MAGNETIZATION OF LARGE C-TYPE ASTEROIDS: A DETECTABLE CONSEQUENCE OF PEBBLE ACCRETION? S. W. Courville[1*], J. G. O'Rourke[1], J. C. Castillo-Rogez[2], R. Oran[3], B. P. Weiss[3], R. R. Fu[4]. [1]Arizona State University, Tempe, AZ. [2]Jet Propulsion Laboratory, Pasadena, CA. [3]Massachusetts Institute of Technology, Cambridge, MA. [4]Harvard University, Cambridge, MA. *swcourvi@asu.edu.

Introduction: The theory of planet formation via pebble accretion suggests that mm- to cm-sized grains rapidly coalesced into large (~100 km) planetesimals in localized regions of instability in the early solar nebula [1, 2]. Later, planetesimals continued to accrete pebbles and grew into protoplanets (1000+ km). This theory circumvents the "meter-sized barrier," in which conventional planet formation models predict that, in general, meter-sized objects would rapidly fall into the Sun [3]. Stellar observations show that solar nebulae have stronger magnetic fields than today's solar wind [6]. Also, meteorite paleomagnetic studies demonstrate that the solar nebula sustained a strong (~5–50 μT) magnetic field [4] which dissipated no later than ~5 Myr after the formation of calcium aluminum inclusions (CAIs) and was shorter lived in the inner solar system [5]. Thus, pebble accretion implies that large planetesimals formed within strong magnetic fields.

We argue that spacecraft missions to some C-type asteroids would detect remanent magnetization acquired during formation by pebble accretion. Identifying large-scale magnetization on an asteroid that never hosted an internal dynamo would constrain its formation time, location, and environment. For a large primitive asteroid to be magnetized, it must be a mostly intact planetesimal that formed before the solar nebula dissipated. To acquire magnetism, the planetesimal must also have had water ice to drive aqueous alteration. Thus, only planetesimals that formed at the right time, and the right distance from the Sun may have nebular magnetism.

We use thermal history models to outline the range of scenarios that could lead to the acquisition and retention of chemical remanent magnetization by nebular fields. Next, we estimate the field strength that a magnetized C-type asteroid could have today in order to demonstrate that such a field could be detected by in-situ spacecraft magnetometer measurements.

Thermal Modeling: Planetesimals could acquire chemical remanent magnetization as they heat from the decay of ^{26}Al. Whether nebular fields magnetize a planetesimal depends on when the temperature required for chemical magnetization is reached—which is driven by the formation of minerals like magnetite though aqueous alteration when water ice melts—and if subsequently the planetesimal reaches the magnetic blocking temperature(s) of its magnetic carrier(s). Depending on when these occur relative to solar nebula gas dissipation, one of three scenarios may occur:

- *Ideal timing*. Aqueous alteration occurs before the gas dissipates, leading to the acquisition of remanent magnetization. Internal temperature may continue to increase for ~10 Myr but never exceeds the Curie temperature causing demagnetization.
- *Late timing*. Water ice fails to melt before the nebular gas dissipates. Aqueous alteration occurs later, but not in the presence of a strong field. Thus, the planetesimal does not obtain large-scale coherent magnetization from nebular fields.
- *Early timing*. Aqueous alteration occurs well before gas dissipates. However, the planetesimal's temperature subsequently exceeds the relevant Curie point(s) and most magnetization is erased.

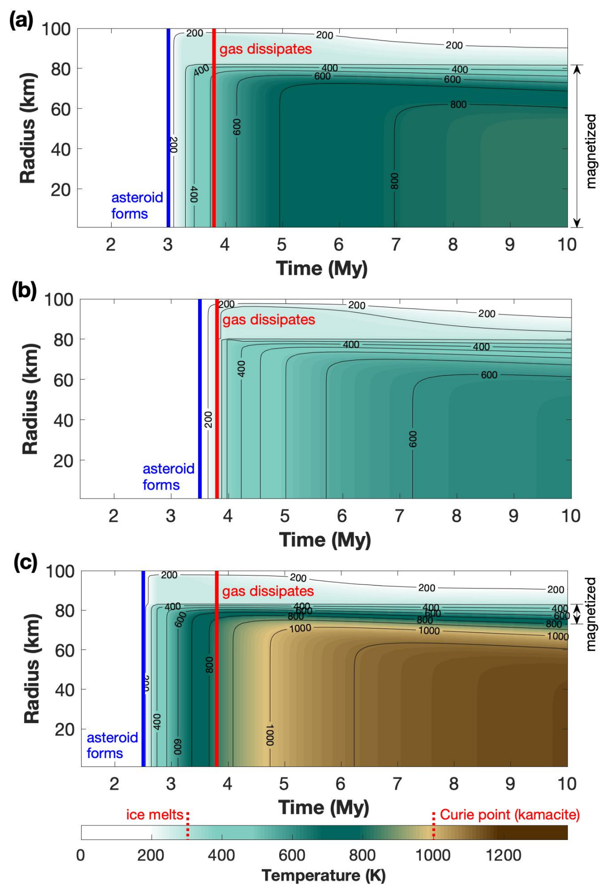

Figure 1. Thermal evolution models of a 100km radius asteroid that accreted with (a) ideal timing at 3 Myr, (b) late timing at 3.5 Myr, and (c) early timing at 2.5 Myr after CAIs. Here we assume nebular gas dissipation at 3.8 Myr.

All three scenarios are compatible with small-scale magnetization from nebular fields in meteoric fragments that originate from particular regions of the parent body [4,7]. However, only the first scenario leads to large scale coherent chemical remanent magnetization that would be potentially measurable by spacecraft. Other formation scenarios could also lead to measurable thermal or accretional detrital remanence.

We use an established thermal modeling code [e.g., 8] to determine how big and when a planetesimal would need to form to acquire remanent magnetization from nebular fields. We use ^{26}Al as the primary heat source for a young asteroid and allow the formation time, radius, and ice/rock ratio of the asteroid to vary. In general, the interiors of larger asteroids reach hotter temperatures, but higher water ice content can lower the maximum internal temperatures by convecting heat away. However, the most important parameter is the formation time. Early forming asteroids reach much higher temperatures than late forming asteroids. Figure 1 illustrates three formation time scenarios for an asteroid with a radius of 100 km and a bulk density of 3000 kg/m^3, corresponding to an initial water ice content of ~20%. Respectively, Fig. 1a, 1b, and 1c show that 3, 3.5, and 2.5 Myr exemplify ideal, late, and early formation timing for magnetization of this asteroid. Comparing Fig 1a and 1c show that large intact asteroids may have similar surface composition, but different interiors. A magnetometer could complement spectroscopy by revealing interior aqueous alteration.

Detectability of Magnetization: To assess the detectability of nebular remanent magnetization, we estimate the field strength for an asteroid with ideal formation timing (e.g. Fig 1a). Assuming the asteroid has remained intact throughout time, we can approximate the remanent magnetization as a single dipole with a total moment of ~2.5×10^{15} A m^2, which assumes a worst case magnetization intensity, ~2×10^{-4} A m^2 kg^{-1}, similar to some chondritic meteorites [9,10].

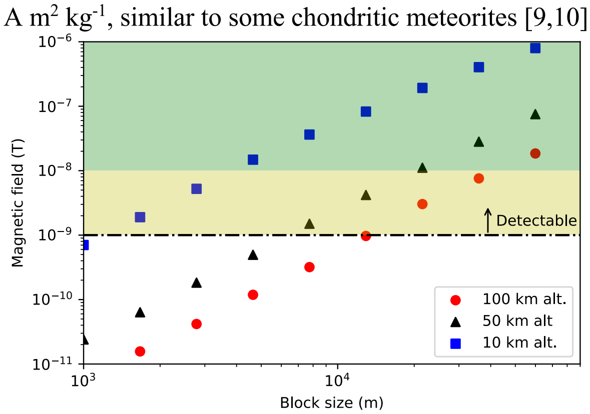

Figure 2. Magnetic anomalies at distances of 10 km (blue), 50 km (black), and 100 km (red) from the surface of a magnetized C-type asteroid with a radius of 100 km.

Not all large asteroids have remained intact since they formed. After the nebular gas dissipated, several planetesimals could have accreted into one larger body. Additionally, many asteroids have been disrupted by collisions, in which case they may be broken into small blocks that become randomly reoriented upon reaggregation. Both scenarios would result in a magnetic field created by a collection of randomly oriented dipoles. Thus, we also calculate the effective dipole moment for a combination of dipoles. In general, more random dipoles lead to a smaller effective dipole moment, and thus a weaker magnetic field.

Spacecraft magnetometers can measure fields with intensities greater than their noise floors, which is typically in the range of 1–10 nT. Figure 2 illustrates the expected magnetic field strength of a 100 km radius asteroid as a function of the mean dipole radius and considering two distances between the spacecraft and the asteroid surface at closest approach: 10 and 100 km. If the asteroid were coherently magnetized, then a signal is easily detectable at either distance. Remanent magnetization with block sizes of ~1–5 km is still detectable with a close approach. However, these calculations assume the magnetized asteroid exists in a vacuum. In reality, a magnetized asteroid would interact with the solar wind [11], which could affect the range of spacecraft flyby distances and geometries that are suitable for making detections.

Conclusions: We hypothesize that some large, C-type asteroids were magnetized in the presence of nebular gas as a consequence of their formation by pebble accretion. These asteroids were large planetesimals that failed to become protoplanets. They formed early enough to acquire magnetization via aqueous alteration in the nebular field, but not so early that they subsequently heated enough to erase magnetization. The ideal formation time depends on the size and composition of the planetesimal. If left mostly intact, a spacecraft mission could detect the magnetization. Broadly, our work shows that magnetometers are useful for missions to primitive asteroids and not just asteroids that are expected to have once been a metallic core that sustained a dynamo.

References: [1] Morbidelli et al. (2009) *Icarus*, *204*, 558–73. [2] Johansen & Lambrechts (2017) *Annu. Rev. Earth Planet. Sci.*, *45*, 359–87. [3] Testi et al. (2014) *Proto. and Planets VI*. [4] Fu et al. (2014) *Science*, *346*, 1089–92. [5] Weiss et al. (2021) *Sci. Adv.*, *7*. [6] Wardle (2007) *Astrophys. Space Sci.*, *311*, 35. [7] Fu & Elkins-Tanton (2014) *EPSL*, *390*, 128–37. [8] Castillo-Rogez & Schmidt (2010) *GRL*, *37*, 1–5. [9] Fu et al. (2014) *EPSL*, *404*, 54–66. [10] Pesonen et al. (1993) Proc NIPR, 6, 401–416 [11] Oran et al. (2018) *EPSL*, *492*, 222–31.