Reports

Asteroid Collisional Evolution: Evidence for a Much Larger Early Population

Abstract. *The present population of asteroids is a remnant of a vastly larger one that contained perhaps a planetary mass, dominantly distributed in planetesimals approximately 500 kilometers or less in diameter. It constituted a large reservoir of objects that plausibly were responsible for cratering the moon, Mars, and Mercury. Much asteroidal dust may have accumulated on Mars and other planets.*

Although there has been occasional speculation that the asteroid population might have been much larger in the past (*1*), none of the asteroid collisional models thus far developed (*2–4*) have been applied to this question. In this report we demonstrate quantitatively that the present asteroid size distribution is the natural state of collisional relaxation from many initial populations, including those containing a planetary mass. Next we show that the size-frequency distributions of different compositional classes of asteroids determined by spectrophotometry enable us to fix the initial population of asteroids smaller than 100 km at roughly 300 times the present number. Finally, we discuss the major role this small planetary mass of material may have played in cratering and accreting on the terrestrial planets.

If N_c is the number of asteroids capable of fragmenting a single asteroid of diameter D by a catastrophic collision, then the depletion rate for N such asteroids is proportional to NN_c. Since the asteroids obey a power law size-frequency distribution, $N_c \propto N$, so

$$dN/dt = -kN^2 \qquad (1)$$

where k is a proportionality constant. Integration yields

$$N = N_0/[1 + (t/\tau_0)] \qquad (2)$$

where time $t = 0$ is taken to be the present, N_0 is the present number of asteroids, and $\tau_0 = (kN_0)^{-1}$ is the present collisional half-life. Evaluation of Eq. 2 for earlier times—that is, using negative t—yields larger numbers of objects in the past. In fact, as t approaches $-\tau_0$, N becomes arbitrarily large. This large increase results from the variation of the collisional half-life with time. Going backward an initial interval of $\tau_0/2$ there were twice as many objects as now; the number doubles again in an interval of only $\tau_0/4$, and so on (Fig. 1, curve A). Thus if τ_0 is similar to the age of the solar system, as indeed Dohnanyi (*3*) and others have already calculated, we should expect that the asteroids might be a remnant of a much larger population.

Asteroid collisional half-lives may be computed by using a standard "particle in a box" approach (as in the kinetic theory of gases), dividing by a factor of ~2 to account for Wetherill's (*4*) more exact calculation. The "box" is the volume of the asteroid belt and the mean encounter velocity of the "particles" in the belt is ~5 km sec^{-1}. Half-lives also depend on collisional cross sections, which are a factor of ~3 larger than previously believed, according to the latest radiometric and polarimetric measurements of asteroid diameters (*5, 6*). Finally, we need to know something about the physics of the collision process in order to determine whether or not a collision actually results in catastrophic fragmentation. We evaluate the smallest-diameter object capable of destroying an asteroid of diameter D by requiring that the kinetic energy of the impacting body equal the sum of the gravitational binding energy of the target asteroid and the comminution energy necessary to fragment it. We adopt the bulk density and material strength appropriate for carbonaceous meteorites, since at least 80 percent of the asteroids appear to be of carbonaceous composition (*6, 7*).

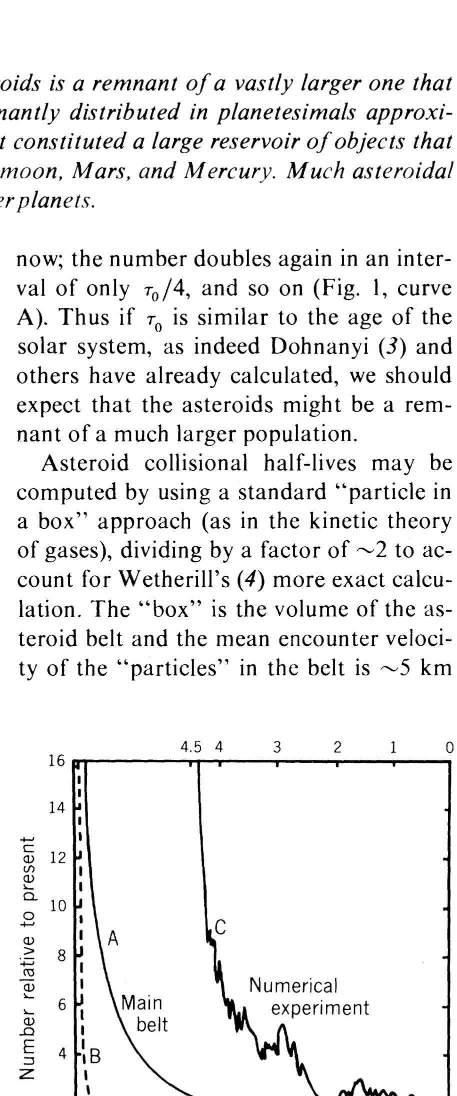


Fig. 1. Decay of asteroid populations through collisions. (A) Equation 2 is plotted for values of $-t$, assuming τ_0 is exactly 4.5 billion years. (B) Decay of a population of asteroids near resonances (librators) colliding at velocities of 7 km sec^{-1} with a main belt population. The latter are assumed to decay according to Eq. 2 from an initial volume density throughout the belt 300 times the present value (they follow a curve virtually identical to curve A). (C) Actual time history of the number of asteroids 50 km in diameter for one numerical simulation (time scale at top).

We must consider not only collisional destruction but also the resulting creation of smaller asteroids by fragmentation of larger ones, in order to determine the evolution of the asteroid size-frequency distribution. We use standard comminution laws for collisions having energies per unit mass not greatly exceeding that required for fragmentation (*8*). As we justify later, we assume that mass is rapidly lost from the belt in the form of asteroidal dust.

We have performed numerical simulations of the collisional evolution of numerous initial asteroid size distributions over the age of the solar system (Fig. 2). Figure 2, a to c, shows initial populations greater than the present one near 100 km in diameter by factors of 3000, 30, and 3, respectively. They all relax, after 4.5 billion years, to a distribution nearly identical to the present one. Figure 2, d and e, shows the effects of moderate variations of the important input parameters. Only two kinds of initial distributions fail to evolve to the present one: (i) those having more than three to five times the present number of asteroids $\gtrsim$ 500 km in diameter (for example, Fig. 2f) and (ii) those having fewer than the present number of asteroids (Fig. 2g). In the first case it takes considerable time to fragment such strongly gravitationally bound objects as Ceres and Pallas (*9*). The latter case shows very little collisional evolution at all and, of course, fails to match the present belt. Thus the present belt could be the remnant of any population ranging from one modestly larger than the present population (for example, Fig. 2b) to one vastly larger, so long as most objects had diameters $\lesssim$ 500 km.

So far we have shown that the asteroid belt could have been much larger in the past, but not that it actually was larger. This result is quite firm, for while we have employed more up-to-date physical parameters and an improved physical model, the same implication would result from the calculations of most previous investigators. But their purposes were chiefly to study the present fragmentation processes of asteroids, not their previous history. For instance Dohnanyi noticed the similarity in slope of the observed diameter-frequency relation for asteroids and the ultimate stable slope resulting from fragmentational evolution, but no one showed that such a distribution would result from a vastly larger population in the available 4.5 billion years.

We now sketch an argument that the population indeed was much larger in the past, and estimate how much larger. Despite the apparent insensitivity of the present asteroid distribution to the initial conditions, information fortunately is retained about the initial state in the size distribution of one compositional subclass of asteroids.

Chapman (*10*) has shown that the unusual size distribution of the S (stony-iron) spectral class of asteroids ($\sim$ 10 percent of all larger asteroids) implies that they are the strong, relatively intact, stony-iron cores of $\sim$ 50 geochemically differentiated proto-S objects whose rocky mantles have been fragmented away. Although the inferred mineralogy (*11*) of a stony-iron mixture does not necessarily imply strength, the size distribution shows that these objects cannot have been collisionally depleted by more than a factor of 3. Hence they must be much stronger than the obviously collisionally evolved carbonaceous asteroids, much like stony-iron meteorites, which indeed are believed to have originated in the cores of bodies roughly the size of Vesta; Vesta is probably the only example of a proto-S object that retains its mantle and crust (*12*). That $\sim$ 50 proto-S asteroids had their mantles fragmented exposing their cores but only one did not (Vesta) implies a much higher bombardment rate than currently exists in the belt. (In 4.5 billion years the present collision rate would fragment only about half the proto-S objects, so there would be roughly equal numbers of S and Vesta-like objects.) A detailed calculation (*13*) shows that the 50 : 1 proportion requires that the proto-S asteroids must have been bombarded by an asteroid population initially about $3 \times 10^{2\pm1}$ times more populous than today (*14–16*). We emphasize that these results depend on the validity of Chapman's (*10*) interpretation of the nature of S asteroids.

The mass contained in this more populous early belt is less reliably determined, but might have been several times the mass of the present belt to several Mars masses, with one to two lunar masses most likely. Still more mass may have existed in planetesimals less than 10 km in diameter or during epochs preceding the differentiation of the proto-S objects. Therefore the asteroid zone did not necessarily have an anomalously low density of solar nebular condensates from the earliest epochs, but probably contained enough material, mainly in planetesimals less than 500 km in diameter and of carbonaceous composition, to comprise at least a small planet. Presumably such a planet was accreting until collisional fragmentation interrupted the process, probably due to nearby Jupiter's influence (*15–17*). The asteroids have been grinding themselves down to dust ever since and are now a mere remnant of the former population. The dust is removed from the belt by radiation effects, as discussed below.

The high early collision rate plus the interpretation of S-type asteroids as iron cores may explain the hitherto puzzling fact that the Kirkwood gaps in the belt are so thoroughly devoid of asteroids (*18*). Figure 1 (curve B) shows that if the initial belt and Kirkwood zones were populated by 300 times the present number of belt asteroids (our nominal result) then there is relative collisional depletion of carbonaceous objects in the gaps by a factor of 10 after 4.5 billion years, which is roughly the depletion actually observed. That collisions have been important in depleting the gaps is demonstrated by the fact that the hard-to-fragment iron-core S asteroids are only slightly depleted in the gaps, while the carbonaceous asteroids are strongly depleted (*6, 13, 19*).

Our interpretation of asteroid evolution also has important implications for the rest of the inner solar system. It is generally believed that the planets were built from planetesimals (*17, 20*). Remnants of only two planetesimal populations still fall on the terrestrial planets today: the comets and asteroids. If, as we believe, the asteroids were originally more numerous than

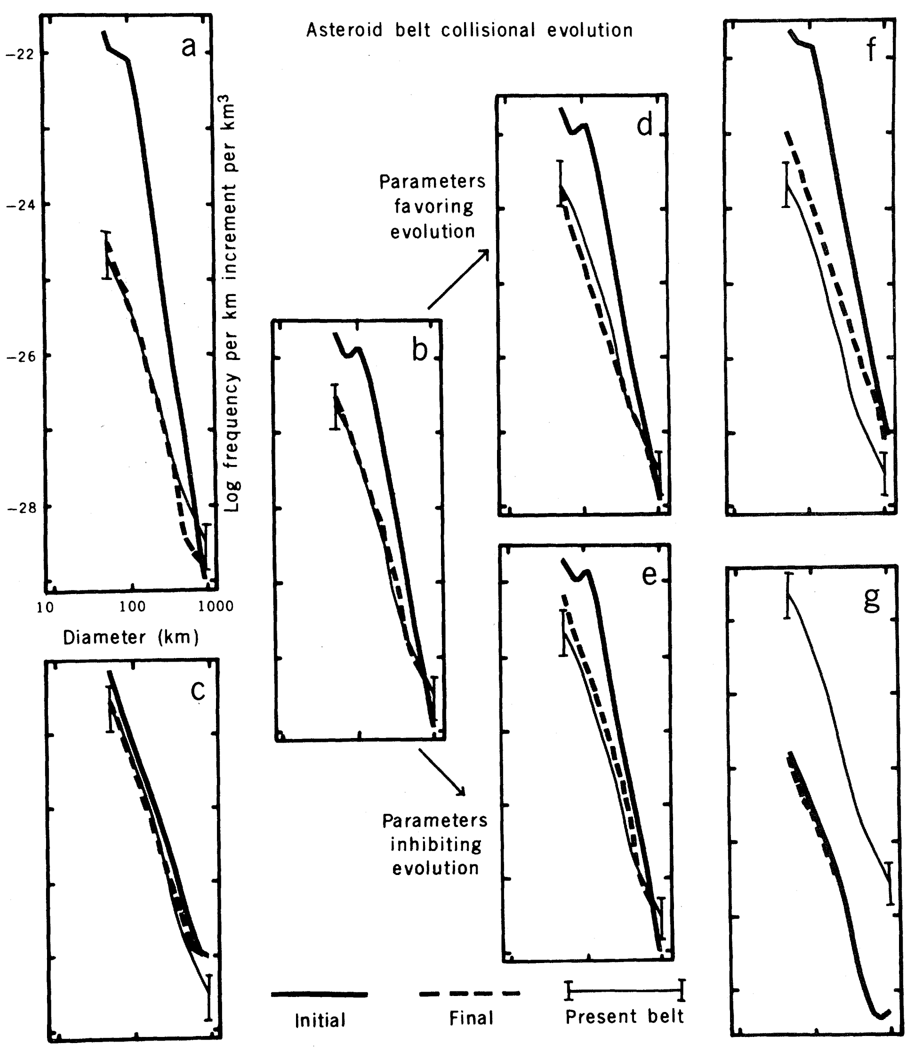


Fig. 2. Collisional evolution over 4.5 billion years of incremental size-frequency relations of asteroids from various initial states, compared with present observed distribution (uncertainty bars indicated). Nominal collisional input parameters (*13*) were used for cases a to c, f, and g. In case a the initial state contains 1.5 Mars masses. Cases d and e start from initial state of case b, but have input parameters that enhance and inhibit collisions, respectively.

now, their importance was correspondingly greater, relative to other planetesimal populations that existed in the past (*21*).

One way asteroids affected other planets was by cratering. If a vast reservoir of asteroids existed during the first half-billion years, some would have been gravitationally perturbed from the belt into orbits crossing those of the terrestrial planets. There has been much recent discussion of an early solar system–wide stage (or even distinct episode) of bombardment, ending about 4.0 billion years ago, which produced the large craters on the moon, Mars, Mercury, and presumably also the earth and Venus (*21–25*). We point to the resemblance between the decline of the asteroid population through collisions, as exemplified in Fig. 1 (curve C), and the decline of the lunar cratering flux over 10^8 to 10^9 years, even including "episodic" bumps. Thus the decay time scale of 10^8 to 10^9 years may well be the time scale for collisional decay of asteroids, rather than for dynamical capture of some other population of bodies that Wetherill has attempted to identify (*21, 26*). Furthermore, the fragmentation ~ 4.0 billion years ago of a very large asteroid appropriately located in the belt could have produced the suspected bombardment episode in the inner solar system and the associated temporary 10^7 year decay of the lunar cratering flux, since it has been shown that meteorites may be obtained from resonances in the belt, and captured by the terrestrial planets on such a 10^7-year time scale (*27, 28*).

The dominant mass-removal mechanism from an early populous asteroid belt was one of several radiation processes affecting the large quantity of dust generated by collisions. The relative importance of the Poynting-Robertson effect, which causes small particles to spiral inward from the belt, radiation pressure, which causes still smaller dust to be blown outward, and other radiation effects (*29*) depends on the efficiency of collisional fragmentation of small particles, which in turn depends in part on the efficacy of jet-streaming among small particles (*30*). If radiation pressure dominated, some asteroidal dust might have been captured by outer planets and satellites, but most might have escaped the solar system (*31*). One current evaluation of these processes (*32*) suggests that inward motion predominates. In this case, a large fraction of asteroidal dust might have accumulated on Mars (*33*) and other inner planets. Since the probable chemical compositions of asteroids are known (*5, 6, 11*) (the large majority are carbonaceous), the importance of late sweepup of asteroidal dust by the moon and Mars may be evaluated from lunar sample studies (*34*) and the inferred martian surface composition (*35*).

In summary, a new model for the collisional evolution of the asteroids and an interpretation of asteroid spectrophotometry and size distributions suggest that the present asteroids are a mere remnant of a much larger early population of planetesimals totaling a small planetary mass. The potential planet was interrupted in the process of accreting in the asteroid zone. Its subsequent and continuing fragmentation has generated perhaps the largest source of material during later epochs of solar system history for cratering and accreting on planetary surfaces. It is indeed fortunate that a significant remnant of this material still resides in the asteroid belt to be studied both by ground-based astronomy and from future spacecraft missions. Indeed, the meteorites that are still falling on the earth today are probably pieces of these same objects (*36*) which may have had such a disproportionate influence in shaping the surfaces of all the terrestrial planets during the first half-billion years of solar system history.

CLARK R. CHAPMAN
DONALD R. DAVIS

Planetary Science Institute,
2030 East Speedway,
Tucson, Arizona 85719

References and Notes

1. For instance, J. R. Arnold, *Astrophys. J.* **141**, 1536 (1965).
2. S. Piotrowski, *Acta Astron. Ser. A* **5**, 115 (1953); E. Anders, *Icarus* **4**, 398 (1965); W. K. Hartmann and A. C. Hartmann, *ibid.* **8**, 361 (1968); J. A. Burns, *NASA Spec. Publ. SP-267* (1971), p. 257; W. McD. Napier and R. J. Dodd, *Mon. Not. R. Astron. Soc.* **166**, 469 (1974).
3. J. S. Dohnanyi, *J. Geophys. Res.* **74**, 2531 (1969).
4. G. W. Wetherill, *ibid.* **72**, 2429 (1967).
5. D. Morrison, *Astrophys. J.* **194**, 203 (1974); B. Zellner, T. Gehrels, J. Gradie, *Astron. J.* **79**, 1100 (1974).
6. C. R. Chapman, D. Morrison, B. Zellner, *Icarus* **25**, 104 (1975).
7. T. B. McCord and C. R. Chapman, *Astrophys. J.* **197**, 781 (1975). The comminution energy is numerically equal to an energy partition factor (determined by experiment) times the cohesive strength of the target, but in any case is small compared with the gravitational binding energy for asteroids more than several tens of kilometers in diameter. Our approximation ignores the energy that heats the target (probably a few tens of percent) and some excess kinetic energy of the fragments. Most earlier papers ignored the more important gravitational term.
8. W. K. Hartmann, *Icarus* **10**, 201 (1969). We ignore the effects of cratering collisions, which involve impacting objects too small to cause catastrophic fragmentation. Dohnanyi (*3*) has shown that these are of relatively minor importance today; they may have been more important in earliest times, in which case our calculations give lower limits to the rates of early collisional evolution of the asteroids.
9. Thus Ceres and Pallas are among the few intact "original accretions"; an object somewhat larger than Ceres might actually have accreted into a planet at the expense of the other asteroids [see W. K. Hartman, *Astrophys. J.* **152**, 337 (1968); ——— and D. R. Davis, *Icarus* **24**, 504 (1975)].
10. C. R. Chapman, *Geophys. Res. Lett.* **1**, 341 (1974).
11. T. B. McCord and M. J. Gaffey, *Science* **186**, 352 (1974).
12. Vesta has a basaltic, hence differentiated, surface [T. B. McCord, J. B. Adams, T. V. Johnson, *ibid.* **168**, 1445 (1970)].
13. C. R. Chapman and D. R. Davis, in preparation.
14. Other shorter-lived populations of planetesimals, such as those Weidenschilling (*15*) and Kaula and Bigeleisen (*16*) have suggested were scattered from Jupiter's zone, may also have contributed to asteroidal fragmentation, stopped planetary accretion in the asteroid zone, and collisionally heated some asteroids. But probably they were gone by the time the differentiated asteroids whose collisional record we interpret here had formed, cooled, and become solid.
15. S. J. Weidenschilling, *Icarus*, in press.
16. W. M. Kaula and P. E. Bigeleisen, *ibid.* **25**, 18 (1975).
17. V. S. Safronov, *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (Keter, Jerusalem, 1972).
18. Kirkwood gaps are zones in the belt containing few asteroids; they occur at semimajor axes corresponding to important orbital resonances with Jupiter. Collision processes have been thought to play some role in depleting them [W. E. Wiesel, *Harv. Cent. Astrophys. Prepr. 204* (1974)], but the present impact velocities of asteroids near resonances are only somewhat larger (we use 40 percent) than those elsewhere in the belt. However, their effect is greatly magnified if the present distribution is a decayed remnant of a much more populous initial distribution. Since only a minority of objects are in the developing gaps, they are strongly depleted by collisions with main belt asteroids.
19. C. R. Chapman, T. B. McCord, T. V. Johnson, *Astron. J.* **78**, 126 (1973).
20. A. G. W. Cameron and M. R. Pine, *Icarus* **18**, 377 (19 P. Goldreich and W. R. Ward, *Astrophys. J.* **183**, 1051 (1973).
21. Compare with the earlier discussion of G. W. Wetherill (in *Proceedings of the Soviet-American Conference on the Cosmochemistry of the Moon and Planets*, Moscow, June 1974, in press).
22. L. A. Soderblom, C. D. Condit, R. A. West, B. M. Herman, T. J. Kreidler, *Icarus* **22**, 239 (1974). We emphasize that the evidence for this solar system–wide bombardment history—especially the hypothesized equivalence of flux on all planets [Murray *et al.* (*24*); G. W. Wetherill, in *Lunar Science VI* (Lunar Science Institute, Houston, Tex., 1975)] and its supposed episodic nature—is circumstantial at best (*25*). The absolute time scale for cratering is known only for the moon, and even for the moon is less certain than commonly stated, in part because the adopted crater densities [for example, see L. A. Soderblom and L. A. Lebofsky, *J. Geophys. Res.* **77**, 279 (1972)] do not adequately account for probable endogenic craters [C. R. Chapman, J. A. Mosher, G. Simmons, *ibid.* **75**, 1445 (1970); G. Fielder, R. J. Fryer, C. Titulaer, A. K. Herring, B. Wise, *Philos. Trans. R. Soc. Lond.* **271**, 361 (1972)] and local secondary craters. Apart from uniformitarian assumptions, nothing at all can be said from examination of Mariner imagery of Mars and Mercury about the absolute cratering rates on those planets (*23*), the experimenters' assertions to the contrary. Nevertheless, solar system–wide early bombardment is a viable working hypothesis and one buttressed by our present results.
23. C. R. Chapman, *Icarus* **22**, 272 (1974).
24. B. C. Murray, R. G. Strom, N. J. Trask, D. E. Gault, *J. Geophys. Res.* **80**, 2508 (1975).
25. W. K. Hartmann, *Icarus* **24**, 181 (1975).
26. To the degree that some investigators [W. K. Hartmann (*25*); *Astrophys. Space Sci.* **17**, 48 (1972)] disbelieve in the supposed episode and would regard the half-life of the general lunar cratering flux at 4.0 billion years ago to be shorter (for instance 10^8 years) than the asteroid decay half-life (5×10^8 years), it would be necessary to rely on some dynamical half-life for capture of asteroids or other bodies by the terrestrial planets to explain the lunar cratering flux. Possibly asteroids were removed from the zone between the 2 : 1 and 3 : 2 Jupiter resonances and captured by terrestrial planets on such a time scale, but calculations have yet to be done. An analogous removal mechanism has been demonstrated, albeit on a much shorter time scale, for the zone between the 3 : 2 and 4 : 3 resonances by M. Lecar and F. Franklin [*Icarus* **20**, 422 (1973)].
27. P. D. Zimmerman and G. W. Wetherill, *Science* **182**, 51 (1973); J. G. Williams, *EOS* **54**, 233 (1973). It has yet to be shown that the efficiency of getting the collisional debris into the inner solar system is adequately high. Another possible asteroidal source involves bodies already in Mars-crossing orbits; a collision of such a body with a main belt asteroid is much more probable than calculated by Wetherill (*21*) if the asteroids were more numerous in the past.
28. G. W. Wetherill, *Annu. Rev. Earth Planet. Sci.* **3**, 303 (1974).
29. E. J. Öpik, *Proc. R. Ir. Acad. Sect. A* **54**, 165 (1951); C. Peterson, *Bull. Am. Astron. Soc.* **7**, 376 (1975).
30. H. Alfvén, *Astrophys. Space Sci.* **4**, 82 (1969).
31. An analogous mode of creating interstellar grains

was proposed by W. K. Hartmann [*Evolution Stellaire avant la Sequence Principale* (Institut d'Astrophysique, Liege, 1970), p. 49] and G. H. Herbig (*ibid.*, p. 13).
32. S. Soter, personal communication.
33. W. K. Hartmann, D. R. Davis, C. R. Chapman, S. Soter, R. Greenberg, *Icarus* **25**, 588 (1975).
34. J. W. Morgan, R. Ganapathy, H. Higuchi, U. Krähenbühl, E. Anders, in *Proceedings of the Fifth Lunar Science Conference*, W. A. Gose, Ed. (Pergamon, New York, 1974), vol. 2, p. 1703.
35. F. P. Fanale, *Icarus* **15**, 279 (1971); J. B. Adams, R. L. Huguenin, T. B. McCord, *Bull. Am. Astron. Soc.* **7**, 370 (1975).
36. The asteroidal origin of meteorites has been advocated by many scientists from W. Olbers [*Berl. Astron. Jahrb.* (1805), p. 108] to E. Anders [*NASA Spec. Publ. SP-267* (1971), p. 429]. This hypothesis has been strongly buttressed by the last few years of research on dynamics (*28*), meteoritics [J. T. Wasson, *Meteorites* (Springer-Verlag, New York, 1974)], and astronomical studies of asteroids [C. R. Chapman, *Sci. Am.* **232** (No. 1), 24 (1975)].
37. Supported in part by NASA contract NASW-2718. This is Planetary Science Institute contribution No. 48.

18 March 1975; revised 3 June 1975

Photoacoustic Effect with Solids: A Theoretical Treatment

Abstract. *Chopped light impinging on a solid sample in an enclosed cell produces an acoustic signal within the cell. A derivation for the acoustic pressure supports the experimental observation that optical absorption spectra may be obtained from the acoustic signal even when the sample is completely opaque to transmitted light.*

Recently, a new technique has been developed for spectroscopic investigation of solid and semisolid materials. The method, photoacoustic spectroscopy (PAS), yields spectra similar to optical absorption spectra for any type of solid or semisolid material, such as crystals, powders, and gels (*1*). Because light scattering presents no severe difficulties with PAS and absorption spectra may be obtained, in many cases, from materials that are completely opaque optically, the technique has already found applications not only in physics and chemistry but also in biology and medicine (*2*). Because of the growing interest in this technique (*3*), a quantitative understanding of the underlying physical effect is essential.

The PAS technique is based on the effect originally discovered by Bell in 1880 (*4*), whereby chopped light impinging on a solid in an enclosed cell produces an acoustic signal within the cell. The periodic acoustic signal produced by this process can be detected with a microphone, and the analog signal recorded as a function of photon wavelength, giving a photoacoustic spectrum of the solid which bears a close correspondence to a true optical spectrum. Motivated by Bell's discovery, Tyndall (*5*) and Röntgen (*6*) found that a sound is also produced when chopped light is directed into a cell containing only a gas. The effect for gases has since become the basis for a well-established technique of gas analysis and is well understood (*7*). A completely satisfactory explanation for the effect with solids has not been published, though Bell (*8*), Rayleigh (*9*), Preece (*10*), Mercadier (*11*), and more recently Parker (*12*) have suggested various possible explanations.

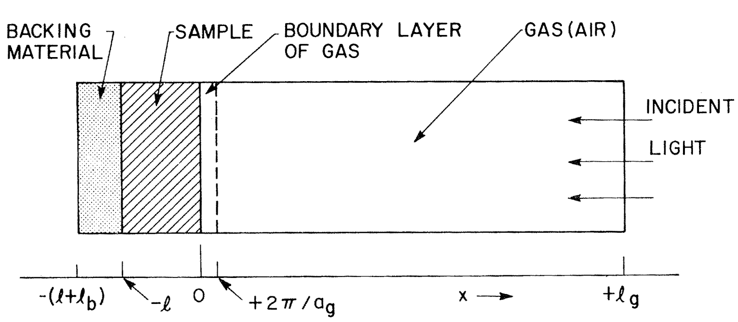
We believe the effect arises from the periodic heat flow from the solid to the surrounding gas as the solid is heated by the chopped light. A thin boundary layer of gas (~ 0.1 cm for air at a chopping rate of 100 hertz) adjacent to the surface of the solid responds thermally to the periodic heat flow from the solid. This layer may be regarded as a vibratory gas piston creating the acoustic signal detected in the cell.

Consider the simple cylindrical cell shown in Fig. 1. The sample is in the form of a disk with diameter D and thickness l. The optically transparent gas column (air) has length l_g, which is smaller than the wavelength of the acoustic signal. The backing material of thickness l_b is generally a poor thermal conductor and is assumed not to be light absorbing. Sinusoidally chopped monochromatic light of wavelength λ and flux I_0 (watt/cm^2) is incident on the sample. The heat density produced at a point x due to light absorbed at this point in the solid is given by $\frac{1}{2}\beta I_0 e^{\beta x}$ $(1 + \cos\omega t)$, where β (cm^{-1}) is the optical absorption coefficient at wavelength λ, ω is the chopping frequency (rad/sec), t is time, and x (cm) takes on negative values in the solid (see Fig. 1).

The thermal diffusion equation in the solid, taking into account the internal heat distribution, is then given by

$$\frac{\partial^2\phi}{\partial x^2} = \frac{1}{\alpha_s}\frac{\partial\phi}{\partial t} - Ae^{\beta x}(1 + e^{j\omega t})$$

where ϕ is temperature, $j = (-1)^{1/2}$, $A = \beta I_0/2k_s$, and α_s and k_s are, respectively, the thermal diffusivity and thermal conductivity of the solid. We assume here full efficiency in the conversion of the absorbed light into localized heat by nonradioactive de-excitation processes within the solid. For the backing and gas (*13*) we use the heat diffusion equations $\partial^2\phi/\partial x^2 = (1/\alpha_i)\phi$, where α_i takes on the appropriate value of thermal diffusivity α_b and α_g for the backing and gas, respectively.



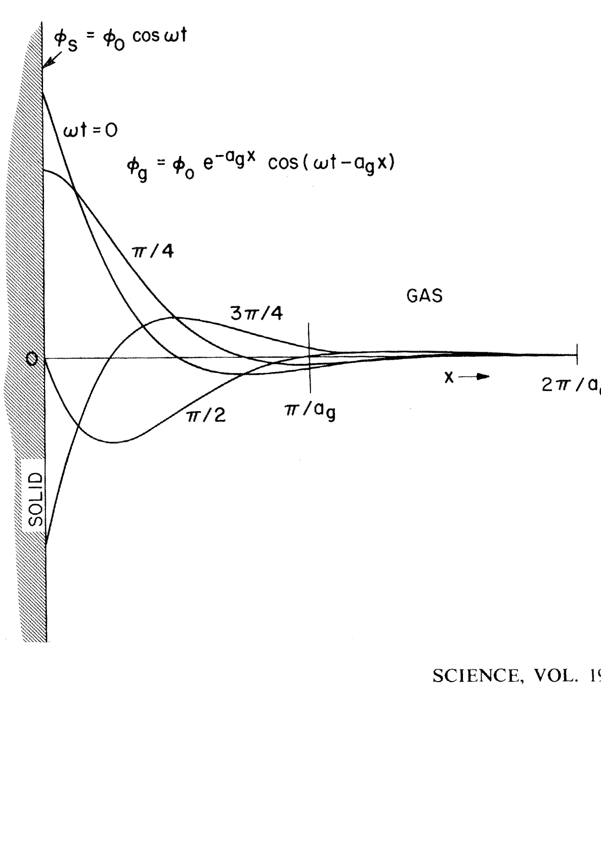


Fig. 1 (left). Cross-sectional view of a simple cylindrical photoacoustic cell, showing the positions of the solid sample, backing material, and gas column. Fig. 2 (right). Spatial distribution of the time-dependent temperature within the gas layer adjacent to the solid surface.