Mass accumulation of Earth from interplanetary dust, meteoroids, asteroids and comets

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The goal of this paper is to determine the mass that reaches the Earth as interplanetary material. For the large objects the flux model by Brown et al. (2002) was used which is valid for bodies greater than 1 m and is based on sensor data of fireballs that entered the Earth atmosphere. For the small sizes the flux model by Grün et al. (1985) was used, which describes the mass flux at 1 AU for meteoroids in the mass range 10^{-18} g to about 100 g. The Grün flux was converted to 100 km height by taking the Earth attraction into account and all units were adjusted to compare the model with the one by Brown. In a second step both models were combined by an interpolation, which lead to a flux model that covers 37 orders of magnitude in mass. Using recent measurements and alternative flux models the uncertainties of the obtained model was estimated. Recent measurements include in-situ impact data on retrieved space hardware and optical meteor data. Alternative flux models are e.g. a NASA model for large sizes that is an extrapolation of known Near-Earth Objects (NEOs) and a model by Halliday et al. (1996) which is based on optical measurements of fireballs. Up to a diameter of 1 km the total calculated mass influx is 54 tons per day.

1 Introduction

Every day, dust, meteoroids and sometimes larger objects from space hit the Earth. Sizes of these objects range from as small as 1 nm to meters or larger. The corresponding total mass range exceeds 30 orders of magnitude. Quantitative information on the flux of the objects comes from various sources. Information on the smallest objects is mainly obtained from the analysis of impact craters (e.g. on lunar samples), or on satellite hardware retrieved from space. From these in-situ measurements the mass range 10^{-21} kg up to 10^{3} kg can be covered. Optical and radar meteors provide information in the mass range 10^{11} kg to a few kilograms. Bright fireballs extend the mass range up to sizes of 10 – 20 m (10^{6} – 10^{7} kg). Even larger objects called asteroids impact Earth in intervals of several hundred, thousands or more years. Their impact rate can be estimated from the crater record on Earth and from simulations of the near-Earth asteroids population. The present paper studies the mass influx on Earth for the complete size range and addresses sources of information and uncertainties.

2 Basic models

Grün Model

The model by Grün et al. (1985) covers the size range of the smallest objects (10^{-21} – 10^{3} kg) and is based on spacecraft measurements, lunar micro crater studies and zodiacal light photometry. The model is given in Formula (1) which describes the flux per m^2 and second to one side of a randomly tumbling plate in dependence of the mass m in gram.

$$F(m) = (2.2\cdot10^{3} \cdot m^{0.306} + 15)^{(-4.38)} + 1.3 \cdot 10^{(-9)} \cdot (m + 10^{11} \cdot m^{2} + 10^{27} \cdot m^{4})^{(-0.36)} + 1.3 \cdot 10^{16} \cdot (m + 106 \cdot m^{2})^{(-0.85)} \quad (1)$$

Since Grün does not make a clear statement about the concrete size range in which the model is valid, the mentioned range was chosen for first calculations. Moreover, the model describes the meteoroid flux at 1 AU, the distance between Earth and Sun in our solar system. Therefore it does not consider the Factor G, which describes the effects of gravitation of the Earth which attracts the meteoroids and therefore increases the number of impacting objects on the Earth.

To calculate this gravitational enhancement factor G a constant velocity v of 20 $\frac{\text{km}}{\text{s}}$ is assumed for impacting meteoroids. Then, Formula (2) (ECSS, 2008) is used to calculate the escape velocity v_{esc} which describes the velocity needed to escape from the Earth's gravitational attraction for a given altitude.

$$v_{esc} = \sqrt{2 \cdot \frac{\mu}{r+H}} \quad (2)$$

It depends on the distance between the altitude of the meteoroid and Earth's center r+H, in which r describes the mean Earth's radius that is equal to 6371 km and H is the altitude above Earth's surface. In this case H is chosen to be 100 km, since this is the altitude in which meteoroids start to become visible meteors. Furthermore it depends on the constant $\mu = 3.986 \cdot 10^{5}\,\frac{\text{km}^3}{\text{s}^2}$, which is the product of the Earth's mass and the gravitation constant. Using the given values v_{esc} is calculated to be

$11.099\ \frac{\text{km}}{\text{s}}$ for H = 100 km. This result is now used to calculate the G-Factor using Formula (3) (ECSS, 2008).

$$G = \frac{v^2}{v^2 - v_{esc}^2} \qquad (3)$$

This calculation yields a factor of 1.445 by which the formula given by Grün has to be multiplied.

Since the function of Grün describes the flux per m^2 and second while we need for further calculations the flux per year and Earth's surface, the Grün model is scaled. It should be mentioned, that in the present study, the Earth's surface is assumed to be at 100 km height, since the meteors start to evaporate at this height and do not reach the Earth's surface as a meteor.

The time scaling of the Grün model is done by multiplying $F(m)$ with a factor of 31536000 s, which is the number of seconds, that equates to one year. Afterwards the Earth's surface S in 100 km height is calculated using Formula (4), where r is again the mean Earth's radius and H the altitude of 100 km.

$$S = 4 \cdot \pi \cdot (r + H)^2 \qquad (4)$$

The Earth's surface in 100 km height results in $5.26202 \cdot 10^{14}$ m^2. This factor is now multiplied to $F(m)$, to get the flux per year and Earth surface. Equation (5) shows the modified formula by Grün.

$$\begin{aligned} F'(m) &= 1.445 \cdot (31536000 \cdot 5.26202 \cdot 10^{14}) \\ &\cdot ((2.2 \cdot 10^3 \cdot m^{0.306} + 15)^{(-4.38)} + 1.3 \cdot 10^{(-9)} \\ &\cdot (m + 10^{11} \cdot m^2 + 10^{27} \cdot m^4)^{(-0.36)} + 1.3 \cdot 10^{16} \\ &\cdot (m + 106 \cdot m^2)^{(-0.85)}) \end{aligned} \qquad (5)$$

This expression gives the predicted Grün model flux per year to the complete Earth at 100 km altitude.

Using this formula the flux according to Grün was plotted in function of mass and diameter as shown in *Figure 1*.

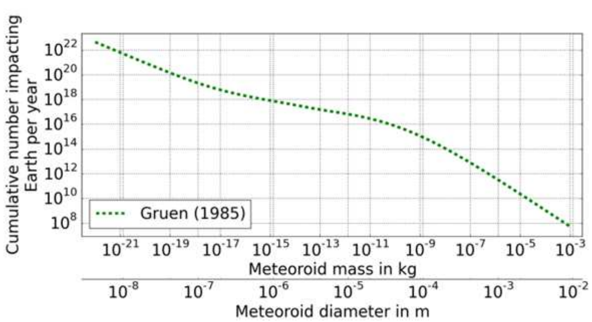

Figure 1 – Flux by Grün in function of mass and diameter.

Brown model

The next step was to plot the function $F_B(E)$ by Brown et al. (2002), which describes the cumulative number of meteoroids impacting the Earth per year in dependence of their energy E, given in kilotons. This formula is derived from satellite sensor data of fireballs that entered the Earth atmosphere and is based on objects with diameters between 1 and 9 m so only in this size range it is strictly valid. Nevertheless, for a first approach of the flux over the total size range it is extended toward larger events up to a size of 20 km diameter. The flux is given in Equation (6).

$$F_B(E) = 3.7\, E^{-0.9} \quad (6)$$

Converting kinetic energy to mass one obtains:

$$F_B(m) = 3.7\, \left(\frac{mv^2}{2 \cdot 4.185 \cdot 10^{12}}\right)^{-0.9} \quad (7)$$

Using this formula the flux according to Brown was plotted in function of mass and diameter as shown in *Figure 2*.

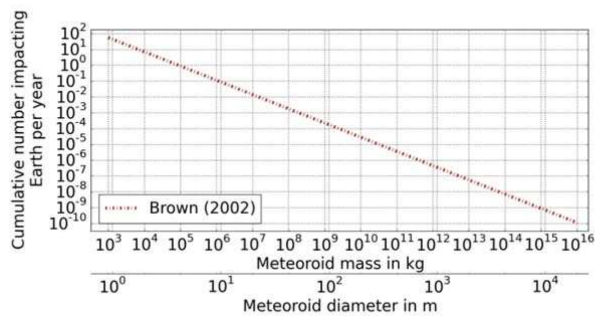

Figure 2 – Flux by Brown in function of mass and diameter.

The next step was to plot the functions of Grün and Brown together in one plot and to extrapolate both to see whether they meet in a reasonable way, or if they have to be interpolated. This is shown in *Figure 3*.

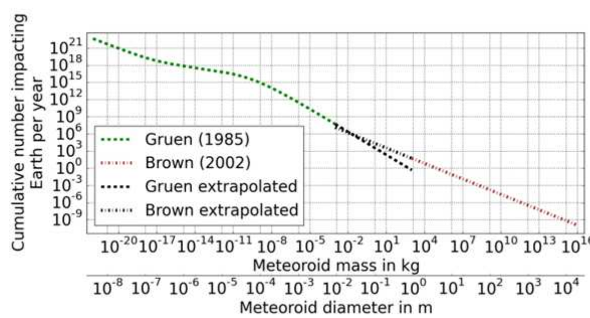

Figure 3 – The flux by Grün and Brown, extrapolated, as a function of mass and diameter.

It can be seen, that their extensions already seem to meet in a pretty acceptable way, since there are no big deviations between both slopes. Anyway an interpolation is made, in order not to overstretch the validity of the original flux models.

Interpolation

The interpolation is done using a power law, which will create a straight line in the double logarithmic plot, which is supposed to connect both slopes pretty well.

Fitting a power law of the form $F_{int} = a \cdot m^b$ to the start- and end value of the models from Grün and Brown, the following expression for the interpolated flux is obtained:

$$F_{int}(m) = 5.59 \cdot 10^4 \cdot m^{(-0.993)} \qquad (8)$$

As a last step F_{int} is used to replace the extensions of Grün and Brown as shown in *Figure 4*.

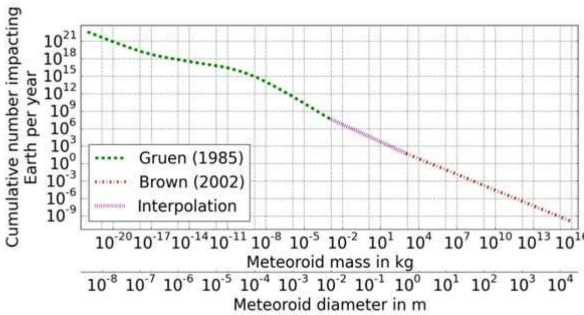

Figure 4 – Interpolation using a power law between Grün and Brown in function of mass and diameter.

Mass calculation

To derive the total mass according to the flux models shown in *Figure 4*, it is necessary to know how many particles there are in each mass interval. For this, the cumulative plot is changed into a differential plot. This is done by subtracting the cumulative flux of the next higher mass, from the flux of the mass that is considered. Afterwards, the derived flux is assigned to the mean mass value of that interval. These steps are repeated for all masses.

Next, the total mass in each bin is calculated. Therefore the flux is multiplied by its assigned mass. By this the total mass impacting Earth per year for each mass bin is derived, as shown in *Figure 5* for two mass intervals per mass decade.

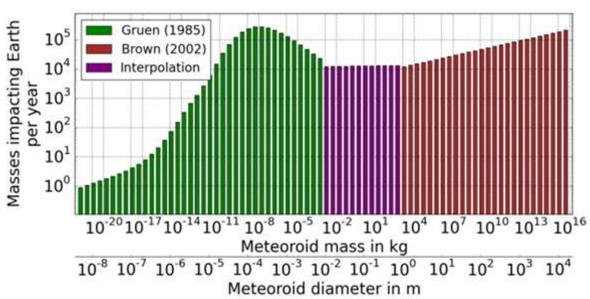

Figure 5 – The mass impacting Earth per year for each mass bin.

The last step is to add all calculated impacting masses together. By this a total impacting mass of $21.9 \cdot 10^3$ t per year and 60 t per day is derived. The upper mass limit considered here is 10^{16} kg, corresponding to a diameter of 20 km for a material density of 2.5 $\frac{\mathrm{g}}{\mathrm{cm}^3}$.

In the following the accuracy of the various models is studied by comparison with available data.

3 Assessment of models

Comparison of Grün model with observations

Hubble Solar Array impact data

The first model to be studied is the one by Grün et al.. The data from the retrieved Hubble Space Telescope Solar Arrays were analyzed (UnispaceKent, 2002). The solar arrays were hit by small meteoroids in space (in 600 km altitude), which created small craters. These craters gave information about the existing flux in this height. The size range of striking meteoroids was between 259.5 and 0.6 micrometers. The used data were taken from *Table 1* of Appendix 1 of UnispaceKent (2002). In this table an impact velocity of 21.4 $\frac{\mathrm{km}}{\mathrm{s}}$ and a density of 2.5 $\frac{\mathrm{g}}{\mathrm{cm}^3}$ for the meteoroids were assumed.

The flux has to be adjusted, so that the same assumptions are made as for the flux by Grün. Therefore several effects have to be considered as the G-Factor, the Earth shielding factor (the solar arrays could not be hit from all around) and the fact that the Hubble Space Telescope is moving in space. These effects lead to a total correction factor of 1.44 by which the flux has to be multiplied. The in-situ impact data from the HST solar arrays agree quite well with the model from Grün. The fluxes are slightly above the model predictions but still within the model uncertainty.

CILBO meteor data

Next the model by Grün is compared to the flux model derived using the CILBO double station camera. A precise description, how this flux was derived is given in these proceeding by Kretschmer et al. (2015). The comparison can be seen in *Figure 6*.

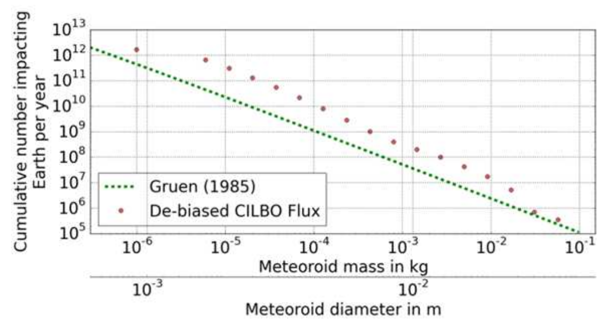

Figure 6 – The flux derived by the CILBO data compared to the Grün model.

The slope of the flux according to the meteor data of the CILBO double station agrees pretty well with the slope of the flux by Grün. However, it also lies slightly above the Grün flux. Therefore, the flux by Grün might underestimate the flux in this size range but overall it seems to be a well validated model and will be used for the further mass calculation.

Check of the interpolation

Halliday fireball data

Next the interpolation is checked. The extrapolations of Grün and Brown, as well as the interpolation, seem to connect the ends of Grün and Brown in a suitable way. Therefore, a third model (from Halliday et al., 1996) is plotted in the same plot, to see with which connection it agrees best. This model is based on fireball observations.

The formula for the flux by Halliday is given in Equations (9.1) and (9.2), where the flux is per year and 10^6 km^2 and the mass has to be passed in gram to the function.

For masses between 0.1 and 2.4 kg:

$$N(m) = m^{-0.48} \cdot 10^{3.3} \quad (9.1)$$

For masses between 2.4 and 12 kg:

$$N(m) = m^{-1.06} \cdot 10^{5.26} \quad (9.2)$$

After multiplying the flux by a factor of 526.202 to get it per Earth surface, it is plotted in the same plot, as the other two extrapolations, as shown in *Figure 7*.

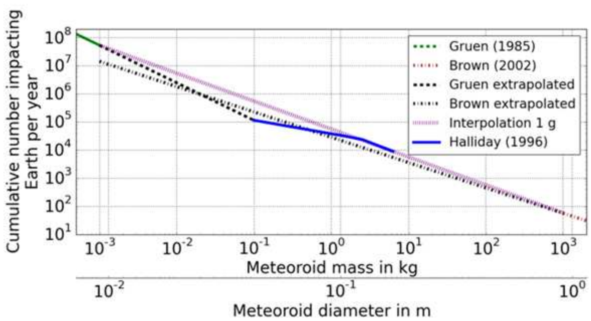

Figure 7 – The three possible interpolations between Grün and Brown.

It can be seen, that for large masses the flux by Halliday agrees very well with the interpolation, but for smaller masses the flux is severely lower and therefore deviates from the interpolation. However, at the lower end of its domain it intersects precisely the extended flux from Grün.

Since the integrated time-area product is less than one full day of global coverage the Halliday results have considerable uncertainties. This is why a second model for this mass range is considered to check the accuracy of the interpolation.

Suggs lunar impact flashes

The model is available as single data points contained in the paper of Suggs et al. (2014) and is based on the observation of lunar impact flashes. A cumulative plot of their data compared to the previous models can be seen in *Figure 8*.

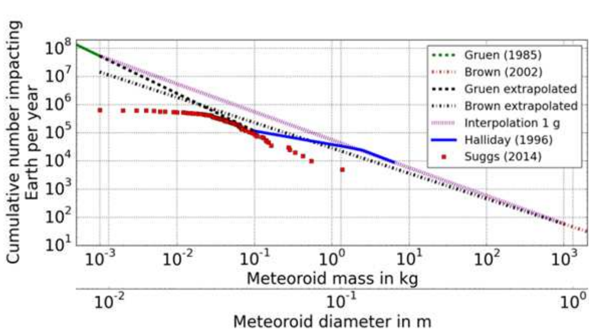

Figure 8 – Data of Suggs compared to the previous models.

For masses larger than approximately 30 g the curve fits perfectly the slope of the extended flux model by Grün. For smaller particles it appears that not all meteors were detected, since there is a decrease in the flux. Moreover, there is only a small amount of data points for large meteors, which leads to random errors. To get significant results a minimal number of 10 events should be contained per mass bin, this is the case for 140 g meteoroids. Therefore, a new plot is created, in which only particles in the mass range of 30 – 140 g are plotted, since these are the most reliable data points. Moreover, the errors of the calculated masses are considered. These are due to uncertainties of the luminous efficiency, which value lies somewhere between $5\cdot10^{-4}$ and $5\cdot10^{-3}$. Therefore the corresponding masses represent the upper and lower error estimation. As mean luminous efficiency a value of $1.5\cdot10^{-3}e^{\frac{-9.3^2}{v^2}}$ was chosen. This is shown in *Figure 9*.

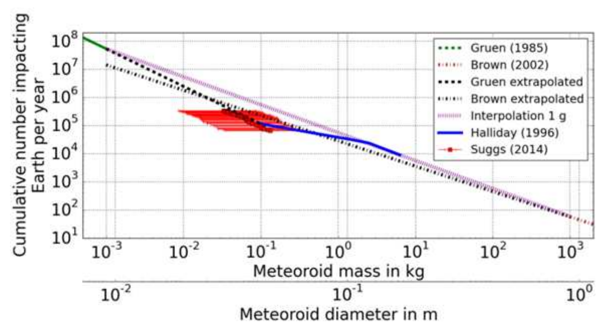

Figure 9 – The most reliable data points of Suggs, including the errors, compared to the previous models.

This plot points towards two findings. The first is, as already mentioned, that the interpolation between the models by Grün and Brown seems to be an upper limit for the flux, since all compared models lie below the predicted flux. The second is that the Grün model seems to be valid for even larger particles than assumed so far. Halliday does connect perfectly with the extrapolation of the flux by Grün and also Suggs does fit this curve very well. Therefore, the Grün model is now assumed to be valid for particles up to at least 100 g, as also stated in the ECCS.

The next step is to calculate a new interpolation between the fluxes by Grün and Brown, because none of the compared models is precise enough to be assumed to be completely correct and therefore an alternative connection between Brown and Grün should be found.

The new interpolation is connected to the flux by Grün at 100 g and gives:

$$F_{int100}(m) = 1.7\cdot10^4 \cdot m^{-0.827} \quad (10)$$

In *Figure 10* all models and connections between Grün and Brown can be seen.

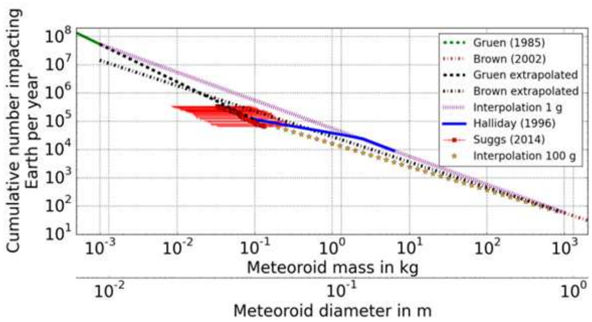

Figure 10 – All considered connections between Grün and Brown.

In *Figure 10* it can be seen, that only the data by Suggs (for objects larger than 100 g) seems to lie slightly below the new interpolation. This might be due to the fact, that Suggs assumes a meteoroid velocity of 24 $\frac{\text{km}}{\text{s}}$ in free space. Therefore the calculated masses are smaller than the one calculated in all other models assuming a velocity of 20 $\frac{\text{km}}{\text{s}}$. By adjusting this discrepancy one would expect that the data points by Suggs would shift towards larger masses and therefore lie in the area between both interpolations.

The new interpolation seems to be a lower limit for the flux in this mass range. However, the extrapolation by Brown seems to be a pretty good alternative to connect with Grün, since it lies central between both interpolations and also crosses the flux by Halliday quite centric. Therefore this extrapolation is used to calculate the total mass.

Flux models for larger objects

Brown stated in a recent paper (Brown et al., 2015) that his flux estimation from 2002 might underestimate the number of impactors larger 10 m. Other models for larger sizes include those from Silber et al. (2009) and NASA (2003).

Those models were assessed as well and considered for the total mass estimation.

4 Mass calculation

The total mass accumulation of Earth depends on the maximum size of infalling objects considered. For a meaningful mass estimation an upper size limit has to be introduced. In this work that limit has been set at a diameter of 1 km. Objects of this size or larger are expected to impact Earth only about every 700000 years. Most of such objects that come closer to Earth than 45 million km (near-Earth objects) are already known and an impact can be excluded.

According to these models, the total mass coming down per day in the mass range of 10^{-21} – 10^{12} kg is 53.9 tons.

5 Conclusion and future work

We studied the mass influx on Earth per day for the mass range 10^{-21} – 10^{12} kg. In-situ impact data, meteor data, lunar impact flashes and asteroid flux models were considered. Up to a diameter of 1 km the calculated mass influx is 54 tons per day. The maximum mass influx comes from sizes around 10^{-11} – 10^{-5} and from the largest sizes. The mass influx in the size range covered by meteors and fireballs has still considerable uncertainties and there are indications for a reduced mass influx in this size range. It is unclear whether there is a physical reason for this apparent minimum in the mass influx. Further analysis of ongoing meteor and fireball data for Earth and the Moon should provide more insight.

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The author, *Sandra Drolshagen*, during her lecture (Photo by *Axel Haas*).