and the other terrestrial planets (Strom et al. 2005). Therefore, the steady bombardment of the terrestrial planets has a clear correlation with the depletion of the asteroid belt. The formation time scale of the terrestrial planets is estimated to be of the order of 10-100 Myr (Chambers 2004). During the accretion stage most of the impactors came from the own accretion zones of the terrestrial protoplanets. Once these zones were depleted, most of the impactors came from the adjacent asteroid belt. The formation of Ceres-size or Vesta-size bodies in the asteroid belt required a primordial mass at least two orders of magnitude greater than at present (Wetherill 1992). The formation of a single large planet was prevented by the early depletion of the asteroid belt that is crisscrossed by a number of unstable orbital resonances with Jupiter and Saturn (Chambers 2004). The material removed from the asteroid belt constituted the source of the intense bombardment of the terrestrial planets that followed the completion of their formation and clearing of their accretion zones.

There may have also been an early massive scattering of icy planetesimals from the formation zones of the Jovian planets (Fernández & Ip 1983), but the Jupiter-Saturn barrier was very efficient in ejecting most of the mass before reaching the terrestrial planet zone, so the probability of collision of this material with any of the terrestrial planets was very low (Fernández et al. 2018).

Most of the objects that hit the Earth are asteroids and only a minor fraction are comets. A piece of evidence in favor of an asteroidal origin for most of the impactors is provided by the deuterium to hydrogen isotopic ratio (D/H) in water molecules of the oceans. The terrestrial D/H ratio shows a good match with that found in meteorites, whose source region is the asteroid belt, but it has a discrepancy of a factor of about two with water molecules in comets (Robert 2001). The size distribution of the impactors that produced the oldest recorded craters on the surfaces of the Moon, Mars, Venus and Mercury (older than 3.8 Gyr) is consistent with that of Main Belt asteroids. On the other hand, younger craters seem to have been produced by impactors with a size distribution more consistent with that of the Near-Earth Asteroids (NEAs) (Strom et al. 2005). The preservation of the size distribution of the oldest impactors would imply a size-independent transport mechanism from the main asteroid belt to the terrestrial planets zone.

Even though the asteroid belt seems to be dynamically very stable on cosmogonic time scales, it steadily loses a small fraction of its mass, essentially through two processes: a) Fragments produced in collisions (from sub-km to ∼ 30 km size) are injected into secular and mean motion resonances after some drifting via the Yarkovsky mechanism. The fragments end up as NEAs or in Jupiter-crossing orbits. b) Smaller fragments continue their collisional comminution until being converted into meteoritic dust that is removed from the planetary region by forces associated to the Sun's radiation (Poynting-Robertson drag, radiation pressure force).

2. The model

We have developed a numerical model to investigate the current mass loss rate from the main asteroid belt and the frequency of collisions of asteroids with the Earth. The numerical integrations were carried out with the Bulirsch-Stoer algorithm of the Mercury package (Chambers 1999). We considered the motion of massless bodies in a heliocentric frame under the gravitational influence of the Sun and seven planets, from Venus to Neptune, while the mass of Mercury was thrown into the Sun. The accuracy parameter was 10^{-12}.

We have integrated samples of observed asteroids that are in the process of leaving the main asteroid belt. The observed asteroids were drawn from the JPL Solar System Dynamics Database and we selected the best-quality orbits (those with quality codes between 0 and 5). The chosen samples were: 1) 1019 Near-Earth asteroids with absolute magnitudes $H < 18$, which is estimated to be complete in more than 90%; 2) 379 Jupiter-approachers or crossers with $1.3 < q < 3.2$ au, semimajor axis $a < 3.91$ au, $Q > 4.5$ au, and $H < 18$. The last sample was selected in such a way that we left aside those asteroids with semimajor axes in the range $3.91 < a < 4.02$ au because most of them are Hildas in stable orbits librating around the 3:2 mean motion resonance with Jupiter. We integrated a total of 1398 objects.

The test bodies were integrated for 200 Myr for Sample 1 and 100 Myr for Sample 2. The integrations were terminated if the body reached one of the following end states: a) ejection to interstellar space (actually, if it reached a heliocentric distance $r \geq 100$ au); b) collision with any of the planets, or c) collision with the Sun. We assumed that a "collision" with the Sun occurred if the body reached a perihelion distance smaller than the Roche radius of $\simeq 0.009$ au.

3. The results

We computed the dynamical lifetimes of the two populations of escaping asteroids as given by the time scale for the decrease of the population by a factor $1/e$. The dynamical lifetimes of NEAs (Sample 1) and Jupiter-crossers or approachers (Sample 2) are found to be 20.5 Myr and 6.3 Myr respectively. About 70% of NEAs end up colliding with the Sun and 5% with the Earth (see Table 1). The size of our sample of

NEAs roughly corresponds to the NEA population with diameters $D > 1$ km (e.g. Harris & D'Abramo 2015).

Table 1. End states of NEAs

End state	Number
Collision with the Sun	705
Collision with Venus	55
Collision with the Earth	51
Collision with Mars	11
Collision with Jupiter	2
Ejection	193

Therefore, the frequency of collisions with the Earth of NEAs with $D > 1$ km can be approximately given by

$$\dot{N}_{coll} = \frac{N_{coll}}{\tau_{dyn}} = \frac{51}{20.5} \simeq 2.5 \text{ Myr}^{-1} \quad (1)$$

or a collision rate of one NEA with $D > 1$ km every ≈ 0.4 Myr.

If we assume an average density of 3 g cm^{-3} for the NEAs, we obtain a total mass of 1.22×10^{20} g for the NEA population, from which about 70% of the mass resides in the largest NEA (1036 Ganymed). This indicates a certain stochasticity in the NEAs mass depending on the largest body that leaks from the main asteroid belt to the NEA region at a given time. For a typical dynamical lifetime of 20.5 Myr we found a mass loss rate

$$\dot{M}_{NEA} = \frac{1.22 \times 10^{20} \text{ g}}{20.5 \text{ Myr}} \simeq 6.0{\times}10^{18} \text{ g Myr}^{-1}. (2)$$

For the case of asteroids diffusing to Jupiter's region ($Q > 4.5$ au), the largest is 1922 Zulu with a diameter $D = 20.6$ km and an aphelion distance $Q = 4.79$ au. We adopt a size distribution $N(D)dD = CD^{-\alpha}dD$, where C is a constant and $\alpha = 3.5$ for $H < 15$, whereas we have $\alpha = 2.5$ for $15 < H < 18$ (Gladman et al. 2009). We obtain

$$\dot{M}_{JUP} = \frac{M(H{\leq}15)+M(15{<}H{\leq}18.5)}{\tau_{dyn,Jup}}$$

$$\simeq \frac{3.2 \times 10^{20} \text{ g}}{6.3 \text{ Myr}} \simeq 5.1 \times 10^{19} \text{ g Myr}^{-1}, \quad (3)$$

where we adopted an average density $\rho = 2$ g cm^{-3} for bodies of the outer main belt.

The results from eqs.(2) and (3) are for asteroids with $D > 1$ km, smaller asteroids do not contribute significantly to the mass budget since the size distribution at the lower end flattens (Ivezić et al. 2001; Mainzer et al. 2011).

A significant fraction of the current mass loss from the asteroid belt goes into dust particles that are swept away by the forces associated to the Sun's radiation (radiation pressure and Poynting-Robertson drag). This is because the time scale required to move asteroid fragments to dynamically unstable regions by the Yarkovsky mechanism is too long as compared to the collisional lifetime. An input rate of about 10 ton s^{-1} is necessary in order to keep the zodiacal dust cloud in steady state (Whipple 1967; Grün et al. 1985), from which about one third comes from the comminution of asteroids (Durda et al. 1992; Durda & Dermott 1997). Therefore, we find a mass loss rate from the main asteroid belt under the form of dust particles of

$$\dot{M}_{dust} \simeq 10 \text{ ton s}^{-1}{\times}\frac{1}{3} = 1.04{\times}10^{20} \text{ g Myr}^{-1} (4)$$

A summary of the mass loss rates from the different sources is shown in Table 2.

Table 2. Mass loss through different escape routes

Escape route	Mass loss (g/Myr)	Source
NEAs	6.0×10^{18}	This work
Jupiter-crossers	5.1×10^{19}	This work
Meteoritic dust	1.04×10^{20}	(1), (2)

(1) Grün et al. (1985)
(2) Durda & Dermott (1997)

By combining all the sources of mass loss, we get for the current mass loss rate

$$\left(\frac{\Delta M}{\Delta t}\right)_o = (0.6 + 5.1 + 10.4) \times 10^{19}$$

$$\simeq 1.6 \times 10^{20} \text{ g Myr}^{-1}, \quad (5)$$

from which about two-thirds are lost as dust particles and the other third as macroscopic bodies.

Let $\dot{\mu}_o$ be the current rate of relative mass loss from the main asteroid belt:

$$\dot{\mu}_o = \frac{(\Delta M/\Delta t)_o}{M_o} \simeq 5.3 \times 10^{-5} \text{ Myr}^{-1}\,, \qquad (6)$$

where $M_o \sim 3 \times 10^{24}$ g is the current mass of the asteroid belt.

From the previous results we can try to answer the following question: what is the fraction of mass leaving the main asteroid belt, f_{Earth}, that ends up colliding with the Earth. We found before that about 5% of NEAs end up colliding with the Earth, but this is only a small fraction of the mass loss, the rest is ejected by Jupiter, collides with the Sun or another planet, or is lost as zodiacal dust. If we take all these losses into account we have

$$f_{Earth} = \frac{0.05 \times 0.6}{(0.6 + 5.1 + 10.4)} \simeq 1.9 \times 10^{-3}\,. \qquad (7)$$

4. The mass loss from the asteroid belt through time: Theoretical estimate

The idea that the current asteroid belt is the remnant of a much larger population is not new (Chapman & Davis 1975). This is shown by the power-law size distribution of asteroids as the result of a collisionally evolved population, being the observed asteroid families the footprints of mega-collisions between massive asteroids that occurred in the past (Nesvorný et al. 2015). In order to extrapolate the current mass loss from the asteroid belt back into the past, we will follow the procedure developed by Chapman & Davis (1975). If we assume that the depletion rate of the $N(M)$ asteroids of masses within $(M, M + dM)$ is caused by mutual collisions, then it will be proportional to N^2, so the loss rate of bodies can be expressed as

$$\frac{dN}{dt} = -kN^2\,, \qquad (8)$$

where k is a constant. If we assume that the objects in the population have an average mass $\bar{m}$, so the mass of the N asteroids is $M = N\bar{m}$, the previous equation can be converted to an equation for the mass loss of the asteroid belt

$$\frac{dM}{dt} = -\frac{k}{\bar{m}} M^2\,. \qquad (9)$$

At present $M = M_o$, so we obtain

$$\dot{\mu}_o = \frac{k}{\bar{m}} M_o\,. \qquad (10)$$

We can integrate eq.(9) between a time t (in the past) and the present time t_o, and introduce eq.(10), leading to

$$M(t) = \frac{M_o}{1 - \dot{\mu}_o(t_o - t)}\,. \qquad (11)$$

By introducing the numerical value of $\dot{\mu}_o$ given by eq.(6), we find that the main asteroid belt was only about 20% more massive about 3 Gyr ago, and the mass loss rate about 40% higher.

5. The early mass loss from the asteroid belt derived from the impact record on the Moon and the terrestrial planets

Our model can be extrapolated back to the last ~3 Gyr by assuming that the asteroid belt has remained more or less with the same dynamical structure as that at present. Earlier times were characterized by a massive loss of material from the asteroid belt with the correlated heavy impact rate of the Moon and the terrestrial planets. In the following we will review the available information about the early impact rate from the geologic record of the Earth and the Moon, and whether it can be smoothly connected to the late slow decrease derived for the last 3 Gyr.

One way to learn about the oldest megaimpacts on the Earth is through the spherule layers preserved in the Earth's stratigraphy. A body hitting the Earth vaporizes a mass of target rock that expands and condenses into molten droplets called *spherules*. The diameter of the impactor can be related to the thickness of the spherule layer deposited on the surface (Johnson & Mellosh 2012). From the impact spherules layer record, Johnson et al.

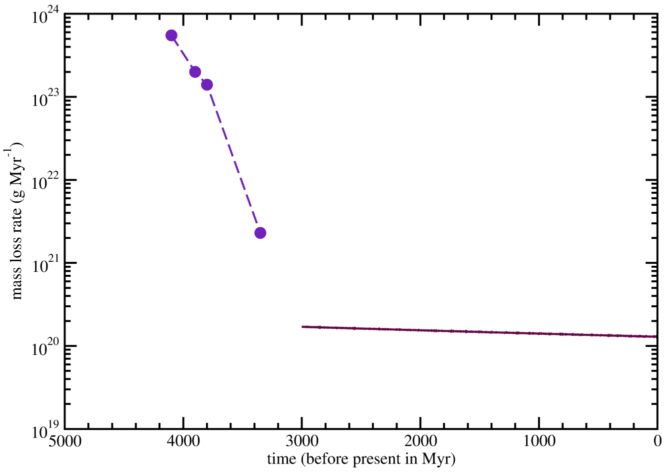

Fig. 1. Mass depletion of the asteroid belt for the last 4.3 Gyr that was characterized by an early period of rapid falloff, that was correlated with a heavy bombardment of the Moon and the terrestrial planets, followed by a smooth decrease for the last 3 Gyr in which the residual asteroid belt settled in a stable dynamical configuration.

(2016) estimate that the flux of large impactors was 20-40 times higher than today between 3472 and 3230 Myr ago, which would correspond to an average mass loss rate of $\simeq 2.3 \times 10^{21}$ g Myr^{-1}.

If we want to have a most complete record of the early impacts we have to analyze the Moon as a proxy since it preserves very old impact structures. Sleep et al. (1989) estimate that the Imbrium basin, with an estimated age of 3.9 Gyr, was caused by a projectile of mass 2×10^{18} kg, while the somewhat younger Orientale basin (age of 3.8 Gyr) was caused by a projectile of mass 1.4×10^{18} kg. These authors also estimate that the Moon received a mass equivalent to 11 Imbrium projectiles after 4.4 Gyr, and that the Earth received 23 times more mass than the Moon due to its much stronger gravitational field.

Estimates of the early mass loss rates of the asteroid belt together with our computed mass loss rate for the last 3 Gyr are plotted in Fig. 1. The figure depicts a tentative profile of the mass loss going from a rapid falloff at the beginning, by about three orders of magnitude, to a very slow steady decline for the last 3 Gyr.

6. Discussion

We have estimated the current relative mass loss rate from the asteroid belt of about 5.3×10^{-5} Myr^{-1}. This result can be extrapolated backwards in time to ~3 Gyr ago, when the asteroid belt might have contained about 20% more mass than at present and the mass loss rate (and the corresponding collision rate with the terrestrial planets) could have been about 40% higher. These represent very modest changes with respect to the current situation. Between about 4.3 to 3 Gyr ago, the asteroid belt lost most of it mass, producing an intense bombardment of the terrestrial planets with an exponential dropoff followed by a smooth decrease for the last 3 Gyr.

Probably the asteroid belt was two-three orders of magnitude more massive ~ 4.3 Gyr ago. At that time the asteroid belt might have contained several Ceres-sized bodies or even larger that caused considerable gravitational stirring that favored the displacement of bodies to dynamically unstable zones from where they were removed to planet-crossing orbits and caused the heavy bombardment of the terrestrial planets.

As regards the origin and development of life on Earth, during the first Gyr frequent mega-collisions were a major disturbing factor causing the annihilation of early life forms that might have attempted to take hold on the planet. It was necessary a more benign environment to protect early microorganisms and allow their further evolution in different ecological niches. This was finally achieved when most of the massive projectiles with deleterious effects on life (say greater than several tens km) were removed from the planetary region.

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