Carbonaceous chondrites as bioengineered comets

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ABSTRACT

The discovery of microfossils on carbonaceous meteorites has electrified the public with the first concrete evidence of extraterrestrial biology. But how these organisms colonized and grew on the parent body-the comet-remains a mystery. We report on several features of cyanobacteria that permit them to bioengineer comets, as well as a tantalizing look at interplanetary uses for magnetite framboids that are found in abundance on carbonaceous chondrites. We argue that these structures provide important directionality and energy harvesting features similar to magnetotactic bacteria found on Earth.

1. INTRODUCTION

The presence of cyanobacterial fossils on carbonaceous chondrites–black, crumbly meteorites widely believed to be extinct comets–suggest that not only has bacterial life thrived in extraterrestrial environments,¹ but that their growth has modified their cometary environment.² In a previous papers^{2–4} we document a number of modifications that cyanobacteria can make to their cometary home: they can provide a polysaccharide binder (slime) that increases the tensile strength of the chondritic or granular matrix; polysaccharides blacken in the presence of ultraviolet light to lower the surface albedo; polysaccharide layers rupture at the high temperatures of the subsolar point to locally generate steam jets that provide an "anti-stellar-accretion" force; and polysaccharides lower the freezing point of pure water so as to provide a longer growing season. All these modifications of the environment are a result of the extracellular polysaccharide sheaths, which cyanobacteria produce in abundance, but whose presence must be inferred from the ubiquitous kerogenic carbon microfossils of the original biomolecules created millions of years ago.

By way of contrast, magnetite grains are essentially unchanged since their origin, and if they are created biologically,^{5, 6} preserve their unique structure for millions of years.⁷ We argue that the magnetite grains in carbonaceous chondrites are even stronger evidence than keragen that not only were they created biologically, but that they modify the cometary environment in subtle ways to enhance the growing season and perhaps even spread life more efficiently to other galaxies. Therefore we first present evidence that the magnetite is biological, we then compare cometary bio-magnetite with terrestrial bio-magnetite, and finally we speculate on the unique properties of cometary magnetite.

1.1. Terrestrial

1.1.1. The presence of biologically produced magnetite inclusions

The literature on this topic is very recent, since the discovery that biology forms magnetite was only made in 1962,⁵ and the discovery of magnetotactic bacteria was only made in 1975.⁶ Since then the field of biomagnetism has exploded.^{8–12} Not only do bacteria orient themselves with chains of spontaneously magnetized, stable single-domain magnetite (SSD), but eukaryotic algae orient with multiple magnetosome chains,¹³ and bees, bats, whales,¹⁴ fish (trout), and homing pigeons¹⁵ are all thought to use the compass-needle effect of a long chain of SSD magnetite. Other magnetic transducers have been examined,¹⁶ but without any evidence that biology uses these weaker responses.

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Figure 1. Left: Magnetic domain type classified by size and shape.²⁰ Right: Polished section of Orgueil showing three sizes of magnetite: (a) large spherules, (b) layered plaquettes, and (c) small (disordered) framboids.²¹

1.1.2. Their presumed function

In magnetotactic bacteria, the compass-needle effect aligns the bacteria along the magnetic field whether alive or dead, demonstrating that the torque exerted by the chain of SSD magnetite is a sufficient force to rotate the bacterium without active control. Likewise in trout, the epithelial cells that respond to magnetic fields need not be alive to align with the magnetic field.¹⁵ Subsequent to this passive alignment, the bacterial flagella or eukaryotic organelles can provide active sensing and motor control, so as to use this information for transport.¹⁷ (It also seems likely that the three-dimensional diffusive transport of bacteria is strongly suppressed in the fractal domain of the institial layer of sandy marine sediments (subdiffusion), but that magnetic alignment reduces the dimensionality of the system to greatly improve diffusive transport.) Therefore both bacteria and eukaryotes likely include compass heading as but one input of directed transport. But whatever additional information is required, the principal use of magnetite in living cells is thought to be the torque effect of a compass needle.^{18, 19}

1.1.3. Fossil magnetite

If biology uses magnetite principally for its torque effect in an external magnetic field, then it must be magnetized, and without a biological equivalent of magnet poling, the only way to magnetize magnetite is by making it a stable single domain crystal. The domain size of magnetite is determined by the minimum energy state of the spin-coupled iron atoms in the presence of thermal noise and external fields. Spherical domains minimize the thermal noise, but also minimize the spin coupling. Prolate domains maximize the spin coupling to external fields, but increase the thermal noise. Consequently there is a transition from small ~ 200 nm domain sizes that are stable single domain (SSD) magnets, to ~ 400 nm metastable single domain (MSD) magnets that require an external field contribution, to ~ 1 micron multiple domain (MD) ferrites (see Figure 1.1.3.)

Most of the magnetite that is found in marine sediments and clays is nanocrystalline SSD, though occasionally micron-sized or larger MD magnetite is found. In the case of chiton teeth, the MD magnetite biominerals are thought to have a crushing function due to their superior hardness. However no one knows if the peculiar, arrowhead shape of some recently discovered MD biofossils served a unique magnetic role or simply a hardened mineral role.²²

Equally mysterious is the function of magnetic framboids, named after the french word for "raspberry" due to their appearance as bags of marbles. Magnetite framboids have been observed as fossils,²³ while greigite framboids have been recovered from fossils and living biofilms.²⁴ Both forms of these several micron diameter spherical assemblages of submicron SSD marbles are magnetic, since Fe_3S_4 greigite is in many respects identical to Fe_3O_4 magnetite, but their spherical shape lacks the compass needle torque of a linear chain. Despite not

knowing their function, we do know they are biologically constructed in a honeycomb-like matrix that gradually fills in 24

The "abiotic production" (ignoring the chemist) of pyrite framboids differs in several respects from both the fossils and the living biofilms. It appears that the pyrite goes through a magnetized greigite phase, probably during precipitation, which may account for the collection of SSD grains into a spherical ball.²⁵ However the SSD grains are coarsely faceted and of various sizes, completely unlike the fossils and living versions, and more representative of diffusion-limited growth from a supersaturated solution.²⁶

1.1.4. Summary

Our brief survey of the terrestrial data on bio-magnetic minerals demonstrates that the size is dictated by the need for SSD crystals, and that they are typically oriented in chains that supply a torque to the entire cell. Occasionally bio-minerals form larger MD crystals whose shape suggests a function unrelated to magnetic activity, but whose finely faceted form reveals a biological control of crystal size. Framboids are likewise made in biofilms with strict control on their shape and size so as to produce highly magnetic assemblages of SSD magnetic marbles, but do not seem to serve either a magnetic torque or a hardened teeth-like function. In all cases, the shape and size of the crystals indicate strict biological control over their formation, and can be easily distinguished from abiotically precipitated minerals.

2. EXTRA-TERRESTRIAL MAGNETITES

Nanocrystalline magnetites have been observed in many extra-terrestrial environments, including martian rocks and primitive carbonaceous chondrites, thought to be the remains of extinct comets..^{1,27} They have not been recovered from the regolith of returned Lunar samples.²⁸ But from magnetite grains embedded in the ice of Antarctica, it estimated that 30-100 kTons of microscopic magnetite rains down on the Earth every year,²⁹ most probably from carbonaceous chondrites.

2.1. ALH84001

Martian meteorite ALH84001 has garnered a great deal of attention as supportive of life on Mars.^{30, 31} Since none of the Martian landers since Viking 1 & 2 discovered life with the Labelled Release experiment^{32–35} have been permitted to look for life, the best microscopic example we have has been meteoritic. And some of the best evidence of biological activity has been magnetite biominerals that survive the trip from Mars.^{36, 37} Buseck finds it compelling that chemists in a laboratory can duplicate the work of bacteria, and thus argues that these minerals are abiotic, though it would just as logical to argue that such "abiotic" production shows these crystals to be far from equilibrium shape and involve quite precise environmental controls, that if anything, are less likely than Levin's Martian biology. As is true of marine sediments on Earth, there is no evidence that any of these Martian nanocrystals are arranged in the chains seen in living bacterial magnetosomes.³⁸ However, all are in agreement that the SSD magnetite embedded in carbonate, with the rounded, 111-faces and prismatic crystal shapes is unlikely to have formed by typical igneous and metamorphic conditions.^{39–41}

2.2. Carbonaceous chondrites

It is entirely possible that the magnetites found on ALH84001 were deposited by meteorites, so the common trait for both Earth and Mars that needs explaining is the ubiquitous presence of nanocrystalline magnetites on carbonaceous chondrites. The parent body of this rare type of meteorite is generally acknowledged to be extinct comets..¹ Originally, carbonaceous chondrites were classified by their water content, though later categorization used the highest temperature experienced by the meteorite.^{27, 42} But examination of carbonaceous chondrites of all classes reveals nanocrystalline magnetite in concentrations of 1–16 percent by weight, roughly correlated with their water content..⁴³

Comets have the characteristics of undifferentiated proto-solar nebular material, since the chondrules are mineral grains thought to have condensed directly from supernovae and Wolf-Rayet stellar winds with little or no igneous or metamorphic reworking as seen on differentiated asteroids and moons, and depending on category, may have never seen temperatures above 100 or 200 C. The only "recent" modification appears to be extensive aqueous alteration, which we attribute to melting when the comet comes inside the orbit of Mars–as it must to have landed on Earth.⁴⁴ If then comets are such pristine material, is the magnetite likewise an ancient chondritic component of the proto-solar nebula?

The most likely scenario for a nebular chondrite is for the iron released in supernovae explosions to have condensed into grains that later oxidized into magnetite. The reaction proceeds slowly at low temperature, but magnetite is not stable above 440K. If we take the very smallest magnetite grains, and assume they were 100nm iron nodules, we find that they did not have time to oxidize completely during the hot (planet-building) phase of the proto-solar nebula.⁴⁵ Thus the magnetite grains are most certainly not pristine chondrules, which is corroborated from analysis of the oxygen isotopes.

The triple isotopes of oxygen can be used to define a fractionation ratio, since many chemical and physical processes operate faster on lighter isotopes than on heavy ones. For example, evaporation of water from the oceans favors O16, so that freshwater lakes are depleted in heavy isotopes while ocean water is enriched in O17/O16 and even more in O18/O16. Multiple hydrologic cycles increase the difference, but always at by the same ratio of ratios. So if one takes the ratio of O17/O16 and plots it against O18/O16 on log-log scale, the data for Earth fall on a straight line whose slope corresponds to this hydrologic ratio. In constrast, the oxygen in meteoritic olivine has never gone through a hydrologic cycle, and hence reflects not the 100 C fractionation of boiling water, but perhaps the sublimation fractionation of nebular material with a much steeper slope. When the oxygen isotopes in magnetite are examined, they are found to fall on the hydrologic fractionation line of Earth, not on the anhydrous meteoritic olivine line, demonstrating that the magnetite was not pristine nebular chondrules, but formed later in the presence of (hydrological cycled) liquid water.⁴⁶

The fact that the liquid water has gone through evaporation and condensation cycle is intriguing, suggesting that the water has persisted long enough for other water-based chemistry to occur. A plot of the total carbonate content versus magnetite content of seven carbonaceous chondrites shows a strong linear correlation.²¹ But carbonates are not only a water-made mineral, they are also highly correlated to biology.³⁹ Is this evidence that the nanocrystalline magnetite is biologically made? The best evidence is morphological, and we now turn to scanning electron micrographs (SEM).

2.3. Three forms (or four)

The standard minerological method of taking thin sections of a rock and examining it under a light microscope has been applied to perhaps the most famous carbonaceous chondrite, the CI meteorite that fell in Orgueil, France in 1864.²¹ The thin section reveals three forms of magnetite that appear somewhat similar in thin section (see Figure 1.1.3), but when SEM became available, analysis showed them to lie in three very distinct classes: framboids, spherules and plaquettes (platelets).^{28, 47–49} (see Figure 1.1.3). Since framboids are made up of dozens of small SSD nanocrystals, it is not clear if there is also a fourth category of individual SSD crystals, or whether they are merely remnants of weathered framboids. There have been no reports of magnetosomes or magnetite chains found on carbonaceous chondrites, so the most common form of biomagnetite found on Earth is not found in comets. In hindsight, this may not be so surprising because a magnetosome acts as a compass needle, but unlike Earth with its large dipole magnetic field, a comet has no discernable dipole field.

2.4. Purpose of Magnetite on a Comet

But without an internal magnetic field, without something that aligns the compass needle, what purpose does nanocrystalline bio-magnetite serve? That is, as Kirschvink has argued for biomagnetite found on Earth,⁴¹ its sole purpose is to provide a compass-needle direction, no other purpose is known. And since comets lack the molten iron core of rocky planets, and are also unlikely to contain a nickel-iron core given their undifferentiated solar-nebula composition, why would biology manufacture magnetite on a comet?

Once again, our best diagnostic are the SEM pictures themselves. The remainder of this paper will address the question of the purpose of the three forms of magnetite on a cometary body, where our principal clues will be the pictures themselves.



Figure 2. Scanning electron micrographs of Tagish Lake framboids at successively higher resolution.

3. FRAMBOIDS

3.1. Observations

As we have mentioned earlier, framboids (raspberries) are 3-10 micron diameter bags of marbles, where the individual marbles are 100-200nm SSD magnetite or greigite, and have been observed in terrestrial sediments as well as carbonaceous chondrites. Some beautiful examples from Tagish Lake (2000) have been taken by Richard Hoover at the NASA/MSFC electron microscope, Figure 2.4. In this section we make a few observations about these extraterrestrial framboids, and discuss their theoretical properties.

3.1.1. Supermagnetic nanostructured domains

The marbles that make up the framboids are clearly SSD magnetite, with the prismatic shape characteristic of magnetosomes.²⁶ Viewed along the (100) or the (110) axis, they appear rectangular, whereas wiewing along the (111)-axis gives a hexagonal appearance, as seen in the tilted crystals in panel (e) of the figure. Panel (d) shows and entire framboid from the (111) direction, with the hexagonal crystals stacked in a close-packed hexagonal array following hexagonal-close-packed (hcp) or A-B-A packing. The spontaneous magnetization of SSD crystals follows along the "easy" (111) direction of magnetization, demonstrating that these framboids are undoubtedly close to their maximum magnetization.

A recent paper by Nozawa et al.⁵⁰ argues that Tagish Lake framboids are formed abiotically as colloidal crystals in either body-centered-tetragonal (bct) or face-centered-cubic (fcc) packing (or A-B-C-A packing), which requires that the marbles have multiple domains that repel each other along the (100) axis, as suggested by spin-polarized SEM photograph.⁵¹ Their MD "marble" example, however, is 2 microns wide, suggesting that they are mistakenly examining a spherule rather than a framboidal nanocrystal. And their MFM analysis of a framboid is consistent with SSD crystals, as admitted in the text. So while our analysis of Tagish Lake framboids

is not as refined, the difference between our hcp and their fcc packing may arise, as Nozawa et al. suggest, because different framboids employ differing nanocrystals and differing packing methods.

In contrast to Nozawa's assumption of MD nanocrystals, we argue for SSD nanocrystals that are placed in close-packed arrays separated by biological spacers so that the magnetization is saturated in the (111)-direction more efficiently than if it had been heated and poled. It also changes the hysteresis properties of the conglomerate, because there is no energy expended on changing domain walls.

A second property of these framboids is their overall ~ 3 micron spherical shape, which is partly a result of minimizing the magnetic energy in a strong external field.⁵² And as the exterior magnetic field rotates, the entire framboid can also rotate, if it is suspended in a liquid. A changing external field cannot induce hysteresis if the change is slower than the rotation rate of the framboid, and thus the framboid cannot be "demagnetized" by low-frequency fields, and maintains its saturated strength character.

This ability to produce powerful magnets through nanostructured domains whose magnetization is insensitive to rotation of the exterior field we refer to as "super-magnetic".

3.1.2. Superparamagnetic marbles

With the property of spontaneous magnetization by SSD nanocrystals, comes the property of spontaneously flipping the direction of magnetization. Although the (111)-direction remains the preferred axis of magnetization, it doesn't specify the direction, which can be either aligned or anti-aligned. At higher temperatures, thermal fluctuations can cause the direction to flip at a characteristic time known as the Néel relaxation time. If the measurement time is longer than this Néel relaxation time, the magnetic field averages to zero. An external field, however biasses the crystal so it spends more time in the aligned direction, causing the magnetization of the crystal to be a function of the applied field but with with no hysteresis. Since this lack of hysteresis differs from ferromagnetism but resembles paramagnetism, while being much stronger than paramagnetism, it is called "super-paramagnetism" (SP).

Now the Néel relaxation is exponentially faster at higher temperature, so that in practice there is a sharp temperature threshold for the transition between cold SSD and hot SP states. Rock magnetism geologists refer to this critical temperature as the "blocking temperature" and it is proportional to the volume of the SSD grain. From theory, the transition between small SP and larger SSD magnetite is about 50nm for a cubical grain, and somewhat smaller for rod-shaped grains.^{20, 53, 54} On the other hand, commercial ferrofluid MAG-UC/A composed of uncoated magnetite grains of 50nm, 100nm and 200nm diameter are said to be SP when used at room temperature.⁵⁵

The blocking temperature for SP grains is always lower than the Curie temperature, which has no volume dependence, and so provides a sensitive measurement of thermal gradients at lower temperatures. The Curie temperature for magnetite is approximately 858K, whereas this blocking temperature can range from 10K up to 373K depending on size. From measurements on terrestrial titanomagnetites from Tiva Canyon tuff, the blocking temperature is found to be about 350K for a volume corresponding to 16nm cubes.⁵⁶ Since the blocking temperature is directly proportional to volume, we assume that these 100nm marbles remain SSD up to the boiling point of water.

3.1.3. Enhanced heat conduction

When the temperature goes above the blocking temperature, the nanocrystal loses its average magnetism. But even before this high temperature is reached, the susceptibility is affected by temperature, so that in an external field, the particle is attracted less strongly. This causes a temperature difference to lead to a force imbalance so that colder grains are attracted more strongly to a permanent magnet. If permanent magnet is also at a higher temperature, so that the magnetic gradient and temperature gradient are coaligned, the system has a convective "magnetothermal" instability. This property allows colloidal suspensions of SSD magnetite to act as an effective thermal conductor.

When SSD marbles are confined to a spherical container, the net result is likely to improve the heat transport. This occurs because the interaction of marbles causes a higher net magnetization, and hence a higher attractive force in an external field. In addition, the larger body experiences a larger temperature gradient, so that the



Figure 3. Left panel: thermal map of P/Temple1 showing non-equilibrium temperature distribution with large lateral heat transport near 273K. Right panel: venting from P/Hartley2 showing low porosity central portion of comet surface.

convective instability is more easily triggered. Finally, heat transport is mostly done by the water, which has a much higher thermal capacity than the magnetite, so it is the viscous coupling of the motion of the framboids and the water that set up the convective cells, and the larger framboids have a much higher viscous drag.

3.1.4. Bioengineered phase transition

The fact that these framboids are found on CI carbonaceous chondrites that are more than half water, suggest that the framboids are suspended in a solvent that can undergo phase transitions between ice, liquid, and vapor. When in water, the framboid is able to rotate, and from DC up to several tens of Hz AC,¹⁵ the framboid follows the external field direction and has no hysteresis. But when the water is frozen into ice, the spherical shape of the framboid is locked to the ice lattice, and the framboid no longer can orient itself to be parallel to the magnetic field. This means that the frozen ice/framboid mixture behaves as a "hard" magnet, demonstrating hysteresis and other bulk magnet properties.

Thus nanostructuring of the spherical framboids gives them a peculiar phase transition at the solid/liquid phase transition of the solvent liquid. Above this temperature, the framboids are "super-magnetic" but below this temperature they behave as normal bulk magnets. However, when the water goes from liquid/vapor at the boiling point, the non-volatile framboids are precipitated out. Their mutual attraction suggests that this sudden phase change may cause them to clump, which may account for the high concentrations of framboids observed in Figure 2.4.

3.2. Purpose

We are now ready to address the mystery of why biomagnetites should exist on comets at all, given that the magnetic field of comets is certainly smaller than that of rocky planets, and is unlikely to provide any global "compass-needle" information.

3.2.1. Ferrofluid Thermal management

As we have argued earlier,^{44, 57, 58} carbonaceous chondrites were once part of a wet-comet with 1-10 meter deep lakes of liquid water. Most of the water would have been near the freezing point of 273K, but the subsolar point can easily rise to 350-400K, above the boiling point of water. (See left panel of Figure 3.2.) Not only does this high temperature weaken the concrete and the sealing ability of polysaccharides, but it raises the vapor pressure and endangers the ecosystem of the comet. We have earlier argued^{44, 57} that the negative feedback of the Rayleigh-Taylor (RT) instability will cause the comet to rotate such that the equatorial surface experiences near zero gravitational force, but this stabilization of the RT also means that heat is no longer convectively removed from the subsolar point.

Therefore it is highly advantageous from the viewpoint of ecosystem survival, for the lake to have ferrofluid properties that would keep the subsolar point cool, and the lake warm. So the first and most important purpose of framboidal magnetite appears to be the creation of an aqueous ferrofluid.



Figure 4. Orgueil spherules (a) SEM photograph⁵⁹ with inset of facet reconstruction;⁴⁹ (b) Magnetic Force Microscope analysis of magnetic domains in a polished section;⁶⁰ and spin-polarized SEM of spherule where contrast corresponds to magnetic field direction.⁵¹

3.2.2. Ferrofluid Anisotropic viscosity

A second property of ferrofluids that may be important on comets, is their anisotropic viscosity. That is, parallel to the field lines, the magnetic forces make a ferrofluid highly viscous and able to transmit force. But perpendicular to the magnetic field, a ferrofluid offers very little resistance to flow. These properties are used in magnetic seals, such as those in pistons or around rotating shafts. Since the interior of a wet-comet must support at least 6 mbar of pressure for liquid water to exist, the concrete "skin" of a wet-comet is prone to developing leaks. But if the concrete is magnetized, then the ferrofluid will be highly viscous and capable of plugging small leaks if the field is normal to the surface. (See right panel of Figure 3.2.)

If the dessicated surface material, composed mostly of insoluble minerals, is laid in layers, where a layer forms when the water of a trapped lake should spontaneously boil due to a loss of pressure, then one would expect layers of framboids that are precipitated out of solution. Since these layers are "self-clumping", they would naturally organize themselves with magnetization perpendicular to the surface, and hence would provide exactly the sort of leak-stopping crustal magnetism.

3.2.3. Supermagnetic phase transition

The peculiar "super-magnetic" phase transition at 273K also plays an important role in the ecosystem. As a comet leaves the vicinity of the sun, it refreezes and locks the framboids into the ice, forming a bulk magnet. When the comet makes a second pass near the sun, the ice-framboid mixture melts, and the magnetic fields in the ice attract the melted ferrofluid, moving heat rapidly into the frozen sections of the comet. This is the opposite of the warming dessicated crust, whose magnetic fields move heat away from the crust into the interior. Thus the supermagnetic phase transition increases the heat transport into the comet thereby lengthening the growing season.

It would thus appear that magnetite framboids do not use compass-needle torques but provide thermal management for cometary ecosystems, as well as some beneficial stop-leak properties.

4. SPHERULES

4.1. Observations

4.1.1. Spherical, non-prismatic crystals

From Figure 1.1.3 we see that spherules are much larger than framboidal marbles, or even entire framboids, consisting of large, 6-10 micron MD magnetite crystals that are not prismatic, but contain many higher-order crystal faces so as to approximate a sphere (see panel (a)Figure 3.2.3). These high-order crystal faces are not minimum energy, but are far from chemical equilibrium which was the characteristic of biominerals discussed earlier.

4.1.2. Multiple, radially structured domains

These crystals are too large to be SSD, and from Figure 1.1.3 we see that they are far larger than even metastable single domain. If the spherules are sliced and polished, a small, magnetized point can be dragged across the crystal to measure the magnetic polarity or the domain structure of the slice. Using this magnetic force microscopy (MFM), the nanometer-scale radial structure of a spherule can be observed, see panel (c) of Figure 3.2.3. This same radial structure is visible with SEM at high electron energies, $^{61-63}$ so it is both a magnetic and a crystal structure. This structure cannot be "poled" from abiotically made bulk magnetite, since it would require a magnetic monopole at the center of the crystal, rather they must be "grown" in such a way as to create radial spokes of magnetic domains, which is again strongly suggestive of biomineralization.

4.1.3. Lowered Curie temp?

The Curie temperature is reached when the average thermal energy of the iron atoms equals the average spin interaction energy, and the alignments are erased. The spin interaction energy is also geometry dependent, so that clumping of the spins into magnetic domains lowers the interaction energy. Therefore a magnet has two levels of organization: a high energy Curie temperature at which individual spins are randomized, and a lower energy at which domains are reorganized (described by coercivity and remnance). The global geometry of the crystal, however, affects the magnetic domains, so that long thin crystals can be spontaneously magnetized into stable single domains (SSD) because the flux trapped in the high permeability crystal lowers the energy of a long thin domain (see Figure 1.1.3).

The coercivity and the remnance then relate to how these magnetic domains rearrange under an external field. An MD crystal made of long thin crystals has a large domain wall structure that dominates the response, so that there is an initially fast response (low coercivity) as thin crystals aligned with the external field flip along their easy axes forming a magnetized cylinder through the center of the spherule, but then a high-coercivity response for the remainder of the non-aligned whiskers.

This same response occurs as the spherule cools down below the Curie point, with radial whiskers aligned with the field becoming highly magnetized, while non-aligned whiskers have domains that average to zero. Hyman et al.⁴³ see this enhanced-magnetization-after-cooling effect and attribute it to oxidation of iron sulfides to magnetite, whereas we attribute it to the nanostructuring of spherules. One way to separate the effects is to see if it is reversible, which the chemistry is not.

This fast response is also spatial, with the center of the spherule having higher permeability for aligned magnetic fields, so that the spherule acts as a funnel to channel magnetic flux through the center. We believe that this is what was imaged by Nozawa et al. in Figure 3.2.3.

Therefore the nano-engineering of radially oriented whisker domains in a spherule gives them extremely low coercivity to any direction external magnetic field, as well as ease of magnetization as they cool below the Curie point. They may be MD crystals, but their fast response to external fields makes them also "super-magnetic".

4.2. Purpose

4.2.1. Crustal magnetism

The following discussion presupposes the "wet comet model" discussed in Hoover [2004] and Sheldon [2005, 2006]. The spherules are too large to be colloidally suspended in the liquid water, and with densities 5 times larger than water, will rapidly settle out in comet's interior "lake". If the comet is spinning, then precipitation "down" is toward the equatorial crust. Generally speaking, the enhanced heat input at the subsolar point engenders steam jets that cause the comet to rotate, so that the comet's rotation axis ends up perpendicular to the orbital plane, and the equator rotates through the subsolar point, the hottest point. Eventually the equatorial crust loses water and dries out, sealing the precipitated spherule in the concretion. No longer able to orient itself to the external field, the "super-magnetic," low coercivity of the spherules enhance and magnify the fluctuating exterior magnetic field to produce macroscopic "domains" that result in a stable magnetized crust.

As the subsolar point rotates and heats the crust, perhaps above the Curie point, it aligns these macrodomains of spherule-dominated crust to be in alignment, much as laser-heating produces epitaxial silicon crystal out of amorphous silicon.⁶⁴ Further rotation of the comet cools these domains, and freezes the magnetic field into the crust. Other considerations will need to be employed to determine the direction of the magnetic field, but the process magnetizes the surface proportional to the density of spherules.

4.2.2. Harvesting solar wind

The solar wind carries magnetic fields from the sun, which is "snagged" by the highly conductive comet, and generates the second, bluish tail of plasma directed anti-sunward of the comet. The subsolar point of this field draping has the highest magnetic field strength because the compression of the flux tubes drives out the plasma and equilibriating pressure is provided solely by the magnetic field.

The plane that contains the draped solar wind flux tubes can be at any angle to the comet spin axis, but remains tangent to the subsolar surface. If this field strength is greater than that of the crust, then it sets the direction and magnitude of the acquired crustal magnetism, which is carried around the equator by the rotation of the comet.

Any fluctuation of the solar wind magnetic field strength is immediately transmitted as magnetic pressure to the crust, so that increased solar wind speed or magnetic field strength results in higher magnetic field at the crust. The effect of these fluctuations, however, do not average to zero, but create a magnetic ratchet that raises the crustal magnetic strength. This effect occurs because a higher crustal field strength repels a larger volume of solar wind flux so as to keep the magnetic pressure of the crustal fields in equilibrium with the solar wind, but a lower solar wind pressure merely expands the cometary plasma bubble or magnetosphere surrounding the comet without weakening the crustal field. Thus fluctuation energy of the solar wind is concentrated and stored in the crust through the mediation of the spherules.

The solar wind magnetic field has a variable direction, and in general this direction will reverse and integrate to zero. The super-magnetism of the spherules, however, allows their magnetism to rotate with the solar wind, and thereby keep the crust magnetized. A change in direction of the magnetic field induces currents and joule heating that prevent a perfect alignment of crust and solar wind direction, so that many direction changes of the solar wind will leave the crustal field oriented so as to minimize the misalignment energy. The direction that minimizes misalignment is perpendicular to the draped field and normal to the crust.

Thus it appears that spherules can "harvest" the solar wind magnetic field and store it in the crust. This crustal field will be larger than the solar wind field through the process of a magnetic ratchet, and is likely to be normal to the surface. This direction is exactly that required to provide anisotropic viscosity to a ferrofluid and seal the crust from leaks. It is significant, then, that the equatorial band of P/Hartley2 in Figure 3.2 is absent any steam vents.

5. PLAQUETTES

5.1. Observations

The observations in panel (e) Figure 4.2.2 show a stack of thin magnetite plates about 100nm thick and separated by about 150nm. The plates have increasing and decreasing diameter so as to fit within a sphere or an oval shape. A carbon sheath surroundes the sphere and containing the plates (with a dimple caused by EDS electron beam erosion). Less well-preserved plaquettes in (c) apparently disintegrate readily and the plates are not attached to each other. The final plate in a stack is also easily damaged, as can be seen in panel (a), which caused Hua and Buseck to hypothesize a spiral for the plates. The presence of separated plates and the lack of a central discontinuity in rock slices suggest they are not spirals, but are loose plates bound by an exterior membrane.

These structures are so far from equilibrium that to our knowledge no one has attempted to explain their formation abiotically. We take this as strong evidence for biomineralization.

5.1.1. MSD and magnetization

Examination of the plot in Figure 1.1.3 shows that flat plates have an anisotropy much greater than 1.0 and would lie far to the right on the x-axis. This means that the high permeability of the magnetite is unable to enhance the domain size, so the SSD boundary drops down to its minimum level, perhaps even below the SP boundary making SSD plates impossible. In fact, plate-shaped ferrites are preferred for magnetic disk storage



Figure 5. (a)Orgueil plaquette;⁵⁹ and (b) cyanobacterial thylakoid membrane in chloroplast.⁶⁵; (c) Tagish Lake plaquettes; (d) plaquette with framboidal particles; (e) plaquette with carbon sheath and framboidal particles.

precisely because they are MD and can hold multiple bits with low coercivity and high remanance where the maximum storage density is achieved with a normal magnetic field direction.

There are four stable or metastable possibilities for plaquette magnetization: (1) aligned and parallel to the surface normal so that plates attract; (2) alternately anti-aligned and parallel to the normal so that plates repel; (3) aligned and perpendicular to the normal so that plates repel; and (4) anti-aligned and perpendicular to the normal so that plates attract.

Close examination of panels (d) and (e) reveal small framboidal nanocrystals are attracted to the plaquettes. Since these SSD crystals are dipoles, they will not just be attracted to the strongest field of the plaquettes, but they will align themselves with the field lines, discriminating among these four possibilities. In panel (d) they appear to cluster at the edges of the plates, which would suggest options 3 or 4, however, panel (e) shows these magnets are in between the plates, which is only consistent with options 1 and 2.

Re-examination of panel (d) suggests that unlike (e), the SSD dipoles are simply too large to fit between the plates, and their clustering near the edge is as close as they can get to fitting between the plates, which lends support to options 1 and 2. In addition, the clustering at 10 o'clock and 2 o'clock is not consistent with options 3 and 4, which puts the highest fields on opposite sides with intermediate angles precluded because of the large torques that would force the plates into option 4.

Since option 1 is a lower energy state than 2, and because many complete plaquettes are found that under option 2 should have fragmented when the binding membrane disintegrated, it would appear that option 1 is the most likely magnetization state. So much like magnetic disk memory, plaquettes are oriented so as to "remember" the magnetic field with low coercivity and high remanance.

5.1.2. Supermagnetic

The second feature of plaquettes is their near-spherical structure. Like framboids and spherules, this means they can rotate when suspended in a liquid, and display super-magnetic properties. Because of the orientation of the magnetic field, they also experience more torque when the field changes direction, as well has having a density that is about half of the other structures. This allows them to have a frequency response to magnetic fluctuations that is 2–5 times higher than the other two structures. But most importantly, it permits the plaquette to orient very accurately along the external field direction.

5.1.3. Spin-caloritronics

A third feature of plaquettes is their high surface area in a compact region. Magnetite is a topological insulator in which the conduction band is created or defined by the surface states, which are a strong function of surface coating. Extensive experiments show that magnetoresistance or magnetically modified conductivity of magnetite depends crucially on the coating or monolayers on the magnetite surface that affect these 2-D excitations of plasmons or magnons.

To understand the importance of magnons for the magnetite surfaces, we need a brief diversion into material science.⁶⁶ Electrons possess three properties that affect their transport in materials: energy, charge and spin with corresponding heat flux, electrical current and spin-flux/current/wave. If we put in heat and extract heat, we refer to their ratio as the thermal conductivity, or if we put in voltage and extract electrical current we refer to the ratio as electrical conductivity. Analogously if we put in spin and extract spin, we refer to the spin-conductivity, which in the case of magnetite, is communicated through the coupling with the unpaired electron spin in Fe2+ ions.

These three properties of electron transport are coupled, so that electronic devices not only convey charge, but also dissipate energy and heat. If we describe a 3x3 matrix where the diagonal elements are the three conductivities mentioned earlier, then the off-diagonal elements represent the coupling between these electron properties. If one puts in heat and extracts charge the cross term is called the Seebeck efficiency, or if one puts in charge and extracts heat, it is called the Peltier efficiency. With similar nomenclature, spin in and electricity out is the spin-Seebeck efficiency, while spin in and heat out is the spin-Peltier efficiency.⁶⁷

The twentieth century was built on the ability to turn energy into electricity, into charge, and this conversion has principally relied on the Carnot efficiency heat engine connected to a dynamo. Higher efficiencies may be possible if one can directly harness the Seebeck effect, as NASA's outer planet missions do with the radioisotope thermal generators (RTG). Ideally one would prefer a material with a low heat conductivity to permit large thermal gradients, while possessing high electrical conductivity to permit extraction of the charge without energy loss. Unfortunately these two diagonal terms in the matrix are highly correlated, since the same electron that carries the charge also carries the kinetic or thermal energy, dooming RTG's to <7% efficiencies.

But spin transport does not require the motion of electrons, only an interaction of spin wave. Then the cross terms in the matrix can convert the spin waves back into electricity, and one can have high electrical conductivity without high thermal conductivity, achieving much higher thermo-electric efficiencies. In free space, thermal conductivity is minimized in a direction perpendicular to the magnetic field, while spin-wave conductivity is maximized at this angle, so that magnetic field direction is crucial in these types of materials.⁶⁸ Magnetite is precisely this sort of material, permitting thermal gradients to be converted into charge potential gradients, or what has been called "spin-caloritronics".⁶⁷

5.1.4. Catalytic behavior

Finally, magnetite possesses a surprising catalytic ability to split molecules. At high temperature, >400C, and in reduced form, it splits nitrogen in the first step of the Haber process for making ammonia from nitrogen and hydrogen.⁶⁹ It is commercially used in the Fischer-Tropsch process to enhance the hydrogen content of the gas feedstock where at elevated temperatures, >200C, magnetite catalyzes the "water-gas-shift" reaction whereby water and carbon monoxide form hydrogen and carbon dioxide.^{70, 71} This ability to split water can also occur at room temperature and low pressure, if the magnetite has been prepared properly.⁷²

5.2. Purpose

It seems clear that the purpose of plaquettes is not the manipulation of the magnetic field, since they possess neither the SSD properties of framboids nor the high permeability of spherules. However they have the largest surface area of these biomagnetite forms, as well as a precise orientation of the surface to the magnetic field. Since the properties of magnetite surfaces are so sensitive to the monolayer that overlays them, and since carbonaceous chondrites have lost most of their nitrogen, the proteins that probably coated the magnetite are irretreivably lost and we can only surmise their function.

5.2.1. Magnetic memory

The high angular precision with which plaquettes orient themselves to the external field provide a "memory" when the comet refreezes. Since the rotation of the comet is unabated by refreezing, the comet maintains its inertial space orientation when it re-enters the inner solar system some years or millennia later. The frozen in magnetic field of the plaquettes will allow the magnetothermal control system to pick up where it left off, without need to reorient the comet or the magnetic materials. Since long-period comets have very short summers compared to their long winters, every day counts, and plaquettes may provide that early restart of the growing season.

5.2.2. Electromagnetic antenna

Magnetite is a semi-metal, and because of its plasmon and magnon frequencies, absorbs very effectively in the GHz to 100's GHz range (centimeter to millimeter waves).⁷³ The plates in one of the plaquettes analyzed are 250nm apart which suggest absorbtive wavelengths of 250, 500 and 1000 nm, corresponding to UV, green and near-IR. The plates are ~100nm thick, which for an anti-reflection coating of $\lambda/4$, would correspond to a wavelengthf 400nm, or very blue wavelengths. Of these wavelengths, plaquettes are most efficient absorbers in the radar wavelengths where they can be tuned by magnetic fields. They are weak absorbers in a few select wavelengths in the visible band, though very little visible light will be able to penetrate through the black crust of the comet.

The alternation of high and low index of refraction materials, from 1 of the interstitial water to 5 for the magnetite make these photonic materials with stop bands or narrow frequency filters. If coupled with an organic molecule like chlorophyll, it may exploit an "optically pumped" molecule that can combine the energy is several photons to initiate a chemical reaction.

There may even be the possibility that the plaquettes separate the charges of a radioactive cascade, so that radioactivity can be harnessed to charge up the plates and convert that charge to chemical reactivity.

5.2.3. Carbohydrate anabolism

But by far the best hint is that the overall structure of plaquettes resemble the thylakoid membrane stacks of chloroplasts in plants, whose chlorophyll splits water so as to combine the hydrogen with carbon dioxide (see Figure 4.2.2 panel e). The membranes are about 100nm apart, similar to the spacing of plaquettes. Since magnetite may also catalyze the splitting of water in a fashion like chlorophyll, it seems possible that plaquettes function as an extraterrestrial chloroplast.

In this case, the energy absorbed either in the visible or microwave part of the electromagnetic spectrum is used to combine the hydrogen ions catalyzed on the surface of magnetite with carbon oxides so as to form carbohydrates. Since cyanobacterial fossils have been found on every carbonaceous comet examined,¹ the plaquettes are undoubtedly operating in a different ecological niche.

Should this be the function of plaquettes, it seems odd that cyanobacterial chlorophyll is found on Earth, but not plaquettes. What would make these magnetite organelles unable to grow on Earth? Several differences with comets are that the Earth has higher gravity, higher gas pressure, more visible light (transparent atmosphere), fixed magnetic field (without the GHz fluctuation power), and very little radioactivity or cosmic rays. One of these is likely the reason for the cometary ecological niche for plaquettes, and my speculative bet is on the last.

6. CONCLUSIONS

One of the signatures of life, is its ability to modify its environment so as to make it more hospitable. Lovelock's thesis is now so widely held as to need no further justification for Gaia.⁷⁴ What the ubiquitous presence of magnetites on extinct comets demonstrate, is that the environmental engineering of life extends far beyond the borders of the ionosphere and even beyond the icy bounds of Pluto to encompass the entire galaxy in a cometary biosphere. We had written earlier^{2, 57, 58} on the ability of cyanobacteria to modify comets to make them more stable, warmer, and stellar-repelling (so as to avoid unwanted accretion into life-threatening environments), which we linked to the perennial problem of cosmological dark matter. Now we see that this large magnetic field enables comets to magnetically accelerate and brake so as to permit inter-galactic transport in excess of 70km/s velocities without danger of incinerating their payloads. These magnetic modifications are even more pervasive and subtle than the polysaccharide cyanobacterial modifications, fine-tuning the response of comets to further their conquest of not just the galaxy, but the cosmos. If Lovelock christened Gaia as the goddess of Earth homeostasis, then perhaps we can christen the goddess of cometary homeostasis "Berenice" who being far older than Gaia, is at least her aunt if not her mother.

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