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MOST STONY METEORITES COME FROM THE ASTEROID BELT

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The place of origin of stony meteorites can be determined from their trapped solar-wind gases. "Gas-rich" meteorites of all classes have only 10^{-3}-10^{-4} the solar noble gas content and $\leq 10^{-2}$-10^{-4} the surface exposure age of lunar soils. These differences suggest that the gas implantation took place between 1 and 8 AU from the Sun, in a region where the cratering rate was 10^2-10^3 times higher than at 1 AU. Both requirements are met by main belt asteroids, not by long- or short-period comets, by Trojan asteroids, or by stray bodies in thinly populated parts of the inner solar system. The observed prevalence of gas-rich meteorites (up to 100% among carbonaceous chondrites, 2-33% among other classes) requires that the parent bodies be large enough, and remain in the asteroid belt long enough, to develop a substantial regolith. These conditions are more readily met by asteroids than by comets. The young ages of xenoliths in gas-rich meteorites (down to 1.4 AE) show that gas implantation is an on-going process in the solar system, not a relic from a hypothetical "early irradiation."

L chondrites, in contrast to H chondrites, show pervasive evidence of outgassing 500 Myr ago, accompanied by shock heating to 950-1250°C for centuries or millennia. Apparently the L chondrite parent body was not a comet, but an asteroid broken up at that time.

Of 27 xenoliths (foreign inclusions) in meteorites, 20 are carbonaceous (mainly C2) whereas 5 are ordinary chondrites or related meteoritic types. Because xenoliths are a relatively unbiased sample of the asteroid belt, it seems likely that ordinary chondrites and their kin comprise the second-most-abundant type of material in the belt. Thus S asteroids may have chondritic rather than stony-iron composition.

SOLAR GASES: CLUES TO THE ORIGIN OF METEORITES

The most direct evidence on the former location of meteorites comes from trapped solar wind (Anders, 1975). I shall present the argument from that paper in updated but greatly abridged form, omitting various qualifications and supporting arguments. In addition, I shall review a few other lines of evidence bearing on the problem.

Do Gas-Rich Meteorites Come from Regoliths?

Almost every stony meteorite class has several "gas-rich" members that are brecciated and contain a characteristic noble-gas component, of solar isotopic and elemental composition (Table 1). Wänke (1965 and earlier papers) was the first to suggest that this component represents solar wind trapped by meteoritic dust in the regolith of the meteorite

Table 1. Prevalence of Gas-Rich Meteorites[a]

Class	%	Class	%
C1 Chondrites	100	L Chondrites	2
C2 Chondrites	61	LL Chondrites	8
C3V Chondrites	60	K Chondrites	25
C30 Chondrites	0	Howardites	33
H Chondrites	12	Aubrites	33

[a]Mazor *et al.* (1970); Schultz *et al.* (1972), Srinivasan and Anders (1977).

parent body. Because solar-wind ions have very low energies, they penetrate only a few hundred Angstroms into the grain, and hence are trapped only by grains residing at the very surface. A later impact cements these dust grains into a coherent rock, which is then ejected from the parent body by still another impact. All stages of this process have been observed in lunar samples, from fresh, unirradiated soils to welded, gas-rich breccias.

Detailed studies of meteoritic breccias have revealed many additional parallels to lunar breccias: charged particle tracks, microcraters, anisotropically irradiated grains, radiation damage, etc. (Wilkening, 1970; Barber *et al.*, 1971; Macdougall *et al.*, 1973, 1974; Poupeau *et al.*, 1974; Rajan, 1974; Maurette and Price, 1975; Price *et al.*, 1976; Goswami *et al.*, 1976). The consensus that has emerged from this work is that gas-rich meteorites formed in a regolith. Wetherill (1978) has contended, however, that only "a few" of the gas-rich meteorites show "the full set of these regolith features," the most clear-cut case being the howardites. Actually, the above studies included aubrites, H chondrites, C1 chondrites, and C2 chondrites, in addition to howardites, and all showed the full set of regolith features (except that no microcraters have yet been reported from aubrites). By Occam's Razor, all are likely to have formed in a regolith.

Model for the Solar Gas Content of Meteorites

To a first approximation, the mean solar gas content G of soil from a given body depends on two parameters: the solar wind flux, which is proportional to the inverse square of the heliocentric distance a, and the mean surface residence time t. The latter is approximately proportional to the inverse of the cratering rate R, which determines the rate at which the topmost layer is blanketed by ejecta; both old soil and freshly cr[illegible]ed rock (Gault *et al.*, 1974). Thus, using symbols $\circ$ and $\star$ for the Moon and meteorite parent body, we can write

$$\frac{G_\circ}{G_\star} = \left(\frac{a_\star}{a_\circ}\right)^2 \left(\frac{t_\circ}{t_\star}\right) \approx \left(\frac{a_\star}{a_\circ}\right)^2 \frac{R_\star}{R_\circ} \qquad (1)$$

Because we know the heliocentric distance of the Moon, at least to a first approximation, we can use lunar soil as "ground truth" to determine the formation distance of gas-rich meteorites.

The conditions under which Equation (1) is valid have been discussed by Anders (1975), and will not be repeated here. The principal requirements are (1) that the bombarding fluxes in both regions be "top-heavy" (*i.e.*, the exponent γ in the differential mass distribution $N = Am^{-\gamma}$ must be less than 2) so that the dominant process will be crushing of fresh rock rather than reworking of old dust, and (2) that the Moon and meteorite parent bodies retain about the same fraction of ejecta. The first requirement is met for the Moon and the asteroid belt, judging from the abundance of siderophile elements in lunar and meteoritic breccias (Anders, 1975). It is probably also met for comets, because both comets and their debris (shower meteors) seem to have $\gamma < 2$. The second requirement certainly is not met by very small asteroids or comets, which lose most of their ejecta and hence cannot develop a regolith. But even a 45 km asteroid should lose only 50% of its impact ejecta, according to data by Gault *et al.* (1963), and loss of *average* soil should have no effect on Equation (1). According to a detailed model by Housen (1976), asteroids of r = 100 km and 20 km can accumulate regoliths of ~100 m and ~10 m in 10^9 years.

A referee has questioned the approximate inverse proportionality of t and R in Equation (1), because blanketing* would involve mainly recycled grains on the Moon and mainly fresh grains on an asteroid. In the first place, we are concerned primarily with the relation between G and t, not R, and that relation is exact whether the blanketing is done by a fresh or a recycled grain: the integrated gas content per unit time and area is the same no matter how many grains share in the integrating.

Second, though the relation between t and R does indeed require that the *major part* of the ejecta be freshly crushed rock rather than recycled grains, it can be shown that this condition is met for all practical purposes. A quantitative statement of this condition is that the integrated flux of crater-forming bodies of mass 0 to M (where M = mass of largest body to strike the planet) be large compared to the flux of bodies unable to penetrate the average regolith, of mass range 0 to m:

$$F \equiv I_0^M / I_0^m = [(M^{-c}-0^{-c})/(m^{-c}-0^{-c})] > 2 \qquad (2)$$

where c is the exponent in the *cumulative* mass distribution. On the Moon, the mare regolith is typically about 5 m thick, so $m \sim 10^7$ g. With $M = 10^{19}$ g, corresponding to a 10 km body, and c = -0.17 (corresponding to γ = 1.83; Dohnanyi, 1971) we obtain F = 110, so the proportionality is good to 1%. For a hypothetical asteroid with a 100 m regolith, $m = 10^{13}$ g and $M = 10^{19}$ g, so F = 10.5 and the proportionality is good to 10%.

Actually the agreement is not quite as good, because the mass distribution steepens below 10^9 or 10^6 g (Chapman, 1972), and the upper limit of integration is not well defined, because the ejecta from the largest craters are not distributed globally, and so do not contribute fully to the *average* regolith (Ganapathy *et al.*, 1970).** However, there is direct evidence for the dominance of juvenile grains in lunar soil cores and especially meteoritic breccias. Charged-particle track studies have shown that grains from a given layer differ in exposure time by $\sim 10^2$-10^3, with the median exposure typically an order of magnitude below the maximum (Poupeau *et al.*, 1974; Price *et al.*, 1975; Goswami *et al.*, 1976, and many references cited therein). And the amount of meteoritic material in lunar soils (1-1.5% in mature soils; down to 0.09% in young soils; Krähenbühl *et al.*, 1973) is comparable to that in gas-rich meteorites (1-4%, Laul *et al.*, 1972; Chou *et al.*, 1976; Hertogen *et al.*, 1978), so that on both bodies, dilution by fresh rock keeps pace with addition of meteoritic material. In any event, since the differences we shall try to explain amount to 2-3 orders of magnitude, errors of even a factor of 2-3 are of no consequence.

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* "Blanketing" is a more accurate term than the widely used misnomer "gardening," because the mixing process is not a simple overturn but a "biased random walk," where many small increments alternate with occasional large decrements (Laul *et al.*, 1971).

**On the other hand, large craters contribute heavily to the total *volume* of the regolith, which is relevant to some aspects of this problem, *e.g.*, the abundance of gas-rich meteorites.

Formation Distance of Gas-Rich Meteorites

According to Equation (1), the gas content G should be proportional to surface exposure age t and the inverse square of the heliocentric distance a (Figure 1). We can calibrate this relation by means of lunar soils (open symbols), which are *known* to have formed at 1 AU. Because lunar soils lose Ne owing to temperature and saturation effects, it was necessary to calculate corrected Ne values from the Xe content, using the Ne/Xe ratio. (This correction has somewhat improved the correlation of G and t, as shown by a comparison of the large and small symbols). The "10 AU" line represents a^{-2} dependence of the solar wind flux.

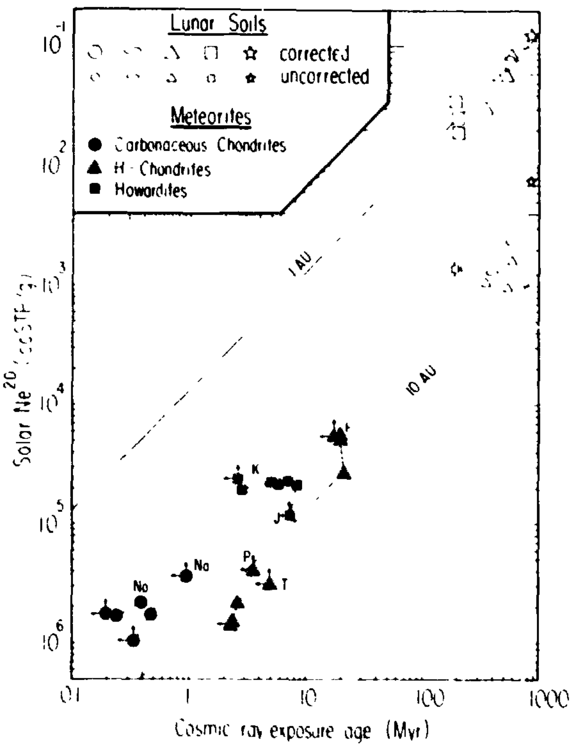


Fig. 1. Relation between solar-gas content and surface exposure age as a function of distance from the Sun (Anders, 1975). Cosmic-ray exposure age of meteorites is only an upper limit of the surface exposure age, and Ne^{20} content may be too low because of saturation effects; thus all meteoritic points should be shifted toward the upper left. Regardless of class, gas-rich meteorites have systematically lower gas contents and exposure ages than do lunar soils. Their parent bodies must have been located in a region of lower solar wind flux ($1 < a < 8$ AU) and higher cratering rate. Both characteristics point to the asteroid belt.

The surface exposure age can be measured by different radiation effects, and generally increases with the penetration depth of the radiation (Table 2). For our analysis, the solar wind exposure age is relevant, but since it is not known for most meteorites, we shall use the cosmogenic noble-gas exposure age as a substitute. Though these two quantities are by no means equivalent (they measure the residence time in the topmost few hundred Angstroms and topmost meter, respectively), there is evidence that they are proportional to each other.

However, for meteorites this proportionality is less strictly valid, because the cosmic-ray exposure age also includes the transit time to Earth, when the meteorite was again bombarded by cosmic-rays. To minimize this effect, I have selected meteorites of short exposure

Table 2. Different Types of Surface Exposure Age for Lunar Soils and Gas-Rich Aubrites

Effect	Effective Depth (cm)	Age (yr)	
		Lunar Soils[a]	Aubrites[b]
Solar Wind	$\sim 10^{-6}$	10^6-10^7	1-100
Solar Flare Tracks	$\sim 10^{-3}$	10^6-10^7	10^3-10^4
Galactic Cosmic-Ray Tracks	10	10^8	10^6
Cosmogenic Noble Gases	100	1-10×10^8	3×10^7

[a]Lal (1975).
[b]Poupeau *et al.* (1974).

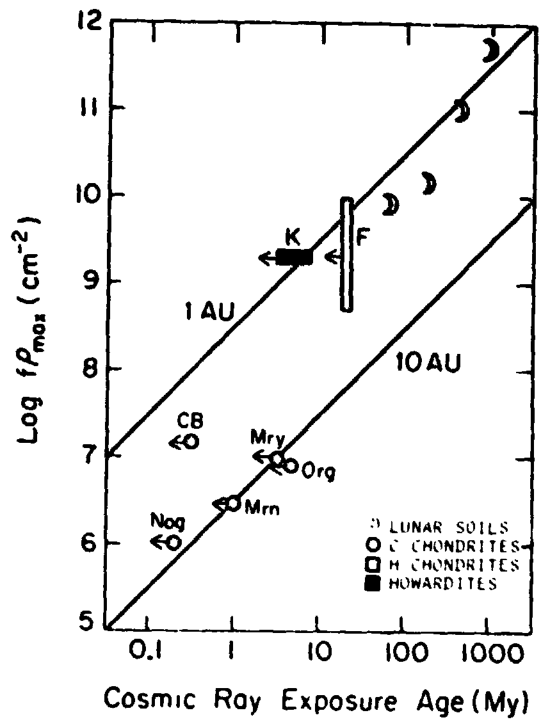
age, but since the transit time is always finite, these ages must be regarded as upper limits of the surface exposure age, which we are after. Arrows are inserted to remind us of this fact. In two cases where the transit time was independently determined from the Al^{26} content (Nogoya, Pantar), the surface exposure age seemed to be on the order of 10^5 years (Anders, 1975). Different samples of the same meteorite are connected by solid lines.

The Ne^{20} contents also may be somewhat too low, owing to diffusion losses. The correction should be much smaller than for lunar soils, because gas-rich grains in meteorites generally lack the radiation-damaged, amorphous surface layers, which are very leaky and are responsible for most of the gas loss from lunar soils (Ducati *et al.*, 1973; Poupeau *et al.*, 1974). Precise corrections cannot be estimated from the Ne/Xe ratio, owing to the presence of planetary Xe, but it seems likely that the correction factors are smaller than 5x or perhaps even 2x. Vertical arrows indicate the direction of the correction.

Gas Content and Surface Exposure Age. In spite of these uncertainties, Figure 1 reveals two stark and simple facts: meteorites have shorter exposure ages and lower gas contents than do lunar soils, by 1-3 and 3-5 orders of magnitude, respectively. Errors in these quantities cannot account for this difference. Exposure ages for meteorites are upper limits because they include the transit time, but any correction for this effect can only enlarge the difference. Ne^{20} contents are lower limits, but are unlikely to be in error by more than a factor of 5. Moreover, Price *et al.* (1975) have shown that this uncertainty can be circumvented by using solar-flare track density rather than Ne^{20} content as an integrator of solar corpuscular radiation (Figure 2). Here the total radiation dose is given by the product $f\rho_{max}$, where f = fraction of track-rich grains and ρ_{max} = maximum track density at the edge of the grain. Two of the most gas-rich, non-primitive meteorites (the howardite Kapoeta and the H chondrite Fayetteville) fall two orders of magnitude below the most heavily irradiated lunar soils, whereas five carbonaceous chondrites fall 3-6 orders of magnitude below.

Taken at face value, the meteorite data suggest a formation distance less than 10 AU, in some cases appreciably less: <2.6 AU for the C2 chondrite Cold Bokkeveld, <1.2 AU for the howardite Kapoeta, and <3.7 AU for the H chondrite Fayetteville. The asteroid belt would seem to be the most likely source.

Fig. 2. Product of solar-flare track density ρ_{max} and fraction of track-rich grains f, a more saturation-proof indicator of surface exposure (Price *et al.*, 1975), correlates with cosmic-ray exposure age in much the same way as Ne^{20} does in Figure 1. Carbonaceous chondrites (circles) again have lower track densities and ages than do lunar soils (crescents), which suggests formation at a greater distance from the Sun, in a region of higher cratering rate. Difference is less marked for howardite Kapoeta (K) and H chondrite Fayetteville (F).



Cratering Rate. These data contain still another, more decisive clue pointing to the asteroid belt: the low gas contents and short cosmic-ray exposure ages of meteorites compared to lunar soils. Apparently meteorites come from a region where the cratering rate is much higher than at 1 AU, so that material stays at the surface for a much shorter time before re-burial. The asteroid belt, with its high flux of rubble, again is the obvious candidate. Indeed, quantitative consideration of cratering rates (Anders, 1975) leads to predicted Ne^{20} contents that agree rather well with observed values (Table 3).

The data in Figures 1 and 2 thus show pervasive, fundamental differences between meteorites and lunar soils: meteorites have consistently smaller gas contents, track densities, and exposure ages than do lunar soils. The differences amount to factors of 10^2-10^6, much larger than the approximations and simplifications involved in Equation (1). Wetherill (1978) maintains that these differences cannot be conclusively interpreted in terms of distance, surface exposure age, and cratering rate until a "detailed understanding of the probable nature of an asteroidal regolith" has been attained. It is not clear, however, what physical parameters other than a, t, and R are capable of accounting for factors of 10^2-10^6, and hence how a more detailed understanding can drastically alter the first-order picture presented here.

Table 3. Predicted Ne^{20} Contents of Lunar and Asteroidal Regoliths

	Moon	Asteroid (r = 100 km)
Heliocentric Distance, AU	1.00	2.5
Cratering Rate, cm/yr	8×10^{-8}	7.3×10^{-5}
Ne^{20} Flux, cc STP $cm^{-2}yr^{-1}$	2×10^{-8}	3.2×10^{-9}
Predicted Ne^{20}, cc STP/g	8×10^{-2}	1.2×10^{-5}
Observed Ne^{20}, cc STP/g	5.6×10^{-2}	2.9×10^{-6}
	(Lunar soils)	(H chondrites)

Depth of Asteroidal Regoliths

There has been some controversy over the thickness of asteroidal regoliths; in particular, whether asteroids can develop thick enough regoliths to account for the great abundance of gas-rich meteorites (Table 1). Let us approach this problem empirically, and see what the meteorites tell us about the regoliths of their parent bodies.

Wänke (1966) has made the important observation that gas-rich H chondrites show essentially the same cosmic-ray age distribution as do all H chondrites, and are present not only in the continuum but also in major peaks such as those at 5 Myr and 22 Myr (Figure 3). This shows that a gas-laden regolith must extend to sufficient depth to assert itself even in the larger and deeper impacts.

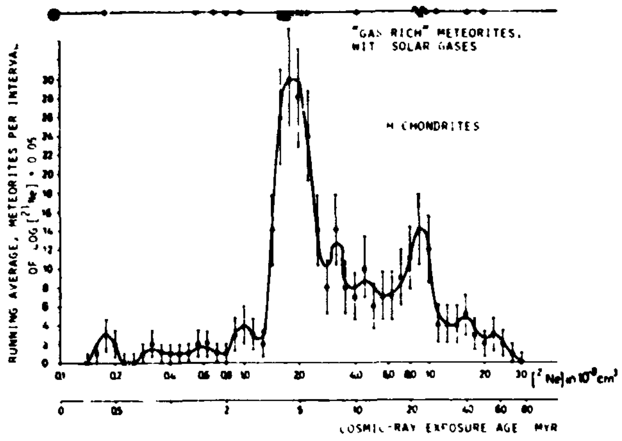


Fig. 3. Cosmic-ray exposure ages of gas-rich H chondrites (top) peak at the same values (5 and 22 Myr) as the ages of all H chondrites, and the proportion of gas-rich meteorites in the continuum is comparable to that in the peaks. Evidently large and small impacts eject about the same proportion of gas-rich meteorites, which suggests that solar-wind irradiated regolith material comprises a roughly constant fraction of the outer layers, down to at least the depth of the largest crater, 0.5-1.2 km. (From Wänke, 1966).

Let us roughly estimate a minimum depth for the largest event in Figure 1, the 5 Myr peak. Some 47% of all dated H chondrites are in this peak, and since H chondrites comprise 37% of all chondrite falls, the 5 Myr peak contributes some 17% of the annual influx of chondrites, $\sim 10^8$ g/yr (Wetherill, 1977). If the dynamical mean life against planetary capture is 30 Myr, and one-third of these meteorites eventually fall on Earth, then the total reservoir of H chondrites from the 5 Myr impact is 1.7×10^{15} g.

This value includes only material in the meteoritic mass range (10^2 g - 2×10^6 g), and we must therefore integrate the mass distribution to larger masses--say 2×10^{12} g, corresponding to a diameter of about 100 m. If we do this for two extreme choices of the population index s in the cumulative size distribution, 2.5 and 3.6, we obtain 2.2×10^{16} g and 2.0×10^{15} g for the total mass.

From these values, we can find the size of the crater. With the Short and Forman (1972) relation for the volume of the crater, and a depth/diameter (h/D) ratio of 0.35, we obtain D = 3.3 and 1.7 km and h = 1.2 and 0.53 km. According to Figure 1, the fraction of gas-rich meteorites in the 5 Myr peak is 10/72 = 0.14, so if this figure is representative, then the regolith thickness would have to be 160 m or 70 m for the two cases.

Actually, the true thickness must be much greater. Wänke (private communication, 1967) has pointed out that each of the larger peaks in the radiation age spectrum (Figure 3) contains chondrites of all petrologic types, from H3 to H6. It does not seem plausible that all these types originated in a shallow zone of $\sim$1 km depth. The peak metamorphic temperatures of H3 and H6 chondrites differed by at least 300°C (<600°C vs. 950 ± 100°C; Wood, 1967; Onuma *et al.*, 1972), and it seems very difficult to establish such a steep temperature gradient over a distance of less than 1 km, let alone maintain it over the $\sim$10[illegible] yr duration of metamorphism.

The obvious answer is that the H chondrite parent body has been extensively mixed by earlier, larger impacts, so that meteorites of all petrologic types, as well as regolith material, are closely juxtaposed and are ejected together even by small-scale impacts. The original stratigraphy may have resembled that of the L chondrite parent body (Figure 4), as reconstructed from the observed frequency of petrologic types. (There is evidence that the L chondrite parent body was completely shattered in a collision about 500 Myr ago (Anders, 1964; Heymann, 1967; see also section entitled "Outgassing of the L Chondrite Parent Body"), and so the L chondrites falling on Earth may be a relatively unbiased sample of this body.) If so, then mixing and br[illegible]ciation must have penetrated at least 0.12 r into the H chondrite parent body, to expose the H6 layer.

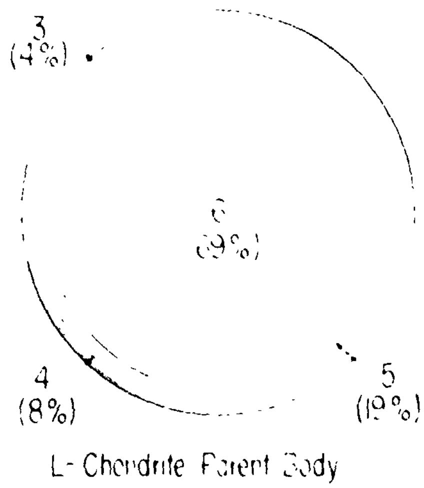


Fig. 4. Cross section of L chondrite parent body, showing volume fraction occupied by each petrologic type. Because L chondrite parent body seems to have completely broken up about 500 Myr ago, volume fraction of each petrologic type should be proportional to its observed frequency.

Apparently, the H chondrite parent body thus has a substantial "megaregolith" (Hartmann, 1975). A rough idea of its average depth may be obtained from the abundance of solar Ne^{20} in meteorites. The mean solar Ne^{20} content of 34 gas-rich H chondrites (Schultz and Kruse, 1977) is 2.9×10^{-6} cc STP/g. With a solar Ne^{20} flux of [illegible] $\times 10^{-9}$ cc $cm^{-2}yr^{-1}$ at 2.5 AU, a 14 km layer of such material could be produced in 4.6 AE. Three observations suggest that this material actually is unevenly mixed through a large volume of the body: the wide variation in solar Ne^{20} content among gas-rich H chondrites ($\sim 10^3$x), the coexistence of H3 to H6 material in a single gas-rich meteorite, and the simultaneous ejection of H3 to H6 material in small cratering events. In the light of these observations, it seems unlikely that the original accretional stratigraphy has been preserved in meteorite parent bodies.

These *observations* (as distinct from inferences) also seem hard to reconcile with the frequent assertion that asteroids can only have thin regoliths. The observations are well-documented, and so perhaps the fault lies with the models that predict thin regoliths on asteroids.

ASTEROIDS OR SHORT-PERIOD COMETS?

Granted that the gas implantation took place in the asteroid belt, was the meteoritic substrate itself asteroidal or cometary? Short-period comets traverse the asteroid belt in the final phase of their history, and could conceivably develop a gas-rich regolith during that period. There are four lines of evidence bearing on this question.

Chemical Composition

Comets appear to have carbonaceous chondrite composition, judging from meteor spectra (Millman, 1972) and from the abundance pattern of the micrometeorite component in lunar soils (Ganapathy *et al.*, 1970). Thus they could indeed serve as a source of gas-rich carbonaceous chondrites. It seems unlikely, however, that they could also furnish the less primitive types of gas-rich meteorites: howardites, aubrites, or ordinary chondrites. All these classes have had a prolonged, high-temperature history under dry conditions, which is hard to reconcile with the volatile-rich composition of comets. Other arguments against a cometary origin have been given by Anders (1971).

Prevalence of Gas-Rich Meteorites

One important constraint is the common occurrence of gas-rich meteorites in nearly all classes of stony meteorites (Table 1). The only exceptions are eight rare classes, with a total of 49 members: E chondrites, C3O chondrites, diogenites, ureilites, nakhlites, angrites, and chassignites.

Thus a fairly large fraction of the source volume of meteorites must have been transformed into a gas-laden regolith. Comets are doubly disadvantaged relative to asteroids in this respect: typically, they are 1-2 orders of magnitude smaller and spend 3 orders of magnitude less time in the asteroid belt. A calculation analogous to that in Table 3 shows that a 30 km comet would develop a regolith of only 4 m thickness in 10^7 yr, corresponding to 4×10^{-4} the mass of the body. This is clearly insufficient to explain the high abundance of gas-rich meteorites. Moreover, since much of this material was near the comet's surface for 4.5 AE, it would show a high cosmic-ray exposure age, contrary to observation

Early Irradiation

The preceding objections against a cometary origin of chondrites at least could be dismissed if cometary matter had acquired its solar gases in a hypothetical "early irradiation" in interplanetary space, rather than on a regolith. But there are numerous objections against this idea.

Owing to the low energy of solar wind ions, the gas must be removed to a residual density of $<10^5$ molecules/cm^3, some 9 orders of magnitude less than the initial density in the solar nebula. It is not obvious how the gas can be removed without carrying the dust along. Also, on this hypothesis, accretion of comets and ejection to the Oort belt still have to take place after irradiation, yet the gas which both processes require is already gone.

Moreover, there exist C2 chondrites without solar gases, and others with gas-rich and gas-poor portions of otherwise identical mineralogy (Nogoya, Murray, Mokoia, etc.). Wetherill (1978), who considers an early irradiation to be a viable proposition, has not explained how these gas-poor materials are to be protected against the early irradiation, how they are to be mixed with irradiated material only of the same mineralogy, and how the correlation in Figures 1 and 2 is to be accounted for.

Most important, the compaction ages of gas-rich meteorites are consistently shorter than 4.55 AE, *e.g.*, 4.22 to 4.42 AE for carbonaceous chondrites (Macdougall and Price, 1974; Macdougall and Kothari, 1976), <1.4 AE for ordinary chondrites (Schultz and Signer, 1977), and <3.6 AE for the howardite Kapoeta (Dymek *et al.*, 1976). Thus, gas-rich meteorites must have been made by processes that still operated in the solar system 1.4 AE ago, not by that durable chimera, the "early irradiation."

Outgassing of the L Chondrite Parent Body

A peculiar trait of L chondrites is the preponderance of short K-Ar and U-He ages, which are discordant between 1 and 4 AE but become concordant at 0.5 AE (Figure 5). These short ages correlate with shock and reheating symptoms, and the obvious explanation therefore is that the L chondrite parent body broke up 0.5 AE ago (Anders, 1964; Heymann, 1967, Taylor and Heymann, 1969, 1971; Turner and Cadogan, 1973; Bogard *et al.*, 1976). The high proportion of strongly heated meteorites (950-1250°C; Wood, 1967, Smith and Goldstein, 1977) implies a high input of kinetic energy per unit mass, and hence a high projectile/target mass ratio. The slow cooling rates of many of the heated meteorites (0.01-1 degree/year) suggest that the primary fragments were of kilometer dimensions.

At least two-thirds of the known L chondrites bear the signature of this 500 Myr reheating event, and hence must have been contained in one or at most two bodies at that time. This is easy to reconcile with an asteroidal but not with a cometary origin, because comets surely did not originate in a single collision, nor were they heated to >1000° for centuries or millennia afterwards.

Wänke (1966) and Wetherill (1978) have questioned this interpretation. In their view, the gas loss occurred during the final collision that ejected the decimeter-sized meteorite from its parent body, and corresponds to the onset of cosmic-ray exposure. The radiogenic "age" of 500 Myr then does not represent a true age, but merely the fortuitous retention of some 6 of the He^4 and 3 of the Ar^{40}.

This hypothesis does not explain why short gas-retention ages are much more common among L than among H chondrites (Figure 5) and why they occur across the full range of cosmic-ray ages (Figure 6). If the gas loss took place only during the impact corresponding to the cosmic-ray age, why are these impacts always more severe on the L chondrite parent body? Studies at lunar and terrestrial craters show that the major part of the

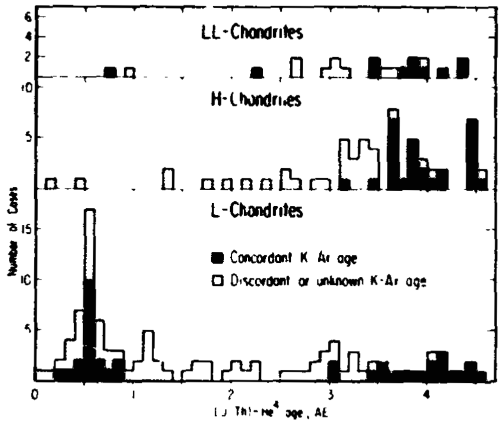


Fig. 5. L chondrites show a large proportion of U-He ages less than 2 AE, accompanied by shock and reheating effects in most cases (Taylor and Heymann, 1969). Because these ages tend to become concordant with K-Ar ages at 0.5 AE, it appears that large portions of the L chondrite parent body were reheated and outgassed at that time, presumably by a collision that produced a Hirayama family.

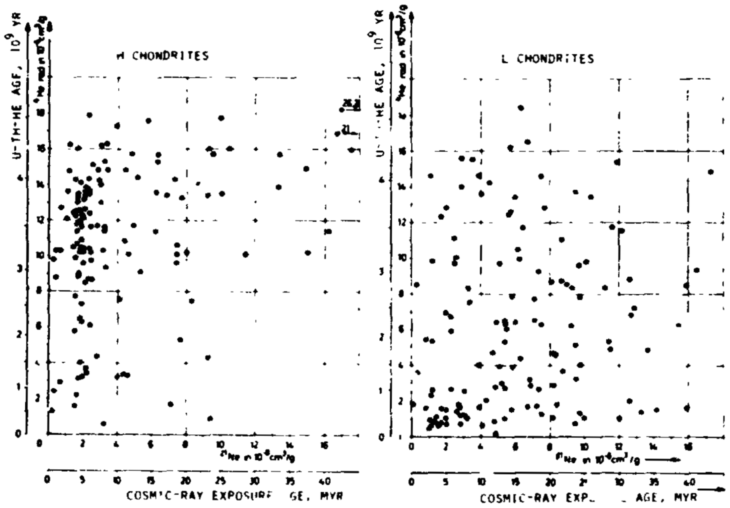


Fig. 6. Regardless of cosmic ray age, short U-He ages are common among L chondrites but rare among H chondrites. Many of these meteorites also were shock-heated to 950-1250°C and cooled at rates of 0.01-1°/yr, corresponding to burial depths of up to 1 km or more. Consequently, the gas loss and reheating cannot have been caused by the impact triggering the cosmic-ray exposure era, but by an earlier, larger event. (From Wänke, 1966).

ejecta is only lightly shocked, and does not have its gas-retention ages reset. Wholesale gas loss, as for the L chondrites (Figures 5 and 6) is very much the exception, and needs to be explained by some exceptional event, such as the collision of two bodies of comparable size.

Moreover, metallographic studies show that many shocked L chondrites cooled at rates of 1 to 0.01 deg/yr, corresponding to burial depths of a kilometer or more. But the impact that started the cosmic-ray exposure by definition must have reduced the meteorite to less than a meter in size, and so cannot be responsible for the heating at 1000 m depth.

METEORITES AND ASTEROIDS

Mineralogy and Accretion Temperature

Evidently, gas-rich meteorites formed as recently as 1.4 AE ago, in a region 1-8 AU from the Sun where the cratering rate was 10^2-10^3 times higher than at 1 AU. These characteristics point uniquely to the asteroid belt. Moreover, asteroid mineralogy, as inferred from spectral reflectivity data, matches chondrite mineralogy to first order. Asteroids, like chondrites, divide into a carbonaceous and a siliceous class, *and since the transition from siliceous to carbonaceous mineralogy occurs at a nebular condensation temperature of 400°K* (Larimer and Anders, 1967; Anders, 1972), it appears that *chondrites and asteroids both condensed in the region traversed by the 400°K isotherm.*

Wetherill (1978) has criticized the condensation theory because it fails to explain why spectrally different asteroids occur at the same heliocentric distance. In the first place, the correlation of mineralogy with distance is not bad, considering that temperatures fell not only with distance but also with time (by some 50-100°; Anders, 1972; Alaerts *et al.*, 1977). Asteroids formed at large distances, where even the initial temperatures were below 400°K, would be carbonaceous throughout; those at small distances, where even final temperatures were above 400°K, would be siliceous throughout; and those at intermediate distances would have siliceous cores and carbonaceous mantles. Breakup of such hybrids would give a mix of C and S objects at the same distance.

Second, there is reason to believe that asteroid orbits have been scrambled since their formation. Whipple *et al.* (1972) have shown that the high inclination of 2 Pallas cannot have persisted throughout the accretion stage, but must be a post-accretional feature caused by an unknown perturbation process. This is also true of other asteroids of high i and/or e. Thus the imperfect correlation between composition and semimajor axis is a problem in dynamics, not cosmochemistry. No matter how this problem is ultimately resolved, the fact remains that both meteorites and asteroids show the distinctive change in mineralogy expected at 400°K. Hence both must have formed in a region of space traversed by the 400°K isotherm.

Xenoliths

All of the objects proposed as meteorite parent bodies--asteroids, comets, Apollos--have orbits that cross at least part of the asteroid belt for at least part of their history. During that time they sweep up a random sample of asteroidal debris, and cement some of it into impact breccias. Meteorites eventually carry this debris to Earth in the form of xenoliths (= foreign inclusions). In this manner, meteorites act as a "poor man's space probe," sampling bodies whose orbits do not allow their debris to reach the Earth directly. (There may be some discrimination against bodies of high encounter velocities, but this will gradually lessen at least for the fine debris, as its orbits become circularized.)

XENOLITHS

HOSTS	C	C1	C2	C3	H	L	LL	Ch	Au
C2				1					
C3			2					1	
H	5	1	5					1	
L	2		1						
LL					1				
Ho			2						
Au								1	
Mes				1				1	2
	7	1	10	2	1			4	2

Fig. 7. Xenoliths (foreign inclusions) in meteorites provide a relatively unbiased sample of material in the asteroid belt. Carbonaceous chondrites, especially C2s, predominate, accounting for 20 out of 27 xenoliths. Ordinary chondrites and their relatives (Ch) are the second most abundant class, with five representatives. None of the meteorite classes tentatively identified with S asteroids (mesosiderites, irons, Fe^{++}-bearing achondrites) have thus far been found among the xenoliths, and so it seems that ordinary chondrites and their kin are more likely candidates for S asteroid material.

Such xenoliths have been studied extensively by several workers, mainly Wilkening and Fodor and Keil (Wilkening, 1973, 1977; Wilkening and Clayton, 1974; Fodor and Keil, 1973, 1976). Their results, augmented by some recent work from Chicago (Leitch and Grossman, 1977; Hertogen *et al.*, 1978) is shown in Figure 7.

All together, 27 xenoliths have been found thus far, within host meteorites representing eight meteorite classes. Of the 27 xenoliths, 20 are carbonaceous, five are ordinary chondrites in an extended sense (having the same mineralogy but different proportions of FeO and total Fe), and two are aubrites.

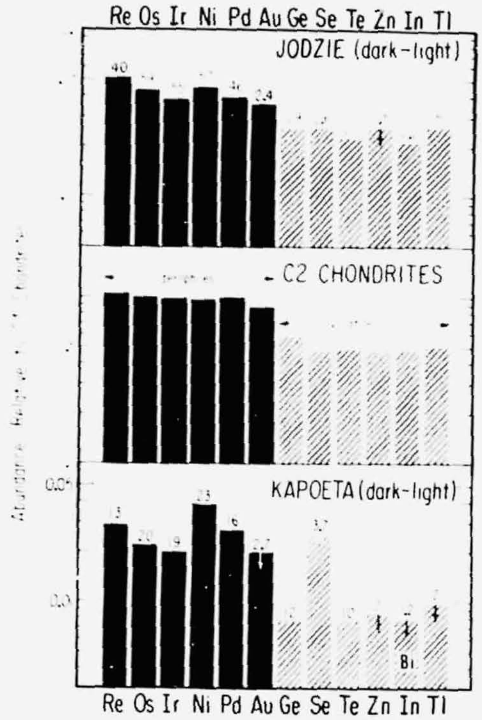
Obviously, these data are of great potential value in characterizing the population of the (inner?) asteroid belt, though at present they are severely limited by statistics and by observational selection. The following tentative conclusions may be drawn from Figure 7 and other evidence.

(1) The ratio of carbonaceous to other chondrites is about 4:1. This happens to match the ratio near the center of the asteroid belt (Zellner, 1978), but the true ratio must be lower because carbonaceous xenoliths are favored by observational selection.

(2) Most of the carbonaceous xenoliths (13 out of 20) resemble known classes, and only a few of the remaining seven are actually new; others merely are insufficiently characterized. Among the identified carbonaceous xenoliths, C2 chondrites greatly predominate, as shown by detailed petrographic studies (Wilkening, 1973, 1978; Bunch, 1975).

The statistical significance of this result is strengthened by noble-gas and chemical analyses of howardites, which provide a comprehensive average of the foreign component in these meteorites regardless of particle size (Mazor and Anders, 1967; Laul *et al.*, 1972; Chou *et al.*, 1976; Hertogen *et al.*, 1978). The foreign component characterized by this comprehensive method closely matches C2 chondrites (Figure 8), and thus proves that material indistinguishable from C2 chondrites dominates in the region of the howardite parent body. Because it is generally conceded that this body is located in the asteroid belt, it follows that C2 chondrites are very abundant in at least one part of the asteroid belt. The spectrophotometric identifications of C2-like material by McCord and his students (McCord, 1978

Fig. 8. Gas-rich portions of howardites contain a foreign component, representing mixed interplanetary debris picked up during their regolith history. Abundance patterns of this component in Jodzie and Kapoeta show some resemblance to C2 chondrites, suggesting that C2 chondrites are the most abundant type of material in the region of the howardite parent body. (From Hertogen *et al.*, 1978).



and references cited therein) thus are strongly supported by tangible samples (Figure 8), and hence hardly need to be prefaced by cautious disclaimers.

(3) "Ordinary chondrites" in the broadest sense comprise the second most abundant group. But only one of five such xenoliths, an H chondr actually corresponds to a *known* class. Thus the ordinary chondrites are not rare s, derived from 1-3 yet-to-be-discovered asteroids of the right reflectance spectrum. , are samples of a rather abundant type of material, of metal content <20%, which is common enough in the asteroid belt to have contributed five out of 27 xenoliths.

Nature of S Asteroids

It is suggestive that the second most abundant group of xenoliths matches the second most abundant class of asteroids, the S asteroids, in gross mineralogy. Both consist mainly of ultramafic silicates and metal. According to some interpretations, however, the S asteroids are much richer in metal (~50% vs. <20%), and thus resemble either stony irons (mesosiderites, pallasites) or coarser-scale (>1 cm) mixtures of silicates and metal, rather than chondrites (McCord and Gaffey, 1974; Chapman, 1976, 1977). This interpretation raises three questions:

1. Why is the second most abundant asteroid class not represented among xenoliths?

2. Why are its meteoritic equivalents so rare among known falls (11 stony irons, or 46 irons and 67 achondrites* among 854 falls)?

3. Why is there no asteroidal equivalent of the most populous class of meteorites, and of the Apollo-Amor objects that resemble them?

The first question has no ready answer. The greater crushing strength of stony irons would cause some underrepresentation, but this is offset by the inconspicuousness of ordinary chondrite xenoliths in ordinary chondrite hosts.

To answer the second question, one might postulate dynamical barriers that prevent the great majority of S asteroids from dispatching fragments to Earth. But this seems unlikely: since S asteroids are the second most abundant class of asteroids, and are fairly evenly spread through the inner half of the belt, they should contribute their share of meteorites and Apollo-Amor objects leaving the belt through various escape hatches. Though their presumably greater crushing strength might cause them to be underrepresented relative to C asteroids, their concentration in the inner half of the belt, where most of the escape hatches are, would offset this factor. Iron meteorites have still higher crushing strengths, and yet about 12 classes of irons (of very diverse chemistry, cooling rate, and hence nebular place or origin (Kelly and Larimer, 1977; Scott and Wasson, 1975)) do get out in copious numbers, although (metallic) M Asteroids are much rarer than S asteroids. And so do various kinds of achondrites, though their asteroidal counterparts are either unobserved, or, in the case of Vesta, unfavorably situated for transmission of meteorites to Earth. Since these rare types are able to assert themselves, and reach Earth in significant numbers, it is not clear how the far more abundant S asteroids are to be prevented from dispatching their fragments to Earth.

Thus we are left with two possibilities. Either the S asteroids are stony irons, in which case we must explain why they are outnumbered in the world's meteorite collections by the meteoritic equivalents of much rarer or unobserved asteroid types. Or they are ordinary chondrites, in which case we must explain why the spectral reflectivity data tell us otherwise. A possible reason is preferential erosion of brittle silicate particles, leaving the surface enriched in metal. I, at least, find it easier to believe that the spectral reflectivity data mislead us than to accept the alternative: that the most abundant meteorite class has no asteroidal equivalent, and the second most abundant asteroid class has no xenolithic and only rare meteoritic equivalents.

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*It is far from clear that coarsely textured, metal-silicate asteroids actually can provide the right environment for the formation of iron meteorites and achondrites.

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DISCUSSION

ARNOLD: The lunar exposure has been comparatively recent, I mean in the last couple of billion years. The exposures that produce these rare gases were older, presumably, and does one not assume that such conditions as the ratio of the age indicating flux to the solar wind flux constant? Certainly the lunar evidence, and common sense also, suggests if we were going back a long time, the cratering rate was considerably higher back at the beginning than at any later point.

ANDERS: Some of these meteorites contain xenoliths and clasts that have been separately dated and some of them are as young as 1.4 billion years. This means the compaction of these rocks happened still more recently and therefore the implantation of these noble gases did not occur at the dawn of the solar system but in recent times, overlapping the formation time of the lunar breccias.

VEVERKA: Are these argon loss ages?

ANDERS: For Kapoeta they are rubidium-strontium ages, for some of the others they are potassium-argon ages.

WETHERILL: I think it is important that you recognize you are talking about entirely different objects here. Kapoeta is a howardite which has all the characteristics of the lunar regolith. On the other hand, ordinary chondrites and carbonaceous chondrites have a very limited regolithic history, and so are not as similar as Kapoeta to the Moon. I think there are problems which are obscured by lumping all these meteorites together.

ANDERS: I am afraid you are entirely mistaken. Ordinary chondrites and carbonaceous chondrites *do* have essentially "all the characteristics of the lunar regolith": microcraters, solar flare tracks, anisotropically irradiated grains, steep track gradients, solar wind gases, etc.--see the paper by Goswami *et al.* (1976) and eight other references cited in my paper. They lack the glassy agglutinates one finds in lunar breccias and in Kapoeta, for the simple reason that they don't contain enough feldspar to make glass--look at any meteorite collection and you'll see that only the feldspar-rich achondrites (like Kapoeta) have shiny, glassy fusion crusts. Ordinary and carbonaceous chondrites have dull, non-glassy crusts, because their principal minerals, olivine and pyroxene, do not readily form glasses.

CHAPMAN: Could you define how the solar wind is being implanted in this top surface layer compared to the meter depth of exposure to cosmic rays? What are the physical requirements that you have for getting implanted gas? Is mixing required?

ANDERS: For solar wind implantation, the grain must be at the very top, with essentially nothing between it and the Sun. As shown by Poupeau *et al.* (1974) in their study of aubrites, meteoritic grains spend much less time at the surface than do lunar grains, *i.e.*, 1-100 years versus 10^6 years. Thus they generally do not develop the amorphous surface layer that is very leaky for light noble gases and prevents lunar grains from building up their full complement of He and Ne relative to Xe. To account for these short ages, some mixing or blanketing process is required. Poupeau *et al.* have shown for aubrites that the solar flare track densities imply a residence time of 10^3-10^4 yrs in the top 10 μm, compared to 10^6-10^7 yrs for lunar grains. Most grains do not show evidence for multiple exposure, and so the process is best described as "blanketing" or "burial," rather than "mixing."

ZELLNER: There are on the order of one hundred S asteroids with diameters larger than 50 km. We have detailed spectra for a little less than half of them. So you cannot exclude that among the S asteroids which have not been studied by more diagnostic techniques there could be ordinary chondritic bodies. And we don't need a lot of them, correct?

ARNOLD: Wetherill's argument is that there are special dynamic means to bring these things to the Earth. If that is true, then it is not the whole collection that is contributing in some proportional way, but three or four objects. There is other evidence concerning bunching of bombardment ages and things of that kind which strengthen those arguments very much, it seems to me. And so it may very well be that most ordinary chondrites are coming from a very limited number of parent bodies which allows, as far as I am concerned, Zellner's point to stand. It may turn out that they are undiscovered.

ANDERS: I agree that the parent bodies of the ordinary chondrites may be just a small subgroup of the S asteroids. But if my arguments are valid, then the majority of the other S asteroids are chondritic with no more than 20% metal.

WETHERILL: With regard to the S asteroids, I don't see why they have to be a mesosiderite of the same sort we have in the laboratory. They could very well be differentiated objects which have mixtures of iron and basaltic materials on the surface, which on a different scale would be a mesosiderite, but they could be in our collections as basaltic achondrites and as iron meteorites.

ANDERS: If that is true, then there should be many basaltic clasts among the xenoliths, and yet not one has been found. According to Figure 7 of my paper, the known meteorite classes comprise some 10 space probes that traverse at least part of the asteroid belt and collect a more or less unbiased sample. Among the first 27 such samples collected, we have found no howardites, no eucrites, and no mesosiderites. I would argue that anything we don't see probably is rare, though this conclusion is limited both by statistics and by observational selection. For example, olivine xenoliths would have been largely overlooked.