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Magnetization of carbonaceous asteroids by nebular fields and the origin of CM chondrites

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Introductory Paragraph:

The solar nebula carried a strong magnetic field that had a stable intensity and direction for periods of a thousand years or more[1]. The solar nebular field may have produced post-accretional magnetization in at least two groups of meteorites, CM and CV chondrites[1–3], which originated from planetesimals that may have underwent aqueous alteration before gas in the solar nebula dissipated[1,3]. Magnetic minerals produced during aqueous alteration, such as magnetite and pyrrhotite[4], could acquire a chemical remanent magnetization from that nebular field[3]. However, many questions about the size, composition, formation time, and, ultimately, identity of the parent bodies that produced magnetized CM and CV chondrites await answers—including whether a parent body might exhibit a detectable magnetic field today. Here, we use thermal evolution models to show that planetesimals that formed between a few Myr after CAIs and ~1 Myr before the nebular gas dissipated could acquire from the nebular field, and retain until today, a chemical remanent magnetization throughout nearly their entire volume. Hence, in-situ magnetometer measurements of C-type asteroids could help link magnetized asteroids to magnetized meteorites. Specifically, a future mission could search for a magnetic field as part of testing the hypothesis that 2 Pallas is the parent body of the CM chondrites[5]. Overall, large carbonaceous asteroids might record ancient magnetic fields in magnetic remanence that produces strong modern magnetic fields, even without a metallic core that once hosted a dynamo.

Main:

Several meteorites in two groups of carbonaceous chondrites, the CM and CV chondrites, host a chemical remanent magnetization (CRM)[3] and possibly also thermoremanent magnetization[6]. CRM in a meteorite implies that chemical reactions produced ferromagnetic minerals within the meteorite's parent body while in the presence of a strong and temporally stable magnetic field. CM and CV chondrites experienced aqueous alteration, but little or no further dehydration or melting[4]. Aqueous alteration can produce minerals that are possible magnetic carriers[4], such as magnetite (Fe_3O_4) and pyrrhotite ($Fe_{(1-x)}S$, x=0 to 0.2). In general, ferromagnetic minerals forming in the presence of a background magnetic field can acquire a CRM in the same direction as the background field[7,8]. Thus, CRM in CM and CV chondrites indicates that their parent bodies may have undergone aqueous alteration in the presence of a strong magnetic field.

The magnetic field sustained by the cloud of dust and gas in the early solar nebula is likely the source of magnetization for the parent bodies of the CM chondrites[3]. Based on telescopic observations of distant solar nebulae and thermal remanent magnetization within chondrules of primitive LL and CO chondrites, the early solar nebula likely had a strong magnetic field that was active in the first few Myr of the solar system[2,9–11]. The nebula likely supported a strong magnetic field until at most ~3.9 Myr after CAIs in the inner solar system, or at most ~4.8 Myr in the outer solar system[1]. Thermal evolution models indicate whether planetesimals could experience aqueous alteration before the nebula dissipated—and thus whether planetesimals could acquire and retain magnetization from the nebular field.

56 During the heating of a planetesimal's interior through the radioactive decay of ^{26}Al, two
57 important thermal events determine the potential for acquiring a chemical remanent
58 magnetization. First, the planetesimal reaches the melting point of water ice (~273 K). When
59 water ice melts, liquid water drives aqueous alteration and produces the magnetic carriers
60 magnetite and pyrrhotite[4]. If formed in the presence of the nebular magnetic field, these minerals
61 acquire CRM. The second event occurs if the planetesimal reaches a maximum unblocking
62 temperature, above which magnetized domains would randomize in zero-field conditions in a
63 time less than the duration of peak heating (as short as ~10^2 kyr). This maximum unblocking
64 temperature, henceforth called the unblocking temperature, is different for each mineral, and also
65 depends on geometric properties of individual grains such as size and shape[12]. Since these
66 properties are stochastic and unknown a priori, we adopt fixed unblocking temperatures that are
67 within empirically measured ranges[3]: 550 K for pyrrhotite and 850 K for magnetite (vs. Curie
68 temperatures of 583 K and 858 K, respectively). If the planetesimal heats above the unblocking
69 temperature(s) of its magnetic carrier(s) after the nebular magnetic field dissipates and stays
70 above that temperature for longer than ~10^2 kyr, then any magnetization in the minerals would
71 be reset as the minerals re-magnetize in zero-background-magnetic-field conditions. If the
72 planetesimal heats above, but then cools below the unblocking temperature(s) prior to the end of
73 the lifetime of the nebula, then it will acquire a thermoremanence, possibly in addition to CRM.
74
75 An undisturbed planetesimal may experience one of three thermal evolution cases
76 depending on the timing of the aforementioned milestones with respect to the lifetime of the
77 solar nebular magnetic field. First, a planetesimal may form too late to reach the temperature to
78 melt water ice before the solar nebula dissipates (Fig. 1a). This case results in no nebular

79 magnetization. Second, a planetesimal may form early enough to undergo aqueous alteration
80 before the nebula dissipates but does not subsequently heat beyond the unblocking temperatures
81 of magnetite or pyrrhotite (Fig. 1b). This scenario could lead to magnetization of nearly the
82 entire planetesimal. Lastly, a planetesimal could form early enough to undergo aqueous
83 alteration, but subsequently heat beyond the unblocking temperatures (Fig. 1c). Our models
84 indicate that an undisturbed planetesimal (i.e., that did not experience impact unroofing and rapid
85 cooling[13]) that heats beyond the unblocking temperature does not cool below that threshold again
86 until many Myrs past when the nebula dissipates. Thus, such a planetesimal that reaches the
87 unblocking temperature before the nebula dissipates would not retain magnetization throughout
88 its interior. However, a thin shell of aqueously altered, chondritic material that does not reach the
89 unblocking temperature could retain magnetization near the surface. Thus, magnetized CM
90 chondrite meteorites could originate from either the second or third case. Only the second case
91 could result in an asteroid with large-scale remanent magnetization from the solar nebula.
92
93 Figure 2 plots the maximum volume percentage of a planetesimal that could be
94 magnetized as a function of the planetesimal's radius and formation time. If the primary
95 magnetic carrier is pyrrhotite, we find that a planetesimal may acquire large-scale magnetization
96 from the solar nebula if it formed between ~3.5 and 3.7 Myr after CAIs, depending on the exact
97 timing of nebular dissipation (Fig. 2a). Since magnetite has a higher unblocking temperature,
98 earlier forming planetesimals that reach hotter temperatures could still retain magnetization. If
99 magnetite is abundant as a magnetic carrier, then we find that large-scale magnetization is
100 possible for formation times between ~2.7 and 3.7 Myr after CAIs (Fig. 2b). These ranges are
101 consistent with the formation time expected for the parent bodies of the CM chondrites[14].

Assuming that the entire volume of possible magnetization in each planetesimal model is coherently magnetized at the strength observed in the CM chondrites (see below for caveats), $\sim 10^{-4}$ A m^2/kg, we plot the maximum possible magnetic dipole moment that each planetesimal might have today (Figs. 2c and 2d). For example, if Pallas formed at ~3.5 Myr after CAIs, its maximum possible dipole moment now is $\sim 10^{16}$ A m^2. For comparison, Earth's magnetic moment is $\sim 8 \times 10^{22}$ A m^2 and the metallic asteroid 16 Psyche may have a moment between $\sim 10^{15}$ A m^2 and 10^{17} A m^2 if it is a disrupted planetary core[15].

The maximum possible dipole moments displayed in Figs. 2c and 2d assume an idealistic scenario wherein the entire volume of the planetesimal has been magnetized unidirectionally. However, aqueous alteration need not occur homogeneously and contemporaneously throughout a planetesimal. If the solar nebular field's intensity and direction change between the time at which two different regions of a planetesimal experience aqueous alteration, then these two different regions would acquire different magnetization directions. The number and size of regions with differing magnetization strengths would depend on the rate of alteration compared to rate of field change. Additionally, impacts could scramble regions of coherent magnetization. The effective dipole moment of the planetesimal would be a function of the length scale of its magnetized regions. The smaller the length scale, the lower the effective dipole moment.

The asteroid 2 Pallas is a candidate parent body for the CM chondrites[5] because it exhibits a hydrated spectral signature in the 3-μm region, which matches CM chondrite spectra[16]. Impacts can produce the observed differences between the visible and near-infrared spectra of Pallas and the CM chondrites[5]. Furthermore, the bulk density of Pallas (~2.9 g/cm^3) is similar to

the grain density of CM chondrites[17]. Pallas also appears to lack a thick icy shell, based on its global morphology[5], unlike Ceres. A possible model for Pallas' evolution is that it underwent aqueous alteration on a global scale and subsequently lost the remaining water ice as a consequence of subcatastrophic impacts, as suggested by the large basins found on its surface[5,18]. An early phase of hydrothermal evolution could limit heating and separation of a metallic core[5]. Based on our thermal evolution models, if Pallas is the parent body of the CM chondrites, then we expect it to be measurably magnetized.

If the solar nebular field magnetized Pallas, then a spacecraft could possibly detect large-scale remanent fields that have persisted until today. To assess detectability, we estimate the magnetopause distance of a spherical asteroid with a radius of 256 km—the effective volume radius of Pallas[5,19]—orbiting at a distance of 2.8 AU in the present solar wind. Fig. 3 calculates the magnetopause distance as a function of the asteroid's effective magnetic dipole moment. This calculation generally agrees with magnetopauses numerically observed in hybrid simulations of asteroid magnetospheres in the solar wind[20,21]. For effective dipole moments above ~10^{13} to 10^{14} A m^2, a spacecraft magnetometer flyby or orbiter could detect the asteroid's magnetosphere. Orbiters or landers could detect magnetization at smaller length scales. The exact minimum moment that is detectable depends on the specific mission design, and the orientation and interaction of the magnetized regions with the solar wind. Furthermore, low magnetic moments could also possibly be detected from orbit via the observation of Alfven waves[22].

The effective magnetic moment depends on the length scale of magnetization (Fig. 4). The length scale of a planetesimal's magnetic field depends on how aqueous alteration occurred

and whether the body has been disrupted by impacts throughout its lifetime. Different models of aqueous alteration predict various upper bounds for the length scales of magnetization (Fig. 4). If the distance over which fluid flows during the time that the solar nebular field is coherent determines the length scale, then the effective permeability of the planetesimal is the critical parameter. Assuming exhalation alteration (i.e., single-pass fluid flow directed to the surface[23]) and effective permeabilities between ~10^{-13} and 10^{-12}, we expect magnetization length scales of ~10–100 km. Alternatively, if aqueous alteration occurs over multiple-pass, pore-fluid convection, then the length and time scale of convection could determine the magnetization length scale. Pore-fluid and/or hydrothermal convection could have length scales of ~10 km but requires a steep thermal gradient, which would only exist near the surface[24,25]. If alteration occurs as the result of effusive events of high temperature fluid and steam escaping the subsurface, i.e., a fumarolic system, then alteration would likely occur in distinct separate events and have scales of less than 10km, perhaps consistent with alteration environments in terrestrial ocean spreading centers[26]. For whole-body "mudball" convection[27], the length scale could be as great as 100 km if alteration occurs homogeneously throughout convective cells within the mudball. Alternatively, aqueous alteration and the production of magnetic minerals may not be dependent on fluid flow, i.e., in models with isochemical alteration[28]. If ice and rock are homogeneously distributed throughout the body, and the body heats homogeneously, then large-scale, coherent magnetization could exist. The length scale of magnetization would represent that of any heterogeneous distribution of water ice, which would cause heterogeneity in the amount of radiogenic heating from the silicate component.

Overall, our work describes how a planetesimal that formed a few million years after CAIs would undergo enough heating to acquire a CRM during aqueous alteration while embedded within the solar nebular field, but not too much heating that would later erase the CRM. Additionally, our work establishes an upper bound on the magnetic dipole moment that is possible for a planetesimal magnetized by the solar nebula. We predict that large C-type asteroids that exhibit evidence of partial differentiation could have magnetospheres detectable from spacecraft. We hypothesize that Pallas is one such asteroid and show that this hypothesis can be tested with low-altitude, magnetic field measurements.

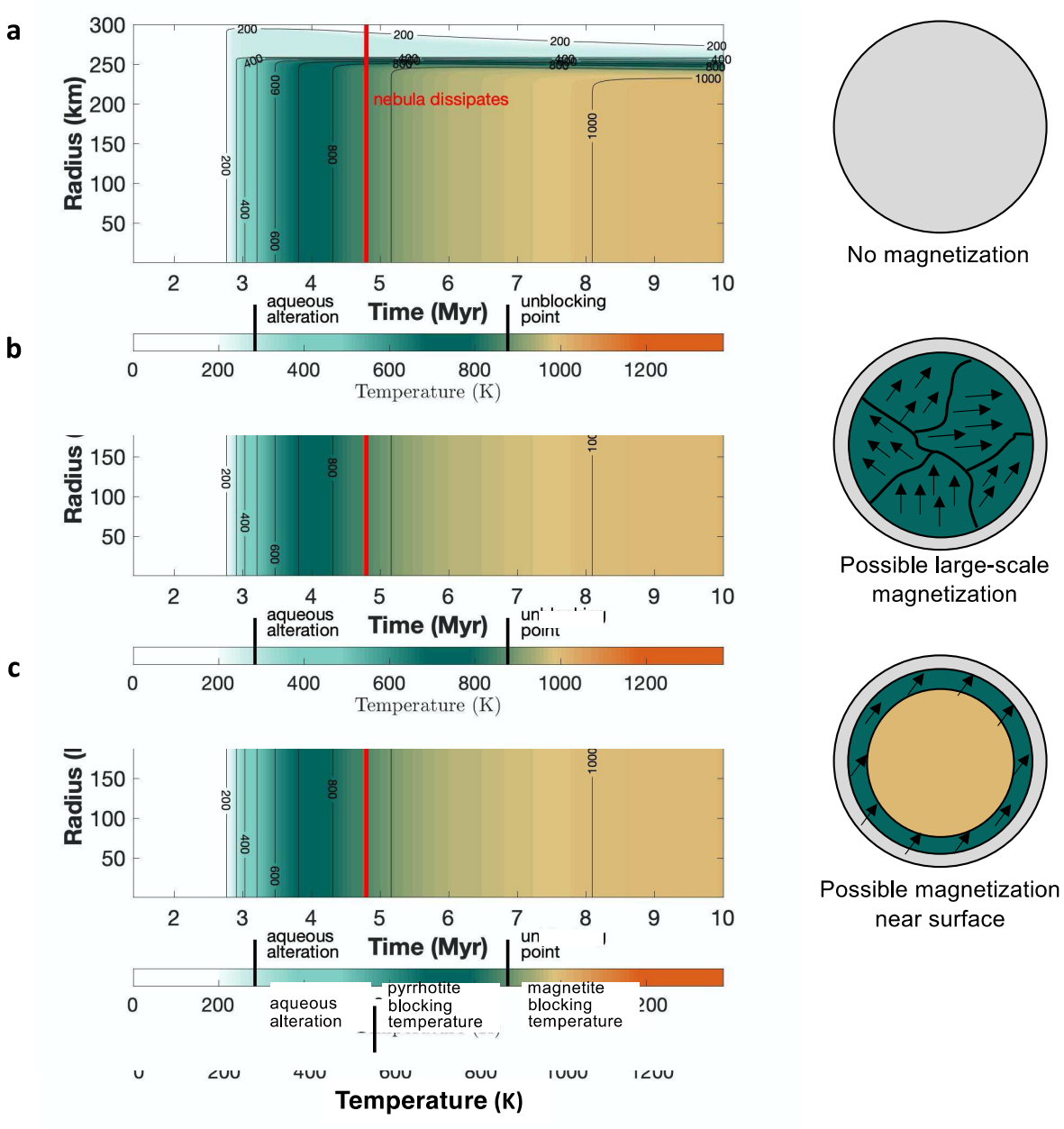

Fig. 1: Planetesimal thermal evolution determines extent of aqueous alteration and thus magnetizable volume. Thermal evolution models for a 300-km-radius planetesimal assuming formation at (a) 4 Myr, (b) 3.2 Myr, and (c) 2.8 Myr after CAIs. In panel (a), the planetesimal forms too late for ^{26}Al-driven heating to trigger aqueous alteration before the solar nebular field dissipates. This case leads to no magnetization. In panel (b), the planetesimal forms early enough

for aqueous alteration to occur but does not subsequently exceed the unblocking temperatures of the magnetic minerals. This scenario leads to possible coherent magnetization throughout the entire body. In panel (c), the planetesimal heats enough to experience aqueous alteration before the nebular field dissipates, but subsequently exceeds the unblocking temperature for most of the interior. This evolution means that the majority of the planetesimal would be demagnetized except for a thin shell near the surface.

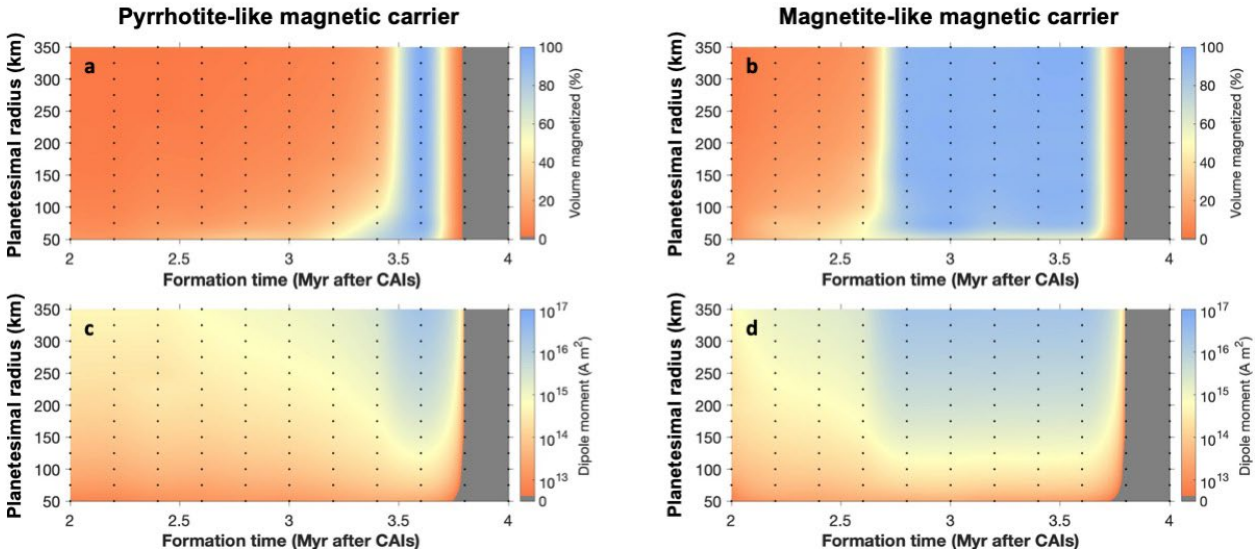

Fig. 2: Formation time determines the maximum possible magnetized rock volume and magnetic moment that a planetesimal could acquire. Panels (a) and (b) illustrate the maximum possible volume of the planetesimal that the solar nebular field could magnetize as a function of the planetesimal's formation time and radius, assuming pyrrhotite and magnetite are the magnetic carriers, respectively. A wide range of formation times lead to ~100% magnetization if the magnetic carrier is magnetite. If the magnetic carrier is pyrrhotite, then the extent of magnetization is more sensitive to formation time. Black dots represent individual thermal model runs. We assume that the solar nebular field dissipated at 4.8 Myr after CAIs and

that the unblocking temperature is 550 K for pyrrhotite and 850 K for magnetite. The greater the volume percentage of a planetesimal that is magnetized, the greater its magnetic dipole moment could be. Panels (c) and (d) illustrate the maximum possible dipole moment where the magnetic carrier is pyrrhotite and magnetite, respectively. Here we use a magnetization intensity of 10^{-4} A m^2 kg^{-1}.

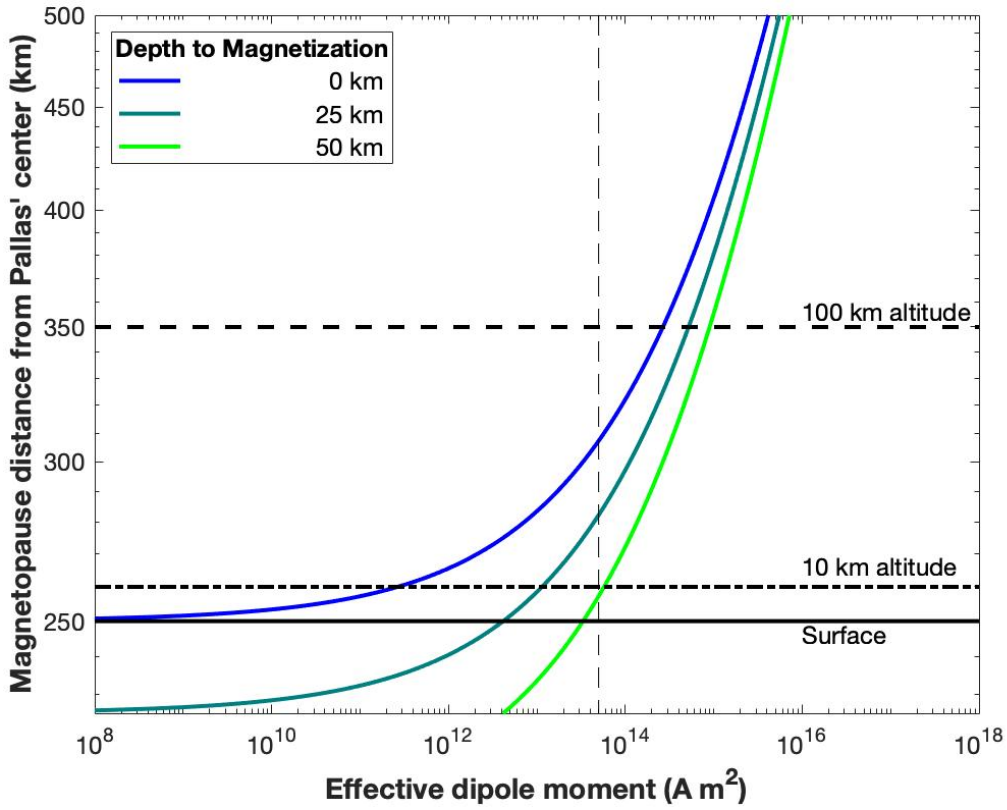

Fig. 3: A magnetized chondritic asteroid can produce a detectable magnetopause. The curves represent the magnetopause distance as a function of a Pallas-sized asteroid's effective magnetic dipole moment. The higher the magnetopause, the more easily detectable the asteroid's magnetosphere. At low magnetic moments and close proximity to the asteroid's surface, the magnetopause distance depends heavily on the depth to magnetization, with deeper

magnetization being more difficult to detect. Moments greater than ~10^{13} to 10^{14} A m^2 are likely detectable during an orbiter or flyby. Lower magnetic moments could be detected by a low orbit or a lander. The exact cutoffs for detectability depend on specific mission parameters.

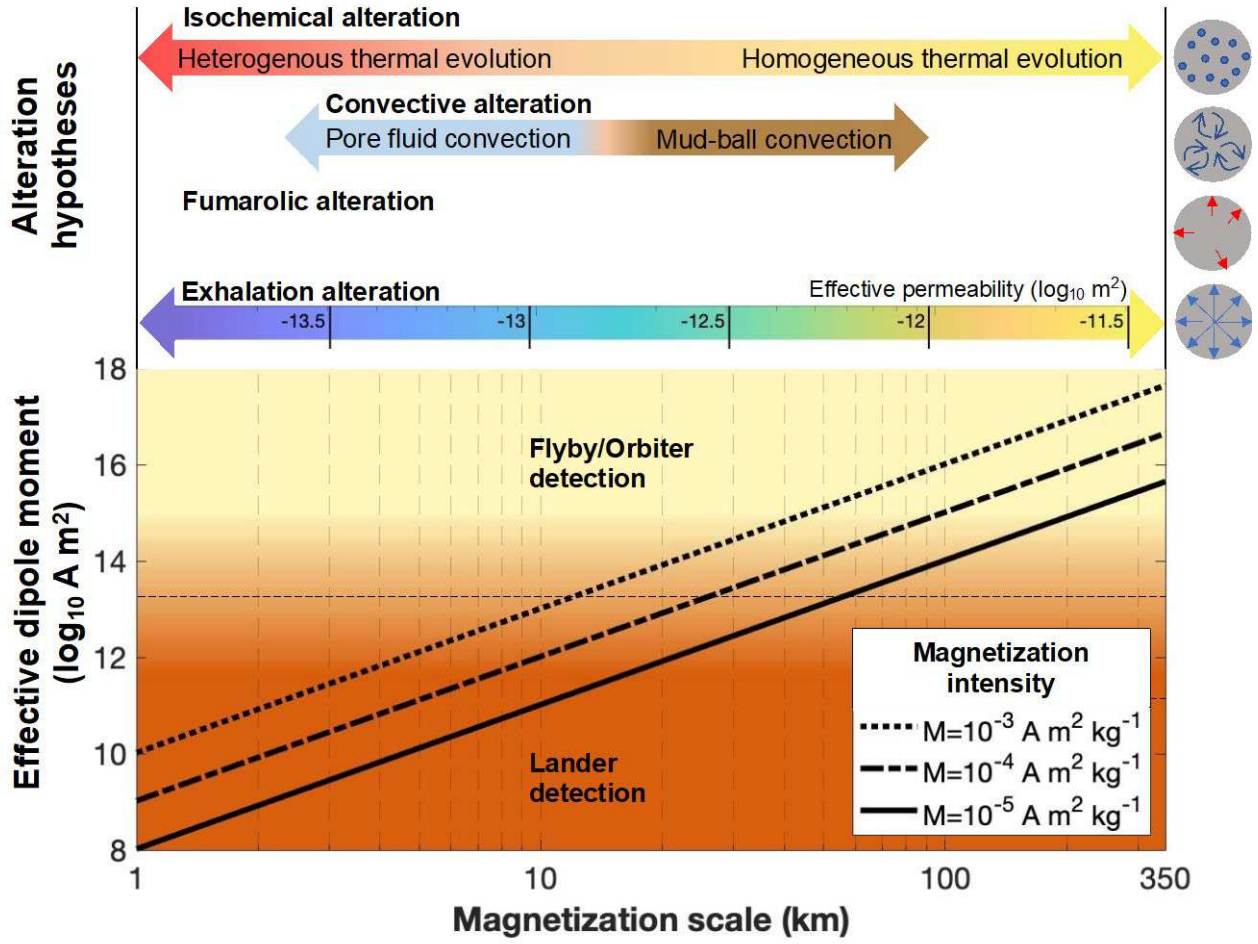

Fig. 4: The aqueous alteration model determines the length scale of coherent remanent magnetization, which determines the magnetic dipole moment. We use three different magnetization values corresponding to the range observed in CM chondrites[3]. The prevailing aqueous alteration process determines the magnetization scale, which is the effective radius of the volume that is coherently magnetized. Many aqueous alteration models exist. For outward

Darcy fluid flow (exhalation flow), effective permeability controls the magnetization length scale. If hydrothermal or fluid convection models control alteration, then the system or convection scale likely determines the magnetization scale. Lastly, alteration may not depend on fluid flow. In an isochemical model, the magnetization scale would depend on the homogeneity of the ice/rock ratio that controls thermal evolution. From Fig. 3, we expect that the lowest detectable dipole moment for an orbiter or flyby over the surface of Pallas is ~$10^{13.5}$ A m^2. Thus, it would be possible to detect magnetization from a spacecraft at Pallas if coherent magnetization exists at a scale greater than ~10–50 km.

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Methods:

Thermal evolution models:

Thermal evolution controls how and when a planetesimal may acquire chemical remanent magnetization through aqueous alteration. We employ the thermal modeling algorithm described in Castillo-Rogez et al. (2007, 2010)[29–31]. This algorithm solves for the temperature profile at each radial extent,

$$\frac{d\left(\frac{k(T)dT(r)}{dr}\right)}{dr}+\frac{2}{r}\left(\frac{k(T)dT(r)}{dr}\right)=\rho(r)C_p(T)\left(\frac{dT(r)}{dt}\right)-H(r),$$

where T is the temperature, r is the radius, k is the thermal conductivity, ρ is the density, C_p is the heat capacity, and H is the specific heat production from radiogenic decay. We assume the initial Al^{26} concentration is 600 ppb and that its specific heat production is 0.146 W/kg. The model time step is 10^4 years. Additionally, this thermal model includes heating from accretion,

$$T(r)=\frac{h_a}{C_p(T)}\left[\frac{4\pi}{3}\rho\, G\, r^2\ +\frac{\langle v\rangle^2}{2}\right]+T_i,$$

where h_a is the fraction of mechanical energy transferred to heat, G is the gravitational constant, v is the velocity of accreting objects, and T_i is the initial temperature. Even for the largest planetesimals we consider, the heat from accretion is only a few 10s of K, so the assumption of instantaneous accretion is acceptable. Full details of the model implementation, including the assumed values of all the parameters, are available in Castillo-Rogez et al. (2007)[31].

We model an array of planetesimals with varying radii and formation time. Radii range from 50–350 km in increments of 25 km and formation times range from 2–4 Myr after CAIs in increments of 0.2 Myr Additionally, we run each model with a starting water ice volume fraction

of 10 and 40%. We also run each model with initial temperatures of 100 and 160 K, which correspond to the expected outer (between the orbits of Jupiter and Uranus) and inner solar system temperatures respectively.

Dipole moment calculation:

The magnetic dipole moment is defined as,

$$m = \iiint \boldsymbol{M}\, dV,$$

where $\boldsymbol{M}$ is the magnetization and V is the magnetized volume. In general, an asteroid can be non-spherical, and the volume could be composed of fractions that have varying magnetization strengths and directions. To calculate the maximum possible dipole moment, we assume that the entire magnetized volume of the asteroid has the same magnetization direction. Additionally, we assume a radially symmetric asteroid. The dipole moment then simplifies to the product of the magnetization magnitude and the magnetized volume,

$$m = MV.$$

The output of a planetesimal thermal model tells us what volume of the planetesimal can be magnetized. We assume that the magnetization value is 10^{-4} A m^2/kg, which falls within the range of values observed in CM chondrites[3]. One could attempt to calculate the magnetization of the planetesimal by assuming a nebular field strength and orientation, without relying on any meteoritic data. However, none of these parameters are constrained enough to provide a more precise estimate than our preferred method[32,33].

Research suggests that the intensity and direction of the solar nebular field was likely stable for periods of ~1 kyr or longer[1]—long enough to allow magnetic minerals to form during a planetesimal's aqueous alteration[34]. However, a rotating planetesimal orbiting around the early

Sun would have had an ever-changing orientation with respect to the nebular field. In this case, the planetesimal would acquire remanent magnetization in the net average direction of the background field parallel to the planetesimal's spin axis[35]. If the planetesimal's spin axis is not perfectly aligned with the disk plane, the projection of the spin axis onto the vertical component of the nebular field in the protoplanetary disk would have a non-zero average, as the vertical component would remain constant as the planetesimal orbits around the sun.

It is idealistic to assume that the solar nebula would magnetize an entire asteroid unidirectionally. If fluid flow from the core to the surface of a planetesimal drives the rate at which aqueous alteration occurs, the permeability of the planetesimal determines the length scale of magnetization. Under the assumption of Darcy fluid flow, the pressure gradient in the body drives fluid to the surface. The pressure gradient at a depth z is defined as,

$$\frac{\mathrm{dP}}{\mathrm{dz}} = \rho g(z)$$

where ρ is density, and g is gravitational acceleration. The linear fluid velocity in a porous medium governed by Darcy's law follows the relationship,

$$v(z) = \frac{k}{\mu\phi}\frac{\mathrm{dP}}{\mathrm{dz}}$$

where k is permeability, μ is fluid viscosity, and ϕ is porosity. Dividing the expected stability time of the nebular field, ~1 kyr, by the velocity v, yields an estimate of the magnetization length scale. We report the length scale using the maximum fluid flow velocity within the body. The fluid viscosity of water is 10^{-3} Pa s. Assuming the length scale corresponds to the radius of a spherical volume, the dipole moment is given by the product of the spherical volume and the magnetization value. At a spacecraft flyby distance (i.e., closest approach of ~100 km or less from the surface of the planetesimal, depending on the mission design), a collection of randomly

306 oriented magnetized regions of similar size would produce a field strength that is approximately
307 the same field strength as would come from the dipole moment of a single magnetized region.
308
309 **Magnetopause distance:**
310 To assess the detectability of a magnetized Pallas, we estimate the magnetopause distance. The
311 magnetopause distance is the point at which the solar wind pressure and the asteroid's magnetic
312 field pressure balance each other.

313 $$D = R_p \left(\frac{f^2 B^2}{2\mu_0 m_H n V^2} \right)^{\frac{1}{6}}$$

314 where R_p is the radius of the body, m_H is the mass of a hydrogen ion, $n = 2$ cm^{-3} is the density of
315 the solar wind at the asteroid belt, $V = 400$ km/s is the solar wind velocity, and $f = 2$ is a
316 geometric factor[36]. B is the field strength on the magnetic equator on the surface. For a magnetic
317 dipole, the field strength is

318 $$B = \frac{\mu_0}{2\pi} \frac{m}{R_m^3}$$

319 Where m is the magnetic moment, and R_m is the distance from the dipole center. This equation
320 approximates the body's magnetic field as a dipole centered in the body. This approximation is
321 valid for strong magnetic moments and magnetopause distances that are far from the surface of
322 the body. However, small dipole moments as generated by groups of small length-scale dipoles
323 would have a more complicated behavior at close distances. In this case, the surface field would
324 be most dominated by the dipole that is closest. Thus, we plot the magnetopause distance
325 assuming that the distance from the dipole center to the surface is the same as the length scale of
326 the magnetization.
327

Supplementary information:

Simulation assumptions and parameter uncertainties

Figure 2 applies to planetesimals that formed in the outer solar system where the nebula dissipated[1] at a given time, in this case, 4.8 Myr. If the nebula dissipated sooner, then the range in formation times that could lead to large-scale magnetization would be narrower. Alternatively, a planetesimal is more likely to retain a CRM if the nebula dissipated later. Additionally, our thermal models assume that the planetesimals contain 40 vol% water ice. A lower water-to-rock ratio or higher concentration of ^{26}Al in the rock fraction would lead to faster heating and a narrower range of formation times that could result in large-scale, magnetization. If heating is sufficiently higher than our nominal scenario, large-scale magnetism dominated by pyrrhotite is not possible because a planetesimal would always exceed pyrrhotite's unblocking temperature. Extended Data Figs. 1 and 2 illustrate the effects of quicker nebular dissipation and a lower water-to-rock ratio, respectively.

The process of aqueous alteration occurs when water ice melts at 273 K. This assumes the ice fraction is pure water ice. In our thermal models, differentiation occurs instantaneously[37]. This assumption is valid because the timescale of water transport is likely much shorter than the timescale of the thermal evolution[30,31]. When the model reaches the water melting point, the water migrates toward the surface of the planetesimal. This time marks the point at which aqueous alteration occurs throughout the planetesimal. Our results are largely independent of planetesimal size for radii greater than ~50 km. For smaller planetesimals, the amount of volumetric radiogenic heat generated versus heat lost radiating from the surface becomes an important factor. However, the thermal models are only accurate for diameters greater than

approximately 50 km; below this diameter, the assumption of instantaneous differentiation leading to the migration of liquid water to the surface is no longer valid. The models are computed accurately under the assumption that the differentiated body has a rocky mantle and water layer. From a thermal evolution standpoint, these models are upper bounds on the max temperature achieved.

Lastly, our modeling assumes that planetesimals instantaneously accreted unaltered material (i.e., no alteration during accretion) and that no disruption occurred to the planetesimal during its thermal evolution. Although C-type asteroids could have accreted material that was already aqueous altered to begin with[14], this assumption would not alter our conclusions so long as additional alteration could take place. The assumption of instantaneous accretion is acceptable because under the paradigm of pebble accretion, planetesimals likely formed quickly relative to the timescale of radiogenic heating[38]. Instabilities in the protoplanetary disc could bring together bodies on the order of 10s–100s of km over kyrs[33]. Indeed, the theory of planet formation by pebble accretion requires a large reservoir of planetesimals of this size which could subsequently grow into protoplanets by continuing aggregation of dust and pebbles. However, alteration during protracted accretion or catastrophic disruptions may still have occurred which we do not consider[39].

Alternative origins of magnetization in planetesimals

Parts of a planetesimal that undergo aqueous alteration could acquire magnetization from either an endogenous or exogenous magnetic field. An endogenous field origin requires that the

374 planetesimal once hosted a dynamo, presumably in a metallic core that is vigorously convecting
375 due to rapid cooling. Therefore, a planetesimal can only host a dynamo if it heated up enough to
376 melt metal and form a liquid core. Chondrites are undifferentiated material; however, they may
377 originate from the outermost shells of parent bodies that are internally differentiated. That is,
378 some chondritic material may remain relatively cold near the surface of a differentiated body[40,41]
379 but experience an endogenous magnetic field from a core dynamo in the hot interior[42]. In other
380 words, steep thermal gradients in the outermost layers of a parent body could keep the exterior
381 cool even if the interior is relatively hot.
382
383 Formation of a metallic cores can occur as early as a few Myr after CAIs for bodies that
384 formed early in the history of the solar system with scant water ice[40]. However, studies of
385 asteroid dynamos suggest that the onset of a magnetic field would not occur until ~5 Myr after
386 CAIs or later[40,42] because the core needs to start cooling to kickstart a dynamo. Radiogenic
387 dating of carbonate minerals associated with aqueous alteration in CM chondrites places their
388 formation time between ~2.4 and 4 Myr after CAIs[43]. Based on alteration sequences proposed for
389 CM chondrites, these minerals likely formed contemporaneously with pyrrhotite and
390 magnetite[2,44]. Thus, it is unlikely that an endogenous magnetic field from a core dynamo
391 magnetized the CM chondrites if model-predicted dynamo timing and the ages of the CM
392 magnetized minerals are correct.
393
394 A spacecraft detection of a magnetosphere around Pallas would add evidence to the
395 hypothesis that Pallas is a possible parent body for the CM chondrites, assuming that the
396 spacecraft could also rule out the presence of a large metallic core. The absence of a metallic

core would rule out a dynamo origin for the magnetization. Measurements of the density of the near-surface material, compared to the bulk density and (if available) the moment of inertia, would help determine the extent of internal differentiation. Knowledge of the internal differentiation state could constrain whether a metallic core may exist to host a dynamo source[42]. Additionally, the magnetization could not be confused with accretional-detrital-remanent magnetization[45]. Accretional-detrital-remanent magnetization is produced by magnetized grains aligning themselves during the process of accretion in the solar nebular field. However, this magnetization process would not produce coherent magnetization above the meter-scale[45], and thus only a magnetometer landed on the surface of an asteroid could detect accretional-detrital-remanent magnetization. Thus, observations of large-scale magnetization on Pallas combined with the absence of a core would uniquely confirm that it formed before the solar nebular dissipated.

In principle, a strong solar wind—as opposed to the solar nebular field—could magnetize parts of planetesimals. Although the early solar wind was stronger than the solar wind today, it was probably still too weak to magnetize chondritic material[35]. Nevertheless, one recent study[46] suggested that the early solar wind could magnetize planetesimals because young planetesimals would behave more like comets and have conductive outer shells that could amplify the magnetizing field by an order of magnitude near the surface. In this scenario, CM chondrites could originate from the magnetized outer shell of a planetesimal. Whether magnetization by the solar wind could produce a planetesimal with a magnetized shell remains controversial[35]. In any case, the solar wind is not expected to produce planetesimal with large-scale magnetization.

Again, observations of a strong remanent magnetization could reveal the timing of the formation of planetesimals like Pallas.

Length scale of magnetization

The rate of fluid flow in planetesimals could have controlled the rate of mineral alteration[23]. In this case, the greater the permeability of the planetesimal, the greater the length scale of magnetization. The permeability of a planetesimal at early times is difficult to determine. Estimates[25,28] based on geodynamical arguments and/or measurements of meteorites and terrestrial analogs range widely from ~10^{-19} to 10^{-11} m^2. Measurements of permeability in meteorite samples tend to favor low permeability values[28,47]; however, geodynamical models of aqueous alteration often assume high permeability[25,48]. These need not be in complete agreement. Although the permeability of a meteorite hand sample is low, the overall effective permeability of a planetesimal could be much greater due to large fractures and fluid conduits[24] or because the material has not yet been lithified[23]. If the effective permeability is high, then fluid could flow quickly from the planetesimal's interior to its surface in kyrs, i.e., exhalation flow[49]. Quick exhalation flow could produce large-scale, coherent magnetization of potentially the entire planetesimal body. Per contra, fast exhalation flow might not allow enough time for chemical reactions to occur[49]. Multiple pass fluid flow, e.g., pore fluid convection, may be required to produce the degree of aqueous alteration seen in CM chondrites[50]. Near the surface of a planetesimal, fluid flow could be dominated by convection[25]. The thermal gradient near the surface would cause warm water to rise while cold water descends. Under this regime, we would expect the magnetization length scale would be approximately the convection length scale. Modeling of pore fluid convection indicates scales of ~10 km. Lastly, high temperature

hydrothermal systems may occur within planetesimals[51]. High temperature hydrothermal reactions in fumarolic-like systems that involve effusive events of steam are potentially able to alter minerals much more quickly (10s of yrs or less) than conventional fluid alteration[34]. However, fumarolic alteration would be limited to small, localized regions. From terrestrial analogs[52], we expect this length scale would be on the order of 1–10 km.

If the permeability of a planetesimal is as low as 10^{-19} m^2, then fluid flow would be so slow that effectively all aqueous alteration would occur with stagnant and chemically isolated water[28]. This model matches geochemical studies of CM chondrites which indicate alteration occurred isochemically[25,28]. In the previous paragraph, we implicitly assume that the length scale of magnetization would be determined by the distance that fluid can travel over the period of nebular field stability (~1 kyr). However, aqueous alteration that occurs from chemically isolated fluids would produce magnetization length scales that depend on the homogeneity of internal heating. If water ice is distributed homogeneously throughout the planetesimal's body, then we would expect most of the interior to reach the ice melting point around the same time. At this point, all rock would be exposed to at least a little water which may or may not be trapped. Under this assumption, the magnetization length scale then depends on how homogenously the body heats, which is dependent on how homogeneously the water ice and radiogenic isotopes are distributed. In the absence of constraints, this could lead to any length scale value.

Finally, debates over permeability and whether alteration was isochemical can be bypassed altogether if aqueous alteration occurred in un-lithified rock. In this case, water melting leads to a muddy mixture of mobile pebbles[27]. Since both the pebbles and the fluid are well

mixed and mobile, a muddy planetesimal may experience "mudball" convection, wherein both solids and fluid move about the asteroid in order to dissipate heating[27,53]. This whole-body convection can extend from the mud-mantle to the core. The sorting of particle sizes and variable water-to-rock ratio throughout a convecting mudball would lead to compositional heterogeneity over short length scales[27]. We expect that magnetization length scales would be on the order of ~10–100 km based on the size of convective cells.

To summarize, if exhalation flow dominates the magnetic length scale, then the scale would be determined by the permeability of the body. Under the assumption of permeable material, we expect magnetization scales to be on the order of 10–100 km. Under the realm of fluid convection dominated alteration, we expect that only the near surface within kms of the surface would have the temperature gradient necessary to sustain convection, so length scales would be ~10 km. If fumarolic systems dominate magnetization, then based on terrestrial hydrothermal scales, the length scale could be on the order of 1–10 km. If the asteroid is not permeable, then alteration scales could take on a wide range of values depending on the homogeneity of temperature increase throughout the body (e.g., from <1 km to > 100km). Finally, "mudball" convection could lead to magnetization length scales of up to 100 km.

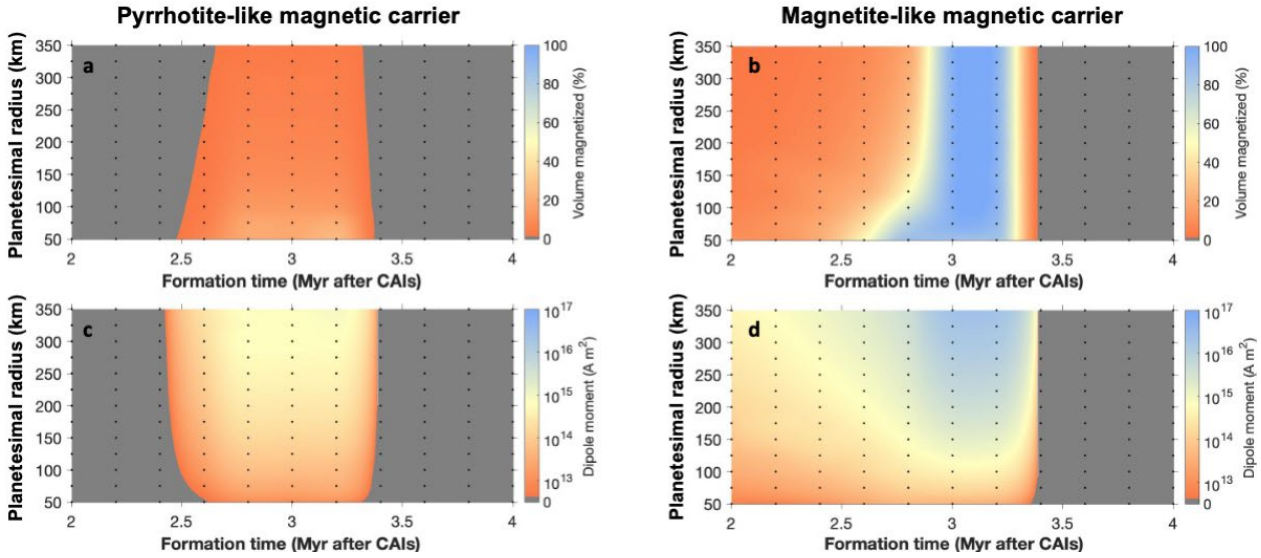
Constraints from spacecraft observations

To date, only one spacecraft with a magnetometer has visited a C-Type asteroid. The MASCOT lander aboard JAXA's Hayabusa2 mission made magnetic field measurements on the surface of the C-type, rubble-pile asteroid (162173) Ryugu[54]. However, the MASCOT lander did not detect a magnetic field intrinsic to Ryugu[54]. This means that if Ryugu has magnetization, it

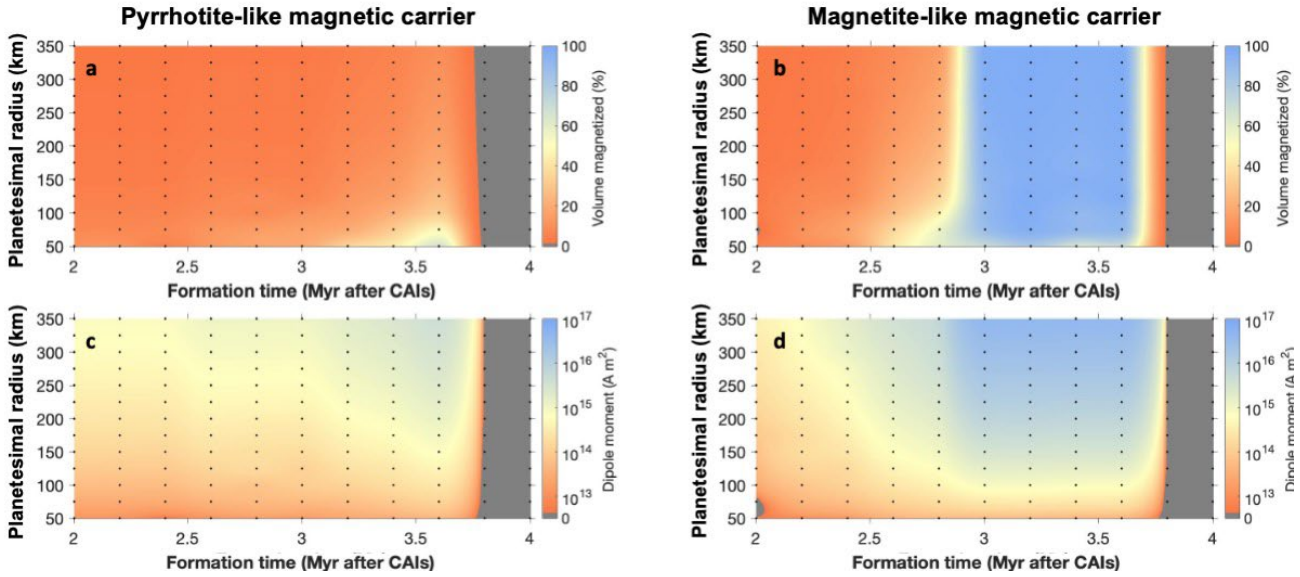
must be at a scale less than 1 cm[54]. This does not preclude the possibility of magnetized C-type asteroids. First, Ryugu is a rubble pile, so strong coherent magnetization is not possible as any magnetized pebbles or boulder would have scrambled orientations. Furthermore, Ryugu's composition may not match that of aqueously altered chondrites, and thus are not applicable to this study. However, if samples from Ryugu do match CM chondrites for example, and do not have any detectable magnetization or evidence that magnetization could have been erased, then this would suggest that magnetization of CM chondrites is not a ubiquitous process occurring throughout the entire body of an original CM chondrite parent body. Preliminary publications suggest Ryugu is more like CI chondrites[55].

Although NASA's Dawn spacecraft did not have a magnetometer, Dawn did visit the largest C-type asteroid, 1 Ceres. Using observations from the Gamma Ray and Neutron Detector (GRaND), one can place an upper limit on Ceres' magnetic field by analyzing the deflection of charged particles[56]. Although GRaND made transient detections of deflected particles, it did not observe a signal consistent with a bow shock from a strong dipolar field in the solar wind[56]. Through this argument, Ceres cannot have a magnetic moment greater than ~10^{16} A m^2 or so[56]. This limit does not rule out large-scale, coherent magnetization, so we cannot exclude the possibility that Ceres has a detectable CRM from the solar nebular field.

Extended Data Figures:



Extended Data Figure 1: Maximum magnetized volume percent for planetesimals with 40 vol% water ice that formed in the inner solar system where the solar nebula dissipated at 3.9 Myr after CAIs and assuming an unblocking temperature of (a) 550 K and (b) 850 K, which correspond to the magnetic carriers pyrrhotite and magnetite respectively. Panels (c) and (d) illustrate the maximum possible dipole moment corresponding to panels (a) and (b) respectively. Quicker nebula dissipation leads to fewer planetesimals that could be magnetized. Compared to the nominal case in Fig. 2, the range of time that can lead to 100% magnetization has been greatly reduced if magnetite is the carrier and eliminated if pyrrhotite is the carrier.



Extended Data Figure 2: Maximum magnetized volume percent for planetesimals with 10 vol% water ice that formed in the outer solar system where the solar nebula dissipated at 4.8 Myr after CAIs and assuming an unblocking temperature of (a) 550 K and (b) 850 K, which corresponds to the magnetic carrier being pyrrhotite and magnetite respectively. Panels (c) and (d) illustrate the maximum possible dipole moment corresponding to panels (a) and (b) respectively. Because there is less water ice, there is more radiogenic heating. More radiogenic heating means it is easier to reach the unblocking temperature(s) and erase magnetization. Compared to the nominal case in Fig. 2, the range in time that allows for 100% magnetization assuming magnetite is the magnetic carrier has been narrowed. No times allow 100% magnetization assuming pyrrhotite is the carrier. A 10 vol% water ice planetesimal would not have enough water to undergo complete aqueous alteration, and low water content is not likely in the outer solar system. Furthermore, even if it did occur, magnetite and pyrrhotite may not form, as hematite and tochilinite could be the preferred minerals. Regardless, this scenario illustrates that models incorporating lower water ice, or greater heating from a higher ^{26}Al abundance, are less favorable for large scale magnetization.

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