The Mass Influx of the Inner Solar System Estimated by a Lunar-like Chronology Model

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Introduction: The aim of this work is to test one of the most simplest and straightforward hypothesis: What if the early highly populated Asteroid Belt (AB) is the main source for the masses impacted in the inner solar system, not only now, but also before 3.0 Ga? We test the model by computing and comparing available impactor masses with masses needed to create all impact craters on terrestrial planets, since crater records on planetary surfaces attest a bombardment history by projectiles of different sizes. From analysis of the lunar impact-crater record and correlation of the crater size-frequency distribution (SFD) with isotope ages of lunar rocks collected at the landing sites, a chronology model for the Moon has been derived [1, 2, 3]. This chronology model,

$$N(1,T) = A \cdot \left(\mathrm{e}^{B\cdot T} - 1, 0\right) + C \cdot T \qquad (1)$$

where A, B and C are coefficients for each planetary body, suggests an exponential decline of mass influx since 4.5 Ga, turning into a steady flux from ~ 3.0 Ga henceforth [2, 4]. Rapid influx increase around 3.9 Ga proposed by [5] based on work of [6] (*late heavy bombardment, LHB)*, is now constrained by a dynamically changing solar system, e.g. the *Nice* model [7]. The dynamics of the model has not been taken into account here, but the flux behaviour, which differs only prior to about 4.0 Ga (formation age of the Nectaris basin [8]) when compared to the above described lunar chronology model. The AB is widely accepted as the primary source of projectiles at least in the inner solar system. Still controverseley discussed is the total mass of the primordial AB and the time-dependency of the mass flux caused by its depletion. In this work, by mapping the crater record of each planetary body via a suitable scaling law into hypothetical projectile masses, the total mass is then estimated from the chronology and the derived projectile distribution. We compare our results with recent mass estimates of the AB using different dynamical *collision efficiencies* and other estimate methods.

Method: Mapping the crater SFD into a corresponding projectile SFD is performed by a scaling law suggested by [10], simplyfied by assuming preliminary average impact velocities v_i (Tab. 1, [2, 9]), impact angle ($\alpha_i = 45°$), average impactor density ($\varrho_{Imp} = 2.5\ \mathrm{gcm}^{-3}$), spherical shape and average target density ($\varrho_{Tar} = 3.0\ \mathrm{gcm}^{-3}$). The integration's minimum equiv. projectile diameter, $D_p = 0.5$ km, has been choosen for comparison with the AB's SFD. The distribution index τ in Eqn. (1) has been choosen to meet a reasonable SFD for basins or maria not covered by the lunar-like polynomial SFD beyond $D = 300$ km. Both Eqns. (1) and (2) are integrated, assuming a uniform influx over the integrated time period

[1]Mean average v_i of ancient and recent Mars orbit

Table 1: Crater-diameter validity ranges of the lunar-like SFD. Beyond this interval, an exponential distribution with distribution index τ is considered valid (log-log scale, Eqn. (2)). Lower limit D_{min} is mapped to an equiv. scaled proj. diameter $D_p = 0.5$ km. D_{vm} marks the upper validity crater-diameter integrated to. The preliminary impact velocities v_i are taken from [9].

Target	$[D_{min}; D_{max}]$ (D_{vm}) km	τ [°]	v_i [km s^{-s}]
Mercury	$11.19 - 1500$ (100)	-2.938	35.4
Venus	$8.61 - 3000$ (300)	-2.25	24.2
Earth	$7.46 - 3000$ (300)	-2.23	19.3
Moon	$9.80 - 2400$ (300)	-2.80	17.5
Mars	$6.37 - 2500$ (300)	-2.845	10.03[1]

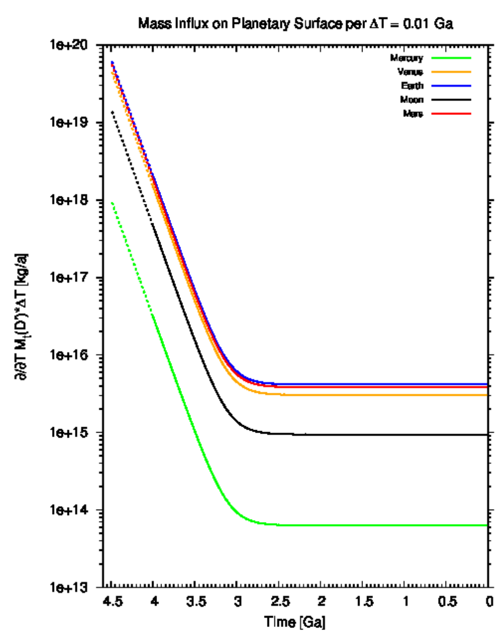

Figure 1: Total impact rates of mass equivalents estimated by a proper scaling law individual for each planetary surface within a time interval of $\Delta T = 0.01$ Ga.

Table 2: Impact mass estimates. Results are also shown as mass ratios with respect to the Moon, $M_{Moon} = 7.349 \cdot 10^{22}$ kg, and (1) Ceres, $M_{Ceres} = 9.35 \cdot 10^{20}$ kg.

Target	M_t [10^{20} kg]		rM_{Moon}		rM_{Ceres}	
	4.5	4.0	4.5	4.0	4.5	4.0
Mercury	0.12	0.004	$1.7 \cdot 10^{-4}$	$5.5 \cdot 10^{-6}$	0.013	$4 \cdot 10^{-4}$
Venus	4.72	0.16	0.006	$2.1 \cdot 10^{-4}$	0.5	0.017
Earth	8.25	0.27	0.011	$3.7 \cdot 10^{-4}$	0.88	0.029
Moon	1.49	0.05	0.002	$6.67 \cdot 10^{-5}$	0.16	0.005
Mars	12.45	0.41	0.017	$5.5 \cdot 10^{-3}$	1.33	0.044
Σ	27.03	0.99	0.036	$6.15 \cdot 10^{-3}$	2.88	0.095

and considering different projectile's hit efficiencies as shown by [11]. Integration has been performed up to 4.5 Ga, as suggested by the model of [2], and 4.0 Ga and compared with results of total mass estimates of the recent AB by [12, 13].

$$\lg N = \begin{cases} a_0 + \sum_{i=1}^{n} a_i (\lg D)^i, & D \in [D_{mi}; D_{ma}] \\ \lg k + \tau D^{\tau - 1}, & D \notin [D_{mi}; D_{ma}] \end{cases} \tag{2}$$

Outlook: Tab. 2 lists preliminary results of the total impacted mass and mass influx for both ages $T = 4.0$ Ga and $T = 4.5$ Ga. Total impact-mass estimates, $M_t = 2.703 \cdot 10^{21}\text{kg}, T = 4.5$ Ga and $M_t = 9.9 \cdot 10^{19}\text{kg}, T = 4.0$ Ga are compared with estimates of the AB's mass presented by [13] ($M_{belt} \approx 3.0 \cdot 10^{21}$ kg) and [12] ($M_{belt} \approx 3.5 \cdot 10^{21}$ kg). In Fig. 2, we compare the total mass influx as a result of our integration, and different so called *collision efficiencies*, which are supposed to be not higher than 10.0%. We estimate the total mass of the source, the AB, by assuming collision efficiencies of 1%, 3%, 5% and 10% and compare the achieved masses with those mass estimates for the AB, shown as horizontal bars in Fig. 2. Total impact mass as shown in Figs. 1, 2, are highly dependend on the estimated physical properties of the target and assumed, preliminary impact velocities of the impactors. Furthermore, since the mass contribution of very large basin-forming impactors dominate the total mass balance, the method used in this approach by approximating the SFD piecewise via Eqn. (2), contains a large error towards high mass contributions. On the conference, we will present new results based on an extended lunar SFD polynomial, extended for up to crater diameters of $D_{max} = 1250$ km and possibly beyond, to overcome this restriction.

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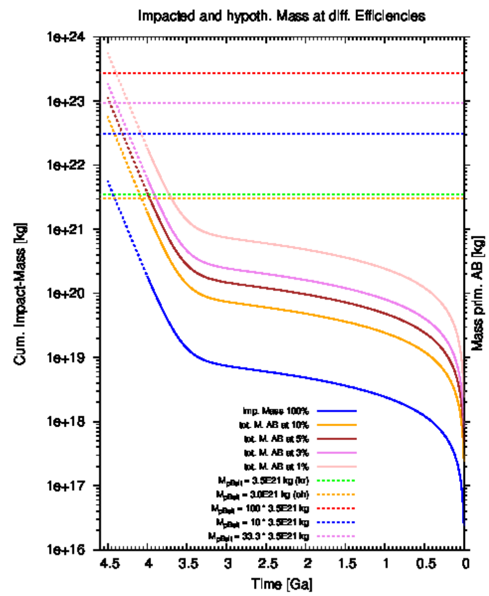

Figure 2: Total mass influx (blue line), derived from lunar-like impact rates shown in Fig. 1, at different dynamical collision-efficiencies. Graphs marked with AB (Asteroid Belt) show hypot. total mass depleted from AB. Horizontal lines mark different estimates of primoridial AB, compared to recent AB mass estimate $\approx 3.5 \cdot 10^{21}$ kg, [12].

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