

Geophysical Research Letters[•]

RESEARCH LETTER

10.1029/2021GL097014

Key Points:

- Meteorite paleomagnetism and hybrid modeling imply that asteroids may form magnetospheres and trap charged particles
- Planning of missions to asteroids requires assessing trapped particle energies, but existing models are not valid for such magnetospheres
- A new nonadiabatic trapping criterion shows that asteroids should not have hazardous particle radiation belts

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

R. Oran, roran@mit.edu

Citation:

Oran, R., Weiss, B. P., De Soria Santacruz-Pich, M., Jun, I., Lawrence, D. J., Polanskey, C. A., et al. (2022). Maximum energies of trapped particles around magnetized planets and small bodies. *Geophysical Research Letters*, 49, e2021GL097014. https://doi. org/10.1029/2021GL097014

Received 18 NOV 2021 Accepted 15 APR 2022

Author Contributions:

Conceptualization: Benjamin P. Weiss, Insoo Jun, Carol A. Polanskey, Carol A. Raymond, Linda T. Elkins-Tanton Formal analysis: Insoo Jun, Christopher T. Russell, Yuri Y. Shprits Funding acquisition: Carol A. Polanskey, Linda T. Elkins-Tanton Investigation: Benjamin P. Weiss, Maria De Soria Santacruz-Pich, David J. Lawrence, Carol A. Polanskey, J. Martin Ratliff, Carol A. Raymond, Jodie B. Ream, Christopher T. Russell, Yuri

© 2022. The Authors.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

Maximum Energies of Trapped Particles Around Magnetized Planets and Small Bodies

Rona Oran¹, Benjamin P. Weiss¹, Maria De Soria Santacruz-Pich², Insoo Jun², David J. Lawrence³, Carol A. Polanskey², J. Martin Ratliff², Carol A. Raymond², Jodie B. Ream¹, Christopher T. Russell⁴, Yuri Y. Shprits^{5,6,7}, Maria T. Zuber¹, and Linda T. Elkins-Tanton⁸

¹Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, ³The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, ⁴Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA, USA, ⁵Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany, ⁶Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA, ⁷Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany, ⁸School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA

Abstract Energetic charged particles trapped in planetary radiation belts are hazardous to spacecraft. Planned missions to iron-rich asteroids with possible strong remanent magnetic fields require an assessment of trapped particles energies. Using laboratory measurements of iron meteorites, we estimate the largest possible asteroid magnetic moment. Although weak compared to moments of planetary dynamos, the small body size may yield strong surface fields. We use hybrid simulations to confirm the formation of a magnetosphere with an extended quasi-dipolar region. However, the short length scale of the field implies that energetic particle motion would be nonadiabatic, making existing radiation belt theories not applicable. Our idealized particle simulations demonstrate that chaotic motions lead to particle loss at lower energies than those predicted by adiabatic theory, which may explain the energies of transiently trapped particles observed at Mercury, Ganymede, and Earth. However, even the most magnetized asteroids are unlikely to stably trap hazardous particles.

Plain Language Summary Radiation belts are regions in space filled with energetic charged particles trapped by a planetary magnetic field. To date, radiation belts were found around Earth, Jupiter, Saturn, Uranus, and Neptune. Understanding radiation belts is important because they can be hazardous to spacecraft. In addition, their emission, if detected remotely, can reveal a planet's magnetic field. The future exploration of asteroids and exoplanets may lead to the discovery of more magnetized bodies, including the upcoming NASA mission to asteroid (16) Psyche, the largest known metal-rich planetary object. Existing radiation belt theory was developed for known radiation belts surrounding the large, highly magnetized planets in the solar system. However, the nature of particle trapping should differ for small bodies like asteroids. We examine these differences to provide predictive tools for the existence of belts that can be applied to any kind of magnetosphere. We find a class of bodies that can sustain belt-like structures but where particle trajectories are chaotic, preventing prolonged stable trapping and associated energization. We show that Mercury and Ganymede's transient trapping is consistent with our predictions. Finally, we show that although asteroids may stably trap low-energy protons and electrons, even the most strongly magnetized metallic asteroids cannot form belts that pose a risk to typical spacecraft hardware.

1. Introduction

Radiation belts consist predominantly of energetic charged particles trapped in a planetary magnetic field. They are of interest due to their role in magnetospheric dynamics and in aiding the detection of planetary fields (Roussos et al., 2019), and the hazard they pose to spacecraft hardware (Baker et al., 2018). Jupiter's and Earth's radiation belts were first detected at the beginning of the space age (Drake & Hvatum, 1959; Van Allen et al., 1958) and analogous belts have since been found around Saturn, Uranus, and Neptune, all exhibiting long-term trapping of particles with energies up to 1 MeV and maybe 2 GeV (Adriani et al., 2015; Mauk & Fox, 2010; Roussos et al., 2018). Around smaller bodies like Mercury and Ganymede, trapped particles of $\sim 10^2$ keV were detected but were likely quickly lost (Eviatar et al., 2000; Ho et al., 2011; Lawrence et al., 2015; Liuzzo et al., 2020; Poppe



Y. Shprits, Maria T. Zuber, Linda T. Elkins-Tanton

Methodology: Maria De Soria Santacruz-Pich, Insoo Jun, David J. Lawrence, J. Martin Ratliff, Christopher T. Russell, Yuri Y. Shprits, Linda T. Elkins-Tanton **Project Administration:** Benjamin P. Weiss, Maria De Soria Santacruz-Pich, Carol A. Polanskey, Linda T. Elkins-Tanton

Resources: Benjamin P. Weiss, Carol A. Polanskey, Linda T. Elkins-Tanton Supervision: Benjamin P. Weiss, Carol A. Polanskey, Linda T. Elkins-Tanton Validation: Insoo Jun, J. Martin Ratliff, Carol A. Raymond, Christopher T. Russell, Yuri Y. Shprits, Maria T. Zuber, Linda T. Elkins-Tanton

Writing – review & editing: Benjamin P. Weiss, Maria De Soria Santacruz-Pich, Insoo Jun, David J. Lawrence, Carol A. Polanskey, J. Martin Ratliff, Carol A. Raymond, Jodie B. Ream, Yuri Y. Shprits, Maria T. Zuber, Linda T. Elkins-Tanton et al., 2018; Williams, 2001, 2004) (Figure 1a and Table S1 in Supporting Information S1). Upcoming missions to potentially magnetized asteroids present yet another, largely unexplored regime. To prepare for this, here we estimate whether small bodies can trap particles and up to what energies, assess the potential hazard to spacecraft, and anticipate science opportunities such as remote detection of planeary magnetism, and studying magnetospheric dynamics.

To date, asteroids explored by spacecraft are thought to be largely rocky and presented no clear evidence of remanent magnetization (Blanco-Cano et al., 2003; Kivelson et al., 1995; Richter et al., 2001; Russell et al., 2018; Scheinberg et al., 2017; Wang et al., 1995). Nevertheless, remanent magnetization has been identified in a variety of meteorites (Terho et al., 1993), suggestive of past dynamo action in their asteroidal parent bodies (Harrison et al., 2017; Scheinberg et al., 2017; Weiss et al., 2010). The upcoming Psyche mission will explore asteroid (16) Psyche (Elkins-Tanton et al., 2020), the largest known iron-rich solar system body (with an effective radius, $R_p = 113$ km; Shepard et al., 2017). Because iron-rich asteroids may carry remanent magnetization similar to that found in iron meteorites, they may have high surface magnetic fields (Table S1 in Supporting Information S1) that may form a magnetosphere and trap particles.

For a typical spacecraft with >2.5 mm of aluminum-equivalent shielding, only energies of >1 MeV for electrons and >20 MeV for protons may pose a risk (Berger et al., 2017). The locations around a dipole field that allow permanent trapping in belt-like structures were first determined analytically under the adiabatic approximation by Störmer (1955). Störmer's method is widely used and was extended to nondipolar planetary fields (Lemaire et al., 2003; Tsareva, 2019). It predicts trapping up to energies of \sim 1–10 GeV around the Earth (Schulz & Lanzerotti, 1974), Saturn, and Jupiter (Birmingham, 1982) and indeed, such trapped populations were detected at those planets (Reeves et al., 2016). However, if applied to Mercury, Störmer's method would erroneously predict trapping of >10 MeV electrons, two orders of magnitude higher than the observed maximal energies of transiently trapped electrons (Ho et al., 2011; Lawrence et al., 2015). While the high day-night asymmetry of Mercury's magnetosphere (Slavin et al., 2007) might explain this discrepancy, it is likely that violation of adiabatic invariance due to the small scale of Mercury's field is at least partly responsible. Störmer method is likely not valid for the still smaller magnetospheres that may be formed by asteroids.

Building on decades of spacecraft in situ measurements, complex radiation belt models for Earth have been developed, incorporating high order particle acceleration and loss mechanisms (Baker et al., 2018). However, these too rely on the assumption of underlying adiabatic motion (Horne et al., 2005) and in any case are not readily applicable for bodies of arbitrary size, planetary rotation rate, and distance from the Sun. Furthermore, Earth's atmosphere is an important source of energetic particles injected into the belts, but such sources are negligible for iron-rich airless bodies (Lawrence et al., 2016). Due to this gap in theory, here we use verified theoretical and computational tools (Supporting Information S1), apply them to the novel scenario of trapping in hypothetical asteroid magnetospheres, and generalize the results to any body size and dipole moment. First, we use hybrid simulations and iron meteorite measurements to establish that magnetospheres could indeed exist around large iron-rich asteroids. To avoid the uncertainty of whether acceleration mechanisms known for the terrestrial magnetosphere would be present, we determine the maximum energies at which particles can be stably trapped regardless of how and whether such particles were created. We consider the limits of adiabatic motion by tracing single particle motion and identify chaotic pitch angle scattering due to high field curvature as a critical limiting factor for trapping even in a steady state dipole field. While nonadiabatic scattering was previously studied in nondipolar regions of planetary magnetospheres (Anderson et al., 1997; Selesnick et al., 2001), it was not applied to study the location and energies of radiation belts, which reside in quasi-dipolar regions and are predominantly adiabatic for large magnetospheres. Finally, we obtain a nonadiabatic trapping criterion that can serve planned and future exploration for any small body, and validate it against relevant observations at Ganymede, Mercury, and Earth.

2. The Possibility of Asteroid Magnetospheres

To allow trapping of particles of a given energy, an asteroidal magnetic field must first be sufficiently strong to form a magnetospheric cavity in the solar wind that is larger than the particles' gyroradii, r_g , so that particles can gyrate without intersecting the surface or the magnetopause. An upper limit for asteroid fields can be inferred from laboratory measurements of the specific magnetization of iron meteorites, some of the most magnetic meteorites known. These mostly fall in the range of 10^{-4} to 10^{-2} Am² kg⁻¹ (Pesonen et al., 1992; Terho et al., 1993). The





Figure 1. (a) Equatorial surface magnetic field for known and hypothetical magnetized bodies organized by radius, R_p , and magnetic moment per unit volume, m_V (Table S1 in Supporting Information S1). Circles denote bodies with confirmed belts (red circles for solar system bodies, blue circle for the magnetized exoplanet/brown dwarf SIMP0136). Orange diamonds denote bodies with transient trapping of <1 MeV electrons. Black arrows mark the upper limits of asteroid magnetization: u marks the extreme case of a uniformly magnetized asteroid and p marks the strongest feasible Psychean dipole moment. (b) 3D hybrid simulation of the maximum feasible Psychean field, marked by p in (a). The dipole axis points in the +z direction, the solar wind flows in the -x direction, and the interplanetary magnetic field points in the +z direction. The color contours show the field magnitude in the x-z plane and on the surface; closed field lines show drift shells with an equatorial field of 330 nT (innermost shell), 31 nT, and 18 nT (outermost shell). Representative open and solar wind field lines are also shown.

maximum hypothetical asteroid field in the solar system would be obtained for the largest iron-rich asteroid, Psyche (mass of $2.72 \pm 0.75 \times 10^{19}$ kg, Carry, 2012), assuming it was uniformly magnetized at the high end of this magnetization range. This yields a dipole moment, $M_d = 2.7 \times 10^{17}$ Am², and an equatorial surface field, $B_e = 19,000$ nT. Although this predicted field is comparable to that of the Earth, the predicted moment is five orders of magnitude less than that of the Earth (Table S1 in Supporting Information S1 and Figure 1a). These values are extreme upper limits given that asteroids are almost certainly nonuniformly magnetized.

The leading hypothesis for Psyche's origin is that it is a mantle-stripped metallic core from a differentiated body (Elkins-Tanton et al., 2020). Such a bare core could have potentially generated a dynamo field lasting for >7 million years (Ma) (Neufeld et al., 2019). Because such a dynamo is expected to be highly multipolar and time-variable (Neufeld et al., 2019), different parts of the body would record different field directions as it cooled. Subsequent impacts may have further changed the magnetization by either remagnetizing or displacing materials. To estimate the maximum dipole moment of such a nonuniformly magnetized body, we assume the outer $\sim 40\%$ of the radius of the body is a magnetized crust, as indicated by a recent dynamo and thermal evolution model of Psyche-like bodies (Neufeld et al., 2019). Crustal fields on Mars, the Moon, and the Earth were shown to be consistent with those of a shell or sphere packed with randomly oriented dipoles sometimes laterally correlated (Voorhies, 1998, 2008; Voorhies et al., 2002; Wieczorek, 2018). We take the limiting case that the magnetization is correlated over a spatial scale equal to 40% of the radius of the body, such that the body is made of closely packed spherical domains of 40 km diameter that are uniformly magnetized in random directions. The number of spheres closely packed into a body of a given volume is given by well-known relationships (Hales, 2005). For 40 km spheres fitted into a 113 km sphere this corresponds to N = 120-130 spherical domains. The dipole moment of such a distribution would be ≈0.1 of the moment of a uniformly magnetized assemblage (Heslop, 2007), yielding $M_d = 2.7 \times 10^{16}$ Am², and $B_e = 1,900$ nT.

The above represents the maximum feasible asteroid field (most asteroids are rocky and consist of weakly magnetic minerals and may lack remanent magnetization altogether). We can estimate the size of the magnetosphere created by such a limiting body by calculating the dayside magnetopause distance, R_{MP} , given the solar wind properties in the asteroid belt. We find (Section S1 in Supporting Information S1) that $R_{MP} \approx 4.7-5.4R_p \approx 530 - 610$ km. In comparison, the solar wind proton and electron thermal gyroradii at the asteroid belt are ~150 km and ~5 km, respectively (Section S1 in Supporting Information S1), implying that the field is large enough to deflect these particles and thus form a magnetospheric cavity.

Radiation belts form in the inner regions of planetary magnetospheres where the field is quasi-dipolar and trapped particle motion can be stably sustained. At larger distances, the interaction with surrounding magnetized plasmas distorts the field and may prevent particles from completing full drift motions (Klida & Fritz, 2009; Schulz & Lanzerotti, 1974; Walsh et al., 2013). To estimate the extent of the inner quasi-dipolar region for our limiting case of an asteroid magnetosphere, we simulated the interaction of a Psyche-sized body with $M_d = 2.7 \times 10^{16}$ Am^2 with the solar wind. Because the proton gyroradius is comparable to R_p , we used a hybrid particle-fluid code, HYB, which treats electrons as a fluid and protons as particles. HYB has been used to simulate the interaction of the wind with various planets, moons, and asteroids (Kallio & Janhunen, 2003). To adapt the model to a metallic body, we set the body's resistivity to zero, consistent with the fact that iron-nickel alloys are highly conducting (Fert & Campbell, 1976). This constitutes the first three-dimensional (3D) hybrid simulation of a perfectly conducting and magnetized asteroid (Section S4 in Supporting Information S1). In previously published 3D hybrid models of a Psyche-sized magnetized asteroid (Fatemi & Poppe, 2018) the body had a conductivity of 10^{-7} S m⁻¹ (similar to the lunar crust). The currents induced within a conducting body should have a minimal effect on the steady state magnetosphere of a body with high magnetic moment but may become important for weaker magnetization or for a realistically time-variable solar wind.

The resulting 3D magnetic field topology is shown in Figure 1b, confirming that a Psyche-like asteroid can form a magnetosphere with a dayside magnetopause distance of $\sim 6 R_p$ (consistent with the above) and with a dipole-like inner region extending up to $\sim 3 R_p$. The maximum feasible dipole moment presented here is $\sim 3-10$ times larger than the dipole moments assumed in Fatemi and Poppe (2018), and R_{MP} is $\sim 1 R_p$ larger than the largest magnetosphere simulated in Fatemi and Poppe (2018). Figure 1b represents the largest feasible present-day asteroid magnetosphere in the solar system.

The 3D hybrid simulations presented here and in Fatemi and Poppe (2018) cannot account for the formation of radiation belts; the simulations' high computational cost limits the simulated time to a few tens of seconds (Section S4 in Supporting Information S1), sufficient to obtain a steady state global magnetosphere, but insufficient time for electrons to accelerate from typical solar wind energies (thermal and bulk flow) of <10 eV to hazardous (>1 MeV) levels. Although Fatemi and Poppe (2018) reported a density enhancement on the night side inner magnetosphere, it is unlikely to be made of trapped energetic particles due to the short simulation time (note that the energies were not reported therein). Moreover, energetic protons would be lost already for energies >10 keV, as we show in Section 4.

3. Violation of Adiabatic Motion

Under the adiabatic approximation, partilec trajectories in quasi-dipolar magnetic fields are fully described by the three adiabatic invariants, J_i (i = 1,2,3), which are integrals of motion taken over three generalized coordinates: Q_1 , the path length along the gyration motion, Q_2 , the path length along the field line due to bounce motions between the mirror points, and Q_3 , the angle spanned by the longitudinal drift motion (Northrop, 1963; Stern, 1971). Particles conserving all three J_i 's are permanently trapped in toroidal shells (Figures 2a–2c). The locations of these shells depend on the value of J_3 through the dimensionless parameter $\gamma_3 \equiv -(1/2)\sqrt{r_{eq}/r_g} \propto J_3$ (Störmer, 1955), where r_{eq} is the radial distance where the field line intersects the magnetic equatorial plane. Permanent trapping can be achieved for $\gamma_3 < -1$ (Gombosi, 2004; Lemaire et al., 2003; Störmer, 1955). This can be rewritten as a condition on the gyroradius:

$$r_g < \frac{r_{eq}}{4} = \frac{LR_p}{4} \tag{1}$$

where $L = r_{ed}/R_p$. Equation 1 defines Störmer's trapping regions, or the maximum allowed gyroradius of trapped particles at a given L shell in a dipole field. However, Störmer's method is only valid for particles conserving all three adiabatic invariants, which in turn requires that the three motions occur on disparate timescales, such that $\omega_a \gg \omega_b \gg \omega_d$, where ω_e, ω_b , and ω_d are the gyration, bounce, and drift frequencies, respectively. For an Earth-strength dipole field, these frequencies are separated by three or more orders of magnitude up to very high energies and large L values [Figure 2d, following Schulz and Lanzerotti (1974)]. In contrast, for asteroidal fields, the three frequencies are much closer together for most locations and energies even in the extreme case of uniform and maximal remanent magnetization ($M_d = 2.7 \times 10^{17}$ Am², Figure 2e). Because the particle is an oscillator with three degrees of freedom, when any pair of frequencies are comparable, the corresponding motions are no longer independent but would resonantly interact, leading to an exchange of energy between them (Chirikov, 1979). In particular, particles with comparable gyration and bounce periods would suffer exchange of kinetic energy between the velocity components perpendicular and parallel to the magnetic field, \mathbf{v}_{\parallel} and \mathbf{v}_{\perp} , respectively. This exchange would manifest as changes in the particle pitch angle, α . For modest nonadiabaticity, the variations in the J_i 's are periodic and bounded, but as nonadiabaticity increases, the variations become chaotic (Chirikov, 1979). This would amount to pitch angle scattering that would cause particles to enter the loss cone (Serebrennikov et al., 2001). This nonadiabatic effect limits trapped particle energies, as observed in plasma confinement devices (Uckan, 1982).





Figure 2. Periodic particle motions in the magnetospheres of Earth and an asteroid. (a) Gyration motion (red) in a uniform magnetic field (black arrow). (b) Bounce motion (red) in a magnetic bottle configuration (gray curves). (c) Particle gyrating, bouncing, and drifting azimuthally (red) around a body (gray sphere) with a dipole field. (d, e) Frequencies of motion as a function of particle energy, *E*, and *L* shell assuming a dipole magnetic field for Earth (d) and for the worst-case uniformly magnetized asteroid with the maximal magnetization (e). The panels (top to bottom) show the gyration, bounce, and drift frequencies, and curves indicating where the frequencies are separated by one, two, and three orders of magnitude.

To estimate these maximal energies, we must quantify the level of nonadiabaticity in a quasi-dipolar magnetic field. Several measures have been developed for distorted field lines at Earth (Anderson et al., 1997; Lee et al., 2006; Sergeev et al., 1983; Young et al., 2008), perhaps the simplest of which is the adiabaticity parameter, $\varepsilon \equiv r_g/R_c$, where R_c is the field line radius of curvature (Anderson et al., 1997). In the limit of $\varepsilon \ll 1$, the motion is adiabatic and $\varepsilon \propto \omega_b/\omega_g$. For $\varepsilon > 1$, the motion is nonadiabatic and even chaotic. At this limit ω_g, ω_b , and ω_d are not well-defined (in fact, the assumptions underlying Figure 2e are no longer valid).

We next derive an expression for ε for a dipole field, assuming it is a bounding case for long-term trapping in drift shells (an assumption we further justify below). The maximal ε that a particle would experience during the bounce motion would occur at the magnetic equatorial plane, where r_g is highest and R_c is lowest, having a value of $R_c = LR_g/3$ (Section S2 in Supporting Information S1). Nonadiabatic motion therefore would occur for:

$$r_g > \frac{\varepsilon_{th} L R_p}{3} \tag{2}$$

where the threshold value for the adiabaticity parameter, ε_{th} , is yet to be determined. Before we do so, we make two observations. First, despite the mathematical similarity between Equation 2 and Störmer's criterion (Equation 1), the two describe fundamentally different regimes and loss mechanisms: Equation 1 assumes J_1 and J_2 are conserved and predicts particle loss due to the violation of J_3 due to particles crossing many L shells. In contrast, Equation 2 marks the violation of J_1 and J_2 due to pitch angle scattering and subsequent particle escape through



the loss cone. Second, Equation 2 highlights how trapping is affected by the body size and moment. We can recast ε as:

$$\varepsilon = \frac{r_g}{R_c} = \frac{\gamma m v_\perp}{q} \frac{3L^2}{R_p B_e} \propto \frac{R_p^2}{M_d}$$
(3)

where *m* and *q* are the particle mass and charge, respectively, and γ is the relativistic Lorentz factor. The last term, showing that $\varepsilon \propto R_p^2$, highlights the fact that smaller bodies have stronger surface fields for the same moment. On the other hand, because $\varepsilon \sim 1/R_p B_e$, even if a Psyche-sized body had a surface field as strong as the Earth's, the limiting gyroradius would be ~60 times smaller than the limiting gyroradius at the same *L* shell at Earth, meaning the limiting energy would be smaller as well.

We next determine the value of ε at which the transition to chaotic motion occurs. For disturbed (nondipolar) magnetic configurations at Earth, values between $\varepsilon \sim 0.1$ –0.3 were derived (Anderson et al., 1997; Lee et al., 2006; Sergeev et al., 1983; Young et al., 2008). Birmingham (1982) set the limiting value for adiabaticity at $\varepsilon = 1$ for Saturn and Jupiter [note that the expression for ε in Birmingham (1982) reduces to the expression we derived in Equation 3 when the former is applied to a pure dipole field]. This limit gives maximum energies well above the energies found in these magnetospheres (Figure 4 therein), implying that the actual limiting value is likely lower. Furthermore, calculating ε for the same range of bodies included in Figure 1a (corresponding to 1 MeV electrons and protons injected at L = 2 with $\alpha_{eq} = 90^{\circ}$) (Figures 3a and 3b) shows that all bodies with known radiation belts are to the right of the $\varepsilon = 0.01$ curves for both electrons and protons, while Mercury and Ganymede, which transiently trap electrons but not protons, fall within the $0.01 < \varepsilon < 0.15$ range for 1 MeV electrons and in the nonadiabatic range ($\varepsilon \approx 1$) for 1 MeV protons. All conceivable asteroids fall well above $\varepsilon = 1$ for protons but the most magnetized among them may reach $\varepsilon \approx 0.26$ for 1 MeV electrons. While this evidence from known trapped populations suggests the transition to chaos would occur around $0.01 < \varepsilon < 0.15$ and above, further analysis is required to obtain a generalized criterion for any small body and predict risk from asteroid magnetospheres.

4. Tracing the Transition to Chaos With Particle Simulations

We next examine under what conditions particle trajectories become chaotic by explicitly solving the equation of motion in a dipole field. This is an optimal case for trapped adiabatic motion because loss is then only triggered by the length scale of the field. Any perturbations and distortions of the field present in a realistic magnetosphere are unlikely to make the motion more adiabatic. While the static dipole approximation is not suitable for examining particle energization, it is the most appropriate for examining whether such particles, if created or injected, could be trapped for arbitrary M_d and R_p . In particular, it is a good approximation of the quasi-dipolar fields where belts reside. We trace the trajectories using an existing fourth order Runge-Kutta solver and apply it to the relativistic Lorentz force (Section S5.1 in Supporting Information S1). Chaotic trajectories are highly sensitive to the initial conditions and therefore also to roundoff errors when they are simulated numerically (Li & Liao, 2018) and the exact trajectory cannot be reliably simulated on standard computers with double-precision floating point representation (Li & Liao, 2018). We therefore do not attempt to capture the exact time of loss (or particle lifetimes) but rather examine whether the particle exhibits pitch angle variations and sensitivity to initial conditions that imply a chaotic regime (Section S5.3 in Supporting Information S1)

Since protons are chaotic for all conceivable asteroids (Figure 3a), we focus on electron motion. We simulated electrons with energy E = 1 MeV around a body with $R_p = 113$ km, injected at the equator at L = 2. The initial speeds, v_{\parallel} and v_{\perp} are in the radial and polar directions, respectively, depending on the initial equatorial pitch angle $\alpha_{eq,0}$. We examine whether the trajectory is chaotic by simulating neighboring trajectories with initial velocities rotated by 0.01° and 0.02° of a degree in the azimuthal direction with respect to the original trajectory. We repeat these sets of three simulations while varying M_d and $\alpha_{eq,0}$ and record α_{eq} each time the trajectories intersect the magnetic equator. The results of all simulations appear in Figures S2–S6 in Supporting Information S1 and are summarized in Figure 3c, where each symbol (circles and stars) marks the value of $\alpha_{eq,0}$ and M_d (and for which three simulations of neighboring particles were performed). Chaotic particles lost during the simulation are marked by stars. For particles that remain trapped (circles), the horizontal bars (dotted white lines) show the maximum variation in α_{eq} that they experienced during a simulation (this can be visually inspected in the





Figure 3. Conditions for trapping protons and electrons around magnetized bodies. (a, b) The adiabaticity parameter, ε , for 1 MeV electrons (a) and protons (b) injected at L = 2 with $\alpha_{eq} = 90^{\circ}$ showing $\varepsilon = 0.15$ (solid black line) and $\varepsilon = 0.01$ (dashed black line). Symbols are as defined in Figure 1a, except for the upper limits for asteroid parameters (white arrows). (c) Adiabatic, nonadiabatic, and chaotic nature of simulated of 1 MeV particles injected at L = 2 as a function of equatorial pitch angle, α_{eq} and dipole moment, overlaid on color contours of (in the same color scale as (a)). Chaotic trajectories that end in loss are marked by stars. Trajectories with bounded nonadiabaticity are marked by dotted lines whose lengths represent the span of variations in α_{eq} during the simulation. Circles mark the initial α_{eq} . For fully adiabatic the span of α_{eq} is too small to be visible. (d) Predicted (shaded regions) and observed (arrows) maximum energies of transiently trapped particles versus *L*. (left) for Earth (protons), Mercury (electrons), and Ganymede (electrons). (right) Electron energies around the largest feasible asteroid magnetosphere for various levels of adiabaticity and chaos. Vertical lines show the altitudes of the Psyche mission science orbits (B, C, and D) (Elkins-Tanton et al., 2020).

corresponding panel in Figures S2–S6 in Supporting Information S1). The values of ε as a function of $\alpha_{eq,0}$ and M_d are plotted for comparison (color contours). We find that for $M_d = 1.35 \times 10^{16}$ Am² (50% of the maximum feasible asteroid dipole moment), even particles with $\alpha_{eq,0} = 85^{\circ}$ become chaotic and are lost almost immediately (Figure S6 in Supporting Information S1). The onset of nonadiabatic motion starts at $\varepsilon = 0.01$ for low $\alpha_{eq,0}$ and full chaos is achieved at $\varepsilon \approx 0.35$ for all $\alpha_{eq,0}$. This value is consistent with the value of $\varepsilon = 0.335$ obtained under

the diffusion approximation for nondipolar magnetic field lines (Young et al., 2008), who solved for the evolution of the entire particle phase-space distribution function. On the other hand, particles with lower $\alpha_{eq,0}$ become chaotic at lower ε , likely because they have higher v_{\parallel} for the same total energy and thus more energy available for resonant interactions between the bounce and gyration motions. This dependence is not captured by ε . The modified adiabaticity parameter, $\varepsilon^* = \varepsilon \cos \alpha_{eq,0}$ (Anderson et al., 1997), does depend on both velocity components, but it would predict that for $\alpha_{eq,0} \approx 80-90^{\circ}$ the motion is adiabatic. In contrast, our simulations show that even large pitch angle particles would experience a transition to chaos in a dipole field with a short length scale. Furthermore, our results are consistent with Cluster measurements that showed depletion of the particle pitch angle distribution for similar ε values near magnetic reconnection topology in Earth's magnetosphere (Zhang et al., 2016).

5. Predictions and Observations of Permanent and Transient Trapping

We apply the ε thresholds established in the previous section to calculate the corresponding maximum energies of trapped populations as a function of *L* around Ganymede and Mercury (electrons) and at Earth (protons) and compare them to observations (Figure 3d). The Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft detected bursts of transiently trapped 100–200 keV electrons at Mercury and no trapped protons (Ho et al., 2011; Lawrence et al., 2015). At Ganymede, the Galileo spacecraft detected trapped <880 keV electrons (Eviatar et al., 2000; Williams, 2001, 2004). Particle simulations (Allioux et al., 2013; Poppe et al., 2018) suggest they likely originated in Jupiter's magnetosphere and only temporarily remained in drift orbits around Ganymede; their high energies do not imply gradual energization of stably trapped particles within Ganymede's magnetosphere, as is typical for radiation belts. Nonetheless, for both Ganymede and Mercury, the observed energies fall well below the energies corresponding to $\varepsilon = 0.15$. This may be due to deviation from a pure dipole field (i.e., the strong day-night asymmetry at Mercury's magnetosphere, Slavin et al., 2007 and the extensive reconnection with Jupiter's magnetic field for Ganymede, Dorelli et al., 2015; Jia et al., 2010; Kivelson, 2007), consistent with our assumption that a static dipole is the worst-case scenario for spacecraft risk.

MESSENGER did not detect trapped protons around Mercury, while Galileo detected <65 keV protons near Ganymede but it was inferred that they moved along open field lines connected to Jupiter (Williams, 2001, 2004; Williams et al., 1997). These findings are consistent with Figure 3b. At Earth, the Payload for Antimatter Exploration and Light-nuclei Astrophysics (PAMELA) detected transiently and permanently trapped protons with energies of 0.2–2 GeV at L = 1.2-2 (Adriani et al., 2015). The PAMELA observations covered a range of α_{eq} . To make the comparison with Equation 2 consistent, we plot the perpendicular kinetic energy of the detected transiently trapped protons. We find that their maximum energies and L values fall remarkably close to the $\varepsilon = 0.15$ curve at low altitudes while at the highest altitudes the energies are below this curve.

A consistent picture emerges from the particle simulations and observations, allowing us to estimate the maximum electron energies around the largest feasible asteroid magnetosphere (Figure 3e). Permanent trapping becomes increasingly unlikely for $\varepsilon > 0.15$ and essentially impossible for $\varepsilon > 0.35$. At $\varepsilon \approx 0.15$ even particles with $\alpha_{eq,0} > 65^\circ$ experience variations of 5–20° in α_{eq} during the simulations. Any disturbances, such as waves or thermally driven motions could scatter them toward even lower α_{eq} values and push them into the chaotic regime. Calculating the maximum energies for protons (not shown in Figure 3e for clarity) shows that even for $\varepsilon = 0.35$, proton energies do not exceed ~10 keV at L = 2, well below risk levels. Nonetheless, low-energy particles may remain trapped.

The threshold of $\varepsilon > 0.15$ corresponds to a maximum gyroradius of approximately:

$$r_g < \frac{r_{eq}}{20} \tag{4}$$

This limit is 5 times smaller than the adiabatic limit. Furthermore, even particles satisfying Equation 4 are not adiabatic and therefore are not guaranteed to remain trapped in a realistic magnetosphere with day-night asymmetries, convective electric fields (which are negligible for asteroids; Section S3 and Figure S1 in Supporting Information S1), reconnection with external fields, and other perturbations. In addition, planetary rings, dusty environments, and neutral particle sources can also absorb or scatter charged particles (Mauk et al., 2004; Nénon & André, 2019; Roussos et al., 2018).

6. Conclusions

We developed a generalized approach for estimating trapped particle energies at any planetary body with a focus on asteroids. Our results have several novel aspects:

- 1. Combining insights from meteorite paleomagnetism and plasma hybrid modeling in 3D, we showed that asteroid magnetospheres are feasible and obtained an upper limit on their size. However, particle motion in such magnetospheres would be nonadiabatic for particle energies typical of radiation belts.
- 2. Particle simulations show that chaotic pitch angle scattering limits trapped particle energies for an adiabaticity parameter $\varepsilon \approx 0.15$ –0.35 even in the optimal case of a static dipole field. The corresponding particle energies are at least 5 times lower than predicted by adiabatic theory. Such a prediction is consistent with observations of transient trapping at Ganymede, Mercury, and Earth.
- 3. Even for the strongest feasible dipole moment, asteroids are not likely to permanently trap and >1 MeV electrons and >10 keV protons at L = 2 and are unlikely to pose risk to typical space flight systems. However, particles of lower energies may be trapped and form structures like a ring-current system.

Data Availability Statement

The HYB code is distributed under the open source GPL v3 license by the Finnish Meteorological Institute (only available at github: github.com/fmihpc/hyb). Figure data are deposited at figureshare.com, a FAIR-compliant repository (https://doi.org/10.6084/m9.figshare.12957821.v1).

References

- Adriani, O., Barbarino, G. C., Bazilevskaya, G. A., Bellotti, R., Boezio, M., Bogomolov, E. A., et al. (2015). Trapped proton fluxes at low Earth orbits measured by the PAMELA experiment. *The Astrophysical Journal Letters*, 799, L4. https://doi.org/10.1088/2041-8205/799/1/14
- Allioux, R., Louarn, P., & André, N. (2013). Model of energetic populations at Ganymede, implications for an orbiter. Advances in Space Research, 51, 1204–1212. https://doi.org/10.1016/j.asr.2012.10.033
- Anderson, B. J., Decker, R. B., & Paschalidis, N. P. (1997). Onset of nonadiabatic particle motion in the near-Earth magnetotail. Journal of Geophysical Research, 102, 17553–17569. https://doi.org/10.1029/97JA00798
- Baker, D. N., Erickson, P. J., Fennell, J. F., Foster, J. C., Jaynes, A. N., & Verronen, P. T. (2018). Space weather effects in the Earth's radiation belts. *Space Science Reviews*, 214, 17. https://doi.org/10.1007/s11214-017-0452-7
- Berger, M. J., Coursey, J. S., Zucker, M. A., & Chang, J. (2017). NIST radiation dosimetry database. NIST. Retrieved from https://www.nist.gov/ pml/radiation-dosimetry-data
- Birmingham, T. J. (1982). Charged particle motions in the distended magnetospheres of Jupiter and Saturn. Journal of Geophysical Research, 87, 7421–7430. https://doi.org/10.1029/JA087iA09p07421

Blanco-Cano, X., Omidi, N., & Russell, C. T. (2003). Hybrid simulations of solar wind interaction with magnetized asteroids: Comparison with Galileo observations near Gaspra and Ida. *Journal of Geophysical Research*, *108*(A5), 1216. https://doi.org/10.1029/2002JA009618

Carry, B. (2012). Density of asteroids. Planetary and Space Science, 73, 98–118. https://doi.org/10.1016/j.pss.2012.03.009
Chirikov, B. V. (1979). A universal instability of many-dimensional oscillator systems. Physics Reports, 53, 263–379. https://doi.org/10.1016/0370-1573(79)90023-1

Dorelli, J. C., Glocer, A., Collinson, G., & Tóth, G. (2015). The role of the Hall effect in the global structure and dynamics of planetary magnetospheres: Ganymede as a case study. *Journal of Geophysical Research: Space Physics*, 120, 5377–5392. https://doi.org/10.1002/2014JA020951

- Drake, F. D., & Hvatum, S. (1959). Non-thermal microwave radiation from Jupiter. *The Astronomical Journal*, 64, 329–330. https://doi.org/10.1086/108047
- Elkins-Tanton, L. T., Asphaug, E., Bell, J. F., III, Bercovici, H., Bills, B., Binzel, R., et al. (2020). Observations, meteorites, and models: A pre-flight assessment of the composition and formation of (16) Psyche. *Journal of Geophysical Research: Planets*, 125, e2019JE006296. 10.1029/2019JE006296
- Eviatar, A., Williams, D. J., Paranicas, C., McEntire, R. W., Mauk, B. H., & Kivelson, M. G. (2000). Trapped energetic electrons in the magnetosphere of Ganymede. *Journal of Geophysical Research*, 105, 5547–5554. https://doi.org/10.1029/1999JA900450
- Fatemi, S., & Poppe, A. R. (2018). Solar wind plasma interaction with asteroid 16 Psyche: Implication for formation theories. *Geophysical Research Letters*, 45, 39–48. https://doi.org/10.1002/2017GL073980
- Fert, A., & Campbell, I. A. (1976). Electrical resistivity of ferromagnetic nickel and iron based alloys. Journal of Physics F: Metal Physics, 6, 849–871. https://doi.org/10.1088/0305-4608/6/5/025

Gombosi, T. I. (2004). Physics of the space environment. Cambridge University Press.

Hales, T. C. (2005). A proof of the Kepler conjecture. Annals of Mathematics, 162, 1065–1185. https://doi.org/10.4007/annals.2005.162.1065

- Harrison, R., Bryson, J., Nichols, C., & Weiss, B. (2017). Magnetic mineralogy of meteoritic metal: Paleomagnetic evidence for dynamo activity on differentiated planetesimals. In L. T. Elkins-Tanton, & B. P. Weiss (Eds.), *Planetesimals: Early differentiation and consequences for planets* (pp. 204–223). Cambridge University Press. https://doi.org/10.1017/9781316339794.010
- Heslop, D. (2007). Are hydrodynamic shape effects important when modelling the formation of depositional remanent magnetization? Geophysical Journal International, 171, 1029–1035. https://doi.org/10.1111/j.1365-246X.2007.03588.x
- Ho, G. C., Krimigis, S. M., Gold, R. E., Baker, D. N., James, A., Anderson, B. J., & Solomon, S. C. (2011). MESSENGER observations of transient bursts of energetic electrons in Mercury's magnetosphere. *Science*, 333, 1865–1868. https://doi.org/10.1126/science.1211141
- Horne, R. B., Thorne, R. M., Glauert, S. A., Albert, J. M., Meredith, N. P., & Anderson, R. R. (2005). Timescale for radiation belt electron acceleration by whistler mode chorus waves. *Journal of Geophysical Research*, *110*, A03225. https://doi.org/10.1029/2004JA010811

Acknowledgments

This work is supported by the NASA Psyche project (CREI 1576768). Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

- Jia, X., Walker, R. J., Kivelson, M. G., Khurana, K. K., & Linker, J. A. (2010). Dynamics of Ganymede's magnetopause: Intermittent reconnection under steady external conditions. *Journal of Geophysical Research*, 115, A12202. https://doi.org/10.1029/2010JA015771
- Kallio, E., & Janhunen, P. (2003). Modelling the solar wind interaction with Mercury by a quasi-neutral hybrid model. *Annales Geophysicae*, 21, 2133–2145. https://doi.org/10.5194/angeo-21-2133-2003
- Kivelson, M. G. (2007). Planetary magnetospheres. In Y. Kamide, & A. Chian (Eds.), Handbook of the solar-Terrestrial environment (pp. 469–492). Berlin: Springer-Verlag. https://doi.org/10.1016/b978-012088589-3/50032-3
- Kivelson, M. G., Wang, Z., Joy, S., Khurana, K. K., Polanskey, C., Southwood, D. J., & Walker, R. J. (1995). Solar wind interaction with small bodies: 2. What can Galileo's detection of magnetic rotations tell us about Gaspra and Ida. Advances in Space Research, 16, 59–68. https:// doi.org/10.1016/0273-1177(95)00209-w
- Klida, M. M., & Fritz, T. A. (2009). The Earth's magnetopause as a source and sink for equatorial nightside energetic charged particles. *Annales Geophysicae*, 27, 4305–4316. https://doi.org/10.5194/angeo-27-4305-2009
- Lawrence, D. J., Anderson, B. J., Baker, D. N., Feldman, W. C., Ho, G. C., Korth, H., et al. (2015). Comprehensive survey of energetic electron events in Mercury's magnetosphere with data from the MESSENGER Gamma-Ray and Neutron Spectrometer. *Journal of Geophysical Research: Space Physics*, 120, 2851–2876. https://doi.org/10.1002/2014JA020792
- Lawrence, D. J., Peplowski, P. N., Goldsten, J. O., Burks, M., Beck, A. W., Elkins-Tanton, et al. (2016). The Psyche gamma-ray and neutron spectrometer: Characterizing the composition of a metal-rich body using nuclear spectroscopy. *Paper presented at 47th Lunar and Planetary Science Conference* (abstract #1622), The Woodlands, Texas.
- Lee, J. J., Parks, G. K., Min, K. W., McCarthy, M. P., Lee, E. S., Kim, H. J., & Hwang, J. A. (2006). Relativistic electron dropouts by pitch angle scattering in the geomagnetic tail. Annales Geophysicae, 24, 3151–3159. https://doi.org/10.5194/angeo-24-3151-2006
- Lemaire, J. F. (2003). The effect of a southward interplanetary magnetic field on Störmer's allowed regions. Advances in Space Research, 31, 1131–1153. https://doi.org/10.1016/S0273-1177(03)00099-1
- Li, X., & Liao, S. (2018). Clean numerical simulation: A new strategy to obtain reliable solutions of chaotic dynamic systems. Applied Mathematics and Mechanics, 39, 1529–1546. https://doi.org/10.1007/s10483-018-2383-6
- Liuzzo, L., Poppe, A. R., Paranicas, C., Nénon, Q., Fatemi, S., & Simon, S. (2020). Variability in the energetic electron bombardment of Ganymede. Journal of Geophysical Research: Space Physics, 125, e2020JA028347. https://doi.org/10.1029/2020JA028347
- Mauk, B. H., & Fox, N. J. (2010). Electron radiation belts of the solar system. Journal of Geophysical Research, 115, A12220. https://doi.org/10.1029/2010JA015660
- Mauk, B. H., Mitchell, D. G., McEntire, R. W., Paranicas, C. P., Roelof, E. C., Williams, D. J., et al. (2004). Energetic ion characteristics and neutral gas interactions in Jupiter's magnetosphere. *Journal of Geophysical Research*, 109, A09S12. https://doi.org/10.1029/2003JA010270
- Nénon, Q., & André, N. (2019). Evidence of Europa neutral gas torii from energetic sulfur ion measurements. *Geophysical Research Letters*, 46, 3599–3606. https://doi.org/10.1029/2019GL082200
- Neufeld, J. A., Bryson, J. F. J., & Nimmo, F. (2019). The top-down solidification of iron asteroids driving dynamo evolution. Journal of Geophysical Research: Planets, 124, 1331–1356. 10.1029/2018JE005900
- Northrop, T. G. (1963). Adiabatic charged-particle motion. Reviews of Geophysics, 1, 283–304. https://doi.org/10.1029/RG001i003p00283
- Pesonen, J. L., Terho, M., & Kukkonen, T. I. (1992). Physical properties of 368 meteorites: Implications of early solar system magnetic fields. In E. M. Zolensky, M. Prinz, & M. Lipschutz (Eds.), Antarctic meteorites XVII (pp. 179–181).
- Poppe, A. R., Fatemi, S., & Khurana, K. K. (2018). Thermal and energetic ion dynamics in Ganymede's magnetosphere. *Journal of Geophysical Research*, 123, 4614–4637. https://doi.org/10.1029/2018JA025312
- Reeves, G. D., Friedel, R. H., Larsen, B. A., Skoug, R. M., Funsten, H. O., Claudepierre, S., et al. (2016). Energy-dependent dynamics of keV to MeV electrons in the inner zone, outer zone, and slot regions. *Journal of Geophysical Research: Space Physics*, 121, 397–412. https://doi. org/10.1002/2015JA021569
- Richter, I., Brinza, D. E., Cassel, M., Glassmeier, K. H., Kuhnke, F., Musmann, G., et al. (2001). First direct magnetic field measurements of an asteroidal magnetic field: DS1 at Braille. *Geophysical Research Letters*, 28, 1913–1916. https://doi.org/10.1029/2000GL012679
- Roussos, E., Allanson, O., André, N., Bertucci, B., Branduardi-Raymont, G., Clark, G., et al. (2019). The in-situ exploration of Jupiter's radiation belts (A White Paper submitted in response to ESA's Voyage 2050 Call). Arxiv E-prints, arXiv:1908.02339.
- Roussos, E., Kollmann, P., Krupp, N., Kotova, A., Regoli, L., Paranicas, C., et al. (2018). A radiation belt of energetic protons located between Saturn and its rings. *Science*, *362*, 6410. https://doi.org/10.1126/science.aat1962
- Russell, C. T. (2018). Space and planetary magnetism: From 1958 to the present. In Sputnik: 60 Years along the path of discoveries (pp. 143–157). Space Research Institute of the Russian Academy of Sciences.
- Scheinberg, A., Fu, R. R., Elkins-Tanton, L. T., Weiss, B. P., & Stanley, S. (2017). Magnetic fields on asteroids and planetesimals. In L. T. Elkins-Tanton, & B. P. Weiss (Eds.), *Planetesimals: Early differentiation and consequences for planets* (pp. 180–203). Cambridge University Press.
- Schulz, M., & Lanzerotti, L. J. (1974). Particle diffusion in the radiation belts. In *Physics and chemistry in space* (Vol. 7). Berlin: Springer-Verlag. https://doi.org/10.1007/978-3-642-65675-0
- Selesnick, R. S., Cohen, C. M. S., & Khurana, K. K. (2001). Energetic ion dynamics in Jupiter's plasma sheet. Journal of Geophysical Research, 106, 18895–18905. https://doi.org/10.1029/2000JA000242
- Serebrennikov, K. S., Gaudin, C., Buzzi, J. M., Bruneteau, J., & Rouille, C. (2001). Non-adiabatic phenomena during magnetic trap confinement and their influence on maximum x-ray energy from electron-cyclotron-resonance-heated plasmas. *Physical Review E*, 63, 046405. https://doi. org/10.1103/PhysRevE.63.046405
- Sergeev, V. A., Sazhina, E. M., Tsyganenko, N. A., Lundblad, J. A., & Soraas, F. (1983). Pitch-angle scattering of energetic protons in the magnetotail current sheet as the dominant source of their isotropic precipitation into the nightside ionosphere. *Planetary and Space Science*, 31, 1147–1155. https://doi.org/10.1016/0032-0633(83)90103-4
- Shepard, M. K., Richardson, J., Taylor, P. A., Rodriguez-Ford, L. A., Conrad, A., dePater, I., & Harris, A. W. (2017). Radar observations and shape model of asteroid 16 Psyche. *Icarus*, 281, 388–403. https://doi.org/10.1016/j.icarus.2016.08.011
- Slavin, J. A., Krimigis, S. M., Acuna, M. H., Anderson, B. J., Baker, D. N., Koehn, P. L., & Zurbuchen, T. H. (2007). Messenger: Exploring Mercury's magnetosphere. Space Science Reviews, 131, 133–160. https://doi.org/10.1007/s11214-007-9154-x
- Stern, D. (1971). Hamiltonian formulation of guiding center motion(Tech. Rep. NASA-TM-X-65700, X-641-71-373, NASA-TM-X-65458, No. X-641-71-56) NASA Goddard Space Flight Center.
- Störmer, C. (1955). The polar aurora. Oxford University Press.
- Terho, M., Pesonen, L. J., Kukkonen, I. T., & Bukovanska, M. (1993). The petrophysical classification of meteorites. *Studia Geophysica et Geodaetica*, 37, 65–82. https://doi.org/10.1007/BF01613921

- Tsareva, O. O. (2019). Generalization of Störmer theory for an axisymmetric superposition of dipole and quadrupole fields. *Journal of Geophysical Research: Space Physics*, 124, 2844–2853. https://doi.org/10.1029/2018JA026164
- Uckan, N. A. (1982). Temperature limit in ECH hot electron plasmas. *The Physics of Fluids*, 25, 2381–2384. https://doi.org/10.1063/1.863723 Van Allen, J. A., Ludwig, G. H., Ray, E. C., & McIlwain, C. E. (1958). Observation of high intensity radiation by satellites 1958 Alpha and
- Gamma (Explorers I and III). Journal of Jet Propulsion, 28, 588–592. https://doi.org/10.2514/8.7396 Voorhies, C. V. (1998). Elementary theoretical forms for the spatial power spectrum of Earth's crustal magnetic field (NASA Tech. Pap. 1998-208608, (p. 38).
- Voorhies, C. V. (2008). Thickness of the magnetic crust of Mars. Journal of Geophysical Research, 113, E04004. https://doi. org/10.1029/2007JE002928
- Voorhies, C. V., Sabaka, T. J., & Purucker, M. (2002). On magnetic spectra of Earth and Mars. Journal of Geophysical Research, 107. https:// doi.org/10.1029/2001JE001534
- Walsh, B. M., Ryou, A. S., Sibeck, D. G., & Alexeev, I. I. (2013). Energetic particle dynamics in Mercury's magnetosphere. Journal of Geophysical Research: Space Physics, 118, 1992–1999. https://doi.org/10.1002/jgra.50266
- Wang, Z., Kivelson, M. G., Joy, S., Khurana, K. K., Polanskey, C., Southwood, D. J., & Walker, R. J. (1995). Solar wind interaction with small bodies: 1. Whistler wing signatures near Galileo's closest approach to Gaspra and Ida. Advances in Space Research, 16, 47–57. https://doi. org/10.1016/0273-1177(95)00208-V
- Weiss, B. P., Gattacceca, J., Stanley, S., Rochette, P., & Christensen, U. R. (2010). Paleomagnetic records of meteorites and early planetesimal differentiation. Space Science Reviews, 152, 341–390. https://doi.org/10.1007/s11214-009-9580-z
- Wieczorek, M. A. (2018). Strength, depth, and geometry of magnetic sources in the crust of the Moon from localized power spectrum analysis. Journal of Geophysical Research: Planets, 123, 291–316. https://doi.org/10.1002/2017JE005418
- Williams, D. J. (2001). Ganymede's ionic radiation belts. Geophysical Research Letters, 28, 3793–3796. https://doi.org/10.1029/2001GL013353
 Williams, D. J. (2004). Energetic electron beams in Ganymede's magnetosphere. Journal of Geophysical Research, 109, A09211. https://doi.org/10.1029/2004JA010521
- Williams, D. J., Mauk, B., & McEntire, R. W. (1997). Trapped electrons in Ganymede's magnetic field. *Geophysical Research Letters*, 24, 2953–2956. https://doi.org/10.1029/97GL03003
- Young, S. L., Denton, R. E., Anderson, B. J., & Hudson, M. K. (2008). Magnetic field line curvature induced pitch angle diffusion in the inner magnetosphere. Journal of Geophysical Research, 113, A03210. https://doi.org/10.1029/2006JA012133
- Zhang, Y. C., Shen, C., Marchaudon, A., Rong, Z. J., Lavraud, B. A., Fazakerley, A., et al. (2016). First in situ evidence of electron pitch angle scattering due to magnetic field line curvature in the Ion diffusion region. *Journal of Geophysical Research: Space Physics*, 121, 4103–4110. https://doi.org/10.1002/2016ja022409

References From the Supporting Information

- Dyadechkin, S., Kallio, E., & Jarvinen, R. (2013). A new 3-D spherical hybrid model for solar wind interaction studies. Journal of Geophysical Research: Atmospheres, 118, 5157–5168. https://doi.org/10.1002/jgra.50497
- Ebert, R. W., McComas, D. J., Elliott, H. A., Forsyth, R. J., & Gosling, J. T. (2009). Bulk properties of the slow and fast solar wind and interplanetary coronal mass ejections measured by Ulysses: Three polar orbits of observations. *Journal of Geophysical Research*, 114, A01109. https://doi.org/10.1029/2008JA013631
- Hosea, M. E., & Shampine, L. F. (1996). Analysis and implementation of TR-BDF2. Applied Numerical Mathematics, 20, 21–37. https://doi. org/10.1016/0168-9274(95)00115-8
- Kao, M., Hallinan, G., Pineda, J. S., Stevenson, D., & Burgasser, A. (2018). The strongest magnetic fields on the coolest Brown dwarfs. *The Astrophysical Journal—Supplement Series*, 23(2), 25. https://doi.org/10.3847/1538-4365/aac2d5
- Kivelson, M. G., & Russel, C. T. (1995). Introduction to space physics. Cambridge University Press.

Lodders, K., & Fegley, B. (1998). The planetary Scientist's Companion. Oxford University Press.

- McComas, D. J., Barraclough, B. L., Funsten, H. O., Gosling, J. T., Santiago-Munoz, E., Skoug, R. M., et al. (2000). Solar wind observations over Ulysses' first full polar orbit. *Journal of Geophysical Research*, 105, 10419–10433. https://doi.org/10.1029/1999JA000383
- Omidi, N., Blanco-Cano, X., Russell, C. T., Karimabadi, H., & Acuna, M. (2002). Hybrid simulations of solar wind interaction with magnetized asteroids: General characteristics. *Journal of Computational Physics*, 107, 1487. https://doi.org/10.1029/2002JA009441
- Parker, E. N. (1968). Dynamical properties of the magnetosphere. In R. L. Carovillano, J. F. McClay, & H. R. Radoski (Eds.), Physics of the magnetosphere. Astrophysics and space science library (Vol. 10). Springer. https://doi.org/10.1007/978-94-010-3467-8_1
- Phillips, J. L., Feldman, W. C., Gosling, J. T., & Scime, E. E. (1995). Solar wind plasma electron parameters based on aligned observations by ICE and Ulysses. Advances in Space Research, 16, 95–100. https://doi.org/10.1016/0273-1177(95)00319-A
- Russell, C. T., Luhmann, J. G., & Strangeway, R. J. (2016). Space physics: An introduction. Cambridge University Press.
- Simon, S., Bagdonat, T., Motschmann, U., & Glassmeier, K. H. (2006). Plasma environment of magnetized asteroids: A 3-D hybrid simulation study. Annales Geophysicae, 24, 407–414. https://doi.org/10.5194/angeo-24-407-2006

Tholen, D. J., Tejfel, V. G., & Cox, A. N. (2002). Planets and satellites. In A. N. Cox (Ed.), Allen's astrophysical quantities (pp. 293–313). Springer-Verlag. https://doi.org/10.1007/978-1-4612-1186-0_12

Supporting Information for Maximum energies of trapped particles around magnetized planets and small bodies

Rona Oran¹, Benjamin P. Weiss¹, Maria De Soria Santacruz-Pich², Insoo Jun², David J. Lawrence³, Carol A. Polanskey², J. Martin Ratliff², Carol A. Raymond², Jodie B. Ream¹, Christopher T. Russell⁴, Yuri Y. Shprits^{5,6,7}, Maria T. Zuber¹, Linda T. Elkins-Tanton⁸

¹Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology,

Cambridge, MA, USA

²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
³The Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA
⁴Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA, USA
⁵Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany
⁶Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA
⁷Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany

⁸School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA

Contents of this file

- 1. Sections S1 to S5
- 2. Figures S1-S6
- 3. Table S1

Introduction This file contains supporting information about data, methods, and standard derivations that were used in this study.

S1. Asteroid magnetospheres sizes

S1.1. Solar wind conditions at the asteroid belt

The solar wind properties at 2.5 - 3.3 AU (the approximate orbital distance of the asteroid belt from the Sun) are different from those found near the Earth. To estimate these, we take advantage of Ulysses observations taken at radial distances between 1 AU to 4 AU (McComas et al., 2000). By fitting the observations to scaling laws, Ebert et al. (2009) found the radial dependence of proton properties. We chose scaling laws derived for slow wind flows characteristic of the ecliptic plane during solar minimum (see

their Fig. 6). Accordingly, we set the proton density and temperature to 2 cm^{-3} and 40,000 K, respectively. The electron temperature is similarly set to 100,000 K using insitu measurements between 1 to 4 AU in the ecliptic plane (Phillips et al., 1995). The bulk speed is set to 400 km s⁻¹ and the magnetic field is set to 2 nT (McComas et al., 2000). The values are approximate, as the instantaneous values may vary around the mean by factors of order unity (Ebert et al. 2009). Given the above temperatures and magnetic field magnitude, the proton and electron gyroradii due to their respective thermal speeds are ~150 km and ~5 km, respectively.

S1.2. Magnetopause distance

The distance of the magnetopause from the body's center, R_{MP} , is determined by the balance between the internal magnetic pressure and the solar wind dynamic pressure. Because the internal magnetic field varies with r^3 for a body-centric dipole, where r is the radial distance from the center of the dipole, we can find R_{MP} from the pressure balance equation:

$$\frac{(fB_e)^2}{2\mu_0} \left(\frac{R_p}{R_{MP}}\right)^6 = m_H n V^2 \tag{1}$$

where B_e is the surface field at the magnetic equator, μ_0 is the permeability of free space, R_p is the body radius, m_H is the mass of a hydrogen ion, n is the solar wind density, V is the solar wind speed, and f is a geometric factor that takes into account the compression of the internal magnetic field by the wind, and can take values between 2-3 (Parker, 1968). At the asteroid belt, we have $n = 2 \text{ cm}^{-3}$ and $V = 400 \text{ km s}^{-1}$. Using the an equatorial surface field of 19,000 nT, representing a metal asteroid uniformly magnetized by the strongest conceivable magnetization, we obtain $R_{MP} = \sim 10.0-11.5R_p \sim 1,130 - 1,300$ km. However, since a Psyche-type likely contains non-uniform remanent magnetization, the equatorial surface field associated with its dipole moment would be at most 1,900 nT. Since higher-order magnetic moments fall off faster than that of a dipole with distance from the body, it is the dipole moment that would predominantly control the magnetopause distance. In this case we would get a day-side magnetopause distance of $R_{MP} = \sim$ $4.7 - 5.4 R_p$.

Eq. (1) has limited validity when the size of the magnetosphere is comparable to the gyroradius of solar wind protons. A more realistic estimation of the magnetosphere size and three-dimensional (3D) shape can be obtained by simulating the interaction of the body with the solar wind. With this goal, we implemented an asteroid magnetosphere model using HYB, a 3D hybrid fluid-particle plasma code (Kallio & Janhunen, 2003) that solves the equations of motion for protons and the magnetohydrodynamic (MHD) equations for electrons (Section S4).

S2. Derivation of field line curvature in a dipole field

Dipolar magnetic field lines can be described by the field line equation (Gombosi, 2004):

$$r(\lambda) = LR_p \cos^2 \lambda, \tag{2}$$

where L is a dimensionless parameter that measures the distance at which the field line crosses the equator normalized by R_p , and λ is the latitude, measured from the magnetic equator. The radius of curvature for a parametrized curve $r=r(\lambda)$ given in polar coordinates is defined as:

$$R_c = \frac{(r^2 + r'^2)^{\frac{3}{2}}}{|r^2 + 2r'^2 - rr''|} \tag{3}$$

where r' and r'' are the first and second derivatives of r with respect to λ , respectively. Taking the derivatives of the curve given by Eq. (2) and substituting them into Eq. (3), we get:

$$R_c = LR_p \cos \lambda \frac{4 - 3\cos^2 \lambda}{6 - 3\cos^2 \lambda}.$$
(4)

The radius of curvature of a dipole field line is smallest at the magnetic equator ($\lambda = 0^{\circ}$), where it takes the value of:

$$R_c = \frac{LR}{3} \tag{5}$$

S3. The effects of the co-rotation electric field on trapped particles

The rotation of a magnetized planetary body induces the so-called co-rotational electric field, **E**, given by (Gombosi, 2004):

$$\mathbf{E} = \frac{\Omega R_p B_e}{L^2} \hat{\mathbf{r}},\tag{6}$$

where Ω is body's angular rotation speed and **E** is directed along the radial direction, $\hat{\mathbf{r}}$. In the equatorial plane, the co-rotational electric field is perpendicular to the the magnetic field, which points in the z direction. This induces an azimuthal drift on trapped particles, with a drift velocity of:

$$\mathbf{v}_{EB} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \tag{7}$$

Object	Radius	Dipole	Surface field	R_{MP}	Observed
		moment	at equator	(Planetary	trapping
	(km)	(Am^2)	(nT)	radii)	
Mercury	2,438	4×10^{19}	140-400	1.5	Partial
Earth	$6,\!371$	7.84×10^{22}	31,000	10	Yes
Jupiter	$71,\!492$	1.55×10^{27}	428,000	70	Yes
Saturn	60,268	4.6×10^{25}	22,000	20	Yes
Uranus	$25,\!559$	3.9×10^{24}	$23,\!000$	18	Yes
Neptune	24,764	2.2×10^{24}	14,000	24	Yes
Ganymede	2,634	1.32×10^{20}	720	1.6	Partial
Metal asteroid (upper limit)	113	2.7×10^{16}	19,000	9	_
SIMP0136	87,105	7.3×10^{29}	110,000,000	_	_

Table 51. Magnetospheric properties of magnetized bo	odies
-------------------------------------------------------------	-------

Note: The first column lists the body's name, the second column lists the mean or effective radius (see below), the third column lists the magnetic dipole moment, the fourth column lists the equatorial surface field, the fifth column lists the approximate distance of the dayside magnetopause (estimated or observed, see below), and the sixth column lists whether the body has radiation belts (if observations are available). Radii for solar system bodies are taken from Lodders & Fegley (1998). Radii of the terrestrial bodies represent mean values, while for the giant planets they rare taken at 1 bar level at the equator. The upper limit metal-rich asteroid radius is based on the shape model of (16) Psyche (Shepard et al., 2017) and represents the effective radius of a sphere with the same volume as the shape model. The radius of SIMP0136 is taken from Gagne et al. (2017). The magnetic moments of the planets and Ganymede are from Tholen et al. (2002). The magnetic moment of the metal-rich asteroid is an upper limit (Section 2). The magnetic moment of SIMP0136 is based on the minimum average surface field (Kao et al., 2018). Surface fields and magnetopause distances for the planets and Ganymede are taken from Kivelson et al. (2007) and calculated in Section S1 for the asteroid using solar wind conditions expected for the asteroid belt. The magnetopause distance for SIMP0136 is not known since it depends on the plasma flow in its environment. The existence of radiation belts around Earth and the giant planets in the solar system is well-established (Kivelson & Russell, 1995; Russell et al., 2016). The detection of partial trapping is based on Ho et al. (2016) for Mercury, and on Eviatar et al. (2000) for Ganymede.



Figure S1. Comparison of drift speeds due to the co-rotational electric field and due to the gradient-curvature drift. (a) The ratio between the two drift speeds as a function of body rotation and particle energy, assuming a body the size of Psyche and the upper limit surface field derived in Section 2 in the main text. (b) The ratio between the two speeds as a function of particle energy, for the case of the Earth and for the case of a body the size of Psyche with a maximal surface field.

This drift can affect radiation belt particles, which are generally moving azimuthally under the gradient curvature drift motion. If the co-rotational drift speed is comparable or larger than the gradient-curvature drift speed, the drift shells may not be symmetric and particles could escape the drift shells. The gradient curvature drift velocity is given by:

$$\mathbf{v}_{GC} = \frac{m}{q} \frac{v_{||}^2 + \frac{1}{2}v_{\perp}^2}{B} \frac{\mathbf{B} \times \nabla B}{B^2}.$$
(8)

where v_{\parallel} and v_{\perp} are the particle's velocity components parallel and perpendicular to the magnetic field, m is the particle mass, and q is the charge. The relative importance of the two types of drift motion depend on the body's size and rotation rate, since these increase the co-rotational electric field drift but not the gradient-curvature drift. We plot the ratio of the two speeds in Fig. S1 for different bodies, showing that for bodies the size of Psyche the effects of the co-rotational electric field would be negligible for particles with energies above 1 keV, even if the body is a very fast rotator.

S4. Method: Hybrid simulations of the interaction of a small magnetized body with the solar wind

The HYB code (Kallio & Janhunen, 2003) is designed to efficiently simulate plasmas where the proton and electron dynamics occur on disparate scales compared to the scale of the problem. For asteroid magnetospheres, the proton gyroradius is comparable to the size of the body, requiring us to resolve their motion in detail. Electrons, on the other hand, would have much smaller gyroradii, so their dynamics may be approximated collectively using a fluid description of the plasma. Hybrid plasma codes enable the combination of the two descriptions in a self-consistent manner. The proton equation of motion is solved for macro particles, which statistically represent the phase-space distribution function. The MHD equations are solved for the electrons while requiring quasi-neutrality. Coupling the relative motion of electrons and protons to Maxwell's equations allows for a self-consistent evolution of the electromagnetic field and the charged particles. Details about the equations and numerical methods used by the HYB code are described at length in Kallio Janhunen (2003).

The HYB code describes the 3D interaction. Hybrid simulations of asteroids, both in 2D and 3D, were previously performed to describe the interaction of asteroids with the solar wind (Omidi et al., 2002; Simon et al., 2006), although they considered the body to be non-magnetized. Fatemi & Poppe (2018) simulated the interaction with a Psychelike asteroid, assuming it was either resistive and magnetized or highly conducting but not magnetized. In the present implementation, Psyche is both magnetized and ideally conducting with zero resistivity inside the body.

To apply the HYB code to an asteroid magnetosphere, we designed a model where the body is treated as a spherical ideal conductor and embedded a dipole field configuration at its center.

Grid design and boundary conditions. The hybrid simulations were performed using a Cartesian 3D grid with a cell dimension $dx = R_p/4$. The x axis points in the direction of the Sun, such that the solar wind flows in the -x direction. The z axis is perpendicular to the orbital place of the asteroid. The dipole axis points in the z direction. The y axis completes a right-handed system. For the simulation with $M_d = 2 \times$ 10^{17} Am², the computational domain limits are $[-16, 20] R_p$, $[-16, 16] R_p$, and $[-16, 16] R_p$ along the x, y, and z directions, respectively. The extended range in the +x is designed to allow the dayside magnetopause to be far from the outer boundary, allowing it to interact with the solar wind. For the simulation with the lower moment of $M_d = 2 \times 10^{16}$ Am², the box size was reduced to save on computational time, with $[-10, 12] R_p$, $[-10, 10] R_p$, and $[-10, 10] R_p$ along the x, y, and z directions, respectively.

The outer boundary conditions are outflow from all boundaries, except the boundary at the +x side of the simulation domain, which is set with inflow boundary conditions with the solar wind properties (Section S1), flowing in the -x direction and carrying a magnetic field in the +z direction.

Initial conditions. The initial condition is a uniform plasma with properties representing the solar wind at the asteroid belt (listed in Section S1) and a magnetic field determined by the dipole moment. The initial bulk speed of the wind is zero, except at the +x boundary. Each cell is initialized with 10 macroparticles representing the protons and a uniform electron fluid, which are initially in thermal equilibrium. We used 10 macroparticles per computational cell. This number is slightly lower than the 15 macroparticles used in Kallio et al. (2003) to simulate Mercury's magnetosphere. We found that increasing the number of macroparticles increases computational cost without producing a significant change in the results, at least for these steady-state simulations. This uniform initial population is used to ensure there are no cells with no particles in the domain, to avoid division by zero when calculating the electron speed and to ensure that the Courant condition will hold from the first time step (Dyadechkin et al., 2013). The initial uniform plasma is washed out as the simulation progresses. The solar wind sweeps through the dipole field, compresses it in the upstream (day) side and stretching it in the downstream (night) side. We allow the simulation to evolve until a steady state is reached. For the simulation with $M_d = 2 \times 10^{17} \text{ Am}^2$, this was achieved after 20 s, while for the smaller magnetosphere a steady state was achieved after 8 s.

Model accuracy and limitations. The model of a magnetized asteroid using a 3D hybrid formulation is similar to that used by Fatemi & Poppe (2018), who simulated a magnetized Psyche. In the present case, however, the body is an ideal conductor while in Fatemi & Poppe (2018) the magnetized body was assumed to be resistive. In addition, the dipole moments chosen here, based on estimations from iron meteorite magnetization, are higher and therefore give a larger magnetopause distance. To validate the model, we simulated other cases to match the choices in Fatemi & Poppe (2018) and verified that the HYB model gives similar results of all published parameters. We note that for the magnetized cases in Fatemi & Poppe (2018), the authors reported a population of trapped particles in the night side. The energies of this population were not reported, but since the initial energies used in Fatemi & Poppe (2018) were < 10 eV and the simulations lasted less than 30 s, it is highly unlikely this is evidence of energetic radiation belts. In addition, the length of the simulation limits the ability to deduce whether these particles would perform full drift motions around the body, especially given that there is no corresponding feature in the dayside. The hybrid simulations in the current work were of lower resolution than Fatemi and Poppe (2018) and did not reproduce a similar feature. However, the goal here is to estimate the magnetopause distance, and to check how it compares to that calculated from simple pressure balance, given the finite gyroradius of protons in the solar wind.

S5. Single particle simulations

S5.1. Numerical solver

For the purposes of validating the trapping criteria and the limit of chaotic motion in a static dipole field, we directly calculated the trajectories of charged particle motion in a magnetic field by integrating the equation of motion under the relativistic Lorentz force:

$$\frac{d(\gamma m_0 \mathbf{v})}{dt} = q \mathbf{v} \times \mathbf{B} \tag{9}$$

where γ is the Lorentz factor, t is the time, and m_0 is the particle rest mass. This equation is applicable to an arbitrary field configuration and makes no a-priori assumptions about adiabaticity. Note that because we assume a static dipole field, there are no electric fields operating on the particles in these simulations. However, this does not affect the generality of our results, as we seek to examine trapping and not particle acceleration.

For a body with dipole moment, M_d , and radius, R_p , the field at every location is given by:

$$\mathbf{B}(x,y,z) = \frac{\mu_0}{4\pi} M_d \left(\frac{3xz}{r^5} \hat{\mathbf{x}} + \frac{3yz}{r^5} \hat{\mathbf{y}} + \frac{3z^2 - r^2}{r^5} \hat{\mathbf{z}} \right).$$
(10)

where x, y, and z Cartesian coordinates, where the z axis is aligned with the dipole axis, and r is the radial distance. The specification of the magnetic field using a functional form allows us to simulate the particle trajectory by direct integration of Eq. (9) using an implicit Runge-Kutta TR-BDF2 solver (Hosea & Shampine, 1996) provided as a standard library in MATLAB. We set the relative tolerance to 10^{-12} and the absolute tolerance to 10^{-14} .

The differential equation solver can accumulate numerical errors for large integration intervals. To reduce this effect, we solve for short segments of the motion with time intervals $t_{int}=0.01$ -0.1 τ_b , where τ_b is the bounce period. Each segment is initialized with the last location and velocity of the particle in the end of the previous segment. While it is customary in particle simulations to treat the gyration period as the fundamental time scale, we worked with segments of the bounce motion instead in order to have better control over the integration along the field line. Each segment solved by the Runge-Kutta solver is integrated with an adaptive time step. Because we are ultimately interested in measuring the temporal evolution of the equatorial pitch angle, we wish to have sufficient points of integration near the magnetic equator. We then use those points to interpolate the value exactly at the equator. We found that this temporal resolution sufficiently reduced numerical errors in the energy, with relative errors $< 10^{-11}-10^{-13}$).

S5.2. Solver Accuracy

We tested the accuracy of the solver in several ways. First, we measure the total kinetic energy and the magnitude of the velocity throughout each simulation. Since there are no electric fields, this quantity should be conserved. We ensured the error in these quantities, relative to the initial value, were below 10^{-11} at the end of the simulation of each particle. Second, we simulated particle trajectories in a uniform field and measured the resulting gyroradius. We found that the gyroradius was consistent with the theoretical value, with the deviation from the theoretical value negligibly small. Next, we tested the motion of particles in a magnetic bottle, and compared their bounce period to theoretical values. Finally, for the simulations discussed in the main text where the limit of regular motion is sought for particles in a dipole field, we first ensured that we obtained the expected results in terms of gyration, bounce, and drift periods when simulating a particle trajectory in a large planet with a large field, where the motion is adiabatic. This increases confidence in our results for non-adiabatic and chaotic particles, at least for the beginning of the dynamics.



Figure S2. Variation of the equatorial pitch angle for particle with initial pitch angle $\varepsilon_{eq,0}=25^{\circ}$ for different magnetic moments, M_d . Particle 1, 2, and 3 all have an energy of 1 MeV and launched from the magnetic equator at L = 2, with velocities slightly rotated from each other as described in the main text. Trajectories that terminate indicate particle loss has occurred.

S5.3. Detailed simulations results

Figs. S2-S6 show the variation over time of the equatorial pitch angle, ε_{eq} for the particle simulations summarized in Fig. 3c, and exploring the transition from adiabatic to chaotic motion. Each panel in each figure corresponds to a triplet of neighbouring trajectories, as explained in the main text. In some case, the trajectories do not diverge, and the curved overlap. Each figure is dedicated to a single value of $\alpha_{eq,0}$, ranging from 25° to 90°. The magnetic moment increases from the top to the bottom panel, in the same order as they appear in the aggregated results in Fig. 3c.



Figure S3. Same as Fig. S2, but for $\varepsilon_{eq,0} = 45^{\circ}$



Figure S4. Same as Fig. S2, but for $\varepsilon_{eq,0} = 65^{\circ}$



Figure S5. Same as Fig. S2, but for $\varepsilon_{eq,0} = 75^{\circ}$



Figure S6. Same as Fig. S2, but for $\varepsilon_{eq,0} = 85^{\circ}$

References

Carry, B. (2012). Density of asteroids. *Planetary and Space Science*, 73(1), 98-118, https://doi.org/10.1016/j.pss.2012.03.009

Dyadechkin, S., Kallio, E., and Jarvinen, R. (2013). A new 3-D spherical hybrid model for solar wind interaction studies. *Journal of Geophysical Research*, 118, 5157-5168, doi:10.1002/jgra.50497

Ebert, R. W., McComas, D. J., Elliott, H. A., Forsyth, R. J., & Gosling, J. T.

(2009). Bulk properties of the slow and fast solar wind and interplanetary coronal mass ejections measured by Ulysses: Three polar orbits of observations. *Journal of Geophysical Research*, 114(1). https://doi.org/10.1029/2008JA013631

Eviatar, A., Williams, D. J., Paranicas, C., McEntire, R. W., Mauk, B.

H., & Kivelson, M. G. (2000). Trapped energetic electrons in the magnetosphere of Ganymede. *Journal of Geophysical Research*, 105(A3), 5547. https://doi.org/10.1029/1999JA900450

Fatemi, S., & Poppe, A. R. (2018). Solar wind plasma interaction with asteroid 16
Psyche: Implication for formation theories. *Geophysical Research Letters*, 45(1),
39-48. https://doi.org/10.1002/2017GL073980

Gombosi, T. I. (2004). Physics of the space environment, pp. 357. Cambridge: Cambridge University Press, August 2004.

Ho, G. C., Krimigis, S. M., Gold, R. E., Baker, D. N., James, A., Anderson, B.

J., Solomon, S. C. (2011). MESSENGER observations of transient bursts of energetic electrons in Mercury's magnetosphere. *Science*, 333(6051), 1865-1868.

https://doi.org/10.1126/science.1211141

Hosea, M. E. & Shampine, L. F. (1996). Analysis and implementa-

tion of TR-BDF2. Applied Numerical Mathematics, 20(1-2), 21-37,

https://doi.org/10.1016/0168-9274(95)00115-8

Kallio, E., & Janhunen, P. (2003). Modelling the solar wind interaction with Mercury by a quasi-neutral hybrid model. Annales Geophysicae, 21(11), 2133-2145. https://doi.org/10.5194/angeo-21-2133-2003

Kao, M., Hallinan, G., Pineda, J. S., Stevenson, D., & Burgasser, A. (2018). The strongest magnetic fields on the coolest brown dwarfs. *The Astrophysical Journal Supplement Series*, 23(2), 25.

Kivelson, M. G., & Russel, C. T. (1995). Introduction to space physics. Cambridge: Cambridge University Press.

Kivelson, M. G. (2007). Planetary Magnetospheres. In: Y. Kamide & A. Chian (eds.), Handbook of the Solar-Terrestrial Environment. Berlin: Springer-Verlag Berlin Heidelberg

Lawrence, D. J., Peplowski, P. N., Goldsten, J. O., Burks, M., Beck, A. W., Elkins-Tanton, L. T., Jun, I., McCoy, T. J., Polanskey, C. A., & Prettyman, T. H. (2016). The Psyche gamma-ray and neutron spectrometer: characterizing the composition of a metal-rich body using nuclear spectroscopy. *Lunar and Planetary Science Conference*, 47, 1622.

Lodders, K. & Fegley, B. (1998). The planetary scientist's companion. New York : Oxford University Press.

McComas, D. J., Barraclough, Funsten, H. O., Gosling, J. T., Santiago-Munoz, E.,
Skoug, R. M., Goldstein, B. E., Neugebauer, M., Riley, P., & Balogh, A. (2000).
Solar wind observations over Ulysses' first full polar orbit. *Journal of Geophysical Research*, 105(A5), 10419-10433. doi:10.1029/1999JA000383

Omidi, N., Blanco-Cano, X., Russel, C. T., Karimabadi, H., and Acuna, M., 2002. Hybrid simulations of solar wind interaction with magnetized asteroids: General characteristics. *Journal of Computational Physics*, 107(A12), 1487.

Parker, E. N. (1968). Dynamical Properties of the Magnetosphere. In: Carovillano

R.L., McClay J.F., Radoski H.R. (eds.), Physics of the Magnetosphere. Astro-

physics and Space Science Library (vol. 10). Dordrecht: Springer.

Pesonen, J. L., Terho, M., & Kukkonen, T. I. (1992). Physical properties of 368

meteorites: Implications of early solar system magnetic fields. In E. M. Zolensky,

M. Prinz, and M. Lipschutz (eds) Antarctic Meteorites XVII(vol. 17, pp. 179-181)

Phillips, J. L., Feldman, W. C., Gosling, J. T., & Scime, E. E. (1995). Solar

wind plasma electron parameters based on aligned observations by ICE and

Ulysses. Advances in Space Research , 16(9), 95-100. https://doi.org/10.1016/0273-1177(95)00319-A

Russell, C. T., Luhmann, J. G., & Strangeway, R. J. (2016). Space physics: an introduction. Cambridge: Cambridge University Press.

Shepard, M. K., Richardson, J., Taylor, P. A., Rodriguez-Ford, L. A., Conrad, A.,

de Pater, I., & Harris, A. W. (2017). Radar observations and shape model of aster-

-16-

oid 16 Psyche. *Icarus*, 281(1), 388-403. https://doi.org/10.1016/j.icarus.2016.08.011 Simon, S., Bagdonat, T., Motschmann, U., Glassmeier, K. H., 2006. Plasma environment of magnetized asteroids: a 3-D hybrid simulation study. *Annales Geophysicae*, 24, 407-414.

Terho, M., Pesonen, L. J., Kukkonen, I. T., & Bukovanska, M. (1993). The petrophysical classification of meteorites. *Studia Geophysica et Geodaetica*, 37(1), 65-82. https://doi.org/10.1007/BF01613921

Tholen, D. J., Tejfel, V. G., & Cox, A. N. (2002). Planets and Satellites. In Arthur N. Cox (Ed.) *Allen's Astrophysical Quantities*, pp. 293-313. New-York: Springer-Verlag.