The Solar Wind at (16) Psyche: Predictions for a Metal World

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Abstract

NASA’s Psyche spacecraft will carry a magnetometer to main-belt asteroid (16) Psyche to search for remanent magnetic fields, and to attempt electromagnetic sounding of the interior. However, the Psyche spacecraft does not carry an instrument to measure solar wind plasmas. We thus combine data from five missions that have measured the solar wind at the orbit of asteroid (16) Psyche. We characterize these upstream conditions for future modeling and reference. We consider the implications of these ambient conditions for the interaction between (16) Psyche and the solar wind, outlining four possible resulting magnetospheres. Any magnetosphere would be dominated by ion-scale (Hall) physics and exotic electron-scale physics, requiring sophisticated physical modeling to describe. Under these different regimes, plasma generates additional electromagnetic fields, resulting in complex magnetism which may complicate the magnetic environment near asteroid (16) Psyche. Future missions to asteroids would benefit from combined magnetic field and plasma measurements.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Asteroid belt (70); Planetary magnetospheres (997); Main belt asteroids (2036); Asteroids (72); Star-planet interactions (2177); Space plasmas (1544); Magnetic anomalies (993); Magnetic fields (994)

1. Introduction

Perhaps one of the most exotic objects in our solar system is asteroid (16) Psyche (Δ) (Hind et al. 1852). This tiny world, just 225 km in diameter (Shepard et al. 2017) lies in the main asteroid belt, orbiting the Sun at distances between 2.51 and 3.33 au (Mitchel 1860). Its high density of ∼4 g cm−3 (Hanus et al. 2017) suggests that (16) Psyche may be as high as 60% metal by volume (Elkins-Tanton et al. 2020), the largest metallic asteroid yet discovered. This metal-rich composition has led some to believe that (16) Psyche may be the remnant of what was once the core of a far larger planetesimal (e.g., Johnson et al. 2020). Alternatively, (16) Psyche may be an enormous chondrite; a “primitive” (unmelted) collection of metal and rock which clumped together during the formation of the solar system (Elkins-Tanton et al. 2020). NASA is currently preparing to launch a spacecraft to this metal-rich world (the first mission to a metal asteroid). The eponymous “Psyche” spacecraft will orbit the asteroid to determine what (16) Psyche is and how it was formed.

One of the clues to the formation of (16) Psyche is whether or not it has intrinsic magnetism. If this planetesimal once generated its own magnetic dynamo field, then it is possible that some remanent of this ancient magnetism may remain frozen into metal-rich (16) Psyche, as at the Moon (Strangway et al. 1970; Binder 1998; Lin et al. 1998; Mitchell et al. 2008) and Mars (Connerney et al. 1999). However, if (16) Psyche formed due to a cataclysmic collision, it seems possible that any orderly remanent magnetism may have been destroyed by the heat and chaos of its birth. At Mars, for example, remanent magnetism is found at the oldest terrain, which has largely laid in place since before the Martian magnetic dipole field turned off, and is absent from more recent meteor impact basins (Acuna et al. 1999).

The “Psyche” spacecraft will carry a magnetometer experiment to search for any remanent magnetism, and to attempt electromagnetic sounding of the interior (Elkins-Tanton et al. 2020). However, unlike previous missions at other worlds tasked with a similar investigation, it does not carry sensors to measure the ambient plasma. Without a plasma spectrometer, the Psyche spacecraft will be unable to measure solar wind plasmas near the asteroid, which are key for modeling and understanding any magnetosphere. In this paper we revisit the data sets of five deep-space probes that explored the solar wind and interplanetary magnetic field (IMF) at the orbit of (16) Psyche. The goals of this study are as follows:

1. To characterize the statistical properties of upstream conditions at asteroid (16) Psyche for future reference and modeling (Section 3).
2. To investigate what modeling tools may be appropriate to fully describe any magnetosphere at (16) Psyche (Section 4).
3. To predict what these solar wind conditions may imply for the interaction between (16) Psyche and the solar wind (Section 5).
4. To advocate that future asteroid missions would greatly benefit from the measurement of both plasmas and magnetic fields (Section 6).

2. Observations: Conditions at the Orbit of (16) Psyche

2.1. The Five Explorers

Six missions have measured the solar wind and IMF at the orbit of (16) Psyche (2.51–3.33 au):

1. Pioneer 10: 1972 September 13 through 1972 December 29 (at orbit of (16) Psyche).
2. Pioneer 11: 1973 October 17 through 1974 January 31.
3. Voyager 1: 1978 March 01 through 1979 June 01.
4. Voyager 2: 1978 March 09 through 1979 June 21.
5. Ulysses: 1991 March 26 through 1991 June 13.
6. Juno: 2014 April 03 through 2014 August 03.

Since Voyager 1 and 2 were so close to each other (compared to the size of the inner solar system), they effectively measured the same solar wind. Thus, to avoid double-counting in this statistical study we shall only concern ourselves with Voyager 2, whose data set from the asteroid belt is more complete. Juno only recorded magnetic fields in the asteroid belt, its suite of plasma sensors being off for the cruise. Additionally, while the asteroid belt was also traversed by Galileo, Cassini, Rosetta, and New Horizons, no plasma data were recorded at the orbit of (16) Psyche.

Figure 1(A) shows a map of the trajectories of these five spacecraft (light green) through the orbit of (16) Psyche. The map is plotted in the International Celestial Reference Frame (ICRF/J2000.0) coordinate system centered at the barycenter of the solar system. The orbits of Earth (dark blue) and Mars (red) are shown for scale. The orbit of (16) Psyche is plotted in light blue, together with a ring denoting the distances between perihelion (2.51 au) and aphelion (3.33 au). All spacecraft in the marked time periods were close to the near-ecliptic inclination of (16) Psyche (3.1°, Mitchell 1860). The solar wind and IMF rotates with the Sun every ~27 days (Carrington 1858; Parker 1958), rotating several times over the course of each spacecraft’s transit through the orbit of (16) Psyche. Thus, in our analysis we may ignore the longitudinal angle of the spacecraft around the Sun, and Figure 1(A) is included purely to orient the reader so they may better visualize the geometry of where data were taken.

Figure 1(B) shows the variation in number of sunspots on the solar disk since 1970. The dates that the five spacecraft flew through the orbit of (16) Psyche are shown as blue vertical bars. Since sunspot number directly correlates with solar activity (such as flares and solar storms), Figure 1(B) lets us compare at what phase in the 11 yr solar cycle the observations were made.

Ulysses and Juno both flew through the orbit of (16) Psyche around solar maximum, although the sunspot number and the solar activity intensity of solar cycles 22 and 24 were different. If the Psyche spacecraft arrives at the asteroid on schedule in 2026, solar activity should also be around maximum. At the time of writing, the latest forecast for the solar maximum of cycle 25 will be about July 2025 ±8 months. Thus the observations by Ulysses and Juno may be the most representative of what conditions might be expected for the Psyche mission. Of all five missions, Ulysses offers by far the most comprehensive data set, being especially designed to measure the solar wind. For the remainder of Section 2, we shall examine what Ulysses encountered when exploring the asteroid belt at the orbital distances of (16) Psyche. In Section 3 we will examine the statistical properties using data from all five missions.

2.2. The 80 Day Voyage of Ulysses Through the Orbit of (16) Psyche

Ulysses is best known as the first spacecraft to orbit over the poles of the Sun. To reach this very high-inclination heliocentric orbit, a flyby of Jupiter was performed in 1992 February, using the gas giant’s gravity field to knock Ulysses out of the ecliptic plane. To get to Jupiter, Ulysses first flew outbound from Earth through the main asteroid belt in the plane of the ecliptic. In this paper, we use data from this early ecliptic phase of the mission.

Figure 2 shows a time series of Ulysses data covering the ~80 days spent between 2.51 and 3.33 au. Figure 2(B) shows the radial distance from the Sun to Ulysses. Figure 2(C) shows magnitude and vector measurements by the Ulysses magnetometer. All data are in the radial, tangential, normal (RTN) coordinate system, where $R$ points along the Sun-spacecraft line, $T$ is the cross-product of the solar rotation axis with $R$, and $N$ completes the right-handed set. Figures 2(D) and 2(E) show plasma observations by the Solar Wind Over the Poles of the Sun (SWOOPS) experiment (Bame et al. 1992); Figure 2(D) shows solar wind electron density and temperature, including
the total (red), and those of the core (blue) and halo (purple) components (Plipp et al. 1987). Figure 2(E) shows SWOOPS ion measurements, subdivided by protons (red) and alphas (blue).

In this paper, solar wind conditions will be divided into three types: (1) “slow” solar wind (with bulk velocities \(<500\, \text{km} \, \text{s}^{-1}\) ), (2) “fast” solar wind (with bulk velocities \(\geq 500\, \text{km} \, \text{s}^{-1}\) ) (Stakhiv et al. 2015), and (3) periods of space weather events (corotating interaction regions, CIRs, and coronal mass ejections, CMEs). Figure 2(A) shows a color-coded timeline of when Ulysses encountered each type of solar wind stream. “Disturbed” periods (red) include the passage of interplanetary shocks, CMEs, and CIRs. These events were previously identified and classified by González-Esparza & Smith (1996; see Figure 5), and thus will
not be discussed in detail here. The frequent passage of CIRs and CMEs means that conditions at (16) Psyche are highly bimodal, alternating between periods of relative calm and disturbed periods of space weather events with enhanced magnetic field strength (e.g., Jian et al. 2008).

Due to the lack of a plasma particle detector, the Psyche mission will not be able to determine the proton and electron gyroradii. This is the standard “yard stick” when studying any magnetosphere. If the gyroradii of both ions and electrons are small with respect to the size of the system (as at Earth’s magnetosphere), then to the first order we can ignore this gyration altogether and treat them as a single fluid. This greatly simplifies the physics required to describe the general global properties of a magnetosphere. However, at smaller systems where the ion gyroradius approaches the size of the system, ion-scale physics introduces new systems of electrical currents on a global scale. Modeling such ion-scale systems requires more physics than is included in the resistive MHD simulations used most ubiquitously throughout space science (e.g., Ledvina et al. 2008).

One known example of such an ion-scale system is the miniature magnetosphere of Ganymede (Dorelli et al. 2015; Collinson et al. 2018), Jupiter’s largest moon. This magnetosphere is the smallest known with respect to the local ion gyroradius and, as a result, the Hall effect plays a dominant role in the global structure and dynamics of the magnetosphere. Hall MHD simulations of Ganymede’s magnetosphere by Dorelli et al. (2015) demonstrated that Hall electric fields resulted in intense global-scale field-aligned currents which are not captured by traditional resistive MHD models. These Hall current systems extended all the way down to the surface, where they may contribute to Ganymede’s aurora. Within the magnetopause and magnetotail, ion-scale (Hall \( J \times B \) forces) accelerate ions, producing a global-scale system of ion drift belts that circulates plasma throughout Ganymede’s magnetosphere (Poppe et al. 2018).

Another known example of an ion-scale system are the distributions of crustal remanent magnetism at the Moon (Fatemi et al. 2015) and Mars (Halekas et al. 2009; Collinson et al. 2020). In both cases, Hall electric fields and their associated current systems play a dominant role in shaping local magnetic field structures and driving plasma dynamics. At both the Moon and Mars, crustal remnants provide local shielding from the solar wind (Brain et al. 2007; Fatemi et al. 2015). If (16) Psyche were to also possess crustal magnetism, then we would expect similar ion-scale or electron-scale (non-MHD) current systems. This shall be discussed in more detail in Section 5.

With Ulysses data we may directly calculate the ion and electron gyroradii at the orbit of (16) Psyche using Equation (1):

\[
r_g = \frac{m v_{\perp}}{|q| B}
\]  

where \( m \) is the mass of the particle, \(|q|\) the magnitude of its electrical charge, \(|B|\) the ambient magnetic field strength, and \(v_{\perp}\) is the thermal velocity of the solar wind particles perpendicular to the magnetic field. For the thermal velocities of solar wind protons and electrons, we assume isotropy. Using Equation (1), Figure 2(F) shows the gyroradius of protons (red) and electrons (magenta) at Ulysses at the orbit of (16) Psyche. While the presence of any magnetism at (16) Psyche would alter the size of the solar wind obstacle, in this paper, we will hypothesize that, to the first order, the size of the obstacle to the solar wind at (16) Psyche is comparable to the size of the asteroid (225 km, dark blue line, Figure 2(F)). This assumption is partly based on experience, since this has been the case at every asteroid so far visited (Acuna et al. 2002; Blanco-Canete al. 2003; Richter et al. 2012; Hercik et al. 2020). However, it is also partly pragmatic, since while the magnetic state of (16) Psyche is yet to be determined, its physical size is known (Shepard et al. 2017). Thus in this paper, we will compare the solar wind gyroradii to the physical size of (16) Psyche, to attempt to glean what physics is required to describe its interaction with the solar wind.

For most of the time, the solar wind proton gyroradius (\(H^+\), red, Figure 2(F)) is close to (or larger than) the diameter of (16) Psyche (\(\phi\), dark blue, Figure 2(F)), whereas the electron gyroradius (\(e^-\), magenta, Figure 2(F)) is always smaller. This puts (16) Psyche firmly in the realm of an ion-scale system, consistent with previous hybrid simulations of the asteroid–solar wind interactions (Omidi et al. 2002; Blanco-Canete al. 2003; Simon et al. 2006; Fatemi & Poppe 2018).

2.3. Extreme Conditions: the Shrinking and Expanding Magnetosphere of (16) Psyche

While (16) Psyche is generally in the ion-scale regime (size between the electron and ion gyroradii), this is not always the case. Extreme swings in solar wind conditions drive substantial changes in gyroradii, with potentially important consequences should a magnetosphere be discovered at (16) Psyche.

Figure 3 shows a close-up of Ulysses observations in the main asteroid belt from April 27 through 1991 May 7. At the end of April, a CIR blew through the orbit of (16) Psyche (González-Esparza & Smith 1996). Figure 3(A) shows a timeline of this 11 day period. Figure 3(B) shows the strength of the IMF (\(|B|\)). Figure 3(C) shows measurements of solar wind plasma. Finally, Figure 3(D) shows the gyroradius of protons (\(H^+\), red) and electrons (\(e^-\), magenta) with respect to the diameter of (16) Psyche (\(\phi\), dark blue dashed line).

Just after passage of the CIR, Ulysses encountered periods where the gyroradii became very large (green on timeline, Figure 3(A)). During this period, the mean proton gyroradius was 1545 km and the mean electron gyroradius was ~54 km. However, around noon on May 3 (and for several hours), the electron gyroradius expanded to 96.5 km, 42% the diameter of Psyche. This raises the possibility that under these extreme conditions, electron-scale physics may begin to play an important role at (16) Psyche. This shall be discussed in more detail in Section 5.

3. “Typical” Upstream Conditions at (16) Psyche

Figure 4 shows histograms of conditions in the solar wind and IMF at the orbit of (16) Psyche. These data were collected from all five spacecraft listed in Section 2.1. For each parameter, three histograms are shown: all collected data (black), slow solar wind (<500 km s\(^{-1}\), blue), fast solar wind (>500 km s\(^{-1}\), purple), and space weather events (CIRs/ CMEs, red). For the mean and mode (marked by solid vertical lines) of these distributions in table form (including a breakdown by spacecraft), please see supplementary information S1.
Interplanetary magnetic field. The modal strength of the IMF ($|B|$; Figure 4(A)) is 1.8 nT, approximately one-third of the typical strength at Earth (Baumjohann & Treumann 1997). $|B|$ more than doubles between conditions in the slow solar wind (1.4 nT) and space weather events (3.7 nT) conditions. Throughout the solar system, the direction of the IMF is highly variable at any given time (Hanlon et al. 2004; Collinson et al. 2015). However, to the first order, one can think of it as acting like a “lawn sprinkler”, shooting out radially near the Sun and spiraling out at ever steeper angles as it flows with the solar wind. For a first-order approximation of the Parker spiral angle ($\delta$) at a given distance from the Sun ($r$), solar wind velocity ($v_s$), and the solar angular rotation rate ($\Omega = 2.9 \times 10^{-6} \text{ s}^{-1}$), we may use Equation (2):

$$\tan \delta = \frac{r \Omega}{v_s}.$$  \hspace{1cm} (2)

Near Earth, this “Parker spiral angle” is near to 45° (Parker 1958, 1963), consistent with the 45.4° angle predicted by Equation (2) for a solar wind velocity of $v_s = 430 \text{ km s}^{-1}$. At (16) Psyche it most commonly lies at around 77° (Figure 4(B)), but with very large variations. This is slightly steeper than Equation (2) predicts (68.5° at 2.51 au, 73.5° at 3.33 au), although the difference is insignificant when
compared to the spread of the distribution of the Parker spiral angle. The distribution of the Parker spiral angle during fast solar wind streams has a very large standard deviation, indicating that fast wind streams bring highly randomized IMF orientations. On average, the IMF tends to lie in the plane of the ecliptic (0°, Figure 4(C)), for all solar wind conditions, although, again, with large variations.

Solar wind. At the orbit of (16) Psyche, solar wind proton densities are most commonly around 0.6 cm$^{-3}$ (Figure 4(D)), 20 times less than at Earth (Köhnlein 1996). This doubles
during space weather events to 1.2 cm$^{-3}$. Ion temperatures (Figure 4(E)) typically hover at around 3.5 eV, rising to 7.9 eV during space weather events. Electron temperatures (Figure 4(F)) remain at a fairly constant 8 eV (although this was only measured by Ulysses). The distribution of solar wind velocities (Figure 4(G)) peaks between 350 km s$^{-1}$ and 450 km s$^{-1}$, but has a very long tail (as at Earth). While individual space weather events can bring faster solar wind streams (e.g., the CIR around the end of April 1991, Figure 3(C)), this is not always the case (Figure 3(E)).

**Gyroradii.** Typical solar wind gyroradii at (16) Psyche are 390 km for protons (Figure 4(h)), and 24 km for electrons (Figure 4(i)). The ion gyroradii vary by more than 2 orders of magnitude. Approximately 65% of the time, the proton gyroradius is larger than the diameter of Psyche. During periods of slow solar wind, lower plasma temperatures (2.6 eV) result in smaller proton gyroradii (since $v_\perp$ decreases; see Equation (1)). Conversely, during fast solar wind streams, weaker $|B|$ results in slightly larger gyroradii. During space weather events (CIRs/CMEs), the increase in plasma temperature (7.9 eV) is balanced by an increase in $|B|$, and thus gyroradii are conserved. At no time did electron gyroradii grow larger than the asteroid. However, in rare cases they do approach this scale. The distribution of electron gyroradii (Figure 4(I)) suggests that the 96.5 km electron gyroradius encountered by Ulysses (Figure 3) represents an extreme case. Under typical conditions, electron gyroradii are fairly consistently around 24 km.

4. Variability of Conditions at the Orbit of (16) Psyche

Table 1 compares and contrasts the most common (mode) conditions in the solar wind and IMF at the orbit of (16) Psyche encountered by each of the five spacecraft (Section 2.1). The average (mean), standard deviation, and most common (mode) of all collected data are shown to the right. Data are again binned into four groups: all data (black), space weather (red), slow solar wind (<500 km s$^{-1}$, blue), and fast solar wind (≥500 km s$^{-1}$, purple). As expected from the nature of the solar wind, upshot conditions at the orbit of (16) Psyche are highly variable.

**Interplanetary magnetic field.** Ulysses, flying through the orbit of (16) Psyche near solar maximum, encountered the strongest IMFs (1.8 nT), more than twice that of Pioneer 11, which flew near to solar minimum (0.6 nT). Interestingly, while Pioneer 10 and Pioneer 11 flew less than a year apart, they encountered notably different IMF field strengths. Pioneer 10, flying midway through descent from solar maximum to minimum, encountered an IMF with a strength of 1.1 nT. The orientation of the IMF varied between missions. The mean Parker spiral angle was around 81° ± 38°, and the mode of all data was 77.13°. The variability of the IMF angle is so great that large differences in Parker spiral angle are observed between missions (59°, Pioneer 11, versus 77°, Pioneer 10). While the IMF was, on average, in the plane of the ecliptic (mean of 0.43°, mode of −1.75°), it is again highly variable with a standard deviation of ±33°.

**Solar wind.** Solar wind densities were most commonly around 0.6 cm$^{-3}$, with a mean of 0.8 cm$^{-3}$, but with a standard deviation of ±0.8 cm$^{-3}$. During space weather events densities increased to between 1 cm$^{-3}$ and 1.3 cm$^{-3}$, with a standard deviation of 1.2 cm$^{-3}$. Ion temperatures were hottest during the Ulysses mission (4.9 eV) near solar maximum, and coolest during the Pioneer 10 (1.6 eV) and Pioneer 11 (1.9 eV) near solar minimum. Solar wind velocities were similarly fastest during the Ulysses mission (421 km s$^{-1}$). Pioneer 10 encountered no “fast” solar wind, and experienced the slowest solar wind streams (365 km s$^{-1}$), which are significantly below the ~390 km s$^{-1}$ typically encountered at (16) Psyche. So far, the only spacecraft to measure electrons at the orbit of (16) Psyche was Ulysses. While the mode electron temperature was similar between slow solar wind (8.2 eV) and space weather (9.6 eV), the temperature is highly variable (±5.3 eV for all data, ±6.5 eV during space weather events), which is important since it has knock-on implications for the electron gyroradii at (16) Psyche.

**Gyroradii.** The most variable and unpredictable heliophysical parameter at (16) Psyche is the gyroradius of the solar wind plasma. In general, Ulysses tended to encounter the largest proton gyroradii (471 km, all data). However, during periods of space weather events (CMEs/CIRs), Ulysses measured proton gyroradii similar with those encountered by Pioneer 11 near solar minimum. The largest proton gyroradius encountered was 17 × 10$^{-3}$ km (Pioneer 11, 1974 January 16), and the smallest was 1.3 km (Voyager 2, 1978 June 3).

Thus, perhaps the most important conclusion is that there are enormous and unpredictable changes in the fundamental physics required to accurately describe any attendant magnetosphere at (16) Psyche, where ion-scale-driven and even electron-scale-driven plasma current systems would play a dominant role. Without a solar wind monitor, the Psyche spacecraft will be unable to determine the local plasma gyroradius. Our analysis reveals that the electron gyroradius will be in the range of 10–30 km, about 4%–13% the diameter of (16) Psyche (224 km; Shepard et al. 2017). This means that electron-scale physics will always be important at (16) Psyche, and should be included when modeling the interaction between the asteroid and the solar wind.

5. Discussion: Predictions for a Metal World

We shall now briefly speculate what implications these solar wind conditions may have for any magnetosphere at asteroid (16) Psyche, and for the magnetometer observations by the Psyche orbiter.

5.1. A Microscopic Magnetosphere

To date, no magnetism has yet been definitively detected at any asteroid. Claims were made as to the detection of dipole magnetospheres at S-class asteroids (951 Gaspra (Kivelson et al. 1993; Wang et al. 1995) and (9969) Braille (Richter et al. 2001). However, these claims are based on very ambiguous magnetic signatures from single flybys. It has subsequently been shown that these signatures were just random fluctuations in the IMF (Blanco-Canó et al. 2003), or, at any rate, cannot possibly be the result of remnant magnetism (Rochette et al. 2003). However, it is not unreasonable to posit that some form of miniature magnetosphere may yet be found at (16) Psyche. Figure 5 shows four possible scenarios for the interaction between (16) Psyche and the solar wind.

(A) **Magnetic dipole field** (Greenstadt 1971). Figure 5(A) shows a hypothetical (16) Psyche that generates a dipole field. Magnetic field lines are shown in white (based on simulations of (16) Psyche by Fatemi & Poppe 2018), and colored regions distinguish different regions of the resulting “submagnetospheric”
(Baumgärtel et al. 1997) solar wind interaction. This type of dipolar asteroid magnetosphere historically has been the most commonly considered, modeled, and discussed (see references above, and Baumgärtel et al. 1994, Omidi et al. 2002, Blanco-Cano et al. 2003, and Simon et al. 2006). Thus, for brevity we refer the reader to this past research and do not discuss this type of magnetosphere in detail. However, we will say that this is probably the least likely scenario presented in this paper. To our knowledge, one necessary prerequisite for the generation of such orderly global dipole fields is a liquid core (although as Venus and Mars show, not all worlds with cores generate dipoles; Bridge et al. 1967). Recent modeling of asteroid (16) Psyche by Neufeld et al. (2019) suggests that its core would have solidified within 6.7–20 Myr. Thus, an orderly dipole magnetosphere at an asteroid would seem highly improbable.

A major contributor to the heating of Earth’s core is radioactive decay, which is responsible for 57% of all terrestrial heat output (Patino Douce 2011). Thus, one might reasonably wonder whether the core of (16) Psyche could also be kept liquid (and thus generate a dynamo field) through radioactive decay. To address this, we can estimate the minimum thermal power (P) required for (16) Psyche to keep its metal core molten, using Equation (3):

$$P = \frac{\Delta T C_p M}{\tau},$$

(3)
where $\Delta T$ is the change in temperature required (1800 K, i.e., heated above the melting point of iron), $C_P$ is the specific heat capacity of the material (let us assume that calculated by Consolmagno et al. 2013 for meteorites of $\sim 500$ J kg$^{-1}$ K$^{-1}$), $M$ is the mass of (16) Psyche ($\sim 2.4 \times 10^{19}$ kg; Carry 2012), and $\tau$ is the time period over which the work of heating the asteroid is done (4.5 Gya). Equation (3) suggests that (16) Psyche would need to output at least $\sim 152$ MW of thermal power over its lifetime to stay melted. Given these assumptions, this would suggest that, on average, every kilogram of (16) Psyche would need to output at least $6.3 \times 10^{-12}$ W of thermal power, twice that of modern-day Earth (Patino Douce 2011).

Thus, it seems highly improbable that a body as small as an asteroid could retain a liquid core, and thus generate a dipole field. To date, there is no credible evidence that any asteroid yet visited generates an orderly dipole field (Blanco-Cano et al. 2003; Rochette et al. 2003). Therefore, the balance of probability would suggest that when the Psyche spacecraft arrives at its target, no dipole magnetosphere will be detected. If the Psyche spacecraft were to discover a dipole field at asteroid (16) Psyche, it would be an extremely noteworthy discovery, and suggestive that the asteroid is far richer in long-lived radionuclides than Earth.

(B) Localized crustal remanent magnetism. If (16) Psyche is a fragment of the core of a planetesimal, the possibility exists that remanent magnetism is retained somewhere on its surface.

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**Figure 5.** Sketches imagining the miniature magnetosphere at (16) Psyche. White lines denote sketched magnetic field lines, colored regions distinguish regions of the magnetosphere. (A) Weakly magnetized Psyche with a full intrinsic dipole “submagnetosphere” (Greenstadt 1971; Fatemi & Poppe 2018); (B) a largely unmagnetized asteroid with pockets of remanent magnetism in the crust; (C) unmagnetized but highly conductive asteroid with an induced magnetosphere; (D) very weak solar wind interaction, with a lunar-like wake as at (433) Eros, arising from a chondritic Psyche, or deeply buried core.
(Figure 5(B)). At Mars, the presence of remanent fields is indicative of ancient, unmelted, unaltered crust (Acuña et al. 1998; Acuna et al. 1999). At the Moon, the cause of lunar magnetic anomaly is more of an open question. One theory is that they are the result of shock magnetization associated with the formation of large lunar basins early in lunar history (Binder 1998; Lin et al. 1998; Mitchell et al. 2008). Another theory is that they are a record of a past dynamo (Weiss & Tikoo 2014). At Mars, crustal magnetic remnants act as a “miniature magnetosphere”, featuring magnetic reconnection (Harada et al. 2018), and powerful “Hall” magnetic fields resulting from ion-scale processes (Halekas et al. 2009).

If crustal magnetic remnants are present at (16) Psyche, the result would be a highly complex tangled magnetic environment. This magnetic topology would constantly change as the asteroid rotates, opening on the dayside and closing again on the nightside as at Mars (Brain et al. 2007; DiBraccio et al. 2018). As at the Moon and Mars, exploration of such a complex environment would be greatly aided by measurement of electrons, which could detangle and map this magnetic topology (e.g., Brain et al. 2007; Mitchell et al. 2008; Xu et al. 2017, 2020).

If the only form of magnetism at (16) Psyche is crustal remanent magnetism (i.e., there is no magnetosphere), then the closest planetary analog for physical comparison would be Earth’s Moon. In this case, as at the Moon (Lin et al. 1998), the magnetic anomalies are directly exposed to the solar wind, which leads to phenomena such as proton reflection (Saito et al. 2008), limb shocks (Ness 1965; Ness et al. 1967; Halekas et al. 2014), and upstream propagating waves (Harada et al. 2014; Harada & Halekas 2016).

(C) Induced magnetosphere (Herbert 1993). Many worlds in the solar system without permanent magnetism nonetheless possess induced magnetospheres that are generated by the flow of the solar wind around them. Examples include Venus (Bridge et al. 1967), comets (Smith et al. 1986), Europa (Kivelson et al. 2000), Titan (Bertucci et al. 2015), and Pluto (Baghramian et al. 2016). All these worlds possess a global-scale conductive layer near the surface (e.g., an ionosphere at Venus; a coma at comets; a liquid water ocean at Europa), in which the flow of magnetized plasma around them induces a global-scale system of currents, generating a small magnetosphere. Thus if an induced magnetosphere is discovered at (16) Psyche (Figure 5(C)), this by definition implies that the asteroid must be electrically conductive on a global scale. Possible hypothetical explanations for such global conductivity include the following.

(1) Near-surface metal that has been melted together at some point in its past. The simplest explanation for how an electrical current may flow around the asteroid is if it is, in essence, a big metal ball (Dyud et al. 1977). In this scenario the flow of the solar wind (and interplanetary magnetic field) around the asteroid induces electrical currents in the outermost skin of metal that has melted together into a continuous global-scale layer. Analogs include Europa (Kivelson et al. 2000), where there is shallow subsurface global conductivity (albeit from water), and Mercury, where deep-subsurface-induced fields have been observed in the relatively large core and upper mantle (Johnson et al. 2016).

(2) A conductive plasma sheath near the surface. If an induced magnetosphere is discovered at (16) Psyche, a final possible cause is that (as at comets) global-scale electrical currents are flowing through a conductive near-surface plasma. This would be the least likely explanation; at the Moon the sheath is thought to extend only a few meters from the surface, and have densities of only ~200 cm$^{-3}$ (Poppe & Horányi 2010; Farrell et al. 2013), insufficient to support a global induced magnetosphere. While the Psyche spacecraft does not carry a plasma spectrometer, it may be possible to constrain the density of the sheath with radio occultation experiments (e.g., Kliore et al. 1972) and eliminate this possibility.

Note that the induced magnetosphere (Figure 5(C)), and crustal remanent magnetism (Figure 5(B)) are not mutually exclusive. As at Mars and Mercury (Hood 2016), it also quite credible that (16) Psyche may yet prove to feature both forms of magnetization.

Caution must be taken in such interpretations, however, since an induced magnetosphere will also form if there is a plasma sheath near its surface. Global magnetic field mapping will help to distinguish between the induced magnetosphere due to high conductivity and that due to local magnetic anomalies. However, the extended duration of the Psyche mission may be able to indirectly search for a near-surface plasma sheath by examining how any induced magnetosphere changes with external conditions.

For an induced magnetosphere at (16) Psyche, we may expect to observe the following: (1) a solar wind stand-off distance very close to (or inside) the surface; (2) a plasma void surrounded by denser “wings” filled with “Whistler” mode waves (discussed below); (3) in the tail, magnetic fields lightly draped but not substantially different in strength to that outside (Fatemi & Poppe 2018); (4) as at Mars (DiBraccio et al. 2018) and Venus (Collinson et al. 2014), the entire magnetosphere will rotate with the interplanetary magnetic field; (5) the possible presence of flux ropes in the tail resulting from magnetic reconnection (Zhang et al. 2012; Harada et al. 2017).

(D) No magnetosphere. Finally, we must consider the possibility that, as at (433) Eros (Anderson & Acuña 2004), Psyche is an unmagnetized body, and largely nonconductive near the surface (Figure 5(D)). In this case, a lunar-like low-density plasma wake would be found in the lee of the asteroid. As at the Moon and Eros, this tail would exhibit distortions of the IMF (Halekas et al. 2005; Poppe et al. 2014; Zhang et al. 2014, 2016). As at the Moon, we may find regions of wave activity connected to either the surface or wake (Bale et al. 1997; Halekas et al. 2012; Poppe et al. 2012; Harada et al. 2014, 2015; Harada & Halekas 2016). This has been the case at all other asteroids so far visited (Acuña et al. 2002; Blanco-Canete et al. 2003; Richter et al. 2012; Hecik et al. 2020) and, thus, from a pure statistical point of view, is a reasonable null hypothesis to compare the eventual magnetic measurements at (16) Psyche.

5.2. Finite Gyroradius Effects and Plasma-induced Magnetism

Our statistical analysis (Section 3) suggests that 65% of the time the proton gyroradii are larger than (16) Psyche but the electron gyroradii are generally smaller. Thus, ion-scale physical processes will play a prominent role in any Psychean magnetosphere (dipole, crustal, or induced; Omidi et al. 2002; Blanco-Canete et al. 2003; Fatemi & Poppe 2018). In such an “ion-scale” regime, the Hall effect dominates the physics of the system, resulting in additional systems of field-aligned currents and complex magnetic distortions on a global scale. Examples include the global Hall currents at the magnetosphere of Ganymede (Dorelli et al. 2015; Collinson et al. 2018), and crustal remanent magnetism at the Moon (Fatemi et al. 2015) and Mars (Halekas et al. 2009; Collinson et al. 2020).
Using Ulysses data, we found that during extremely calm times, the electron gyroradii begin to approach the size of (16) Psyche. At this extreme, exotic electron-scale physics may begin to become important at any attendant Psychean magnetosphere. We have never encountered a magnetosphere at such electron-scale sizes, and (16) Psyche may be a fascinating natural laboratory for investigating new physical processes on these scales. Ion-scale and electron-scale processes may produce global current systems and magnetic distortion at (16) Psyche, complicating interpretation of magnetometer data. Thus, these observations by Ulysses strongly motivate future models of (16) Psyche under these extreme conditions, taking into account electron-scale physics. Also, this suggests that future missions to asteroids would benefit from combined measurements of both plasmas and magnetic fields.

5.3. Whistler Waves and Whistler Wings

Finally, one long-predicted feature of asteroid magnetospheres are the presence of “Whistler wings” (Kivelson et al. 1993). As posited by Baumgärtel et al. (1997), wave generation may be the dominant interaction process between an asteroid and the solar wind. As at the bow-wake of a ship, the flow of the solar wind around the asteroid generates ripples and waves (in this case, in the “Whistler mode”). Any waves which propagate upstream at the solar wind velocity appear to stand in place (the rest being blown away). The resulting pattern of stationary waves results in a wake with a rippled structure (Figures 5A, B, C; Blanco-Cano et al. 2004). Such a Whistler wake around (16) Psyche should be readily detectable by NASA’s Psyche orbiter.

6. Conclusions

NASA is currently planning a mission to orbit asteroid (16) Psyche (A), a main-belt asteroid thought to be composed of as much as 60% metal by volume (Elkins-Tanton et al. 2020). The Psyche spacecraft will carry a magnetometer to search for any remnant magnetic fields and to attempt electromagnetic sounding of the interior. However, the Psyche spacecraft does not carry any sensors to measure space plasmas. Thus, to support the Psyche mission, we used existing measurements from five spacecraft to characterize conditions in the solar wind and IMF at the orbit of asteroid (16) Psyche.

6.1. A Statistical Analysis of Solar Wind Conditions at the Orbit of (16) Psyche

A crucial prerequisite for any modeling study at any planetary magnetosphere is to characterize the upstream conditions. While conditions in the asteroid belt in general have been described previously (e.g., González-Esparza & Smith 1996), we focused explicitly on data collected at the orbit of (16) Psyche to present a tailored statistical analysis of upstream conditions at this asteroid. Solar wind data were subdivided into four subclassifications: (1) “slow” solar wind (with bulk velocities <500 km s\(^{-1}\)), (2) “fast” solar wind (with bulk velocities \(\geq 500 \text{ km s}^{-1}\)), as per Stukhiv et al. (2015); (3) periods of space weather events (CIRs/CMEs); and (4) all data combined. The mean and mode of each was calculated as a reference for future modeling studies, and are shown in Figure 4 and Table 1.

6.2. Pure Hybrid Models may be Inadequate to Fully Describe Asteroid Magnetospheres, Especially Under Extreme Conditions

For more than a decade, hybrid simulations (and some particle simulations) have increasingly become the standard tool for simulating asteroid magnetospheres (e.g., Omidi et al. 2002; Blanco-Cano et al. 2003; Fatemi & Poppe 2018). We examined the range of upstream conditions at (16) Psyche to investigate how appropriate such hybrid models may be at this asteroid.

As an example, at Ganymede the upstream ion gyroradius is approximately 8.5% of the diameter of the Moon (Dorelli et al. 2015). As a result, ion-scale (Hall) physics dominate at Ganymede, altering the global convection of plasma through the magnetosphere (Collinson et al. 2018) and shaping the global structure of field-aligned currents (Dorelli et al. 2015). Thus, while a classical resistive MHD model can reproduce some of the general bulk features of Ganymede’s magnetosphere, it does not have sufficient physics to capture many of these important details (Dorelli et al. 2015).

At (16) Psyche, not only is the ion gyroradius a significant fraction of the size of the system, it is larger than the asteroid itself 65% of the time. Thus, we may safely conclude that (as expected) ion-scale (Hall) physics included in hybrid modeling are very important in describing any attendant magnetosphere. However, what was unexpected is that we also find that the electron gyroradii at (16) Psyche are also relatively large (4%–13% the diameter of the asteroid). During extremely calm times, the electron gyroradii expand to such an extent that they may also begin to approach the size of the asteroid. This strongly suggests that electron-scale physics may also be important in describing the physics of the interaction between the solar wind and any magnetosphere at (16) Psyche. Should this be the case, then such physics are not captured by pure hybrid models.

One key conclusion of this study is to flag that a combination of ion-scale and electron-scale physics may be important at (16) Psyche, and that these should be considered and included in modeling of the asteroid–solar wind interaction (especially in the presence of any kind of magnetosphere). These results strongly motivate preparatory simulations of (16) Psyche under the full range of upstream driving conditions. We also note that an asteroid magnetosphere would be an interesting target for future kinetic-modeling studies to explore what happens when electron gyroradii become a substantial fraction of the size of the magnetosphere.

6.3. Predictions for the Solar Wind–Asteroid Interaction at (16) Psyche

We considered four possibilities for the asteroid–solar wind interaction, and their implications for the formation of Psyche (Figure 5): (A) a dipole magnetosphere; (B) localized crustal remnant magnetism; (C) an induced magnetosphere; and (D) no magnetosphere. Regardless, Whistler waves likely play a dominant role in the interaction between any asteroid magnetosphere and the solar wind (Baumgärtel et al. 1997), and the resulting Whistler wake should be detectable by the Psyche orbiter.

Historically, the type of asteroid magnetosphere most commonly considered, modeled, and discussed (e.g., Baumgartel et al. 1994; Omidi et al. 2002; Blanco-Cano et al. 2003) is a magnetic
highly noteworthy discovery, and suggestive that magnetosphere gyro radii effects become important in modeling magneto-fundamental physics of what happens at the edge-cases when itselfs. Absence the discovery in nature of such a tiny spheres nonetheless still have great intrinsic merit all by argue that theory and modeling of such tiny dipole magnetospheres nonetheless still have great intrinsic merit all by themselves. Absence the discovery in nature of such a tiny dipole field, such models are the only way to investigate the fundamental physics of what happens at the edge-cases when gyroradii effects become important in modeling magnetospheres. Their smaller size also makes them an ideal topic of study when setting up a new code before scaling up to larger magnetospheres.

While it is quite plausible that we may encounter remnant (permanent) magnetism at (16) Psyche, past experience at the Moon (Binder 1998; Lin et al. 1998; Mitchell et al. 2008) and Mars (Acuña et al. 1998; Acuna et al. 1999) would suggest that this would more likely exhibit a complex multipolar magnetic topography, and not be in the form of a singular orderly dipole field.

6.4. Future Missions to Asteroids Would Benefit from Combined Measurements of Both Plasmas and Magnetic Fields

Combined particle and fields measurements were key to the success of previous planetary missions such as the Lunar Prospector (Mitchell et al. 2008), the Mars Global Surveyor (Ness et al. 1999), and Venus Express (Svedhem et al. 2007). These missions frequently used plasma measurements to map magnetic field topology, interpret magnetic field measurements, quantify plasma-induced magnetism, and understand the interaction with the solar wind. However, asteroid missions (such as Near Earth Asteroid Rendezvous (NEAR) and Psyche) have typically only taken a magnetometer alone.

Given the enormous variability in solar wind conditions, it would be highly advantageous for model-data comparisons of future asteroid missions if the upstream conditions could also be measured in situ in addition to magnetic fields. While solar wind propagation models can provide some assistance, even at Earth such models are supported by real-time measurements at L1. Thus, we argue that future asteroid missions would greatly benefit from the inclusion of instrumentation able to measure space plasmas near their targets.

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