HYPERVELOCITY IMPACTS AND THE MAGNETISM OF SMALL BODIES IN THE SOLAR SYSTEM

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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]. Here we present a quantitative model evaluating the extent of magnetization by hypervelocity impacts–one of a few magnetizing mechanisms previously suggested–using shock and post-shock temperature calculations and a fracturing model by Housen and Holsapple [4]. We conclude 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.

When rocks are shock heated to temperatures higher than the Curie point of their embedded ferromagnetic metals, and then cooled down through the Curie point, they can be magnetized strongly by the magnetic field that may present at the time. We calculated the shock and post-shock temperature as functions of shock pressure using the Tillotson equation of state for lunar rock [5] at several initial porosities. For solid rock, the needed shock pressure is about 50 GPa; for rocks of 50% porosity, the pressure is lowered to less than 10 GPa. From the Holsapple-Schmidt scaling of planetary impacts [6], the radius inside which the target is shocked above the threshold pressure in various impact conditions are obtained and shown as solid lines in Figure 1.

An important question in the model is whether the target can remain largely integral when it is shock-magnetized. Housen and Holsapple in [4] developed a catastrophic fragmentation (CF, defined as when the largest fragment mass is half that of the original target) threshold based on dimensional analysis and fragmentation experiments in the strength regime. The threshold was then extrapolated into the gravitational regime by replacing the impact-induced tensile stress (σ_{I}) with that in excess of the gravitational stress ($\sigma_{\mathrm{I}} - \sigma_{\mathrm{G}}$). A slightly relaxed threshold was given for larger bodies where fragments could reaccumulate under their own gravity. The fragmentation and reaccumulation limits for 1, 10, 100 and 1000 km-radius, solid or porous targets are shown in Figure 1 as broken lines. The magnetization zone is always within the CF limit, therefore our model predicts the target cannot be magnetized by an impact without breaking up. 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.

We further developed the model by Housen and Holsapple to predict the mass of the largest fragment when the impact is not at the CF threshold. The equation we used is:

$$\frac{M_{\mathrm{L}}}{M} = 0.5 \times \left[\frac{\sigma_{\mathrm{F}}}{\sigma_{\mathrm{I}} - \sigma_{\mathrm{G}}}\right]^{\beta} \tag{1}$$

where σ_{F} is the fracture strength at the prevailing strain rate, β is a constant and is determined from laboratory experiments in the strength regime ($\sigma_{\mathrm{G}} = 0$). Another change we made from [4] is that we included the depth-dependence of the lithostatic stress σ_{G}:

$$\sigma_{\mathrm{G}}(r) = \frac{2\pi}{3} G\rho^2 (R^2 - r^2) \tag{2}$$

Assuming both Gaspra and Ida were impact-magnetized, and they are remanent fragments from the same impacts that magnetized them, we can obtain a constraint on the minimum sizes of the impactors. Then, requiring the largest fragments be larger than Gaspra or Ida, lower limits on the pre-impact asteroid sizes can be set using Equation 1. 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 91 km and the impactor at least 7.4 km in radius; For Ida, the minimum radii for parent body and impactor are 330 and 27.5 km respectively. The impactor radius is a strong function of impact velocity, while the parent body radius is almost constant with regard to impact velocity.

Based on geometrical considerations, Gradie *et al.* estimated the minimum radius of the parent body of the Koronis family should be 45 km [7]. Our minimum parent body radius reduced only by about a factor of 2 (to 138 km) when we artificially made its fracture strength 10^3 times the normal value in the calculations, therefore the reason for the surprisingly small size of the proto-Ida asteroid cannot be its strength. The present analysis thus suggests that if Gaspra and Ida are fragments from the impact on a protoasteroid and this impact magnetized them, their parent bodies had to have radii greater than 91 and 330 km, respectively. Or, the possible magnetization of these objects is unrelated to the impact process which created them from larger proto-asteroids.

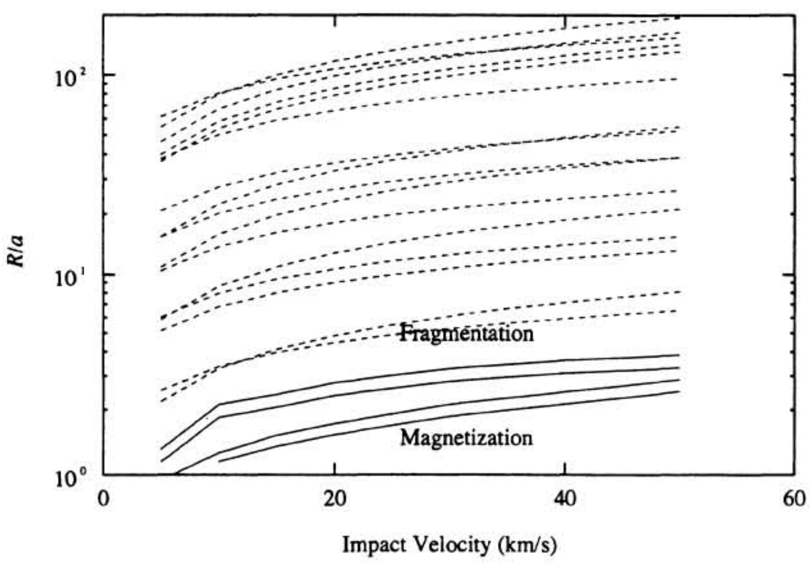

Fig. 1: Magnetization radius (solid lines) and catastrophic fragmentation threshold (broken lines) R, normalized to impactor radius a, plotted as functions of impact velocity. The four solid lines correspond to shock temperature or post-shock temperature based calculations for porous or non-porous rock; the 16 broken lines are fragmentation or gravitational reaccumulation thresholds for R=1, 10, 100 and 1000 km, porous or nonporous rock. The target will be magnetized if R/a lies below the solid lines; it will be fragmented if R/a is above the broken lines. All broken lines are above solid lines, meaning a planetary body cannot be totally magnetized while remaining integral.

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