POSSIBLE MAGNETIC INTERACTION OF ASTEROIDS WITH THE SOLAR WIND

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Investigation of extraterrestrial objects is habitually accompanied by the observation of extraterrestrial magnetic fields, which often have significant effects on the solar wind in the vicinity of the objects. Should we be surprised to find this experience repeated at an asteroid?

A recent study considered the conditions that would have to be satisfied by the surface magnetic field of a small planetary body at asteroidal distances so that the field would be an obstacle capable of stopping the solar wind or deflecting it sufficiently to generate a detectable magnetic interaction (Greenstadt, 1971). Meteoritic and lunar data indicate that magnetic field levels associated with material found in, or retrieved from, the extraterrestrial environment are compatible with levels demanded by the limiting conditions for the existence of identifiable magnetospheres around the largest asteroids. The conditions for asteroidal magnetospheres in the region $1 \leqslant r \leqslant 3.5$ AU, as applied to hypothetical spherical bodies of dipole magnetic signature, are summarized below and related to measurements of meteorite magnetizations, fields detected on the lunar surface, and magnetizations of lunar samples.

CONDITIONS FOR MAGNETOSPHERIC TYPE OF INTERACTION

The magnetic field of a small planetary body must fulfill three scaling conditions to maintain a recognizable magnetic cavity from which the solar wind is excluded. First, the magnitude B_s of the stopping field transverse to the solar-wind flow at the upwind interface, or subsolar magnetopause, must be large enough to balance the bulk flow pressure; otherwise, there can be no magnetospheric barrier as we know it. Second, the field must extend at least the order of its own proton gyroradius across the solar-wind flow direction (Shkarofsky, 1965); otherwise, the plasma will be deviated rather than halted; edge-effect instabilities will predominate; the barrier, if any, will be ephemeral; and the field and plasma will intermingle, generating electromagnetic noise in various plasma wavemodes (Bernstein, Ogawa, and Sellen, 1968; Sellen and Bernstein, 1964). Finally, the field must extend upwind from the body a sufficient distance, on the order of the geometric mean of proton and electron gyroradii, to reverse the solar-wind particles before they intersect the body's surface (Dungey, 1958, p. 143); otherwise, only the body itself will properly constitute a barrier. Figure 1 illustrates these three conditions conceptually.

The conditions just enumerated yield expressions (Greenstadt, 1971) for the stopping field,

$$B_s \cong 9.39 v_{sw} r^{-1} n_1{}^{1/2} \times 10^{-2}\ \gamma$$

the proton radius,

$$p \cong 111 r n_1{}^{-1/2}\ \text{km}$$

and the stopping distance,

$$L \cong 2.595 r n_1{}^{-1/2}\ \text{km}$$

where v_{sw} is the solar-wind velocity in kilometers per second, r is the solar distance in astronomical units, and n_1 is the solar-wind proton number density at $r = 1$ AU, per cubic centimeter. These quantities are plotted in figure 2 for a quiet solar wind with $v_{sw} = 320$ km/s, $n_1 = 5\ \text{cm}^{-3}$. The number distribution of asteroids versus solar distance r is superimposed (Alfvén and Arrhenius, 1970), and the radii and the orbital semimajor axes of several selected asteroids are indicated in the figure. Note that except for Eros, their sizes are comparable to, or larger than, the "quiet" proton gyroradius p.

If a dipolar field is assumed for an asteroid so oriented that the solar-wind velocity v_{sw} is in the plane of the dipole's equator, i.e., the magnetic axis is normal to the solar-wind flow, then the equatorial surface field B_a must exceed the following values to permit the establishment of a magnetosphere:

For the proper minimal upwind stopping distance,

$$B_0 = 9.39 \frac{v_{sw}}{r}\ n_1{}^{1/2} \left(1 + 2.595 \frac{r}{R n_1{}^{1/2}}\right)^3 10^{-2}\ \gamma \qquad (1)$$

and for an upwind standoff distance and, therefore, a lateral dimension greater than $2p$,

$$B_0 = 10.3 \frac{v_{sw} r^2}{n_1} \frac{1}{R^3}\ 10^5\ \gamma \qquad (2)$$

where R is the radius of a postulated spherical asteroid, in kilometers. Steps in derivation of expressions (1) and (2) are given by Greenstadt (1971).

Figures 1 and 2 illustrate that for large asteroids, the criterion of adequate lateral dimension is satisfied by the diameter of the body itself, so that the criterion of stopping distance, equation (1), is the important one B_0 must

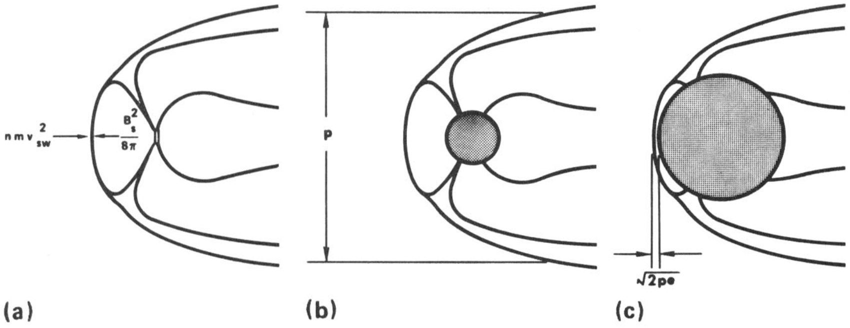

Figure 1.–Conceptual view of conditions governing minimal asteroid magnetospheres caused by dipole field, as seen in noon-midnight meridian plane. (*a*) A solar-wind pressure of density *nm* grams per cubic centimeter and at velocity v_{sw} from the left of the diagram is balanced by energy of stopping field B_s. (*n* is the proton number density and *m* is the proton mass.) (*b*) Proton gyroradius *p* is at least commensurate with magnetospheric diameter. (*c*) Balance takes place far enough, at stopping distance approximating geometric mean of proton and electron gyroradii *p* and *e* (in field B_s), to keep particles from hitting surface.

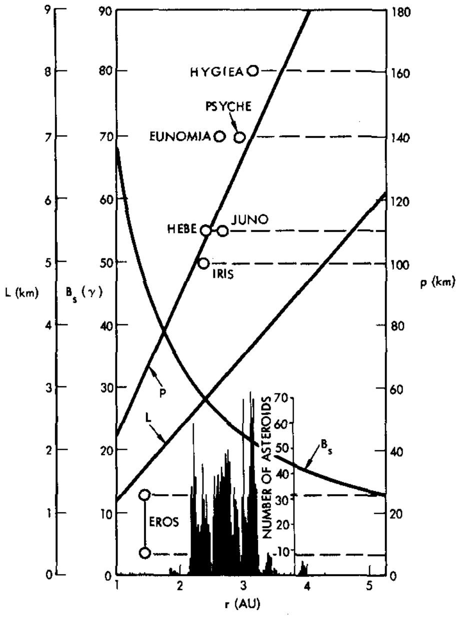

Figure 2.–Dependence of stopping field B_s, stopping distance L, and proton gyroradius p in field B_s on heliocentric distance r for quiet solar wind. Asteroid number distribution at bottom; dimensions and orbital semimajor axes of selected asteroids shown above on p, r scales, respectively. Dimensions of elongated Eros are from Roach and Stoddard (1938).

satisfy to guarantee a magnetopause standing away from the surface. For smaller asteroids, the field of equation (2) must provide the minimal transverse dimension, the diameter of the body being too small; the condition for minimal stopping distance is then automatically satisfied, because $L \ll p$ always.

APPLICATION TO ASTEROIDS UNDER QUIET SOLAR-WIND CONDITIONS

Figure 3 shows the dependence of minimal surface field B_0 on asteroid radius R for the quiet conditions defined above at selected heliocentric distances. The distinct behavior of the two sets of curves reflects the distinction between criteria of stopping distance and lateral dimension for magnetosphere maintenance. The shaded area representing acceptable combinations of R and $B_a \geqslant B_0$ is bounded by curves corresponding to the range of most common asteroid aphelia, $2 \leqslant r \leqslant 3.5$ AU. Values of R corresponding to

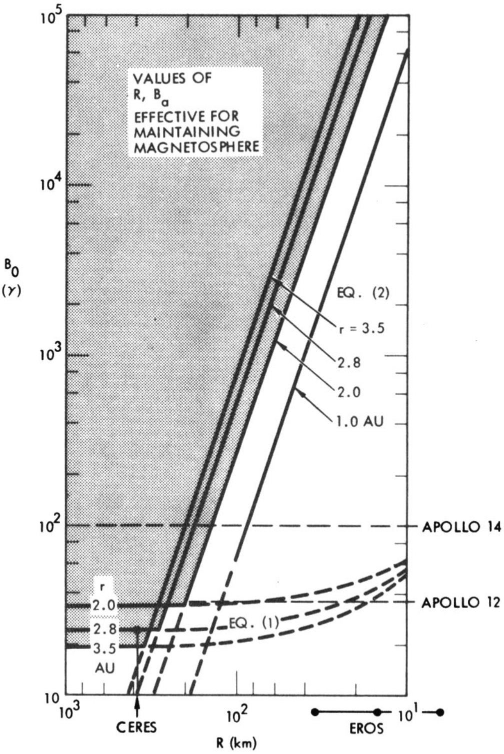

Figure 3.–Dependence of minimal equatorial dipole surface field B_0 on assumed asteroidal radius R (curves), defining values of R and surface field B_a (shaded) capable of maintaining magnetosphere. Local fields measured by Apollos 12 and 14 indicated at right; radii of Ceres and Eros at bottom. R increases to the left.

Ceres and to Eros, a proposed destination for an asteroid mission, are indicated at the bottom of the figure. The range of dimensions of ellipsoidal Eros was obtained from Roach and Stoddard (1938). The lines designated Apollo 12 and Apollo 14 will be discussed in a later paragraph.

The scale of minimal fields B_0 covered in figure 3 is well within the range found for naturally occurring objects on Earth and in the solar system. Minimal surface fields as low as a few tens of gammas are sufficient to form an identifiable magnetic cavity around the largest asteroids. Fields on the same order as Earth's, $B_0 = 50\,000\gamma$, on the other hand, would be necessary for bodies of radii a few tens of kilometers to maintain magnetospheres against the pressure of the undisturbed solar wind at normal asteroid distances. The requirement on Eros' field is somewhat more lenient because of its smaller semimajor axis, but depends on which dimension is chosen to represent it in this application. In any case, minimal surface fields above 1000γ to $10\,000\gamma$ do not seem so unlikely that asteroids of radius 20 to 30 km or less should be excluded from consideration as magnetically potent objects on the basis of B_0 alone. Larger bodies are perhaps more easily envisioned as likely to display the small surface fields required of them, however.

RELATIONSHIP TO EVIDENCE OF EXTRATERRESTRIAL MAGNETIZATIONS

Equivalent Magnetization

In the preceding paragraphs, specification of fields was limited to "surface" values. Induced fields involving plasma sheaths or conducting materials are, of course, potential sources of B_a. For this discussion, however, the source of B_a will be attributed to hypothetical asteroidal magnetization to relate B_a directly to lunar and meteoritic measurements. In this context, minimal equivalent uniform magnetizations for spherical asteroids having radii corresponding to the B_0 curves for $r = 2.8$ AU in figure 3 run between 6×10^{-5} and 2.5×10^{-1} emu/cm^3. At an assumed density of 3 g/cm^3, magnetizations might also be expressed as 2×10^{-5} to 8.34×10^{-2} emu/g. Because many asteroids are apparently not spherical, these figures can only serve as order of magnitude approximations.

If the conditions on B_0 are thought of in terms of equivalent magnetization, what are the prospects that these conditions will be met by any asteroid? The evidence on which to base an answer to this question is sparse, being limited to a few data on meteoritic and lunar materials.

Meteorite Magnetizations

Magnetic characterizations of meteoritic material have led to the inference that the samples examined had been naturally magnetized in fields of extraterrestrial origin. Remanences of several samples of about 5×10^{-5} to 4×10^{-3} emu/cm^3 were attributed by Lovering (1959) to cooling in the presence of a magnetic field. Stacey et al. (1961) investigated the thermomagnetic properties of chondritic meteorites and concluded that measured magnetizations resulted from cooling in extraterrestrial fields of 0.15 to 0.9 Oe. Additional results of a similar nature were reported by Stacey and Lovering (1959). The source of meteorite magnetizations was credited by the authors to cooling in the crust or mantle of a primary meteorite body with a fluid core generating an appreciable field much like Earth's. Insofar as the results cited apply to material that may be representative of objects in the asteroid belt, the presence there of small planetary bodies with magnetizations comparable to those required for minimal magnetospheres is not ruled out and would be consistent with the meteorite data.

Apollo Measurements

Direct measurements of local, steady magnetic fields have been made on the lunar surface with magnetometers carried by Apollos 12 and 14. Preliminary results from Apollo 14 indicate that a field of 100γ was detected, but data were insufficient for determining the extent or character of the source (Palmer Dyal, personal communication). Apollo 12's ALSEP magnetometer, self-contained and more elaborate than Apollo 14's, gave steady readings in the neighborhood of 36γ, together with gradient measurements that have been analyzed in some detail. The steady field was attributed to a source of moment between 1.4×10^{14} and 1×10^{23} γ-cm^3 located from 0.2 to 200 km from the apparatus (Dyal, Parkin, and Sonett, 1970).

The horizontal lines in figure 3 are entered at the appropriate field levels for the Apollo 12 and 14 results. The Apollo 12 measurement is shown as a line running from $R = 200$ km to small values of R beyond the edge of the graph. The Apollo 14 measurement is drawn as a dashed line across the graph because no dimensional inferences are available. The Apollo 12 field value is 50 percent larger and the Apollo 14 value four times larger than the B_0 that would be needed to give Ceres a distinct magnetosphere. The Apollo 14 field is, in fact, about double the stopping field at the subsolar point of Earth's magnetopause. The Apollo 14 field, in contrast, is a factor of 30 smaller than the B_0 necessary for Eros to balance the solar wind magnetically, even if its size were taken as large as 35 km. Neither result provides a combination of R and B_a unambiguously inside the shaded region. On the other hand, neither result is confined to combinations of R and B_a so far from the minimal curves of the shading boundary as to make later discovery of admissible combinations highly improbable, at least for asteroids of dimensions above 100 km. Eros would not be a candidate for magnetic opposition to the solar wind, based on these figures.

Lunar samples returned to Earth by Apollo 11 have been tested in the laboratory for their magnetic properties. A variety of results was described by numerous authors in the Moon issue of *Science* (Abelson, 1970). Of importance to this discussion was the measurement of a remanent magnetization of one breccia sample of 2.8 × 10^{-3} emu/g (Strangway, Larson, and Pearce, 1970), attributable to ancient cooling in the presence of a field comparable to that of Earth and substantially within the range of equivalent minimal magnetizations imposed by the curves of figure 3.

The origin of the onsite fields on the Moon and of returned sample magnetizations in lunar samples is unsettled. Interpreted at face value, the levels of field and magnetization recorded so far are on the order of those that could support the establishment of well-defined magnetic envelopes around the larger asteroids of radii greater than about 100 km.

SOLAR-WIND INTERACTION

Magnetospheric Interaction

A full-scale asteroidal magnetosphere will interact with the solar wind in a familiar way and should be detectable by conventional spacecraft magnetometers, although a close flyby will be necessary (Greenstadt, 1971). The interaction would include generation of a plasma shock ahead of the body and a magnetic tail downstream. The latter might be the most reliable indication of the existence of an asteroidal magnetic field, for a mission of limited target capability, because it would extend considerably behind the asteroid and be detectable much further from the body than would the magnetosphere proper. Transient components of Explorer 35's magnetometer measurements in the lunar wake have been attributed to the effect of asteroid-sized deposits of fossil magnetism on the Moon's surface (Binsack et al., 1970). The distance at which Explorer 35 detected these fluctuations behind the assumed lunar anomalies is equivalent to 5 to 10 Ceres radii and 20 to 40 radii of a 100 km asteroid.

Magnetospheric interaction would not be confined to simple exclusion of the solar wind from a magnetic cavity, but would include the generation of plasma waves and electromagnetic noise that would also be detectable far from the body.

Submagnetospheric Interaction

Fields less than those required for maintaining magnetospheres might still perturb the solar wind sufficiently to create measurable wave signals, as discussed by Greenstadt (1971). This type of "submagnetospheric" interaction seems the most probable, because the uniform magnetization of entire asteroids, especially the larger ones, that would be necessary to satisfy the stated conditions on B_0 would be an unjustified assumption. The convenient assumptions of dipolar fields and axes normal to the solar wind are also unlikely. Especially interesting prospects would be the presence of a severely tilted or displaced dipole or a field of multipole origin in a body of nonuniform magnetization, or perhaps inhomogeneous conductivity. A hovering rendezvous spacecraft might record a complex magnetic signature as the asteroid rotated in the solar wind nearby. A magnetometer might thus serve as an important advance guide to favorable locations on the asteroid for collection of the most scientifically useful samples. Correlation of magnetic signature with optical appearance and other physical characteristics of the asteroid might yield definitive inferences on how it was formed. The question of how various combinations of asteroid features, including detectable magnetic fields and noise wakes, or even miniature magnetospheres, might relate to asteroidal formation is a suitable subject for further study. There seems to be no reason at present to believe that measurements made by a sensitive magnetometer borne to the neighborhood of an asteroid will prove less valuable than the many measurements made by similar instruments carried by spacecraft to numerous other destinations in the solar system.

CONCLUSION

The fields demanded by theory in order that the larger asteroids support a magnetic interaction with the solar wind are compatible with fields found associated with extraterrestrial objects. Steady fields detected by Apollo magnetometers on the lunar surface are comparable to equatorial fields with which the largest asteroids could support small magnetospheres. Magnetizations found in meteorites and in material from the lunar surface could, if duplicated in the bodies of the few asteroids of radius greater than 100 km, maintain magnetic cavities, or, more probably, multilobed magnetic cavities around these small planets. It would be worthwhile to conduct a theoretical investigation in advance of an asteroidal mission to determine the extent to which magnetic measurements at an asteroid might serve to distinguish among models of asteroidal origin.

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