The Deflection of Menacing Rubble Pile Asteroids.

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Introduction: For a couple of decades now, researchers have taken seriously the notion that impacts on the earth of large asteroids or comets has occurred in the past, and will, without active intervention, occur again; with devastating affects on the earth and all living creatures. About ten years ago, researchers [1,2,3] suggested and studied a number of ways that an asteroid could be diverted from an impending collision with the earth by pushing it sufficiently to change its course, making it miss the earth.

The methods envisioned included the use of nuclear explosives, the impact by large masses at high velocities, the blowing off of material by either the concentration of solar energy using giant mirrors or by zapping it with lasers, and more mundane methods such as simply attaching a propulsion device or throwing dirt off at sufficient velocity to escape the asteroid. Among the methods suggested, it is generally accepted that with only a very short warning time, such as a few years, only the nuclear bomb approach would work.

The analysis of the various methods relies on data accumulated for cratering, disruption and material properties of terrestrial materials. In most cases those are for silicate materials with mass densities of 2-3 g/cm^3. However, it is becoming generally accepted that many of the asteroids are re-accumulated rubble pile bodies of very low density and strength. The comets are certainly thought to have that structure. Therefore, I report here some initial studies of the effects of a low-strength porous structure on the various mitigation methods.

Background:

Modeling of porous materials. Various models of the thermodynamical behavior of porous materials were developed several decades ago, in response to interest in porous materials as a method to protect weapons systems from the damaging influences of the x-ray deposition from nuclear bombs. One of the most used is the "p-alpha" model developed by Walter Herrmann at Sandia. It is a component of the Sandia WONDY and CTH wave codes which are used by many in the planetary impact community.

The mechanical behavior of the model is essentially the same as an elastic-plastic model, but for the dilatational (pressure-volume) component, not the deviatoric shear component of plasticity theories. The model assumes that the material is comprised of small particles of normal 'solid' density $\square_{solid}$ (say about 3 g/cm^3) separated by intervening pore spaces. That gives a net mass density of a lower value $\square_{porous}$. The ratio $\square_{solid}/\square_{porous}$ is the parameter $\square$, the distension ratio . Then, as pressure p is applied, the material permanently crushes to a larger density as the pores collapse. That crush behavior is defined by a curve of $\square$ versus pressure p. If the pressure is removed, there is a small elastic recovery, but no change in the permament crush.

The thermodynamic assumptions are that the internal energy is contained in the solid particles, so that the energy per unit mass of the solid particles and the porous material are the same. The pressure of the porous material is a factor 1/$\square$ of the pressure of the solid particles.

Inherent in this model is the assumption that this crush behavior is instantaneous. That is a consequence of the assumption that the particles are small, so that the time scale of pressure equilibrium of the particles is negligible compared to time scales of a problem. For larger particles, this model would not be appropriate.

Experiments in porous materials. Few experiments have been made of impacts into highly porous, low strength materials. There are those reported in [4] for moderately porous materials, and, more recently, those by Housen [5] and Housen and Holsapple [6], and those by Dan Durda [7] in highly porous materials. One should note the wide range of results these investigations produced, because there are many different types of 'porous materials'. In [4], the results by Shultz are not different in nature from those for conventional materials: craters form primarily by excavation. Shultz assumes that conventional gravity scaling defines extrapolations to low gravity. In [6] craters are also formed, but mostly by compaction, not by excavation. Strength scaling is found for low gravity. Durda, in [7] shoots projectiles entirely through open-pore foam materials with no cratering at all, but at an impact velocity lower than those of interest.

Consequences for mitigation: The effects of porosity are primarily due to a very low strength, and due to the energy absorption properties of a crushable material. For that reason, there is little affect on the 'low force, long time' methods such as mass drivers and propulsive methods. The only issues for those methods would be the difficulties of anchoring devices on a very low strength regolith. The focus here is on the impulsive methods, which are discussed in turn.

Impact Methods. The deflection of an asteroid by an impactor is a result of the momentum transferred to the target asteroid by the impact of a mass at a high velocity, several tens of km/sec. The velocity of the asteroid need change by only a few cm/sec to make it miss the earth, if it is done a decade or so before an impending impact with the earth [1]. For an impact into most materials, a large amount of ejecta is thrown out as a crater forms. Some of that ejecta will re-impact the asteroid, and some will escape into space. There is no net change in momentum of the asteroid from the ejecta that re-impacts, but there is a contribution from the ejecta that escapes. Further, on a 10 km asteroid the escape velocity is only a few m/s, so most of that ejecta escapes. Thus, the total momentum change of the target asteroid is that of the impactor, plus that of the ejecta that escapes.

The momentum transferred from the impactor is simply its mass *m* times its velocity *U*. The most direct way to calculate the momentum of the ejecta is from a plot from experiments of the velocity of the ejecta versus the mass of that ejecta. The figure 1 shows such a plot, it is a scaled plot of the mass of ejecta with speed greater than a velocity *v* versus that velocity *v*.

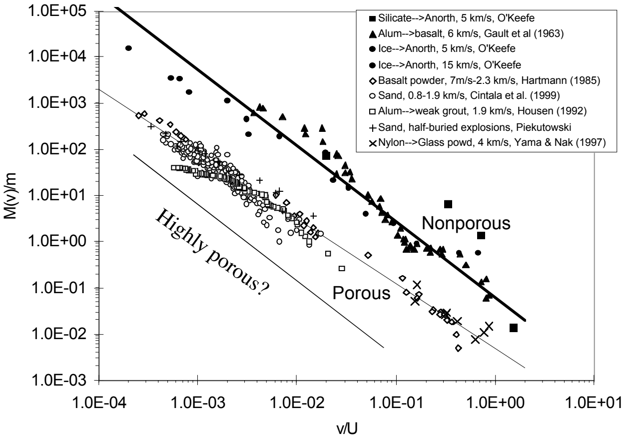

Figure 1. The mass of ejecta with velocity >*v* as a function of *v*, from experiments and calculations. The ordinates of the points at the left approach the total crater mass due to excavation. Plotted in this scaled way, the data for all non-porous materials are on one curve, and the data for the moderately porous materials on another. Results for velocities for very porous materials have not been obtained, but the component of excavation has been determined to be very small for those materials [4]. A possible line for those materials is also indicated.

Without describing the details, the momentum of the ejecta can be determined from this plot. For the curve labeled 'non-porous', the result is about *13 mU*, or *13* times the momentum of the impactor. (The fact that impacts into non-porous materials impart a momentum change that is many times that of the impactor is called 'momentum multiplication') On the other hand, for the curve labeled 'porous' the result is only *0.2 mU.* Adding back the impactor momentum, the total momentum change of the asteroid would be, in these two cases, *14 mU* and *1.2 mU*. Obviously, for an even higher porosity target, the momentum of the ejecta becomes of no consequence, and only the momentum *mU* of the impactor is transferred to the asteroid. This is a what is called a 'perfectly plastic' impact.

A direct consequence of this result is that, without the momentum multiplication factor of *14*, the mass required to change the velocity of an asteroid by *10 cm/sec* for a given impact speed increases by a factor of *14.* In [1,2,3] the mass required to deflect a *1 km* asteroid with an impact velocity of *10 km/s* is estimated to be from *200* to *1500 tons*. The integration of the upper curve of figure 1 gives *700 tons*. Then, for a porous asteroid, these masses get multiplied by a factor of *14,* to give a requirement of about *10 kt* mass, an unreasonably large number to deliver to the asteroid, at least for a single impact.

Surface or subsurface Nuclear Exposions. I know of no calculations or experiments for explosions in highly porous materials. While there are numerous experiments for cratering by explosives in dry sands, those sands do not have the low crush strength that produces large compression craters and the small amounts of ejecta compared to the highly porous materials. However, there are experiments for impacts into low strength, highly porous materials [6], and it is commonly thought that there is a close analogy between impacts and explosives buried a small distance under the surface. Therefore, as a crude estimate, the explosive methods might also be decreased in efficiency by a factor of *15* or so. In [1] it is determined that to deflect a *1 km* asteroid by a surface-burst nuke would require a *90 kt* device. If this is increased by a factor of *15*, it would then require a megaton device for a *1 km* asteroid, and a gigaton device for a *10 km* asteroid. A gigaton in a single device is larger than ever developed, and larger that most would think is prudent to develop. Clearly, much more analysis and experimentation is needed for explosions in porous materials.

Standoff nuclear explosions. There is doubt about energy deposited directly into an asteroid, because of the possibility of splitting it into two or more parts, which then still might impact the earth. Consequently, it has been suggested to use a nuclear explosion at some distance from the asteroid. The energy from the device, largely in the form of x-rays and neutrons, streams out to intercept the surface of the asteroid, heating a surface layer a few tens of cm thick almost instantaneously. That heated material will then expand, and, if it has little strength, will be blown off the surface into space. That imparts a momentum to the asteroid.

I have used the WONDY code with the p-alpha model to calculate the amount of momentum for both porous and non-porous materials. There is a dramatic change when the porosity and low strength are included. I revisited the case favored in [1] with a standoff distance of *0.4* times the asteroid radius. For a *1 km* asteroid, that required a device with a yield of

100 kt to *1 Mt*. The heated layer is *20 cm* thick, which, assuming a uniform energy deposition, attains an initial specific energy of *2* 10^9 *ergs/g*, well below the melt or vaporization energy of silicates. (For an asteroid with porosity, that depth is increased to include the same amount of heated mass.) For a solid material, the resulting pressure is about 10^{10} *dynes/cm*^{2} or *10 kbars*. However, at that same specific energy in a material with porosity, the pressure is reduced to only the crush pressure of 10^7, or *10 bars*. That factor difference in pressure of *1000* reduces the momentum imparted by the blowoff by a factor of *1000*. Therefore, the predicted change of velocity of *10 cm/s* by that device is reduced to only a negligible *0.01 mm/s*. Conversely, the device required for deflection using the standoff mode is increased by a very large factor, which would likely become unreasonably large.

This reduction in effectiveness is a direct consequence of the magnitude of the pressure that the heated layer develops when it is heated. That pressure, multiplied times a time interval equal to a transit time for a wave to travel across the heated layer, times the area of heated material, is the momentum transferred to the asteroid.

Figure 2 shows the pressure developed as a function of the energy per unit mass deposited into a heated material, both for a conventional solid material and for p-alpha porous materials. At the specific energy of *2* 10^{10}, the porous curves are about a factor or *1000* less than the solid curve, resulting in that *1000:1* reduction in transferred momentum.

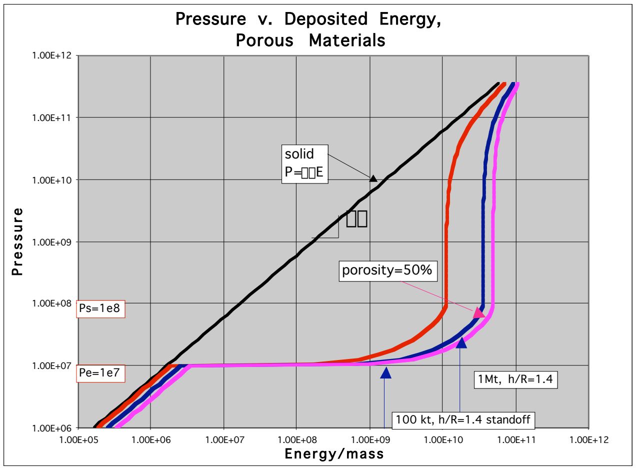

Figure 2. The pressure in a material instantaneously heated to a given energy per unit mass. Curves are for a solid material, and for porous materials with different porosity . It is assumed that crushing begins at a pressure of 10^7 dynes/cm^2 and is completed at the pressure of 10^8.

The physical reason for this large effect can be described. When a porous material is heated to give a pressure above its crush pressure, the solid particles can, according to the p-alpha model, instantaneously expand into the pore space. Even a pore space that is *10%* of the volume will allow the solid particles to expand by *10%.* A change of density of *10%* in a solid gives a reduction in pressure of *10%* of the bulk modulus, which is on the order of several times 10^{11} *dynes/cm*^{2}. Therefore, the reduction in pressure is on the order of 10^{10} *dynes/cm*^{2}, or to the crush pressure, whichever is greatest. That is almost all of the pressure originally in the solid particles. It is noted that the important property leading to that large reduction in pressure and transmitted momentum is not especially the porosity, but the crush pressure. In a material like a dry sand, the crush pressure is on the order of 10^9 so this effect is still present, but reduced to a factor of *10* or so.

Laser and concentrated solar heaters. These methods also rely on the heating of surface material with resultant blow-off and momentum transfer. However, they are different from the case of a nuclear standoff explosion in that the time scales of energy deposition may be longer, the penetration depths much more shallow, and the specific energies are high enough to vaporize material. Unfortunately, the only calculations and experiments are again for non-porous and strong materials. For example, in [2] are reported experiments using a high-powered laser focused on a basalt target. Again, I know of no experiments or calculations in highly porous materials, but they could be done fairly easily. Thus, much more analysis and experimentation needs to be done before we can consider these methods to be viable.

Summary: Porous, low-strength materials are very effective at absorbing energy. That is why they are used for packing materials and for protection from impacts. They were contemplated during the cold war as a way to protect weapon systems from x-ray deposition from nuclear weapons. It should therefore come as no surprise that it is hard to divert a porous asteroid or comet. From the estimates derived here, all of the short-time, large-impulse methods may be of questionable effectiveness. Even for a non-porous asteroid, the presence of a low porosity regolith only a few cm deep could lead to these same problems. That leaves the low force, long time methods. However, even in those cases the problems of anchoring devices to the surface may make them very difficult. If a 10 km asteroid with our name on it is discovered in the next few years, there is no method contemplated that will surely work to divert it.

A focused program of synergistic laboratory experiments and code calculations could clarify the questions raised here. Missions to asteroids and comets can determine more about their actual structure, if their surface is poked or impacted. Such progrmas must be a component of larger programs to study the issues of the mitigation of the effects of large body impacts into the earth.

There is much research to be done. “We knew a lot more about asteroids 10 years ago than we do now” [8].

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