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Chapter

Hematite Spherules on Mars

Anupam K. Misra and Tayro E. Acosta-Maeda

Abstract

In 2004, the observation of large amounts of hematite spherules on Mars by the NASA's Mars Exploration Rover "Opportunity," which landed in Eagle crater on Meridiani Planum, created tremendous excitement among the scientific community. The discovery of hematite was significant as it suggests past presence of water on Mars. Furthermore, the hematite spherules were widely suggested to be concretions that formed by precipitation of aqueous fluids. Among the various observed mysteries of Martian hematite spherules, also known as "blueberries," one regarding to their size limit was very puzzling. All of the millions of blueberries observed on Mars were smaller than 6.2 mm in diameter. Because the concretions on Earth are not limited in size, the formation of the Martian blueberries became difficult to explain. In this chapter, we will discuss the observed properties of Martian hematite spherules and explain why a cosmic spherule formation mechanism provides a possible solution to the puzzling observations on Mars.

Keywords: Martian hematite spherules, Martian blueberries, cosmic spherules, concretions

1. Introduction

In 1996, NASA launched the Mars Global Surveyor (MGS) spacecraft to perform global mapping of Mars. One of the instruments on the MGS is the thermal emission spectrometer (TES), which would map the mineralogy of the Martian surface using infrared spectroscopy. TES imaging revealed the presence of crystalline gray hematite on Mars in Sinus Meridiani. **Figure 1** shows the global distribution of minerals on Mars [1, 2]. The distribution of hematite is shown in pink and labeled as H in the areas of Aram Chaos and Sinus Meridiani. The bottom image shows the distribution of hematite in Sinus Meridiani. According to [1] and [3], the hematite covers an area of over 175,000 km^2. The hematite boundary is abrupt and immobile and all the hematite is very possibly confined to a thin layer. According to [3], this layer could be only 100 microns, because TES gives surface measurements. The age of hematite is estimated over 3.5 Ga. The unnamed crater shown in the bottom image (**Figure 1**) shows no hematite, indicating that it was formed after the hematite deposit. Similarly, the inflow from top may be newer than hematite. The authors suggested that these hematite deposits were formed by chemical precipitation from aqueous fluids, and TES data provide evidence that liquid water has been stable for millions of years on early Mars.

The Mars Exploration Rover "Opportunity" landed in Eagle crater on Meridiani Planum in the western part of the Sinus Meridiani region on January 24, 2004. Within a few days of landing on Mars, the Opportunity rover sent pictures of large numbers of spherules, as shown in false-colored images in **Figures 2** and **3** [4].

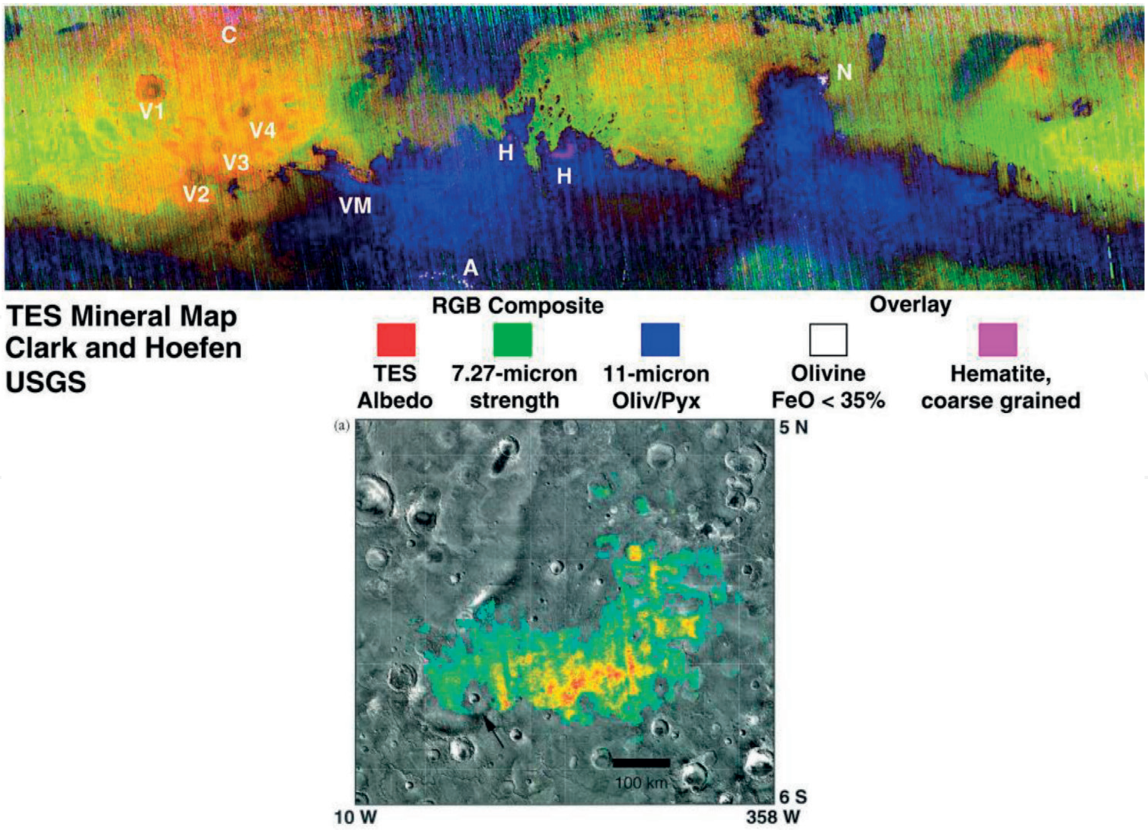

Figure 1.
Global distribution of hematite on Mars using the thermal emission spectrometer on the Mars Global Surveyor Spacecraft (top image). Bottom image is a close-up view of hematite abundance in Sinus Meridiani. (Image courtesy of USGS, NASA/JPL).

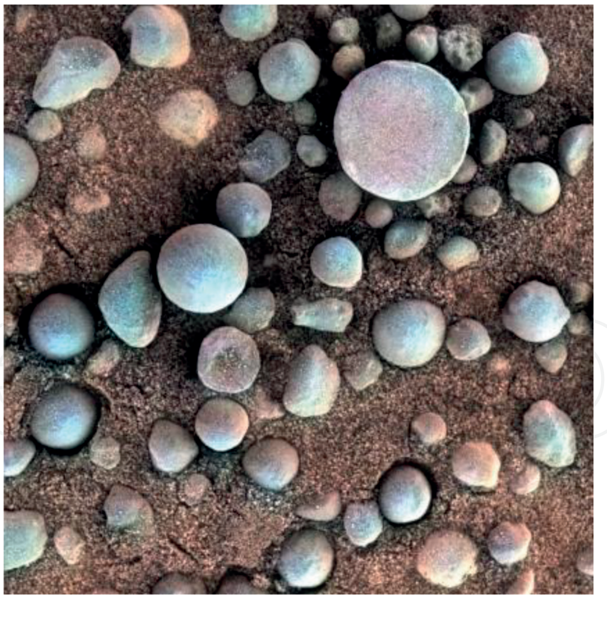

Figure 2.
Observations of hematite spherules at Meridiani, Mars, by the Opportunity rover. (Image courtesy of NASA/JPL).

The spherules were studied using instruments on board the Opportunity rover. The Mössbauer spectrometer was used to confirm the mineralogy of the spherules as hematite. A rock abrasion tool (RAT) was used to cut some of the spherules and concluded that spherules are also very hard. The rover instruments provided ground validation data confirming the presence of hematite on Mars as predicted by the orbital TES data obtained by the MGS spacecraft. The gray hematite spherules

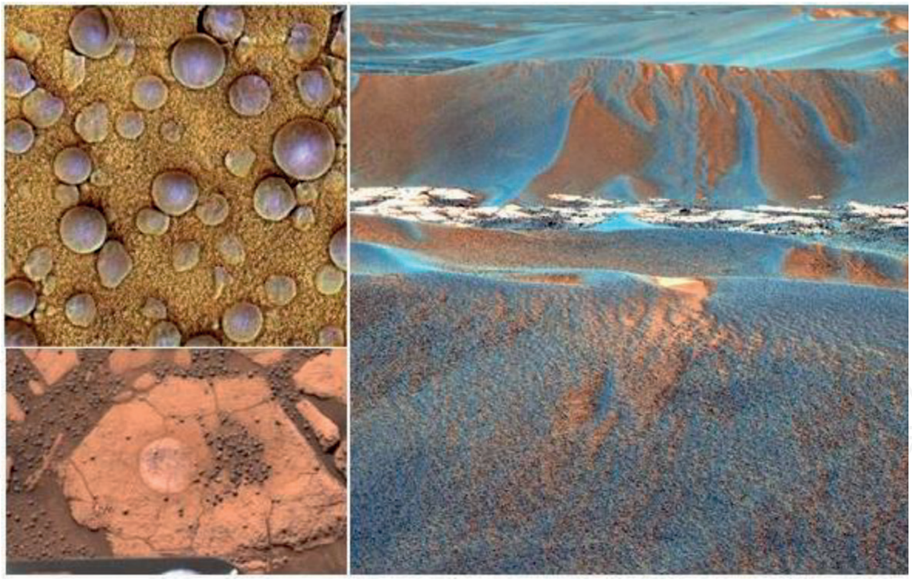

Figure 3.
Observations of hematite spherules at Meridiani, Mars, by the Opportunity rover. (Image courtesy of NASA/JPL).

appeared blue in the false-colored data from Mars and were therefore nicknamed "blueberries." The discovery of Martian blueberries quickly became an exciting scientific discovery as leading scientists concluded that hematite spherules were concretions and that their discovery proved the presence of water in Mars history.

The idea that the Martian hematite spherules are concretions has been largely accepted by most planetary scientists for the past several years [3, 5–15]. Several scientists also found concretion terrestrial analogues in southern Utah, in the Jurassic Navajo Sandstone [16], and in Lake Brown, Australia [17]. In the next section, we will discuss the observed properties of the Martian hematite spherules, which will lead us to the controversy of the origin of these spherules.

2. Observed properties of Martian hematite spherules

Within a few days of operations, the Opportunity rover surprised the science community by sending pictures of a large number of spherules on Mars, now commonly known as blueberries [18]. The follow-up investigation [11, 13] by the NASA science team found several interesting observations of blueberries. Some of these observations are as follows: (i) the primary carriers of hematite at the landing site are blueberries and their fragments; (ii) the hematite was located mostly on the surface of the landscape; (iii) the deeper soil is mostly basaltic sand and is free of hematite; (iv) the blueberries are mostly perfect spheres; (v) the typical diameters of the blueberries are 4–6 mm; (vi) the blueberries are hard; (vii) the blueberries are made of very fine grain material; and (vii) the blueberries have no internal structure. In addition, all the hematite spherules appear to be located within the upper 10 mm thickness of the surface soil.

Figure 4 shows the result of the RAT used on the Martian surface to cut open some of the soil-embedded spherules. The spherules were found to be hard and difficult to cut. The spherules showed no internal structure with grain size below the detection limit (31 μm) of the Microscopic Imager (MI). Further investigation of the spherules found that there are two types of blueberries: larger blueberries with average size of 4 mm in diameter and microberries with average size of 0.79 mm in diameter. All blueberries were smaller than 6.2 mm in diameter with a median size of 4.2 mm.

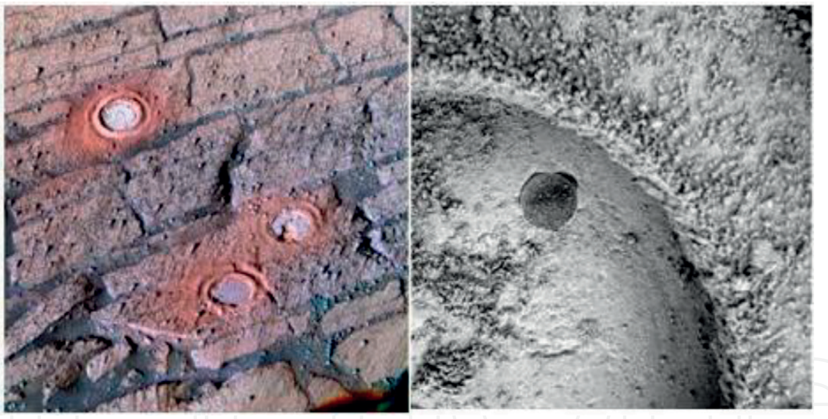

Figure 4.
Rock abrasion tool (RAT) was used to cut some of the spherules embedded in the soil. The hematite spherules show no internal structure. (Image courtesy of NASA/JPL).

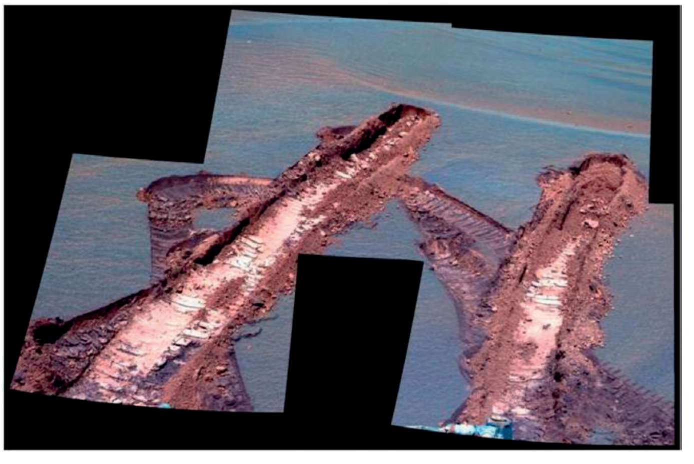

Figure 5.
Jammerbugt (sol 842) showing the trenches dug by the Opportunity rover. All hematite is located on the Martian surface and no blueberry was found in the deeper soil. (Image courtesy of NASA/JPL).

On sol 833, Opportunity got stuck in a fine-grained soil (named Jammerbugt) and it took 8 days for the operation team to free the rover. During this process, the rover's wheel dug deep trenches on Martian soil. **Figure 5** shows images of Jammerbugt taken by the rover on sol 842 (June 7, 2006) using the panoramic camera. **Figure 5** shows that all the hematite (blueberries, microberries, and fine dust) is limited to the top surface and trenches dug by the rover showed no sign of blueberries in deeper soil.

In summary, a very large amount of Martian hematite spherules was found to be mostly perfect hard spheres less than 6 mm in diameter with fine grain, no internal structure, and located within 10 mm of the Martian surface.

3. Comparison of Martian hematite spherules and Earth's concretion analogues

It has been suggested by various scientists that the Martian hematite spherules are concretions. Because concretions are formed by water on Earth, this carries the significant scientific implication of proof of water in Martian history. We will first examine the properties of Earth's concretions to see if they are suitable for classifying them as terrestrial analogues of Martian spherules. A concretion is a compacted mineral body that is embedded in a host rock, which has a different chemical composition. Terrestrial concretions are formed from liquid phase by precipitation, nucleation, and growth processes.

Figure 6.
Earth's concretion analogue samples from the Jurassic Navajo Sandstone, southern Utah (courtesy William Mahaney). A 6.4 mm diameter steel ball is also shown for size reference.

The concretions can grow in size and are found in various sizes and shapes. They are rarely perfect spheres and have no size limitation. Examples of terrestrial concretions (Jurassic Navajo Sandstone, southern Utah), which have been cut to show their internal structure, are displayed in **Figure 6**. The concretions are usually round objects with heterogeneous internal structure and are rarely perfect spheres. They are not limited in size and can grow to a diameter of several centimeters and even meters. **Figure 6** also shows a steel ball with a diameter of 6.4 mm. The blueberries on Mars are all less than 6.4 mm in diameter and have similar physical properties to the steel ball.

Next, we look at the chemical composition of the concretions found on Earth. Raman spectroscopy is considered as a fingerprint technology for chemical identification. Raman spectra represent the vibrational modes of a molecule and all different chemicals have unique Raman spectra; for example, no two chemicals have the same Raman spectrum. Hence, Raman spectra can identify a chemical with 100% confidence level. Presently available commercial micro-Raman systems are capable of identifying small mineral grains in the nanogram range. Micro-Raman spectroscopy with 785 nm laser excitation has been used to identify the chemical compositions of Earth's concretions. Raman spectra were measured at multiple locations on all the samples. **Figure 7** shows representative Raman spectra of hematite, rose quartz, and goethite with both brown and black grains of Earth's concretions. The Raman spectra of the brown grains of concretions, which are located inside of concretions, are same as the Raman spectrum of quartz. This confirms that the interior composition of Earth's concretions is quartz with grain size of the order of 150 microns. The outer darker layers of the concretions also show the quartz Raman band along with Raman peaks of goethite. This suggests that the dark layers are made of quartz coated with a thin layer of goethite. This chemical analysis of Earth's concretions suggests that they are not hematite, which is consistent with reference [19].

In the formation of concretions, water containing dissolved minerals cement around the grains of the host matrix, which is why grains of host matrix are always included in the Earth's concretions [17]. In fact, none of the concretions on Earth are made of pure hematite; they can be hematite-coated quartz or calcite. The concretion mechanism cannot remove the grains of the host matrix (quartz, calcite, etc.) and replace them with pure hematite mineral. It may be possible to form pure

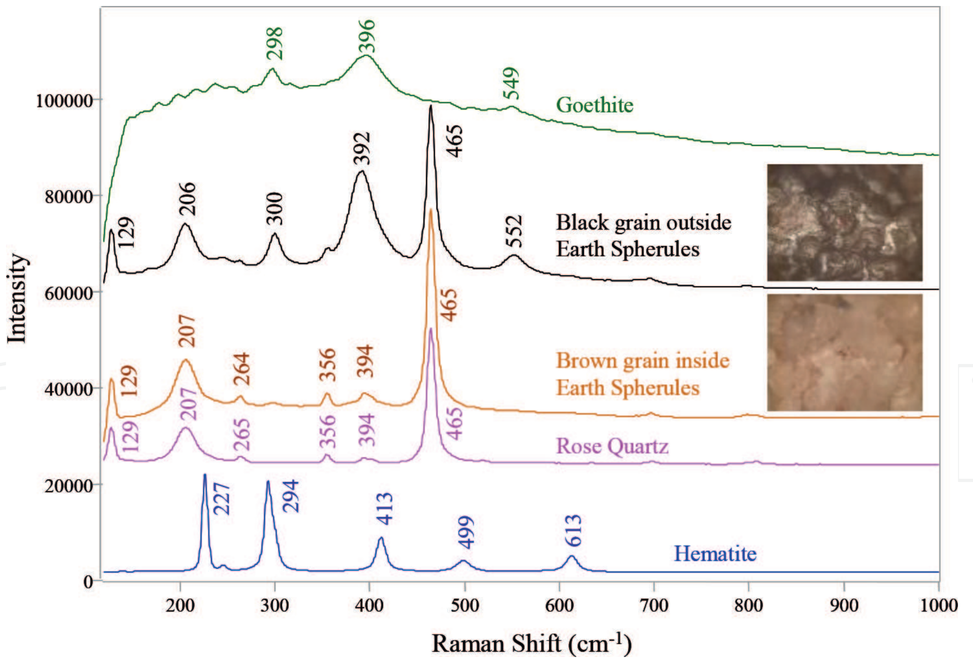

Figure 7.
*The Raman spectra of concretions shown in **Figure 6** confirm that the interior of the concretion is mainly quartz. The outer dark grains are made of quartz, which are coated with goethite.*

hematite crystals from an aqueous solution but it will have the shape of a crystal and not a perfect sphere. A recent attempt to form spherules by freezing an aqueous hematite nanoparticle suspension failed in a laboratory setting [20]. The concretion model does not explain the following: (i) why are the Martian hematite spherules limited in size? (ii) why are the spherules pure hematite? and (iii) why are grains of the host soil missing from the interior of the spherules? The formation of concretion from aqueous media also leads to another interesting fact: concretions are formed deeper in the soil. This is because during the dry season, the level of ground-water goes down. This increases the concentration of dissolved chemicals in the subsurface soil, which favors the formation of concretions in deeper soil. For Earth's concretions, a relatively larger number are observed in the deeper soil [17] than the top surface layer. In contrast, the Martian blueberries are mostly concentrated within 1 cm of the top surface [11, 13, 17, 21]. No blueberries were observed in the deeper soil when trenches were excavated on Mars [6, 11–13] as shown in **Figure 5**.

In addition, Earth's concretions are not as shiny as some of the Martian blueberries. This is because on Earth erosion plays a critical role in the formation of concretions. Concretions are formed inside the host matrix and are released from the host matrix by eroding away the surrounding material. The erosion of surrounding material takes several thousand years. Therefore, it is easy to see signs of erosion, pitting, and flow patterns due to the presence of aqueous media on Earth's concretions, which appear as dull metallic-looking objects [16, 17]. The erosion process plays a critical role in the formation of concretions and dictates that the Earth's concretions are very old [17].

Figure 8 shows an image (sol 251) of a large 1 m long rock, "Wopmay," found on the Endurance Crater, showing hundreds of blueberries on its surface. The NASA science team suggested that the blueberries in the region are embedded in the rocks and eroding from them [11, 13]. One of the problems with this conclusion is that all the blueberries observed on the rock are fully exposed spherules and no blueberry is seen emerging from the rock. It is expected that the erosion process would reveal some partially exposed blueberries on the rock if they are concretions. In addition, rock erosion produces soil that has a similar reddish color as the rock and would

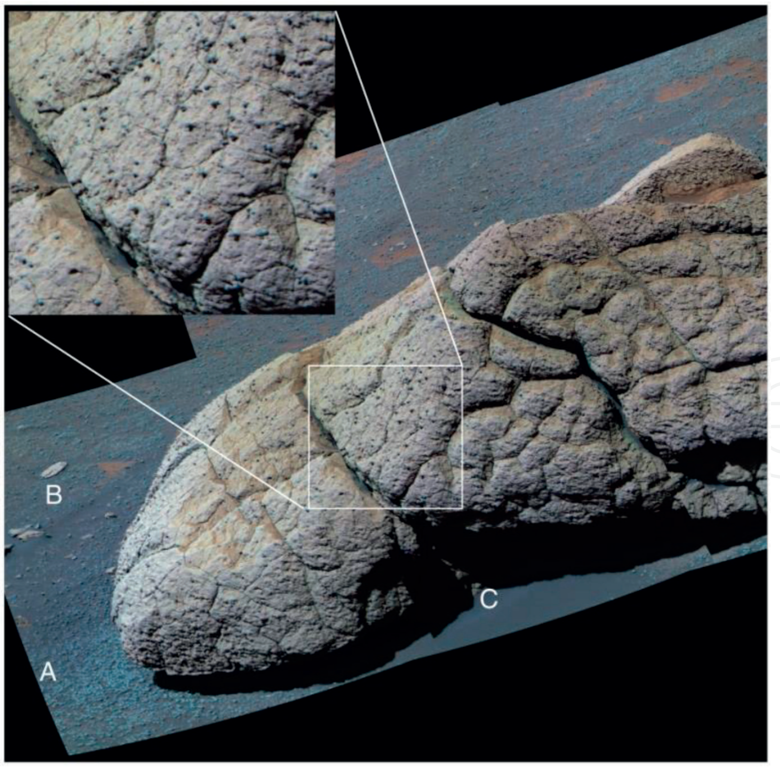

Figure 8.
Image showing hundreds of fully exposed blueberries on "Wopmay Rock" and nearby area. No blueberries are observed in region C (sol 251). (Image courtesy of NASA/JPL).

be mixed in with the bluish-looking soil. Lastly, the distribution of blueberries in the region and around the rock is consistent with the hypothesis that they fell from above. Region A, which is near the slope of the rock, shows a high concentration of blueberries as compared to region B, which is away from the rock. Also, in region C, in the shadow of the rock, there are no spherules, which contradicts the concretion mechanism. Another interesting observation is that spherules are heavy and therefore not easily transported by dust devil events. Otherwise, there would be no spherules on the slopes of the rock and region C would be filled with spherules. The observation of spherules on Wopmay rock suggests that blueberries fell from the top and are not eroding out of the rocks. The hypothesis of deposition of blueberries from the top is also consistent with the observation that the entire blueberry inventory is within 1 cm of the top surface layer.

4. Blueberries as cosmic spherules

There are two possible methods for depositing large number of hematite spherules from the top: (1) meteorite deposition and (2) volcanic deposition. Out of these two models, we suggest that the meteorite model is more consistent with all the observations of blueberries on Mars because, at present, there are no active volcanoes on Mars. Later, in this chapter, we will see evidence that some of the blueberries are very young as they have recently landed on the rovers and heat shield. This also favors the meteorite theory over volcanic deposition. According to the meteorite theory, meteorites of various sizes enter the Mars atmosphere at high speed and low temperature. When meteorites enter the Martian atmosphere, they feel friction and ram pressure, which heats up the meteorite. On Earth, commonly observed shooting stars suggest that heating can achieve very high temperatures, which make the meteorites glow. Under Martian conditions, the smaller meteorites can be completely melted. The liquid melts and then breaks down immediately into

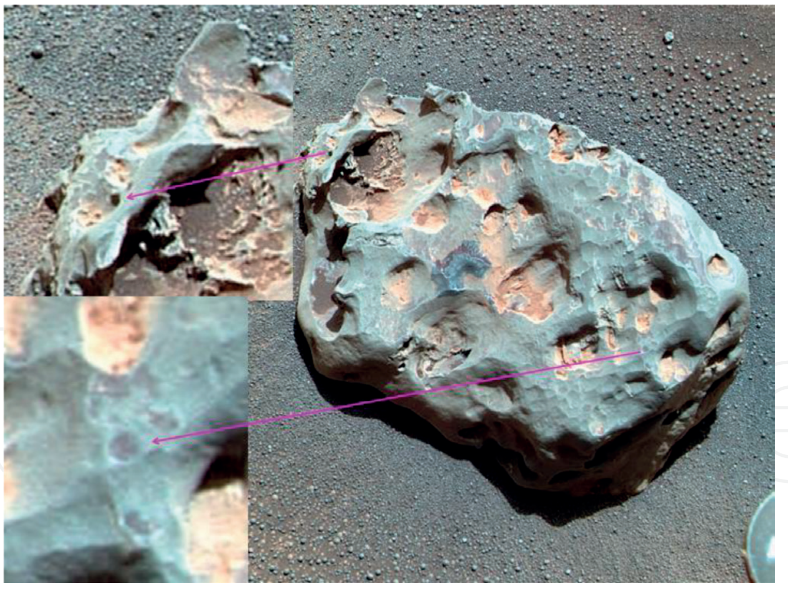

Figure 9.
Image of "Heat Shield Rock," an iron meteorite observed on Mars. Several blueberries and microberries are observed in the close vicinity of the meteorite. Image taken from Sol 352, courtesy of NASA/JPL/Cornell.

smaller spherical drops whose size is determined by the surface tension of the liquid and the atmospheric drag force. Smaller drops soon achieve terminal velocity due to lower mass, which causes the temperature of the liquid drop to fall and become solid. Depending on the size of the meteorite and the time of flight, some of the drops will hit as solid balls and others as liquid drops that form microberries on collision with the ground [22]. Larger meteorites need more time to melt completely because of their mass. In bigger meteorites, melting begins at the meteorite surface, and as soon as the surface liquid reaches a critical depth, the liquid falls away as drops. This prediction suggests that the fusion crust on a meteorite should be also limited in thickness, and meteorites should also show imprints on the surface matching the size of the liquid drop, which was removed from the surface.

On sol 339, the Opportunity rover observed an iron meteorite on Mars, which was named "Heat Shield Rock." **Figure 9** shows an image of Heat Shield Rock, which is mainly iron with kamacite as the primary Fe-bearing mineral and around 7 wt.% nickel [23, 24]. A first look at the immediate surroundings of the meteorite confirms the presence of large number of microberries and blueberries near the meteorite. The surface of the fusion crust shows regmaglypts and several circular imprints. The circular imprints give an estimate of the size of the molten drops that fell off from the meteorite. This size matches with the size of blueberries lying on the ground. Several microberries and miniberries also form on meteorite impact with the ground from the liquid layer, which is still attached to the meteorite before impact. These microberries and miniberries will be distributed near the meteorite. A larger concentration of smaller blueberries and nano–dust particles forming a halo can be seen in the immediate surroundings of the meteorite (**Figure 9**). The image also shows several spherules on top of the meteorite. This image provides very strong direct evidence that Martian blueberries are cosmic spherules formed from the ablation of a meteorite. In addition, the same image also provides a strong evidence that blueberries are not concretions as iron meteorites do not carry enough water for concretion formation.

The formation of blueberries through molten meteorite drops also explains why all the observed blueberries on Mars are limited in size and are mostly perfect spheres with no internal structure and fine grain size. The size and shape of the blueberries are determined by the phenomenon commonly known as surface tension. On Earth, we can use raindrops as analogues: their sizes and shapes are controlled by the surface tension of water. The size of a raindrop can be estimated by assuming that the water drop will break up if the atmospheric drag force is greater than the surface tension force. When the gravitational force equals the atmospheric drag force, the raindrops achieve terminal velocities. These conditions give the estimated diameter of the raindrop (D) to be proportional to [25]:

$$D \propto \sqrt{\frac{\sigma}{g\rho}} \tag{1}$$

where σ is the surface tension of the liquid, *g* is the acceleration due to gravity, and ρ is the density of the liquid. The above equation can be simplified using two different types of liquids to give equation:

$$\frac{D_2}{D_1} = \sqrt{\frac{\sigma_2 g_1 \rho_1}{\sigma_1 g_2 \rho_2}} \tag{2}$$

where subscripts 1 and 2 represent two different types of liquids. By assuming that the melting of iron meteorites forms spherules, we can estimate the diameter (D_2) of Martian spherules. Using σ_1 = 0.073 N/m surface tension of water, g_1 = 9.8 m/s^2 as Earth gravity, ρ_1 = 1000 kg/m^3 as density of water, σ_2 = 1.46 N/m surface tension of molten iron [26], g_2 = 3.675 m/s^2 as Mars gravity, and ρ_2 = 7860 kg/m^3 as the density of iron gives D_2 = 2.6 D_1. According to the U.S. Geological Survey (USGS) website, raindrops that are spherical in shape are usually 1–2 mm in size (**Figure 10**). Larger drops with diameter of 3 mm are sometimes formed but are not spherical in shape [27, 28]. When the raindrop reaches a diameter of 4.5 mm, it opens up like a parachute and immediately breaks up into smaller drops and microdrops. One of the important features of the meteorite model is that it puts a size limit on the diameter of hematite spherules on Mars. Accordingly, hematite spherules on Mars would be spherical in shape if the diameter is less than 5.2 mm. Larger spherules are not expected to be perfect spheres and no spherules are expected to reach the size of 12 mm, which corresponds to immediately breaking up into smaller spherules and microspherules by opening up like a parachute. The meteorite theory correctly predicts the size limit of millimeter-size blueberries and also predicts the formation of a large number of perfectly spherical microberries and nanophase material.

One of the puzzling observations on Mars is that there are very large numbers of blueberries (**Figure 3**) and the vast majority of spherules are isolated spheres. The Opportunity rover observed doublets and triplets [3, 5, 13, 15] as shown in **Figure 11** but these instances were very rare. It is important to note that the observation of large numbers of blueberries and microberries does not suggest a large number of meteoritic

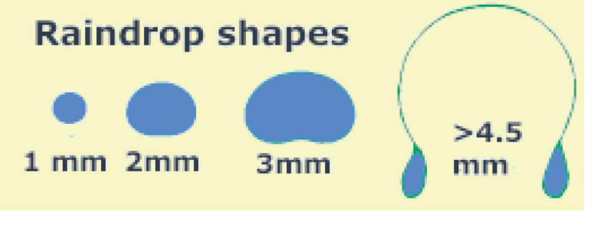

Figure 10.
Raindrop shapes with various sizes. (Courtesy USGS website).

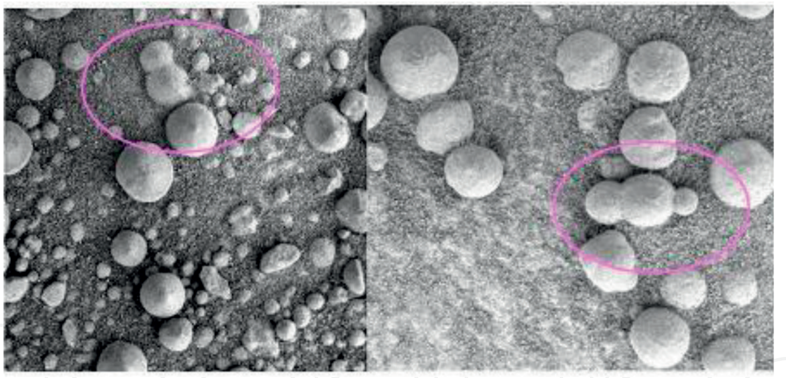

Figure 11.
Observed doublet and triplet blueberries on Mars.

events on Mars. A single small meteorite can produce a large number of spherules. For example, a 2-inch diameter meteorite is equivalent to 2048 spherules with diameter of 4 mm. In addition, a small meteorite entering the Martian atmosphere will distribute thousands of spherules over a large area on Mars along its trajectory. A very large number of spherules could also be formed during a meteorite shower event. Another important observation is that the population of doublets and triplets is very low in comparison to isolated spherules, which can be explained by the meteorite ablation mechanisms. The doublets can be formed when two liquid drops come in contact. However, in the liquid phase, this simply forms a bigger drop and immediately splits up into smaller drops. Similarly, two solid spherules will simply stay as two individual spherules and not form a doublet. For a doublet to form, the recombination of two spherules must occur near the liquid-solid phase transition. This significantly reduces the probability of the formation of a doublet or triplet. The meteorite model also predicts that doublets and triplets are more likely to have spherules of different diameters than the same diameter. This is because the doublet is more likely to form when one drop is moving faster than the other drop. Because the terminal speeds of drops are proportional to their masses, the doublets and triplets would be composed of spherules of different sizes as shown in **Figure 11**.

Because meteorites can fall on Mars at any time, there are other requirements that need to be satisfied for a meteorite ablation model. The first requirement is that new young cosmic spheres should be observed along with older spherules. The second is that cosmic spherules of other compositions should also be observed. **Figure 12** shows very shiny younger spherules among the older spherules.

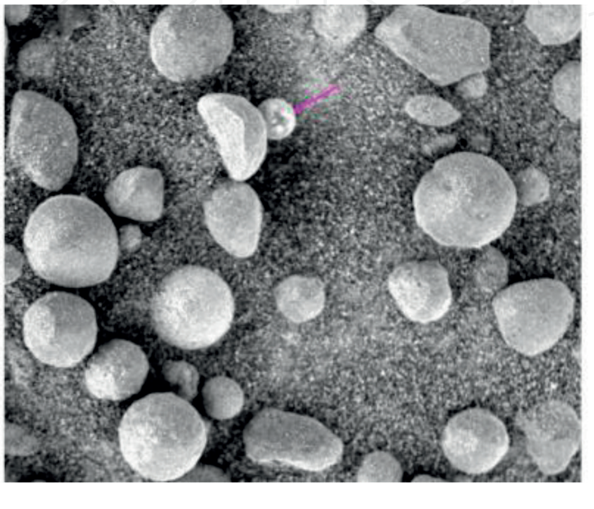

Figure 12.
Coexistence of younger and older spherules on Mars.

Figure 13.
Coexistence of yellow berries along with blueberries.

This observation is in agreement with the meteorite ablation model. However, it is very difficult to explain the coexistence of old and new spherules on Mars with the concretion model, which will require evidence of water appearing, disappearing, and reappearing on Mars. **Figure 13** from sol 319 shows the coexistence of both blue and yellow berries. In this false color image, the color indicates a change in optical reflectance, which indicates different chemical compositions for the blue and yellow berries. In the next section, we will look at the evidence that strongly supports the cosmic spherule mechanism.

5. Further evidence of cosmic spherules

The observations on Mars made by rovers shown in this section can only be explained by a meteorite model. There is a very small probability that man-made objects such as the rovers and heat shield will collect cosmic spherules from recent meteoritic events. However, for the meteorite model to be correct, there are few conditions: (1) the sizes of the spherules must obey the predicted size limit and (2) the spherules must look shiny in comparison to older blueberries, indicating younger age because the rovers landed on Mars in 2004.

Figure 14 from sol 339 shows a piece of the heat shield of the Opportunity rover. Because blueberries are spherical, they are most likely to collect at the bottom of a slope on the heat shield. The photograph clearly shows several fresh-looking blueberries collected on the heat shield. The size and texture can be compared with the older blueberries seen on the ground.

The images taken by the Opportunity rover of itself are shown in **Figure 15** (top image: sol 322; bottom image: sol 323), which show few blueberries collected by the rover. The size of these shiny spherules are similar to the size of the older, dull-looking blueberries lying on the ground as seen in the top right corner of the image shown in **Figure 15**. Further strong evidence in support of meteorite model is shown in **Figure 16**. If the spherules are formed by molten drops of falling meteorites, then they are expected to be very hot. **Figure 16** shows the image (1M156679326EFF3981P2979M2M1) taken on sol 321 of the solar panel by the microscopic imager on Opportunity. The image shows a burned impact mark at location 'B' along with few microspherules nearby shown as 'A.' The burn mark size and shape match the nearby spherules.

The other Mars rover "Spirit" landed in the Gusev Crater area. According to the MGS satellite image, this site is not rich in hematite. Hence, Spirit rarely observed spherules on the ground. The images from the Spirit rover taken on sol 330 show a few spherical objects on the solar panels marked by green circles (**Figure 17**, left).

Figure 14.
Evidence of fresh blueberries collected by heat shield. Image 1P158281536EFF40C2P2368L6M1 (sol 339). Image courtesy: NASA/JPL & M Lyle.

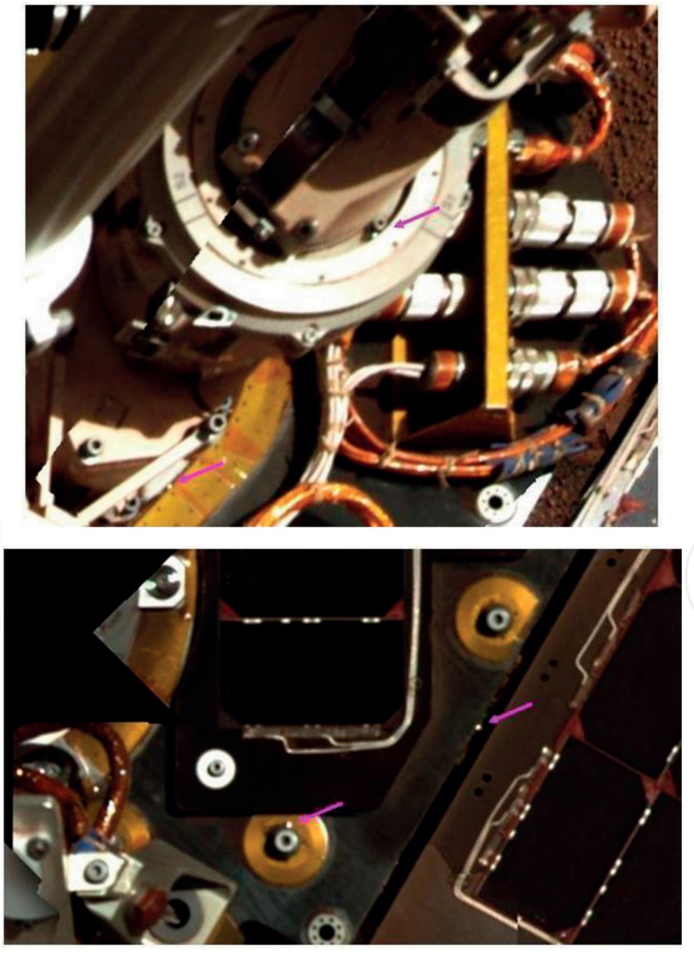

Figure 15.
Images of Opportunity rover showing shiny spherules collected by the rover. Sol 322 (top image) and Sol 323 (bottom image).

An image (**Figure 17**, right) of the same solar panels taken on sol 583 almost a year later shows that two of the objects have rolled off leaving behind the impact prints. A few new spherical objects have appeared near the electrical wirings. The ability

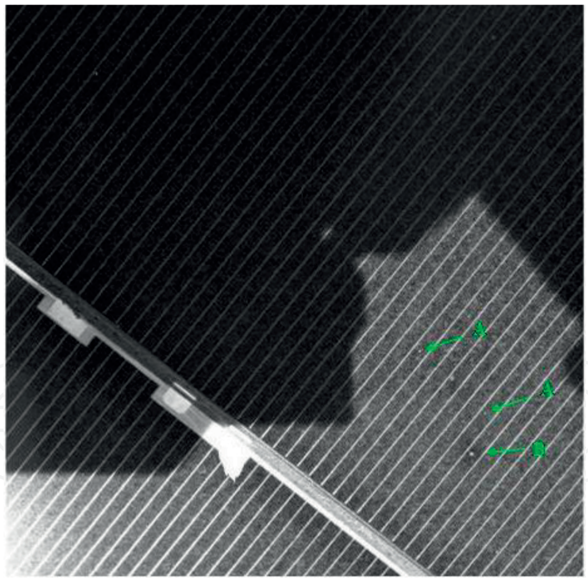

Figure 16.
Opportunity solar panel sol 321.

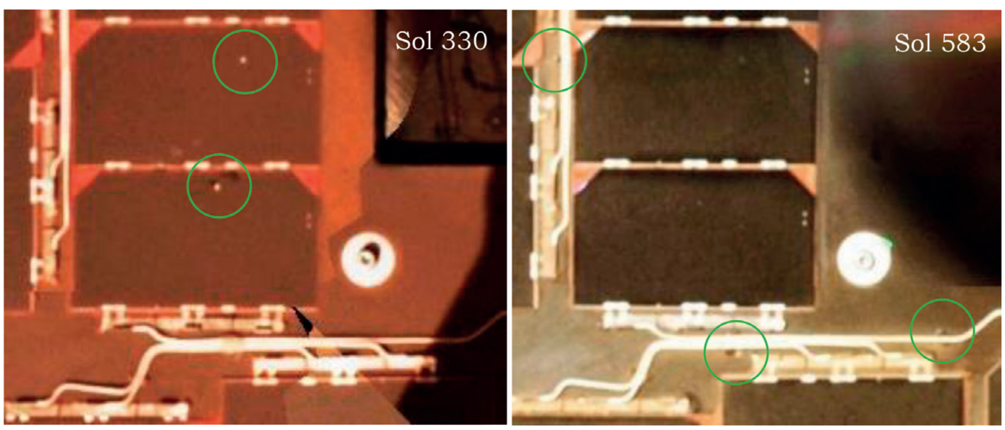

Figure 17.
Images comparing the same solar panels of Spirit rover from sol 330 and sol 583 showing blueberries that have rolled off a year later from solar panels.

of these round objects to leave impact marks on the solar panels indicates the high terminal speed of the spherules.

6. Discussion

The various observations of Martian blueberries strongly support the theory that the spherules are cosmic spherules formed from the ablation of meteorites. The images shown in **Figures 9** and **14–18** can only be explained by the meteorite model. In the meteorite ablation model, the cosmic spherules are formed from the liquid phase. Hence, they will be perfect spheres, hard, and size limited. The interior of the spherules will be glassy or extremely fine grained, and will not show nucleation or inclusions of basaltic grains of Martian surface. The blueberries, microberries, and nanophase material will be located only on the top soil and missing from the deeper soil. To date, all observations (listed in **Table 1**) made on Mars are consistent with the meteorite ablation model. To the best of our knowledge, no hematite concretions have been found on Mars and concretions made of pure hematite do not exist on Earth. The cosmic spherule mechanism also suggests that hematite found on the surface of Mars is extra-Martian and not native to Mars.

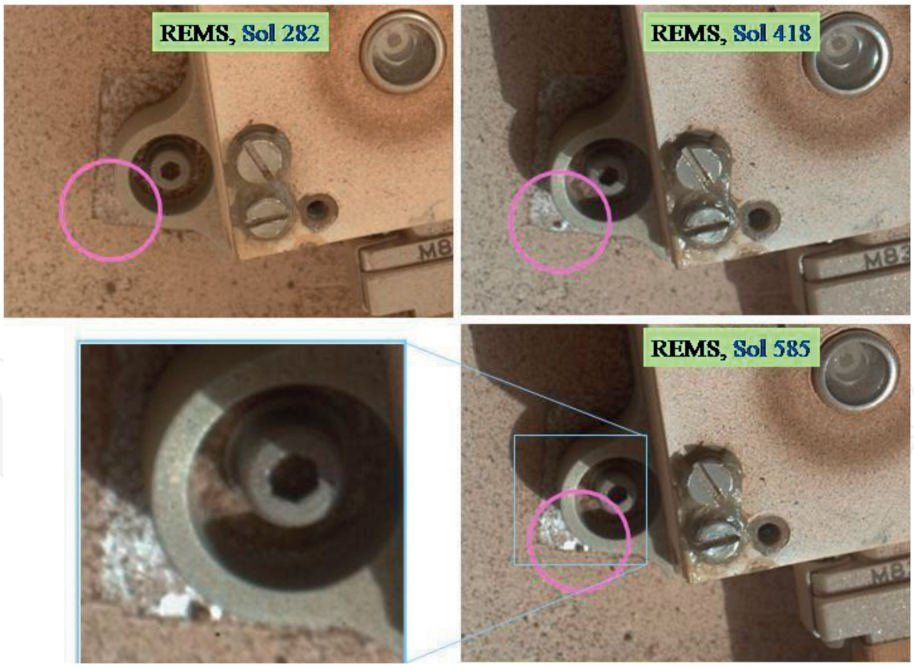

Figure 18.
Images of REMS-UV sensor on Curiosity rover showing a cosmic spherule impact.

A big iron meteorite or a few meteor shower events can produce a large number of spherules on Mars. About a billion spherules of 4 mm in diameter can be produced by a 4 m diameter meteorite. Because the spherules are heavy, the distribution of spherules at the Meridiani is expected to be sharply defined, immobile, and elliptical due to trajectories of the meteors. The age of the hematite deposit on Meridiani has been suggested by reference [3] to be in excess of 3.5 Ga. Opportunity rover did discover several large iron meteorites in the Meridiani Planum [23, 29]. Some scientists [30] have argued that the six iron meteorites found at Meridiani are the result of a single rare event of a large meteorite impact.

Mössbauer data from the Opportunity rover concluded that blueberries at Meridiani Planum are made of hematite [18]. It is possible to form hematite in a CO_2 atmosphere at temperatures above 900°C from high-FeO glass-rich basalts [31]. One possible redox reaction for the formation of hematite from iron meteorite is $2Fe + 3CO_2 = Fe_2O_3 + 3CO$. For meteorites that have some iron, it is possible to form hematite-coated spherules. Cooper et al. in Ref. [32] determined that at 700°C and FeO concentration > 1.9 wt%, the Fe migration is favored over Ca and Mg migration. The evidence for the formation of hematite particles at 60 km altitude on Earth has been suggested by [33].

It is interesting to note that Earth's Moon has no atmosphere and meteorites on the Moon do not get heated due to drag force. The spherules formed on Moon are mostly due to impact heating and are known as impact glass spherules. On Earth, millimeter-sized cosmic spherules are found in abundance [34–37]. The large amount of cosmic spherules on Mars could be due to its proximity to the asteroid belt [23]. Mars also has low gravity and thin atmosphere that are favorable conditions for forming large spherules.

A direct evidence of a cosmic spherule on Mars is shown in **Figure 18**. In 2012, NASA's "Curiosity" rover landed in Gale Crater. **Figure 18** shows images of the REMS-UV sensor, which is placed within the rover deck facing the sky. The sol 418 image shows that a small cosmic spherule has landed on the UV sensor, which was not observed in a previous image (Sol 282). The image taken on sol 585 shows that the spherule has rolled slightly to the right revealing the original impact spot.

Observations	Agreement with meteorite model
1. Millions of blueberries found on Mars (population)	Yes
2. All blueberries are less than 6.2 mm in diameter (size limitation)	Yes
3. Predominantly perfect spheres (shape)	Yes
4. Blueberries show no grain structure (internal structure)	Yes
5. Blueberries show no nucleation (mechanism)	Yes
6. Coexistence of old and fresh blueberries (age difference)	Yes
7. Coexistence of blue and yellow berries (chemical difference)	Yes
8. All blueberries limited to top soil and missing in deeper soil (location)	Yes
9. Interior of blueberries missing grains of host soil (pure phases)	Yes
10. Hematite (composition)	Yes†
11. Large amount of microberries observed only on top surface (population and location)	Yes
12. Blueberries appear embedded in soil (location)	Yes
13. Hard (mechanical strength)	Yes
14. Circular burn spot on solar panel (hot impact)	Yes
15. Rare observation of doublets and triplets (mechanism)	Yes
16. Doublets and triplets are made of different-sized spherules (mechanism)	Yes
17. All blueberries on Wopmay rock are fully exposed (mechanism)	Yes
18. Blueberries found on man-made objects (heat shield and Opportunity and Spirit rovers) (recent events)	Yes
19. Blueberries on heat shield and rovers are shiny (young age)	Yes
20. Blueberries found on and near iron meteorites (mechanism)	Yes

†*Other chemical phases are also possible.*

Table 1.
Observations and physical properties of Martian blueberries and their comparison with a meteorite model.

7. Conclusion

Some of the important observations of Martian blueberries cannot be explained by a concretion model. These observations include the following: (1) spherules are size limited, (2) they are located only on the top soil, (3) they show no internal structure, and (4) they lack grains of the host matrix. In addition, the distribution of spherules suggests that they fell from above, as shown in **Figure 8**. The observations of spherules collected by the heat shield and rovers suggest that these spherules are very young and cannot be explained by the process of aqueous alteration, which requires a significantly longer period of time. The observations of spherules and nanophase materials near the meteorites are direct evidence that spherules are meteoritic in nature. The meteorite ablation model producing cosmic spherules on Mars explains all the observations and properties of Martian blueberries. According to this mechanism, while traveling through Martian atmosphere, a meteorite gets very hot, reaches melting temperatures, and forms liquid molten drops that reach terminal speeds due to drag force and cool down to solid spherules and microspherules. The maximum size of the spherules is limited by the surface tension of the molten material and atmospheric drag force. The spherules are expected to be mostly perfect hard isolated spheres, with no internal structure and nucleation, and located only on the top surface layer. The meteorite mechanism also suggests that hematite found on the surface of Mars is extra-Martian.

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