Title:

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MATERIALS OF VARIOUS STRENGTHS**

Author(s):

Gregory H. Canavan, DDP

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Gregory H. Canavan

Similarity solutions are used to discuss impacts on asteroids of various strengths, concentrating on the voids produced, the mass ejected, and its thermodynamic and mechanical state. Numerical calculations have advantages and limitations for the next step in complexity.

It reviews relevant similarity solutions, which both provide useful interim answers and illustrate of the types of arguments used in and the results from more complicated geometries and analyses. Such a result is the limitation imposed on similarity solutions by conservation of energy and momentum, which also hold in more complex geometries. An impact or explosion at the surface of a cold gas illustrates the complexity of three dimensional interaction. It suggests a simplified model in which the expansion is spherically symmetric and conservative, which produces predictions for the thermodynamic state of material flowing out of the impact hole and for the total amount of material vaporized by the shock. That permits an estimate of the asteroid's compressive strength; an extension provides an estimate of the amount of material ejected by impact, which permits an estimate of the asteroid's tensile strength. An extension of the model provides quantitative estimates of the impact of porosity, which impacts the propagation of shocks through material.

For detailed predictions, numerical models are appropriate. They have reached a level of detail at which they can readily predict most of the phenomena seen in the vaporization phase. However, they depend on heuristic models of fracture mechanics and postulated distributions of flaws in target materials. These deficiencies cannot be eliminated by theory or calculations alone. Some amount of in situ experimentation with real asteroid materials is necessary to determine the material parameters that determine the difficulty of subsequent applications.

High speed impacts act as impulsive loads on gases or solids. While the detailed phenomena are complex, similarity solutions are available for important cases. While planar solutions are not directly relevant to impact studies, they serve as a simple illustration of the types of arguments used in more complicated geometries and the results obtained in them. Figure 1 shows the density, pressure, and velocity for a strong, planar impulsive load on a cold gas. For velocities greater than 10-20 km/s, solids unload approximately like gases, so similar profiles apply to them as well. The impulsive pressure applied produces a sharp jump in density; a strong shock, which attenuates as it propagates into the material; and a velocity profile in the direction of the shock behind it, which reverses and expands into the vacuum at negative x . For this one

dimensional problem, near-exact similarity solutions are available, which have been reviewed and summarized by Zel'dovich and Yu. P. Raizer,¹ that have the form

$$p \sim 1/M^n, \quad (1)$$

$$u \sim 1/M^{n/2}, \quad (2)$$

where p and u are the pressure and velocity behind the shock and M is the mass of material put into motion by the shock. These solutions as functions of n correspond to various values of the specific heat ratio γ .

Table I. Ratio of specific heats as function of expansion exponent n .

γ	1	1.1	7/5	5/3	2.8	∞
n	2	1.52	4/3	1.28	1.2	1.12

As γ increases, n decreases, and the shock wave is attenuated more slowly. The pressure, density, and velocity profiles are otherwise similar for various values of γ . A strong shock with $\gamma \approx 1.2$ would give $n \approx 1.4$. For $n = 2$, $Mu \approx \text{constant}$, and momentum is conserved. For $n = 1$, $p \approx 1/M$, i.e., $pM \approx \text{constant}$, and energy would be conserved. A discussion of the similarity solutions indicate that $1 < n < 2$ is necessary to conserve energy and momentum. These one dimensional similarity solutions are not pursued below because there are other solutions that better approximate impactors.

Impact or explosion at surface of a gas. Figure 2 illustrates a strong impact or explosion at the surface of a cold gas of initial density ρ . If the mass of the impactor is m , its initial velocity is u_0 , its initial energy is $E = mu_0^2/2$. If the impactor decelerates close to the surface of the target, which requires that its density be comparable to that of the target, the thermalization of its kinetic energy drives a shock out in all directions. The hole at the surface weakens the shock somewhat at the top, which produces a bowl shaped cavity. When the shock encompasses a mass $M \gg m$, the average pressure and velocity in the bowl again fall as in Eqs. (1) and (2), which specialize to²

$$p \approx (E\rho/m)(m/M)^n \approx p_0(m/M)^n, \quad (3)$$

$$u \approx \sqrt{(p/\rho)} \approx \sqrt{[(E/m)(m/M)^n]}, \quad (4)$$

Figure 3 shows the pressure and shock speed for a 10 kg, 10 km/s impactor on the surface of a $\rho = 0.001$ g/cc target, for which $n = 4/3$. The shock pressure is initially about 500 atmospheres (bars). It falls to about 20 bars, where it becomes a weak shock, when the shocked mass reaches $M \approx 100$ kg—roughly 10 times the initial impactor mass. The kinetic energy in the bowl is roughly

$$E_k \approx Mu^2/2 \approx Mp/p \approx E(m/M)^{n-1}, \quad (5)$$

Energy leaks out of the hole, so n must be greater than 1. The momentum in the bowl is

$$I \approx Mu \approx I_0(m/M)^{(n-2)/2}, \quad (6)$$

which increases with time due to the outflow of material. Thus, $1 < n < 2$, as above. Figure 4 shows the similarity kinetic energy and momentum in the bowl. The kinetic energy starts at the 500 MJ of the impactor; by the time the mass increases 10-fold, the kinetic energy falls to about 250 MJ. The momentum of the material starts at about 100 kg-km/s and slowly increases to about 300 kg-km/s as the recoil of the material ejected increases the momentum of the material remaining in the bowl.

Similarity solutions assume the shock advances in depth as $z \sim At^\alpha$, where A is a constant that can be determined in one dimension but not in three. It is possible to determine the exponent α by using the result that the mass of shocked material increases in $M \sim z^3 \sim t^{3\alpha}$ in the pressure $p \sim 1/\sqrt{M}$ to derive

$$dz/dt \sim t^{\alpha-1} \approx u \sim \sqrt{(p/\rho)} \sim 1/M^{n/2} \sim 1/t^{3n\alpha/2}, \quad (7)$$

which gives $\alpha - 1 = -3n\alpha/2$, or $n = 2(1 - \alpha)/3\alpha$. For a strong shock $\gamma = 7/5$, this similarity solution gives $n = 4/3$, or $\alpha = 1/3$, which implies that $M \sim t$ and $z \sim t^{1/3}$. For the 10 kg impactor assumed in the illustration above, the thermalization time is about $(m/\rho)^{1/3}/u \approx 0.1$ ms, so the shock becomes weak after about 1 ms, at which time the radius of the hole has expanded to about $(10m/\rho)^{1/3} \approx (10 \times 10 \text{ kg} / 10^{-6} \text{ kg/cc})^{1/3} \approx 400$ cm.

These analytic solutions are useful in indicating how the pressure, density, and velocity vary with position and with gas dynamic variables, but they do not take into account the detailed flow field within the bowl, for which a more detailed solution is required. There are a few similarity solutions for special cases, and a few detailed numerical solutions for specific cases of interest. The next section discusses the former; a later section summarizes the latter.

Two dimensional results. In contrast to the near-exact similarity solutions for planar expansions, the similarity solutions of the partial differential equations for the two-dimensional problem of the impact of a small object on a large one are difficult and approximate. However, the principal trends largely correspond to those from the idealized results discussed above. For example, in the solution for $n = 1.07$, or $\gamma = 1.205$, which is appropriate for high-speed impact, it is found that the hole at the top of the bowl, which roughly spherical, is large, but that only about 1.6 percent of the mass escapes through it. That is largely because the density in the hole is only $\approx 0.02 \rho$, which means the shock remains strong, resembling an explosion within an infinite material. Conversely, the density of the material at the bottom of the bowl is $\approx 10.3 \rho$, which is approximately the value expected from a strong shock. These results are only approximate, but they do not vary strongly with γ , which indicates that the flow field in the bowl is but weakly sensitive to gas dynamic parameters and hence should not be strongly dependent on the details of

impactor material and geometry. Of particular importance is the result that the energy loss out of the hole is not large.

High speed impact on solids. This suggests a simplified model of high speed impact that uses the similarity results that the underground cavity is roughly spherical and that energy losses out of the hole are small, which produces a model in which expansion is taken to be spherically symmetric and conservative. It is, however, necessary to extend these models to incorporate the thermodynamic strength of the target material. If the impactor's initial mass and speed are m and v , its initial energy is

$$E = mv^2/2. \quad (8)$$

Symmetry and conservation imply $n = 1$ or

$$p \sim 1/M, \quad (9)$$

$$\epsilon \approx E/M, \quad (10)$$

and $2(1 - \alpha)/3\alpha = n = 1$, or $\alpha = 2/5$ and $z \sim t^{2/5}$. The shock vaporizes the material it passes over as long as its strength satisfies $\epsilon_k \geq KU$, where U is the heat of vaporization, which is about 10^{11} erg/gm for rock, including dissociation, and $K \approx 10$ is the factor by which the shock strength must exceed U to produce vaporization on unloading. The amount of rock vaporized is set when the energy density behind the shock falls to $\epsilon_k \approx E/M_k$ to be $M_k \approx E/\epsilon_k \approx m(v^2/\epsilon_k) \approx m(v/v_k)^2$. For rock, $v_k \approx \sqrt{(10 \times 10^{11} \text{ erg/gm})} \approx 10 \text{ km/s}$. If $v \approx 10v_k$, the amount of material vaporized is about $100m$, but due to the quadratic dependence of vaporized mass on impactor velocity, if the velocity fell to v_k , the amount of material vaporized would fall to about m .

Figure 5 shows the amount of material vaporized by a 10 kg impactor as a function of v from 10 to 100 km/s for $U = 1, 10$, and 100 MJ/kg, which represent typical carbonaceous or cometary, rock, and iron asteroids, respectively. For iron, little material would be vaporized below about 50 km/s. For stone, about as much rock as impactor would be vaporized at about 15 km/s. For carbonaceous or cometary material, about 10 times the impactor mass would be vaporized at 15 km/s. Most asteroids that are targets of opportunity are stony; only a few percent of them are metallic. Thus, it is likely that an experiment would be on a stone asteroid at a closing velocity of 10-15 km/s, which is not likely to evolve a mass of vaporized material much larger than that of the impactor. Although it would require considerable additional speed to get out of this low-vapor regime, it would be useful to trade kinetic energy of a large impactor for a higher velocity of a small impactor, if possible.

An essential difference between the gas dynamic solutions of the previous sections and those of Eqs. (9) and (10) is the greatly different time scales involved. In the impact on a gas, the energy density is initially thermalized over a volume $(m/\rho)^{1/3} \approx 200 \text{ cm}$, which occurs over a time scale $\approx 200 \text{ cm} / 10 \text{ km/s} \approx 0.1 \text{ ms}$. The resulting shock becomes weak in about twice that time, when its radius has expanded to about $\approx 400 \text{ cm}$ and its volume has increased 10-fold.

In the impact on a solid, the mass density is already that of the target, so thermalization is immediate. The initial shock is strong, on the order of $\rho v^2 \approx 1 \text{ g/cc} \times (10^6 \text{ cm/s})^2 \approx 1 \text{ Mbar}$ for a 10 km/s impactor, but as soon as its diameter expands about a factor of two, the shock drops below the energy for vaporization. The time for that is about the diameter of the object divided by the sound speed, or $\approx 10 \text{ cm} / 10^6 \text{ cm/s} \approx 1 \text{ microsecond}$. Thus, the overall phenomena in impacts on gases and solids are similar, but the time scales for the latter are compressed by about the ratio of their densities.

Pulverization. Even after the shock is too weak to continue vaporizing material on unloading, it can still evolve chunks of pulverized material as long as the stress in the unloading wave exceeds the tensile strength of the target material. The magnitude of the effect can be bounded roughly by estimating the mass at which the shock strength falls below the tensile strengths of the asteroid materials, which are on the order of tens to hundreds of atmospheres. By analogy to the previous section, the amount of rock pulverized is roughly

$$M_p \approx E/\epsilon_p, \quad (11)$$

where ϵ_p is the specific energy for pulverization set by the structural flaws in the target material. It is possible to use instead the empirical relationship³

$$M \approx 0.5m(\rho/\rho_i)(\rho v_i^2/Y)^x, \quad (12)$$

where ρ_i and v_i are the density and mass of the impactor, ρ is the density of the target, and the empirical exponent $x \approx 0.7$. For $\rho = \rho_i$ and $x = 1$, Eq. (11) reduces to $M \approx m v_i^2 / 2(Y/\rho)$, which is equivalent to the simpler Eq. (10).

Figure 6 shows the variation of M with strength for $Y = 1, 30$, and $1,000 \text{ bar}$, i.e., cometary, carbonaceous or stony, and metallic asteroid material. The metallic object would release about 500 kg, or 50 times the mass of the impactor at 10 km/s. The amount would increase to about 10 tons at 100 km/s. The carbonaceous or stony material would release about 1,000 to 200 tons. The cometary material would release 100 to 2,000 tons. The amount of mass removed by pulverization is greater than that removed by vaporization by about a factor of $M_p/M_k \approx E/\epsilon_p / E/\epsilon_k \approx \epsilon_k/\epsilon_p \approx KU/Y \approx 10 \times 10^{10}/10^8 \approx 10^3$, which should produce a much larger velocity signature. However, this larger amount of material will evolve at a much later time and lower temperature. The pulverized material will not be strongly shock heated; thus, it may have low opacity and little optical signature. Thus, inferring quantities of interest from the pulverized material will require special attention. That would appear justified because the amount of material ejected is inversely proportional to the asteroid strength Y , which is one of the key parameters to be measured.

Impact on porous materials. Porosity has a major impact on the propagation of shocks through material. It is thought that asteroidal materials have low porosity because the samples recovered have low porosity. However, that could be an artifact of sampling, if only pieces with

low porosity have sufficient strength to survive transit of the Earth's atmosphere. Thus, it would be useful to have an in situ measurement of the porosity of the whole asteroid as it would have to be engaged in space.

Material porosity is important because it significantly reduces the amount of material vaporized, which rapidly attenuates the shock. It does so because the collapse of the voids creates a two part Hugoniot curve, which converts shock kinetic energy into internal energy that is not available to maintain the shock. That process is described in a number of sources. The discussion below covers only the essential results, which are that a material with porosity on loading of⁴

$$k = dp/p, \quad (13)$$

expands as in Eqs. (3) and (4) with a mass exponent

$$n = (1 + \beta)/\beta, \quad (14)$$

where

$$\beta = 3/(k + k^{2/3} + k^{1/3}). \quad (15)$$

Figure 7 shows β and n as functions of k . For $k > 0.01$, β falls roughly as $1/\sqrt{k}$, which is an average of the exponents in Eq. (14). For k small, $n \approx 1 + 1/\beta$ or $n - 1 \approx \sqrt{k}$. The velocity energy decays as

$$u \approx 1/M^{n/2}, \quad (16)$$

which is shown in Fig. 8 for $k = 0.01$ to 1 . The velocity falls more sharply for larger k because of the removal of energy from the shock. By the transition to a weak shock at $M \approx 10m$, the velocity has fallen to $\approx 0.3 u_0$ for $k = 0.01$ and 0.1 for $k = 1$. The kinetic energy thus decays as

$$E \approx Mu^{2/2} \approx M^{1-n}, \quad (17)$$

which is shown in Fig. 9. Even for $k = 0.01$ the kinetic energy falls by 20% by $M \approx 10m$. For $k = 1$, it falls by a factor of 10. The kinetic energy shows much more spread than the velocities, because much of the decrease in the velocities is due to spreading momentum over a rapidly increasing amount of shocked material, which is accounted for in evaluating E in Eq. (17). The total impulse varies as

$$I \approx Mu \approx M^{1-n/2}, \quad (18)$$

which is shown in Fig. 10. For $k = 1$, impulse does not change. For larger k , I increases with time, reaching ≈ 3 times its initial value for $k = 0.01$, for which energy is roughly conserved.

Reduction of mass ejection. Porosity causes shock strength to fall more rapidly with mass or radius, which causes less material to be ejected. The reduction of the amount of pulverized ejecta can be bounded with the result from Eq. (3) that $p \approx p_0(m/M)^n$. For high speed impact on non-porous rock this reduces to $p \approx p_0 m/M$, which determines the amount of pulverized ejecta as that mass at which the energy density behind the shock falls to the yield strength or $M_s \approx p_0 m/Y$. For a material with porosity k , the pressure falls as $p_0(m/M)^n$ with $n >$

1, as shown in Fig. 7, which ejects an amount of material determined by $Y \approx p_0 m / M_p$. If the ratio of Y/p_0 is the same for both materials,

$$M_p / M_s \approx (M_s / m)^{1/n-1}, \quad (19)$$

which is shown in Fig. 11 for ratios of ejected to impactor masses of $M_s / m \approx 10, 100$, and $1,000$. The ratios of $1,000$ and 100 correspond to stony and metallic materials, respectively. For small levels of porosity, the amount of mass ejected is close to that from solid materials for all ratios. By 10% porosity, the ejected mass falls by about a factor of two for a ratio of 10 , three for a ratio of 100 , and five for a ratio of $1,000$. For larger porosities, the ejected mass continues to fall, reaching $\approx 30, 10$, and 0.03 for unit porosity. It is thought that asteroidal materials have porosities of a few percent, which would put them on the steep part of the curves.

The top curve for a ratio of 10 corresponds roughly to the reduction in the amount of vaporized material ejected from impacts. In the region of 1 to 10% porosity, the expected amount of material ejected falls from about 80% of nominal to about 60% of nominal. This reduction is less than that for the stony and metallic materials, largely because the amount of material removed by vaporization is much smaller even in the absence of porosity. However, it could be enough to impact the small signals anticipated.

These results indicate that even a few percent porosity could change the time dependent mass, velocity, and pressure enough to compromise measurements of the compressive strength of materials thought to be homogeneous. And a small amount of porosity could degrade the strength of the shock rapidly enough to significantly reduce the amount of material pulverized and ejected, which could compromise the tensile strength of asteroidal materials as well.

Integration of results. The results discussed above have largely come from analytic, similarity solutions. They show the qualitative features of the overall solutions, but cannot address the details of impact geometries and material properties. For such details, investigators have increasingly turned to numerical solutions. That shift occurred rapidly in the west shortly after WW II. The shift in the east has largely occurred after the publication of *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* as high speed computers became more available there. The progression was similar in both scientific communities. First, it started with Lagrangian formulations that followed the individual pieces of rock like fluids. However it was found that the distortions were too great to follow until craters were fully formed. Then, research shifted to Eulerian formulations, in which the fluid flowed through a fixed grid. However, that led to numerical diffusion too great to resolve shocks and mixing. More recently, they shifted to a combination of Lagrangian and Eulerian codes, which have had much more success in resolving large distortions accurately. A brief summary of that progression is given by Academician A. Bushman, one of its leaders.⁵

While it is generally difficult to compare similarity and numerical examples, some useful benchmarks do exist. There are now a number of calculations of the impact of large (1-10 km) asteroids in the Earth's seas or oceans reported, if not fully described, by Academicians Bushman, Fortov, Nemchinov, and others in the *Hazards Due To Comets & Asteroids*.⁶ The overall phenomena seen in those calculations are broadly consistent with the trends described above. However, those numerical calculations tend to be at higher collision velocities than those of the impact experiments described above. Thus, they are less sensitive to material tensile strength, vaporization energies, and pulverization mechanisms that dominate the interaction with real materials at ≈ 10 km/s. Moreover, they are oriented more towards the phenomenology of the widespread damage caused by impacts than to the physics of individual impacts.

There are a few directly relevant calculations. Academician Bushman cites the results of the overall results from a detailed impact by a 3 m metal projectile on a 100 m rock asteroid, which scale directly as Eqs. (9) and (10) and whose vaporized bowl scales as in Fig. 5. It is interesting, and appropriate, that those hydrodynamic calculations were terminated at the end of vaporization, as that was the point at which their treatment of the solid became suspect.

For higher velocities the numerical models can treat the solid much as an ideal gas—particularly for the metals for which they were developed. At lower velocities, it is necessary for them to model the fracture process. That is typically done by using some plausible model for fracture as a function of strain and strain rate and assuming a random distribution of weaknesses in the cold material. The fracture models and the distribution of initial flaws are then adjusted to best meet the scarce data, with heavy emphasis given to esthetic assessments of the appearance of the results of calculations.⁷ That is adequate for describing the transfer of momentum and energy to the shock into the solid, but it has not proved adequate for predicting even gross bowl hydrodynamics, let alone crater dimensions. As the latter are of primary interest for the impact experiment, the lack of knowledge of real asteroid equation of state is a serious drawback that cannot be addressed by current numerical calculations. However, once data are available to normalize those calculations, useful predictions of other interactions should be possible.

Summary and conclusions. This note discusses impacts on asteroids of various strengths, concentrating on the masses ejected and their thermodynamic and mechanical state. It reviews the relevant similarity solutions, which serve as simple illustrations of the types of arguments used in and the results obtained from more complicated geometries. A key result is the limitations imposed on similarity solutions by conservation of energy and momentum, which also hold in more relevant geometries. An impact or explosion at the surface of a cold gas illustrates the complexity of three dimensional interaction. Similarity results determine the asymptotic time dependence of all quantities. Approximate results show that the flow field is weakly sensitive to gas dynamic parameters, impactor material, and geometry and that the result

that energy losses are not large. That suggests a simplified model, in which the expansion is spherically symmetric and conservative, that produces concrete predictions for the thermodynamic state of material flowing out the hole and for the total amount of material vaporized by the shock, which permits an estimate of the asteroid's compressive strength. An extension provides an estimate of the amount of material pulverized and ejected by impact, which permits an estimate of the asteroid's tensile strength.

An extension of the model provides quantitative estimates of the impact of porosity, which impacts the propagation of shocks through material. Porosity reduces the amount of material vaporized because it rapidly attenuates the shock. Even a few percent porosity could compromise measurements of the compressive strength of materials thought to be homogeneous, and degrade shock strength enough to significantly reduce the amount of material pulverized and ejected, compromising the measurement of the tensile strength of asteroidal materials.

The similarity solutions discussed above provide a good basis for estimating the amount of material vaporized promptly in an impact, and, to a lesser extent, the amount of pulverized material ejected later. It has proven difficult to extend these analytic models beyond this level. For more detailed predictions, numerical models are appropriate. They have reached a level of detail at which they can readily predict most of the phenomena seen in the vaporization phase. However, they depend on heuristic models of fracture mechanics and postulated distributions of flaws in target materials, which limit their ability to predict cavity dimensions and total mass ejected. These deficiencies cannot be eliminated by theory or calculations alone. Some amount of in situ experimentation with real asteroid materials is necessary to determine the material parameters that determine the difficulty of subsequent applications.

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Fig. 1. Density, pressure, and velocity distributions for the problem of an impulsive load.

Fig. 2. The velocity field for a concentrated impact.

p & u vs M

Fig. 3. Pressure and shock speed for impact on surface of a gas.

Ek & I vs M

Fig. 4. Energy and momentum versus shocked mass.

mass vaporized vs v; Q

Fig. 5. Mass vaporizes versus 10 kg impactor velocity for various heats of vaporization (MJ/kg).
Impactor velocity (km/s)

Fig. 6. Mass ejected versus impact velocity.

Chart4

Fig. 7. Beta and n versus porosity.

porous vel vs M_i ; k

Fig. 8. Velocity versus relative mass.

Fig. 9. Kinetic energy versus relative mass.

porous I vs M; k

Fig. 10. Impulse versus relative mass.

relative mass vs porosity

Fig. 11. Mass enected versus porosity.