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# Mass accumulation of earth from interplanetary dust, meteoroids, asteroids and comets

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A R T I C L E I N F O

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A B S T R A C T

Using new data and recent models this paper derives a total combined flux model of the mass reaching Earth as interplanetary material. For the small sizes the interplanetary flux model by Grün et al. (1985) was used which describes the mass flux at 1 AU for meteoroids in the mass range $10^{-21}$ kg to about $10^{-1}$ kg. For the large objects the flux models by Brown et al. (2002) were used which were derived for bodies greater than 1 m and are based on sensor data of fireballs that entered the Earth atmosphere. For the intermediate size range interpolations and alternative models based on meteor and fireball data were used. All flux models were converted to an altitude of 100 km above the Earth surface to make them comparable. The total combined flux model covers more than 34 orders of magnitude in mass. Using recent measurements and alternative flux models the uncertainties of the obtained model were estimated. Recent measurements include in-situ impact data on retrieved space hardware and optical meteor and fireball data. Depending on the models and interpolation used the interplanetary material that enters the Earth atmosphere per day is in the range of $30-180$ t with a best guess value of 54 t per day for an upper cut-off size of 1 km. If the upper size limit is placed at 0.5 m which is the largest size where statistically a daily impact is expected, the expected mass influx is slightly more than 32 t per day. The combined models with interpolations suggest deviations from a simple power law. The flux in the diameter range of 0.01–0.1 m appears not as large as suggested by a simple power law interpolation.

## 1. Introduction

The mass accumulation of Earth from interplanetary dust, meteoroids, asteroids and comets has been estimated repeatedly using such diverse methods as analysis of sedimentary rock on Earth, meteor studies, space based in-situ impact data and simulations (see e.g. Hughes, 1978; Dermott et al., 2002; Love and Brownlee, 1993; Carrillo-Sanchez et al., 2015). A detailed review on previous studies of the cosmic dust entering Earth's atmosphere is given by Plane (2012). Estimations of the mass influx to Earth can be split into 2 broad groups: those that base it on measurements in Earth's atmosphere or on ground and measurements in space by either in-situ dust detectors or by zodiacal cloud estimations. Radar and optical observations of meteors fall somewhere in between. All measurements have inherent uncertainties. Direct measurements of dust residues either in the atmosphere or in ice cores or deep sea sediments require assumptions on the ablation process during atmospheric entry. Meteor observations are biased towards faster objects and the conversion from measured velocity and brightness to the mass of the incoming particle is rather uncertain. Observations of the dust population in space (e.g. of the zodiacal cloud) need a simulation of the particle dynamics and of the flux densities near Earth. Direct measurements by in-situ impact detectors or by the analysis of retrieved hardware (e.g. impact craters on lunar material, analysis of retrieved space hardware from LDEF (Love and Brownlee., 1993)) or the Hubble Space Telescope (McDonnell et al., 2005) require the conversion of measured impact crater dimensions to the size of the impactor. In addition, for material from low Earth orbits impacts from natural meteoroids and man-made debris have to be distinguished. Previous estimates of the terrestrial mass accretion rate range from about 5–300 t per day (Plane, 2012). Space based measurements tend to indicate the higher values. From the analysis of retrieved LDEF samples Love and Brownlee (1993) calculate a mass influx of $110+/-55$ t per day for particles up to $10^{-7}$ kg in mass. Where this question is addressed the previous studies agree that for sub-m sized particles the maximum of the mass influx is in the size range of some tens to hundreds of microns.

Recent data from optical meteor observations and data from the impact analysis of retrieved solar arrays of the Hubble Space Telescope

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(HST) provide new information which allows us to re-asses the mass influx of Earth. For the small sizes up to masses of some grams the interplanetary meteoroid flux density model by Grün et al. (1985), is taken as reference and compared to the HST in-situ data and to optical meteor data from the double station cameras of the Canary Island Long Baseline Observatory (CILBO), (see Koschny et al., 2017, in this issue). These data and the model by Grün et al. (1985) are compared and connected to other flux density models which are based on different observation methods and are derived for different size ranges from mm to km. By doing so, a flux density model which exceeds a total mass range of 34 orders of magnitude can be obtained. For a proper comparison all models are adapted to each other and applied for a common reference altitude of 100 km. Size ranges where no reference model exists or where several models exist which are not in agreement have to be covered by an interpolation. The combined model allows to calculate the total mass influx of Earth as function of the upper mass limit considered. An estimate of uncertainties is provided as well.

## 2. Existing flux models

### 2.1. The model from Grün et al. (1985)

The model by Grün et al. (1985) covers the size range of the smallest objects ( $> 10^{-21}$ kg) and is mainly based on in-situ measurements by spacecraft, lunar micro crater studies and zodiacal light photometry. The flux model is a simple polynomial which is repeated in the equation below. It describes the flux per $m^2$ and second to one side of a randomly tumbling plate as a function of the mass *m* in gram. In this paper this model will be called the Grün model.

$$F(m) = (2.2\cdot 10^{3}\cdot m^{0.306} + 15)^{(-4.38)} + 1.3\cdot 10^{(-9)}\cdot (m + 10^{11}\cdot m^{2} + 10^{27}\cdot m^{4})^{(-0.36)} + 1.3\cdot 10^{16}\cdot (m + 106\cdot m^{2})^{(-0.85)} \quad (1)$$

No clear upper size limit is defined for this model but it is considered to be valid to at least $10^{-3}$ kg and can be extrapolated to larger size still. The model is applicable for interplanetary space at a distance of 1 Astronomical Unit (AU). If applied for the vicinity of Earth the gravitational attraction has to be considered which leads to an increase of the flux expressed by the gravitational enhancement factor, *G*.

The *G*-factor can be obtained (ECSS, 2008) from the formula $G = v^2/(v^2 - v_{esc}^2)$, where v is the meteoroid velocity and $v_{esc}$ the escape velocity. For an Earth altitude of 100 km, a corresponding escape velocity of 11.1 km/s and a constant meteoroid velocity, *v*, of 20 km/s a value of $G_{100} = 1.445$ is obtained for the gravitational flux enhancement. This value changes only by a few percent (to 1.40) if a realistic velocity distribution is used instead of a fixed velocity (Drolshagen and Kretschmer, 2015).

For comparison with other models the flux from the Grün model is extrapolated to a period of 1 year and to the surface area of Earth (calculated for an altitude of 100 km).

For the conversion of meteoroid masses to diameters a material density ρ of 2500 kg/$m^3$ and a spherical shape are assumed.

Fig. 1 shows the cumulative number of impacts on Earth as predicted by the Grün model for a period of 1 year.

### 2.2. The Model from Brown et al. (2002)

Brown et al. (2002) present the function $F_B(E)$ which describes the cumulative number of objects impacting the Earth per year as a function of their energy *E* given in the equivalent of kilotons TNT (1 kt TNT corresponds to $4.185\cdot 10^{12}$ J). This formula is derived from sensor data of fireballs that entered the Earth atmosphere and is based on objects with diameters between 1 m and 9 m. Therefore, it is only strictly valid in this range size. Nevertheless, for a first approximation

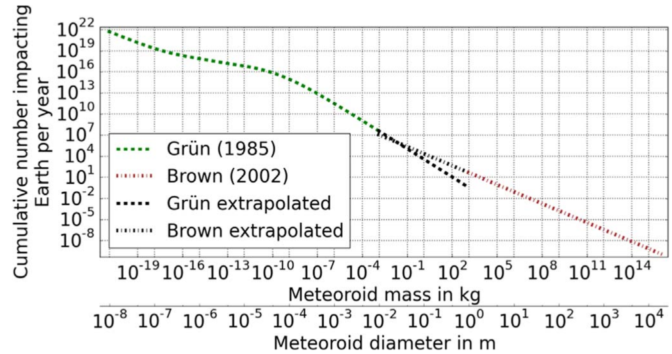


**Fig. 1.** Flux densities of the models by Grün et al. and by Brown et al. with extrapolations as function of mass and diameter.

of the flux density over the total size range it is extended towards larger events up to a size of 20 km. The flux density as function of energy is given by Brown et al. (2002).

$$F_B(E) = 3.7\cdot E^{-0.9} \quad (2)$$

For comparison with the other models the impact energy is converted to masses by again assuming a fixed velocity of 20 km/s. In this paper this model will be called the Brown model.

Fig. 1 shows the flux predictions of the Grün and Brown models in one plot together with tempted simple extrapolations of both to cover the full mass range. It can be seen that the flux curve from the Grün model has a steeper slope than the curve from the Brown model.

### 2.3. Interpolation

Simple linear extrapolations of the models already lead to a realistic looking intersection point and overall shape of the flux density curve. However, in order not to overstretch the validity of the original flux density models an interpolation is made as alternative.

The interpolation is done using a power law of the form of $F_{int} = a\cdot m^b$ which will create a straight line in the double logarithmic plot. Combining the flux value from the Grün model for $10^{-3}$ kg with the flux value from the Brown model for 1309 kg (the lower energy limit) gives for the interpolation function the expression: $F_{int}(m) = 5.59\cdot 10^{4}\cdot m^{(-0.993)}$. The resulting curve is included in Figs. 5, 7 and 10.

### 2.4. Initial Mass Calculations

To derive the total mass according to the flux density models the cumulative fluxes are changed into differential fluxes. Numerically this was done with mass intervals of 0.001 decades and by assigning the mean mass to each interval. Multiplication with the assigned mean mass gives the mass in each bin. The result is shown in Fig. 2. For better visibility the bin size here is reduced to two mass bins per decade.

According to these models a pronounced maximum of the mass influx to Earth is predicted for meteoroid sizes in the range 100 µ–

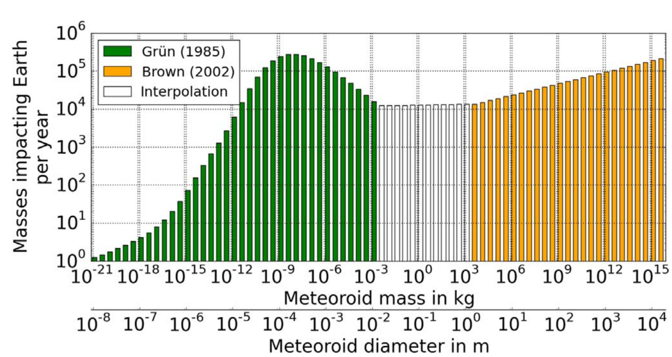


**Fig. 2.** The mass impacting Earth per year for each mass bin.