Lunar and Planetary Science XIX

Nineteenth Lunar and Planetary Science Conference

PRESS ABSTRACTS

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PRESS ABSTRACTS

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PREFACE

The Program Committee for the Nineteenth Lunar and Planetary Science Conference has chosen these contributions as having the greatest potential interest for the general public. The papers in this collection have been written for general presentation, avoiding jargon and unnecessarily complex terms. More technical abstracts will be found in *Lunar and Planetary Science XIX.*

For assistance during the conference, call the NASA Johnson Space Center News Center at (713)483-5111. Telephone numbers of the first author of each contribution will be found on page *iii.* Feel free to call for more information.

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The Origin of the Moon: Further Studies of the Giant Impact

by **W. Benz** and **A. G. W. Cameron**
Harvard-Smithsonian Center for Astrophysics
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The paper discusses a number of technical improvements in the calculations which simulate the most violent event that has occurred to the Earth during its history: its collision with the next largest body which was present in its region of accumulation in the early solar system. This body was a planet in its own right, an object a little more massive than the planet Mars. The collision created a disk of molten and gaseous debris in orbit around the protoearth, and it is believed that the dissipation of this disk resulted in the formation of the Moon.

The paper also discusses a serendipitous discovery that has emerged from the simulations: the role played by a huge, hot, rotating bar of rock and iron, which is formed immediately after the collision, in transferring angular momentum to much of the rock that is put into orbit, and in robbing the iron of angular momentum so that it falls promptly into the protoearth.

Curiosity about the origin of the Moon played an important part in persuading NASA to establish the Apollo project that placed men on the surface of the Moon almost twenty years ago. At the time there were three competing theories of the origin of the Moon:

1. Capture theory. It was postulated that the Moon was formed elsewhere in the solar system and was captured by the Earth.
2. Formation of the Moon in orbit. It was postulated that the Moon was formed from material that had been captured into orbit around the Earth after the Earth was mostly formed.
3. Fission theory. It was postulated that the Earth spun fast enough so that it became deformed and a piece broke off to become the Moon.

As the Apollo project progressed it became noteworthy that very few scientists working on the project were changing their minds about which of these three theories they believed was most likely to be correct, and each of the theories had its vocal advocates. In the years immediately following the Apollo project, this continued to be true. One observer of the scene, a psychologist, concluded that the Moon scientists were extremely dogmatic and largely immune to persuasion by scientific evidence. But the facts were that the scientific evidence did not single out any of the three theories. Each one of them had several grave difficulties as well as one or more points in its favor.

In the mid-1970's other ideas began to emerge. W. K. Hartmann and D. R. Davis, of the Planetary Sciences Institute in Tucson, pointed out that the Earth, in the course of its accumulation, would undergo some major collisions with other bodies having a substantial fraction of its mass, and that these collisions would produce large vapor clouds that they believed might play a role in the formation of the Moon. A. G. W. Cameron and W. R. Ward, at Harvard, pointed out that a collision with a body having at least the mass of Mars would

be needed in order to give the Earth the present angular momentum of the Earth-Moon system, and they also pointed out that such a collision would produce a large vapor cloud that would leave a substantial amount of material in orbit about the Earth, the dissipation of which could be expected to form the Moon. From these suggestions has emerged the Giant Impact theory of the Moon's origin.

These ideas produced relatively little comment in the scientific community during the next few years. However, when a scientific conference on the origin of the Moon was organized at Kona, Hawaii, in 1985, a surprising number of papers were submitted which discussed various aspects of the Giant Impact Theory. At the same meeting the three classical theories of formation of the Moon were also discussed in depth, and it was clear that all of them continued to present grave difficulties. Giant Impact emerged as the "fashionable" theory, but everyone agreed that it was relatively untested and that it would be appropriate to reserve judgment on it until a lot of testing had been carried out. The next step clearly called for numerical simulations to be carried out on supercomputers.

The authors of this paper were among those who undertook such simulations. H. J. Melosh, with C. P. Sonett and A. M. Vickery at the University of Arizona and M. E. Kipp at Sandia Laboratories, Albuquerque, used conventional techniques to study two-dimensional representations of the planetary collision hypothesis; they confirmed that a large cloud of vapor would be formed in the collision and that a significant part of it would be left in orbit around the Earth. Benz and Cameron, together with W. L. Slattery at the Los Alamos National Laboratory, used an unconventional technique called smoothed particle hydrodynamics to simulate the planetary collision in three dimensions. With this technique they were able to follow the simulated collision for many hours of real time, determining the amount of mass that would escape from the Earth-Moon system, the amount of mass that would recollide with the Earth, and the amount of mass that would be left in orbit, as well as the relative amounts of rock and iron that would be in each of these different mass fractions. They carried out simulations for a variety of different initial conditions, and were able to show that a "successful" simulation was possible if the impacting body had a mass not very different from 1.2 Mars masses, that the collision occurred with approximately the present angular momentum of the Earth-Moon system, and that the impacting body was initially in an orbit not very different from that of the Earth.

The Moon is a compositionally unique body, having not more than four percent of its mass in the form of an iron core, and more likely only two percent of its mass in this form. This contrasts with the Earth, a typical terrestrial planet in bulk composition, which has about one-third of its mass in the form of the iron core. Thus a simulation could not be regarded as "successful" unless the material left in orbit was iron-free or nearly so and was substantially in excess of the mass of the Moon. This uniqueness highly constrains the conditions that must be imposed on the planetary collision scenario. If the Moon were formed of a typical composition of other terrestrial planets, it would be far more difficult to determine the conditions that led to its formation.

We turn now to the specific developments reported in our paper for the 19th Lunar and Planetary Science Conference.

In conventional hydrodynamics the volume of space in which the action takes place is divided into a grid, or mesh, with the fluid (liquid or gas) occupying cells within this

mesh. If the mesh is fixed in space and the fluid moves through the mesh from one cell to another, the mesh is called an Eulerian mesh. If the mesh is not fixed in space but moves with the particles in their motion, it is called a Lagrangian mesh. The two-dimensional calculations carried out by Melosh and his colleagues were of the Eulerian type. In the smoothed particle hydrodynamics (SPH) method there is no mesh at all. The fluid is represented by a distribution of mass points, each of which is considered to have a finite volume whose radius is represented by a quantity called the smoothing length. SPH is thus intrinsically a Lagrangian method. Such bulk properties of the fluid as density and pressure are determined by averaging over the distribution of particles.

The early SPH simulations of the Giant Impact were carried out at Los Alamos and used several hundred hours of Cray XMP supercomputer time there. Since then a number of improvements have been made in the method:

1. The shape of the smoothed particles has been changed. Initially the density within the particles fell off exponentially with increasing distance; now the density goes to zero at twice the smoothing length. This allows a more accurate representation of the density in an object.
2. The method of calculation of the mutual gravitational attraction between the particles has been changed to one that is computationally more efficient.
3. The material assumed to represent rock in the calculation has been changed from the originally-assumed granite to dunite, a common material (olivine) which better represents the properties of the Earth's mantle. The thermodynamic properties of the rock and the iron have been better represented through the use of a different equation of state.

With the improved computational efficiencies of the revised SPH code, it has been possible to run the SPH code on very fast small computers, which must be dedicated to the program. The results reported in the paper were carried out with a Sun 3/260 workstation and a with Definicon 780+/4 attached processor (an insert card for a personal computer), both at Harvard University. The improvements in the speed of the code have been much greater for these small computers that for parallel processors such as the Cray; thus for SPH (but not for other more typical programs) the speed on the Sun has been about ten percent of that on the Cray and the speed on the Definicon board has been about three percent of that on the Cray.

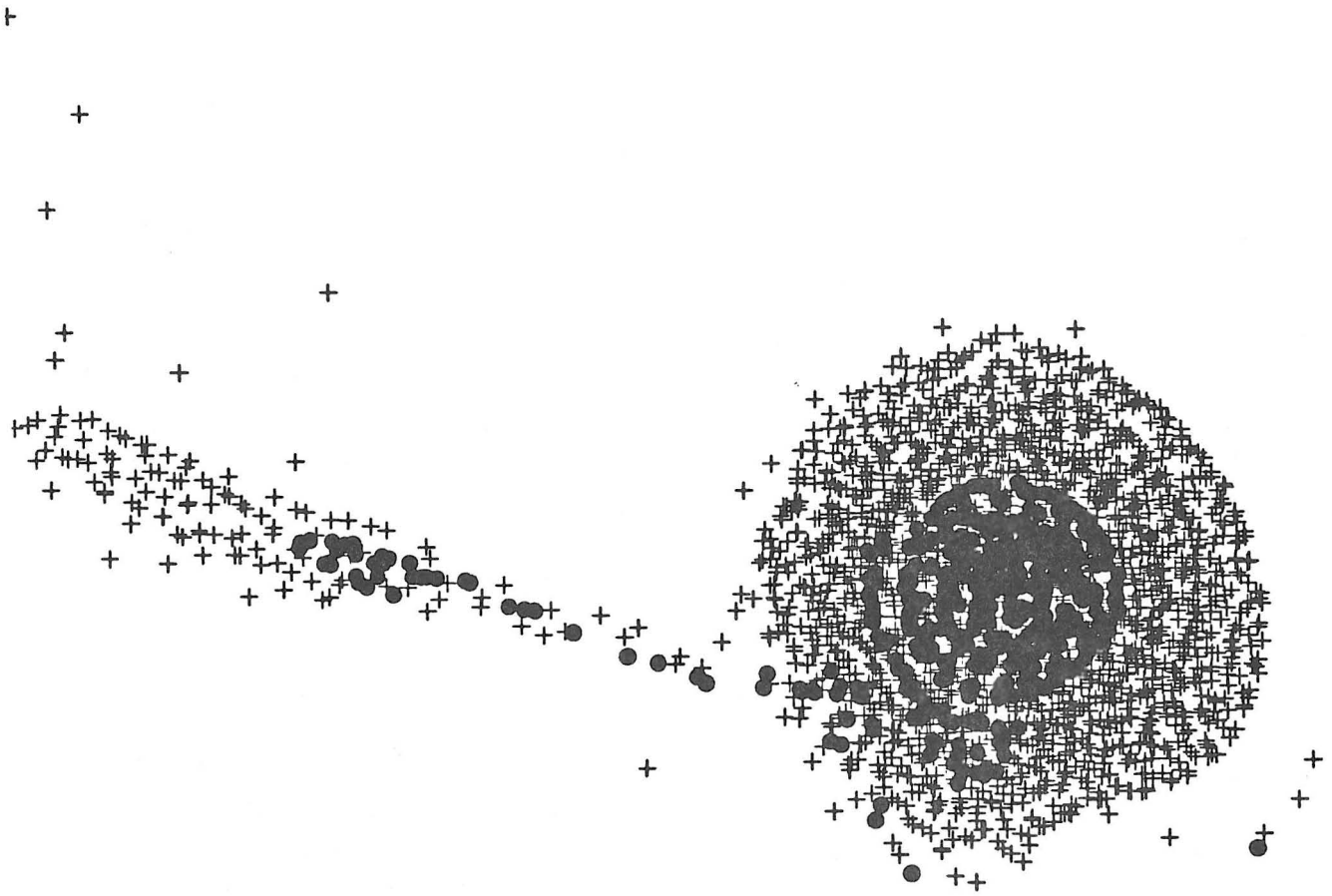
The revised SPH code should give a more accurate representation of the Giant Impact. We were therefore somewhat disappointed to find that less rock was placed into orbit and that its mean orbital radius was less than in the original Los Alamos runs under similar starting conditions. For this reason we decided to run some cases with increased angular momentum, the argument being that the angular momentum of the Earth-Moon system has diminished somewhat with time because of the action of solar tides on the Earth. Indeed, we found that a large increase in the mass put into orbit and of its mean orbital radius occurred when the angular momentum in the problem was increased over the old value by just five percent. Any larger increase results in placing a lot of iron in orbit, an unacceptable result. These results were gratifying but raised an important question: why were the results so sensitive to the initial conditions?

An examination of the most successful current run indicated that a very unusual process

had taken place. After the main part of the collision had taken place and a big debris cloud had splashed off the Earth, much of this debris cloud organized itself into a slowly rotating bar, which became extraordinarily straight and thin as the organization of it progressed. The iron from the impacting body was contained in that half of the bar nearest the Earth, while the outer part of the bar was composed of rock. The bar was extremely efficient at transporting angular momentum; rock particles peeled off from the bar into high orbit about the Earth. The angular momentum which had been given to these outer rock particles came at the expense of the iron particles, which were robbed of their angular momentum and streamed straight into the Earth, where they penetrated through the Earth's mantle and wrapped themselves around the core. After about half of an orbit around the Earth, the remaining rock particles in the bar gradually drifted apart, and the bar lost its coherence.

A bar is a greatly elongated prolate spheroid; rotating spheroids of that type are gravitationally stable objects. That is why one commonly sees them at the centers of barred spiral galaxies. However, that is the only place where they are commonly found in nature. It was a surprise to us to find that such bars can play an important role in planetary collisions. This opens up a fascinating subject for further research.

Below on this page we show a picture of the bar in operation. Rock particles are represented by crosses and iron particles are represented by filled circles.



EXOTIC MINERALS IN 3,500 MILLION YEAR OLD ROCKS EVIDENCE FOR LARGE METEORITE IMPACTS

G. R. Byerly, D. R. Lowe, Louisiana State Univ.; F. Asaro, Univ. of California

A relatively small area of mountainous terrain in southern Africa has been providing scientists from all over the world a "look" at what the surface of the Earth was like three and a half billion years ago. The Barberton Mountains lie astride the borders of the Republic of South Africa, Mozambique, and the Kingdom of Swaziland. At this month's Lunar and Planetary Science Conference in Houston Gary R. Byerly and Donald R. Lowe of Louisiana State University and Frank Asaro of the University of California at Berkeley reported to international planetary scientists the discovery of several widely distributed deposits that were likely formed by major terrestrial impacts of large extraterrestrial bodies during this early period of Earth's history.

About 65 million years ago and again about 39 million years ago large extraterrestrial bodies collided with the Earth to produce worldwide catastropic effects. Large volumes of surface material were melted, perhaps even vaporized, and hurled into Earth orbit. As this material re-entered the atmosphere it had a major effect on diminishing sunlight reaching the Earth's surface. The resultant lower surface temperatures and decrease in photosythetic activity by plants, led to widespread extinctions.

Sediments related to such meteorite impacts contain unusual concentrations of elements that are much more common in meteorites than in terrestrial rocks. Another unusual feature of these rocks is the presence of sand-sized spherical glassy objects that apparently formed in the hot cloud of material produced by the impact. The three and a half billion year old Barberton Mountains impact deposits share many of the characteristics of the younger, generally accepted impacts at 65 and 39 million years ago. The Barberton impact deposits contain small spherical objects whose texture indicates that they were originally glass beads. The deposits are widespread, perhaps covering the full known extent of rocks of this age in southern Africa, but at least an area of some 1000 square kilometers. And most significantly, the Barberton impact deposits contain unusually high concentrations of elements such as iridium that also characterize younger impact deposits, and are regarded as derived from the impacting extraterrestrial body.

The Barberton impact deposits are being studied by electron microscopy by geologists Byerly and Lowe and by neutron activation by physicist Asaro. Although the compositions of the original glass and minerals were modified

sometime after deposition in the shallow seas that covered the area that is now the Barberton Mountains, some important aspects of the present composition of the deposits appear to be original. In addition to iridium, several other elements seem to have been unaffected by surface alteration. These include aluminum, titanium, zirconium, and vanadium. The abundance patterns for these elements suggest that the impact was at a site like modern oceanic crust, that is, on basaltic volcanic rock. The data further suggest that the impact-derived sediment contains about a 20% meteoritic component. The size of the meteorite may be estimated through observations made in the field area. The impact deposits in the Barberton Mountains appear to be far removed from the impact site and yet are very thick, up to 100 centimeters of nearly pure impact-generated spherules. This suggests an impacting object that was perhaps even larger than the one, estimated to have been about 10 km in diameter, that slammed into the Earth 65 million year ago.

The Barberton impact deposits were examined for minerals that might either show the effects of shock metamorphism or compositions unusual in terrestrial rocks. Quartz grains are commonly found to contain shock-induced lamellae in deposits formed by younger impacts. No shocked quartz grains have been found in the Barberton deposits, but quartz would have been a very minor component in the proposed impact target of basaltic oceanic crust. One unusual mineral occurs in the Barberton impact deposits - - an oxide that contains abundant nickel and other transition metals. Experimental studies have shown that this mineral is likely to crystallize only from high temperature sulfide or metal liquids. Such liquids may have coexisted with the more abundant silicate liquids produced during the impact. These nonsilicate liquids may also have concentrated such elements as iridium. If these exotic oxide minerals do prove to be the carriers of iridium in the Barberton rocks, they may provide scientists with a mineralogical tool for prospecting for early terrestrial impacts. The concentration of transition metals in sulfide or metal melt phases may also be of potential economic value if the actual impact site can be located.

Because of the abundance of meteorite impact craters on the Moon, planetary scientists generally agree that the first five hundred million years of Earth's history was characterized by many large impacts with extraterrestrial objects. Also generally accepted, but somewhat more controversial, is the role of rare large-scale impacts up until the present. The evidence of extraterrestrial impacts from the Barberton Mountain Land may allow planetary scientists to refine models of how impacts affected the early development of the Earth.

Geologists from Louisiana State University have made a number of major discoveries in rocks from the Barberton Mountains over the past ten years. They recently reported in the international journal NATURE evidence of fossilized bacteria, the oldest found on Earth; and stromatolites, the colonial mounds built by such microorganisms. A long-term goal of this research is to further our understanding of how volcanism, impacts, and the changing composition of the Earth's early atmosphere and hydrosphere affected surface conditions during this critical time in the initial formation of landmasses and the evolution of life.

PRESS RELEASE FOR "CHEMISTRY AND MINERALOGY OF EARLY ARCHEAN IMPACT DEPOSITS" Gary R. Byerly and Donald R. Lowe, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803 USA, and Frank Asaro, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720 USA

NON-ATMOSPHERIC NOBLE GASES FROM CO_2 WELL GASES; M. W. Caffee[1], G. B. Hudson[1], C. Velsko[1], E. C. Alexander, Jr.[2], G. R. Huss[2], and A. R. Chivas[3]. [1]Lawrence Livermore National Laboratory, Livemore, CA, 94550, [2]Dept. of Geology and Geophysics, Univ. of Minn., Minneapolis MN 55455, [3]Research School of Earth Sciences, Australian Natl. Univ., Canberra, A.C.T. 2601, Australia.

In recent years a number of studies of both terrestrial and extra-terrestrial material has allowed us to piece together a picture of events occurring in the early solar system (4.5 Gyr ago), including the formation of the Earth. However, before this picture can be completed with an appropriate amount of detail it will be necessary to make further advances. One of the areas where we are lacking is in our knowledge of the chemical and isotopic composition of the Earth as a whole. The lack of knowledge has less to do with the capabilities of modern techniques than with the availability of samples to study. About 99.6% of the Earth's mass is contained in the Earth's mantle and core, leaving less than 1% in the crust and atmosphere. Although the crust is derived from the mantle it has undergone extensive changes and it is therefore difficult (although not impossible) to use crustal material to study events occurring 4.5 Gyr ago. More information about the early Earth could be obtained from studies of the mantle but it is difficult to obtain mantle material, because the mean thickness of the crust is 17 km., much greater than even our deepest mines or drill shafts.

There are however, two types of mantle samples available to us. The first are igneous magmas coming from the mantle. An example of these are the basaltic rocks found on the ocean floor. Another possible source of mantle samples are gaseous emanations from deep wells. We have analyzed the noble gases (helium, neon, argon, and xenon) from three separate CO_2 gas deposits, two in Colorado (McElmo Dome and Sheep Mtn.) and one in Australia (Caroline). Xenon is in some ways an ideal probe for studying geologic activity because of its low initial abundance means that the xenon composition is sensitive to differences in source composition. In addition, the nine isotopes of xenon (masses 124 through 136) can be produced in a variety of ways. The heavier xenon isotopes are preferentially produced by the fission of heavy nuclei, uranium, for example. Indeed, it is sometimes possible to determine the parent nuclei, whether it be uranium or plutonium, based on the relative abundance of the xenon daughter isotopes. Based on our initial analyses of the CO_2 gases, about 9% of the xenon has an isotopic signature resembling the xenon found in meteorites rather than the xenon found in the Earth's atmosphere. The remainder of the xenon is atmospheric xenon plus some xenon derived from fissioning heavy nuclei.

There are three known reservoirs of xenon in our solar system. The first and largest is the xenon in our Sun. The isotopic composition of solar xenon is known primarily from our studies of solar-wind-implanted xenon in lunar soils and a few special meteorites. The second reservoir of xenon is that found in meteorites, and is referred to as planetary Xe. The isotopic composition of the light xenon isotopes (124-128) of planetary xenon is almost indistinguishable from solar xenon. This is not the case for the heavy xenon isotopes, which are noticeably different. This composition difference cannot be explained in a simple fashion and has been a topic of controversy for several decades. The third reservoir of xenon is that found in the Earth's crust and atmosphere. The light xenon isotopes in atmospheric xenon are related to the other two reservoirs by mass-fractionation. When or how this mass-fractionation occurred is unknown. Again, the relationship between the heavy atmospheric xenon isotopes and the heavy isotopes from either of the other two sources is not simple. It is certain that atmospheric xenon contains ^{129}Xe from ^{129}I decay. This nuclide was present in the early solar system but owing to its short half-life ($t_{1/2}$=17 Myr) it is no longer present. It is also likely that heavy isotopes of atmospheric xenon contain xenon from the decay of ^{244}Pu. Again, this nuclide was present in the early solar system but is now extinct because of its short half-life ($t_{1/2}$=82 Myr).

The primary question that needs an answer is whether the xenon isotopic composition of the mantle differs from the present-day atmosphere. There are several reasons why they might differ. The first has to do with the formation of the Earth's atmosphere. Our present-day atmosphere is not a primordial atmosphere as are the atmospheres of the gaseous giant planets. These atmospheres were probably gravitationally captured from the solar nebula by the planets during their formation. It is possible that the Earth also had such an atmosphere but for reasons that are unknown lost it. Indeed, none of the terrestrial planets have retained their primordial atmospheres. The Earth's present-day atmosphere originated from the solid Earth, that is the mantle. In simple terms, the Earth was heated to the point that volatile elements in solid material were released. These outgassed volatiles were gravitationally bound (excepting hydrogen and helium) to the Earth and formed an atmosphere. By studying the isotopic composition of xenon in mantle-derived samples we hope to learn whether the mantle outgassed very

quickly long ago, or has been slowly outgassing for 4.5 Gyr? Consider the possibility that the atmosphere formed very quickly 4.5 Gyr ago. If this were the case then much of the xenon in the mantle would have been outgassed to the atmosphere before all the ^{129}I and ^{244}Pu decayed. If the remaining mantle xenon has not been mixed with atmospheric xenon, then present-day mantle xenon would have an excess, relative to the atmosphere, of fission-derived xenon. Such excesses have been observed by other investigators in both igneous rocks and CO_2 for ^{129}Xe, derived from ^{129}I. Given this we would also expect excesses of ^{244}Pu-derived xenon, since Pu has a longer half-life, however, no clear-cut evidence for excess ^{244}Pu-derived xenon has been found. If, on the other hand, the mantle has outgassed slowly over the history of the Earth the xenon isotopic composition of the mantle would be the same as the atmosphere.

A second reason for having the mantle differ in composition from the atmosphere is the possibility that the mantle contains the remnant of a more primordial composition. Recall that the light xenon isotopes are related to the other two xenon reservoirs (solar and planetary) by mass fractionation. Broadly speaking there are two possible models to account for this fractionation. One possibility is that the material that accreted to form the Earth brought with it a primitive xenon component. Subsequent to the accretion of the Earth some process (perhaps related to the loss of the primordial atmosphere or to the formation of the present-day atmosphere) fractionated the xenon. Diffusion, for example, is capable of producing this type of mass-fractionation. If the processes that are responsible for producing this mass-fractionation were not global some portion of the mantle may yet contain a xenon component similar to one of the components found in meteorites. If such a component could be found it may be possible to learn something about the material that accreted to form the Earth. Complicating this issue is the possibility that the mantle accreted heterogeneously. For example, the lower portion of the mantle may have accreted from different material than the upper mantle. In this case, samples from different portions of the mantle may have different xenon compositions.

The other possibility is that the fractionation occurred in the nebula, i.e. before the accretion of the solid Earth. In this case it is possible that xenon adsorption onto small grains from the nebular gas created the mass-fractionation. This is a difficult model to test for two reasons. The first is that the state of the early nebula is difficult to quantify. Secondly, even if we knew conditions in the nebula before the formation of the Earth, it is difficult to reproduce these conditions in the laboratory. Consequently, it is hard to even propose a test of this particular model.

From a noble gas point of view, what can be said about the mantle?

Helium: Other investigators have found high $^{3}He/^{4}He$ ratios in mantle samples. This is taken as evidence that some portion of the mantle (usually assumed to be the lower mantle) is not totally outgassed.

Neon: Several types of mantle samples, including diamonds, have $^{20}Ne/^{22}Ne$ ratios higher than atmospheric neon. There are two possible explanations. The first is that the neon is severely mass-fractionated. The second is that the mantle contains a reservoir of solar-neon. All of the CO_2 well gases we analyzed have high $^{20}Ne/^{22}Ne$ ratios.

Xenon: Previous studies indicated an excess of ^{129}Xe, derived from , in some mantle-derived samples. This may indicate that the Earth's atmosphere formed quickly, i.e. almost 4.5 Gyr ago. Surprisingly, no unequivocal evidence of Pu-derived Xe has been found. This lack of Pu-derived xenon does present some problems for the conclusion about a quickly outgassed mantle. In the Caroline CO_2 gas sample we analyzed the most likely composition is 9% meteoritic (either planetary or solar) and the remainder atmospheric. There are fission excesses at the heavy isotopes. These are dominated by ^{238}U-fission however it is possible that about 20% of the fission is due to Pu decay. Given their somewhat complementary compositions, the presence of the meteoritic xenon, tends to hide the presence of fission xenon from ^{244}Pu. The result for the xenon in the Caroline CO_2 sample strengthens the case for the early outgassing of the Earth since ^{244}Pu fission xenon apparently accompanies the iodine-derived ^{129}Xe observed in the Caroline sample.

UREILITES ARE NOT IGNEOUS DIFFERENTIATES, Robert N. Clayton and Toshiko K. Mayeda, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

Although almost all meteorites are as old as the solar system (4.5 billion years), they can be subdivided into primitive and evolved groups, depending on the extent of their chemical and physical processing. Primitive meteorites, most of which are chondrites, are assemblages of dust and millimeter-sized pellets from the pre-solar nebula, which have not been extensively heated and processed since their assembly. Thus they provide information about the conditions in the nebular cloud. Many of the evolved meteorites are achondrites, which are igneous rocks produced by melting on or within an asteroidal object known as the "parent body". A major unsolved problem in solar system studies is identification of the source of heat which led to melting of the achondrites.

The most poorly understood of the achondritic meteorites are known as ureilites. Until recently, only about ten of these were known; the Antarctic collections have more than tripled the number of ureilites. These meteorites have the appearance of igneous rocks, but are unique in also containing about 3% elemental carbon, some of which is in the form of diamond. Previous models for the origin of ureilites, based primarily on trace-element abundances, have suggested a complex history of melting, solidification, and re-melting in a large parent body.

Oxygen isotopes play an important role in establishing genetic relationships among meteorites. All rocks from a single geologically active parent body follow a simple straight-line relationship between $^{17}O/^{16}O$ and $^{18}O/^{16}O$, where ^{16}O, ^{17}O, and ^{18}O are the three stable isotopes of oxygen. This simple relationship has already been seen for rocks from four planetary bodies: (1) the Earth, (2) the Moon, (3) the SNC parent (possibly Mars), and (4) the eucrite parent body. Rocks from each of these bodies can be recognized as having a common source on the basis of their oxygen isotopes. The same test applied to the ureilites, however, reveals a totally different pattern, indicating that the ureilites are not produced by large-scale igneous activity on a partially molten parent body. The isotopic pattern for ureilites is far from random, however, and in fact follows closely the pattern previously observed for the C3 carbonaceous chondrites — one of the most primitive of all meteorite groups. Thus the ureilites possess a peculiar combination of properties: evidence for both a primitive origin of their raw materials as well as a high-temperature, but necessarily localized, melting event. Some sort of impact-melting, perhaps on a large scale, but of short duration, may have been involved.

A few of the ureilites are known to be breccias -- fragmented rocks containing materials of diverse composition and texture. The oxygen isotopic patterns of the individual fragments show that they were derived from different parts of a heterogeneous parent body of the carbonaceous chondrite type. If the ureilite precursor was really as primitive as the carbonaceous chondrites, it may be possible to detect the decay product of radioactive ^{26}Al, which is known to have been present when the carbonaceous chondrites formed. Preliminary searches for the decay product, ^{26}Mg, have failed to produce evidence for ^{26}Al in the ureilites. Establishment of a time-scale for ureilite formation will be important for understanding accretion of asteroidal bodies, as well as the above-mentioned heat source for melting of planetesimals.

It was noted above that most of the ureilites have been found on the Antarctic ice, as part of the American and Japanese collections over the last 15 years. In fact the results described here could not have been obtained without the Antarctic samples, which provide a much wider variety of ureilite compositions than is available in the non-Antarctic specimens.

NEW TYPE OF PRIMITIVE METEORITE FOUND IN ANTARCTICA.

J.N. Grossman[1], A.E. Rubin[2], G.J. MacPherson[3], E.R.D. Scott[4], M.K. Weisberg[5,6], M. Prinz[5] and C.E. Nehru[5,6]. 1) U.S. Geological Survey, National Center MS 990, Reston, VA 22092; 2) Inst. Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024; 3) Department of Mineral Sciences, Smithsonian Institution, Washington, D.C. 20560; 4) Institute of Meteoritics, Dept. of Geology, University of New Mexico, Albuquerque, NM 87131; 5) Amer. Museum of Natural History, New York, NY 10024; 6) Brooklyn College, CUNY, Brooklyn, NY 11210.

A stony meteorite found in Antarctica in 1985, recently identified as a new type of chondrite, probably represents material from a previously unsampled region of the solar system. Scientists are currently debating how the unique object formed.

Preliminary results on Allan Hills 85085 (ALH85085) were presented in a special session dedicated to this 12-gram meteorite at the 19th Lunar and Planetary Science Conference in Houston on March 16, 1988.

Most researchers conclude that ALH85085 is an unusual and unique chondrite. A group composed of J.N. Grossman (U.S. Geological Survey), A.E. Rubin (UCLA) and G.J. MacPherson (Smithsonian Institution) believes that ALH85085 is a carbonaceous chondrite. M.K. Weisberg, M. Prinz and C.E. Nehru (American Museum of Natural History) conclude that ALH85085 is intermediate between ordinary and enstatite chondrites. E.R.D. Scott (Univ. New Mexico) points out that ALH85085 has properties of all three chondrite groups, but may not belong to any of them.

All of the current studies agree that ALH85085 is extremely fresh and has not been altered since it formed. Thus, whatever type of chondrite ALH85085 proves to be, this meteorite may provide fundamental insights into the earliest events in the solar system.

The carbonaceous chondrites are thought to have formed farthest from the sun, the ordinary chondrites at an intermediate distance and the enstatite chondrites closest to the sun in the early solar nebula. The properties of the Earth indicate that it formed from material similar, but not identical to the known chondrite groups.

If ALH85085 is intermediate between enstatite, ordinary and carbonaceous chondrites, it could be the first sample of a previously unknown asteroid. But, it is not yet clear where ALH85085 formed in the solar system.

Chondrites are the most common type of meteorite to fall on the Earth. These rocks are mixtures of all the different types of material that formed or were present in the solar nebula. They have survived without much change for the 4.5 billion years since the solar system formed, and offer the only direct means by which workers can learn about processes that took place very early in the history of the solar system.

ALH85085 is much finer grained than most chondrites. Like the chondrite groups, ALH85085 contains particles of metallic Fe-Ni as well as objects called chondrules and inclusions that are composed of silicate and oxide minerals. Metal, chondrules and inclusions alike are more than 10 times smaller in ALH85085 than in other chondrites.

The major chondrite groups have variable amounts of volatile elements, but contain much more of these elements than the Earth or the other inner planets. ALH85085 is very low in volatile elements. Grossman and co-workers suggest that this may be due to the fact that ALH85085 formed earlier than most carbonaceous chondrites when temperatures were higher. Scott suggests that there may be entire asteroids that, like ALH85085, are low in volatiles, a fact that would be important in terms of understanding the origins of the planets. Weisberg and co-workers think that the meteorite lost its volatiles by an unknown process.

The Antarctic Meteorite Working Group, which controls the allocation of samples from the U.S. Antarctic Meteorite Collection, deferred the distribution of fragments of ALH85085 pending the initial description and characterization of the tiny meteorite. Some of the most important characteristics of the meteorite, including its chemical composition and isotopic properties, will not be known until samples are distributed later this year.

EVIDENCE OF THE IN-SITU DECAY OF ^{26}Al IN A SEMARKONA CHONDRULE

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A long-standing problem in the study of meteorites, with broad implications for the evolution of the solar system, is the source of heat for melting small planets. Meteorites, such as the eucrites, were obviously the result of a melting process on a small planet, yet the decay of the long-lived radionuclides present on the earth, ^{40}K, ^{235}U, ^{238}U and ^{232}Th, could not have provided nearly enough heat to initiate melting ~ 4.5 aeons ago, even on bodies 1000 km in diameter. This problem was addressed by H. C. Urey in 1955, who recognized that the presence of short-lived (and now extinct) radionuclides such as ^{26}Al (half-life of ~ 720,000 y) in the early solar system would have provided an abundant heat source for melting small asteroid-size bodies. Since any ^{26}Al initially present in the solar nebula would have completely decayed after only a few tens of millions of years, the problem became one of finding evidence of ^{26}Al, in the form of excess ^{26}Mg, in meteorites.

Early attempts to search for evidence of ^{26}Al were unsuccessful and it was concluded that ^{26}Al was not an important heat source at the time many equilibrated meteorites formed. However, in 1974, Lee and Papanastassiou found small excesses of ^{26}Mg in material from the Allende carbonaceous chondrite and in 1977, Lee, Papanastassiou and Wasserburg discovered large excesses of ^{26}Mg (up to ~ 9°/$_{\infty}$) in anorthite from a refractory, Ca-Al-rich Allende inclusion. The magnitudes of the ^{26}Mg excesses were linearly correlated with the Al/Mg ratio in each mineral, demonstrating the existence of live ^{26}Al in the inclusion at the time it crystallized. The inferred abundance of ^{26}Al was quite high, corresponding to a $^{26}Al/^{27}Al$ ratio of ~ 5×10^{-5}. If this abundance of ^{26}Al was representative of bulk solar system material, it would provide ample heat to melt all bodies over a few kilometers in diameter.

Since that time, the presence of ^{26}Al has been confirmed in nine additional meteorites, eight carbonaceous chondrites and one unequilibrated ordinary chondrite. However, two facts have prevented a firm assessment of the solar system-wide distribution of ^{26}Al from these data: (1) the occurrence of radiogenic $^{26}Mg^*$ (the decay product of ^{26}Al) is restricted to refractory inclusions that comprise only a minor fraction of normal meteorite material; and (2) the initial abundance of ^{26}Al inferred from these data is not constant but the $^{26}Al/^{27}Al$ ratio ranges from a commonly observed value of ~ 5×10^{-5} to values less than 1×10^{-7}. These data have led most authors to conclude that ^{26}Al was heterogeneously distributed in the nebula and to point out that no evidence of ^{26}Al has been found in meteorites that must have formed by melting on a planet.

If ^{26}Al was a major heat source on small planets, some evidence of this should be preserved in "old" igneous rocks that cooled on a time scale comparable to the ^{26}Al half-life. The preservation of isotopic effects is strongly affected by the extent of thermal metamorphism or reprocessing experienced by a meteorite and the search for evidence of ^{26}Al has focused on an unequilibrated ordinary chondrite, Semarkona, that is perhaps the least metamorphosed chondrite. Semarkona is a member of the very low iron subgroup (LL) of the most common type of meteorite, the chondrites. Historically, Semarkona has been grouped together with other unequilibrated chondrites as a member of the LL3 subgroup. A recent study by R. Hutchison

and colleagues, however, has established that Semarkona formed in an environment similar to that of the type 2 carbonaceous chondrites. These authors proposed that Semarkona is significantly less reprocessed than other LL3 chondrites and is actually one of only two members of a new LL2 subgroup.

In the course of their work, Hutchison et al. also found another unusual feature in Semarkona, a chondrule containing the Al-rich, Na-Mg-poor mineral anorthite. Anorthite is relatively abundant in chondrites that have been thermally reprocessed (equilibrated) but is generally believed to be a secondary phase, i.e. produced during metamorphism. The presence of crystalline anorthite containing no detectable Na indicates that this chondrule formed at high temperatures and was not subsequently altered. The chondrule, CC-1, is ~ 1 mm across with a roughly pentagonal, rather than circular, outline and is composed predominantly of the common silicates, olivine and pyroxene. Olivine was the first phase to crystallize, followed by pyroxene and finally anorthite. The texture and mineral chemistry indicate that CC-1 is an abraded fragment of an igneous rock and not a quenched liquid droplet. CC-1 belongs to a relatively rare, noritic group of chondrules that share a number of similarities with lunar highland ANT (anorthosite-norite-troctolite) rocks and with the eucrite meteorites.

The chondrule was found in a polished thin section of Semarkona only ~ 10 μm thick and its isotopic composition could not be analyzed by conventional mass spectrometric techniques. The Mg isotopic composition of CC-1 was measured using the PANURGE ion microprobe. The ion probe uses a finely focused beam of oxygen ions to sputter material from the surface of the chondrule and then analyze the isotopic abundances of the sputtered material. With this technique, it is possible to make isotopic measurements on areas only a few microns across. The isotopic data from CC-1 (Fig. 1) show small but clearly resolved excesses of ^{26}Mg. The ^{26}Mg excesses are linearly correlated with the Al/Mg ratio, characteristic of the in situ decay of ^{26}Al in a well-behaved igneous system. The slope of the correlation line indicates that ^{26}Al was relatively abundant, $^{26}Al/^{27}Al = 7.7\times10^{-6}$, when the chondrule crystallized.

The major result of this study is the demonstration that live ^{26}Al was not confined to Ca-Al-rich refractory materials associated with early nebular condensation at extremely high temperatures. The Semarkona chondrule is the first object with a chemical composition close to that of normal meteoritic material to exhibit evidence of ^{26}Al. Furthermore, the exceptionally low abundance of Na and the mineral chemistry indicate that CC-1 is a fragment of volatile-poor parent material produced by a melting (differentiation) process on a small planet. It would be very difficult to produce a chondrule with a chemical composition similar to CC-1 by a nebular process. Thus, the presence of excess radiogenic $^{26}Mg^*$ in Semarkona CC-1 indicates that small planets accreted early enough to have incorporated a substantial amount of ^{26}Al. Since CC-1 appears to be the product of a melting event, the time scale for accretion and differentiation of small planets must be comparable to the mean life of ^{26}Al, ~ 10^6 y. These data are the first direct evidence that asteroidal-size bodies formed and begin to melt within a few million years of the origin of the solar system.

Since the Semarkona chondrule is more representative of normal meteoritic material, the isotopic data provide evidence that ^{26}Al was reasonably widespread in the early solar system. If ^{26}Al was present in the nebula at the level found in CC-1 (~ 1 ppm), it is clear that ^{26}Al ws the dominant heat source in all planetary bodies that formed very early. A ^{26}Al

abundance of ~ 1 ppm will heat the center of a 100 km diameter body to a temperature in excess of 1250°C, causing incipient melting. It should be remembered that the measured $^{26}Al/^{27}Al$ ratio refers to the ^{26}Al abundance when CC-1 solidified. If planets formed earlier, before some ^{26}Al had decayed, melting will be widespread. For smaller bodies, heat loss due to conduction may be significant, lowering the maximum temperature. For a 40 km diameter stony body, 1 ppm of ^{26}Al will heat the interior 75%, to temperatures greater than 600°C. Thus, even if widespread melting did not occur, the Semarkona data demonstrate that ^{26}Al played a major role in thermal metamorphism on small planets.

This study has shown that ^{26}Al was not restricted to refractory inclusions, a minor component of most meteorites. The demonstration that ^{26}Al was present in a wide variety of meteoritic materials at the ~ 1 ppm level requires a more thorough investigation of the Mg isotopic composition of anorthite-bearing clasts and chondrules in unequilibrated meteorites. These studies are in progress.

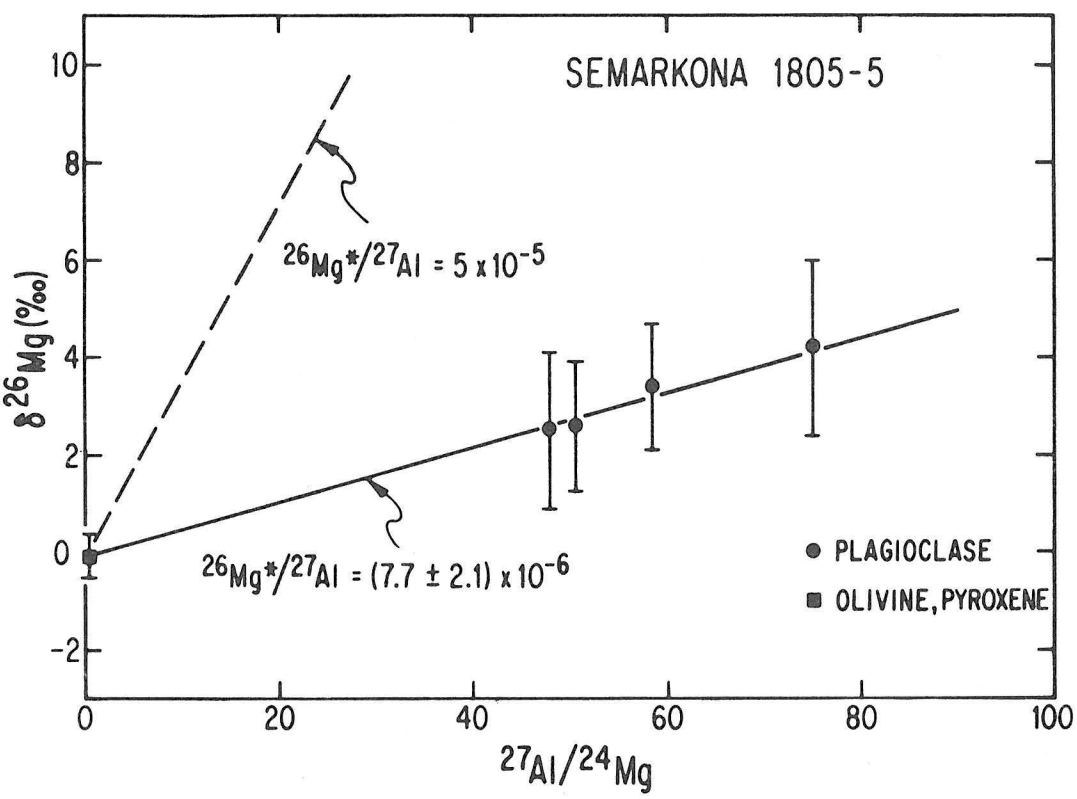

Fig. 1. ^{26}Al-^{26}Mg evolution diagram for three coexisting phases in Semarkona CC-1. Anorthite contains small $^{26}Mg^*$ excesses clearly resolved from normal Mg (2σ errors).

LSU SCIENTISTS DISCOVER EVIDENCE OF LARGE METEORITE IMPACTS ON THE EARLY EARTH

Donald R. Lowe and Gary R. Byerly, Louisiana State University

Recent discoveries by scientists at Louisiana State University may provide a direct window through which we can view and study early planetary accretion and evaluate the role of large meteorite impacts on the evolution of life and the Earth's surface.

Following the main stage of planetary accretion 4.6 to 4.5 billion years ago, meteorite impacts continued to play a fundamental role in sculpturing planetary surfaces in the solar system. The cratered surfaces of the moon and Mars reflect this late violent phase of planetary construction, which lasted over 500 million years, until about 3.8 to 3.9 billion years ago. On Earth, the surficial record of these formative events has been erased by later processes of plate movement, mountain building, weathering, and erosion. Our present knowledge of accretionary events derives exclusively from the study of extraterrestrial bodies, especially the moon. Now, the discovery by scientists Donald R. Lowe and Gary R. Byerly at Louisiana State University of 3.4 to 3.5 billion year old deposits containing debris apparently produced by several large meteorite impacts on the early Earth offers a possible means of directly documenting the processes of terrestrial accretion and of evaluating the influence of late, large-body meteorite bombardment on the origin and evolution of life and development of the Earth's crust and continents.

The deposits are contained within rock sequences known to be among the oldest on Earth, 3.2 to 3.5 billion years old, in south Africa and western Australia. The sequences are made up largely of volcanic rocks and probably formed as broad oceanic shield volcanoes resembling Hawaii today. The impact debris is contained within thin sedimentary layers, 10 to 100 centimeters thick, made up of spherical particles, or spherules, formed by the fall and rapid cooling of molten rock droplets. The vast geographic extent of these layers, their unusual compositions, and style of deposition suggest an origin related to impact events on the early Earth. Of particular importance is the element iridium, which is 10 to 100 times more abundant in the spherule deposits than in any associated sedimentary or volcanic rocks and is especially abundant in meteorites.

Reconstruction of events leading to the formation of these deposits suggests the following scenario. During the deposition of these rock sequences 3.4 to 3.5 billion years ago, the Earth's surface was subject to continuing bombardment by large

meteorites representing the last stages of planetary formation. The energy released during large-body impacts melted and vaporized enormous volumes of target and meteorite rock. Although coarse rubble and rock ejecta would have formed broad carpets flanking impact sites, clouds of rock vapor blasted upward and outward immediately following impacts may, at time, have blanketed the entire Earth. The condensation and solidification of this rock vapor produced the droplets that, like hailstones, rained down on the surface to form the spherule deposits.

Impacts in the oceans also generated enormous waves that spread away from the points of impact and may have circled the Earth many times. The spherule layers discovered by Lowe and Byerly, where deposited in shallow-water, appeared to record the passage of these waves by the presence of coarse debris torn from underlying layers mixed with the spherules.

These same ancient rock sequences also contain the oldest known life forms, and it appears that life evolved and early organisms lived within an environment subject to periodic catastrophic disruption due to large meteorite impacts. The effect of impacts on early organisms and the strategies by which ancient bacterial communities survived such catastrophic and potentially lethal events are currently under study.

PRESS RELEASE FOR "IDENTIFICATION AND EFFECTS OF LARGE, EARLY ARCHEAN, TERRESTRIAL METEORITE IMPACTS: A GEOLOGICAL PERSPECTIVE ON LATE ACCRETION" Donald R. Lowe and Gary R. Byerly, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803-4101.

CRYSTAL STRUCTURE AND DENSITY OF HELIUM TO 232 KBAR

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The properties of helium and hydrogen at high pressure are topics of great interest to the understanding of planetary interiors. These materials constitute 95% of the entire solar system. The giant planets consist primarily of helium and hydrogen in mass proportions of roughly 30% helium and 70% hydrogen. The pressures and temperatures of the He-H shell above the "ice" core of the planets may reach 200 kbar (1 kbar equals 1000 times atmospheric pressure) and 2200°C in Uranus and Neptune, to as high as 40,000 kbar and 15,000°C in Jupiter (1). The equations of state and phase diagrams of He-H specify the most crucial information for constructing compositional and evolutionary models of the giant planets. The equation of state specifies the density as a function of pressure and temperature. The phase diagrams include the melting curves, the phase separation of helium and hydrogen, and the metallization of hydrogen.

In the past, owing to the experimental difficulties, properties of helium and hydrogen at the conditions of planetary interiors almost entirely depend on theoretical calculations at ultrahigh pressures and measurements at low pressures - with a large gap in data in between. With the development of diamond-anvil high-pressure cell, 600 kbar in helium (2) and 1470 kbar in hydrogen (3) have been reached at room temperature for optical studies. These studies, however, do not give direct information about crystal structures and densities.

The measurement of the crystal structure by x-ray diffraction is perhaps the most fundamental property to be measured. Such a measurement provides direct identification of the phase at a given pressure-temperature condition and provides the most accurate means available for determination of the pressure-volume relations or equation of state. Despite the continued advancement of high-pressure measurement techniques, there has been no direct measurement of the crystal structure of solid helium at high pressure above a few kbar. This problem arises from the extremely low scattering cross-section for the the helium atom (the atomic number $Z = 2$) and the high compressibility of the material, which gives an exceedingly small volume at high pressure (*e.g.,* of order 10^{-11} liters at 10 GPa in a diamond-anvil cell). The intensity of the x-ray diffraction, which is proportional to the sample volume and to the square of the atomic number, is therefore extremely low, much lower than the background signal. In an ordinary x-ray diffraction experiment, helium is "invisible".

Recently, we presented a new technique for the measurement of x-ray diffraction from single-crystals of low-Z condensed gases in a diamond-anvil cell at high pressure (4). The first such single-crystal x-ray diffraction measurements on solid hydrogen to 26.5 GPa were presented. In this talk, we present the application of this technique to the problem of the crystal structure, equation of state, and phase diagram of solid helium. Crucial for x-ray diffraction studies of these materials are the use of a synchrotron radiation source which provides high brilliance, narrow collimation of the incident and diffracted x-ray beams to reduce the background noise, and energy-dispersive

diffraction techniques with polychromatic (white) radiation, which provides high detection efficiency. The measurements were performed on the 'wiggler' line at the Cornell High-Energy Synchrotron Source (CHESS), which is a million times more brilliant than a conventional x-ray generator.

Helium was compressed in a diamond-anvil high-pressure cell designed for condensed-gas single-crystal x-ray diffraction (5). The pressure in the diamond-anvil cell was increased at room temperature above the 118 kbar, and helium froze from the fluid to form a single crystal. The diamond-anvil cell was then mounted on a two-circle rotation apparatus for x-ray diffraction. Pressures were measured by ruby fluorescence excited by the x-ray beam. Diffraction patterns at four pressures from 156 to 233 kbar were measured, and excellent signal-to-noise ratio was observed. Contrary to theoretical calculations that helium should be in the face- or body-centered cubic structure, in the entire range of pressures of this study, the measurements demonstrate that helium crystallizes in hexagonal-close-packed structure (Fig. 1), which is the same as that of solid hydrogen under these conditions.

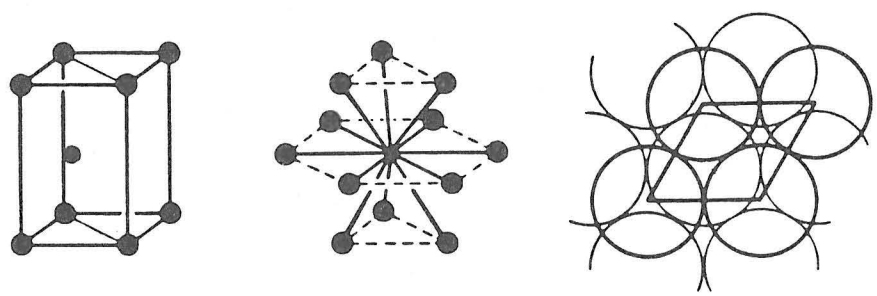

Fig. 1 Three views of the hexagonal close-packed (hcp) structure, after Megaw (7).

The pressure-volume equation of state for solid helium is shown in Fig. 2. From 156 to 232 kbar the density (calculated from the molar volume) changes from 1.013 gm/cc to 1.168 gm/cc, a 15% increase which is the largest of any material at these pressures. The pressure-volume data below 200 kbar agree well with a "soft" theoretical equation of state calculated on the basis of an exponential-six potential of Ross and Young (6), as shown in the figure. At higher pressure, the experimental result indicates that a still softer potential potential is required. It is therefore necessary to re-examine theoretical models of solid helium to account for both the unexpected crystal structure and the "softer" equation of state found experimentally. The present results expand our knowledge of the crystal structure and equation of state of this fundamental material by two orders of magnitude in pressure. It is hoped that improved theoretical calculations that satisfy the new experimental data for helium will have more reliability for predicting the behavior of materials at the still higher pressures and temperatures characteristic of the interiors of the giant planets.

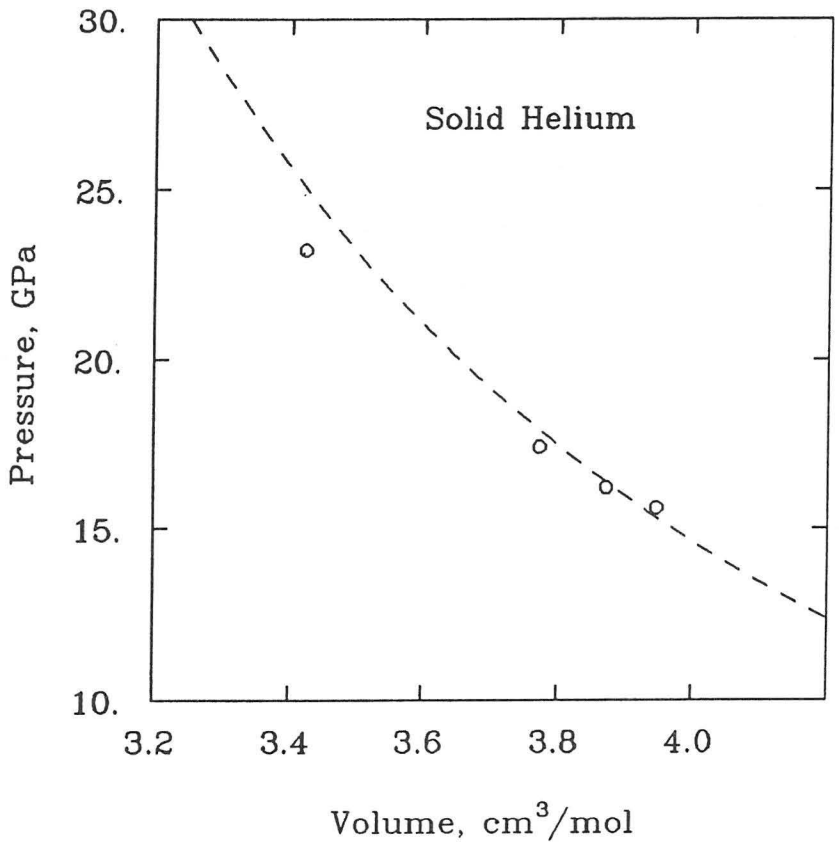

Fig. 2. Pressure-volume data for hcp helium at 300 K and the equation of state calculated by Ross and Young (6).

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LEWIS CLIFF 86010 - A UNIQUE ANTARCTIC METEORITE: POSSIBLE NEW CLUES TO THE EARLY HISTORY OF THE SOLAR SYSTEM

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A fundamental goal in planetary science is to learn more about events which occurred during the earliest history of the solar system, prior to and during the formation of the sun and planets. Most of our information about this period of solar system history comes from detailed studies of meteorites. Meteorites constitute an extremely diverse suite of objects, and have been classified into many different groups based on their chemical and mineralogical characteristics. Meteorites are thought to have formed on various "parent bodies," some of which are probably asteroids, some comets, and some perhaps even planets, all orbiting the sun at various distances. It is generally believed that meteorites of the same group come from the same parent body, or at least from a small number of parent bodies with similar orbits and histories. The parent bodies themselves are believed to have formed through accretion of dust which condensed from the hot gas cloud, or solar nebula, from which the sun was formed.

The ultimate physical, chemical, and isotopic characteristics of meteorites are the result of two basic types of processes. Some processes involve condensation, transportation, and mixing of dust grains within the solar nebula and are called "nebular" processes. Other processes involve chemical and thermal processing of initially primitive material within the parent body, and are called "planetary" processes. Among the goals of the study of any meteorite are to understand both the planetary processes which gave rise to that meteorite on its parent body, and to try to look back through those processes, to understand the nebular processes which gave the parent body its fundamental chemical and isotopic characteristics. In order to obtain as complete a picture of the early nebula as possible, it is desirable to study meteorites from a wide variety of different parent bodies, and in order to understand the range of planetary processes, it is desirable to have a number of different samples from each parent body, representing a range of materials affected to varying degrees.

Hence, the more samples we have from within any meteorite group, and the more groups we have represented in our collections, the better off we are. One of the benefits of the antarctic meteorite collection program has been the great increase in the number and variety of meteorites available for study. This program has been in existence for more than 10 years, and has resulted in the collection of thousands of meteorites, many of which are of ordinary and common types, but a number of which are of extremely rare and interesting types.

One antarctic sample, LEW 86010, collected from the Lewis Cliffs region in 1986, is particularly interesting. It appears to be a sample of a very rare group, which, prior to the discovery of the antarctic sample, contained only one known member, Angra Dos Reis (ADOR). ADOR, which fell in Brazil in 1869, is a very important meteorite for two reasons. First, its strontium isotopic composition is among the most primitive ever observed. In this case, "primitive" means having a low ratio of radiogenic ^{87}Sr to non-radiogenic ^{86}Sr, and implies that the Sr contained in that sample was isolated from the radioactive parent

element, Rb, very early in solar system history, before a significant amount of Rb could decay to ^{87}Sr and raise the $^{87}Sr/^{86}Sr$ ratio of the ADOR precursor material. In addition to having a primitive Sr isotopic ratio, ADOR has a very old crystallization age, 4.54 billion years. Members of another group of meteorites called basaltic achondrites have similar ages, but less primitive Sr isotopic ratios. An important question is whether the differences in Sr isotopic ratios between ADOR and the basaltic achondrites arose through nebular or planetary processes. It is possible that ADOR and basaltic achondrites are from different parent bodies, and that the dust which formed the ADOR parent body condensed and was isolated from the nebular gas cloud at very high temperature, after condensation of most of the refractory element Sr, but before the condensation of much of the highly volatile element Rb. The basaltic achondrite parent body, on the other hand, could have formed form dust condensing at lower temperature, with higher Rb content, or else condensing at a similar high temperature, but at a later time, after decay of Rb within the nebula had raised the $^{87}Sr/^{86}Sr$ ratio. Alternatively, it is possible that ADOR and the basaltic achondrites are from the same parent body. In that case, the differences in Sr isotopic ratios could have arisen because the region of the parent body sampled by ADOR was subjected to a differentiation episode which removed all of the Rb at an earlier time than the basaltic achondrite source region, and thus had less opportunity to accumulate ^{87}Sr through radioactive decay. Thus ADOR contains vital information regarding the chronology of events in the early solar system.

A second reason ADOR is important is because its abundances of a number of key elements are fractionated, relative to primitive, unprocessed material. Again, there are two possible ways these fractionations could have been generated, through either nebular or planetary processes. Differential condensation or formation from non-representative material, such as the white clasts found in the meteorite Allende (a very primitive sample belonging to the group called carbonaceous chondrites) might give the ADOR parent body its unusual chemical characteristics. Alternatively, they might be the result of chemical processing and differentiation on a parent body which was initially more representative of the average composition of material which condensed from the solar nebula.

Study of additional meteorites related to ADOR might provide further information on the nature of differentiation processes on the ADOR parent body. Such information could shed light on the timescale of those processes, and reveal whether they are capable of generating the observed ADOR chemical and isotopic characteristics from average solar system material, or whether nebular processes and a chemically unusual parent body are required.

Therein lies the significance of LEW 86010, the unique antarctic meteorite from Lewis Cliff. Preliminary examination of this sample by Brian Mason, of the Smithsonian National Museum, suggested a number of chemical and mineralogical similarities to ADOR. Additional, more detailed study of LEW 86010 by the authors of this abstract confirmed Mason's findings. These similarities to ADOR include unusual enrichments of several elements. For example, in both ADOR and LEW 86010, the mineral pyroxene is unusually enriched in Al and Ti, suggesting that pyroxene grew under similar conditions in both meteorites. As another example, olivine, another common meteoritic mineral, is unusually Ca-rich in both samples.

Additional similarities between the two meteorites have been discovered using a newly developed technique called secondary ion mass spectrometry, which permits analysis of individual mineral grains for elements present in very low quantities. Such analyses for a particularly diagnostic set of "trace" elements, the rare earth elements, reveal strong

similarities in their abundances between the two meteorites, further supporting a relationship between these samples. Other similarities include depletions of volatile elements (those condensing from the solar nebula at low temperatures) and enrichments in refractory elements (those condensing at high temperatures). Based on the above similarities, it appears likely that these samples might be from the same parent body.

Our studies have also revealed some important differences between LEW 86010 and ADOR, which might provide important clues to differentiation processes on their parent body (or bodies, if they turn out to be different). The shapes and compositions of mineral grains in ADOR indicate a high degree of equilibration, as if, after forming from a melt, the sample was subjected to a long episode of heating at a temperature hot enough to recrystallize its minerals. Thus it is possible that the record which minerals in most igneous samples contain of the chemical characteristics of the melt from which the minerals crystallized has been erased from ADOR. LEW 86010, on the other hand, has mineral shapes which strongly suggest that it has undergone little recrystallization since it cooled from a melt. Additional evidence supporting minimal recrystallization includes typical igneous variation in the composition of pyroxene grains from core to rim, in contrast to the homogeneous minerals in ADOR. Finally, minerals having the same unusual compositional characteristics as those in LEW 86010 have been produced in melting experiments performed on synthetic analogs of this meteorite. Thus evidence supporting an igneous origin for LEW 86010, with much less recrystallization than ADOR, is unequivocal.

Demonstration of an unambiguous igneous origin for LEW 86010 is significant because it allows us to look back through the crystallization event to learn much about the composition of the melt. This, in turn, allows us to draw conclusions about the nature of the source region where the melt was formed, within the mantle of the parent body. For example, with additional study, it might be possible to accurately compute the degree of chemical fractionation which such a melting episode produced, thus allowing an estimate to be made of what proportion of the fractionation occurred on the parent body, and what proportion occurred via nebular processes.

In summary, our results on LEW 86010 indicate that it is an extremely interesting meteorite of clear igneous origin, and is probably closely related to ADOR. Several important questions await further detailed study. The most stringent test of the relationship to ADOR will come from measurement of the oxygen isotopic composition. Another important question involves the time-scale and extent of magmatic activity on its parent body, and will be addressed through isotopic and chronologic measurements. Another major issue is the nature and origin of the volatile-depleted material which was partially or wholly melted to form the sample. One possibility proposed by some of us is that LEW 86010 represents a partial or total melt of a mixture of material similar to the white Allende clasts and more ordinary "chondritic" meteorite material. Several lines of investigation will contribute to resolving this question. Further melting studies will be performed to determine whether LEW 86010 represents molten lava, or whether it differs from a lava by being enriched in one or more minerals through gravitational accumulation. These studies will place constraints on the pressures and temperatures of melting, and the nature of the material which was melted. In addition, to test the connection with Allende, isotopic studies will look for "anomalous" isotopic compositions which are ubiquitous in Allende white inclusions. All of these studies will be performed on a tiny sample which weighs only 5 grams, and is smaller than a marble, but which contains important clues to events which occurred during the birth of our solar system.

NOBLE GASES, C, N AND Si ISOTOPES IN INTERSTELLAR SiC FROM THE MURCHISON CARBONACEOUS CHONDRITE; **Tang Ming** and **Edward Anders**, Enrico Fermi Institute and Department of Chemistry, University of Chicago, Chicago, IL 60637, USA, and **Ernst Zinner**, McDonnell Center for the Space Sciences and Physics Department, Washington University, St. Louis, MO 63130, USA.

This paper presents isotopic measurements of presolar interstellar silicon carbide. Silicon carbide has recently been identified in a primitive meteorite, Murray. There exists strong evidence that the silicon carbide predates the formation of the solar system and originated in the atmospheres of certain stars. Thus, this material provides a link with its stellar sources and gives us the opportunity to study processes taking place in distant stars.

Primitive meteorites are among the oldest objects to be found in the solar system. They consist of a collection of many different types of materials, most of which were formed in the solar system from gas and dust that originally collapsed into the solar nebula. Thus, all meteoritic matter is presolar in the broadest sense of the term. However, until approximately 15 years ago it was generally believed that all the dust was vaporized during the early stages of solar system formation, mixed with the existing gas, and that new minerals were formed from this mixture. Thus, no solid material existing before the collapse of the solar nebula should have retained its identity.

In the last 15 years there was mounting evidence that this picture was not quite correct and that some solid material survived the formation of the solar system and was incorporated into primitive meteorites. This evidence is mainly based on the isotopic composition of a number of elements measured in certain parts of meteorites.

Isotopes are different types of a given element, distinguished by the varying number of neutrons in the atomic nucleus. In addition to neutrons the nucleus of an element contains a constant number of protons that determine the nucleus' charge and the chemical identity of the element. All elements except hydrogen and helium are made in stars. Depending on the type, mass and age of a star the elements are produced in different proportions with different abundance ratios of their isotopes. Thus, material originating from a particular star carries a characteristic fingerprint in form of the unique isotopic compositions of its elements, distinct from material originating from another star.

Many different stars are thought to have contributed to the gas and dust that finally collapsed into our solar system. If all this material would have been vaporized and thoroughly mixed, the isotopic compositions of the different original components would have been homogenized, their fingerprints would have been lost. Although this is generally the case and most solar system materials, including terrestrial and lunar rocks as well as meteorites, show a fairly uniform isotopic composition, certain constituents of primitive meteorites have isotopic compositions that deviate significantly from the solar system average, indicating that isotopically distinct components of presolar origin had been preserved.

Such isotopically anomalous (or "exotic") components were found among the noble gases neon (Ne) and xenon (Xe). The exotic Ne component is named Ne-E and consists essentially only of one of the three Ne isotopes, ^{22}Ne. Xenon has nine isotopes and features two different exotic components, Xe-HL, enriched in the heavy and light isotopes and Xe-S, enriched in the isotopes ^{128}Xe, ^{130}Xe and ^{132}Xe. These exotic noble gas components are contained in only a small fraction of the whole meteorite. Over the last decade, considerable efforts were made to identify the carriers of the exotic noble gas components. The main

experimental procedure consisted of chemical and mechanical separation of meteoritic material.

During these efforts it became clear that carbon phases were the carriers of the anomalous noble gases. The findings of isotopic anomalies in other elements such as carbon and nitrogen in these phases provided additional arguments for the presence of presolar material. However, although it was common to speak of presolar, circumstellar or interstellar grains, until approximately a year ago the detailed physical and chemical nature of these grains was unknown. The main reason for this was the fact that the presolar material constitutes only a tiny fraction of the whole meteorite and that individual dust grains are exceedingly small.

The first discovery of presolar grains was the identification of diamonds associated with exotic Xe-HL [1], followed by the identification of silicon carbide [2]. The silicon carbide was found in chemical separates from the carbonaceous meteorite, Murray, which were 20,000 fold enriched in exotic Ne-E and Xe-S. It comprises less than one part in 100,000 of the total meteorite and exists in the form of grains between a tenth of a millionth to a few millionths of an inch in diameter.

Several lines of evidence point to a presolar origin of the silicon carbide. First, its formation requires that carbon is more abundant than oxygen, a condition that was not met in the early solar system but is satisfied in the atmospheres of certain stars such as red giants. Previous astronomical observations had indicated the presence of silicon carbide grains in the atmospheres of carbon-rich stars. Second, not only are exotic Ne-E and Xe-S associated with meteoritic silicon carbide [3], but its carbon, nitrogen and silicon isotopic compositions are also highly anomalous [4]. The isotopic measurements of these three elements were made with an ion microprobe, an instrument that enables us to make isotopic measurements in samples of a millionth of a millionths of a gram.

The present abstract describes the extension of this work to a second carbonaceous meteorite, Murchison. In order to extract the silicon carbide, this meteorite was treated with hydrofluoric acid to dissolve silicates, followed by several oxidizing agents to remove organic and amorphous carbon. The resulting residue, consisting mostly of spinels (oxide minerals) and diamonds, was separated into different size fractions. The diamonds are concentrated in the finest fraction, the other fractions were treated with phosphoric acid to dissolve spinels and with perchloric acid to yield the purest silicon carbide samples obtained to date. They have the highest Ne-E and Xe-S concentrations ever measured.

Ion probe analysis of carbon, silicon and nitrogen revealed large isotopic anomalies in these elements. Silicon, which has three isotopes of atomic masses 28, 29 and 30, shows a scatter of compositions between individual samples, indicating that at least three distinct isotopic components must be present. Since during each analysis many silicon carbide grains are consumed, yielding a complicated isotopic mixture, the compositions of the pure components of the silicon isotopes making up this mixture are still unknown. Carbon has isotopes with atomic masses 12 and 13, ^{12}C and ^{13}C. Interstellar silicon carbide shows the presence of an isotopically heavy carbon component whose $^{13}C/^{12}C$ ratio is higher than in solar system material. However, similar to silicon, the carbon isotopic composition varies from sample to sample with $^{13}C/^{12}C$ ratios exceeding the solar system value by as much as a factor of eight. Nitrogen, with two isotopes of atomic mass 14 and 15 is both enriched and depleted in the isotope ^{15}N relative to the solar system.

The variability in the isotopic composition of interstellar silicon carbide from carbonaceous meteorites indicates that several stellar sources contributed this material to the solar nebula. The formation of silicon by nuclear processes requires a different stellar environment than the formation of the lighter elements carbon and nitrogen. It has been proposed that all three elements were generated in a supernova, a massive star that exploded, thereby ejected its elements into the interstellar medium, and that the silicon carbide grains formed in the expanding shell of this explosion. However, it is more likely that silicon produced in supernovae was incorporated into other stars that are the sources of the carbon and nitrogen. Certain late type stars such as red giants that have exhausted most of their hydrogen could produce carbon with a relative excess of isotope 13 and nitrogen with a relative depletion of isotope 15. In addition, the chemical composition of the atmosphere of such stars favors the formation of silicon carbide. Other stars such as novae could be the sources of the heavy nitrogen, i.e. nitrogen with an excess of isotope 15, measured in some silicon carbide samples. What makes this hypothesis attractive is that novae have been identified as a possible source for Ne-E.

In summary, while the identification of specific stellar sources has to await the results of further studies by astrophysisists, all available evidence points to a circumstellar origin of the silicon carbide found in primitive meteorites. Thus we now have star dust available for study by sophisticated microanalytical techniques in the laboratory. It is expected that these studies will yield important information on processes taking place in stars and will ultimately provide a link to our stellar past.

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Did the Greenhouse Effect Kill the Dinosaurs?

(Based on "IMPACT PRODUCTION OF CO_2 BY THE K-T EXTINCTION BOLIDE, AND THE RESULTANT HEATING OF THE WHOLE EARTH" by John D. O'Keefe and Thomas J. Ahrens, Seismological Laboratory 252-21, California Institute of Technology, Pasadena, CA 91125.)

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According to a study at the California Institute of Technology, the carbon dioxide (CO_2) released by a meteor or comet striking the Earth 65 million years ago could have doomed many species of animals and plants by dramatically **raising** temperatures worldwide.

The results of the study, conducted by John D. O'Keefe, visiting associate in planetary science, and Thomas J. Ahrens, professor of geophysics, will be presented on March 16, 1988, at the 19th Lunar and Planetary Science Conference in Houston, Texas.

For decades, scientists have wondered what could have caused the massive and rapid extinction of plants and animals, including the dinosaurs, at the boundary between the Cretaceous and Tertiary periods (the K-T boundary) approximately 65 million years ago. The discovery several years ago of an abnormally high level of iridium in sedimentary rocks laid down at the time of the K-T boundary has led many researchers to hypothesize that a comet or a massive meteor may have struck the Earth, leading to the mass extinctions.

Most previous studies of this impact event have concentrated on the so-called "nuclear winter scenario," which holds that dust and smoke filled the atmosphere after the impact, blocking the sun, **lowering** temperatures, and driving many species out of existence. These studies have always been controversial, since others have argued that the dust could not have made the Earth cold enough for long enough to cause the specific pattern of mass extinctions observed in the fossil record.

The present study concentrates on the effects of the gases liberated when a large body strikes the Earth. If this body strikes at a place that contains carbonate-rich sedimentary rock, large amounts of CO_2 would be injected into the atmosphere. Such carbonate-rich sedimentary layers are found in shallow ocean beds or on dry land that had once been undersea. They are absent in the deepest part of the ocean. If a comet with a radius of 50 kilometers (30 miles) struck the Earth at a 4-kilometer-thick carbonate-rich layer, there would be an immediate hundred-fold increase in the amount of CO_2 in the atmosphere.

This would lead to an increase in average temperatures of about 20 degrees Celsius (36 degrees Fahrenheit) within only 10 days due to the greenhouse effect. In the greenhouse effect, CO_2 in the atmosphere prevents the sun's heat from escaping from the Earth into space, so the Earth heats up; the more CO_2 in the atmosphere, the more heating. Even in the case of a smaller impact on a thinner carbonate layer -- say a meteor with a radius of 20 kilometers landing on a 1-kilometer-thick layer, worldwide temperatures would increase by a still-significant 5 degrees Celsius (9 degrees Fahrenheit). The increased CO_2 levels would persist for about 10,000 years.

One can compare these temperature increases with those that many scientists believe will result from a century's worth of fossil fuel burning. Some studies indicate that the greenhouse effect may cause a gradual 2 to 3 degree Celsius increase in average temperatures by the next century, and this may be enough to melt a portion of the polar ice caps, inundating coastal cities. An almost instantaneous increase of between 5 and 20 degrees would have unimaginably dire consequences for all life on Earth.

Marine ecology, for example, would be completely disrupted since higher temperatures in the upper ocean would result in lower concentrations of dissolved CO_2. Without

dissolved CO_2, plankton cannot construct their shells. Since plankton are at the very base of the ocean's major food chain, many marine species would be expected to become extinct. This is exactly what is found in the fossil record. The higher temperatures would also disrupt land-based food chains, which may explain the relatively rapid disappearance of the dinosaurs. But it is noteworthy that this scenario does not lead to an **immediate** disappearance of many species. This agrees with recent data indicating that the K-T extinctions, while rapid in a geological sense, did not happen instantaneously.

O'Keefe and Ahrens performed their analysis in Caltech's Helen and Roland Lindhurst Laboratory of Experimental Geophysics. In this lab are four powerful guns capable of accelerating projectiles to very high speeds. The present experiments simulated impacts on calcite (limestone) of up to 4 to 6 kilometers per second (9,000 to 13,500 miles per hour) and measured the resultant release of CO_2 as a function of pressure. The researchers used the data gathered in these experiments to conduct computer simulations of meteors or comets of various sizes striking the Earth on carbonate-rich sedimentary layers of various thicknesses.

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DEBRIS FLOWS OF THE SIMUD-TIU OUTFLOW SYSTEM OF MARS

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The problem of the origin of outflow channels on Mars

Planetary enthusiasts awe at features such as Olympus Mons and Valles Marineris on Mars, as seen in Viking images, because of their immense size. Scientists have determined that the Martian crust has been relatively stable since its formation and that erosive forces, for the most part, have been mild. It is not surprising, then, that some Martian volcanoes spewed lava for hundreds of millions of years, while neighboring landscapes remained relatively unscathed for the past several billion years.

Outflow channels on Mars, commonly over 60 miles wide, over 600 miles long, and more than a mile and a half deep (half again as deep as the Grand Canyon in Arizona), also inspire wonder. The channels flow into Chryse Planitia--a vast, lowland plain on which the Viking 2 lander landed and still rests. They originate from deep depressions in the Martian highlands that are commonly filled by knobby hills (known as chaotic terrain), suggesting that bedrock material somehow was undermined and removed. On Earth, the closest analogies are large channels produced by catastrophic floods from glacial lakes and the valleys scoured by broad glaciers and ice caps in Antarctica. However, the outflow channels on Mars formed within an atmosphere having much less pressure and humidity than found on Earth, and they originated from equatorial latitudes. Therefore, the channels seemingly could not have formed by breaching of lakes or melting ice caps, or by runoff from heavy rainfall.

Dr. Michael H. Carr (U.S. Geological Survey) proposed in 1979 that the water for the channels came from pores and cavities within near-surface rock materials. Carr's proposal tries to overcome the problem of where the water came from, but it limits the amount of water available to produce the channels. Dr. Dag Nummedal and Dr. David B. Prior (Louisiana State University) later hypothesized that the channels were carved by turbulent flows composed of rock debris and water (or "debris flows") originating from the chaotic terrain. The chaotic terrain and the channels are similar in appearance (but not in size) to features associated with submarine debris flows in the Mississippi delta. Nummedal and Prior argued that because of the immense size of the Martian debris flows, the flows would have been able to travel the extraordinary distances required. However, Nummedal and Prior could not find evidence for the deposits resulting from the flows in Viking images.

Debate over the origin of the outflow channels continues, and more than one process of channel erosion may actually have occurred. Channels and canyons associated with the Simud-Tiu Valles system are particularly broad and deep, so obviously enormous volumes of material were removed. I think that the erosion of this channel system is chiefly attributable to the debris-flow mechanism of Nummedal and Prior. As I demonstrate in the following, the occurrence and appearance of chaotic terrain in the channel system, as well as geologic studies on the nature of the Martian crust, support the debris-flow hypothesis. And of additional interest to you and I: this process has utterly devastated the landscape of an area roughly equivalent to half of the conterminous United States. Could it happen somewhere here on Earth, too?

Chaotic terrain as debris flows

The knobby hills that characteristize chaotic terrain appear on canyon

floors throughout the channel system. In some areas, the hills are closely spaced and occur beside the highlands. Because they look like highland landforms, they probably formed by undermining of or limited sliding of highland material. In other areas, however, the hills are widely spaced and do not appear to be related to local highland outcrops. In fact, some occur on channel floors that might be expected to be very smooth if glaciers or floods had come through (Figure 1).

The more widely spaced hills commonly form groups that have tongue-shaped outlines, consist of smaller hills downstream, and appear partly buried (Figure 1). These features are expected to be seen in debris-flow deposits. The tonguelike shapes indicate that the hills were part of a continuous flow of debris. These hills were huge blocks of "earth" that were torn away from the highlands (many of the blocks were larger than the Great Pyramid of Cheops). As the flow progressed, the blocks jostled and broke apart. The muddy base of the flow came to rest as a smooth deposit perhaps tens to hundreds of feet thick that partly buries the great blocks it had once carried.

Most of the absent highland material removed from the canyons, channels, and chaotic terrain must have been dispersed as thin, smooth deposits in Chryse Planitia, as envisioned by Nummedal and Prior. These earlier flows were more effective at gouging deep channels into the landscape. The debris flows whose deposits I have documented in the Simud-Tiu Valles system therefore were merely the last, minor outpourings of what likely were the most catastrophic series of debris flows to ever occur on any body in the Solar System.

Nature of the Martian crust

At this point we naturally ask why such huge debris flows have formed on Mars, when only debris flows of much smaller size have occurred on Earth. In a related study presented in the 19th Lunar and Planetary Science Conference by Dr. David J. MacKinnon (U.S. Geological Survey) and myself, we examine the distribution of impact ejecta (material thrown out when a meteorite hits the surfaces) on Mars and its geologic role. Impact ejecta may be more than a mile thick in places, according to theoretical work by Dr. Alexandar Woronow of the University of Houston. Moreover, this material, when wet, could become a muddy quagmire if shaken. On Earth, buildings have collapsed when the ground beneath them became like quicksand during earthquake shaking.

The source areas of the proposed debris flows are in the lower parts of a broad, highland basin on Mars informally called the "Chryse trough". Within the basin are ancient impact craters, showing that the ground is largely composed of impact ejecta. Also, many valleys were formed in the trough before the outflow channels, which shows that water existed in the area and was transferred from higher areas into lower parts of the trough, concentrating the water there. Valles Marineris, the elongate, deep valleys immediately west of the source areas of the channels, formed at about the same time as the channels. Evidence of fault scarps in Valles Marineris shows that large earthquakes were probably associated with its formation, and these quakes could have transformed the water-saturated impact ejecta into slurries that resulted in massive debris flows.

Implications

We see that the magnitude of geologic happenings are commonly quite different between the Earth and Mars because of differences in the makeup and breakup of their crusts. By assessing the differences, and the similarities,

between the planets, we often can succeed in understanding more fully the geologic history of Mars. The identification of debris-flow deposits in channels of Mars, for example, helps to establish which of several competing explanations for the origin of the channels actually occurred. In turn, we are forced to view the Earth in new, and commonly enlightening, perspectives. By the way, we are fortunate that on Earth, thick sequences of impact ejecta are not found that could be transformed into the monstrous debris flows that have devastated the Martian surface.

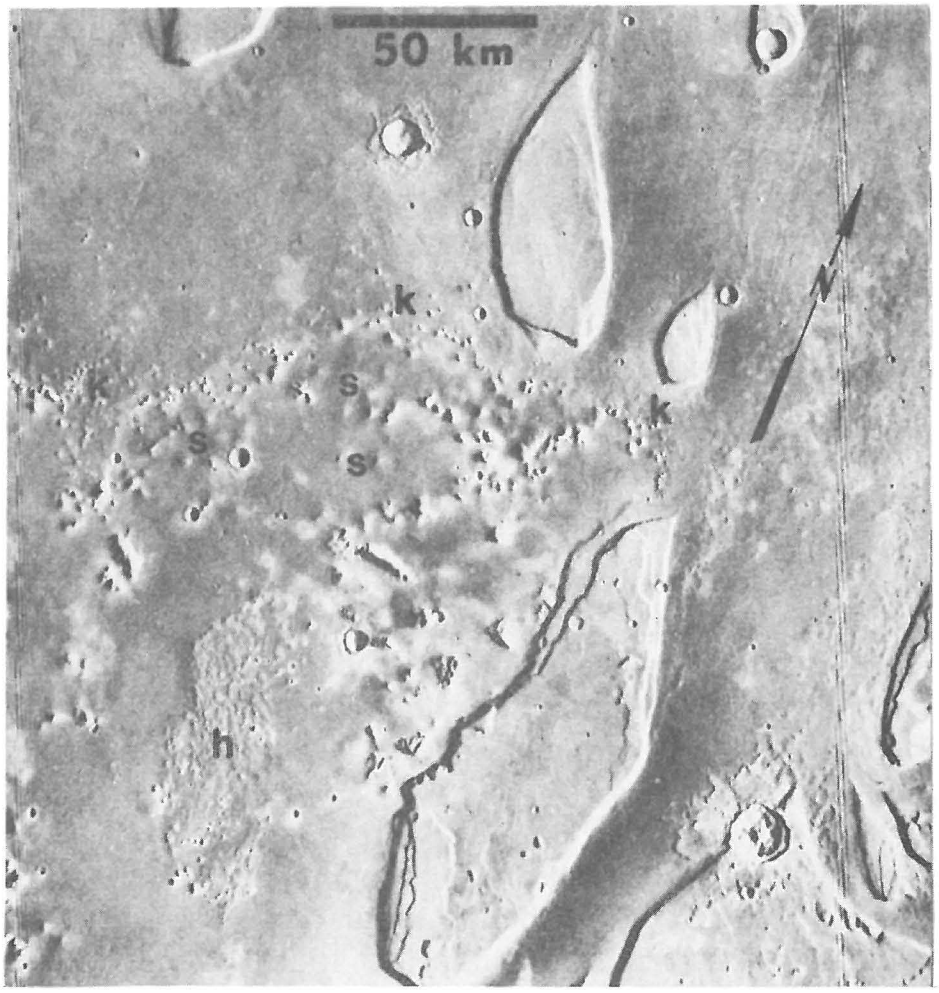

Figure 1. This Viking image (366S04) shows part of northern Simud Vallis where a field of hills covers the channel floor. Bumpy (hummocky) terrain (h), subdued hills (s), and a ring of small knobby hills (k) suggest that the hills were blocks of material that were carried by a muddy flow (see text).

HIGH-RESOLUTION (30 M) LUNAR RADAR IMAGES

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INTRODUCTION

A project has been under way for about 15 months to produce new high-resolution radar images of the lunar surface, using the Haystack Observatory range-doppler radar system.

Radar images of the moon and Venus (as well as terrestrial scenes) have been made for some time. However, thanks to the advances in digital technology which began about the time of the Apollo program, the best attainable radar resolution has improved considerably since the earliest days of planetary radar observations,

The new radar images, which have the appearance of oblique aerial photographs, have a resolution of about 20-30 meters, equivalent to about 0.01 arc-sec at the distance of the moon. This is considerably better than could be obtained with the best earth-based optical telescopes. It is achieved because the range-doppler radar imaging process is more nearly equivalent to an optical laser hologram than an ordinary optical image. Futhermore, the hologram is not created with optical photo-emulsion techniques, but rather with more precise digital-computer techniques.

The information obtained from a radar image can be quite different from an optical photograph. Although radar data is not usually analyzed in this way, one can consider that the radar image is an ordinary photograph which was taken at a widely different "color" than the usual optical image. That is, the brightness of the radar image depends on the planetary suface mechanisms which reflect or scatter cm-wavelength electromagnetic (radar) radiation, as opposed to those which scatter micrometer-wavelength (light-wave) radiation.

For any surface reflection mechanism, the major factors which influence its brightness are the material of which the upper layer of the surface is made, its morphology, and its physical state. In the case

of radar, the reflectivity thus depends on the the mineral composition of the upper meter or so of the surface layer; its general smoothness and surface arrangement (i.e. tilted or level, planar, duned, furrowed, chaotic); and its grain size, porosity and the number of small craters, exposed or buried rocks, or other discontinuities.

But in addition to this fundamental difference, the radar image is taken with man-made radiation rather than natural sunlight. This has the advantage that the detailed parameters and waveshape of the transmitted radar signal (frequency, polarization, etc.) are known precisely. We can therefore investigate some of the more subtle details of the moon's surface by their effects on the radar wave.

EXPERIMENT

The goals of this work are twofold:

a) to investigate the decameter-scale properties of the lunar surface, as an aid in the understanding of the geophysical history of the moon; and

b) to improve our understanding of the mechanisms of planetary radar backscattering, and so to aid in the interpretation of the coarser-resolution images which have been and will be obtained from planetary probe missions and other earth-based observations.

Some of the geophysical research with the new, high-resolution data is similar to earlier radar investigations carried out for both the moon and Venus, except for the ability to analyze smaller-scale features. In addition, however, for the present experiments we measured simultaneous images of both the specular and opposite polarizations of the echo, including the relative phase between them.

These dual-polarization images have allowed us to search for coherently cross-polarized areas, which exhibit the peculiar type of echo which could originate, for example, from a double reflection from the intersecting corner of a horizontal plain and a vertical rock face.

Large vertical cliffs of this type could be seen directly, of course, in the radar images. However, such cross-polarized echoes (which

were observed, in fact, in our first attempt, in a narrow region in one wall of the crater Copernicus) would also be observed even in corners much too small to be seen with the 25-meter resolution of these images. The reflecting surfaces need only be significantly larger than 3 centimeters, that is, the wavelength of the radar signal.

This last type of analysis begins to encroach on the second of the goals mentioned above, that of investigating how various details of the lunar surface can produce observable differences in the radar images. The basic question is "What are the planetary (lunar) surface details that we can infer from a close examination of the radar images?"

Such investigations have been and will continue to be important goals of all planetary and terrestrial radar research. Radar experiments are sufficiently varied, complicated and expensive that there has not yet been produced even one set of multi-frequency co-registered radar images analogous to the multi-spectral optical/infrared images that are now commonly available. As a result, geological researchers who use radar images generally make more and more use of subtleties in the "monochrome" radar images. As a result, their relationship to geological details on the planet's surface are themselves being understood better and better as the research progresses.

It is expected that the current investigations of small-scale planetary surface phenomena which are being undertaken with this new set of radar images will bring a significant improvement to our understanding of this relationship.

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