

Out of This World: Sampling for Micro Meteorites

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ABSTRACT

Micrometeorites are extraterrestrial cosmic dust particles whose origin and collection remain active areas of scientific investigation. Their extraterrestrial nature is confirmed through isotopic analysis of cosmic-ray nuclei, with newly recovered specimens validated by comparison against established Antarctic reference collections. Unlike meteorites, which derive primarily from the asteroid belt, micrometeorites may originate from multiple sources within and beyond the Solar System. Six principal source regions are currently recognised: the asteroid belt, short-period comets from the Kuiper Belt and long-period comets from the Oort Cloud, planetary ejecta, geysers and volcanoes on icy moons, presolar and interstellar grains, and dust from interstellar comets. Prior to atmospheric entry, particles accumulate in the Zodiacal Cloud, a lens-shaped dust structure in the ecliptic plane estimated to contain ten billion tonnes of material. Cosmic dust influx to Earth is estimated at approximately 100 kilograms per day for presolar grains alone. Methodologically, micrometeorite recovery relies on three core principles: magnetic extraction, flotation, and size fractionation. Flat, large, older PVC-covered rooftops and rain gutters represent productive urban collection sites, with aeolian deposition concentrated at roof edges and corners. Approximately 80% of cosmic spherules are magnetic, enabling efficient field extraction using neodymium magnets. Accurate sample labelling and curation are emphasised as essential for scientific value. Distinguishing genuine micrometeorites from abundant terrestrial spherules requires systematic training, for which reference atlases and classified collections serve as primary tools.

1. The origins of micrometeorites

At the opening of the stardust exhibition in New York City, NASA's Mike Zolensky stated that more scientists ought to be willing to say "I don't know" when that is the correct answer. This courageous statement has become my mantra.

And as far as I know, nobody else knows for certain either. However, I can share some thoughts on this interesting topic. Simultaneously, I will also address another question I received a few days ago: how do we know for sure that micrometeorites are extraterrestrial?

The answer to the latter is that micrometeorites were initially confirmed to be extraterrestrial through isotopic analysis of high-energy cosmic-ray nuclei. All matter exposed to cosmic radiation in space undergoes subtle isotopic changes that are readily detectable. The micrometeorites in the Antarctic reference collections were analysed and found to contain cosmic nuclei. Later findings, including my own urban collection, are

being compared analytically with the original reference material, the type specimens. And if there is a match, the new micrometeorites are also extraterrestrial. This is how empiricism works.

Therefore, we know today that micrometeorites definitely originate in space. Last week, someone commented on my Facebook that this could not be true because of the firmament. I had to look up the word, but I will not get caught up in that rabbit hole. Clearly, we still have a road to walk.

Micrometeorites are cosmic dust particles, small even in space. Contrary to common belief, micrometeorites are neither ablated from meteorites nor directly related to them. But where do they originate from? Do they share a common parent body? There are possibly as many opinions on this as there are scientists in our field, but they can broadly be divided into two schools: asteroid belt and/or comet material.

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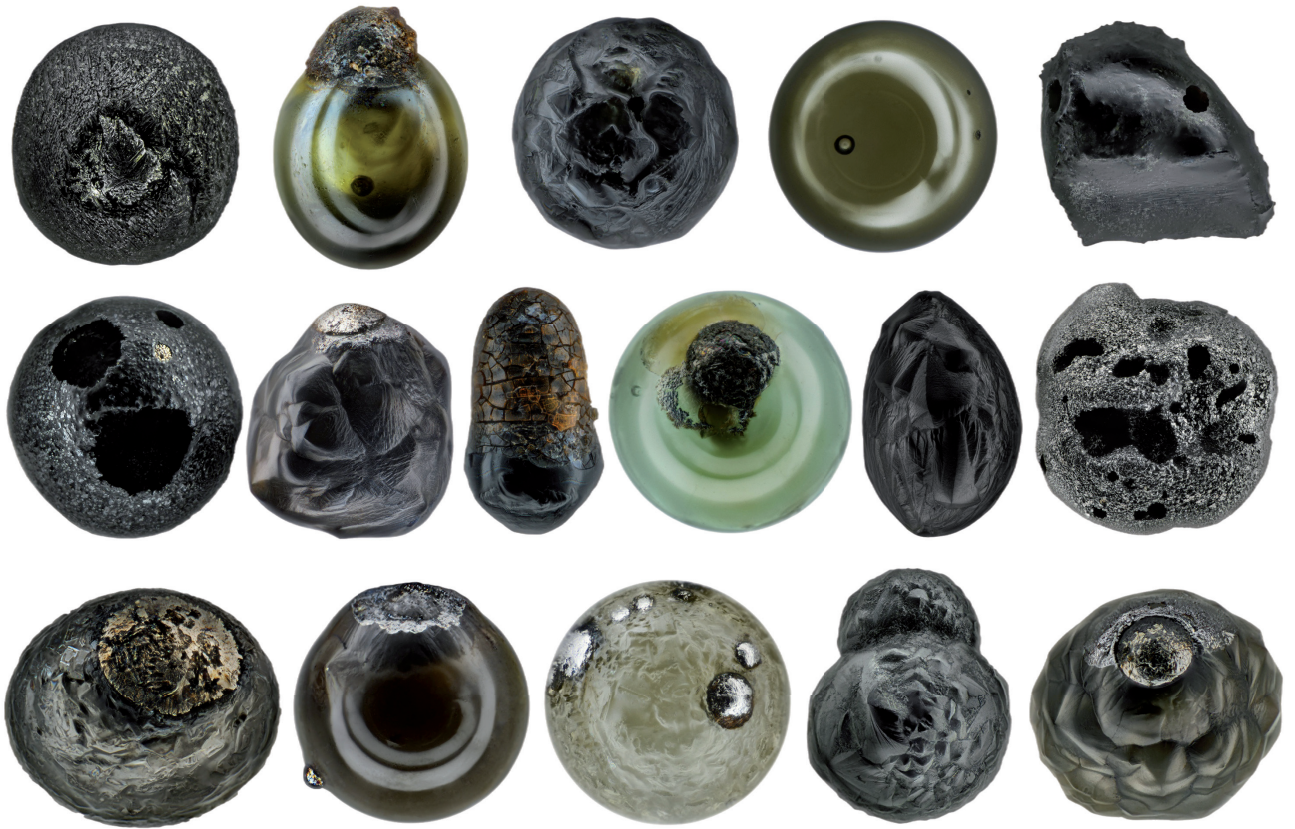


Figure 1: Micrometeorites, highlights of the year 2023 (Photo: Jan Braly Kihle / Jon Larsen).

Currently, several intriguing projects are in progress to explore this further. Some aim to link morphological and textural properties to specific parent bodies. Others are conducting new isotope measurements of a wide range of elements across all types of micrometeorites to identify their origin within the solar system, thus providing clues about asteroidal or cometary sources.

Micrometeorite pioneer Michel Maurette used chemical and mineralogical analysis and claimed in his 2006 book *Micrometeorites and the Mysteries that micrometeorites originate from “comet-like objects beyond Neptune”*. Since then, new data has been published, and it now appears more complex.



Figure 2: An impression of the asteroid belt. In reality, the average distance between 10m objects is 500 km. You can not see from one to another.

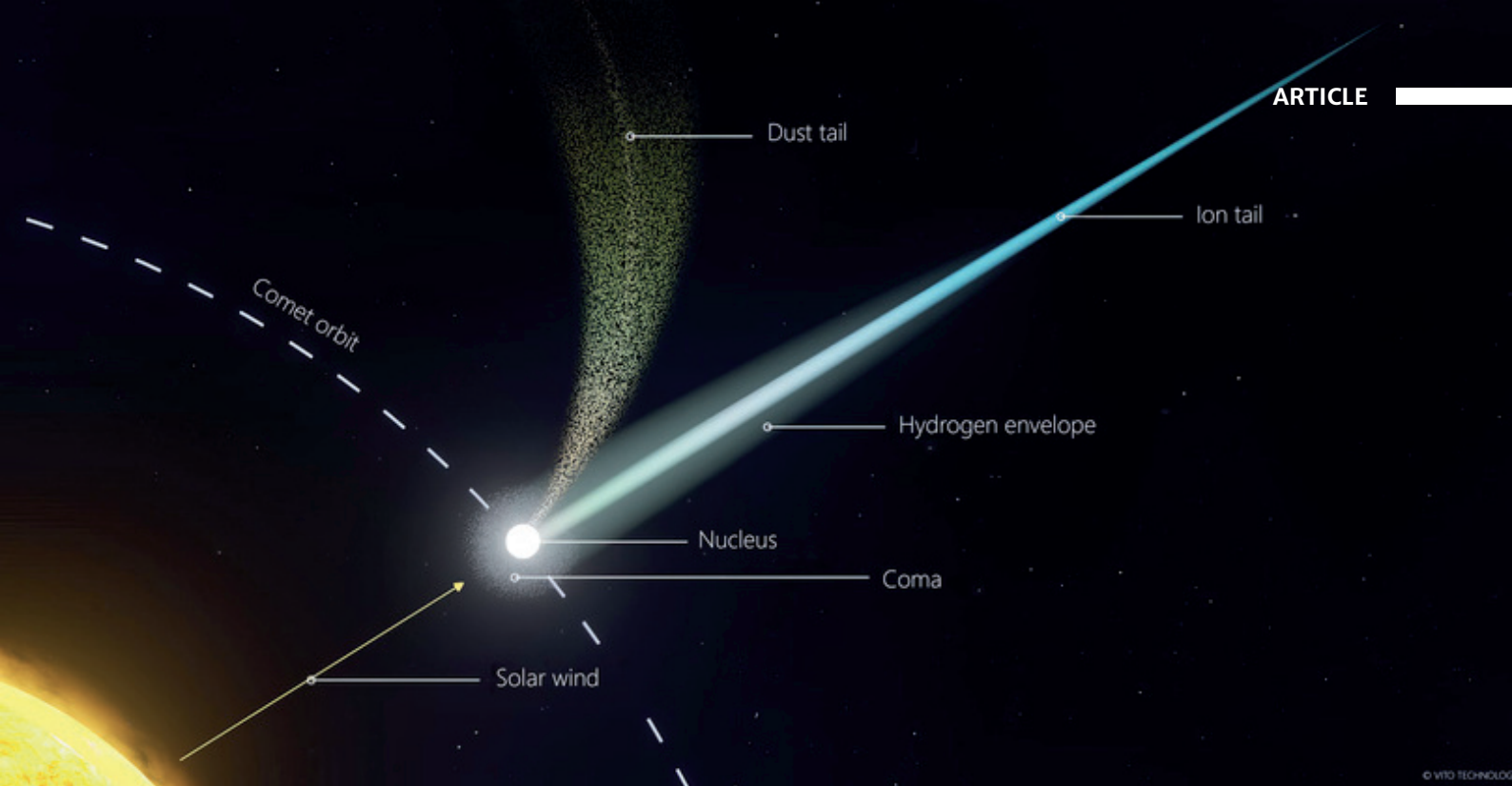


Figure 3: Anatomy of a comet. In our context, the dust tail is of special interest.

One day, hopefully, we will be able to identify the exact parent body of any given micrometeorite.

While we are gradually advancing in our quest to determine the exact origins, it may be useful to remind ourselves of the six possible sources of micrometeorites:

1. The Asteroid Belt between Mars and Jupiter. The asteroid belt contains a variety of ordinary chondrites, carbonaceous chondrites, burned-out comet cores, and other types. Matthew Genge and others point out the Koronis belt as the primary source of micrometeorites.
2. Short-period comets originating from the Kuiper Belt, and long-period comets from the Oort Cloud. These mysterious objects from the outskirts of our Solar system are often described as dirty snowballs—water ice with mineral particles and volatiles. David Nesvorný and others claim that as much as 85% of the cosmic dust, including the interplanetary dust particles, originate from comet's dust tails.
3. Planetary ejecta. We have identified achondritic meteorites from the Moon, Mars, Vesta, and other differentiated bodies. Matthieu Gounelle was the first to discover a micrometeorite of this origin. Data from the spacecraft Juno have led some researchers to believe that dust kicked up by Martian dust storms may be a significant source of the cosmic dust.
4. Particles from geysers and volcanoes on Enceladus, Europa, Io, and other moons.
5. Presolar and interstellar grains. It is estimated that ~1% of the cosmic dust entering Earth consists of presolar grains, which equals 100 kilograms per day. The platinum group nuggets which frequently appears on micrometeorites, originate from supernovae.
6. Dust from interstellar comets. Three of these have been observed entering our Solar System during the past decade alone. At least two of them, Comet 2I/Borisov and Comet 3I/ATLAS, with dust tails. Some of these extremely old particles may fall to Earth and be retrieved as interstellar micrometeorites.

Cosmos is a dusty realm. In the Solar System, regardless of the source, cosmic dust particles, as they journey towards the Sun, accumulate in the Zodiacal Cloud. The timeline of this process is the subject of Queen guitarist Brian May's thesis.

The lens-shaped dust cloud in the ecliptic plane is estimated to contain 10 billion tonnes of small particles. This is roughly equivalent to 285,000 years of Earth's cosmic influx. Over geological time scales, this is very short, especially considering how small Earth's accretion is compared with that of the Sun. There is, in other words, a large-scale renewal and continuous replenishment of cosmic dust in the Zodiacal Cloud, and an eternal exchange of dust particles among all celestial bodies: stars, planets, asteroids, comets, and moons. Meteorites are from the asteroid belt. Micrometeorites are from everywhere.

FACTBOX - Origin of Micro Meteorites

For readers steeped in planetary geology and who have an interest in the cosmologic origin-of-things, here is an excerpt from a recent Ph.D. from Vrije Universiteit, Amsterdam – a Micro Meteorite academic gem:

Jonker, G. (2026). “To catch a falling star: Micrometeorites as proxies for the chemical diversity and evolution of the Solar System”. [PhD-Thesis – Research and graduation internal, Vrije Universiteit Amsterdam]. <https://doi.org/10.5463/thesis.1585>

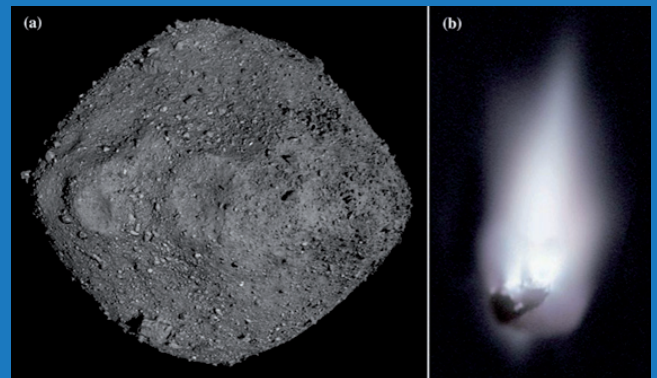
What makes micrometeorites important to study?

Although easier to analyze, larger meteorites do not provide a full representation of the Solar System’s composition and only offer us a limited range of materials to study. Compared to these meteorites, micrometeorites sample a much larger diversity of precursor materials and parent bodies. In addition, their continuous and globally distributed flux allows us to observe potential flux changes through time. This enables us to obtain a clearer and more complete view of the full diversity of parent bodies and materials present in the Solar System, and its dynamical evolution through time.

Asteroids versus comets

The question of whether micrometeorites primarily originate from asteroids or comets is deceptively simple, but the discussion has been ongoing since the discovery of the first micrometeorites. Other planetary bodies are generally considered to have a low to negligible contribution to the cosmic dust flux to Earth, e.g., only a single micrometeorite has so far been proposed to have a lunar origin (Fernandes & Rudraswami, 2025). The dust production mechanism of comets is dominated by sublimation and occasionally by fragmentation of the nucleus, producing vast amounts of small particles. On the contrary, asteroids and possibly other planetary bodies produce debris mainly through impacts and collisions with other bodies, which are generally rare (Figure 1.2; Brownlee, 1985). As stated before, the number of particles with ordinary chondrite affinities increases with particle size, and thus, the cosmic dust flux $>500\ \mu\text{m}$ is likely dominated by asteroid-derived particles. However, for smaller micrometeorites, typically with carbonaceous chondrite affinities, both an asteroidal and cometary source is possible.

A cometary origin may be supported by the scarcity of chondrules in unmelted micrometeorites, which are abundant in asteroids but may be subordinate in comets (Engrand & Maurette, 1998; Genge et al., 2005; Taylor, Matrajt, et al., 2011).



Possible origins of cosmic dust: (a) Bennu, a carbonaceous chondritic rubble pile asteroid, as imaged by the OSIRIS-REx spacecraft during the sample return mission (NASA). (b) Halley, a short-period comet consisting of a conglomerate of ice and dust, as imaged by the Giotto spacecraft. The comet’s nucleus is shrouded in a dense cloud of gas and dust formed through ablation as the comet neared the Sun in 1986 (ESA). Figure 1.2 in Jonker, G. Ph.D. thesis (2026).

Furthermore, numerical models of particle dynamics within the Solar System suggest that the bulk of the zodiacal cloud in the $\sim 10\text{--}1000\ \mu\text{m}$ size range consists of comet-derived particles, particularly from Jupiter-family comets (JFCs), but also Kuiper Belt and Oort Cloud comets at larger heliocentric distances. Micrometeoroids relating to confirmed comet-derived meteor showers typically have high atmospheric entry speeds well over $20\ \text{km s}^{-1}$ (Brownlee, 1997; Love and Brownlee, 1991). However, cometary dust from the zodiacal cloud could have relatively low mean atmospheric entry speeds of $14.5\ \text{km s}^{-1}$, which, coupled with comparatively lower densities, should allow such cometary particles to survive atmospheric deceleration (Genge et al., 2020; Poppe, 2016; Nesvorný et al., 2010; Yang & Ishiguro, 2018).

This suggests that the contribution of comets relative to asteroids in the production of micrometeorites smaller than $\sim 300\ \mu\text{m}$ could be more substantial than previously assumed. On the contrary, the hydrated and fine-grained nature of most micrometeorite precursor particles is difficult to reconcile with the bulk chemistry and petrology of directly collected cometary materials from the comet 81P/Wild 2 sample return mission, which are mostly anhydrous (Genge, Suttle, et al., 2017, 2020; Taylor, Matrajt, et al., 2011).

Numerical models and petrochemical observations are thus difficult to reconcile. The spatial origin of individual micrometeorites can also be deduced using cosmogenic nuclides. Their abundances may be used to determine the duration of irradiation, i.e., the cosmic-ray exposure (CRE) age, which documents the time of release from the parent body and accretion onto another body (Trappitsch & Leya, 2013). Using Poynting–Robertson dynamics, heliocentric distances at which micrometeoroids were released from their parent body can be calculated.

According to Feige et al. (2024), CRE ages deduced for micrometeorites and cosmic spherules are mostly ~10–1–102 Ma, corresponding to heliocentric distances of ~1–40 AU, mostly consistent with a likely asteroidal origin in the inner Solar System (near-Earth objects or Asteroid Belt; $n = 4$), or a cometary origin in the outer Solar System (JFCs or Kuiper Belt; $n = 7$). Noble gas measurements on a few Antarctic micrometeorites provide equally few absolute constraints on either asteroidal or cometary sources (Baecker et al., 2022). CRE ages determined for two relatively small IDPs are >900 Ma, corresponding to heliocentric distances of >150 AU, pointing to a cometary origin somewhere between the Kuiper Belt and Oort Cloud (Feige et al., 2024; Trappitsch & Leya, 2013). This would be in accordance with the consensus that most IDPs originate from comets (Genge et al., 2020). However, CRE ages may include a substantial period of irradiation prior to release from the parent body. Long periods of pre-irradiation would result in pronounced overestimations of the heliocentric distances, and may thus lead to misidentification of cometary versus asteroidal origins. Finally, coarse-grained UnMMs are linked to asteroidal ordinary chondritic sources (Genge, 2008). Rare ultracarbonaceous Antarctic UnMMs have been found to be highly enriched in deuterium, with excesses 10–30 times terrestrial values, and contain anomalously high concentrations of N-rich organic matter (50–90%), significantly higher than typical micrometeorites and IDPs. These rare particles, along with chondritic porous IDP-like micrometeorites, are believed to be the building blocks of comets formed within the cold outer reaches of the protoplanetary disc beyond the N snowline (Dartois et al., 2017; Duprat et al., 2010; Noguchi et al., 2015). They are among the only confirmed micrometeorites of cometary origin.

The discrepancy between numerical models and petrochemical observations persists to this day, meaning our understanding of either asteroid and comet chemistry or dust production and evolution is severely deficient.

Interstellar origins

Dust from outside the Solar System, i.e., interstellar micrometeoroids, may contribute a significant portion to the zodiacal cloud and the cosmic dust flux to Earth, but their existence is highly disputed and severely lacking scientific evidence. Hawkes and Woodworth (1997) suggest that ~1% of ~10 μg meteoroids could be of interstellar origin. However, these particles are characterized by extreme velocities of ~21–78 km s^{-1} , much higher than typical Solar System dust particle velocities, and hyperbolic trajectories associated with low zenith entry angles. These conditions make their survival in Earth's atmosphere and subsequent accretion on the surface highly unlikely. On the other hand, Hawkes and Woodworth (1997) argue that the existence of interstellar IDPs is not improbable, as radiation pressure from the host star could effectively eject these particles, with the Sun's radiation pressure conversely decelerating the particles sufficiently to allow atmospheric survival. Alternatively, interstellar matter could be transported into the Solar System by larger bodies. Such interstellar visitors include asteroid 11/'Oumuamua (2017), comet 2I/Borisov (2019), and the recently discovered comet 3I/ATLAS (2025). 2I/Borisov produced a tail ~11 times Earth's diameter with an estimated dust production rate of ~2 kg s^{-1} , a total coma mass of 1.3×10^7 kg, and an effective particle diameter of ~200 μm (Jewitt & Luu, 2019). Although this dust could intersect with the Earth's orbit, the relative contribution of this mass compared to the zodiacal cloud's estimated mass of 3.5×10^{16} kg is minimal. Various stellar sources contributed to the cloud of gas and dust from which our Solar System formed. Most of this information has been obscured by extensive reprocessing in the Sun's accretionary disc. Tiny (sub)micron pre-solar grains form the exception and are found in some primitive meteorites, micrometeorites, and IDPs. These grains consist of various silicates, oxides, carbides, and metals (Yada et al., 2008; Zinner, 2004). Although not truly interstellar *sensu stricto*, the identification of these pre-solar grains allows the study of the most primitive materials from which our Solar System formed.

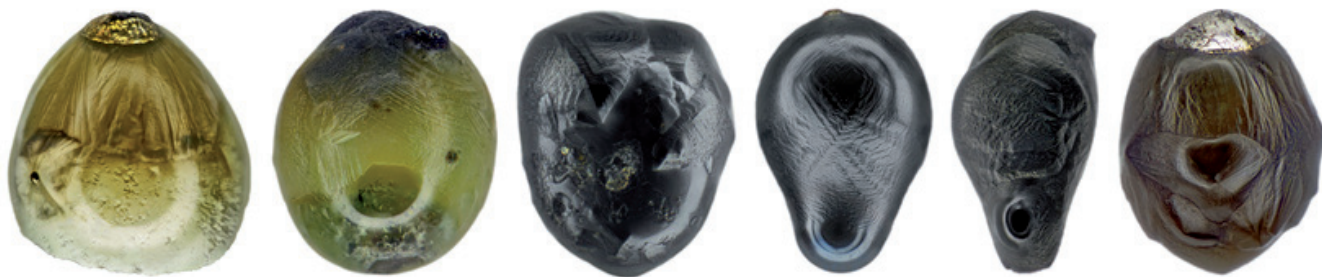


Figure 4: Micrometeorites in transitional stages between glass and crystalline (Photo: Jan Braly Kihle/Jon Larsen).

2. How To Find Micrometeorites

Great discoveries often originate from modest beginnings, and discovering your first micrometeorite is an unforgettable experience. To achieve this, we adhere to three principles: 1) magnetic extraction, 2) flotation, and 3) size fractionation.

In 27 steps, each with an illustration and a brief description, I outline a method for anyone to discover their own unique grain from space. This is just a basic introduction to get you started. I encourage you to enhance the process wherever possible.

1) Searching for micrometeorites can be done simply by placing a ladder against a rain gutter on a pitched roof. On a dry day, magnetic particles can be extracted in situ. Use a paintbrush to gather the dry particles and use the magnet directly in the rain gutter. When finished, you may jump straight to point six to continue the cleansing process.



Figure 5: Search in the school's rain gutter. The kids found 18 micrometeorites

If the rain gutter is filled with damp debris, I wear rubber gloves and collect everything in plastic bags. On the ground, it is placed in water-filled buckets to separate mineral particles from organic matter by flotation. Then you may continue from point fifteen.

But if you want to find a larger number of micrometeorites relatively easily, I recommend starting by searching for the right roof. A flat roof with a vinyl (PVC) cover is ideal, as it doesn't increase the number of particles on the roof. The larger and older, the better. I use Google Earth to locate large roofs. The lighter ones, like the one in the picture below, are usually covered with PVC.

When I identify a promising roof, I contact the owner with a brief explanation of my project and some references. Then I ask for permission to access the roof on a dry day and keep an eye on the weather forecast. When it's wet, the magnet doesn't work effectively, and we need to use a different method. In this post, we'll focus on how to extract magnetic micrometeorites from a dry roof. How to collect non-magnetic micrometeorites and work on a wet roof in a separate post.

The roof in the photo below is my local shopping centre. The first time I contacted them, a year ago, I found no fewer than twenty-one new micrometeorites here. Now, I want to see if any new spacerocks have fallen since then.

2) On the roof, there isn't much to see. It looks to be empty and has hardly any visible dust. Additionally, it has been raining, and water remains in the lowest parts of the roof, where the micrometeorites are situated. However, it is mostly dry, so let's give it a try.



Figure 6: On the roof, there isn't much to see.

3) I use my dust broom to gather loose debris and extract magnetic particles with a neodymium magnet. The instructions for holding the magnet and using plastic bags to collect the yield are shown in the photographs and explained further in the book *How To Find Stardust*.

Approximately eighty per cent of cosmic spherules are magnetic. The rest have experienced such high peak temperatures and rapid quenching during atmospheric entry that the nickel and iron have evaporated.

Today, we will extract the magnetic particles directly from the roof and collect them in a small plastic bag. This is the first of the three principles we use to find the needle in the haystack—one extraterrestrial particle among billions of terrestrial ones: Magnetism.

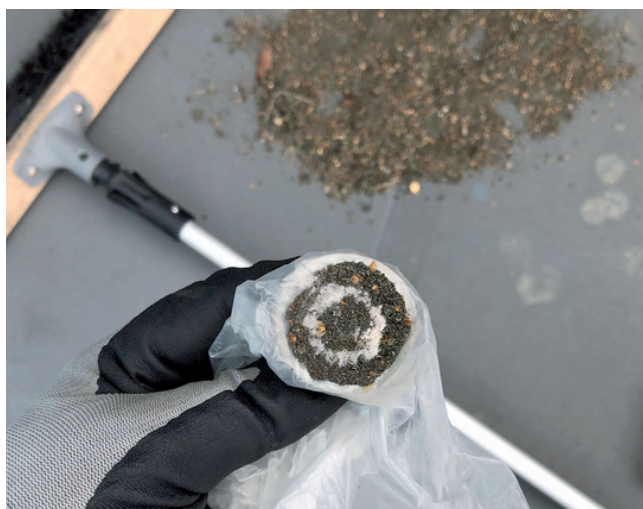


Figure 7: Magnetic particles attached to the hand-held magnet.

4) Micrometeorites are so small that they are carried by the wind. This is known as aeolian sediments in geology. On the ground or roof, rainwater washes them down to the lowest parts of the roof, usually near the drains. There, the micrometeorites may disappear. However, along the edges and in the corners, aeolian particles tend to gather, much like dust bunnies indoors.

In my area, the prevailing wind blows from the southwest, which means most of the wind-blown particles are in the northeast corner. The people on the ground are happily unaware of the cosmic drama unfolding right above their heads.

5) After three hours on the roof, I have collected a field sample of about 30 grams. Unfortunately, it rained the day before, so there is still water in the lowest areas of the roof, where dust particles (including micrometeorites) gather. I could have collected the entire slush in larger plastic bags and processed it later on the ground, but today it's mainly a quick check for really fresh stones from space.



Figure 8: The trophy bag in situ.

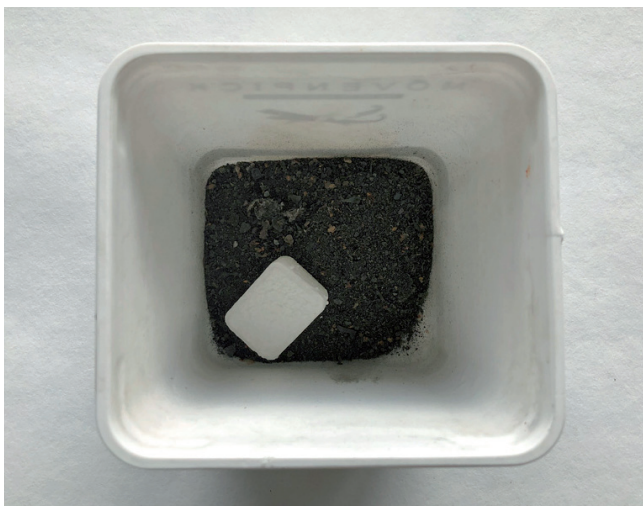
Before I leave the roof, I mark the sample with the find spot and date, as well as information about how the sample was collected (M for magnetic extraction) and the field search number. This is my field search number 986. Each field search takes a day or two, so I have spent years hunting for stardust, and I still love it!

It is crucial to properly label the field sample if you plan to collect multiple samples during the peak season and examine them later. In the book *How To Find Stardust*, there is a chapter about curating your collection. A handwritten journal with one entry per field search is recommended, as it will increase the scientific value of your collection.

6) This is the equipment we'll use for processing the field sample: a plastic box, a plastic spoon, some dishwasher detergent, and a flat plate. The methodology is still new, so it has great potential for improvement. Use my tips to get started, and then let your imagination take over to enhance it.



7) To begin the process, I place the sample from the roof into a bowl, in this case, an empty ice cream container. Along with the dust, I add some dishwasher detergent. This is not required. Alternatively, one may use a sonicator and/or distilled water. If the roof is inhabited by birds, I sometimes use alcohol first to kill bacteria from the droppings.



8) Fill up with water and use the plastic spoon to stir gently around. The aim is to clean the surface of each dust grain in the sample and rinse away the submicron dirt particles by flotation. This means that organic particles and submicron dirt float to the surface, while mineral particles, including micrometeorites, sink to the bottom.



9) After a while, we reach a crucial point in the process. Do nothing!

Let the sample rest for a moment without touching it. This is a moment of Zen. Allow gravity to do its work and let the dense particles sink to the bottom, while the smaller dirt particles float or swirl in the water. If you absolutely must do something, I suggest either observing the bubbles or closing your eyes and contemplating for a moment that you are reaching for the stars. And that somewhere in the dirt in front of you, right now, a stardust particle may be sinking to the bottom after a journey of billions of years through space and time. It's magical!

Then, gently pour off the dirty water. Ensure the heavier particles at the bottom stay in the bowl. A magnet placed beneath the bowl, or at the side where you pour out the water, can be helpful.





10) Refill with water (I use warm water), stir, and let the mineral particles settle at the bottom again. After a while, carefully pour off the dirty water.



13) Continue until it looks clean.

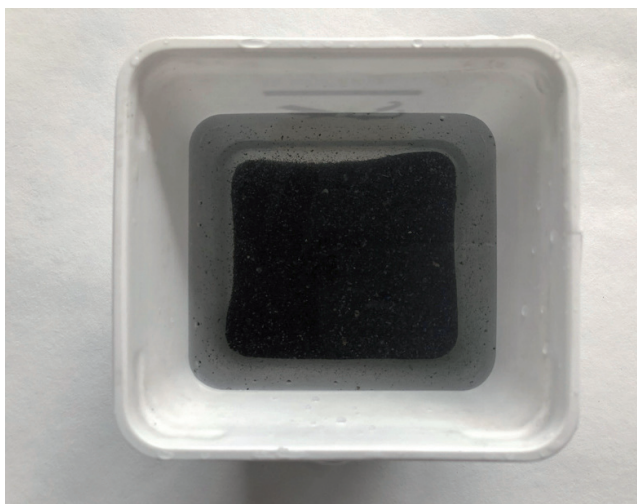


11) Repeat, refill with clean water, stir, and allow the precipitate to settle at the bottom. Wait patiently; do not disturb the work of gravity. Patience is beneficial for us.

The young Buddha claimed he was only capable of two things: fasting and waiting. By searching for micrometeorites, you will not only expand humankind's knowledge about space but also develop your own patience.

12) Continue rinsing the sample, pour off the dirty water, and repeat the process. Gradually, the water becomes clear.

During this step, we apply the second of the three principles in the search for micrometeorites: flotation, which separates the dense mineral particles from the rest. Simultaneously, the micrometeorites are being cleaned, which is essential for accurately identifying both terrestrial and extraterrestrial particles under the microscope.



14) Now the water stays clear, and it's time to move on to the next step.



15) Pour the wet dust particles onto a flat plate and tilt it slightly to remove most of the water.



15) Below is the clean sample. We have washed away approximately one-third of the initial mass, mainly consisting of dirt, organic material, and mineral particles with diameters of up to 50 microns.

Now, I place the plate to dry. On a sunny day, the quickest way is to put it outside in the sunlight. Alternatively, let it dry slowly indoors. Efficient warming lamps, drying cabinets, air fryers, and professional laboratory drying ovens are all available for those who can afford them.



Some scientists prefer to proceed directly to microscopy from here and complete the final part in wet conditions. I suppose this is a matter of personal preference. After a day on the roof and rinsing the sample, I usually take a shower and have a siesta while it dries.

16) Either way, after some time, the sample dries and we can proceed.



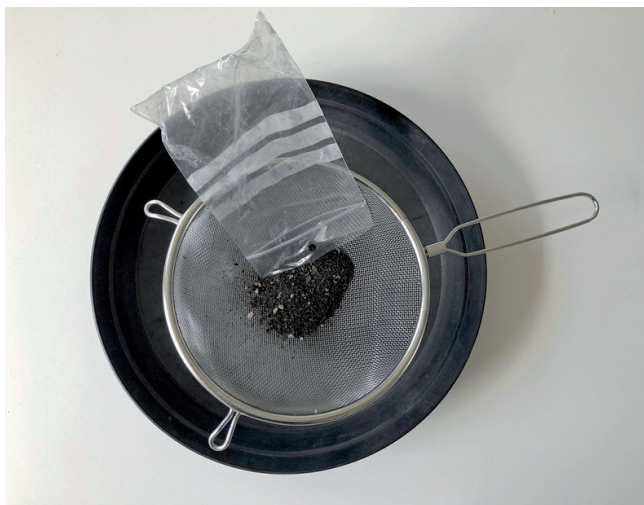
The sample now includes dry particles of all sizes, from roughly 50 microns and larger. It is quite remarkable how large particles the wind can transport, and the birds even bring bigger pebbles.

In this specific case, most of the sample consists of rust—small flakes from various mechanical installations on the roof, such as solar panels, air conditioners, antennas, tubes, drains, signs, and doors. Because of its monotony, examining this much rust under the microscope can be quite tedious, but the good news is that it is easily distinguishable from potential micrometeorites.



18) Begin by pouring the sample through a sieve with a 1.5 millimetre (~0.06 inches) mesh to remove particles that are too large. Most cosmic spherules are between 150 and 400 microns. We then apply the third principle to narrow down the sample for finding micrometeorites: size fractionation.

The purpose of fractionating the particles is to make it more efficient to examine particles of the same size under the microscope. At high magnifications, the depth of field is shallow. Zooming in and out on particles of different sizes is inefficient and eye-straining.



19) The particles remaining in the sieve are larger than 1.5 millimetres. These can be quickly examined under a microscope at a relatively low magnification or discarded.

From Antarctic collections, we know that a few super-giant micrometeorites exceed 1.5 millimetres, but such specimens are rare. The largest of the 5,600 micrometeorites I have found measures 1 millimetre.



20) The particles passing through the 1.5 millimetre mesh are then filtered through a finer mesh of 0.4 millimetres (0.015 inches, or 400 μm).

The largest particles (400 to 1500 μm) are now examined under the microscope at a relatively low magnification of around 25x. This process is quick, taking only a few minutes for this size range and magnification,

because the dark aerodynamic, complete stones from space are very different from the angular terrestrial mineral grains and rust. The key is knowing what to look for and what to ignore.

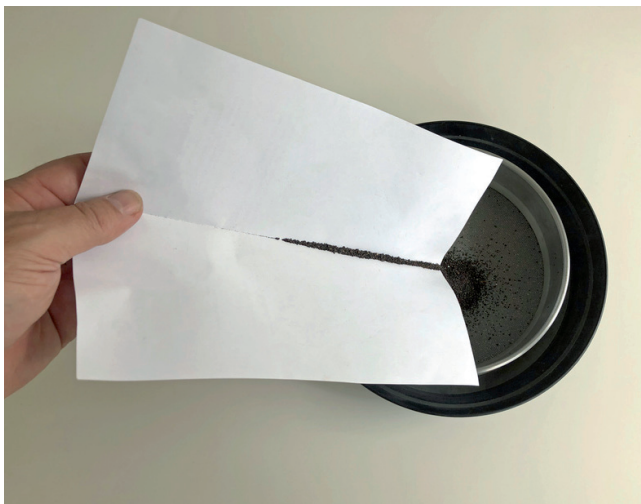
Recently, I obtained a sieve with a 0.5 mm (500 μm) mesh, which adds an extra step in the fractionation process. However, it also facilitates the identification of the not-unusual micrometeorites in the 400-500 μm range. This time, I found no large micrometeorites in the 400- to 1500- μm fraction, so I moved on to the next step: the particles that passed through the 400- μm mesh.



21) The <400 μm particles are now passed through a third sieve, this time with a mesh of 200 μm . What remains in the sieve are particles between 200 and 400 μm , where, according to Michel Maurette, most of the cosmic spherules are.



22) Below. I use folded paper as a funnel to collect the particles moving between the plates and sieves.



23) What passes through the sieve with the 200 μm mesh are particles smaller than 200 μm (0.2 millimetres). These can be further divided into even smaller sizes, where many micrometeorites might be present, but this requires specialised equipment, a powerful microscope, and keen eyesight. Micrometeorite expert Susan Taylor recommended ignoring particles smaller than 50 μm .

Today, however, I will focus on the most important fraction—the sweet spot. This refers to what's remaining in the 400 μm sieve—particles between 200 and 400 μm in size. Most of the cosmic spherules are found in this range. Or, according to others, more specifically in the 123 to 300 μm size range.



24) The sample in the 200 to 400 μm fraction now weighs 7.1 grams, roughly 20% of the initial sample collected from the roof. Most of these particles are magnetic, but not all. All will, however, be examined under the microscope at approximately 63x magnification.



25) Now it's time to move on to the final part: microscopy. The photo below shows my equipment, which I have been using for years. It includes a Zeiss binocular microscope, water, two pointed wooden sticks, and a small plastic box with an air-tight lid to store potential micrometeorite candidates.

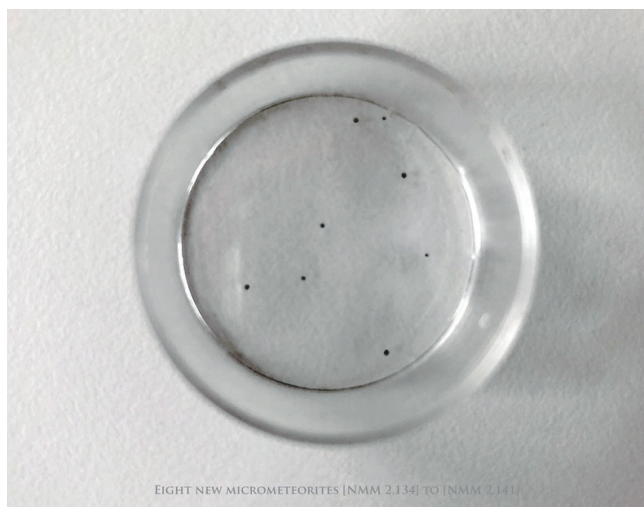


26) This is the proverbial search for the needle in a haystack, and it is important to know what to look for (the micrometeorites and their characteristic textures) and what to disregard. The various particles are described in the book *How To Find Stardust*.



With experience, as you become familiar with micrometeorite textures, it becomes possible to listen to a podcast or your favourite music during microscopy. Today, I played a double album of 70s prog rock and enjoyed both the music and the microscopy. By the time side four was over, so was the microscopy.

27) Here is the result: no fewer than eight ultra-fresh micrometeorites! Three barred olivine (BO) types, two scoriaceous (ScMM), one porphyritic olivine (PO), and one glass (V-type) with a metal bead.



The entire process — from contacting the shopping mall, sampling in situ, processing, and microscopy — has taken about eight hours. This is certainly acceptable, but not an ideal outcome. On two similar roofs, which I sampled for the first time this year, I found over 100 micrometeorites on each. However, today was a quick check, and the roof was somewhat wet.

In any case, one micrometeorite per hour, or roughly one micrometeorite per gram of sample (within the correct fraction), is not too bad either. When I started with this in 2009, it was considered utopian. Pure science fiction.

3. What to ignore

The micrometeorite community is expanding, and this month alone, hundreds of new hunters are reaching for the stars more or less from scratch. With a fresh sample from a rain gutter, a car park or a flat roof, it's time to enjoy the magical microcosmos under the microscope. Perhaps the first thing you'll see is something like this:



Figure 9: Particles in the 0.2 to 0.4 mm size range in ~30x magnification.

If so, I suggest using higher magnification to clearly see the surface structure of each particle. Among the sand grains, you'll notice several rounded objects, or spherules. But are they micrometeorites or just terrestrial contaminants? At first, it can be overwhelming—so many unusual shapes. Every experienced micrometeorite collector has faced this, examining countless spherules one by one. Over time, though, you start recognising the common types and can set them aside while hunting for the real micrometeorites.



Figure 9: The same particles in ~60x magnification.

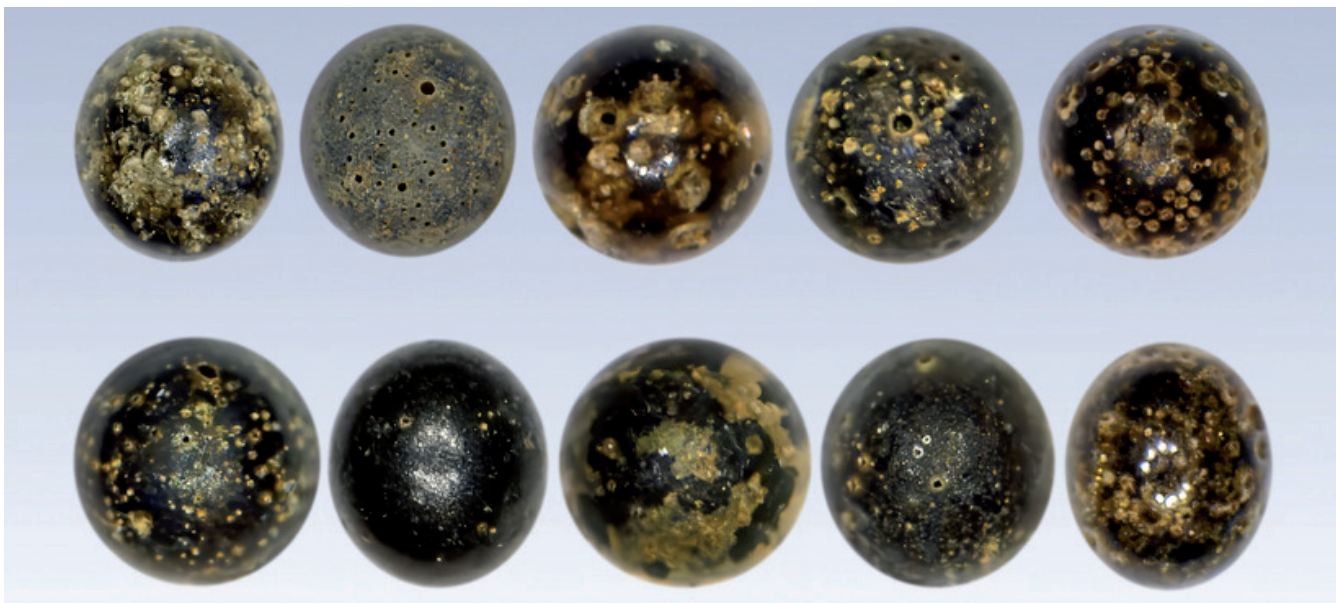


Figure 10: Achneliths, from a volcano (Photo: Jan Braly Kihle / Jon Larsen).

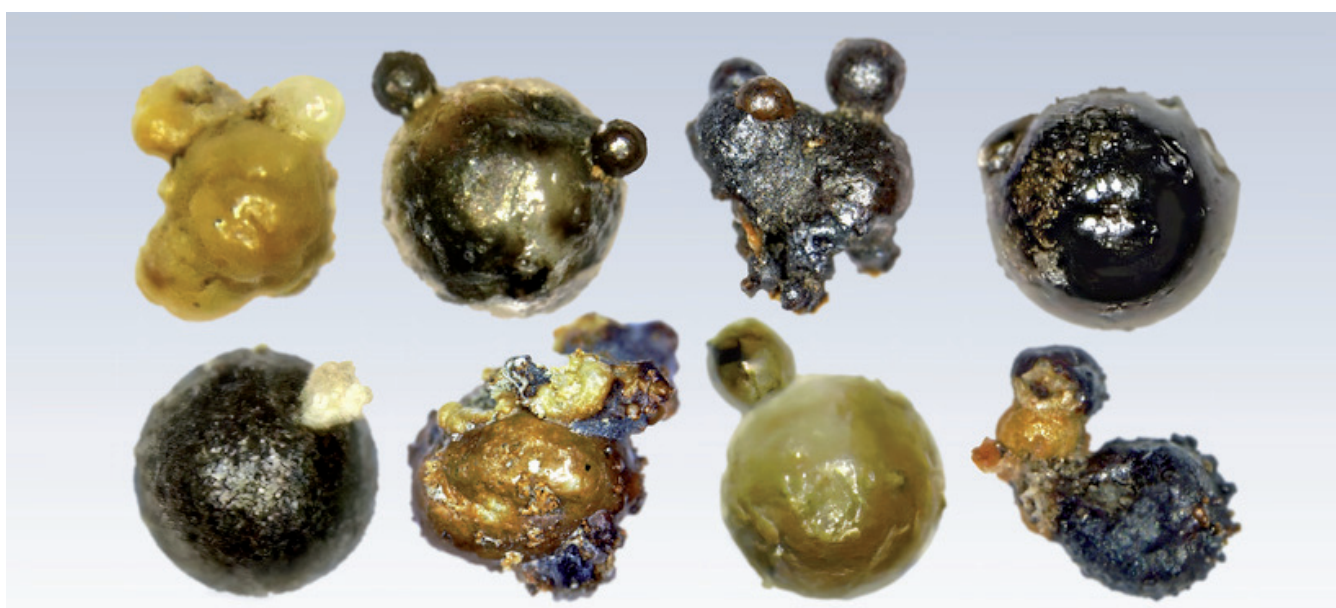


Figure 11: Fulgurites, from lightning (Photo: Jan Braly Kihle / Jon Larsen).

A fast way to learn about the terrestrial spherules is the textbook *In Search of Stardust*. It took me seven years to figure everything out, but you'll get it in a couple of hours. The book contains more than 1,500 photos of identified and classified spherules. When you've read the book, you'll be able to identify them all.

The key to scanning a dust sample under the microscope and spotting that needle in the haystack—a genuine micrometeorite—is knowing the most common terrestrial contaminants.

With practice, the process becomes quick, and you can even enjoy some music or a podcast while working at the microscope.

Remember, there are only nine types of micrometeorites, but a zillion different types of terrestrial spherules.

Happy hunting!

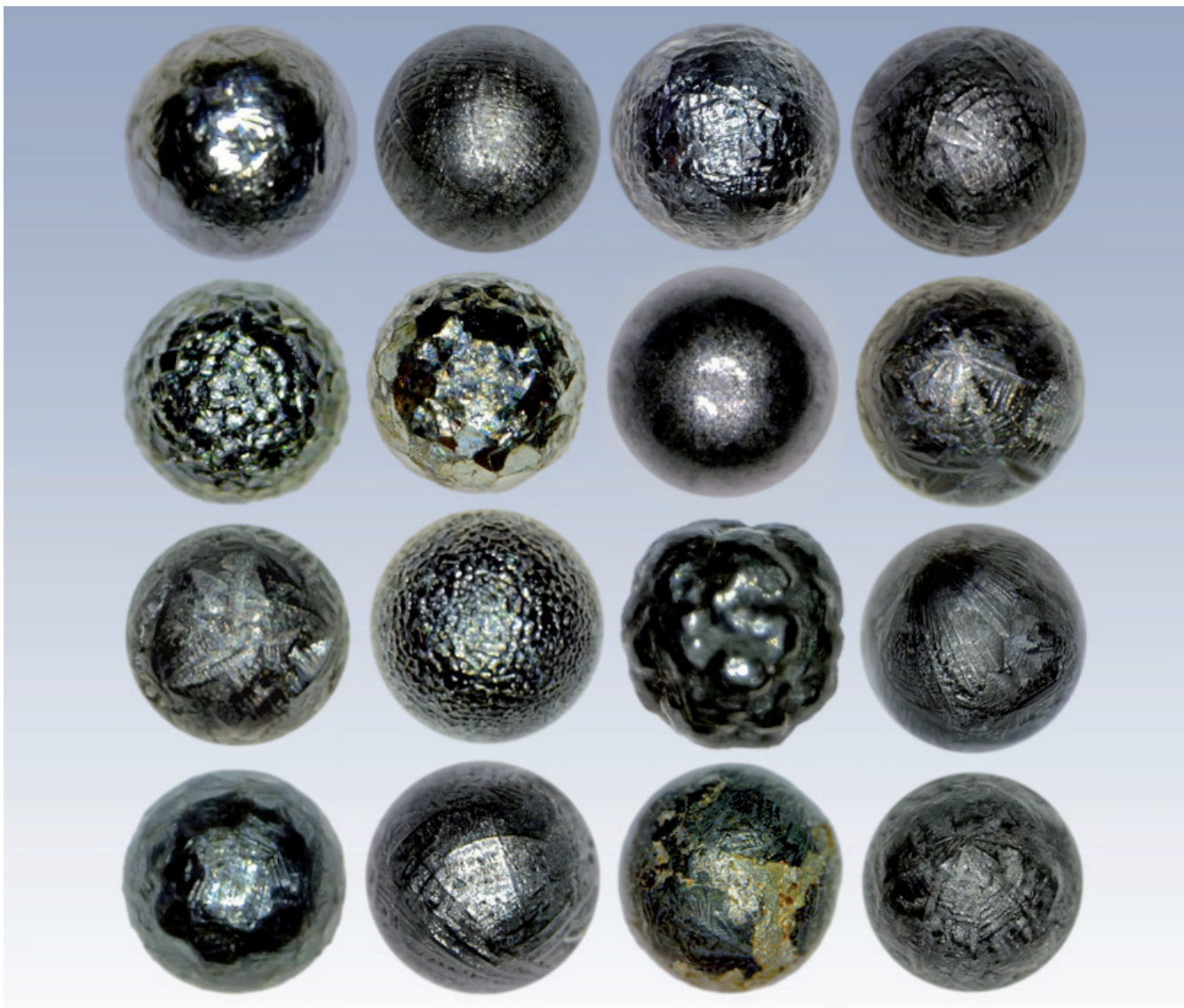
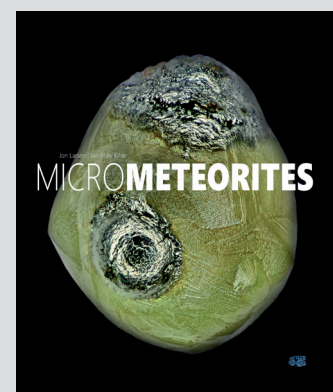


Figure 12: Industrial iron oxides from power tools (Photo: Jan Braly Kihle / Jon Larsen).

ATLAS OF MICROMETEORITES AND MORE ON PATREON

Legendary coffee table book with the World's most beautiful micrometeorites in large hi-res colour photos by Kihle/Larsen. Each photo has a short explanatory text, peer reviewed by Martin D. Suttle. Prefaces by Michael Zolensky (NASA), Matthew Genge (Imperial College, London), and the author, Jon Larsen.

You can find a lot more on Patreon, just sign up at patreon.com/ProjectStardust826/



FACTBOX - The Ten-Point Checklist for Micrometeorites

The ten-point checklist is used to determine whether a stone is a micrometeorite or not. Based upon what you can observe, or not, under the microscope, the identity of a candidate can be verified in seconds. Once you are familiar with these ten simple yes-or-no questions, the checklist will, in most cases, guide you through the maze.

The first six questions are confirmatory criteria, where the answers should be yes. The last four are exclusionary, and the answers are no. Karl Popper (1902–1994) claims in his *Empirical Falsification* that confirmatory criteria cannot be trusted because it is always possible to find supporting evidence, even for an incorrect hypothesis. A falsification, on the other hand, is more reliable (Photos: Jan Braly Kihle / Jon Larsen).

Confirmatory Criteria

1. Is the rock aerodynamic? Does it show signs of melting and hypervelocity?



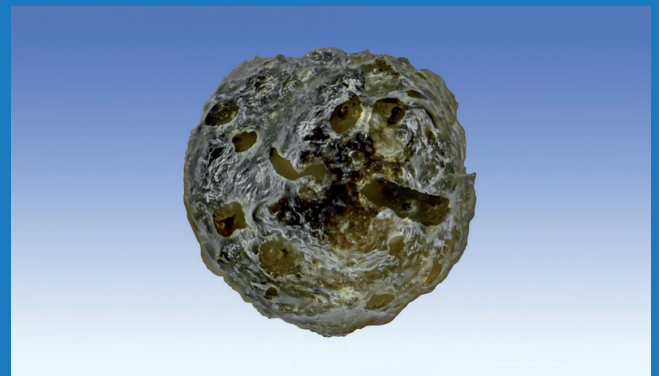
A micrometeoroid entering Earth's atmosphere at hypervelocity melts due to frictional heating. This causes an elemental differentiation in the particle, where dense elements (nickel and iron) gather as a core, surrounded by silicates, whereas the volatile elements evaporate and escape. Almost like a planet formation in miniature. Because of its small mass, the subsequent increase in atmospheric pressure leads to an abrupt deceleration where the metal core migrates to the front due to inertia.

The drop in temperature is followed by solidification and recrystallisation. This formation process, which is over in the blink of an eye, is different from all other types of rock formations on Earth. And it is the typical signs from this unique experience we are looking for when we identify micrometeorites by their visual appearance. This was sci-fi only ten years ago.

In most cases, cosmic spherules obtain visible flight characteristics, like slight elongation, a symmetric length axis, and characteristic elemental distribution:

Heavy metal (beads) in the front, followed by silicates, and escaping volatiles (vesicles) at the rear end. In the photo above, note also the pale area next to the metal bead, apparently drained of iron.

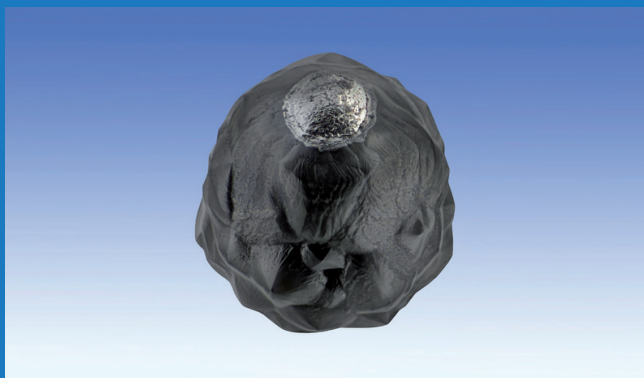
2. Are the colours, lustre, and translucence (if present) like those of most micrometeorites?



Unlike terrestrial rocks, which have extreme variations in mineralogy and chemical content, rocks from Space are surprisingly homogeneous. They are chondritic, which is the chemical signature of our Solar system at large. This means a limited range of colours, characteristic lustre, and translucence. The dominant mineral in stoney micrometeorites is olivine, in the magnesium variety forsterite. These crystals are often colourless, but for unknown reasons, most micrometeorites are black. Porphyritic olivine (PO) types are at times completely colourless and translucent olivine crystals glued together by a dark glass matrix. More frequently, due to minor traces of iron, they display hues of green (Fe²⁺) or brown (Fe³⁺).

Confirmatory Criteria

3. If there are metal beads on the surface, are they located in places that are consistent with aerodynamics, rapid deceleration from hyperspeed, and/or spin?



Ninety-nine per cent of all micrometeorites are stoney, only one percent is metallic iron oxide. They do, however, often contain metal beads, and where they are situated on a spherule, and what they look like can help us identify its origin.

In most cases, micrometeorites are oriented stones with one single nickel-iron metal bead in the front. The dense metal may have triggered crystallisation in the rock, in a way that is different from terrestrial spherules. An additional secondary bead, often enriched in nickel, may be situated at the rear end of the micrometeorite, due to spin perpendicular to the direction of flight.

If the stone has short terrestrial age and is fresh from Space, the metal bead may be surrounded by a thin, shiny sulfide rim. At times, you can see several beads caused by a more chaotic spin.

With experience, these unique features get quite easy to recognise. On the other hand, terrestrial spherules have not gone through the strong forces like the cosmic spherule formation, and their surface metal beads are placed more randomly. Here is a typical cosmic spherule, a cryptocrystalline turtleback variety, with a metal bead in the front surrounded by a thin sulfide rim. The bead has triggered crystallisation backwards, which is down in this photo. Note the exquisite symmetry along the length axis.

In the case of a V-type (vitreous, glass) micrometeorite, the metal bead is most often surrounded by a thin, shiny sulfide rim, and/or crystallisation in the glass. Characteristically, a glass micrometeorite may have a metal bead in the front, which has triggered a conical crystalline area, standing out from the spherical glass body. At times, we can also observe the characteristic Soap Bubble Effect, umbrella-like pyramidal crystal domains growing independently in the glass. On the opposite side of the glass micrometeorite, in the back, we can often observe an additional indication: A large open vesicle from degassing.

4. Is it a single rock without twin formations or aggregates? Is it complete all the way around?



Micrometeorites are lonely wanderers through Space and fall to the ground as solitary, aerodynamic, and complete stones. Contrary to angular, fractured, broken, and/or worn terrestrial mineral grains. To my knowledge, fused micrometeorites do not exist. Twin formations, triplets, spherule aggregates, and similar structures are common in terrestrial spherules, especially those created by industrial power tools.

When a micrometeorite lands on a rooftop with little activity compared with the turbulence down on the ground, it remains pristine, complete all around. A smooth, dark, undamaged spherule with recognisable textures (see point five). This is surprisingly rare in the urban dust.

Confirmatory Criteria

5. Does the rock exhibit any of the characteristic micrometeorite textures?



Three out of four cosmic spherules (melted micrometeorites) are classified as one of the three most typical textures: Barred olivine (BO), cryptocrystalline (CC), or porphyritic olivine (PO). And of these, the majority is barred olivine. If you learn to recognise what these three types look like, you may easily pick them out in a dust sample. They stick out.

In addition to these three types, around twenty per cent of the micrometeorites are glassy V-types. Here is a post about separating nonmagnetic glass (V-type) micrometeorites from anthropogenic glass spherules: ET or T glass spherules?

6. Is it the right size?



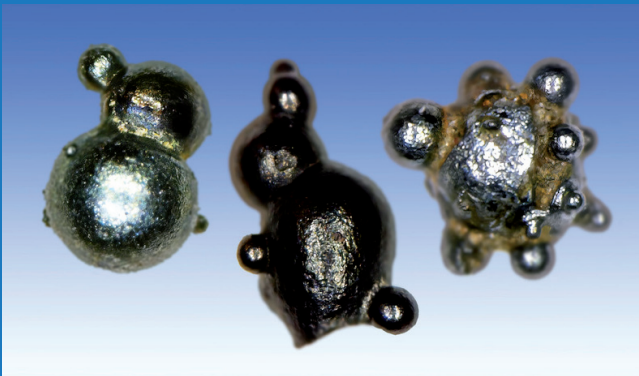
Most micrometeorites are between 0.1 and 0.3 millimetres in diameter. Objects smaller than 0.05 and larger than 1.0 millimetres in diameter are suspect.

Yes, there are micrometeorites smaller than 0.05 mm (50µm), but that is the lower limit recommended by Susan Taylor, who discovered the MMs in the South Pole Water Well. And there are other problems. First of all, smaller than that, the MMs get increasingly difficult to identify in an ordinary microscope; you need an electron microscope. Secondly, smaller sizes tend to be too small to melt during atmospheric entry, and unmelted micrometeorites are difficult to identify at all in a light microscope. Besides, in these small sizes, we enter the realm of the enigmatic and fluffy aerosol particles, floating in the atmosphere. They have so small a mass that they hardly fall to the ground at all. More about these interplanetary dust particles, later.

There are also micrometeorites larger than 0.3 mm, according to Maurette one in 250 may reach 0.5 mm. Larger than that, we call them giants, and if they get near 1.0 mm we call them supergiants. I have only found a handful (1/1000) of those. From the blue ice in Greenland and Antarctica, Maurette has reported about extremely rare MMs up to 3.0 mm, and Susan Taylor about “one strange object”, a spherule of stunning 0.5 mm. Larger than that, they will most likely burn up in the atmosphere. So the peak in the mass distribution of micrometeorites is somewhere between 0.1 and 0.3/0.4 millimetre. I recommend laboratory sives to find the sweet spot.

Exclusionary Criteria

7. Does the candidate have twin formations or complex forms (aggregates)?



This is common for industrial spherules but does not exist in micrometeorites. See also point four.

9. Does the object possess one or more tails?



This is common on man-made spherules, but rare in micrometeorites.

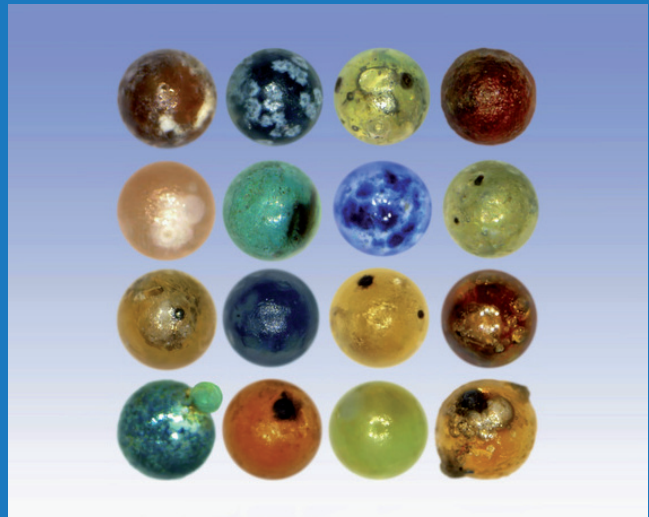
8. Are there any crash, splash, or roller marks?



This is frequently observed on industrial spherules, where the spherule may have hit the ground in a semi-liquid state.

Micrometeorites, on the other hand, solidify in the upper atmosphere. Their kinetic energy is transformed into heat, and the small Space rocks fall to Earth cold, and at “terminal velocity”, only pulled by Earth’s gravity. Again, see point four.

10. Is the object rusty or does it have vibrant colours?



Olivine and magnetite in micrometeorites do not rust. Vibrant colours are common in fireworks and other anthropogenic spherules, but rare in micrometeorites. See point two.

If the conclusion remains unclear after going through the checklist, a chemical analysis is recommended. If a particle is chondritic and has the right textures, it is a micrometeorite.