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Mass distribution of interstellar and interplanetary particles

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Abstract. The proportion of possible interstellar particles to interplanetary ones, observed with different techniques, was found to be much higher for small particles obtained from high power radars and cosmic dust detectors in comparison with results of photographic observations from the IAU Meteor Data Center in the range of large meteoroid particles. This contradiction may be explained by different mass distributions of interstellar and interplanetary particles. Moreover, the break in the mass distribution function in the mass range of $10^{-10} - 10^{-11}$ kg corresponds to the mass range limit of inclusions of interstellar origin in meteorites. This coincidently shows as a possible explanation of the break in the mass distribution function caused by different physical processes leading to populations of interstellar and interplanetary particles.

Key words: ISM: dust – interplanetary medium – meteors, meteoroids

1. Introduction

The problem of the contribution of interstellar particles to the Solar System meteoroid population was a serious one from the very beginning and in spite of great progress in the development of observational techniques it still remains open. This is probably the main reason why so many authors deal with it.

In view of the present controversy, it is interesting to note that the first Catalogue of bolides by Hoffmeister from 1925, as well as the results of Öpik's Arizona meteor expedition from 1931 - 33, supported the leading opinion of the first half of the last century that the majority (up to 80 %) of meteors are of interstellar origin. A substantially different opinion was given by the Harvard photographic meteor program by means of Super-Schmidt cameras, published by Jacchia and Whipple (1961) allowing a much more precise determination of bolide velocities. The results gave so few hyperbolic velocities that they raised the question of whether interstellar meteors existed at all. Moreover Whipple (1940) has shown that the main stream of "interstellar meteors" in Hoffmeister's Catalogue is associated with the Comet Encke, the comet with the shortest period of revolution and aphelion in the asteroidal belt.

This history may be in some way instructive for the present time constructions of interstellar streams of faint particles, without giving reliable results on the velocity determination of those particles.

The present work is an attempt to give a possible explanation of controversial results on possible interstellar fluxes in the range of faint particles, accepting them (as given in Tab.1) under the assumption that the particle velocities considered as interstellar (especially for high fluxes) will be confirmed by more precise observations.

Table 1. Interstellar particle flux data

Source	Methods of observation	Detected flux Φ $(m^{-2}s^{-1})$	Observed mass range Δm (kg)	No of values
Wehry, Mann 1999a	space detectors Ulysses	$(1.4 - 8.5)$ x 10^{-4}	1 x 10^{-17} − 1 x 10^{-18}	2
Wehry, Mann 1999b	space detestors Ulysses	1.5 x 10^{-4}	1 x 10^{-15}	1
Baguhl et al. 1996	space det. Ulysses and Galileo	1 x 10^{-4}	6 x 10^{-16}	1
Grün 1994	space detectors Ulysses	1.5 x 10^{-4}	3.2 x 10^{-16}	1
Grün 1997	space detectors Ulysses	1.5 x 10^{-4}	1 x 10^{-17}	1
Grün 2000	space detectors Ulysses	3 x 10^{-4} − 8 x 10^{-6}	2 x 10^{-18} − 2.1 x 10^{-14}	12
Krüger et al. 1999	space det. Ulysses 1993 - 95	7 x 10^{-5}	3 x 10^{-16}	1
Landgraf et al.2000	space det. Ulysses and Galileo	1.5 x 10^{-4} − 1.5 x 10^{-6}	1 x 10^{-19} − 1 x 10^{-14}	14
Landgraf et al. 1998	space det. Ulysses and Galileo	2.2 x 10^{-4} − 4 x 10^{-7}	1 x 10^{-16} − 3.2 x 10^{-13}	18
Landgraf et al. 2000	radar, AMOR	2 x 10^{-8}	3 x 10^{-10}	1
Mathews et al. 1998	UHF radar, Arecibo	5 x 10^{-8}	1 x 10^{-12} − 1 x 10^{-9}	1
Baggaley 1998 a, b	radar, AMOR	4 x 10^{-9}	3 x 10^{-10} − 1 x 10^{-7}	1
Taylor et al. 1994	radar, AMOR	4.2 x 10^{-9}	1 x 10^{-9}	1
Taylor et al. 1996	radar, AMOR	7 x 10^{-9}	1 x 10^{-9}	1
Hawkes, Woodworth 1997	television and radar	6 x 10^{-11}	1 x 10^{-8}	1
Hawkes, Woodworth 1998	television observation	1.25 x 10^{-11}	5 x 10^{-8}	1
Lindblad 2003	radar IAU MDC	2 x 10^{-14}	5 x 10^{-6}	1
Ceplecha 1964	photographic	8 x 10^{-17}	1 x 10^{-4} − 1 x 10^{0}	1
Hajdukova 1993, 1994	photographic IAU MDC	8 x 10^{-18}	1 x 10^{-4} − 1 x 10^{0}	1
Hajdukova, Paulech 2002	phot. IAU MDC updated	1 x 10^{-18}	1 x 10^{-4} − 1 x 10^{0}	1

2. Controversial results on hyperbolic and interstellar particles from observations by different techniques

Significant contributions have been made in the last decade to the controversial problem of hyperbolic or interstellar particles by Earth-based or space-born observations. In particular the reports on high-power radar results from the Advanced Meteor Orbit Radar - AMOR in New Zealand deal with highly hyperbolic orbits, or simply with interstellar meteors in the mass range of $10^{-7} - 10^{-10}$ kg (Baggaley 1993, 1995, 1999, Taylor et al. 1994, 1996, Landgraf et al. 2000). In addition the space-born observations, mainly from the Ulysses and Galileo spacecrafts, report on the detected interstellar particles, here from the mass range of $10^{-11} - 10^{-19}$ kg, in some cases from even broader mass intervals (Baguhl et al. 1994, 1996, Grün 1994, 2000, Krüger et al. 1999, Landgraf et al. 2000, Mann 1996, Wehry and Mann 1999a, 1999b).

As far, as the AMOR results speak on about 1 percent of extremely hyperbolic orbits, with meteor geocentric velocities of hundreds of km s^{-1}, the space-born observations deal with a predominance of interstellar particles. However, in comparison with photographic observations, the velocity determination by radar is less precise and from space born observations indirect.

All these results contradict, in some way, the most precise classical photographic observations as well as the broader photographic data included in the IAU Meteor Data Center (MDC) Catalogue (Lindblad 2001), with very few meteors slightly exceeding the hyperbolic velocity limit and with the possible contribution of interstellar meteors less than 2.5 x 10^{-4} of the total amount, in the mass range of large particles corresponding to $10^{-4} - 10^{1}$ kg (Hajdukova 1994, Hajdukova and Paulech 2002). Hawkes and Woodworth (1997a, 1997b), Hawkes et al. (1999), by the video detector technique obtained a contribution of hyperbolic meteors at the level of 1 - 2 percent of the mass range between $10^{-4} - 10^{-9}$ kg. Mathews et al. (1999), using an ultra high frequency (UHF) radar technique, detected a small level of hyperbolic particles in the mass range of $10^{-9} - 10^{-12}$ kg reaching the upper mass limit of space-born particles. A survey of the main results of the reported interstellar fluxes is summarised in Table 1 in order from the highest to the lowest fluxes observed.

The question arising from the above, in some aspects controversial results, is whether it is possible to bring all the above mentioned data to a common view upon the real contribution of interstellar particles to the interplanetary material along the broad scale of mass, exceeding 20 orders of magnitude, or should we search for errors in the results or methods leading to them.

3. The interstellar particle flux over 20 orders of mass scale and the mass distribution function of interstellar particles

¿From the position of the whole Solar System in the Galaxy and the studies of processes in the interstellar medium it is clear that the Solar System is not an isolated system; its interaction with the interstellar medium should lead to the presence of interstellar particles. The substantial question, how many interstellar particles we should register in comparison with those belonging to our interplanetary cloud, has led to many searches, the main results of which are presented in Tab.1. Fig.1 is constructed from these results. In some cases a number of values are given by the authors along the mass scale; to recognize them, Fig.2 shows the data from different authors in the mass range of their superposition ($m < 10^{-11}$ kg). Hence the combination of values in Tab.1 and Fig.2 give the full identification of data, with their summary in Fig.1. The heavy line represents a second order polynomial of interstellar fluxes, over the whole mass scale from all given data. The fainter lines represent the second order polynomial for the interplanetary flux data given by Divine et al. (1993)

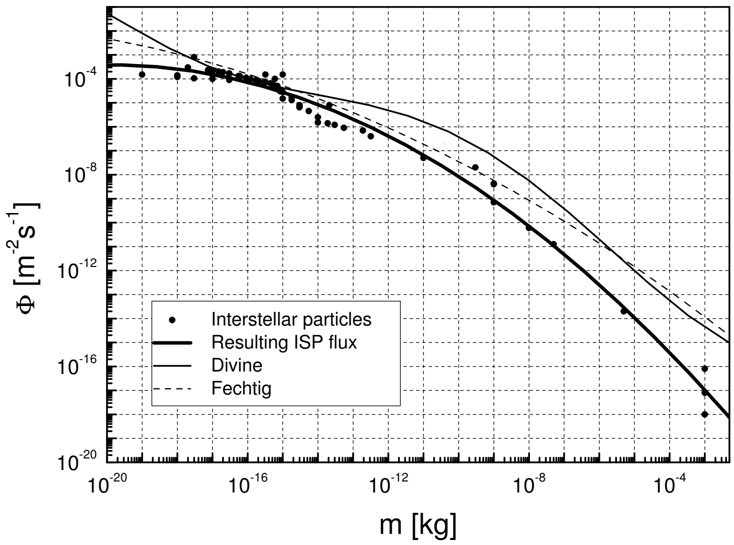

Figure 1. Flux of interstellar particles along the mass range (heavy line), from observations by different techniques, listed in Tab.1 (dots), in comparison with the flux of interplanetary particles according to Divine (solid line) and Fechtig (dashed line).

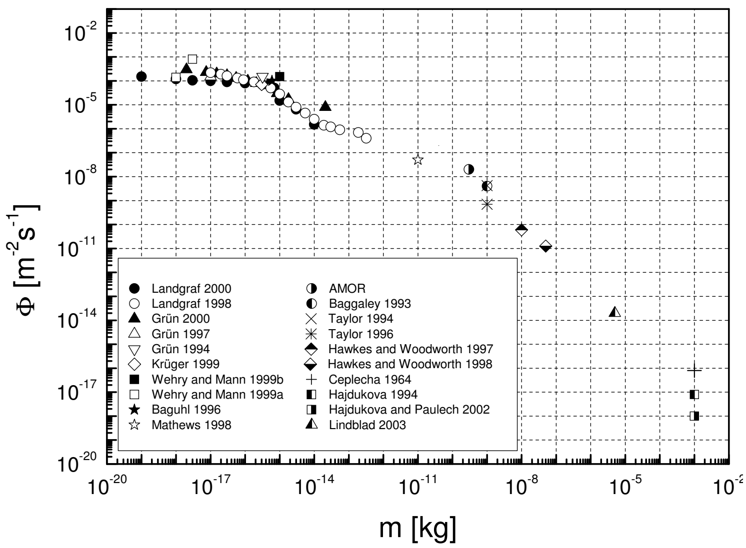

Figure 2. Interstellar particle flux estimates by different authors along the mass range.

(solid line) and Fechtig (1973) (dashed line) constructed from much broader results and showing that there is little difference in the mass distribution of interplanetary particles between older and new data, except for the range of the faintest particles with the highest scatter in data. In his original paper Fechtig (1973) interprets the data with a sharp break in the mass distribution in the position between 10^{-10} and 10^{-11} kg. Divine et al. (1993) prefer a smooth change in their curve following the experimental data, but anyway a substantial change in the integrated mass distribution index s, defined by relation $N = k.m^{(s-1)}$, (where N is the cumulative number of particles, m the mass limit and k the constant expressing the mass interval) is also in the mass interval between $10^{-10} - 10^{-11}$ kg, at which s changes from $s > 2$ for larger particles to $s < 2$ for fainter ones. The critical value of $s = 2$ means that the contribution of the particle flux is one order for one order of particle mass.

As it is seen from Fig.1, the flux of interstellar particles is more than 2 orders of magnitude lower than the flux of interplanetary ones in the mass range of large particles, but it increases towards the fainter particles. Their mass distribution is steeper, however the critical value of $s_{is} = 2$ corresponds to almost the same mass interval, between $10^{-10} - 10^{-11}$ kg.

The interplanetary dust distributions by Divine et al. (1993) and Fechtig (1973) differ slightly in the range of our scope of interstellar particle data ($10^{-19} - 10^{-1} kg$) but they do not change the critical value of the break of both distributions. The root mean square lines of these distributions give critical values of $m_{crit.Divine} = 5$ x 10^{-11} kg and $m_{crit.Fechtig} = 8$ x 10^{-11} kg with a small uncertainty factor of 2. The interstellar particle data yield $m_{crit.is} = 5$ x 10^{-11} kg but with an uncertainty factor of 10. The observed breaks are not yet satisfactorily explained, but they divide the particle fluxes for each distribution into two branches with different mass indices s, which are given in Tab.2.

It is seen from Fig.1 that the mass index changes continuously, increasing towards higher masses. The data implies 3 distinct mass intervals, however a substantial change of s values is between $10^{-11} - 10^{-10}$ kg as a break in the interstellar flux distribution as a square root means for the two branches of data.

It is necessary to add some comments to the data, from which the above mass indices for the interstellar data have been derived:

First of all, it should be mentioned that all data announced as "interstellar" are called so by the authors of quoted results as they correspond either to hyperbolic orbits (when derived from orbital characteristics), or to hyperbolic velocities, or assumed hyperbolic velocities (especially data from space-born detectors).

The values of fluxes Φ for $m \geq 10^{-11}$ kg are related to the flux Φ_{all} given by the Divine model as a proportion of the hyperbolic particles to all observed particles in a particular observation. Naturally, the hyperbolic orbits, or hyperbolic velocities do not mean necessarily interstellar particles, they rather represent the upper limit of them. (For explanation of differences see Hajdukova 1994.)

The fluxes of space observations, represented by dots in Fig.1 and separately for different observations identified in Fig.2, are given directly by the authors of quoted papers for $m < 10^{-11}$ kg including one value (upper limit) for $m = 2$ x 10^{-8} kg from AMOR (Landgraf et al. 2000) also with a given flux value. The data from the Ulysses and Galileo space probes, especially in the mass range between $10^{-15} - 10^{-17}$ kg, shows that interstellar particles dominate in this mass range over interplanetary ones, representing more than 50 percent of all observed particles. Baguhl et al. (1996) in this mass range of $m < 10^{-17}$ kg place "the dropoff value of interstellar dust particles that cannot be explained by the sensor treshold". They explain it by defocusing Lorentz forces, which kept the smaller interstellar particles out of the heliosphere.

How reliable are the results in Fig.1? It should be mentioned that neither the mass, nor the velocity of particles is measured directly in space detectors. These quantities are derived mainly from particle charge, orientation angle and the position of detectors, which were calibrated for the mass range of $10^{-9} - 10^{-19} kg$ and velocity range from $2 - 70$ km s^{-1} with mean errors of a factor of 2 for velocity and a factor of 10 for mass (Krüger et al. 1999). The errors in the measured flux correspond to a factor of 1.5 at 10^{-14} kg and they are smaller for smaller masses (Landgraf et al. 2000). Naturally, these uncertainties (especially in mass) can shift the plotted values for interstellar particles to the population of interplanetary ones, meeting the Divine model curve in the range of small particles and hence substantially lower the proportion of interstellar particle contribution. The authors argue for their interstellar origin using three criteria: their orientation (opposite to interplanetary), a high impact speed and independence on the ecliptic latitude (Frisch et al. 1999, Krüger et al. 1999). The uncertainty of the flux values for interstellar particles with $m \geq 10^{-10}$ kg is inversely proportional to the number of observed particles (as $\Delta N \sim \sqrt{N}$), hence, the highest uncertainty is from the most powerful equipment and precise velocity determination of Arecibo radar but deduced from 1 hyperbolic case from the 32 observed. For the most reliable values we can consider the values derived from the IAU MDC 4581 photographic meteors.

Table 2. Mass indices for interstellar particles

mass index $s \pm \Delta s$	mass interval Δm
1.35 ± 0.15	$10^{-19} - 10^{-15}$ kg
1.75 ± 0.10	$10^{-15} - 10^{-11}$ kg
2.40 ± 0.05	$10^{-11} - 10^{-3}$ kg

4. Interstellar meteors from IAU MDC catalogues

The database of the most recent version of the IAU Meteor Data Center contains 4581 photographic meteor orbits and 62 906 radar orbits (Lindblad 2001, Lindblad et al. 2001). Of these 527 photographic orbits (11.5%) and 1875 radar orbits (3%) are hyperbolic, with $e > 1$. As it was shown earlier (Hajdukova 1994) and tested on the Perseid shower photographic meteors recently (Hajdukova and Paulech 2002) the vast majority of the hyperbolic orbits are a consequence of measurement errors in the determination of a meteor velocity. Further analysis shows that the gaussian distribution of values of heliocentric velocities causes hyperbolic excesses. An example of such gaussian distribution around the mean value $v_{HPer} = 41.7$ km s^{-1} is given in Fig.3. The number of hyperbolic meteors found within meteor showers increases with the velocity approaching the hyperbolic limit of the particular shower. The results of tests made for the data from 5 meteor showers from the MDC photographic catalogues are given in Fig.4. The somewhat higher numbers of hyperbolic orbits with parameters belonging to the Orionid shower may be explained by a larger spread in their radiant distribution, contributing to larger elongation differences of the radiant position from the apex and hence implying larger errors. Anyway, there is no doubt that almost all of 257 hyperbolic orbits (from the total of 976 investigated

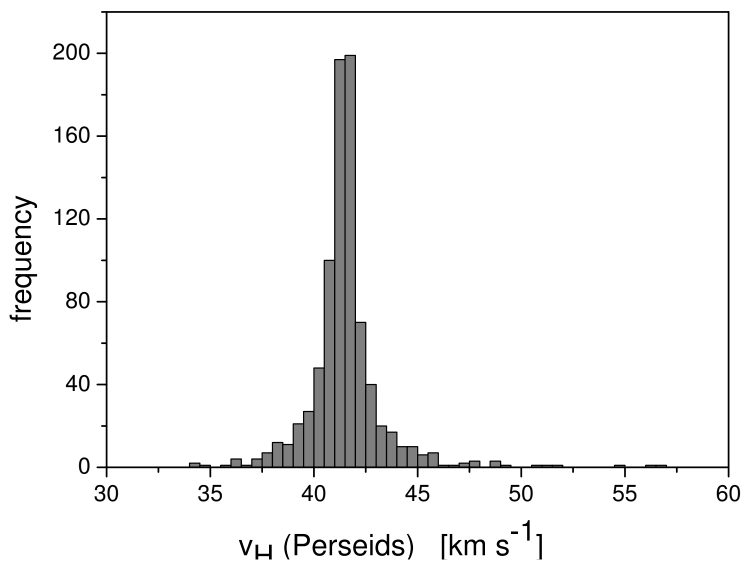

Figure 3. Frequency distribution of heliocentric velocities v_H of 835 Perseids in the IAU MDC photographic data, 224 of which exceed the hyperbolic limit $v_H = 41.70$ km s^{-1} for the Perseid shower.

shower meteors) with other parameters belonging to meteor showers (in Fig.4) (except 16 Perseids and 2 Orionids with $v_H > 46.6$ km s^{-1}) are consequences of measurement errors. Meteors with velocities over the limit $v_H = 46.6$ km s^{-1}, deduced from the radial velocities of close stars (Hajdukova 1994) as an expected velocity of interstellar meteors, should be examined individually, however this doesn't mean that they are necessarily interstellar. Applying these results to all 527 hyperbolic orbits among the 4581 photographic orbits in IAU MDC, 59 of which exceed $v_H = 46.6$ km s^{-1}, we may obtain the upper limit of interstellar meteors as $N_{is}/N_{all} = 0.013$. As it was shown from the analysis of individual cases the real number of interstellar orbits is at least 1 order of magnitude less (Hajdukova 1994) supporting the data in Tab.1.

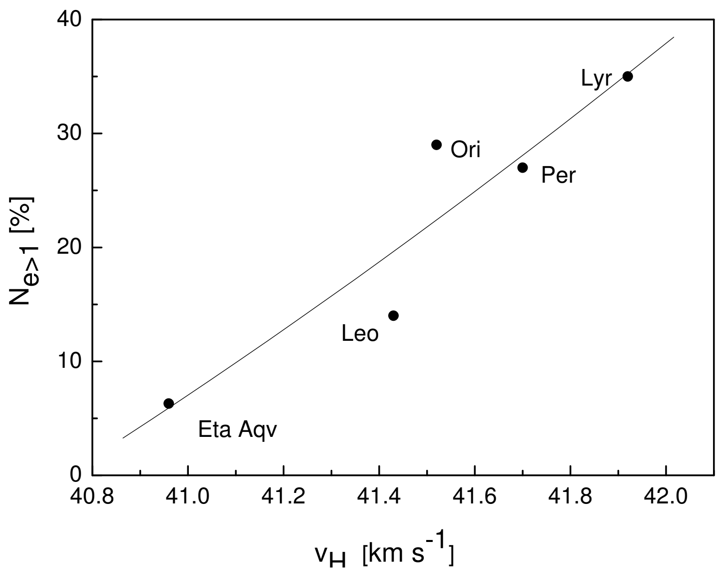

Figure 4. The dependence of the contribution of hyperbolic meteor orbits in the IAU MDC photographic data on the mean heliocentric velocity of particular meteor showers.

The radar data in general is of lower precision, however the used value here is taken from the most precise Harvard and Havana radio program data on approx. 40 000 meteors, and the value represents the upper limit of hyperbolic orbits. The well defined resulting curve gives a satisfactory reliability of the deduced fluxes and mass indices for the interstellar meteors in this broad mass range. The question remains what the reason is of the change of the flux distribution along the mass scale and why it substantially changes at about $10^{-10} - 10^{-11}$ kg.

5. Discussion of differences in interplanetary and interstellar mass vs. flux distribution

The break in values of the mass index of the interplanetary particles between $10^{-11} - 10^{-10}$ kg can be found in many observations, the earlier of them summarized by Fechtig (1973) indicating a sharp break at about 10^{-10} kg. The model of Divine et al. (1993) indicates a break in the interval $10^{-10} - 10^{-11}$ kg. It can scarcely be by chance that the interstellar particle distribution shows an even sharper break at the same interval at about $10^{-10} - 10^{-11}$ kg. Of course the Divine model for small particles ($m < 10^{-11}$ kg) derived from space detectors is not independent from the interstellar particle curve. But from the five populations of interplanetary particles discussed in the paper by Divine, only the eccentric and asteroidal population show their breaks far from the mentioned mass interval (and their role at 1 AU is small), whilst the core population's break is identical and the halo population break is at 10^{-11} kg.

The main break in the interplanetary particle distribution can be connected with a sharp decrease in the sporadic background mass distribution from a maximum at 10^{-8} kg to 10^{-10} kg particles, followed with a decreasing spatial mass concentration towards fainter particles from 10^{-24} g cm^{-3} at $10^{-8} kg$ up to 10^{-30} g cm^{-3} at 10^{-20} kg. (McDonnel 1978).

Kortenkamp and Dermott (1998) obtained a particle size cutoff at about $200\,\mu$m diameter, or 4 x 10^{-9} kg from the analysis of hypervelocity micrometeoroid impact craters preserved in lunar material and on the panels of the Long Duration Exposure Facility (LDEF), ascribing it to collisionally evolved asteroidal dust. In agreement with Gustafson (1994) they argue that a collisional lifetime of dust particles larger than $100\,\mu$m (or 10^{-9} kg) is shorter than the time required for their orbits to decay from the asteroid belt to Earth. Laboratory experiments on cosmic material (Colangeli et al. 2003) give a size - range of cosmic particles 5 to $50\,\mu$m with an average of about $15\,\mu$m, corresponding to about $10^{-15} - 10^{-10}$ kg, or 10^{-12} kg respectively, at the overall density of about 2 g cm^{-3}.

As suggested by Baguhl et al. (1996) and Frisch et al. (1999) interstellar dust grains with masses $m < 10^{-16}$ or 10^{-17} kg are underabundant in the solar system, because such small grains do not penetrate the heliosphere. The break in their flux contribution between $10^{-10} - 10^{-11}$ kg may be connected with the origin of interstellar particles. Searching the presolar dust grains in meteorites Hoppe and Zinner (2000) found that primitive meteorites contain small concentrations of presolar dust grains of grafite, silicon carbide or silicon nitride as inclusions of sizes from 0,2 to $20\,\mu$m. They are presolar fossils, the final step of which is the formation of parent bodies of the meteorites in which we find them. The sizes of these inclusions at their densities of 2.5 g cm^{-3} yield masses of $m = 8.4$ x 10^{-11} kg for their upper limit of $20\,\mu$m and $m = 1.05$ x 10^{-17} kg for $0,2\,\mu$m particle. Whether this is a satisfactory explanation or not is questionable, but it supports the acceptation of the presence of interstellar particles in the proportions presented in this paper.

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