INTERNAL CONSTITUTION AND MECHANISMS OF ASTEROID FRAGMENTATION

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It has been generally assumed in the past that the fragmentation of asteroidal bodies and the production of meteorites are solely the result of collision events. (See Dohnanyi, 1969; Hartmann and Hartmann, 1968; Wetherill, 1967.)

A possible mechanism of noncollisional fragmentation will be proposed below, its proper framework of applicability will be defined, and evidence suggesting and supporting its existence will be adduced. Briefly, it is shown that the presence of even trace amounts of hydrogen in meteoritic metal phases (Edwards, 1955) may have caused the parent bodies of iron meteorites to undergo, spontaneously, delayed brittle fracture under the action of prolonged slow stresses, the imprint of which has been recorded in the phase structure of meteorites (Baldanza and Pialli, 1969). This phenomenon, termed "hydrogen embrittlement," has been amply documented in the literature on the metallurgy of ferrous metals (Bernstein, 1970; Tetelman, 1969).

INTERNAL CONSTITUTION OF ASTEROIDAL BODIES

Inferences on the internal constitution of asteroids are based on several lines of evidence.

First, an *average density* can be obtained if independent determinations of the mass and diameter of the body are made. Such data exist for Vesta and Ceres, yielding $\rho \sim 5 \pm 1$ g/cm^3 in the latest estimate by Schubart.[1] These densities are compatible with a high content of metallic nickel/iron, corresponding on the average to mesosideritic or pallasitic ($\rho \sim 5$ g/cm^3) composition (~50 percent by volume of meteoritic Ni/Fe).

Second, recent spectral reflectivity data (Chapman, Johnson, and McCord;[2] McCord, Adams, and Johnson, 1970) may yield information on the *surface composition* of the asteroids. The identification of the ferromagnesian silicate pyroxene on Vesta and the similarity of the overall spectrum to that of basaltic

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[1]See p. 33.
[2]See p. 51.

achondrites do not rule out a high metal content for Vesta because basaltic achondrites (stony meteorites) are similar in composition to the silicate component of mesosiderites (stony iron meteorites). The possibility of high metal content is supported also by the fairly high density inferred for Vesta and is consistent with its very high albedo (Hapke[3]). Compositional differences between Ceres, Pallas, and Vesta are also apparent in spectral reflectivity data (McCord, Adams, and Johnson, 1970). This may be the rule in the asteroid belt, rather than the exception, as Levin (1965) suggested. An expectation of compositional diversity arose with the study of meteorites, which provides the largest body of evidence brought to bear, by implication, on the structure and composition of asteroidal bodies. The view that meteorites originated in asteroidal bodies (Anders, 1964) is entirely consistent with the assumption that many observed properties of meteorites are primordial and thus reflect the conditions prevailing during the condensation and accretion of small bodies in the solar system (Anders, 1964; Arrhenius and Alfvén, 1971). Such an assumption is particularly important with regard to metallic (Ni/Fe) phases in all meteorites, which have been used extensively and exclusively to determine cooling rates and parent body sizes (Buseck and Goldstein, 1968; Goldstein and Short, 1967; Powell, 1969; Wood, 1964; Wood, 1967).

It was recently shown (Fricker, Goldstein, and Summers, 1970) that for very slowly cooled classes of meteorites such as the pallasites (0.5 to 2 $K/10^6$ yr) or mesosiderites ($\sim$0.1 $K/10^6$ yr) the parent body size cannot be specified uniquely and may be larger than asteroidal. In any case, the cooling rates of various classes of meteorites alone provide a strong argument against an origin of stony irons in the same (differentiated) parent body with iron or stony meteorites (Buseck and Goldstein, 1968; Fricker, Goldstein, and Summers, 1970; Powell, 1969). Sizes of iron meteorite parent bodies, however, based on cooling rates of 0.5 to 500 $K/10^6$ yr, encompass the range 10 to $\sim$450 km in radius and are still compatible with observed sizes of asteroids, although the models are inadequate for discrimination between a "core" or a "raisin" origin (Fricker, Goldstein, and Summers, 1970; Levin, 1965).

The evidence from meteorites clearly suggests an origin in a multiplicity of parent bodies (required by the existence of discrete chemical groups and different cooling rates for various classes of meteorites, as well as by the scatter in cooling rates within a class) of relatively large sizes (as required by slow cooling rates and by the large-scale continuity of Widmanstätten patterns in iron meteorites), which were fragmented in a few, discrete, large events (as indicated by the conspicuous clustering of cosmic-ray ages). (See Anders, 1964; Hartmann and Hartmann, 1968.)

Mass balance arguments (Arnold, 1965), as well as the longer cosmic-ray exposure ages of iron meteorites, make an origin of these objects in fairly massive asteroids compatible with most evidence to date. Yet the study of size

[3]See p. 67.

and mass distributions of various groups of asteroids (Anders, 1965; Brecher and Alfvén, 1969-70; Hartmann and Hartmann, 1968) indicates that very few major collision events have altered the reconstituted primordial distribution and that the long collision lifetimes ($\tau > 10^9$ yr for $m > 10^{18}$ kg) preclude frequent collisional disruption of massive bodies; moreover, secondary collisions are also less frequent than expected (Dohnanyi, 1969), as reflected in the relatively narrow spread in cosmic-ray exposure ages of meteorite classes (Anders, 1964; Anders, 1965; Arnold, 1965; Hartmann and Hartmann, 1968).

An interesting alternative to their destruction in collision events can be conjectured for some massive parent bodies of iron meteorites (with a low probability of collisional destruction but with a considerable amount of strong Ni/Fe) and for parent bodies with a mesosideritic or pallasitic structure; i.e., with the metal (Ni/Fe) phase continuous in three dimensions conferring structural strength. It involves spontaneous brittle failure of the parent body due to hydrogen embrittlement of the Ni/Fe phases.

HYDROGEN EMBRITTLEMENT AND THE PRODUCTION OF IRON METEORITES

In a recent study of the mechanical properties of iron meteorites, Gordon (1970) found the internal structure of about 150 samples to have preserved surprising perfection over large dimensions for bodies presumed to have resulted from violent collisions. Moreover, no evidence was found of the large-scale plastic deformation or ductile fracture expected on the basis of shock loading experiments on the Odessa iron. He concluded that the iron meteorites appear to have formed in brittle fracture events; yet the metal of the Gibeon octahedrite was remarkably ductile and strong. Moreover, no tendency was found in the samples studied for preferential fracture along octahedral planes nor for embrittlement due to inclusions. The fact that the meteoritic metal was not intrinsically brittle (and it did not become brittle at any testing temperature down to 100 K) forced Gordon to conclude that "a mechanism of embrittlement must function for all meteorites having a Widmanstätten structure if these are to be considered fragments of a larger metal mass." Unable to find such a mechanism, he assumed that small, meteorite-size masses of Ni/Fe must have been embedded in intrinsically brittle silicates.

A well-known embrittling agent of ferrous metals is gaseous hydrogen, and the phenomenon of hydrogen embrittlement has been extensively reviewed. (See Barth and Steigerwald, 1970; Bernstein, 1970; Groeneveld, Fletcher, and Elsea, 1966; Nelson, Williams, and Tetelman, 1971; Tetelman, 1969.) The loss in ductility caused by the introduction of hydrogen into Ni/Fe alloys to levels of a few parts per million is *not* detectable under impact loading conditions (i.e., at collisions), but only at very low strain rates of $\dot{\epsilon} < 0.05$ per minute (Tetelman and McEvily, 1967) and under static or sustained stresses. Thus, the susceptibility of meteoritic metal to structural hydrogen embrittlement could not have been detected at the relatively high strain rates ($\dot{e} < 0.3$ per minute) in Gordon's (1970) tests. Nor is the hardness or the yield strength of iron meteorites affected by the presence of hydrogen, so that data available for the Gibeon (Gordon, 1970), Odessa, Sikhote-Alin, Canyon Diablo, and Henbury irons and for the Brenham pallasite (Baldanza and Pialli, 1969; Knox, 1970) may reflect the intrinsic, structure-dependent properties of meteoritic Fe/Ni alloy phases (Baldanza and Pialli, 1969, table 1). The presence of hydrogen, however, reduces the fracture strength so that microcracks can start to propagate unstably after an incubation time during which the internal hydrogen reaches a critical configuration (Tetelman, 1969). Thus the body undergoes seemingly spontaneous brittle fracture, often after having withstood previous dynamic impacts or high loads. The incubation time before failure is relatively insensitive to stress level but is sensitive to stress rate. The embrittlement is promoted not only by low strain rates or prolonged quasi-static loading but also by concentration gradients in hydrogen.

The physical picture of hydrogen embrittlement is briefly that of local stress fields in the metal lattice caused by screened protons at interstitial sites, by atomic H pinned at defects and grain interfaces, and even by H_2 molecules recombined in internal voids. The amounts sufficient to cause brittle failure in steel can be less than 1 ppm by weight of average H content. Details about solubility in the α and γ phases of Ni/Fe, and about the possible mechanisms of embrittlement will be given elsewhere (Brecher, 1971). Suffice it to say that a variety of environments can supply the internal and/or external hydrogen necessary for brittle fracture of a metal body, such as corrosive atmospheres of H_2S and H_2O (which may have existed at various stages of the formation of meteorites), fields of accelerated protons implanting hydrogen such as the solar wind, or partially ionized and dissociated low-pressure interplanetary gas media containing atomic hydrogen as an important constituent (Arrhenius and Alfvén, 1971; Nelson, Williams, and Tetelman, 1970). The seed of self-destruction may have been planted in parent bodies of iron meteorites at birth as hydrogen was occluded during the grain condensation and growth stages, in the presence of abundant hydrogen. Moreover, continuous surface implantation of solar-wind protons may have provided the local hydrogen pressure gradients and local strains known to initiate microcracks and thus may have promoted failure by brittle fracturing under unstable crack propagation.

Is there evidence for the presence of hydrogen in iron meteorites? The old work on thermal release patterns of gases reported by Farrington (1915) showed that hydrogen was the most abundant gas phase released from iron meteorites at levels of 3 to 55 ppm; by chemical methods, Nash and Baxter (1947) detected minimal levels of a few tenths of a part per million of H_2. More sophisticated determinations by Edwards (1953, 1955) revealed surprisingly high levels of hydrogen in iron meteorites (up to ~33 ppm average content, and up to ~55 ppm in the fine-grained fraction), leading Edwards (1955) to conclude that the hydrogen "must have been originally incorporated during the formation of the meteorites." The H/D ratios typical of iron

https://doi.org/10.1017/S0252921100089144 Published online by Cambridge University Press

meteorites (Edwards, 1953, 1955) in comparison with terrestrial steels seem to exclude terrestrial contamination as the source of hydrogen.

MORE SUPPORTING EVIDENCE

Supporting evidence for the conjectured brittle failure of parent bodies of iron meteorites can be drawn from several areas of research.

One area is the study of preterrestrial deformation effects in meteorites (Axon, 1969; Baldanza and Pialli, 1969). For example, in their study of "dynamically" deformed structures in irons and chondrites, Baldanza and Pialli found extensive evidence that "shear forces of a slow character" acted to distort the phase structure in irons, and concluded that "the pressure was related to a slow dynamic event and temperature was confined to relatively low values." Such effects are not expected in collisional shock events. Moreover, the recrystallization observed mainly along faults (indicating local loss in ductility, i.e., embrittlement), "shear fractures," and "deformation due to prolonged stress action" seem to fit well the path leading to hydrogen brittle failure, as does the history formulated for these meteorites (culminating in the production of "split" bodies, when conditions of low temperatures were attained). It is remarkable that the critical range of temperature for failure due to molecular hydrogen is 173 to 373 K (Bernstein, 1970), thus bracketing the values relevant for iron meteorites at 1 AU (~363 K) to 3 AU (~223 K). Moreover, in the presence of atomic hydrogen, brittle failure occurs over a wider range of low temperatures (Nelson, Williams, and Tetelman, 1971), whereas "hydrogen cathode charging" of steels (which is equivalent to solar-wind implantation of hydrogen) is known to cause irreversible brittle failure at levels of 5 to 8 ppm of H_2 even at 77 K (Barth and Steigerwald, 1970).

Another significant fact is the presence of very high levels of hydrogen ($\sim 8.4 \times 10^{-2}$ cm^3/g) in some gas-rich meteorites (Lord, 1969) as well as proton contents of 4×10^{19} to 2×10^{20} per gram found in various chondrites (Chatelain et al., 1970), all being accountable by $\sim 10^4$ equivalent irradiation years at 1 AU in typical solar-wind proton fluxes of $\sim 3 \times 10^8$ cm^{-2}-sec^{-1} ($E > 1$ keV). Not only is the hydrogen effectively implanted by solar wind into the grain surfaces (possibly prior to their aggregation (Lord, 1969) or while suspended in jetstreams (Arrhenius and Alfvén, 1971; Trulsen, in this book[4])), but it also is released mostly above ~700 K from stones (Lord, 1969), whereas in irons it can be held as "residual hydrogen" to above 1000 K (Johnson and Hill, 1960). In Apollo 11 Moon material (Fireman, D'Amico, and De Felice, 1970), a hydrogen concentration gradient was found to exist in rocks, and the abundant hydrogen content of the lunar soil (1.2 cm^3/g) was only in part attributable to solar wind, thus suggesting that some primordial hydrogen was retained.

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[4]See p. 327.

https://doi.org/10.1017/S0252921100089144 Published online by Cambridge University Press

The solar wind therefore could establish in surface layers a local concentration gradient of hydrogen and an equivalent quasi-static internal stress known to facilitate an eventual fracture of the parent body. It also could establish a trapping layer for hydrogen at irradiation-caused or other defects and dislocations close to the surface.

Can the evidence of shock in some iron meteorites (Jaeger and Lipschutz, 1967; Jain and Lipschutz, 1969) rule out the occurrence of noncollisional fragmentation? It seems that it cannot do so because shock of mild to moderate levels appears to be limited to certain groups of iron meteorites (such as the group III octahedrites, which also cluster in cosmic-ray ages at $\sim 650 \times 10^6$ yr). Other groups, like the hexahedrites, show no evidence of shock; unshocked octahedrites, although randomly distributed among the Ga-Ge groups, also seem to exhibit peaks in their cosmic-ray age distribution at 200 to 500 and 800 to 1000×10^6 yr, suggesting a formation in noncollisional discrete events (Jain and Lipschutz, 1969; Voshage, 1967). Even some group III octahedrites, like Henbury and Cape York, are apparently unaltered; although they are believed to have been mildly shocked (at 130 to 400 kb levels).

There are at least two massive, well-studied finds of iron meteorites that appear to have undergone spontaneous brittle failure prior to entering the atmosphere. They are Gibeon (Bethany) in Southwest Africa and Cape York in Greenland. Nininger (1963) remarks that in the case of Gibeon, more than 50 irons totaling 15×10^3 kg were recovered. The fact that all were strongly ablated and that the scatter ellipse covered an area of several hundred square miles indicated that Gibeon meteorites arrived as a "preatmospheric swarm." Similarly, the giant Greenland irons (specimens weighed 36, 3.5, 3, and 0.4×10^3 kg) were scattered widely over ~ 250 km^2 and seemed to have traveled as a "swarm" along the same orbit without suffering any further fragmentation upon entering the atmosphere. In contrast, in the large fall of Sikhote-Alin, several thousand fragments resulting from atmospheric fragmentation were scattered within less than 2.5 km^2 and exhibited a wide range of sizes from grains to several tons. In both Gibeon, whose mechanical properties suggested to Gordon (1970) the formation in a brittle fracture event, and in Cape York, hydrogen was found at levels of ~ 7 and ~ 25.5 ppm, respectively (Edwards, 1955). One could thus assume that, in the presence of internal hydrogen and under repeated stress and intense solar-wind bombardment at ~ 1 AU perihelion approach, brittle failure of the parent body might have occurred and that the pieces were not dispersed considerably from the common orbit in this gentle type of preatmospheric fragmentation. The time of the fragmentations may be indicated by the fairly long cosmic-ray ages of iron meteorites.

This type of seemingly spontaneous splitting of a parent body has been well known to occur in comet nuclei at perihelion approach when unusual stresses on compact nuclei could facilitate unstable cracking. Such fragmentation was observed, for example, in the comets Biela (1826), Olinda (1860), Taylor

(1916I), which split in two, and the large comet 1882III, which split into six pieces. In these cases, the centrifugal force about the Sun at perihelion approach and/or the intense irradiation by the solar wind may have aided in disrupting the nucleus (Dauvillier, 1963). The propensity of Eros to disrupt and fragment was also noted during its 1931 close approach to Earth (Dauvillier, 1963). In view of the possibly compact, rigid bodylike nature of some comet nuclei (Whipple, 1963) and of the plausibility of a cometary origin for at least some classes of meteorites (see paper by G. W. Wetherill in this volume[5]), and in the light of a possible evolution of some comets into asteroidal objects (see paper by B. G. Marsden in this volume[6]), the splitting of comet nuclei into a few large pieces may be highly suggestive of a mechanism for low-energy fracture.[7]

CONCLUSIONS

It has been shown previously that the mechanical properties of iron meteorites (Gordon, 1970) required their production in brittle fracture breakup events. It was suggested above that the excess hydrogen found in iron meteorites (Edwards, 1955) is likely to be the necessary embrittling agent. A survey of the metallurgy of hydrogen embrittlement (Barth and Steigerwald, 1970; Bernstein, 1970; Groeneveld, Fletcher, and Elsea, 1966; Nelson, Williams, and Tetelman, 1971; Tetelman, 1969) indicated that an iron meteorite parent body could suffer delayed brittle fracture under the action of low rate (accumulated or periodic) stresses whose imprint was found in the metal phase structure (Axon, 1969; Baldanza and Pialli, 1969). Such fracture would occur when the internal hydrogen distribution has reached a critical configuration, which could facilitate rapid propagation of cracks. Two large groups of iron meteorites (Gibeon and Cape York), which are thought to have arrived as preatmospheric swarms, were found to contain sufficient amounts of hydrogen to have been produced in brittle fracture (noncollisional) fragmentation of their parent bodies.

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[5]See p. 447.

[6]See p. 413.

[7]*Note added in press:* An alternative mechanism for low-energy fracture of iron meteorite parent bodies has just been proposed by H. L. Marcus and P. W. Palmberg (1971) in J. Geophys. Res. 76, 2095.

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DISCUSSION

DOHNANYI: Have you had a chance to examine this problem to see if a critical object size exists beyond which the fragments would tend to stick together? It seems that there should be a critical size where gravity is strong enough to keep the fragments together despite other perturbations.

BRECHER: It is difficult to appraise such a critical object size without making very particular assumptions about the size, density, fragmentation spectrum, and orbit of the body, as well as about the mode of disruption and the type of forces (self-gravitation, tidal, solar-wind dynamic pressure, torques, etc.) acting at breakup.

Order of magnitude estimates for 10^3 kg sized pieces of meteoritic iron seem to indicate that they may be kept in contact by mutual gravitational attraction, if the perturbations acting on them are less than ~1 μN/kg (~10^{-4} dyne/g). Compared to the solar gravitation of 6 mN/kg (0.6 dyne/g) at 1 AU, tidal forces exerted by the Sun and Earth, which are ~10^{-13} and ~10^{-18} N/kg-m (~10^{-13} and ~10^{-18} dyne/g-cm), respectively, for 1 AU approach, or ~10^{-10} and ~10^{-15} N/kg-m (~10^{-10} and ~10^{-15} dyne/g-cm) for 0.1 AU approach, may be neglected. Similarly, rotational instability will not prevail over mutual gravitation of such 10^3 kg sized chunks, if the rotation period of the body was initially larger than 1 hr. This holds for asteroids, whose spin periods range from 2 to ~10 hr.

But the solar-wind dynamic pressure, at the present 1 AU flux of kiloelectron volt protons, would suffice to transfer a momentum of ~5×10^4 g-cm/s per unit area, allowing a body with a 1 m^2 area to acquire a velocity of ~5 m/s after only 10 million yr of "storage" in a geocentric orbit (Arnold, 1965); if iron meteorites were stored in such an orbit during the ~500 million yr that have elapsed since breakup, different surface areas of fragments may have led to considerable scatter velocities.

Compare the above to the extremely small initial differential velocities of ~2×10^{-7} cm/s inferred for the presumed members of the Cape York "preatmospheric swarm" from the dimension (~25 km) of their scatter ellipse (Nininger, 1963), if breakup occurred 500 million yr ago. It seems that some cohesive forces (cold welding), or the gentle fracture mode, may have allowed some fragments to hold together in spite of dispersive perturbations. For a 10^5 kg body, the escape velocity is only ~0.2 cm/s and, indeed, it is hard to see how 10^3 kg sized chunks could have had smaller scatter velocities at breakup. (I thank Dr. Anders for pointing out this fact.) One could only hope that, just as for asteroidal families assumed to form by collisional breakup, extremely long lifetimes

(~2.2 billion yr) against dispersal were found (Anders, 1965), similarly long lifetimes may hold for smaller fragments resulting from noncollisional fracture modes.

DISCUSSION REFERENCES

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