CONSTRAINTS ON MAGNETIC FIELD INTENSITY IN THE OUTER SOLAR NEBULA DURING FORMATION OF COMET 67P/CHURYUMOV-GERASIMENKO FROM PHILAE MAGNETOMETRY.

J. B. Biersteker[1], B. P. Weiss[1], P. Heinisch[2], D. Herčik[2], K.-H. Glassmeier[2], and H.-U. Auster[2], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [2]Institut für Geophysik und Extraterrestrische Physik, Technische Universität Braunschweig, Braunschweig, Germany.

Introduction: Mass and momentum transfer in protoplanetary disks are believed to be largely driven by nebular magnetic fields [1]. Evidence for a nebular magnetic field in the inner solar system (~2 – 3 AU) was recently obtained from paleomagnetic measurements of chondrules from the Semarkona meteorite [2]. However, there have been no measurements of the magnetic field in the outer solar system (2 – 80 AU).

It has been proposed that comets may also retain a record of the nebular field, which could provide a measurement of the field intensity beyond ~30 AU. These bodies may be magnetized on length scales larger than individual chondrules by “compass-needle” alignment of ferromagnetic grains in a background field during accretion (accretional detrital remanent magnetization, or ADRM) [3]. This can, depending on the nebular environment during planetesimal formation, create regions of coherent magnetization ranging in scale from centimeters to meters or larger. Such large regions of coherent magnetization could be detected by spacecraft magnetometry.

The Rosetta mission to comet 67P/Churyumov-Gerasimenko (67P) measured the magnetic environment around 67P using the Rosetta Plasma Consortium magnetometer (RPC-MAG) [4] on the orbiter and the Rosetta Lander Magnetometer and Plasma Monitor (ROMAP) [5]. These measurements placed an upper limit on the remanent magnetic field intensity of 2 nT [6]. Assuming the comet to be composed of 1 m^3 regions of coherent magnetization, the resulting maximum specific magnetization is $j = 3.1 \times 10^{-5}$ A m^2 kg^{-1} [6], near the low end of the range observed for bulk chondrites and individual chondrules (i.e. 10^{-5} – 10^{-1} A m^2 kg^{-1} [7,8,2]).

The constraint from ref. [6] was calculated for a single size scale and without incorporating the comet’s topography. By incorporating the lander trajectory, the comet shape model, and multiple length scales, we substantially lower the upper limit on specific magnetization. With these limits, and other observations of 67P, we then constrain the intensity and morphology of magnetic fields in the the outer nebula during 67P’s formation, with implications for the mechanisms of stellar accretion and planetesimal formation.

Methods: We simulated the remanent magnetic field of 67P, assuming it to be filled with equal-sized, equal-density, and equal magnetization uniformly-magnetizated spheres with random orientations. We generated the collection of dipoles by performing sphere-packing in the comet shape model (“SHAP 5” [9]) using a hexagonal close-packed lattice and a modified ray-casting algorithm.

We simulated the expected field along Philae’s trajectory [10] (from first touchdown to the collision with the Hatmehit crater rim) for spheres ranging in radius from 0.10 to 50 m. Comparing these simulations to the 2 nT upper bound on field intensity, and assuming a comet density of 535 kg m^{-3} [11] and a dust-to-ice ratio of 3 [12,13], we calculated an upper limit on the specific magnetization of cometary dust.

Results: We find that extremely low values of specific magnetization, $j < 10^{-5}$ A m^2 kg^{-1}, are required for consistency with the Philae data, even at the smallest scales of coherent magnetization that we considered (Figure 1). Such a low upper bound implies that the dusty material on 67P has no coherent magnetization consistent with ADRM on length scales of 10 cm or higher.

Discussion: The absence of any ADRM signature on 67P suggests either that nebular conditions could not support acquisition of ADRM during 67P’s formation or that 67P has undergone significant post-accretional alteration.

It has been suggested that, rather than being primordial, comets are collisional fragments from larger parent bodies [14] or have been significantly restructured by collisions [15]. Alternatively, it has been ar-

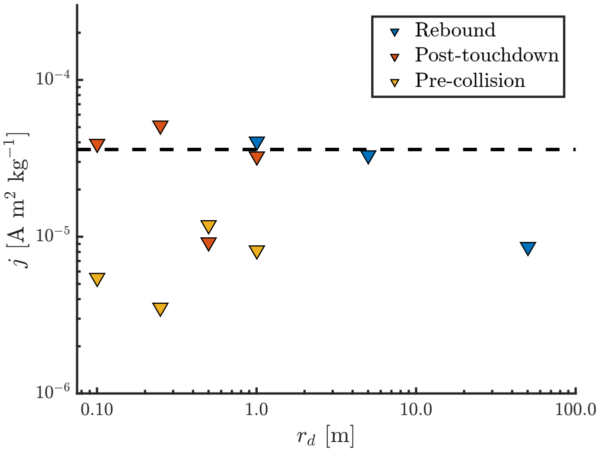

Figure 1. Maximum specific magnetization of cometary dust (j) consistent with Philae magnetometry for different scales (sphere radii) of coherent magnetization (r_d). The dashed line is the previous constraint [6], adjusted to the same density and dust-to-ice ratio.

gued that the low density, high porosity, low tensile strength, abundance of supervolatiles, and preservation of fractal dust particles require a primordial origin for comets like 67P [16,17,18,19]. In either case it is unlikely that impact brecciation of 67P to ~10 cm scales would preserve these ostensibly primitive features.

Therefore, the absence of a magnetic signature suggests that the formation scenario for 67P did not enable ADRM acquisition. Recording ADRM requires specific conditions (Figure 2). In particular, 67P would have to: (1) form through the gentle gravitational collapse of a cloud (2) of ~0.1 mm – 1 cm size pebbles (3) in the presence of a nebular magnetic field sufficiently intense to enforce pebble alignment.

67P's low tensile strength and high porosity are expected features of comets formed by streaming instability concentration of ~cm pebbles followed by gravitational collapse [20,13,16]. The preservation of fractal dust particles suggests a gentle cloud collapse, with dust mutual velocities ≤1 m s^{-1} [19]. In addition, multiple lines of evidence, including 67P's thermal inertia, porosity, and images of the surface taken by Philae, suggest that 67P formed from ~mm size pebbles [21,18].

If 67P formed as a pebble-pile, then the absence of ADRM can be caused by the failure of condition (3), the nebular field's ability to align pebbles during formation. For alignment, the magnetic torque on the pebble must exceed all other torques (e.g. Brownian motion, aerodynamic drag, etc.). For conditions expected at the approximate formation location of 67P (≥20 AU) and the observed pebble size, the absence of ADRM requires a background field intensity ≤0.1 μT. Late accretion of 67P, after the decay of the nebular field, could explain the low intensity. But formation as a pebble-pile requires concentration through the streaming instability, which in turn requires the presence of significant nebular gas. Since the dissipation of the gas disk is thought to occur within 0.5 Myr of the end of accretion and the disappearance of the nebular field [22], we consider weak fields in the outer disk during planetesimal formation a more probable explanation.

Conclusions: A magnetic field intensity of ≤0.1 μT at distances ≥20 AU is consistent with MHD models of the outer solar system, although it is less than the maximum values predicted by numerical models [23,24]. Such a low field intensity likely cannot support accretion at the assumed rate of 10^{-8} solar masses per year by radial-azimuthal field stresses (i.e. the magnetorotational instability or large-scale toroidal field), but is consistent with accretion driven by vertical-azimuthal field stresses (i.e. magnetocentrifugal winds). Finally, this suggests that formation in a low-intensity field could be used as a tracer for materials which formed in the outer solar system [25].

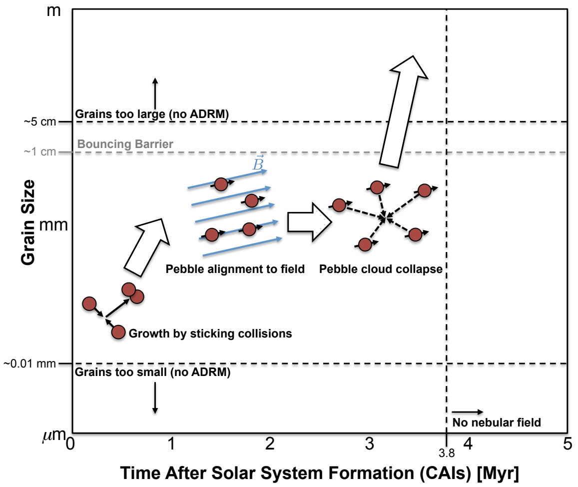

Figure 2. Schematic of ADRM acquisition for 67P with relevant constraints. The minimum and maximum grain sizes are determined by comparing the magnetic torque to other forces acting on dust grains, following [3]. The bouncing barrier is the upper limit of grain growth through sticking collisions [18]. The end of the nebular field renders ADRM impossible and occurs <3.8 Myr after the formation of calcium aluminum-rich inclusions (CAIs) [22].

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