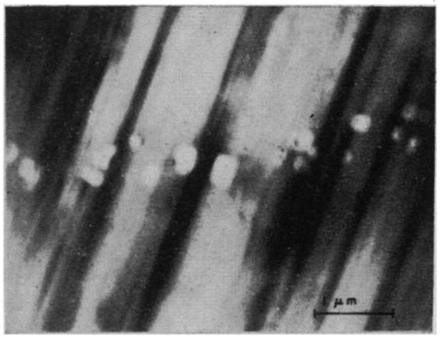

Fig. 4. Negative crystals (bubbles bounded by low-index crystal faces) in chrondrule pyroxene showing exsolution.

with and amplify those of Van Schmus (*20*), from which he concluded that type III (C3) carbonaceous chondrites have not been produced by metamorphism of type II (C2) carbonaceous chondrites. We thus conclude that the Allende meteorite consists of virgin planetary material. Its low content of water and some other volatile species indicates either formation in a region of the early circumsolar plasma deficient in these elements, or accretion under conditions unfavorable to condensation or entrapment of these components.

Note added in proof: Fireman, DeFelice, and Norton (*21*) have recently reported U, Th-^{4}He, and K-^{40}Ar ages for Allende in which the chondrules date older than the whole rock (and hence the matrix). These results are consistent with the results reported here.

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7. We cannot completely rule out the possibility that the intergranular film consists of nonbiogenic organic material, but we prefer to believe that it consists of graphite because of the correspondence of the lattice spacing indicated by the diffraction ring to the (0002) spacing of graphite.
8. Barred olivines are dendritic crystals with parallel tabular inclusions of glass or of extremely fine-grained material. A section cut through this structure reveals parallel "bars" of olivine in crystallographic continuity, separated by "bars" of the included material. They probably are the result of crystallization during very rapid cooling, having much in common with the structure found in quenched melts by E. Roedder and P. Weiblen [*Proceedings of the Apollo 11 Lunar Science Conference*, A. A. Levinson, Ed. (Pergamon, New York, 1970), vol. 1, p. 818, figures 30 and 31].
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11. Larger, optically visible bubbles are common in the lunar basalts and in many terrestrial igneous rocks, especially in peridotites. These inclusions commonly contain glass and silicate crystals, and the ones from peridotites usually contain liquid carbon dioxide under pressure. E. Roedder [*Amer. Mineral.* **50**, 1746 (1965)] and E. Roedder and P. Weiblen [*Proceedings of the Apollo 11 Lunar Science Conference*, A. A. Levinson, Ed. (Pergamon, New York, 1970), vol. 1, p. 801] interpret these bubbles to be droplets of an immiscible liquid incorporated during crystallization. Most of these larger inclusions are not negative crystals, but are subspherical. The shape of the bubbles in Allende crystals and the lack of condensed phases within them suggest the different origin suggested above, that is, intracrystalline precipitation of a gaseous phase.
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16. It is well known that the production of radiation damage is most pronounced at the end of the "range" of the particles in the radiation flux, when the rate of energy loss is highest. Passage through the initially isolated submicroscopic crystallites may not attenuate cosmic rays or other damage-producing particles sufficiently for them to produce damage. We do not presently understand the absence of the black-spot structure in the barred olivine chondrule; the structure was found in other chondrule olivine crystals which contain similar inclusions. Although perplexing, these observations are in accord with the sporadic occurrence of black-spot structures in the lunar material (*9, 12*).
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A Mechanism for Producing Magnetic Remanence in Meteorites and Lunar Samples by Cosmic-Ray Exposure

Abstract. *An irradiation of 3×10^{17} neutrons per square centimeter in a reactor core produced an increase in the coercive force of iron and kamacite of 16 to 21 percent. The alternating-current demagnetization spectrum of saturation isothermal remanence was shifted toward higher coercive forces. Similar neutron fluences produced by cosmic-ray exposure may be capable of converting soft isothermal remanence in meteorites and lunar samples to remanence with a higher coercive force.*

A new mechanism is proposed by which magnetically soft isothermal remanence acquired by meteorites and lunar samples may be converted to remanence with a higher coercive force. The mechanism is the creation of lattice defects and their associated stress fields by exposure of iron and kamacite to cosmic radiation. Centers of internal stress are known to be ef-

Table 1. Bulk coercive force of iron and kamacite samples before and after neutron irradiation, as found by hysteresis experiments.

Sample	Coercive force (oersteds)		Increase produced by irradiation (%)
	Before irradiation	After irradiation	
Iron	0.28	0.34	21
Kamacite	1.65	1.91	16

fective in pinning domain walls by magnetostrictive interaction. Such pinning is capable of yielding large changes in the coercive force spectrum of magnetic minerals, especially if the initial coercive force is low (*1*). Magnetic anisotropy may also be increased by the introduction of anisotropic defects during irradiation (*2*). We have exposed samples of iron and kamacite to a neutron radiation level comparable to that experienced by meteorites and lunar samples and have observed an increase in coercive force of 21 and 16 percent, respectively.

Protons with an average energy of 4 Gev constitute 80 percent of the cosmic radiation flux (*3*). Reactions of cosmic-ray protons with atomic nuclei produce neutrons as by-products. A recent study of the isotopic composition of gadolinium in the Norton County aubrite (with a cosmic-ray exposure age of 240 million years) indicated that the isotopic abundances are compatible with a neutron fluence (time-integrated flux) of 6×10^{15} neutrons per square centimeter (*4*). Approximately one-half of these secondary neutrons had energies of several million electron volts. Our research was therefore focused on the question of whether high-energy protons or neutrons with energies of several million electron volts are capable of changing the structure-sensitive magnetic properties of iron or kamacite.

The basic phenomenon in producing lattice damage by radiation is the collision cascade (*5–7*). The collision of a bombarding particle with a lattice atom imparts energy to the struck atom. This atom is termed the primary knock-on and may be displaced from its lattice site if the energy transferred is large enough. If the primary knock-on has enough energy to displace other lattice atoms, a showering of displacements known as the collision cascade results.

Quantities that are important in determining whether a particular irradiation will result in the production of large collision cascades include the following (*5, 6*):

1) T_m: Maximum energy that can be imparted to a primary knock-on by a bombarding particle.

$$T_m = [4M_1M_2/(M_1 + M_2)^2]E$$

where E = energy of the bombarding particle, M_1 = mass of the bombarding particle, and M_2 = mass of the lattice atom.

2) $\overline{T}$: Average energy transferred in a collision. For charged particle irradiation

$$\overline{T} = [(E_dT_m)/(T_m - E_d)] \ln (T_m/E_d)$$

where E_d = the energy necessary to displace an atom from its lattice site. For neutron irradiation

$$\overline{T} \cong T_m/2$$

3) $\overline{\rho}$: Mean number of displaced atoms per primary knock-on.

$$\overline{\rho} = \frac{1}{2}\frac{T_m}{T_m - E_d}(1 + \ln\frac{T_m}{2E_d})$$

for charged particle irradiation and

$$\rho \cong T_m/4E_d$$

for neutron irradiation of iron. The end result of a collision cascade is a cluster of vacancies with interstitial atoms in the surrounding lattice. This could be thought of as a large number of Frenkel defects. Some of the damage will anneal because of the mobility of interstitial atoms. However, a tangle of vacancy loops and small vacancy clusters will remain.

Charged particles lose energy almost entirely by ionizing the target until their energy drops below a threshold level, defined by Dienes and Vineyard (*5*) as E_i. For a metal target, this threshold is given by:

$$E_i = \frac{1}{16}\ (M_1/m)\ E_f$$

where M_1 = mass of the bombarding charged particle, m = mass of electron, and E_f = Fermi energy of the target metal. For an iron target, we find that protons will not interact elastically with the lattice atoms until their energy drops to below 1 kev. For cosmic-ray protons bombarding an iron target, we find that T = 425 ev and $\overline{\rho}$ = 8.08. The result would be only eight Frenkel defects per collision. We conclude that primary cosmic-ray protons will not yield a significant level of lattice damage.

The situation is quite different for neutron irradiation where all energy is dissipated by collisions with lattice atoms. For a 2-Mev neutron bombarding iron, T = 70 kev and $\overline{\rho}$ = 640. The number of displaced atoms in this case is large enough to significantly change the internal stress and possibly to increase the coercive force.

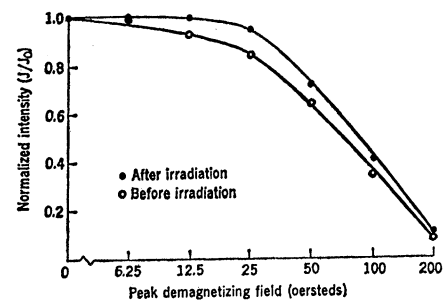

Fig. 1. Alternating field demagnetization of saturation isothermal remanence of annealed iron. Open circles are results of the unexposed sample. Solid circles are results after irradiation of 3×10^{16} neutrons per square centimeter in the energy range $\geqq 3$ Mev. Before irradiation, the sample was given saturation remanence. The intensity of saturation remanence before irradiation was 1.60×10^{-2} emu/g, and after irradiation it was 1.45×10^{-2} emu/g. An increase in coercive force spectrum is indicated by the shift of the curve toward the right.

The following experiments were undertaken to determine whether the expected increase in coercive force could be observed in metals with compositions similar to those found in meteorites and lunar samples. Iron samples were machined from a puron rod (99.95 percent iron) and annealed in hydrogen gas up to 1200°C. Hysteresis experiments showed an initial coercive force of 0.28 oersted. Kamacite samples were fabricated by alloying puron and electrolytic nickel (99.97 percent nickel) to a final composition of 5 percent nickel by weight. These samples were also annealed in hydrogen gas at 1000°C. An initial coercivity of 1.65 oersteds was observed in these samples.

In addition to the measurements of bulk coercivity, a-c demagnetization of saturation isothermal remanence of one iron sample was also measured. This experiment yielded more detailed information about the coercivity spectrum than could be obtained from simple hysteresis measurements. Prior to irradiation, this sample was again given saturation remanence.

A total fluence of 3×10^{17} neutrons per square centimeter was produced by a 3-hour exposure in the core of the U.S. Geological Survey reactor.

Approximately 10 percent of the fluence was composed of neutrons with energies of 3 Mev or greater. The effects of this irradiation on the bulk coercive force and the a-c demagnetization spectrum of saturation isothermal remanence are summarized in Table 1 and Fig. 1, respectively. Increases in coercive force are substantial for both pure iron and kamacite. The larger increase in iron is probably due to its more complete state of anneal rather than to any compositional effect.

Two important conclusions can be drawn from the a-c demagnetization experiments. First, strong isothermal remanence is not destroyed by the flux of thermal neutrons or by the lattice damage produced by the high-energy neutrons; second, the coercive force of the isothermal remanence is increased. In fact, the reactor irradiation in this experiment decreased the intensity of the preirradiation saturation isothermal remanence by only 10 percent, whereas it *increased* the intensity of remanence with coercivity greater than 100 oersteds by 5 percent. This appears (Fig. 1) as a shift of the a-c demagnetization curve toward higher fields. Apparently the lattice damage has resulted in stronger pinning of some of the domain walls responsible for the original remanence. The introduction of anisotropic defects may also have produced an anisotropy that favors the domain configuration present during the irradiation.

Our conclusion is that the stability of isothermal remanence in meteorites and lunar lava samples may be increased by neutron irradiation of the type encountered during cosmic-ray exposure. Whether this process can account for the natural remanence of such samples depends on the answer to two questions. The first is whether the process here reported also occurs in samples with higher initial coercivities such as those found in meteorites and lunar samples. Experiments to determine this are in progress. The second is whether a mechanism exists by which the samples may acquire initial isothermal remanence. A possible mechanism is the production of interplanetary magnetic fields of from 10 to 20 gauss by strong solar magnetic flares, as has been proposed by Sonnet *et al.* (*8*). Only one such magnetic pulse would be needed during the history of the solar system if it occurred after the time of formation of the youngest lunar lavas. Subsequent conversion to more stable remanence would then occur during exposure to cosmic radiation.

This explanation of natural remanence in chondritic meteorites and lunar samples does not require the possession of a magnetic field by the parent bodies. Natural remanence in chondritic meteorites has previously been considered as evidence that meteorites were derived from a lunar-sized parent planet whose iron-nickel core acted as a magnetohydrodynamic generator (*9*). The theory that meteorites originated in such a parent body was advanced by Ringwood (*10*). The findings of this report could bring paleomagnetic evidence into accord with the theory of meteorite origin proposed by Wood (*11*). The parent bodies in Wood's theory are asteroidal in size and would not be expected to possess a magnetic field. The present mechanism differs from earlier ones in not requiring a planetary magnetic field in each of the meteorite bodies.

If the remanent magnetization of lunar lavas is thermoremanence, then it is necessary to assume that a magnetic field existed at the time of formation of *each* of the lavas. Since the ages of the Apollo 11 and Apollo 12 lavas are approximately 3.6 and 3.3 billion years, respectively (*12*), the thermoremanence mechanism requires that the field, if it was not intermittent, persisted for an interval of at least 300 million years. The source of such a continuing field might be either the earth's field during a close orbit of the moon (which is unlikely) or a magnetohydrodynamic generator in a fluid lunar core. However, if the remanence of the lunar lavas was acquired by the mechanism advanced in this report, only one magnetic pulse is required at some time subsequent to the age of the youngest lunar lavas.

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Mariner 6 and Mariner 7 Ultraviolet Spectrometer: In-Flight Measurements of Simulated Jupiter Atmosphere

Abstract. *An experiment has been performed in interplanetary space which closely simulates the observations that would be made by an ultraviolet spectrometer observing the atmospheres of the jovian planets. A mixture of ammonia, nitrogen, and hydrogen was released from the Mariner spacecraft, and spectra were recorded while these gases were illuminated by sunlight. The principal emissions observed were the HI 1216-angstrom Lyman-α line, the H_2 B–X Lyman bands, and the NH c–a and A–X bands.*

In December 1970, experiments were performed by the Mariner 6 and Mariner 7 spacecraft to simulate the ultraviolet spectrum that would be viewed by an ultraviolet spectrometer observing Jupiter or the other outer planets. The Mariner spacecraft were in interplanetary flight 240 million km from Earth and 120 million km from the sun nearly in the plane of the ecliptic, after having made measurements on Mars 16 months earlier.

Sunlit gaseous dissociation products of the course-correction motor on the