MAGNETIC FIELD MEASUREMENTS AT 10 HYGIEA AND 24 THEMIS COULD CONSTRAIN MODELS OF THEIR FORMATION AND EVOLUTION S. W. Courville[1*], J. G. O'Rourke[1], J. C. Castillo-Rogez[2], R. R. Fu[3], R. Oran[4], B. P. Weiss[4], Linda T. Elkins-Tanton[1]. [1]Arizona State University, Tempe, AZ. [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. [3]Harvard University, Cambridge, MA. [4]Massachusetts Institute of Technology, Cambridge, MA. *swcourvi@asu.edu.

Introduction: Many planetary bodies are targets for spacecraft missions with magnetometers because the bodies have intrinsic magnetic fields from an active magnetic core dynamo or remanence from one in the past. Excitingly, paleomagnetic studies reveal that some primitive carbonaceous meteorites—originating from primitive bodies *without core dynamos*—may have magnetization from external magnetic fields [1,2]. Our previous work shows that the asteroid 2 Pallas could have a measurable magnetization imparted by the solar nebular magnetic field present during the first few million years of the solar system [3]. In this work, we apply the same approach to the asteroids 10 Hygiea and 24 Themis. We find that they, too, are potentially magnetized worlds. In general, we wish to highlight the potential value of magnetometry for investigating the interiors, origins, and evolution of C-complex asteroids.

10 Hygiea and 24 Themis: These large, dark carbonaceous asteroids both have collisional families [4] and likely formed a few million years after calcium aluminum-rich inclusions (CAIs) beyond 3 AU [5]. But their internal evolutions are unknown [6,7,8].

10 Hygiea is the fourth largest object in the asteroid belt. Like 1 Ceres and 2 Pallas, it is nearly spherical [7]. Since 10 Hygiea has a collisional family, a significant quantity of material must have been excavated from its surface. Yet, telescopic imagery does not reveal any large impact basins (Fig. 1). To reconcile these observations, Vernazza et al. [7] suggest that, more than 2 Gyr ago, an impact pulverized 10 Hygiea, producing the Hygiea collisional family; subsequently 10 Hygiea reaccreted into a nearly spherical body from the rubble. Alternatively, there never was a catastrophic impact. 10 Hygiea experienced normal impact bombardment, and naturally relaxed toward hydrostatic equilibrium, aided by a high volume-fraction of ice, which is consistent with Hygiea's low density of ~2 g/cm^3 [4,7]. Future exploration of 10 Hygiea should seek to answer the question: has Hygiea preserved most of its integrity or is it re-accreted from catastrophic disruption?

24 Themis is approximately half the radius of 10 Hygiea, but the parent body of the Themis family was likely similar in size to 10 Hygiea [6]. 24 Themis's parent body likely accreted a mixture of ice and rock that may have subsequently partially separated [6,8]. Partial separation of the ice from rock would explain the wide range of spectral signatures and densities of the bodies within the Themis family [6,8] and the detection of water at 24 Themis's surface [9]. If so, future exploration of 24 Themis should check for evidence of internal aqueous alteration.

We argue that in-situ magnetic field measurements from spacecraft could probe the two asteroids' interior structures, and thus their formation and evolution.

Magnetized chondrites: CM and CV chondrites are aqueously altered carbonaceous meteorites. Their parent body, or bodies, are likely within the broader C-complex [e.g., 10]. Some CM and CV chondrites have remanent magnetization [1,11]. Although, 10 Hygiea and 24 Themis need not be the specific parent bodies of the CM or CV chondrites found on Earth, the process that magnetized the CM and CV chondrites could occur on large scales within C-type bodies.

CM and CV chondrites consist of chondrules and refractory inclusions within a matrix. In at least some specimens, the matrix harbors a coherent remanent magnetization [1,11]. Magnetization within the matrix of CM and CV chondrites is likely the result of aqueous alteration and/or thermal metamorphism in the presence of a background magnetic field. Liquid water interaction with the unaltered iron and sulfur in the mineral matrix produces magnetite and pyrrhotite [12]. Both are magnetically susceptible minerals [1,11]. When formed in the presence of a magnetic field, they can acquire a chemical remanent magnetization [1,11].

The background magnetic field was likely the solar nebular magnetic field [2]. During the formation of the solar system, matter condensed out of a cloud of dust and gas [2,5]. The ionized cloud supported a strong magnetic field [2]. The magnetic field component perpendicular to the disc plane was likely stable over 1000's of years [2]. When the nebular gas dissipated, no later than 4.8 Myr after CAIs beyond 3 AU [2], the magnetic field dissipated too. Thus, the solar nebular field could have magnetized the CM and CV chondrites during a period of thermal metamorphism or aqueous alteration that began before 4.8 Myr after CAIs.

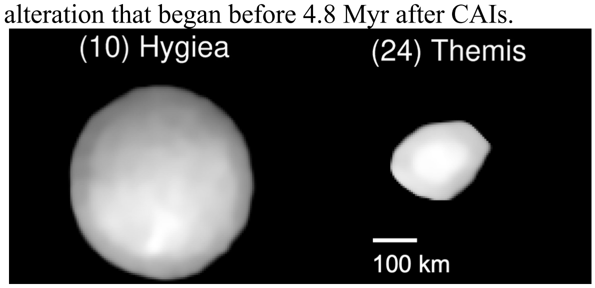

Figure 1. 10 Hygiea and 24 Themis (VLT/SPHERE [4])

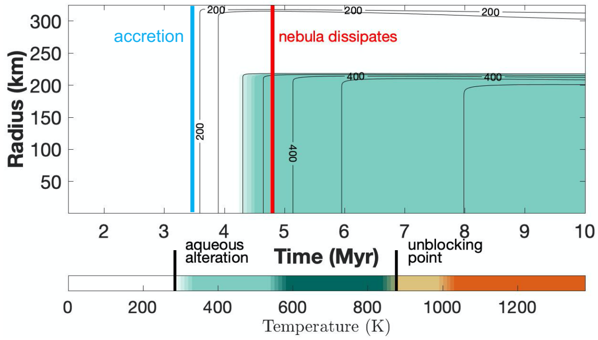

Figure 2. Thermal evolution model of 10 Hygiea or 24 Themis' parent body demonstrating that the two asteroids could be magnetized because they heated enough to melt water ice before the solar nebular magnetic field dissipated.

Thermal evolution models: Whether 10 Hygiea or 24 Themis could have magnetic remanence like the CM and CV chondrites depends on whether the asteroids experienced thermal metamorphism or aqueous alteration in the presence of the solar nebular magnetic field. Here we consider the case of aqueous alteration. We use thermal models to determine whether they would melt water ice before the nebula dissipated. We assume that 10 Hygiea and 24 Themis accreted rapidly [13,14] with 40 vol% water ice [6] and heated through radioactive decay of ^{26}Al.

Castillo-Rogez & Schmidt [6] suggest that the 24 Themis parent body formed before 4 Myr after CAIs (a hypothesis also applicable to 10 Hygiea). We find that for formation times between ~2.5 and ~3.5 Myrs after CAIs, 10 Hygiea and 24 Themis could undergo aqueous alteration before the nebular field dissipated, and thus become magnetized (e.g., 3.4 Myr in Fig. 2). If formed earlier, then greater heating from ^{26}Al would bring the interiors past the Curie temperatures of magnetite and pyrrhotite (~550 and ~850 K respectively [10]), erasing magnetization. If formed later, ice could not melt on a global scale before the nebula dissipated.

Our models assume that water flows to the surface differentiating from rock as it melts. The water may later refreeze and sublimate. Though not considered here, alternative aqueous alteration regimes, like convecting mudballs [15], could similarly promote magnetization.

Hypothesis: We hypothesize that 10 Hygiea and 24 Themis could have measurable intrinsic magnetic fields. Figure 3 maps the detectability of a magnetic field at one of these asteroids to their internal structure and formation history. Magnetic field measurements at these bodies could yield one of the following results:

1). Large magnetosphere: A magnetosphere around the asteroid that extends more than ~10 km away from the surface would indicate that the asteroid has large-scale, coherent magnetization at a scale greater than 10 km. Such a detection is consistent with the asteroid experiencing large scale aqueous alteration and no catastrophic disruption through impacts.

2). Small magnetosphere: A marginally detectable intrinsic magnetic field may extend to ~10 km from the surface at sporadic locations. Such a detection would indicate near-surface magnetized regions 1–10 km in scale, and that the body coalesced from blocks of this size, or that the body is mostly intact with aqueous alteration that was heterogeneous at that scale.

3). No Magnetosphere: The absence of a magnetosphere detection would mean that the length scale of magnetization is <1 km, or that there is no magnetization. Thus, the absence of a magnetosphere detection would not uniquely constrain models of an asteroid's evolution.

Conclusion: Future exploration of large C-type asteroid evolution should include magnetometry.

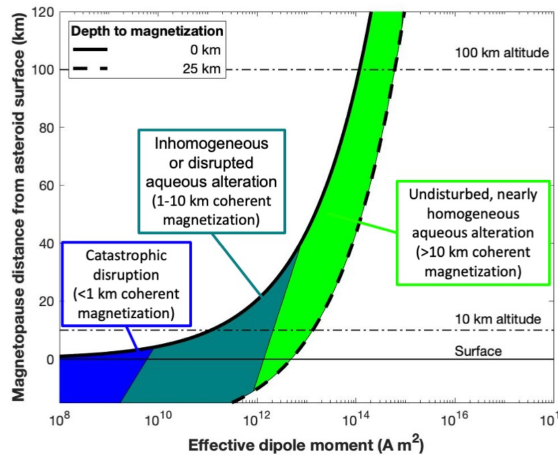

Figure 3. The magnetopause distance [16] would constrain formation history. The dipole moment is a function of the length scale of magnetization, and the magnetopause distance is a function of the depth to magnetization beneath the crust, and the dipole moment

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