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Citation: AIP Conference Proceedings **370**, 929 (1996); doi: 10.1063/1.50597
View online: http://dx.doi.org/10.1063/1.50597
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/370?ver=pdfcov
Published by the AIP Publishing

THEORY OF SHOCK MAGNETIZATION OF ASTEROIDS GASPRA AND IDA

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The observed magnetism of asteroids such as Gaspra and Ida (and other small bodies in the solar system including the Moon and meteorites) may have resulted from an impact-induced shock wave producing a thermodynamic state in which iron-nickel alloy, dispersed in a silicate matrix, is driven from the usual low-temperature, low-pressure, α, kaemacite, phase to the paramagnetic, ϵ (hcp), phase. The magnetization was acquired upon rarefaction and reentry into the ferromagnetic, α, structure. The degree of re-magnetization depends on the strength of the ambient field, which may have been associated with a solar-system-wide magnetic field. A transient field induced by the impact event itself may have resulted in a significant, or possibly, even a dominant contribution, as well. The scaling law for catastrophic asteroid impact disaggregation imposes a constraint on the degree to which small planetary bodies may be magnetized and yet survive fragmentation by the same event. Our modeling results show it is possible Ida was magnetized when a large impact fractured a 125±22 km-radius proto-asteroid to form the Koronis family. Similarly, we calculate that Gaspra could be a magnetized fragment of a 45±15 km-radius proto-asteroid.

INTRODUCTION

Magnetism of the Moon and other small bodies in the solar system has been a controversial topic (see, *e.g.* (1, 2)), and has only become more interesting since the recent flybys of the asteroid 951 Gaspra and the larger asteroid 243 Ida by the Galileo spacecraft, which have found that both of them may be sufficiently electrically conducting so as to perturb the interplanetary magnetic field, or they are magnetic (3). Ida is a member of the Koronis family, a group of asteroids with similar eccentricities and inclinations which are thought to all be the post-collision fragments of a single proto-asteroid. Here we present a quantitative model evaluating the extent of magnetization by hypervelocity impacts–one of a few magnetizing mechanisms previously suggested–using phase diagrams of magnetic minerals, shock and post-shock temperature calculations, and a fracturing model by Housen *et al.* (4). We conclude pressure-induced structural changes are responsible for magnetization of low-porosity rocks; Impacts are generally incapable of magnetizing a planetary body throughout, but impact magnetization may offer a valid explanation for small magnetic asteroids like Gaspra or Ida which are thought to be impact fragments of larger bodies.

SHOCK-INDUCED MAGNETIZATION

We first study metallic iron embedded in a silicate (lunar rock, as described in (5)) matrix. Shock temperature calculations are shown with iron's phase diagram in Fig. 1. Three distinct magnetization mechanisms are possible in different shock pressure-temperature regimes:

1. If the Hugoniot in P-T plane crosses the Curie point at pressures between 0 and about 1.75 GPa (Fig. 1), natural Curie-point writing occurs during or after being shock-heated to above the Curie temperature (1043K for pure iron at 1bar). The phase change is second order. This mechanism requires intensive shock heating and only occurs upon shocking silicate iron-bearing rocks that are less than ~40% of crystal density.

2. If the Hugoniot crosses the phase boundary between (1.75 GPa, 1043 K) and the α-ϵ-γ triple point at (11.0 GPa, 750 K), iron undergoes a first order phase transformation from ferromagnetic body-center-cubic (bcc) structure (α phase) to paramagnetic face-center-cubic (fcc) structure (γ phase) (6, 7). When on the release of pressure the system returns through the phase boundary, the reverse transition occurs and the material becomes stably magnetized. Silicate rocks with between 40 to 80% of crystal density containing kaemacite can be magnetized via this method.

3. Shocked silicate rock with greater than ~ 80% crystal density may be magnetized upon the crossing of the Hugoniot with the α-ϵ phase boundary (between the α-ϵ-γ triple point and (273 K, 14 GPa)). The high pressure ϵ phase has hcp structure and is paramagnetic. The transition pressure is slightly temperature dependent (from about 14 GPa at room temperature to about 11 GPa at the triple point), but can be taken to be approximately 13GPa.

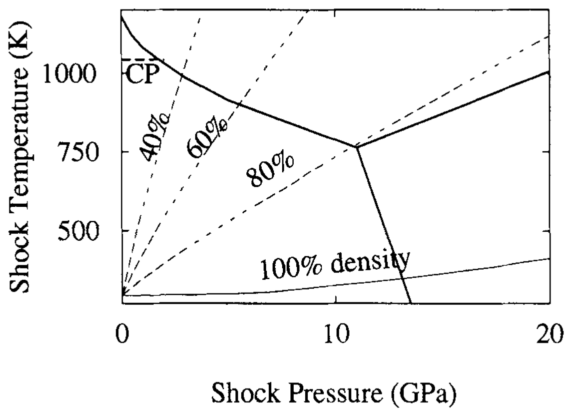

FIGURE 1. Shock temperatures vs. shock pressure of gabbroic anorthosite of different porosity values. "100% density" is 2.936 g/cm^3. Iron phase diagram is superimposed to demonstrate different transitions at different porosities. The dashed line with the label "CP" is the Curie temperature of iron.

Similar calculations have been conducted for more realistic magnetic carriers, *e.g.*, kaemacite (FeNi) and magnetite (8). Although they have different Curie temperatures and phase diagrams than those of iron, the conclusion remains that phase changes at relatively low pressures (<20 GPa) are a major shock magnetization mechanism.

From the Holsapple-Schmidt scaling of planetary impacts (9), the radius inside which the target is shocked above the threshold pressure (hereafter called magnetization radius) can be obtained for various impact conditions.

FRAGMENTATION OF ASTEROIDS

An important question is whether the proto-asteroid can remain largely integral and yet be driven to a sufficient shock pressure when it is shock-magnetized. Housen *et al.* (4) developed a catastrophic fragmentation (CF, defined as when the largest fragment mass is equal to one-half of that of the original target) threshold based on dimensional analysis and laboratory fragmentation experiments. The ratio of the largest fragment mass (M_L) to the total proto-asteroid mass (M) is given by:

$$\frac{M_L}{M} = F'\left(\frac{Y_t + \sigma_G}{\sigma_I}\right) \qquad (1)$$

where Y_t is the material fracture strength, σ_G is the lithostatic stress, and σ_I is impact-induced tension. The above equation suggests lithostatic stress has the effect of strengthening the target, which was demonstrated in Housen *et al.*'s hydrostatically loaded fragmentation experiments (4).

The function $F'(x)$ has the form:

$$F'(x) = 1 - 2^{3\mu/2-1}K'x^{-3\mu/2} \qquad (2)$$

where μ is a measure of shock wave attenuation in the target material (μ=0.4 for sand, 0.55–0.6 for rock), K' is an experimentally determined constant ($\sim 2.4 \times 10^{-3}$).

CONCLUSION

At a given impact velocity and target size, there is a maximum impactor size above which the proto-asteroid is fragmented catastrophically. The radius of magnetization at this impactor size is the limit of magnetization for the target, if it survives the impact. This limit (*vs.* impact velocity) is plotted in Fig. 2. It can be seen from the figure that it is very unlikely or impossible to magnetize an asteroid by hypervelocity impact without severely fracturing it. On the other hand, impact-induced magnetization on an unfragmented body (like the Moon) must be limited to the vicinity of impact center, and if it has been under multiple impacts, its magnetic field should have a "patchy" characteristic.

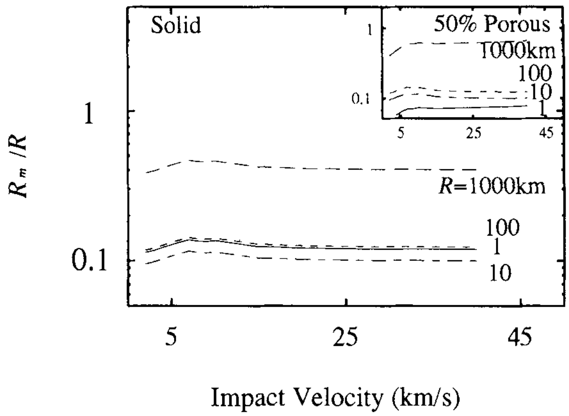

FIGURE 2. Ratio of magnetization radius (R_m) over proto-asteroid radius (R) at catastrophic fragmentation threshold for 100% density rock. Inset: same calculation for 50%-porosity rock. Calculations are done for difference proto-asteroid sizes, the radii are labeled next to the curves. All curves are below R_m/R=0.9, suggesting that the proto-asteroid is fragmented before it can be completely magnetized.

DISCUSSIONS

Assuming both Gaspra and Ida were completely impact-magnetized, we can obtain a constraint on the minimum sizes of the impactors. Then, requiring the largest fragments (from the same impact) be larger than Gaspra or Ida, lower limits on the pre-impact asteroid sizes can be set using Equation 1 (Fig. 3). At 5 km/s impact velocity, which is about the most probable in the asteroid belt, we obtained that the proto-Gaspra body was at least 45±15 km and the impactor at least 7.6±0.8 km in radius; For Ida, the minimum radii for parent body and impactor are 125±22 and 27±2 km respectively.

Based on geometrical considerations, the estimated minimum radius of the parent body of the Koronis family (of which Ida is a member) is 45 km to 56 km (10, 11). Considering the numerous uncertainties, especially the importance of frag-

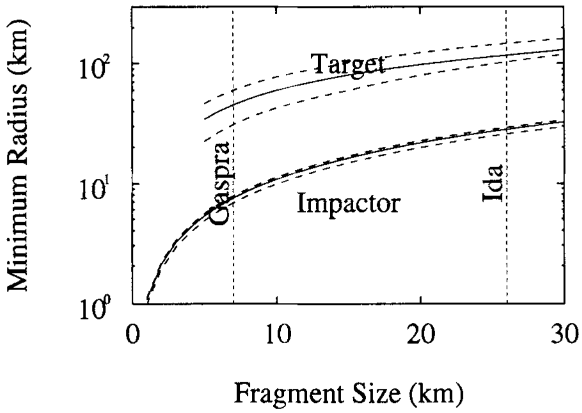

FIGURE 3. Dependence of minimum radii of impactor and pre-impact body on size of the final magnetized fragment, for a given impact velocity of 5 km/s. The dashed lines are obtained by varying target strength and density to determine uncertainty of the model. The minimum radius of impactor is calculated such that R_m is twice the fragment radius.

ment reaccumulation after break-up, we suggest that the present analysis allows, but does not prove, Ida could have been magnetized when a large impact fragmented a proto-asteroid to form the Koronis family.

ACKNOWLEDGMENTS

Research supported by NASA Grant NAGW-1941. Contribution #5592, Division of Geological and Planetary Sciences, California Institute of Technology.

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