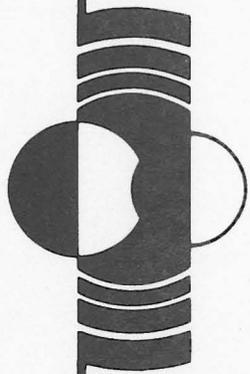


# Lunar and Planetary Science XVI



*Sixteenth Lunar and Planetary  
Science Conference  
March 11-15, 1985*

*PRESS ABSTRACTS*

**NASA**

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**Lyndon B. Johnson Space Center**  
Houston Texas

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LUNAR AND PLANETARY INSTITUTE  
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PRESS ABSTRACTS

SIXTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE

MARCH 11-15, 1985

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## PREFACE

The Program Committee for the Sixteenth 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 XVI*.

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 *ii*. Feel free to call for more information.

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## ASTEROID AMPHITRITE: SURFACE COMPOSITION AND PROSPECTS FOR THE POSSIBLE GALILEO FLYBY.

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The asteroids are of fundamental importance to understanding the origin and evolution of the solar system for several reasons: 1) They probably represent remnants of the population of small bodies which accumulated to form the planets, and preserve an otherwise lost intermediate stage in the formation of planetary systems, between dust and planets; 2) Some of them have escaped the melting processes which have destroyed evidence of the original geochemistry in planetary rocks; 3) Study of meteorites has provided a vast body of geochemical, mineralogical, and isotopic data which probably refers to some asteroids; 4) The asteroid belt is located between the rocky inner planets and the the icy outer solar system and should preserve the compositional transition between these radically different classes of bodies. While much has been learned about the size, shape, and composition of asteroids from telescopic observations, no spacecraft has visited an asteroid. However, studies of the trajectory of the Galileo mission to Jupiter recently revealed that the spacecraft can pass close to one of the largest asteroids (#29 Amphitrite). NASA has therefore altered the mission plan of the Galileo spacecraft to include a possible close flyby of Amphitrite in early December 1986, if the condition of the spacecraft allows. If this option is actually implemented, Amphitrite will become the only asteroid for which any high-spatial resolution images and reflection spectra will be available. To evaluate the value of this data and place Amphitrite in the context of the more than 600 asteroids for which some compositional information exists, we have reexamined existing data, obtained new telescopic spectra of Amphitrite, and constructed simulated Galileo data sets.

Previous studies of Amphitrite have provided good information on its size and shape. Observations of infrared thermal emission indicate that Amphitrite has an average diameter of about 200 kilometers, and that its surface reflects about 15% of the sunlight falling on it. The amount of reflected light varies with a period of 5.39 hours in a highly irregular fashion, which indicates a jagged "pyramidal" shape with projections possibly as much as 30 kilometers above the mean radius. Attempts to deduce the orientation of the rotation pole from the light variations have produced solutions which differ radically; this parameter must be considered essentially unknown. Measurements of the polarizarion of reflected light indicate that the surface is covered with a layer of pulverized material, presumably created by small impacts.

Studies of the spectral distribution ("color") of reflected light provides the best means of determining asteroidal surface compositions. Data obtained in the visible spectral region (0.3 to 1.1 microns wavelength) indicate that Amphitrite belongs to the common spectral class S. These objects are characterized by strongly reddened spectral curves with shallow absorption bands diagnostic of the silicate minerals olivine and pyroxene. Among the 14 asteroid spectral classes identified in the most recent taxonomic analysis (by David J. Tholen, based on the University of Arizona 8-color asteroid survey),

the S-types are the only abundant class with such complex spectra. Unfortunately, this class is also the most controversial, with two opposing schools of thought supporting contradictory interpretations of the spectral data. The conventional method of interpreting asteroid spectra is to pulverize meteorite samples to approximately the texture of asteroid regoliths (as indicated by the polarization data), obtain spectra in the laboratory, and compare them with asteroid spectra. This is an imperfect technique, because some meteorite classes are very rare and museum curators dislike having them destroyed, and because many common types contain large masses or networks of nickel-rich iron alloy (with mechanical properties similar to man-made stainless steel) which makes them difficult to pulverize. In fact, none of the meteorite spectra obtained to date match the S-type asteroid spectra closely. This fact is explained in two ways: A.) The most common meteorites (ordinary chondrites) also contain shallow olivine and pyroxene absorption bands, but lack the steep red slope also present in S asteroids. Since the red slope appears in pure iron meteorites, slope should be correlated with metal abundance. Increasing the metal abundance in an S-type regolith would tend to increase the spectral slope. Therefore, the S-type asteroids are undifferentiated ordinary chondrites covered with a regolith whose apparent metal abundance is enhanced by the regolith-forming process. The simulated regoliths prepared from ordinary chondrites found on Earth do not spectrally resemble the natural regoliths on asteroids because their pulverization is an inadequate simulation of the real regolith-altering processes. B.) The spectral differences between S-type asteroids and ordinary-chondrite meteorites represent a real compositional difference. The lack of spectral matches for S-asteroids in the meteorite spectra collection is an artifact of the incomplete nature of that data set. S-asteroids are composed of differentiated stony-iron material similar to the pallasite and lodranite meteorites, for which no lab spectra have been obtained.

These two opposing interpretations have radically different implications in many areas. If interpretation A is correct, 1) the most common meteorites correspond to the most common asteroids; 2) asteroid spectra are highly non-representative of the bedrock beneath; 3) S-type asteroids were only slightly heated and metamorphosed. If interpretation B is correct, 1) the most common meteorites have no known parent body in the asteroid belt, and the most common asteroid type is the source of some of the rarest meteorite types; 2) asteroid regoliths are merely pulverized bedrock and asteroid spectra are easily interpretable; 3) S-type asteroids were strongly heated and melted, but the segregation of silicate and metal components was still incomplete when the heat source decayed and the melt solidified. The controversy thus cuts to the very heart of asteroid and meteorite research.

Several lines of research over the past several years have converged to suggest that interpretation B is the correct one (see also paper by M. J. Gaffey at this conference). D. J. Tholen has defined a new spectral class "Q" of which asteroid #1862 Apollo is the prototype. Spectra of this object are nearly identical with that of some pulverized ordinary chondrites. About 10-20% of the asteroids of Earth-crossing orbits appear to belong to this class, which is totally absent in the main belt. The abundance of ordinary chondrites in meteorite collections may therefore be a artifact of current orbital relationships between their parent bodies and Earth. Gaffey has produced simulated ordinary chondrite regoliths in which the metal abundance is enhanced by magnetic separation. Surprisingly, even very metal-rich

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simulations show no increase in the red slope thought to be characteristic of nickel-iron metal. Apparently the spectral signature of metal in undifferentiated meteorites differs from that in differentiated meteorites. Gaffey also has made observations of asteroid #8 Flora (which has been nominated by promoters of interpretation A as the best match for ordinary chondrites) to search for mineralogic variations across its surface. Such variations were found and exhibit trends not found in chondritic meteorites. J. F. Bell and B. R. Hawke have conducted the first comprehensive asteroid spectral survey in the near-infrared spectral region, which indicates that Gaffey's conclusions for Flora extend to S-type asteroids in general. Finally, a newly defined spectral class "A" has been shown by Bell to correspond closely to spectra of simulated stony-iron regoliths created by dispersing olivine grains on a metal substrate. This method avoids the problems of pulverizing metal-rich meteorites; with the addition of pyroxene it should be possible to simulate S-type regoliths as well. Recent observations by Bell and D. P. Cruikshank suggest that the S and A types are not distinct as indicated by earlier low-spectral-resolution data, and that both belong to a large and highly varied group of asteroids which is the source of most types of stony-iron meteorites. Despite these developments, several prominent and vocal supporters of interpretation A remain active; discussions between the two factions continue to enliven coffee breaks at scientific meetings.

As part of the infrared spectral survey mentioned above, J. F. Bell and B. R. Hawke obtained a spectrum of Amphitrite at the NASA Infrared Telescope Facility on 28 December 1983 which covers the 0.8-2.5 microm wavelength range. This is about half the wavelength coverage of the Near Infrared Mapping Spectrometer aboard the Galileo spacecraft (0.7-5.2 microns). In the attached figure this spectrum is combined with shorter wavelength data obtained by C. R. Chapman in 1971. From this it is apparent that Amphitrite has the typical S-type infrared spectrum. The absorption band near 0.95 microns is due to a combination of olivine and pyroxene bands, while the band near 2 microns is due to pyroxene alone. Comparison of the relative strengths of these bands with a calibration derived from lab spectra indicates that the silicates in Amphitrite are about 40% olivine / 60% pyroxene. Wavelengths of the pyroxene absorptions indicate a low-calcium, medium-iron pyroxene. The olivine abundance and pyroxene mineralogy are inconsistent with any type of chondritic meteorite. Together with the curved red continuum, this indicates a differentiated stony-iron assemblage according to the principles of interpretation B above. The only meteorites which could be derived from Amphitrite are a few rare "anomalous stony-irons" or "primitive achondrites", most likely the lodranites which are meteorites composed of olivine and pyroxene crystals enclosed in a metal matrix. The very small number of such meteorites relative to the large number of S-type asteroids makes it very unlikely that we have a fragment of Amphitrite available for analysis on Earth.

As an aid to Galileo mission planning, we have used our telescopic spectra to construct simulated mapping spectrometer data sets. These indicate that the instrument, although intended for compositional mapping of the satellites of Jupiter, is ideally suited for the Amphitrite encounter. Even in the lowest resolution modes useful compositional data can be obtained.

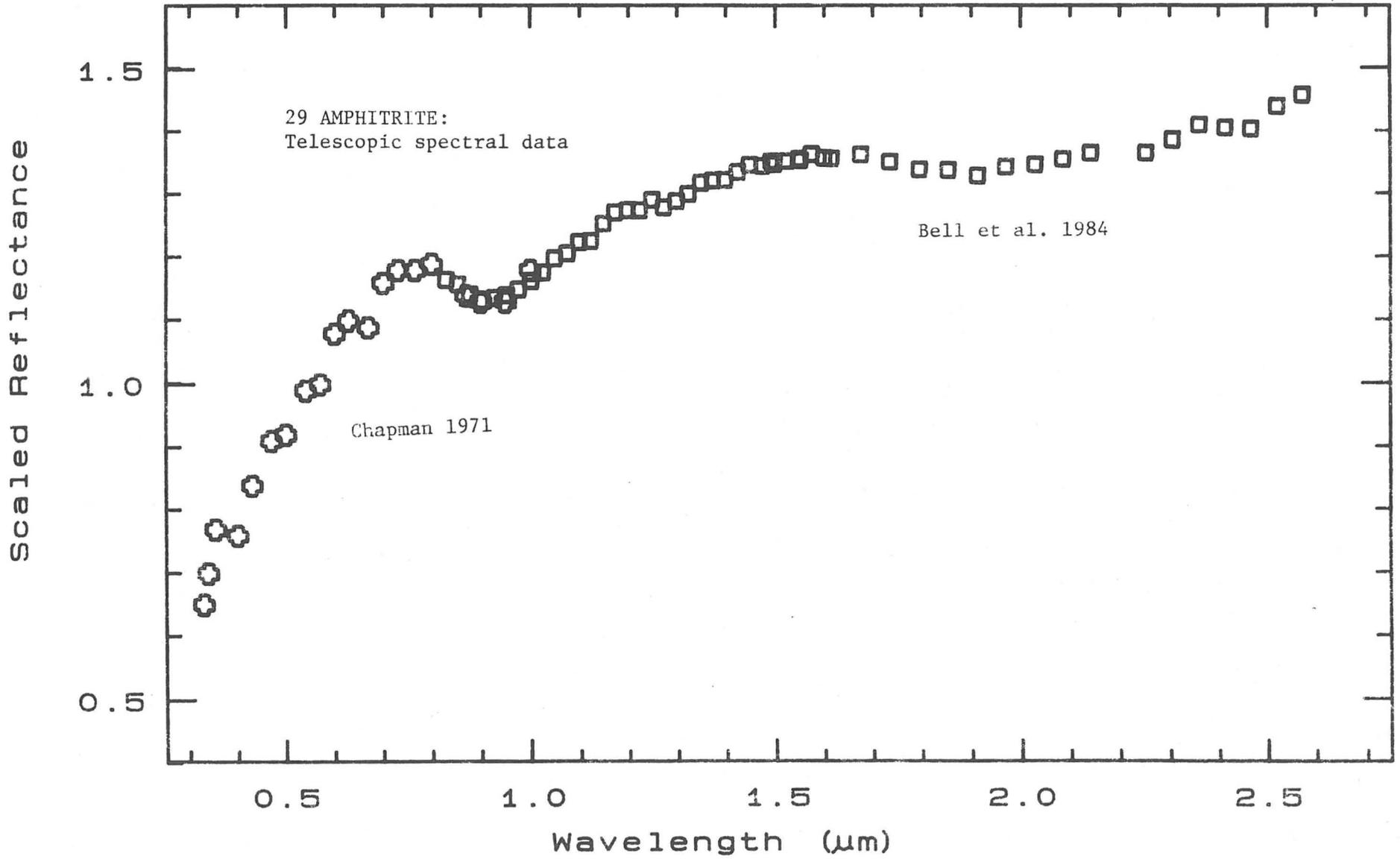
Since we already possess a spectrum of Amphitrite essentially identical to those to be returned by Galileo, how will the possible flyby data help us resolve the dispute outlined above? The spatial resolution possible with the

Galileo mapping spectrometer will allow the mapping of spectral units on the surface. Under interpretation A, Amphitrite should be essentially homogenous (except for small differences due to metamorphism). However, if it has melted and differentiated to some extent, different depths should have different mineralogies. The highly irregular surface of Amphitrite was presumably created by impact erosion of a larger parent body, and higher "mountains" should correspond to shallower layers. Provided that the regolith gardening on the surface has not completely obscured the differences in the bedrock, the Galileo spectral maps should resolve radial differences in mineralogy. There is some evidence for spectral units on a hemispheric scale from telescopic data. Unpublished 0.3-1.0 micron, spectra obtained by Gaffey in August 1978 indicate variations in the spectrum on the order of 2% correlated with rotation. If these are real they suggest that we can expect a fair amount of structure in the spectral maps from Galileo. The authors plan to look for these variations with improved instrumentation during the May 1985 opposition of Amphitrite. In any case the Galileo imaging experiment will provide the first detailed information on the shape, crater density, and surface structure of an asteroid. At present these parameters are inferred from unconvincing theoretical models or analogies with the moons of Mars (which have a totally different composition and bombardment environment.) The irregular shape inferred for Amphitrite suggests that the images should prove highly interesting.

In summary, the Amphitrite encounter is the right mission with the right instruments to the right asteroid at the right time to fill major gaps in our knowledge of asteroids. It will provide a firm foundation for planning future dedicated asteroid belt missions and Earth-based observational programs.

FIGURE 1

J. F. Bell 2 Nov. 1984



ASTERIOD AMPHITRITE...  
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29 Amphitrite /sun (old CRC data 22oh)	fb007	f 507	a5e2d
29 Amphitrite /75Cno s1 (ave. of 4)	fb007	f 515	a3e1p213
29 Amphitrite /75Cno s2 (ave. of 4)	fb007	f 523	a4e1p213

**EVIDENCE IN METEORITES FOR AN ACTIVE EARLY SUN:** M. W. Caffee<sup>1</sup>, J. N. Goswami<sup>2</sup>, C. M. Hohenberg<sup>1</sup>, T. D. Swindle<sup>1</sup>. (1) McDonnell Center for the Space Sciences and Dept. of Physics, Washington Univ., St. Louis, MO. 63130. (2) Physical Research Laboratory, Ahmedabad-380009, India.

Was the sun once brighter than it is today? Recent meteorite studies suggest that the sun may have gone through a period of intense solar flare activity as a young star 4.5 billion years ago. Astronomical observations of a class of stars called T-Tauri stars, stars that are similar in size to our sun but in a much younger stage of evolution (several million years old or less), show that this class of stars can be very active. Scientists have suspected that our sun also went through a period of increased activity, but it's difficult to find direct evidence for an event that happened so long ago.

However, in the same way that spacecraft are sent to other planets to gather new information, meteorites can serve as probes into our solar system's early activity. Most meteorites formed about 4.5 billion years ago, and have been altered little since then. Some of these meteorites contain grains that were individually exposed to energetic particles before formation of the meteorite. These grains have preserved a record of the early solar activity that can be studied. We have found that these grains have surprisingly large abundances of a rare isotope of neon, which can only be produced by energetic particles. These particles can come from only two sources: galactic cosmic rays or solar flares. Unless the grains were exposed to galactic cosmic rays for a much longer period than is predicted by current theories, this excess neon must have been produced by solar flares at least 100 times more intense than those of our present sun.

A simple history for this type of meteorite includes three stages. In the first stage, which occurred at least 3.5 billion years ago (more likely 4.5 billion years ago), some mineral grains were exposed to the sun, while others, deeper in clumps or within the rubble surface of a small asteroid-like body, were not. In the next stage, many grains, only a few of which had been exposed to the sun, were compacted together in a solid object, shielded from further bombardment by energetic particles. This stage constitutes the major period of a meteorite's history. Finally, sometime within the last 30 million years or so, this larger body broke apart, probably the result of collisions that also placed the meteorite on a collision course with the earth.

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We can learn about these three stages of exposure from the records the grains have retained. For example, if we treat the grains with acid and look at individual grains under a microscope, we find that some grains (5 to 10 percent of the grains in the meteorites we've studied) show evidence of exposure to solar flares. During a solar flare, the sun ejects particles at a high enough energy that they will penetrate the first 10-20 microns (millionths of a meter) of a rock, leaving a scar in the rock that the acid attacks and enlarges to make a visible "track." Since these solar flares are stopped in such a short distance, grains with solar flare tracks must have been exposed directly to the sun. Furthermore, those grains must have been exposed to the sun in the first stage of their history, since they were recovered from inside the meteorite.

Meteorites are also bombarded by galactic cosmic rays. The galactic cosmic rays, which do not come from our solar system, are mostly protons that are moving at nearly the speed of light. They have energies comparable to those produced by the most powerful particle accelerators on earth. These cosmic rays can penetrate only a few meters of soil or rock, so grains in meteorites can be exposed to them during the early and recent stages of their history, but not during the long intermediate stage of deep burial. When a cosmic ray proton collides with an atomic nucleus within a rock, it can break off ("spall") part of the nucleus, converting it into a different element. We study neon, which can be produced from common elements like magnesium or silicon in this type of reaction. One particular isotope of neon, neon-21, is rare in meteorites unless such spallation reactions have occurred. Solar flare particles can also produce spallation reactions, but in the modern solar system, the number and intensity of solar flares are low enough that the products of such reactions are rare and difficult to detect. However, this might not have been true of the early solar system.

In our experiment, we compared the amounts of neon-21 produced by spallation reactions in grains that had been exposed to the sun (in other words, grains that had solar flare tracks) and grains that had not. Since all the grains had the same exposure in all but the earliest stage of the history of the meteorite, we hoped to find out something about that earliest stage. In three different meteorites, grains that had been exposed to solar flares had much more neon-21 (by factors as large as 50) than those that had not. If the neon-21 were produced by galactic cosmic rays, these grains must have had early exposures of

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up to several hundred million years, much longer than models of meteorite evolution predict. On the other hand, if solar flares were much more numerous and much more energetic when the sun was young, those flares could have produced the effects we see in a much shorter time span. For instance, solar activity 100 times greater than current solar activity would require pre-compaction exposure times of only a few million years. These times would then agree with most models for meteorite formation.

There are questions remaining to be answered before accepting this evidence as proof that the early sun was more active. For example, we need to know precisely when the early production of neon-21 took place. This is important since the period of enhanced solar flare activity would not be expected to last more than several million years. Therefore, if any of the grains containing the excess neon-21 are much younger than 4.5 billion years old (for example, if they are only 3.5 billion years old), a different explanation would have to be found. There are currently experiments under way that we hope will answer these questions.

Interstellar  $^{26}\text{Al}$  and Excess  $^{26}\text{Mg}$ ; Donald D. Clayton, Rice University, Houston, TX 77251.

When groups in Australia and Caltech first showed that aluminum-rich minerals within the CaAl-rich inclusions from the Allende meteorite carried an excess of the heaviest isotope of magnesium,  $^{26}\text{Mg}$ , it was concluded that a supernova explosion beside the forming solar system must have peppered the solar cloud with radioactive  $^{26}\text{Al}$ . The inference was that later, after the solar system and the meteorites had assembled in much their present form, that  $^{26}\text{Al}$  decayed to  $^{26}\text{Mg}$  by nuclear beta decay within the Allende minerals. The highest concentrations observed suggested that 50 parts per million of aluminum was the radioactive mass-26 isotope, whose half-life for decay to  $^{26}\text{Mg}$  is one million years. The believed requirement of a supernova accompanying the birth of the sun derived from the belief that the interstellar gas would not normally have nearly enough radioactive  $^{26}\text{Al}$  within it, so that a synchronized thermonuclear explosion was accepted as the source of the cosmic radioactive "fallout" that the Allende minerals have recorded.

Now this situation has been vastly shaken by the actual detection of radioactive  $^{26}\text{Al}$  in the interstellar medium today. The first detection, an historic first detection ever of interstellar radioactivity, was made by the HEAO 3 spacecraft [Mahoney *et al.* 1984, *Astrophys. J.*, 286, 578] which recorded a measurable flux of 1809 keV gamma rays striking the solar system. The 1809 keV gamma rays are a well known electromagnetic radiation given off following the beta decay of each  $^{26}\text{Al}$  nucleus. The HEAO 3 spacecraft measured that about 480 such gamma rays impact a square meter every second, coming from the general direction of the center of our Galaxy, but at an unknown distance. Lingering doubts about the reality of this astonishing discovery have now been removed by a confirmation of its correctness. The Solar Maximum Mission that was so dramatically repaired by the Shuttle astronauts carried a gamma ray spectrometer that had since February 1980 taken unintentional periodic looks at our Galactic center. That spectrometer team (Share *et al.* 1985, submitted to *Astrophys. J.*) confirms about 400 gamma rays per square meter per second from the direction of the Galactic center, in direct agreement with the HEAO 3 measurement. It can now be asserted without reasonable doubt that some source of radioactive  $^{26}\text{Al}$  lies in that general direction.

The analysis of the magnitude of this gamma ray flux and its implications for both the origin of the elements in explosions of stars and for the origin of the Allende minerals was undertaken by Clayton (1984, *Astrophys. J.*, 280, 144). He came to three startling conclusions: (1) if the  $^{26}\text{Al}$  is spread uniformly throughout the interstellar gas, its concentration of about 10 parts per million of aluminum is rather close to the fossil evidence found in Allende minerals, suggesting that the requirement of a special supernova trigger to solar formation may have been unwarranted; (2) supernova explosions are not adequate to maintain this average level of interstellar radioactivity, so that nova explosions or gas streaming away from giant stars are the more likely origins of the radioactive aluminum. The ineffectiveness of supernovae in maintaining the observed concentration also argues against implicating a special supernova with the solar origin. These two conclusions, when added to other arguments that Clayton had advanced prior to the detection of  $^{26}\text{Al}$  gamma rays, have almost eliminated that supernova-trigger concept. On the other hand, Clayton's third conclusion was that if the observed  $^{26}\text{Al}$  is not assumed to be spread throughout the interstellar medium, it could in fact be local debris from a single supernova explosion that occurred very near the earth only about 100,000 years ago, in which case it might give renewed emphasis to the concept of a similar explosion near the forming solar system 4.5 billion

Interstellar  $^{26}\text{Al}$  and Excess  $^{26}\text{Mg}$ 

Clayton, D. D.

years ago. Other evidence bearing on the exciting possibility that Earth is now located in a supernova remnant is being analyzed by Clayton and his colleagues, who reported at the "Galaxy and Solar System" Meeting in Tucson in January possible evidences for this recent nearby supernova, primarily long standing puzzles in the cosmic radiation.

At Lunar and Planetary Science 16, Clayton argued that the interpretation of the excess  $^{26}\text{Mg}$  in Allende aluminum-rich minerals depends upon the correct interpretation of the  $^{26}\text{Al}$  gamma-ray line. The correct interpretation of the gamma rays requires better information on their angular distribution. Because of their wide viewing angles and serendipitous measurements, the HEAO 3 and Solar Maximum Mission teams have been reluctant to be very precise about the angular distribution. Although they describe it as being "consistent with" radioactivity concentrated in the galactic plane having peak intensity near the Galactic center, they stop short of claiming that the data requires that interpretation. The single supernova neighbor could happen to be toward the general Galactic center, but it would occupy a large circular area on the sky, perhaps a  $30^\circ$  to  $90^\circ$  cone, and it would be most unlikely that the center of such a nearby distribution would happen to lie in the plane of the Galaxy. If the observing teams can successfully show that the latitude distribution is narrow and centered on the plane, Clayton said that we will be forced to accept the interpretation of the  $^{26}\text{Al}$  concentration as a general feature of the gas as well as reaffirming the need of a nonsupernova source (e.g., novae) of the young  $^{26}\text{Al}$ .

To aid this interpretation, Clayton presented theoretical angular distributions and isotopic concentrations that would be consistent with the observed gamma ray flux. He and Leising (1985, *Astrophys. J.*, in press) made several different assumptions about the distribution of the production of  $^{26}\text{Al}$  in the hopes that at least Gamma Ray Observatory, if not HEAO 3 or Solar Max, will be able to identify the actual angular distribution. The four cases they modelled assumed  $^{26}\text{Al}$  production proportional to, respectively: (1) the mass distribution of cold molecular clouds; (2) the total mass distribution of interstellar matter; (3) the rate of optical emission from the surface of the disk; or (4) the distribution of Galactic novae. Their results offer good hope of recognizing the true situation. Easiest to recognize would be  $^{26}\text{Al}$  production by novae because it would be much more strongly peaked toward the Galactic center than would the others. The corresponding Galactic concentration near the sun would be the lowest of those possibilities, however, only about 2 atoms of  $^{26}\text{Al}$  per million Al atoms. The highest concentration, 10  $^{26}\text{Al}$  atoms per million Al atoms, exists in molecular clouds if the production occurs primarily within them, as it would if massive stars are its primary source.

Clayton emphasized that the isotopic concentration  $^{26}\text{Al}/^{27}\text{Al} = 10$  parts per million, which is consistent with the gamma-ray flux for the first three of these distributions, lies squarely between but distinct from the concentration 50 parts per million seen in some, but not all, aluminum-rich Allende minerals and the much smaller concentration less than 1 part per million that could be maintained there by supernova explosions. Thus the observed Allende concentrations of excess  $^{26}\text{Mg}$  are still too large to be interpreted as being the average interstellar concentration, so that if the  $^{26}\text{Al}$  was actually once alive in the Allende minerals seen today there must have been some source of  $^{26}\text{Al}$  enhancement in the solar cloud as it was collapsing to form the solar

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system. Whether this contamination resulted from a nearby nova or red giant, its ejecta will have contained other nuclear clues that must be detailed and sought.

Clayton's final remarks reopened his assault [see for example Lunar Planet. Sci., 13, 115 (1982); Astrophys. J. 251, 374 (1981)] on the belief that the  $^{26}\text{Al}$  was actually alive in the Allende minerals. He pointed out that whatever the source of the  $^{26}\text{Al}$  observed by today's gamma radiation, those objects are necessarily ejecting  $4 M_{\odot}$  per million years into the interstellar medium. By contrast supernova eject  $24 M_{\odot}$  of new stable aluminum and stars reinject  $60 M_{\odot}$  of old stable aluminum over the same million years. Arguing that all of these ejecta condense into refractory aluminum-rich solids as they leave their respective sources, that the  $^{26}\text{Al}$  decays to  $^{26}\text{Mg}$  within the resulting mixture of well mixed dust grains, Clayton showed that the ratio  $^{26}\text{Mg}/\text{Al} = 0.05$  results within the aluminum-rich dust, fully a thousand times greater than the correlation that later survives in the aluminum-rich minerals. This high interstellar correlation of excess  $^{26}\text{Mg}$  with Al could not have been totally removed by evaporation, because the Allende minerals carry other isotopic anomalies that demonstrate that they were not evaporated totally at any stage prior to their assembly. Thus Clayton concludes that the  $^{26}\text{Mg}$ -Al correlation observed in Allende minerals is a manifestation of a cosmic chemical memory. He laid down a challenge to mineral chemists to demonstrate how this memory survives the process of mineral formation and substantial extraction of magnesium from them.

GANYMEDE AND CALLISTO: BEAUTY IS ONLY SKIN DEEP. Steven K. Croft. Dept. of Planetary Science, University of Arizona, Tucson, AZ 85721

Ganymede and Callisto, the two giant icy satellites of Jupiter, have very nearly the same size, composition, and location in the solar system, yet their surfaces are profoundly different. A new scenario of their geologic histories indicates that the differences may be only skin deep.

The disparate appearances of Ganymede and Callisto constitute a major puzzle to our understanding of planets. Ganymede's surface consists of roughly equal portions of light and moderately dark terrain. The dark terrain is moderately cratered and marked by frequent curved furrows and seams. The light terrain is only thinly cratered, but almost completely covered by closely spaced grooves in patterns reminiscent of contour-plowed fields or broom-sweep patterns in loose sand. The light terrain is evidence of extensive flooding due to internal melting, while the furrows and grooves are the result of internal stresses and strains. In contrast, Callisto's surface is very dark and heavily cratered, with no evidence of the flooding and cracking so common on Ganymede. Current theories of the formation of planets and the shaping of their surfaces indicate that two planets of similar size and composition, like Ganymede and Callisto, should be subject to the same geologic processes both inside and out, and should have similar surface features. Thus, since Ganymede underwent extensive flooding and fracturing, Callisto should have also. Explaining how Callisto came to have none of the features (except craters) so common on Ganymede is comparable to explaining how one tract house had no water inside during a major flood while the neighboring house was filled to a depth of, say, 8 feet.

Previous geologic models proposed for Ganymede have suggested that its interior was largely or completely melted, allowing the rocky material inside to sink to the center and leaving behind a thick rind of pure ice on the outside. Such models have difficulty explaining either how Callisto underwent similar extensive melting without ending up with Ganymede-like surface features or what subtle factor allowed Ganymede to melt completely while Callisto remained solid. An additional problem for a largely melted Ganymede concerns the nature of the material forming the light terrain. The light terrain, with its sharp, linear edges and depressed topography, is suggestive of flooding of valleys by liquid water. But water, being

more dense than ice, could not reach the surface of a pure ice layer. Blobs of warm ice could rise to the top of a cold icy layer and flow outward across the surface like glaciers to form the bright material. But such deposits would be rounded and stand above the surrounding terrain, an appearance very different from that actually observed for the bright terrain.

The new geologic model resulted from further analysis of Ganymede's surface features. The dark terrain has a lower crater density than Callisto implying that it, like the light terrain, is a flooded surface. Recent work on the distribution of craters with dark ejecta and on patterns of different shades within the dark terrain show that the dark terrain is complexly layered, both vertically and horizontally, again indicative of surface flooding. Similarly, the light terrain has been shown to be at most a few kilometers thick and considerably thinner in many places. The complexity and appearance of the light and dark terrains virtually require flooding by liquid water. The presence of liquid water on the surface of Ganymede requires that the outermost layer had to retain enough rocky material to keep subsurface pressures high enough to force the water out. Thus, the outermost layer never completely melted. The lack of extensive disruption of Ganymede's surface after the formation of the bright terrain which would have been produced had melting continued at depth implies that the interior of Ganymede did not melt either. Thus, the new geologic model suggests that, at most, only part of the outermost layer of Ganymede underwent melting. Compared to the rest of the planet, the melting of only the outer 100 kilometers or so of Ganymede represents only a few percent of the planet's volume, and thus is merely a "skin effect." The reason this skin effect produces such a dramatic change in the visual appearance of Ganymede is because it is precisely the altered surface that we see. We do not directly see the virtually unchanged bulk of Ganymede's interior.

This model for marginal melting provides a natural explanation for the difference between Ganymede and Callisto: The heat required to melt the outermost layer of Ganymede is only a few percent (or less) of the total radioactive heat output during the estimated billion years or so over which the light and dark terrains formed. Thus the temperature at depth only just barely reached the melting point of ice under pressure (had the

temperature ever substantially exceeded the melting point. Ganymede would have melted completely). Thus if the interior heat production were slightly less (figuratively, if the interior "thermostat" were lowered slightly), melting would not have occurred at all. Callisto is somewhat smaller than Ganymede and has slightly less rocky material (which contains the radioactive elements), thus its "thermostat" is approximately 20% lower than Ganymede's and thus melting never occurred. In the analogy of the flooded houses above, the flood was only a small one and the flooded house had only a few inches of water in it. The floor of the neighboring house was a foot or so higher and thus remained dry.

In addition, the new "marginal melting" scenario for Ganymede will allow us to better understand the heat transport properties of ice-rock mixtures found in icy satellites, and thus improve our understanding of the geologic histories of the other icy satellites. It also provides a new framework for attempting to understand the unique, even bizarre, appearance of the grooved terrain on Ganymede, which as yet have no satisfactory explanation. This new framework is rich enough in possibilities to be able to account for the observed complexity of features on Ganymede's surface. Some promising preliminary steps in the detailed study of the origin of many of Ganymede's unusual features have already been taken.

REFRACTORY INCLUSIONS IN THE ORNANS C30 CHONDRITE; Andrew M. Davis, James Franck Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637.

## INTRODUCTION

Several types of meteorites contain unusual objects 10 micrometers to 2 centimeters across that are enriched in refractory elements such as calcium, aluminum and titanium. These objects, commonly known as refractory inclusions, are most abundant in the meteorites known as carbonaceous chondrites. This abstract describes the refractory inclusions that have been found in the Ornans meteorite, a member of a little-studied group of carbonaceous chondrites. Some refractory inclusions in Ornans resemble those found in other meteorites, while others are unlike any seen before. The unusual inclusions in Ornans contain minerals with extraordinary enrichments in highly refractory elements.

First, a background section will describe carbonaceous chondrite types, the refractory inclusions found in them and the techniques used for finding and studying refractory inclusions. Then, the inclusions in Ornans will be described and compared with those found in other carbonaceous chondrites. The implications of the new work will be given at the end.

## BACKGROUND

### *Carbonaceous Chondrite Types*

Carbonaceous chondrites contain objects set in a fine-grained matrix. These objects include chondrules (spherical objects consisting of the common minerals olivine  $[(\text{Mg},\text{Fe})_2\text{SiO}_4]$  and pyroxene  $[(\text{Mg},\text{Fe})\text{SiO}_3]$  and glass, which have textures indicating rapid cooling); chondrule fragments; aggregates of olivine or pyroxene or both; grains of iron-nickel and iron and iron-nickel sulfides; and refractory inclusions. Three classes of carbonaceous chondrites are discussed in this abstract. C2 chondrites have an abundant black, fine-grained matrix (50 to 80% by volume) made of water-bearing minerals related to those found in clay. The chondrules and inclusions are small (up to 0.5 millimeters across). C30 chondrites have a fine-grained gray matrix of olivine (15 to 40% by volume) and small chondrules and inclusions up to 0.5 millimeters across. C3V chondrites have a fine-grained gray olivine matrix (20 to 50% by volume) but have larger chondrules, up to 2 millimeters across. Refractory inclusions up to 2 centimeters across have been found.

### *Refractory Inclusions in C3V Chondrites*

Refractory inclusions have been studied in C3V chondrites for over 15 years. Most of those studied are from the Allende meteorite, which is the largest and best known C3V chondrite (over 2 tons of it fell in Mexico in 1969). The inclusions are composed of minerals rich in highly refractory elements. These minerals are rare on earth and only found in refractory inclusions in meteorites. They include melilite  $[\text{Ca}_2(\text{MgSi},\text{AlAl})\text{SiO}_7]$ , spinel  $[\text{MgAl}_2\text{O}_4]$ , fassaite  $[\text{Ca}(\text{Mg},\text{Al},\text{Ti})(\text{Si},\text{Al})_2\text{O}_6]$ , perovskite  $[\text{CaTiO}_3]$  and hibonite  $[\text{CaAl}_{12}\text{O}_{19}]$ . These minerals are the first ones predicted by thermodynamic calculations to condense from a cooling gas of solar composition. Since equilibrium thermodynamic calculations cannot predict the direction of temperature change, the mineralogy of the inclusions is also consistent with their being residues left from extensive evaporation of normal solar system material (e.g., bulk carbonaceous chondrites). Allende inclusions can be divided into

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two major types, fine-grained and coarse-grained, based on whether or not mineral grains can be seen in a normal optical microscope. Both types of inclusions have been altered before they were incorporated into the Allende parent body. During alteration, refractory minerals are replaced by minerals stable at lower temperature. The high temperature minerals are more extensively altered in fine-grained than in coarse-grained inclusions. Fine-grained inclusions are only now being studied in detail, because the grains in them are so small that they can only be seen in an electron microscope. There are two major types of coarse-grained inclusions in C3V chondrites: Type A and Type B. Type A inclusions consist of melilite and spinel with minor hibonite and perovskite and Type B inclusions consist of fassaite, melilite and spinel with minor perovskite.

Allende coarse-grained inclusions are enriched in all refractory elements by about 20 times relative to normal solar system condensible material. Thus, they are thought to represent the first 5% of condensible material to have condensed as the primitive solar nebula cooled. Conversely, they could represent the final 5% left after evaporation of normal solar system condensible material. Allende inclusions are the oldest objects known. Radiometric dating by the uranium-lead method shows that they formed 4.56 billion years ago when the solar system is believed to have formed. About 10 years ago, it was discovered that the Allende inclusions contain excess magnesium-26 from the decay of aluminum-26. Nucleosynthesis of aluminum-26 must have taken place before the collapse of the presolar cloud to form the solar system. Since half of the aluminum-26 decays every 720,000 years, the inclusions must have formed within only a few million years of formation of the solar system. It is in Allende inclusions that isotopic anomalies in many elements have been found. These anomalies provide information on the mechanism of nucleosynthesis of the elements.

#### *Refractory Inclusions in C2 Chondrites*

Most of the refractory inclusions studied in C2 chondrites have come from the Murchison meteorite, which, like the Allende meteorite, is large and widely available. The inclusions are much smaller, usually 200 micrometers across or less. The major types found are: Spinel-diopside, consisting of spinel rimmed by diopside [ $\text{CaMgSi}_2\text{O}_6$ ]; spinel-hibonite, consisting of spinel, hibonite and minor perovskite; melilite-rich, containing melilite, spinel and minor hibonite and perovskite; monomineralic grains of hibonite and spinel; and ultrarefractory, containing hibonite and corundum [ $\text{Al}_2\text{O}_3$ ]. The Murchison inclusions are generally more highly enriched in refractory elements than are inclusions in C3V chondrites and are thought to form at higher temperatures than the C3V chondrite refractory inclusions.

#### *How Refractory Inclusions are Found*

Inclusions in Allende are large and abundant. A stone of Allende, typically 10 centimeters in diameter, is sliced like a loaf of bread, with each slice 0.5 to 1 centimeter thick. The inclusions are easy to find, because they are white and the matrix and other objects are a medium gray. Inclusions can be sampled with dental tools for bulk methods of analysis or they can be impregnated with epoxy and made into a 30 micrometer thick section with a polished surface. Such a polished thin section can be studied with optical and electron microscopes and analyzed for its major and minor element chemical composition with an electron microprobe and its trace element chemical and major element isotopic composition with an ion microprobe. The sampling method used for Allende inclusions favors large inclusions.

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More recently, refractory inclusions have been studied in the Murchison C2 chondrite. The inclusions are small and less abundant, so it is difficult to find them on the surfaces of slices. The most successful method of separating refractory inclusions from Murchison is as follows. A stone of Murchison is disaggregated by soaking it in water and repeatedly freezing and thawing it. Since ice expands as it cools (which is why pop bottles burst when frozen), the meteorite is broken into tiny pieces. Hard objects like chondrules and inclusions are separated from the porous and weak matrix. The resulting powder is placed in a dense liquid, where the very dense inclusions and mineral fragments sink and the less dense matrix minerals float. The dense fraction is dried and examined under a low power optical microscope. Many refractory inclusions can be distinguished by their shape and color. Hibonite is especially easy to find because it is bright blue. The separated inclusions can be analyzed by bulk methods such as neutron activation analysis and mass spectrometry or they can be mounted in epoxy, polished and studied with microscopes and microbeam analytical methods. Since weak inclusions are destroyed by the disaggregation process and many inclusions do not contain colorful, attractive minerals, the samples obtained by this method are probably not representative of the population of refractory inclusions in C2 chondrites.

The only way to obtain a representative sample of inclusions is to look at a large sample of a carbonaceous chondrite and examine all objects in it. This has been done by examining polished thin sections of the C3V chondrites Allende and Mokoia and the C2 chondrite Mighei with optical and electron microscopes. These studies have only included those objects that are larger than 100 to 200 micrometers across. As we will see below, many of the most interesting inclusions are smaller than this.

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##### *Experimental Methods*

In the work done here, a polished thin section of the Ornans meteorite was examined under a scanning electron microscope which was equipped with an X-ray detector. When the 15 kilovolt electron beam strikes an atom in a sample, the atom gives off X-rays. Atoms of each element give off X-rays of different energies. The X-ray detector detects a wide variety of energies of X-rays at once and displays the X-ray energy spectrum on a computer monitor. The approximate chemical composition of the area under the beam can be determined by a glance at the computer monitor. An accurate chemical analysis can be made by collecting X-rays from a spot for a couple of minutes and using the computer to calculate the composition from the collected X-ray data. Spots as small as 1 micrometer across can be analyzed.

The area of the thin section of Ornans studied was about 75 square millimeters. This entire surface was examined at 500 times magnification, where an area 130 by 170 micrometers is viewed at once. In each area, the computer monitor was watched to see when there was a high concentration of calcium or aluminum, since these elements are strongly enriched in refractory inclusions. All inclusions greater than 20 micrometers across were photographed and analyzed.

##### *Results*

Using the method above, 44 inclusions ranging in size from 30 micrometers across to 350 by 500 micrometers, were found. 26 of these inclusions were

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melilite-rich. They contain melilite, spinel and minor perovskite and hibonite. Their mineral chemistry and textures resemble those found in some Allende Type A coarse-grained inclusions, but they are smaller and more refractory than Allende inclusions. The melilite in them is lower in magnesium and silicon and higher in aluminum than melilite in Allende inclusions. This indicates that they formed at higher temperatures. No inclusions like Allende Type B inclusions were found, since no fassaite was found in any inclusion. 15 spinel-rich inclusions were found. Some convoluted inclusions have spinel cores and diopside rims like inclusions in Murchison, while others are compact inclusions consisting almost entirely of spinel with occasional perovskite grains.

The most interesting inclusions found are the 3 ultrarefractory inclusions. One is a 150 micrometer diameter inclusion composed almost entirely of 10 by 100 micrometer hibonite blades. It has many voids, so it is unlikely to have crystallized from a molten droplet. Thus it is probably not an evaporation residue. The second ultrarefractory inclusion is a single crystal of hibonite which encloses two grains of perovskite. The perovskites contain about 2% yttrium oxide. Yttrium is an extremely rare and refractory element and is normally present in perovskites from refractory inclusions at levels below 0.5%. The most exotic inclusion has been given the name OSCAR. It consists of an unusual mineral rich in calcium, aluminum, silicon, scandium, titanium and zirconium, which seems to be related to fassaite. This mineral contains 11 to 18% scandium oxide and 1.5 to 7% zirconium oxide. The other major mineral in this inclusion is perovskite which contains 6% yttrium oxide and 1% levels of some of the most refractory of the rare earth elements. This extraordinary inclusion is enriched in some refractory elements by a factor 10000 relative to normal solar system condensible material. It is difficult to believe that it could be extreme evaporation residue. OSCAR was described at the Meteoritical Society Meeting last summer in Albuquerque, New Mexico. An abstract about it is in press (A. M. Davis, 1984, A scandalously refractory inclusion in Ornans, *Meteoritics* 19).

Recall that most Allende inclusions have had some of their refractory minerals altered to lower temperature minerals prior to emplacement of the inclusions into the Allende parent body. The inclusions in Ornans have also been altered in a similar manner, but the alteration is less extensive than in the Allende inclusions. The Ornans refractory inclusions, as well as chondrules and mineral fragments, have experienced a second alteration step in the parent body. In this second step, there has been chemical exchange and reaction with the iron-rich olivine matrix.

#### CONCLUSIONS

The highest temperature history of the early solar system can only be deciphered by examining inclusions from a variety of meteorites, since different meteorites seem to have different populations of refractory inclusion types. It is important to characterize inclusions down to very small sizes, certainly much less than 100 micrometers. The three most unusual inclusions in Ornans are all quite small. If exotic inclusions like OSCAR were much larger, they would significantly affect bulk analyses of the meteorite. As it is, the amount of scandium that would normally be found on a 25 square millimeter area of Ornans is concentrated into an area only 60 micrometers across. It is hoped that further study of the chemical and isotopic compositions of the Ornans refractory inclusions will broaden our knowledge of conditions in the early solar system.

Nd-isotopic Evidence for the Origin of the Sudbury Complex by Meteoritic Impact; B. E. Faggart, A. R. Basu, Department of Geological Sciences, University of Rochester, Rochester, New York 14627; and M. Tatsumoto, U.S. Geological Survey, Box 25046, Denver, Colorado 80225.

The Sudbury geologic structure in Ontario, Canada has long attracted the interest of many generations of geologists. It is possibly scientifically the most intriguing and at the same time economically the most profitable igneous rock body on this planet. The Sudbury Complex is famous as the world's largest single supplier of nickel, although the original interest in the Sudbury ore was due to its copper content which is found in equal abundance with nickel. In addition to nickel and copper, the Sudbury rocks have produced significant amount of platinum, palladium, iridium, osmium, rhodium and ruthenium. The value of different minerals produced from Sudbury is indeed remarkable. For example, in 1981, Sudbury supplied nearly 19 per cent of the world's total nickel production, and before 1940, 80 percent of the world's nickel market was captured by Sudbury. The reserves of nickel at Sudbury is estimated sufficient for continued production into the twenty first century.

The nickel and copper are found as sulfides, along with the platinum group of metals, which are associated with a huge body of igneous rocks, collectively known as the Sudbury Igneous Complex. This complex is outlined at the surface as an elliptical ring structure, 60 km long by 27 km wide, elongated in an east-northeast direction. In general, the complex may be divided into two sections: a lower lying norite-gabbro rock body, beneath the base of which are the ore deposits of greatest economic importance, and an upper coarse-grained granophyric rock, referred to as the micropegmatite. The outer margin of the complex generally dips inward at 30° to 50°, producing a basin-like structure for the complex. The ore deposits occur around the outer and lower edge of the noritic rocks which also shoots as radial dikes into the surrounding rocks, known as the Footwall breccias. The Footwall breccias consist of rock units

characterized by deformational and shock-metamorphic features related to the Sudbury cratering event. According to some geologists, the Footwall may be 35 to 40 km wide south of the complex. The term shock metamorphism describes changes in rocks and minerals which result from the passage of high pressure shock waves and which causes permanent structural damage to minerals and rocks. In the Sudbury Footwall rocks, microscopic and macroscopic shock-metamorphic effects are common. Another shock-metamorphic feature, known as "shatter cones" have been found around the entire Sudbury Igneous Complex for distances as much as 17 km away from it. These are conical fracture surfaces with striations that fan from an apex. These cones are up to 3 meters long in adjoining rocks around the Sudbury Complex. These breccias in the Footwall of the Sudbury Igneous Complex are some of the most intriguing rocks related to the Sudbury Structure, and in spite of many studies, the origin of these breccias remains controversial.

The close spatial association of the norite rocks with the sulfide ore deposits suggests a genetic relationship and it is generally accepted by the experts that the sulfides were introduced as immiscible sulfide liquids which segregated from the silicate magma of noritic composition in the same way as oil and water unmix.

The Sudbury Igneous Complex is also overlain by a sequence 1800 meters of heterogeneous layers of breccias, known as the Onaping Formation. The Onaping Formation consists predominantly of pyroclastic rocks, which are typically produced in terrestrial volcanoes. These rocks occur only within the Sudbury Basin where they are also intruded by the granophyres of the upper layers of the Sudbury Igneous Complex. The origin of the Onaping Formation is

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controversial, although there is general agreement among workers that the origin of this unit has an important bearing on the origin of the Sudbury structure.

There was great interest in the early sixties in the discovery and cataloguing of ancient meteorite impact scars or astroblemes on earth. It was during this period in 1964 that Dietz suggested the most provocative hypothesis that the Sudbury Structure was an astrobleme which was produced by the impact of a large meteorite. Dietz's basic thesis was that this impact was responsible for the formation of the Sudbury Breccia and the shatter cones. The impact also caused fracturing in the crust and generated magma in the deep crust which then filled the impact-crater producing the rocks of the igneous complex. Although Dietz's revolutionary idea was accepted by a few geologists, many prominent workers rejected this hypothesis. For example, in a centenary volume on Sudbury geology, commemorating the first discovery of nickel-copper ore in the Sudbury area in 1883, Dr. A. J. Naldrett, one of the editors of this volume, states on page 549 "...the author regards the impact model as a reasonable working hypothesis. It is not proven, in fact, it rests on distinctly less certain grounds than it did 15 years ago."

We have undertaken a Neodymium isotopic study of the various rock units of the Sudbury Igneous Complex along with members of the overlying Onaping Formation. The decay of Samarium 147 to Neodymium 143 with time has been used very successfully in determining the ages of lunar rocks, meteorites, as well as for terrestrial rocks. In addition to determining the ages of crystallization or time of formation of a rock body, the Samarium(Sm)-Neodymium(Nd) isotope system is also being used widely in tracing the source of origin of various types of rocks. Since the ionic radius of Nd is slightly

larger than that of Sm, partial melting of the earth's mantle causes Nd to be somewhat more concentrated in the partial melt relative to Sm. Eventually this Nd-enriched melt crystallizes to form the earth's crust. As a result, the earth's crust has become progressively enriched in Nd compared to Sm through time and the mantle, likewise, is relatively depleted in Nd. Thus the isotopic signatures, in terms of the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, for the crust and the mantle of the earth are distinctly different. This difference is more elegantly expressed in terms of a parameter called epsilon Nd ( $\epsilon\text{Nd}$ ). Positive  $\epsilon\text{Nd}$  means a mantle signature, whereas negative  $\epsilon\text{Nd}$  signature means a crustal source.

We have analyzed the Sm and Nd isotopes of sixteen rocks from along two traverses, one in the north and one in the south, of the complex. Ten mineral separates from five of these rocks were also analyzed. From these analyses, we obtained an age of 1845 million years for the time of crystallization of the Sudbury Complex. This age is in excellent agreement with other workers, who determined this age using the Uranium-Lead radiometric clock. The  $\epsilon\text{Nd}$  parameter calculated at 1845 million years before present for the different Sudbury rocks ranges from -7 to -8.8, with the majority of the rocks at around -7 to -8. These large negative  $\epsilon\text{Nd}$  values, as explained above, are diagnostic signatures of the crust. In fact, our data suggest that all the different rock members of the Sudbury Igneous Complex, along with the different members of the overlying Onaping Formation could have formed by melting of the crustal rocks at Sudbury. In other words, we do not see any isotopic signature of a mantle component (i.e. positive  $\epsilon\text{Nd}$  values) in these Sudbury rocks. The only viable explanation for this crustal Nd-isotopic signature is that the Sudbury Complex formed from the melting of crustal rocks by way of meteoritic impact. This

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interpretation is compatible with previous observations, such as shatter cones in the surrounding country rocks as well as shock features, including planar features within the mineral fragments of the Onaping Formation. It is also instructive to calculate the model ages of all the Sudbury rocks. Model ages are estimated as time of separation of a rock from its ultimate parent, the primitive or pristine mantle. All the Sudbury rocks define a narrow range in this model age of  $2.56 \pm 0.13$  billion years. This model age is remarkably similar to the age of the metamorphosed volcanic and sedimentary rocks which are known to have formed the basement rocks underlying the Sudbury Structure. It is our proposition that these heterogeneous groups of rocks were impact-melted to produce the Sudbury magma(s) which underwent sulfide-rich magmatic segregations to produce the ores in the lower part of the complex.

PERIODIC COMETARY SHOWERS: REAL OR IMAGINARY?

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Since the initial reports in 1980, a considerable body of chemical and physical evidence has been accumulated to indicate that a major impact event occurred on earth 65 million years ago. The effects of this event were global in extent and have been suggested as the cause of the sudden demise or mass extinction of a large percentage of life, including the dinosaurs, at the end of the geologic time period known as the Cretaceous. Recent statistical analyses of extinctions in the marine faunal record for the last 250 million years have suggested that mass extinctions may occur with a periodicity of every 26 to 30 million years. Following these results, other workers have attempted to demonstrate that these extinction events, like that at the end of the Cretaceous, are temporally correlated with large impact events. A recent scenario suggests that they are the result of periodic showers of comets produced by either the passage of the solar system through the galactic plane or by perturbations of the cometary cloud in the outer solar system by a, as yet unseen, solar companion. This hypothesized solar companion has been given the name Nemesis.

The implications of this scenario of periodic cometary showers go beyond their suggested potential to regularly reshape the evolution of the terrestrial biosphere. In fact, it has been suggested that such showers may be responsible for modulating changes in global sea level, various types of tectonic activity and reversals in the earth's magnetic field. If such a periodic extraterrestrial driving force is indeed responsible for such a wide variety of related biological and geological changes on earth, then its recognition and acceptance would rival plate tectonics in terms of revolutionizing geologic sciences.

Since this imaginative hypothesis has such far-reaching and exciting implications, it deserves to be examined carefully. Many of the arguments calling for periodic cometary showers result from model astrophysical calculations, which were generated out of the desire to account for the apparent periodicity of the extinction record. The only offered evidence with a physical basis is from the ages of known terrestrial impact craters. It has been suggested that, as required by this hypothesis, the terrestrial cratering record shows a periodicity similar to that of the marine extinction record. At face value, this would appear to be supportive evidence. However, there are problems in the application and interpretation of statistical methods of searching for periodicities in the terrestrial cratering record.

The record of terrestrial cratering is woefully incomplete. Unlike the surface of the moon, the earth's surface retains relatively few recognizable impact craters. This is the direct result of the presence of oceans, which retain no known record of cratering, and such processes as erosion, deposition and tectonism which serve to remove, mask and destroy those craters on the land surface. For example, recent analyses indicate that even in geologically stable areas but under the unfavorable circumstance of glaciation, a 20 kilometer diameter impact crater may be removed as a recognizable geologic structure in as short a geologic time period as 120 million years.

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Compounding the problem of crater retention is the problem of crater recognition. The search for terrestrial impact craters and their study is a relatively new facet of geologic sciences and owes much to the recent exploration of the planets, which has emphasized impact cratering as an important geologic process in planetary history. Few systematic searches for impact craters have been carried out. Impact craters are often found by chance following the discovery of an unusual circular feature on an aerial or space photograph or on a geologic map. The current inventory of terrestrial craters stands at slightly over 100 with two or three new discoveries generally being made each year.

In addition, the entire sample of known craters is not suitable for statistical analysis. Only those structures with well-constrained ages for their formation can be used to search for periodicities. Here again, there are problems. The restriction to well-constrained ages reduces the number of craters available for analysis. The most reliable age estimates for impact events are supplied by isotopic analysis of the original target rocks melted by the intense heat accompanying the high shock pressures generated on impact. This melting causes a resetting of the isotopic clocks. Even when available, however, such age estimates are not without problems in interpretation; particularly, if the melt rocks contain unmelted fragments of the target which have not had their isotopic systems completely reset. At some craters, different isotopic dating methods have yielded different ages. At others, no isotopic dating has been undertaken and the "well-constrained" age is based on the occurrence of fossils in sediments filling the crater depression. These latter ages can also be unreliable. The database of crater ages is constantly being upgraded and refined and there have been cases in recent years where new revised age estimates have differed considerably from previous estimates. There are inherent dangers, therefore, in accepting a generalized listing of crater ages without close scrutiny for use in sophisticated statistical analyses.

Problems with the completeness of the cratering record and reliable ages notwithstanding, an updated listing of known craters with diameters greater than 5 kilometers and relatively reliable ages of between 0 and 250 million years has been compiled. This data set of 26 craters was analysed for periodicities. The problem is that a number of statistical periodicities can be defined. For the entire database there are two periods; a period of approximately 18.5 million years with the first peak at 2 million years occurs, as does one at approximately 29.5 million years with the first peak at 9.5 million years. If one restricts the analysis to the 20 craters with isotopic ages, in the belief that these age estimates are likely to be more accurate, then only the 18.5 million period is present. If the craters with ages less than 5 million years are omitted, based on the argument that young craters are best preserved and most easily recognized and thus they may bias the sample, then a period of 21 million years with the first peak at 15 million years can be defined. If the database is restricted to the 17 craters occurring on the geologically stable central portions or cratons of N. America and Europe, where there have been active programs to search for craters and where the database may be the most complete, the most dominant period is approximately 13.5 million years. Some other subsets of the data fail to indicate periodicities. These various statistical periodicities with different times for the onset of the first peak raises the question of which, if any, have a real physical significance?

Tests with a series of random numbers indicate that, for the threshold value of the statistic used to detect the above periodicities, it is possible to define a periodicity one time out of four. In addition, relatively small changes in the ages of some of craters are sufficient to change the dominant period or drop previously defined periods below the threshold of significance. It would appear, therefore, that the statistical support for these periodicities is not particularly strong.

This conclusion would seem at odds with previous claims that the odds of defining a periodicity in the cratering record are one in a hundred. However, these claims are for a periodicity coincident with that suggested for the marine extinction record. In the present analysis, the concern is with the chances of defining any periodicity regardless of its value. The ability to derive a periodicity of choice depending on the database used makes statements regarding periodic impacts and their relation to extinctions less than categorical. They require additional evidence above an apparent statistical coincidence based on the less than ideal record of known crater ages on earth.

There is, in fact, some additional evidence that can be used to address this problem. The initial argument used to call for a major impact at the end of the Cretaceous was the discovery of enrichments in so-called siderophile elements in the boundary clay layers. These elements have an affinity for iron and are depleted in the earth's crust, having been scavenged by the earth's core. This is not the case for some types of meteorites which never underwent a core-forming event. By examining the relative abundances of various siderophile and other elements in impact melt rocks, it has been possible in recent years to identify the type of projectile that formed some terrestrial craters. Although open to interpretation in some cases, due to chemical weathering and the fact that some of these meteoritic elements occur at levels of abundance of a few parts per billion or less, it appears that several of the craters used to define periodicities were formed by different types of bodies. This is not what would be expected if they were all formed by periodic showers of comets.

Although the cratering record may be relatively unsuitable for detailed statistical analysis, it has been possible to estimate the average cratering rate by restricting the analysis to large craters, diameters greater than 20 km, with relatively young ages, less than 120 million years old, occurring in the stable and well-studied N. American and European cratons. The estimated rate is equivalent to that calculated independently from observations on earth-crossing asteroidal bodies known as Apollos. The craters used to calculate a terrestrial cratering rate are in many cases the same craters used to call for periodic cometary showers. If they were formed in fact by comets then where are the large craters formed by Apollos, which are well known to have the potential to form craters on earth? Although there are large uncertainties attached to these rate estimates, due to concerns about completeness of search, the coincidence of the crater-derived and Apollo-derived rates would suggest that the simplest explanation is that most of the craters were in fact the result of the impact of Apollo bodies, not the suggested cometary showers.

In summary, the question of the reality of periodic cometary showers can not be answered by statistical arguments alone. It requires additional data involving the expansion and upgrading the database on terrestrial craters. The discovery of additional craters, more precise age estimates and analyses for projectile composition would reduce some of the present uncertainties. The more general question of the relationship between large-scale impact and biological extinctions is better addressed through additional detailed studies of the faunal record and searches for indications of large-scale impact at the precise time period of an extinction event. Given the present status of knowledge, we would caution against the general acceptance of the hypothesis that the earth was subjected to periodic cometary showers which exerted an extensive control over biological and geological evolution. Exciting although this hypothesis may be, the cited evidence is open to interpretation and in some cases favors the alternate, more traditional view that the bulk of terrestrial craters were formed by the impact of asteroidal-like Apollo bodies. Whether or not large-scale extraterrestrial impacts have exerted some influence over the evolution of the terrestrial biosphere and geosphere will undoubtedly be the subject of much future work and debate. Whatever the answer, these studies and hypotheses serve to remind us that the earth does not exist in isolation but may be subjected to external processes beyond those generally considered relevant to earth evolution.

## DUST EMISSION OF COMET HALLEY AT LARGE HELIOCENTRIC DISTANCES.

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Comet Halley is currently approaching the inner solar system. Four spacecrafts (NASA's ICE spacecraft, two Russian VEGA probes and the Japanese MS-T5 spacecraft) have already been launched to encounter the comet in March 1986. Two additional Halley probes (the European Giotto spacecraft and another Japanese Planet-A probe) will be launched in mid-85 to join the armada. In order to accurately guide these spaceprobes to their meeting point with the comet, its trajectory has to be known precisely; e.g. to aim the Giotto spacecraft, which will come closest (approximately 500 km) to the comet nucleus, the position of the Comet has to be known with an accuracy of 100 km. Therefore, ever since the rediscovery of Comet Halley in 1982, astronomers have followed its course with the largest telescopes in order to improve the knowledge about its orbit.

In December 84 and January 85 when the comet was still 650 million kilometers away from the earth (at about the distance of Jupiter's orbit), it was observed with the 2.2 m telescope of the German-Spanish Astronomical Center at Calar Alto, Spain. At that distance individual observations yield a positional accuracy of only about 1000 km, but major improvements are expected by future observations when the comet is much closer to the earth.

The nucleus of Comet Halley is believed to be a "dirty snowball" of about 6 km diameter (according to a model of Fred Whipple from the Smithsonian Astrophysical Observatory, Cambridge, Mass.). When it comes close to the sun, its temperature rises and the ices start to evaporate releasing large amounts of gas and dust which eventually form an atmosphere of about 100 000 km diameter and a tail of several 10 million km length.

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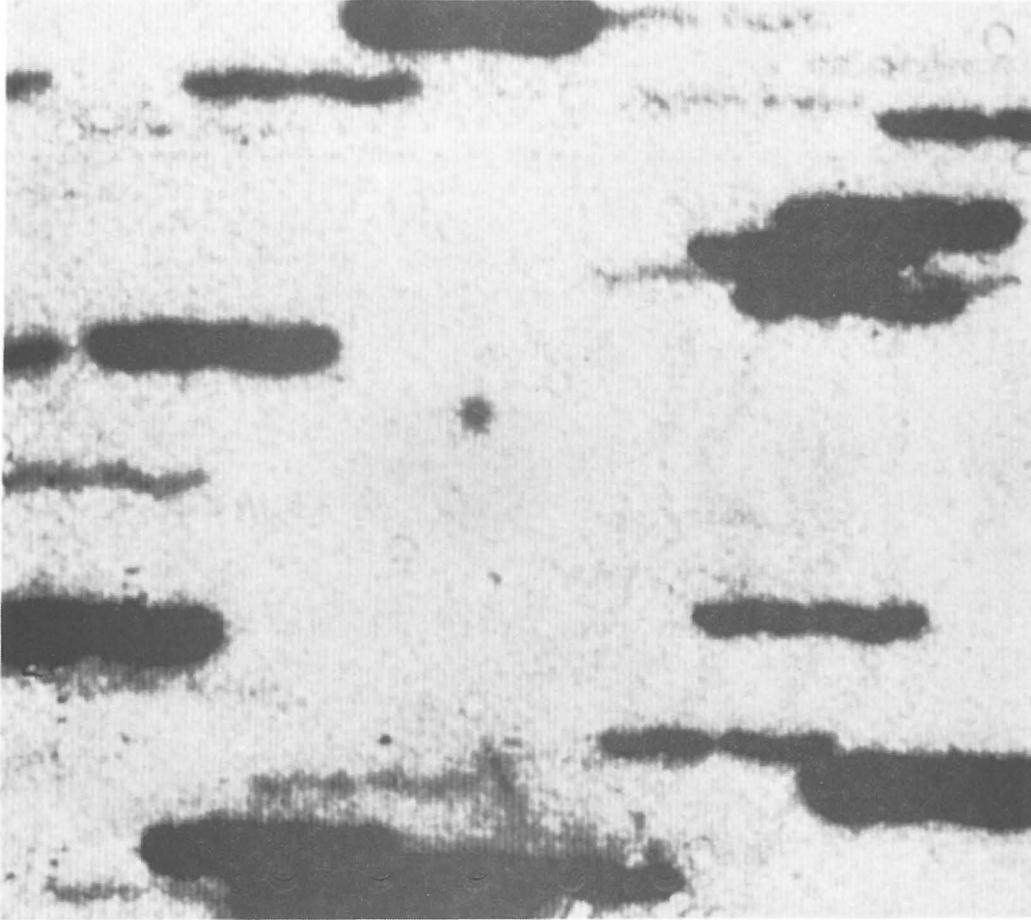


Fig. 1: CCD image (negative) of Comet Halley (spot near center of the frame) obtained with the 2.2 m meter telescope at Calar Alto, Spain, on December 17, 1984. At this time the comet was at a distance of 650 million kilometers. The image was obtained by tracking the comet's motion with the telescope for 30 minutes. Therefore images of stars are stretched to lines.

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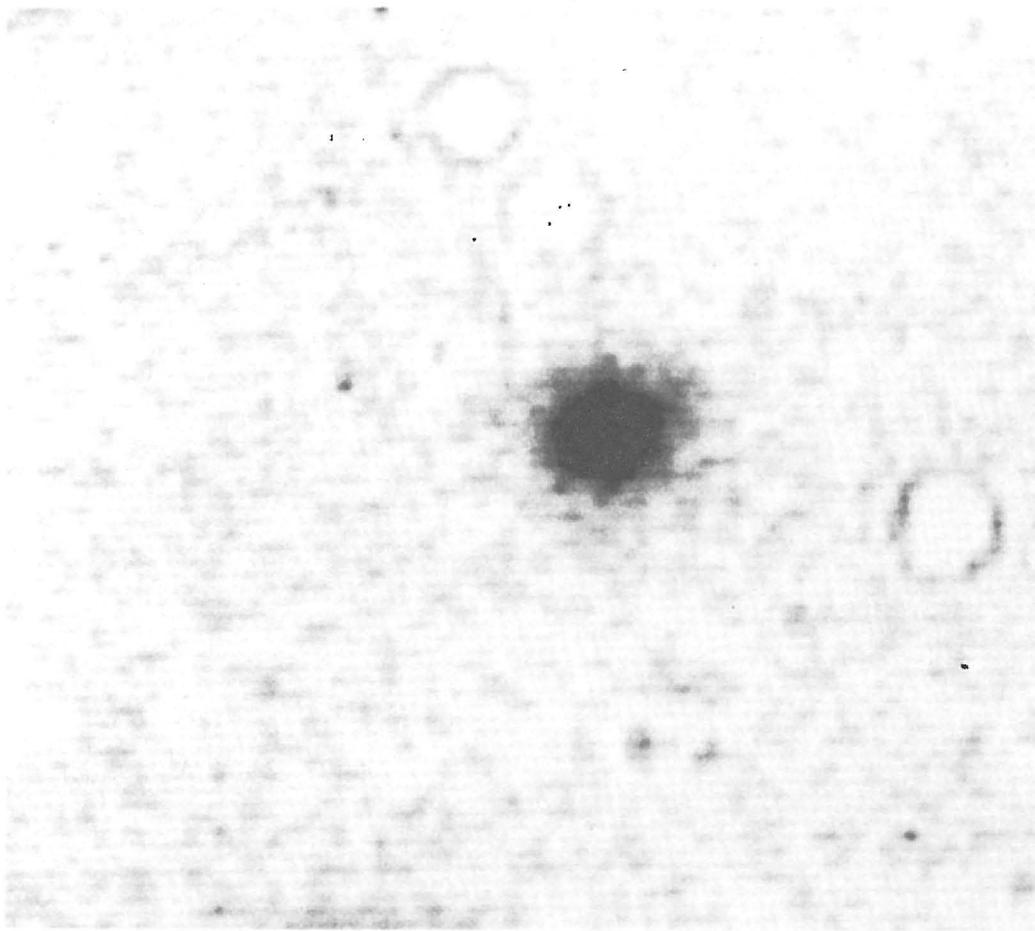


Fig. 2: Blow-up of an image (negative) of Comet Halley indicating a diffuse halo around the central nucleus.

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Before 1984 the comet had a starlike appearance and no direct sign of evaporation activity. However, by the end of 1984 when the comet was observed from Calar Alto the image showed a significant extension. The width of the image corresponds to a halo of 3000 to 10 000 km diameter around the nucleus. The formation of a halo indicates the onset of evaporation of cometary ices. From an estimated surface temperature on the nucleus of  $-160$  to  $-140$  °C (corresponding to  $-256$  °F to  $-220$  °F) it is concluded that the evaporation of ices more volatile than water ice (e.g. carbondioxide) causes the emission of particulates from the nucleus. The emitted dust grains in the halo become visible because of the reflected sunlight. The study of dust emissions from Comet Halley will eventually determine the fly-by strategy of the Giotto spacecraft by taking into account the distribution of dust in the vicinity of the nucleus and the associated hazard for the spacemission.

The observations were performed at the German-Spanish Astronomical Center, Calar Alto, Spain, which is operated by the Max-Planck-Institut für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.

CARBON ISOTOPES IN BULK CARBONACEOUS CHONDRITES; Jérôme Halbout\*, Toshiko K. Mayeda, and Robert N. Clayton, University of Chicago, Chicago, IL 60637. \*Present address: Université de Paris, 75251 Paris Cedex 05, France.

At the present time, astronomers observe the formation of new stars as a consequence of gravitational contraction of "lumps" of gas and dust in large cold clouds within our galaxy. Our own sun and solar system may have formed in a similar fashion some 4.6 billion years ago. In order to learn more about the raw materials from which our solar system was formed, and also about the chemical and physical processes involved in its formation, we try to identify and study the most "primitive" matter accessible to us. Such matter has been found on a microscopic scale in a variety of meteorites: fragments of small solar system bodies that were never part of a large planet. This primitive matter has, in most cases, been identified by the presence of anomalous abundances of some isotopes of the chemical elements. These abundances are called "anomalous" if they cannot be accounted for by any known physical or chemical process occurring within the solar system. In some cases, the anomalies have been attributed to chemical reactions that took place in the cold cloud before formation of the solar system, at temperatures of  $-370^{\circ}\text{F}$  or lower; in other cases the anomalies appear to result from nuclear reactions in exploding stars.

The element carbon has two stable isotopes:  $^{13}\text{C}$  and  $^{12}\text{C}$ . On earth, the relative abundances of these isotopes are fairly uniform, with the ratio of the number of  $^{12}\text{C}$  atoms to  $^{13}\text{C}$  atoms averaging 89, and ranging from about 88 to 94. The variations are due to small differences in the chemical properties of the two isotopes.

Of particular interest for carbon isotope studies are the primitive meteorites known as "carbonaceous chondrites." As their name implies,

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they are relatively carbon-rich (typically 1 to 3% by weight). Carbon is present in a variety of chemical forms, including graphite, carbonate minerals, and a large number of complex organic molecules. The presence of such an array of compounds attests to the primitive nature of these meteorites, since they could not have survived extensive heating. The carbonaceous chondrites are, therefore, prime candidates for the preservation of chemical substances that pre-date formation of the solar system.

Two previous studies, one at the University of Cambridge, the other at the California Institute of Technology, showed that the carbonaceous chondrite Murchison, which fell in Australia in 1969, contains a minute fraction of carbon with more than twice as much  $^{13}\text{C}$  as terrestrial carbon. These studies were carried out on samples which were minor residues left after chemical dissolution of the main constituents of the meteorite. In our work, involving four other carbonaceous chondrites as well as Murchison, we have analyzed all of the carbon in the meteorites, using a selective oxidation technique to sort out the carbon contained in different chemical forms (graphite, carbonates, and organic matter). We confirmed the presence of the  $^{13}\text{C}$ -rich component, and resolved additional carbon components with different, but characteristic, isotopic signatures.

Comparison can be made between the carbon isotope ratios in meteorites and the ratios observed in interstellar molecules by the techniques of radio astronomy. In interstellar molecules of carbon monoxide ( $\text{CO}$ ) and formaldehyde ( $\text{H}_2\text{CO}$ ), ratios of  $^{12}\text{C}$  to  $^{13}\text{C}$  range from about 20 to 100, with an average value of 67. The lowest  $^{12}\text{C}/^{13}\text{C}$  (i.e., highest  $^{13}\text{C}$ ) ratios observed in meteorites are 42 (Cambridge and Chicago) and 36 (Caltech). It should be noted that the interstellar molecules and the meteorite samples represent two different times in the evolution of the galaxy, since the meteoritic

materials have been locked up in mineral grains since their formation more than 4.6 billion years ago. The large variations in isotopic abundance in both the interstellar molecules and in the meteoritic materials are probably a consequence of nuclear reactions in stars, with subsequent ejection of matter from the stars into the interstellar medium.

OCCULTATION DETECTION OF A NEPTUNE RING SEGMENT; W. B. Hubbard<sup>1</sup>,  
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 Roques<sup>2</sup>, B. Sicardy<sup>2</sup>, and F. Vilas<sup>1,\*</sup>

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In the stellar occultation technique, planetary astronomers use high-speed photometers to observe a star as it passes behind a planetary system. The star acts as a distant beacon to trace material near the planet and in the planet's atmosphere. Material which is located between the star and the observer causes an interruption of the starlight. Observers at different locations on the earth trace different paths through the planet's neighborhood, and their data can be combined to build up an "image" of the occulting material. Small objects close to planets can frequently be readily detected by this technique, even though such objects are difficult or impossible to image directly because they tend to be lost in the glare of light from the planet itself.

A stellar occultation in 1977 revealed the rings of Uranus, and astronomers immediately sought to apply the same technique to a search for material around Neptune. The first good opportunity for Neptune came in 1981, when worldwide observations of three stellar occultations were used to probe for Neptune rings. But no ring material was found. With one exception, there were no interruptions of the starlight by anything except the planet. The one exception was an 8-second interruption of the light observed in two experiments operated by University of Arizona scientists at observatories near Tucson. But a continuous ring like the Uranus or Saturn rings would have to interrupt the light twice (once when the star went inside the ring, and once when it came back out). The Arizona group didn't observe a second occultation, and so they decided that the single event was caused by an unknown small satellite with a diameter of about 100 km, probably located in an orbit at a distance of about 75,000 km from Neptune's center (three planetary radii). Some scientists were bothered by the low probability of getting such an occultation by a single small satellite, and wondered if there might be more than one such occulting body.

In 1982, a group of astronomers from Villanova University examined some old Neptune occultation data, and argued that their results indicated a close-in Neptune ring system extending from about 1.14 to about 1.31 Neptune radii. The 1981 data hadn't probed this region. But the Villanova observations weren't confirmed by other observatories, and have not been accepted as definitive for this reason.

More observations were made in 1983, this time including the region occupied by the proposed "Villanova ring", but no occultations by the ring were seen. Planetary scientists concluded that Neptune had no ring system, at least none which could be detected from the earth.

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Another opportunity to search for Neptune rings occurred in July, 1984. The occultation was potentially visible from the western hemisphere, although the initial prediction indicated that the shadow of Neptune would pass only over the southern part of the earth. A further refinement to the prediction indicated that the shadow was even farther south, so that not even South America would be included in the path. There seemed to be little opportunity to learn anything new about Neptune, but nevertheless planetary astronomers set up experiments at two observatories in Chile. A group from Paris Observatory and other European institutions monitored the star from two telescopes at the European Southern Observatory (ESO). About 100 km to the south, Faith Vilas from the University of Arizona observed at three different wavelengths from a single telescope at Cerro Tololo Inter-American Observatory (CTIO).

Both of the ESO telescopes detected a strong occultation event when the star was approaching the planet, at a distance of about three Neptune radii. The European astronomers issued a bulletin to other observers, noting that the event was "less than two seconds long", and that the star light dropped by about 35%. They saw no other event. Vilas was not monitoring her data in real time at a rate fast enough to reveal such an event, and did not immediately confirm it. She brought her data back to Tucson in the form of a magnetic tape which contained a record of the stellar intensity at the three wavelengths at 1/100 second intervals.

The theorist in charge of the Arizona experiment, William Hubbard, examined the CTIO data in detail in December. He found that Vilas' data actually did contain a very similar event to the one reported by the ESO group earlier, and he contacted the theorist in charge of the ESO group, Andre Brahic of the University of Paris. Hubbard and Brahic met in Tucson in January, and exchanged their data. They have obtained the following results from comparison of the data sets from the two Chilean observatories. These results will be presented at the Lunar and Planetary Science Conference in a paper authored by the above-listed personnel, and given by Hubbard. A detailed paper is in preparation and will be submitted shortly for publication elsewhere.

The Chilean observatories (ESO and CTIO) detected a segment of occulting matter which is at least 100 km long, and which is about 15 km across. It is in an orbit which is probably in the Neptune's equatorial plane, approximately 75,000 km from the planet's center. Matter is not densely packed in the occulting segment, which is about 70 per cent transparent. The event occurred 0.13 seconds earlier at ESO than at CTIO, and from the time difference it can be determined that the position angle of the segment is nearly the same as the predicted position angle of an equatorial ring segment. The profiles measured at ESO and CTIO appear to be identical. The multichannel data from CTIO prove that only the star and not Neptune was occulted during the event, adding further credibility to the detection. Since the segment was observed by three telescopes in all, there can be no doubt about its reality.

Nothing is seen on the other side of Neptune, where a complete ring should have been crossed a second time. It thus appears that the object is not a complete ring, but rather a localized swarm of particles which follows a ring orbit over a limited range of longitudes. In order to avoid confusion with the standard use of the word "ring", Brahic and Hubbard suggest that the feature be called an "arc" (which has the same meaning in English and French).

It is not yet clear how the 1984 arc detection is related to previous

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observations, in particular to the 1981 8-second event. The latter could also be interpreted as an arc, but if so, it is quite different from the 1984 event. If it was an arc, it was nearly completely opaque, and had a width of about 75 km.

The distance of the arc zone from Neptune is not precisely known because so far there has been no confirmed occultation by both an arc and the planet. Hubbard has reported a possible very weak, broad, occultation from 1983 Neptune data at a distance of about 76,400 km from the planet's center, but this feature lacks confirmation. In any case, it is clear that the arc zone lies outside the conventional Roche limit of Neptune. Within the Roche limit, tidal forces from Neptune prevent the aggregation of small particles into moons, while outside the Roche limit, the mutual gravity of the particles should ultimately prevail, causing them to form satellites. Perhaps the arcs are an intermediate stage in this process.

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IDENTIFICATION OF THE YOUNGEST METEORITES AND A DISCUSSION OF THE POSSIBILITY THAT THEY CAME FROM MARS. John H. Jones, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

The shergottites are a group of basaltic meteorites which are very similar in appearance to terrestrial basalts. On the Earth basalts are formed by volcanic activity; for example, basalt is the primary constituent of volcanic islands such as Hawaii. Thus, the shergottites appear to be the products of igneous (i.e., volcanic) activity from a planet or asteroid in another part of our solar system.

Because the shergottites so resemble terrestrial basalts and because they are apparently very young ( $<1.3$  billion years), it has been inferred that they come from a large planet. Small planets and asteroids lose heat from their interiors quickly and stop producing hot basaltic liquids early in their history. The Earth's Moon, for example, began to stop producing basalts about three billion years ago - at least two billion years before the shergottites were formed. The inference, therefore, is that the shergottites had to come from a large planet such as Venus or Mars. Further, it appears that gases trapped in one shergottite found in Antarctica (EETA 79001) are chemically similar to the martian atmosphere (as measured by the Viking mission). These observations have led to the exciting and controversial speculation that the shergottites are samples of Mars.

In this context, the time that the shergottites crystallized from basaltic liquids is particularly important. The younger the crystallization age, the more probable it is that the shergottites came from Mars. The conventional interpretation is that the shergottites crystallized 1.3 billion years ago and that a meteor impact ejected them from their parent body (Mars?) 180 million years ago - 1.1 billion years later. If this interpretation is incorrect the martian-origin hypothesis is either strengthened or weakened, de-

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pending on whether the 1.3 b.y. crystallization age is too old or too young, respectively.

The time of ejection from the Shergottite Parent Body (SPB) alluded to earlier (180 m.y.) is based on the age of a radioactive "clock" in the shergottites (in this case the rubidium-strontium chronometer) and the assumption that this clock was reset by the shock event that ejected these meteorites from the SPB and into space. The only way that such a radioactive clock can be reset is if the different minerals within a rock chemically communicate with each other. The most probable means of achieving this communication through a shock process is if the shock heats the rock. At high temperature the chemical elements in the minerals of the rock can diffuse and migrate through the rock; communication is achieved; and the clock is reset.

The chemical and physical characteristics of the shergottites themselves belie the conventional chronology. It is difficult to imagine that there can be excellent communication between minerals if there is poor communication within a mineral. Yet the shergottite minerals are not chemically uniform but retain chemical variations which shock heating has not homogenized. If shock has not erased chemical zoning, then the rubidium-strontium clock has not been reset and the 180 m.y. age must be an igneous crystallization age. The shergottites are apparently very young - the youngest meteorites yet discovered by far.

The implications of such a young crystallization age are rather far-reaching. (1) As was discussed earlier, the SPB must have been a rather large body for basalt production to have continued for so long - supporting the martian-origin hypothesis. The term continued is chosen with some care. The shergottites are closely related to other meteorites, the nakhlites and Chassigny (together with the shergottites comprising the SNC suite) which clearly crystallized 1.3 b.y. ago. Further, both the shergottites and the

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nakhlites show evidence of there having been igneous activity very early in the history of the SPB. Thus, the SPB appears to have been producing basalts throughout its history, and, therefore, the shergottites are not likely to have been produced by a random event such as a meteor impact.

(2) If Mars is the SPB, the extremely young age of the shergottites places severe restrictions on their point of origin. The only area of Mars which could be young enough (based on the density of impact craters) to have produced the shergottites is the Tharsis region, the location of the enormous, young martian volcanoes such as Olympus Mons. The youngest portions of Tharsis, those near Olympus Mons and Arsia Mons are about the same age as that inferred for the shergottites - 100-300 m.y.

(3) The most viable means of ejecting samples from Mars is by meteor impact. It appears that an approximately 30 kilometer crater is necessary to eject 1 meter fragments rapidly enough so that these fragments escape the planet. Since no young, fresh craters in the Tharsis region are greater than 30km in diameter, then, if the shergottites are martian, they must have been ejected as small (<1m) fragments.

(4) When objects float in space they are often struck by high energy particles called cosmic rays. These cosmic rays induce nuclear reactions so that by the time meteorites fall to Earth they are very slightly radioactive. This radioactivity can be used to measure how long an object has been exposed to cosmic rays. In the case of the shergottites, because they were ejected as small fragments, the cosmic ray exposure age probably represents the time that the shergottites floated in space. Thus, the cosmic ray exposure age may well represent the time of ejection from the SPB.

(5) The cosmic ray exposure ages of the shergottites appear to fall into two groups (~0.5m.y. and ~2m.y.). Unless it is possible to eject large (>10m)

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objects from 30km craters (so that the interiors are shielded and protected from cosmic rays), it appears that two large, fresh craters are required in the Tharsis region for the shergottites to come from Mars. Preliminary inspection of the Viking orbiter images does show two such craters (25km and 27km diameter) in the region northwest of Olympus Mons, but this observation should be interpreted with care since high resolution images of these craters are not available and their freshness is thus disputable. An added concern is that, two large, proximal cratering events in <5m.y. imply extremely high cratering rates. Thus, the presence of two large craters within 1200km of the summit of Olympus Mons is consistent with the age relations discussed above but is not conclusive support.

(6) Interestingly, if the ages of the shergottites inferred above are correct, the much-discussed "oblique impact" crater near Ceraunius Tholus is probably not the source of the shergottites. Even though it is a large crater in (or near) young terrain, the oblique impact crater is cut by a channel and does not appear fresh.

Summarizing, it appears, based on the presently available data, that the shergottites are extremely young, 180 million years old - the youngest meteorites yet discovered. This observation strengthens arguments that these interesting objects come from Mars. If the shergottites did come from Mars, they must have come from the youngest Tharsis terrain.

EXAMINATION OF RETURNED SOLAR-MAX SURFACES FOR IMPACTING ORBITAL DEBRIS AND METEOROIDS. D.J. Kessler, H.A. Zook, A. E. Potter, D.S. McKay (NASA/JSC, Houston, TX 77058), U.S. Clanton (Dept. of Energy, P.O. Box 14100, Las Vegas, NV, 89114), J.L. Warren, L.A. Watts (Northrop, P.O. Box 34416, Houston, TX 77234), R.A. Schultz (Purdue Univ., Dept. of Geosciences, West Lafayette, IN 47907), L.S. Schramm, S.J. Wentworth, and G.A. Robinson (Lockheed, 1830 NASA Rd. 1, Houston, TX 77058).

Previous theoretical studies (1) predicted that in certain regions of earth orbit, the man-made earth orbiting debris environment will soon exceed the interplanetary meteoroid environment for sizes smaller than 1 cm. Recent analyses of impact measurements obtained from Explorer 46 (2), Skylab experiment S-149 (3), The Apollo/Skylab windows (4), and the STS 7 Shuttle window (where a 2mm high-velocity impact crater was found to contain titanium with a trace of aluminum) suggest that a significant orbital debris population already exists in earth orbit (5). However, these experiments had either short exposure times, no conclusive technique to differentiate debris from meteoroids, or an altitude or time of flight where a lesser amount of debris would be expected. The surfaces returned from the repaired Solar Max Mission (SMM) by STS 41-C on April 12, 1984, offered an excellent opportunity to examine both the debris and meteoroid environments.

Solar Max was launched on February 14, 1980, into a near circular orbit at 570 km altitude, and an inclination of 28.5°. By April 10, 1984, the orbit had decayed to 500 km and SMM was captured for repair in the shuttle payload bay, after nearly 50 months of exposure to space. The returned surfaces included about 1.5 sq.met. of thermal insulation material and 1.0 sq. met. of aluminum thermal control louvers. The thermal insulation consisted of 17 layers of aluminized kapton or mylar, each separated by a dacron net, and the louvers consisted of 2 layers of heavy aluminum foil separated by about 3 mm. These types of surfaces offer excellent opportunities to obtain chemistry of impacting particles.

To date, approximately 0.7 sq. met. of the thermal insulation and 0.05 sq. met of the aluminum louvers have been mapped by optical microscope for crater diameters larger than 40 microns. Smaller craters were recorded in some cases; however, smaller craters are increasingly difficult to recognize optically. In addition, atomic oxygen has eroded up to 20 microns of the exposed kapton surfaces(6), removing the older and smaller craters. Figure 1 shows the crater size distribution found on 3 different kapton surfaces. Craters larger in diameter than about 100 microns found on the initial 75 micron thick Kapton first sheet on the MEB (Main Electronics Box) blanket are actually holes and constitute perforations through that blanket. Similarly, 70 micron craters form complete holes through the initial 50 micron thick first sheet of thermal blankets #6 and #9. About 160 craters were found to have penetrated these surfaces. Based on very limited calibration data, this is a factor of 2 to 5 above what would be expected from the meteoroid flux alone.

The chemical study of these craters is only in the initial stages. About 250 chemical spectra have been recorded of particles observed in or around impact pits or in the debris pattern found on the second layer beneath impact holes in the outer layer. Chemistry is obtained via a PGT 4000 Energy Dispersive Spectrometer on a JEOL JSC-35CF Scanning Electron Microscope (SEM).

The following populations have been found to date in impact sites on these blankets:

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Meteoritic material-characterized mainly by particles or droplets composed primarily of Si, Mg, Fe, Ca, and Al, or less often, iron-nickel sulphides. A more detailed analysis of the meteoritic component is given in (7).

Paint particles - Characterized by titanium and zinc, whose oxides form pigments for white thermal paints. The chemistry of these particles also includes potassium, silicon, aluminum, and chlorine. Potassium silicate is used as a "binder" to cement the pigment grains together. Aluminum is apparently used for pigmentation. The source of the chlorine in these particles is not yet understood. It is not yet clear whether the paint particles have impacted at high or at low velocity. This may become understood when the aluminum louvers are examined in detail.

Aluminum droplets-For these craters, only aluminum droplets are observed in the ejecta on the second sheet. The ejecta patterns observed on the second sheet are well spread out and are composed of finely divided particles or droplets. These impacts are most likely caused by man-made space debris.

Waste particles-This single impact went through three layers of the blanket. Chemistry was Na, K, Cl, P and minor amounts of sulphur. Sodium and potassium chlorides, sulphur, and minor amounts of phosphates are consistent with urine residue. This particle was almost certainly an ice particle from the Shuttle waste management system.

The Solar Max thermal blankets (and louvers) represent a very valuable resource of information about the near-Earth impacting particle population. The chemistry found within most of the craters is consistent with an origin other than meteoroids. Because of the many different sources of particles, some time is required before the chemically different populations can be quantitatively separated into clearly recognized origins.

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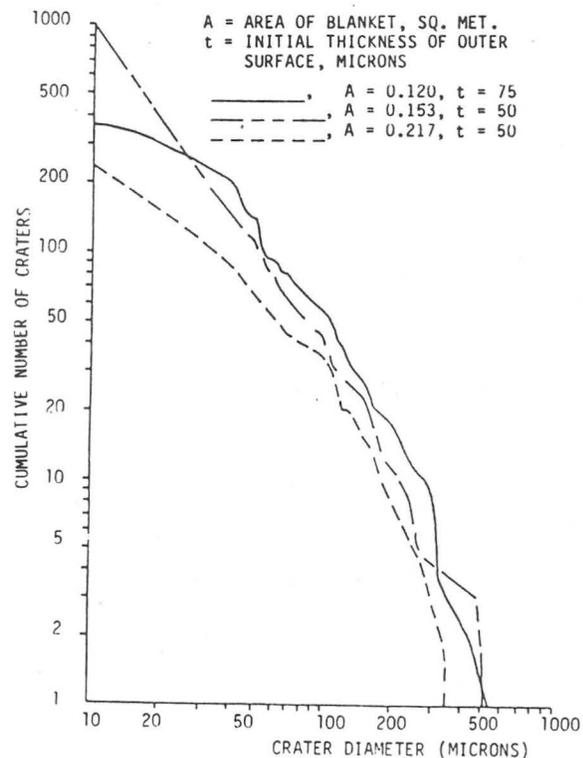


FIGURE 1. COMPOSITE OF CUMULATIVE SIZE PLOTS FOR SOLAR MAX MEB, 9, and 6 BLANKETS

ELECTROLYSIS OF SIMULATED LUNAR MELTS. Robert H. Lewis, David J. Lindstrom and Larry A. Haskin, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130.

The Moon is our nearest source of extraterrestrial material, which we will need for expanding industrial activities in space early in the coming century. Our expanding industrial base will require increasingly large structures and increasing quantities of propellants in space. It takes only a small fraction as much energy to lift material from the Moon's surface to low-Earth orbit as to lift the same amount of material from Earth. Economy dictates that the Moon would be a cheaper source for constructional materials and propellants than Earth is if we can find needed raw materials there and develop sufficiently inexpensive methods to extract and use them.

We still do not know the full range of available resources on the Moon, but we do know that Moon, because of its dearth of water, free oxygen, and other gaseous materials, did not produce the same kinds of ores we are accustomed to using on Earth. Nevertheless, common lunar rocks are rich in oxygen, silicon, iron, aluminum, magnesium, calcium, and, in some cases, titanium. This is adequate for a considerable industry, provided that we develop appropriate technologies for extracting these elements.

Electrolysis of molten lunar soil or rock is, in principle, an attractive means of wresting useful raw materials from lunar rocks. It requires only heat to melt the soil or rock and electricity to electrolyze it, and both can be developed from solar power. Sunlight is abundant on the lunar surface half the time and in orbit nearly full time. There are no alternative sources of power present on Moon's surface or in orbit. Nor does Moon have water, or reducing agents such as coal, or expendable reagents as are available on Earth. To avoid the expense of importing large amounts of expensive materials, we must learn how to use sunlight and lunar rock as the basis for a constructional industry in space and to provide propellant and materials for life support.

In electrolysis, we pass electrical current between two electrodes. At one, the anode, a chemical element in ionic form is oxidized to elemental form. For example, oxygen bound in the silicate of lunar rocks would be oxidized to oxygen gas, a desirable product for propellant. Simultaneously at the other electrode, the cathode, a metallic ion, for example, iron ion, is reduced to the metallic form. Iron metal is also potentially a very useful product for construction in space. If iron metal were cheap, we could use it in space in ways in which we use other elements on Earth; iron might become the principal electrical conductor. Preliminary experiments show that both iron and oxygen can fairly easily be obtained by electrolysis of molten silicates, including simulated lunar lavas, on the small scale of laboratory conditions.

Lunar lavas have melting temperatures between 1100 and 1200 degrees Celsius, so we must electrolyze them at high temperature. If we raise the temperature to above 1535 degrees, the iron is produced in the molten state and sinks to the bottom of the electrolytic cell, from which we could tap it off for casting of parts, drawing of wire, and extrusion into beams or rods.

In order for electrolysis to be efficient, a high fraction of the electrical energy passing through the cell must yield the desired products by the oxidation-reduction process. Electrical current outside the cell occurs by transport of electrons through wires. Inside the cell, we need for it to occur mainly through transport of negatively charged ions toward

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the anode and positively charged ones toward the cathode. These ions are the silicate and metal ions of the molten rock. We need for the transfer of current between the melt and the external portion of the circuit to occur mainly by the oxidation-reduction processes. The oxidation of each oxygen at the anode releases two electrons to the electrode and its wire lead; reduction removes two electrons from the cathode and its wire lead and places them on an ion of iron. This enables the movement of electrons from the anode to the cathode through the wires of the outside portion of the electrical unit.

If the ions of the melt are too difficult to move, i.e., if the silicate melt has a low electrical conductivity (a high electrical resistance), a high voltage will be required to pass current through the melt. That would result in high energy loss as heat (analogous to the high-resistance wire in a toaster). Thus, we have to know the conductivities of common lunar materials when they have been melted. Conductivities are related to the mobilities of the individual ions that make up the melts. To gain a theoretical understanding of the contributions of the different ions of the melts, we must measure conductivities before there has been any significant migration of negative ions toward the anode and positive ions toward the cathode. That is because the net separation of charged ions increases the resistance of the melt relative to that of the perfectly mixed state. We make these measurements using alternating current, which rapidly changes the anode to a cathode and vice versa, then back again, many times. This switching precludes much separation of the ions. To simulate the condition of an electrolytic cell, we must make our measurements using direct current, so that the anode and cathode must retain constant identities and separation of ions does occur. We have to accept the increased resistance that this causes as part of the energy cost of doing electrolysis.

Our early experiments showed that rocks rich in the mineral ilmenite produced melts with much higher conductivities than did those low in ilmenite. We found that melts with a wide range of conductivities could be obtained just by controlling the amounts of ilmenite present. (Ilmenite has the chemical formula  $\text{FeTiO}_3$ , and is thus rich in both iron and titanium.) Since ilmenite is plentiful on the Moon, this would seem to be a great convenience in design of cells for electrolysis. If the anode and cathode can be separated from each other by several centimeters distance, then a cell can be easily designed. However, as we increase the distance between them, the resistance to passing electrical current increases, and the higher the conductivity we need to maintain efficient use of electrical energy. Our ability to control conductivities turns out not to be as useful as desired, however, for allowing convenient design of electrolytic cells. It has been known for several years that some silicate melts have the properties of semiconductors; i.e., they allow some electronic conduction at even low voltages. The addition of ilmenite increased the semiconductivity of our simulated lunar rock melts. The direct passage of electrons through the melt in this manner does not contribute to electrolysis. It further heats the melt and ineffectively uses up part of the electrical energy.

To evaluate the magnitude of the problem, we measured the conductivities of the simple silicate, diopside,  $\text{MgCaSi}_2\text{O}_6$ . Then we added to it either iron oxide or titanium oxide to determine the effect on the conductivity. The titanium produced only the effect expected for ionic conduction. The iron, however, brought about substantial electronic conduction. The effect of the iron was so great that, if molten lunar rocks behaved in the same way, their electrolysis would be inefficient indeed! Fortunately, lunar

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rocks have more complex compositions than diopside, making electrolysis possible.

We measured the conductivities of simulated lunar lavas and the fractions resulting from ionic and electronic conductivities. The simulated basalt had an AC conductivity nearly a factor of two higher than that of diopside, reflecting the basalt's slightly higher total concentration of the 2+ ions Ca, Mg, and Fe that are the dominant charge carriers. Electrolysis experiments, in which the cathode was weighted to measure directly the efficiency of electrolysis, showed that electrolysis was about 30% efficient for the basalt composition. This value agrees with an estimate obtained from comparing AC and DC conductivities. Results of similar experiments with pure liquid ilmenite,  $\text{FeTiO}_3$ , suggest electrolysis efficiencies of about 20%, while an equal mixture of basalt and ilmenite has an efficiency of less than 5%.

As a result of these experiments, we have shown that the fraction of ionic conductivity remains high enough that we can still expect to be able to electrolyze lunar lavas with reasonable efficiency to produce oxygen and iron. Cell design is more of a problem that we might prefer, however, because melts of only medium conductivity can be used. We now understand that iron is the principal contributor to the electronic conductivity and can seek ways of obtaining higher conductivities without using iron-rich minerals.

The scarred and cratered surfaces of the Moon, Mars, and Mercury bear witness to the major role meteorite impacts played in the early evolution of the planets. Current theories on the origin of the Solar System depict an early phase when dust, gas, and rock material forming the Solar Nebula were accreted through a complex, and still poorly understood series of events to form the primitive planets. The final stage of this accretionary history involved the intense bombardment of the planetary surfaces by meteorites representing much of the remaining interplanetary rock debris. Lunar rocks collected on the Apollo manned missions have shown that, on the Moon, this period of meteorite bombardment ended between 4,000 million and 3,900 million years ago. By 3,500 million years ago, impact rates on the lunar surface were only slightly higher than the low level of today. On Earth, a much more dynamic planet than most of its neighbors, the record of this terminal bombardment has been obliterated by weathering, erosion, and the recycling of crustal rocks due to tectonism. Until recently, it seemed probable that this portion of the Earth's history could be studied only by examination of materials collected on the Moon or in other parts of the Solar System.

In an attempt to develop a clearer picture of the early evolution of the Earth and its crust, geologists from the Department of Geology, Louisiana State University, have, for the past several years, been studying 3,500 to 3,300 million year old rocks in parts of Western Australia and South Africa. These form the oldest, relatively unaltered volcanic and sedimentary sequences preserved on the Earth, and are only slightly older than the oldest known terrestrial rocks, 3,800 million years old, from western Greenland. The LSU research team has included to date 5

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undergraduate students in geology, 7 graduate students working toward Masters and Ph.D. degrees, and 4 LSU geology faculty members. This research has been supported by grants from the National Science Foundation. The work has been directed at a wide variety of projects dealing with the evolution of the Earth's early crust, oceans, atmosphere, and biosphere. Some of the more important results have demonstrated the importance, abundance, and diversity of life on Earth 3,500 million years ago.

In the course of this research, we have identified two rather inconspicuous layers, one in Western Australia and a second in South Africa, that contain abundant unusual spherical particles closely resembling chondrules. True chondrules are particles generally 0.1 to 2.0 millimeters in diameter, commonly roughly spherical, that are abundant constituents of many meteorites. They apparently formed over 4,500 million years ago by processes, as yet poorly understood, active during the accretion of matter within the primitive Solar Nebula. Chondrules also occur in small quantities in lunar soils. Their origins on the Moon have been attributed to both meteorite impacts and volcanic processes.

Chondrules and chondrule-like bodies are, however, rare in terrestrial settings. They have been reported as trace components of ejecta blankets around one or two relatively young meteorite impact craters. Similar particles, apparently produced by the melting of meteors during passage through the Earth's atmosphere, occur sparsely within deep-sea sediments. Chondrule-like particles have also been reported from 65 million year old detritus formed by the catastrophic meteorite impact that may have led to the extinction of the dinosaurs and many other groups of animals.

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In Western Australia and South Africa, chondrule-like particles have been found in two layers, each less than 1 m thick, interbedded within thick sequences of volcanic and sedimentary rocks. The chondrule-like grains appear to have accumulated almost instantaneously by the fall of material from the atmosphere into a wide variety of surficial sedimentary environments. Many of these environments were affected by wave and current activity, and the chondrule-like grains were transported and mixed with a variety of other detritus.

Most of these 3,500 million year old chondrule-like grains are spheroids that show internal structures and textures indicating that they formed by the rapid cooling and quenching of liquid silicate droplets. Their temperatures were probably in excess of 1000° Centigrade. The compositions of the particles suggest that the droplets represented melted portions of the immediately underlying rock sequences. The complex compositions, wide distributions, and absence of closely associated volcanic materials argue that the chondrule-like particles in these ancient terrestrial rocks also formed by melting of heterogeneous target rocks during meteorite impacts.

If formed by impact melting, these deposits document the oldest recorded terrestrial impact events. They lend strong support to the idea that some chondrules in meteorites could have formed on the surfaces of planet-sized bodies during impact events. Similar chondrule-like objects are extremely rare in the much more voluminous younger geologic record and abundances like those in these ancient deposits are unknown except in meteorites. These features suggest that a part of the Earth's terminal

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bombardment history is preserved in the geologic record and available for study, and also that conditions favoring chondrule formation, not present today, existed on the early Earth.

MINING COSMIC DUST FROM THE BLUE ICE LAKES OF GREENLAND. M. Maurette<sup>1</sup>,  
D.E. Brownlee<sup>2</sup>, L. Fehrenback<sup>1</sup>, C. Hammer<sup>3</sup>, C. Jehano<sup>4</sup>, H.H. Thomsen<sup>5</sup>.

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Each year as the Earth orbits the sun, it collides with 10,000 tons of extraterrestrial material, mostly debris from the disintegration of comets and asteroids. Only a tiny fraction of this material is found on the ground as conventional meteorites. Most of it invisibly settles to Earth's surface as dust particles smaller than a millimeter in size. Particles of 1/10 millimeter size (twice the diameter of a blond human hair) fall at a rate of one per square meter per year. They occur everywhere but are usually nearly impossible to find because they are mixed in with much larger numbers of Earthly dust and dirt. Finding an extraterrestrial dust particle in a bucket of ordinary dirt is literally like searching for a needle in a haystack. In very special environments, however, the particles can be collected with comparative ease. Collection is important because the "cosmic dust" particles that are recovered can potentially provide important information about comets. Comets are the most important source of dust in the solar system and they are probably the major source of extraterrestrial dust that is collectable at the Earth's surface. Comets are mountain-sized bodies of ice and dust that have been preserved at low temperature since the origin of the planets. Comets are believed to be samples of the original building blocks that the outer planets, Uranus, Neptune and Pluto, formed from.

Typical dust particles in the size range from 1/10 to 1 millimeter in diameter melt during high velocity entry into the atmosphere to produce spheres. A few percent of the particles are not so strongly heated and do not melt. The first collection of "cosmic spheres" occurred over a century ago when scientists on the H.M.S. Challenger expedition discovered them in mud recovered from the floor of the Pacific Ocean at a depth of over two miles. Cosmic spheres could be collected from this site because of its isolation from sources of terrestrial particles of similar size and shape. The deep ocean floor is an important collecting site for cosmic spheres, but it has serious shortcomings. The recovery of large amounts of extraterrestrial material is difficult from such great depths and the particles that are collected are chemically altered by weathering processes in the sea floor sediment. We report here a new collection site for cosmic dust which is on land and is in an environment where degradation by weathering is minimal.

We have found that the blue ice lakes on the Greenland ice cap provide an ideal location for collection of extraterrestrial dust particles larger than 1/10 millimeter in size. The lakes occur in pure ice for a short period of time each summer. For the rest of the year they are frozen solid. The lakes are basins where dust released by the melting of billions of tons of ice is concentrated. The lakes are a unique location where cosmic dust is more highly concentrated than another spot on Earth. The extraterrestrial particles in the lakes originally fell onto ultra-pure ice in the interior of Greenland, a remote location that is isolated from significant sources of Earth dust in the millimeter-size range. Particles that fall in the interior are buried and remain embedded in the glacial ice that slowly flows outwards to the coast. Several thousand years after their fall the particles reach the zone along the coastline where ice melts during the summer. Particles from the melting ice are carried by temporary streams and deposited into the blue lakes that form at low

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points in the ice.

We discovered this concentration mechanism last summer when we mounted a French-Danish expedition to Greenland to search for extraterrestrial particles in the blue lakes. Particles were collected by magnets and by suction hoses that were used to vacuum sediment deposits from the lake bottoms. We found that the lakes contain enormous amounts of cosmic dust and that the dust is much better preserved than similar particles recovered from the ocean floor. During the previous decade it was found that unique properties of Antarctica made it the world's best location for finding meteorites. It now is evident that unique properties of Greenland make it the best region on Earth for collecting cosmic dust. On future expeditions it is expected that large numbers of particles will be recovered from the pristine and also beautiful blue ice lakes formed each summer near the southern coastal regions of Greenland. Analyses of these samples will give important new insights into the nature of comets and other primitive solar system materials.

THE MARS ANCIENT CRATERED TERRAIN - SMOOTH PLAINS BOUNDARY:  
IMPLICATIONS OF VIKING COLOR DATA FOR EVOLUTION OF THE AMENTHES REGION.  
Ted A. Maxwell and Thomas R. Watters, Center for Earth and Planetary  
Studies, National Air and Space Museum, Smithsonian Institution,  
Washington, D.C. 20560

The Mars cratered terrain boundary is a highly fractured region that divides the ancient cratered terrain in the southern hemisphere of the planet from the smooth plains of the northern hemisphere. The boundary is clearly exposed in the Amenthes region which is located in the eastern hemisphere of Mars. Here, cratered terrain is elevated approximately 3 to 4 km above the northern plains, and the boundary is marked by both broad plateaus and knobby terrain. In southeastern Amenthes, in particular, there is a clear continuum between large detached plateaus, smaller smooth topped plateaus and knobby hills. Knobby terrain, however, is not restricted to areas adjacent to the boundary, but extends some 1000 km to the north where isolated knobs can be mapped. Mapping of the structural features in the Amenthes region indicates that the faults present are oriented parallel to the boundary in the eastern hemisphere, and that the orientation of elongate knobs and detached plateaus is also parallel to the cratered terrain boundary. These results imply that the evolution of the cratered terrain boundary has involved normal faulting caused by stresses acting perpendicular to the boundary.

If the knobby terrain is truly remnant of the ancient cratered terrain, then the far northerly occurrence of the knobs implies that at least part of the northern plains may be underlain by the ancient terrain. In order to look at possible compositional variations to test this hypothesis, we have investigated the global color set compiled by the Mars Consortium.

The application of the martian surface color data to geologic interpretation of the boundary has been initially confined to the Amenthes region in an attempt to limit the numerous problems inherent in the Viking II approach color data. The two most serious problems with the color data as applied to this study are atmospheric contributions that increase with latitude, and the high correlation, or interdependence, among the three color bands. Such a correlation in the color data reduces the amount of useful information. One method to reduce the correlation among the three colors (red =  $.59 \pm .05$  microns, green =  $.53 \pm .05$  and violet =  $.45 \pm .03$ ) has been to ratio one color to another. This method, however, does not maximize the amount of information from the data.

In order to characterize terrain units in the Amenthes region previously defined on the basis of high spatial resolution photogeologic mapping, the three colors of the Viking II approach data were used at the original (1/4 degree) resolution. The color data for this region do not differ significantly from the global color data set in that all three colors are highly correlated. In order to reduce the correlation between the three colors a principal components analysis was performed using a computer. The principal components method transforms the color data thereby reducing the interdependency of one color relative to another. This effectively maximizes the amount of useful information that can be obtained from the color data. After the principal components transformation was performed the resulting data set showed correlation values of 0.50 (red to green), 0.26 (violet to red) and 0.88 (violet to green), where a value of 1.0 indicates perfectly correlated data.

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The decorrelated color data were then subjected to an unsupervised classification. Unsupervised classification is a statistical analysis, performed by the computer, in which the color data are used to generate statistically unique color groups. The advantage of using an unsupervised classification method is that it assumes nothing about the data. The result of such processing is an image in which the different areas in the Amenthes region are classified on the basis of surface color. The number of classes of the initial computer generated classified image were then interactively reduced and compared with the geologic mapping results of the Amenthes region. This allowed us to determine the geologic significance of the various color units. The final classification resulted in the definition of 13 units, 4 of which were related to atmospheric variations in northern Amenthes. In southern Amenthes the classified units show areas of possible mixing between cratered terrain and smooth plains. Consequently, despite the problems inherent in the color data, some geologically meaningful correlations exist between surface units and the transformed color data in the Amenthes region. The knobby terrain protruding through the plains units appears to be remnants of ancient cratered terrain extending northward beneath the more youthful smooth plains.

WHAT WE KNOW ABOUT MARS (BUT OTHERWISE WOULDN'T) IF IT IS THE SHERGOTTITE PARENT BODY. Harry Y. McSween, Jr., Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996.

One of the major scientific triumphs of the last several Lunar and Planetary Science Conferences has been the presentation of evidence that some meteorites may actually be samples of fairly large solar system bodies, specifically the moon and the planet Mars. The proposed martian meteorites, called shergottites after the first example which fell in Shergotty, India in 1865, are igneous rocks that crystallized from molten magmas. Their crystallization ages are much too young to have formed by internal melting within small asteroids, and the unusual chemical composition of gases trapped when these rocks were severely shocked matches that of the martian atmosphere measured by Viking. These meteorites were presumably ejected from Mars by some catastrophic impact.

In a paper presented to the 16th Lunar and Planetary Science Conference, Harry Y. McSween, Jr. of the University of Tennessee discussed the implications of these samples for martian evolution. In a nutshell, his conclusion is that if Mars is the shergottite parent body, the martian interior is much more like that of the earth than has been previously thought.

The compositions of magmas produced by partial melting of rocks in the interior varies depending on the depth. It is possible to estimate the depth of melting from the height of martian volcanoes, assuming that magmas are forced upward by the weight of the overlying material. This information can be used to constrain the mineralogic and chemical composition of the martian mantle. McSween argued that shergottite magma compositions could only be produced at the inferred depth of martian melting if the mantle is more earth-like in composition than previously published estimates. Certain assemblages of minerals in shergottites also indicate that the martian mantle is oxidized like that of the earth, rather than reduced like the moon.

The evolution of a planet is driven by the heat it can generate internally. One of the great problems in constructing martian thermal models is uncertainty in the amounts of radioactive heat sources in the planetary interior. However, data from shergottites indicate that the abundances of the radioactive isotopes of potassium, thorium, and uranium are similar to terrestrial values.

The most important event in planetary evolution is the separation of a core, a process called differentiation. At present, the time of martian core formation is constrained only by rather uncertain thermal models to have occurred anywhere from 4.5 to 0.9 billion years ago. Data in shergottites indicate that their parent planet suffered differentiation very early, at approximately 4.5 billion years ago. We know very little about the martian core, other than the fact that it is probably small. Many models predict that it should consist of iron-nickel sulfides, rather than iron-nickel metal as in the earth's core. An estimated composition of

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the shergottite parent body mantle by Heinrich Wanke and coworkers at the Max Planck Institut fur Chemie in Mainz, Germany, is similar to that of the earth's mantle, except for the proportions of a few elements that were extracted to form the core. Those elements which have strong affinities for sulfur, such as cobalt and copper, are significantly depleted in the shergottite parent body mantle, but elements like tungsten that have affinity for metal are not. The inference that Mars has a sulfide core is apparently correct. The estimated mass fraction of the shergottite parent body that is core is about 22 percent.

The magnetic field of Mars is the least understood of all the planets visited by spacecraft, and a major question remains about whether Mars even has a magnetic field. Shergottites apparently record the presence of a small magnetic field at the time they were shocked. Similar unshocked meteorites have not been analyzed, but may offer the potential for determining the presence of even more ancient magnetic fields.

The proportion of highly volatile elements in Mars is an important characteristic, because escape of volatiles as the planet heats up produces an atmosphere. Some earlier interpretations of Soviet data, as well as the present thin atmosphere, suggested that Mars is a volatile-poor planet. However, measurements in shergottites indicate that volatile element concentrations in Mars should be similar to the earth. Some of the early martian atmosphere has apparently been lost, and the planet may have been outgassed less efficiently than the earth.

Shergottites may also provide an explanation for the great lengths (up to 800 kilometers) of volcanic flows on the martian surface. McSween's calculations of the physical properties of shergottite magmas suggest that they would be dense and highly fluid, just the kind of characteristics that would allow long flows. The compositions of shergottites also provide a good comparison for martian soil analyses by Viking. The similarity in compositions suggests that soils may be derived directly from volcanic bedrock, and that no drastic chemical changes occur during weathering. This is very different from weathering on the earth and implies that the ratios of water to rock were low on Mars.

The return of lunar samples by Apollo missions revolutionized scientific thinking about the moon. Although we have learned a great deal about our other planetary neighbors since the Apollo program, the absence of returned samples has hampered progress in understanding their geologic evolutions. Shergottites may be the Apollo samples of Mars.

### THE IMPACT EJECTION OF LIVING ORGANISMS INTO SPACE;

H. J. Melosh, Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721.

Can natural processes blast living organisms into space? Although this may at first seem too far-out for a serious scientist to suggest, Dr. H. Jay Melosh, an Associate Professor of Planetary Science at the Lunar and Planetary Lab of the University of Arizona, finds that this is not as ridiculous as it may seem. Rocks ejected from the Earth by a giant meteorite or comet impact can carry microorganisms into space. Such microscopic Earth life would have an opportunity to colonize the other planets if it can survive the rigors of space until it falls into the atmosphere of a hospitable planet.

There is already evidence that some process can blast chunks of rock into space from the surfaces of the Moon and perhaps Mars. Some of these rock fragments go into orbit about the sun and eventually encounter the Earth, falling to the ground as meteors. A consortium of meteoricists announced the discovery of a meteorite from the Moon, AHLA 81005, several years ago at the Lunar and Planetary Science Conference in Houston. Other scientists feel that the long-known Shergottite, Nakhelite, and Chassignite (SNC for short) meteorites originated on Mars.

How did these meteorites leave their parent planet? Volcanic eruptions, although they can hurl large rocks many miles, are not capable of ejecting material into space. Even the giant volcanic eruption plumes discovered on Jupiter's satellite Io are incapable of throwing solid rocks out of the satellite's gravitational field. Only the impact of a very large meteorite

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on a planet's surface is able to blast boulder-size rocks into space. The lunar meteorite was launched by the impact of a small asteroid whose diameter was at least the length of a football field (about 100m). The SNC meteorites, if they do come from Mars, could only have been launched by the high-speed impact of an asteroid or comet several miles in diameter. Although such large impacts are not common, even on the Moon or Mars, the cratered surfaces of these planets show that many large impacts have taken place over geologic time. One large impact every ten or one hundred million years would still eject enough of a distant planet's surface to explain the occasional discovery of a rock from its surface on Earth.

The discovery of rocks from other planets on Earth caused Dr. Melosh to wonder whether rocks from Earth might be found on the other planets. Giant impacts are well known on Earth. Louis and Walter Alvarez at the University of California at Berkeley, among others, showed that the Age of Dinosaurs was probably ended by a 7 mile (10 km) diameter asteroid that crashed into one of Earth's oceans. The scars of other giant impacts are recognized at Manicouagan, Quebec, Canada, and at Popigai in Siberia, among other places.

Dr. Melosh showed that a large impact ejects a thin layer of near-surface material in nearly its original state. Deeper-lying rocks are also ejected, but these are crushed or melted by the shock of the large meteorite striking the ground at high speed. The small quantity of unaltered surface material thrown off at high speed, however, is the most biologically active portion of

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Earth's surface. Although the accelerations at the time of launch are too high for multicellular organism to withstand (thousands of times larger than the Earth's surface gravity acceleration), microorganisms or bacterial spores might survive.

The Earth's atmosphere probably offers little impedement to the escape of high-speed surface rock fragments. Eugene Shoemaker, of the U. S. Geological Survey in Flagstaff, Arizona, showed that the 7 mile diameter asteroid that ended the Age of Dinosaurs must have blown the atmosphere aside for a distance of 250 miles (400 km) around the impact site. An atmospheric hole this big takes nearly a minute to close again. The high speed ejecta takes only ten seconds or less to leave the Earth's surface and fly free into space. The ejected surface rock fragments are thus long-gone by the time the atmosphere flows back over the impact crater.

Although this reasoning is theoretical, the undoubted presence of at least a few rocks from the Moon and perhaps Mars makes it plausible that, sometime in its past, the Earth suffered a number of impacts that lofted millions of tons of its surface rock intact into space. Many of these rock fragments would have been boulder-size, some as large as a Volkswagen (several meters). It is possible that dormant microorganisms or spores might survive inside these rocks, protected from radiation and extreme temperature changes. The vacuum of space could aid preservation by freeze-drying the microorganisms.

## IMPACT EJECTION

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What will eventually happen to these life-carrying Earth rocks? Most are doomed to spend geologic periods, tens to hundreds of millions of years, in space. Some will re-impact the Earth, others will impact the surfaces of airless satellites or asteroids at high speed, vaporizing their substance during the collision. A few, however, may eventually fall toward a planet possessing an atmosphere: Mars, Venus, or even Jupiter, Saturn or Saturn's large satellite Titan. Atmospheric friction would slow the entering rock and atmospheric drag forces would break it open. Earth organisms would then have the opportunity to colonize this new environment. Of course, it is most likely that they would find it inhospitable and perish.

However unlikely this chain of events may seem for any particular piece of Earth's surface rock, the total quantity of rock ejected from the Earth by large impacts is large enough that the scenario described above probably happened not once, but several times over the history of the solar system. If there is life on any of the other planets, a reciprocal process may already have brought samples of this life to Earth. Like the continental land masses on the Earth, the solar system may be divided into separate, but not wholly isolated, biological provinces. If living organisms are discovered elsewhere in the solar system they may thus turn out to have fundamental similarities to terrestrial life.

A SEARCH FOR EVIDENCE OF LARGE BODY EARTH IMPACTS ASSOCIATED WITH BIOLOGICAL  
CRISIS ZONES IN THE FOSSIL RECORD

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Were the Earth's great biological catastrophes caused  
by impacts of asteroids or comets?

Background

Five years ago, a University of California-Berkeley team (Luis Alvarez, Walter Alvarez, Frank Asaro, and Helen Michel) reported a discovery and a hypothesis that have had a dramatic effect on the way we think about the natural history of the earth--how the present plant and animal species developed, how others completely died out, etc. They were studying rock samples from strata in the neighborhood of the Cretaceous-Tertiary boundary, that is, strata that were deposited at the time of the great extinction 65 million years ago that marked the end of what Earth scientists have labeled the Cretaceous period. The extinction had wiped out many forms of terrestrial life, from land plants and microscopic marine life, to apparently, the dinosaurs. The rock strata sampled and studied by the Alvarez team were located near Gubbio, Italy, and at the time they were deposited, had actually been sea bottom. What these researchers found was that, exactly at the stratigraphic level corresponding to the extinction, a thin clay layer was greatly enriched, relatively speaking, in the rare element iridium. [Enriched in the other five elements of the platinum family as well, however, iridium can be measured more sensitively by the use of neutron activation.]

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Iridium normally occurs at very low concentrations--a few parts per trillion--in the Earth's crust. It is much more abundant (100 to 10000 times more, though still rare) in solar system matter, but when the iron settled to the center of the molten Earth, the iridium went with it. Most meteorites contain the solar system abundance, whereas comets, which are thought to be mostly ice, probably range between solar system and Earth crustal iridium concentrations.

Taking into account these and other factors, the Alvarez team hypothesized that the excess iridium at the boundary came from a large asteroid-like object, of the order of 6 miles in diameter, that hit the earth. And, they also hypothesized that the impact of this object threw up a dust cloud dense enough and long-lasting enough to bring about the extinction of a wide variety of plants and animals, producing the unique break in the fossil record now called the Cretaceous-Tertiary boundary. Their observations on the samples from Italy were soon confirmed by similar observations on other (originally sea-bottom) samples taken in Spain, Denmark, and New Zealand, showing that the hypothesized catastrophe had been world-wide. The required impact crater has not yet been found, but this is not a fatal concern; the object might have hit at sea.

This radical asteroid-collision hypothesis provided a great wave of interest and controversy in the scientific community. Among the geological counter-arguments was one that was harder to dismiss: that all of the iridium-enriched samples measured up to that time had come from strata laid down at the bottom of the sea and, thus, that the iridium enrichment could have been caused by natural chemical processes in sea water, processes not yet well understood. The counter-argument was countered, in turn, by a discovery that we, in collaboration with USGS geologists, announced the next

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year (1981). Taking samples from a drill core that spanned the Cretaceous-Tertiary boundary deposited under freshwater conditions at a site in what is now the Raton Basin of northern New Mexico and southern Colorado, we found the same iridium and platinum metals enrichment in a thin clay layer that corresponded with the boundary as defined by sudden radical changes in plant populations. In subsequent sampling we have confirmed the iridium enrichment at other freshwater-origin sites in the Raton Basin and in similar sites in Montana.

#### The Present Work

The geochemical evidence for a major impact catastrophe 65 million years ago is now firm and fairly widely accepted in the scientific community. But, the terminal Cretaceous event might not stand alone. Studies of the fossil record have shown other major extinctions in the Earth's biological history--around a dozen or so depending on one's criteria--and other studies looking into the frequency of meteorite/comet impacts and how it varies with the object's size have shown that there ought to have been several terminal Cretaceous-scale events in the approximately 600 million years for which we have fossil evidence of advanced biological forms.

Shouldn't it be possible, then, that some of these other well-established extinctions were also brought about by impact catastrophes? The work we report today is an attempt by the Los Alamos team and some of its collaborators to obtain answers to this question.

Following the Snowbird Conference on Large Body Impacts in October 1981 at Snowbird, Utah, we directed our primary effort to searching for geochemical signatures of large body impacts at extinction boundaries that predate the terminal Cretaceous event.

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In collaboration with paleontologic and stratigraphic experts, we have measured elemental abundances in samples collected across most of the recognized extinction boundaries. In several cases, we have performed these measurements on two or more widely-separated exposures of the same boundary, because we recognize that preservation of thin fallout beds is sensitive to erosion and mixing processes and, thus, the geochemical signature could be missing from some of the sections.

To date, we have made measurements across the following extinction boundaries: 1) Precambrian/Cambrian boundary (570 million years ago); 2) two trilobite crisis zones in the Upper Cambrian (515 and 520 million years ago); 3) Cambrian/Ordovician boundary (505 million years ago); 4) Ordovician/Silurian Ashgillian extinction (440 million years ago); 5) Upper Devonian Frasnian/Famennian boundary (365 million years ago); 6) Permian/Triassic boundary--recognized by paleontologists as the largest extinction in the fossil record (245 million year ago); 7) Triassic/Jurassic boundary--a large Canadian impact structure has a similar date (about 210 million years ago); 8) a biological crisis in the Jurassic Toarcian Stage (about 185 million years ago; and 9) the Upper Cretaceous Cenomanian/Turonian Stage boundary that is characterized by marine black shales (about 90 million years ago).

Thus far, we have not found any firm evidence for the association of a large body impact with any of the above boundaries. In collaboration with an Australian geologist (Phillip Playford) and two Canadian geologists (Digby McLaren and Wayne Goodfellow) we have discovered a moderate iridium and platinum anomaly (15 to 20 times local background amounts) at the Frasnian-Famennian boundary zone in an Upper Devonian age reef complex in northwestern Australia. Our evidence indicates that bacteria enriched these elements and several others (some not prominent in meteorites) from seawater. It is difficult, however, to preclude the possibility that there were higher

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concentrations of iridium and platinum in the ocean at that time due either to an impact or to nearby volcanism. Work in progress on a drill core from the reef complex might provide some further answers to this problem. We have also examined other Frasnian/Famennian boundary sequences exposed in New York and in Europe, but have found no indication of excess platinum-group elements. Again, we can not rule out possible lack of preservation at those sites.

Reports of iridium anomalies at the Precambrian/Cambrian and Permian/Triassic boundaries have added fuel to the recent "Death Star" hypothesis that suggested extinctions were caused by cyclic swarms of comets. However, in duplicate sets of samples from both boundaries we were unable to reproduce the high concentrations of iridium reported by others; we measured very low Earth crustal amounts that ranged from 1 to 35 parts per trillion.

In summary, our measurements at the Cretaceous-Tertiary boundary in freshwater deposits from New Mexico to Montana support the Alvarez hypothesis of a large body impact at that mass extinction horizon. Thus far, we have not found any evidence for the association of a large body impact with any of the major extinction boundaries that predate the terminal Cretaceous event. And recent hypotheses that suggest extinctions were caused by periodic (26 to 33 million year cycles) comet swarms are not supported by our measurements. However, one should accept our negative results with some caution, because preservation of thin fallout beds is sensitive to erosion and mixing processes, thus the geochemical signature might be missing from some of our sampled sections. Although the amount of iridium deposited on the Earth's surface from a comet impact might be considerably less than from a similar size asteroid, our detection methods for iridium are so sensitive we can pick up iridium concentration changes only one percent as large as the world-wide anomaly at the Cretaceous-Tertiary boundary.

## TELESCOPE IN LUNAR ORBIT

Thornton Page

NASA JSC Code SN (483-3728)

In order to support the establishment of a lunar base around AD 2000, this paper proposes the use of a large telescope in high lunar orbit 4000 km (2500 mi) above the Moon's equator. After this idea was first proposed at the National Academy of Science Symposium on Lunar Bases last Oct in Washington, DC, it was recognized that NASA's Hubble Space Telescope (ST), scheduled to be launched into low Earth orbit by Shuttle in 1986, will provide the necessary capabilities if it can be transferred to lunar orbit. The Orbital Transfer Vehicle (OTV), expected to be in service by the mid-1990s, will be able to make such a transfer. With a few modifications, ST will then be able to scan the lunar surface, locate small outcrops of minerals important to base development, and support early base operations. It can then undertake detailed geophysical exploration of the whole lunar surface more expeditiously than geologists making long traverses on Lunar Rovers.

Space Telescope was designed for astrophysical observations from low Earth orbit (LEO), but it is shown that high lunar orbit offers several major advantages for this purpose as well as for the proposed unconventional use to survey the lunar surface. It is noted that these advantages can be thoroughly checked during 10 years' use of ST in LEO before transfer to lunar orbit. They are:

- 1) Absence (in lunar orbit) of red "Shuttle Glow" and the foreground ultraviolet light of the geocorona, both of which will tend to obscure faint astronomical sources to be detected and analysed by ST,
- 2) Lower orbital velocity (1 km/sec in lunar orbit vs 8 km/sec in LEO) which affects spectra by the Doppler shift, and greater sky coverage (the Earth blocks almost half the sky from LEO), and
- 3) The ability to observe close to the Sun for several minutes just before sunrise and just after sunset in lunar orbit. Preliminary operating rules forbid pointing ST closer than  $45^{\circ}$  from the Sun, which rules out observations of Venus, Mercury, the solar corona, comets, asteroids, and other celestial objects that happen to be close to the Sun. (In LEO, the intervals before sunrise and after sunset are much shorter, and the Earth's atmosphere intervenes.)

Although many astronomers oppose changes in plans for ST, which was designed for 15 years' use in LEO, it is emphasized that this proposal leaves 10 or more years in LEO and will extend ST's later usefulness in lunar orbit. Modifications

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to the six initial ST instruments -- cameras, spectrometers, polarimeters, photometer, and measurer of very accurate star positions -- will undoubtedly be undertaken in LEO during the first 10 years, and some upkeep (replacement of batteries and solar cells) will probably be necessary, all accomplished by Shuttle astronauts on EVA, or by returning ST to Earth. The modifications necessary for use in lunar orbit involve extending instrument sensitivity from deep red to infrared wavelengths (from 700 nm to 3000 nm). For pointing at targets on the Moon rather than at stars and galaxies in the sky, new computer programs must be written for ground-based computers at the ST Control Center at Goddard Space Flight Center in Greenbelt, MD.

With these modifications, ST will be able to measure near-infrared colors and the spectrum of sunlight reflected from rocks and soil on the lunar surface at selected locations such as the Apollo landing sites, where 12 astronauts spent a total of 81 hours collecting samples and doing experiments on EVA. Because of these past explorations, these six Apollo landing sites will certainly be considered as potential locations for a permanent Lunar Base. Other locations will probably be proposed. One important requirement will be easy access to minerals such as ilmenite (titanium-iron oxides) from which oxygen can easily be obtained by heating in a solar furnace. Scans by ST will show the location of ilmenite outcrops as small as three to five meters (10 to 16 ft) in extent, and give the distance and direction from the Base. After assembly and construction at Space Station, metal habitats, radioactive electric generators, and supplies of oxygen, water, food, etc. will be transferred to lunar orbit and landed at the selected Base site along with three or four astronauts and equipment to dig in the habitats and cover them with three to five meters of soil.

If all goes well in the first year at Lunar Base (with crews rotated every three months), the production of oxygen and iron should be underway, and geophysical research starting. ST in lunar orbit will help the research effort by scanning for mineral content of soil and rocks along designated west-east traverses and across the layers exposed in crater walls, detecting layers as thin as three meters. The results should provide planetary scientists with data to improve their theories of the history of the lunar surface, including the back side, which even lunar-based geologists cannot easily reach. All the data gathered by ST are radioed back to Earth by the TDRSS satellites, and also to Lunar Base. In between these geophysical observations, ST will continue astrophysical observations of galaxies, stars, planets, and objects close to the Sun -- hence

its proposed name, Geophysical-Astrophysical Lunar Telescope (GALT).

As a final service to planetary scientists, GALT/ST can monitor gases released from Lunar Base that might contaminate the pristine lunar surface which the geologists hope to sample and study for evidence of events during the Moon's 4.5-billion-year history. This can easily be done by recording the spectra of early-type (hot) stars along the line of sight from ST just above Lunar Base from lunar dusk to dawn. (In lunar daytime, the gases would undoubtedly escape to space, but during the night they can be blown across the surface by the solar wind.) If the stellar spectra show increasing amounts of gases like CO, CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, O<sub>2</sub>, metals, and metal oxides, the Lunar Base crew must take steps to prevent the release.

Much of this may sound like science fiction, and it was, about 20 years ago, when Robert A. Heinlein's book "The Moon is a Harsh Mistress" was published by G. B. Putnam, NY, 1966. Heinlein portrays lunar cities in the year 2075, and has most of his facts straight except for the prevalence of water ice on the Moon. (There is no evidence of water on the Moon, but speculation that there may be some ice in craters near the poles never reached by sunlight.)

As the abstract indicates, ideas for this paper were contributed by planetologist Michael B. Duke of NASA JSC (not by Heinlein). The use of reflected sunlight to detect minerals on the lunar surface was developed by several geophysicists including Carle M. Pieters, now at Brown University in Providence, RI, who reviewed the MS. The use (or misuse) of ST as GALT was reviewed by C. R. O'Dell, ST Principal Scientist, now at Rice University in Houston.

A SPECTACULAR NITROGEN ISOTOPE ANOMALY IN BENCUBBIN;  
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At the present time, astronomers observe the formation of new stars as a consequence of gravitational contraction of "lumps" of gas and dust in large cold clouds within our galaxy. Our own sun and solar system may have formed in a similar fashion some 4.6 billion years ago. In order to learn more about the raw materials from which our solar system was formed, and also about the chemical and physical processes involved in its formation, we try to identify and study the most "primitive" matter accessible to us. Such matter has been found on a microscopic scale in a variety of meteorites: fragments of small solar system bodies that were never part of a large planet. This primitive matter has, in most cases, been identified by the presence of anomalous abundances of some isotopes of the chemical elements. These abundances are called "anomalous" if they cannot be accounted for by any known physical or chemical process occurring within the solar system. In some cases, the anomalies have been attributed to chemical reactions that took place in the cold cloud before formation of the solar system, at temperatures of  $-370^{\circ}\text{F}$  or lower; in other cases the anomalies appear to result from nuclear reactions in exploding stars.

The element nitrogen has two stable isotopes:  $^{15}\text{N}$  and  $^{14}\text{N}$ . On earth, the relative abundances of these isotopes are fairly uniform, with the ratio of the number of  $^{14}\text{N}$  atoms to  $^{15}\text{N}$  atoms averaging 270, and ranging from about 258 to 274. The variations are due to small differences in the chemical properties of the two isotopes. Earlier studies of the isotopes of nitrogen in iron and stony meteorites revealed a considerably greater range in the abundance ratio, from about 230 to 300. Furthermore, the

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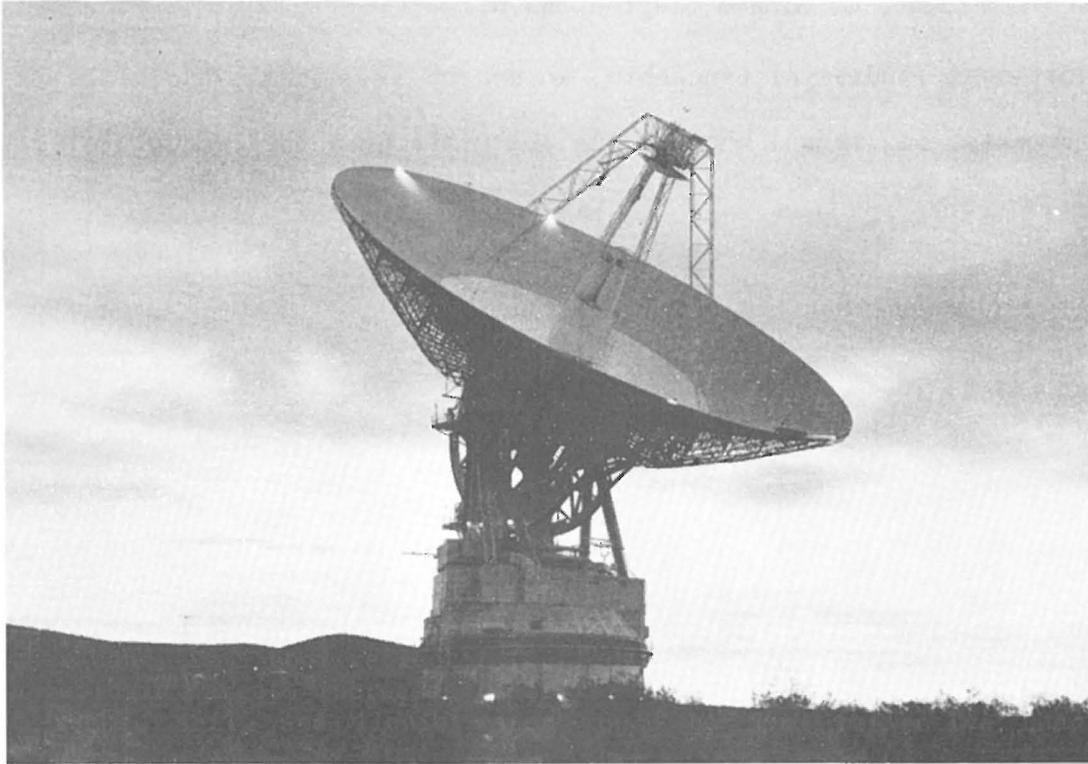
abundance ratio of nitrogen in the solar wind (as measured in solar atoms implanted into surfaces of solid grains in the lunar surface soil) has varied over geologic time from at least 320 in the past to 270 today. Clearly there are processes in the sun and solar system that are much more effective in separating or producing isotopes of nitrogen than any processes acting on earth. Whether these are predominantly chemical reactions or nuclear transformations remains to be resolved.

The new result reported here is an isotopic measurement on an unusual stony-iron meteorite named Bencubbin, which was found in Western Australia in 1930. Nitrogen from both the metallic and stony parts of the meteorite was analyzed, and in both materials large excesses of  $^{15}\text{N}$  were found, resulting in values of the  $^{14}\text{N}/^{15}\text{N}$  abundance ratios as low as 137. That is,  $^{15}\text{N}$  is enriched in Bencubbin by about a factor of two relative to terrestrial nitrogen. This is by far the largest  $^{15}\text{N}$  enrichment of any known natural material. The effect is so large that chemical processes are probably inadequate to account for it, and one looks, therefore, for possible nuclear reactions. The isotopes of nitrogen are known to play an important role in the main energy-production processes in many stars, through a series of nuclear reactions known as the CNO cycle (involving the elements carbon, nitrogen, and oxygen). However, in the normal CNO cycle,  $^{14}\text{N}$  is produced and  $^{15}\text{N}$  is destroyed, which is in the opposite direction to what we see in Bencubbin. In fact, radio astronomers observe enhancements of  $^{14}\text{N}$  in parts of our galaxy due to the operation of this cycle in stars. An alternative possibility is the production of  $^{15}\text{N}$  in the explosive stellar phenomenon known as a nova. Nova explosions have previously been called upon to explain the production of  $^{26}\text{Al}$ , a radioactive isotope that was present in the early solar system when the meteorites were formed.

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Additional studies of Bencubbin, in search of isotopic anomalies in other elements, may reveal whether the postulate of a nuclear origin is supported.



MARS: SEASONALLY VARIABLE RADAR REFLECTIVITY; L. E. Roth, G. S. Downs, and R. S. Saunders, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109; G. Schubert, Department of Earth and Space Sciences, University of California, Los Angeles, California 90024.

Reconnaissance by radar from Earth is one way of exploring our closest planetary neighbors, Mercury, Venus, and Mars. Radar exploration of Mars, begun in mid-sixties (1,2) produced a wealth of information on the topography, roughness, and reflectivity of the planet. In dealing with the radar reflectivity, the work discussed here indirectly addresses the question of liquid water on Mars, a subject tainted by the memory of the extravagant claims of Percival Lowell made at the turn of the century (3). We have analyzed the 1971/1973 Mars data set acquired by the Goldstone Solar System Radar (4,5) and established that the seasonal variations in radar reflectivity thought to occur in only one locality on the planet (the 'Solis Lacus radar anomaly' (6)) occur, in fact, over the entire subequatorial belt observed by the Goldstone radar. Since liquid water appears to be the most likely cause of the reflectivity excursions, a permanent, year-round presence of sub-surface water (frozen or thawed) in the Martian 'tropics' can be inferred.

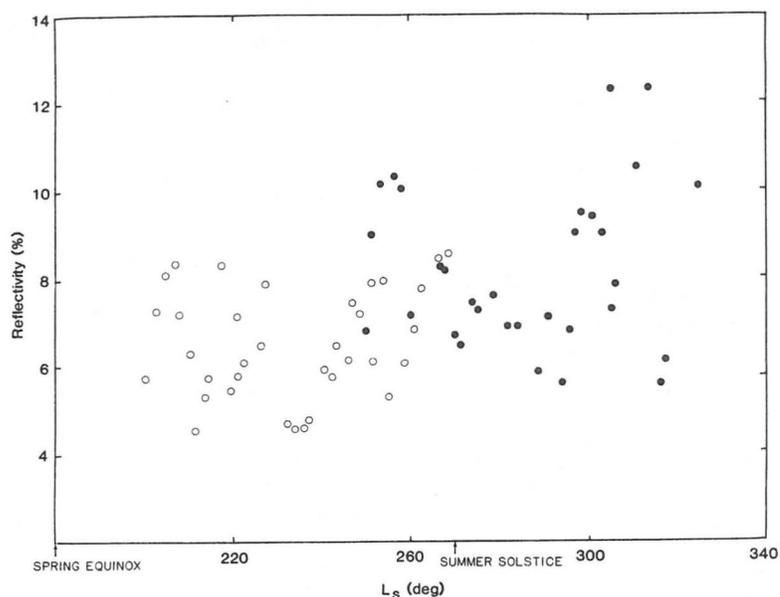
This conclusion is based on the following ideas: The ability of materials or objects to reflect electromagnetic waves is expressed through a quantity called reflectivity. The magnitude of reflectivity ranges from 0.0 for ideal absorbers to 1.0 for ideal reflectors. Both the common rocks and the water ice are poor reflectors (reflectivity  $\sim 0.1$ ). Liquid water, on the other hand, is a good reflector (reflectivity  $\sim 0.8$ ). Presence of liquid water in geologic targets increases their reflectivity. A target containing mixture of rocks, soil, and liquid water would be more reflective than the same

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mixture, but with solid ice instead of liquid water. Since the reflectivity is a quantity characteristic of a given target, the same target examined by radar at two different occasions should have the same reflectivity. If the reflectivity varies from one experiment to the next, the target must have undergone a change during the intervening period. This change could either be internal, involving the composition/phase of the target itself, or external, involving the geometry/texture of its surface.

During the 1971/1973 oppositions, the Goldstone radar scanned the Southern Martian latitudes on almost 70 occasions. The observations extended from the early Martian spring to the Martian mid-summer. Applying the notions of our terrestrial calendar to Mars, the observations would have started on 10 (Martian) April and terminated on 15 (Martian) August. Many areas were scanned more than once. Intervals between some observations corresponded to up a few (Martian) months. (The analogy with the terrestrial calendar is helpful; it should not be taken literally, however. A year on Mars is almost twice as long as a year on Earth; a (Martian) month, in the context of our analogy, is almost twice as long as a month on Earth, a (Martian) week almost twice as long as a week on Earth.) In view of what we said before, the reflectivity of an inactive, unchanging target should always be the same, regardless of how often or at what time intervals the target is scanned by radar. Analysis of the Goldstone data shows, however, that the Mars reflectivities do not conform to the expected, steady pattern. Instead, starting from the lower values in the Martian spring, they tend toward higher values in the Martian summer (Fig. 1). This overall trend can be observed

FIGURE 1



over the entire planet. For instance, in Solis Lacus/Sinai Planum (6) (Fig. 2) an average reflectivity of 0.08 was measured on 6 (Martian) June; an average reflectivity of 0.11 was recorded five (Martian) weeks later, on 10 (Martian) July. As still another example, consider the cratered highlands

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in Margaritifer Sinus (Fig. 3) and Aeolis (Fig. 4). Those radar scans that followed each other by less than about one (Martian) week ( $\Delta L_s < 10$  deg) show no change in reflectivity (i.e., the ratio of respective reflectivities equals unity). An increase in the interval of separation from about one (Martian) week to two-to-three (Martian) months is usually accompanied by a corresponding increase in the average reflectivity (the ratios of respective reflectivities are larger than unity).

FIGURE 2

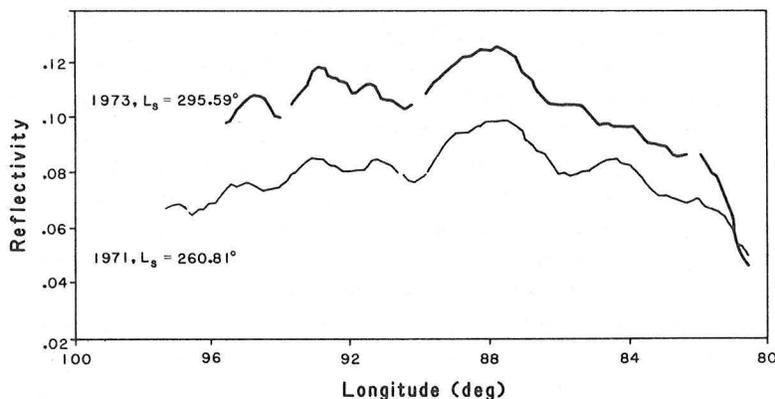


FIGURE 3

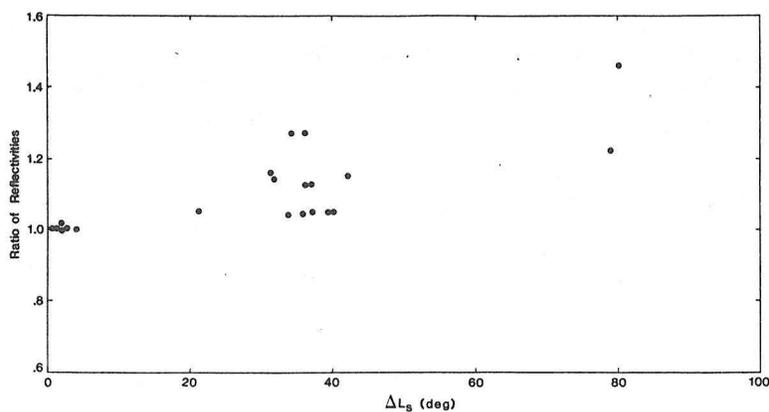
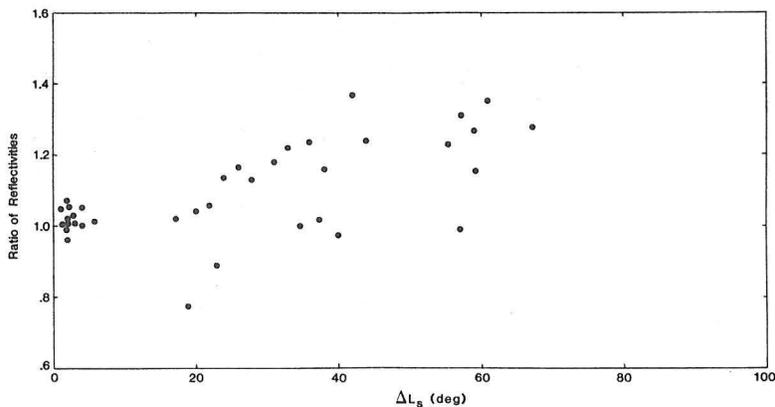


FIGURE 4



What should be the interpretation of this puzzling phenomenon? Discarding the unlikely case of a systematic increase in the instrumental bias/calibration error, we are left with two possibilities: (a) Seasonal variations in Mars reflectivities are due to changes taking place on the

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planet's surface. These changes could be related to the action of wind and associated with it redistribution of dust. Even though this mechanism cannot be ruled out entirely, a significant contribution does not seem to be supported by the photogeologic evidence. (b) Seasonal changes in Mars reflectivities are due to changes taking place below the planet's surface. What is the most probably subsurface change that could occur in parallel with the progress of the Martian seasons from the early spring to the mid-summer? It has to be the thawing of water ice and the emerging presence of the liquid water as a temporary constituent of the Martian soil. This brings us full circle to the beginning of our story: Since the liquid water is the most likely cause of the observed reflectivity excursions a permanent, year-round presence of sub-surface water (frozen or thawed) in the Martian 'tropics' can be inferred.

The final judgement on this controversial issue should be suspended until more data are available and the reality of the effects observed in the 1971/1973 Goldstone data is confirmed. Until then, the possibility of the presence of liquid water in the Martian soil should be treated as a working hypothesis rather than an established fact. Mars is a difficult object to observe; geometric considerations make the subequatorial areas on Mars visible to radar from Earth only during 2-3 favorable oppositions out of the full cycle of 7-8 oppositions. The last pair of favorable oppositions took place in 1971/1973. The forthcoming apparitions, favorable ones in 1986/1988 and an intermediate one in 1990, should make it possible to enlarge the Mars radar data base and allow a new attempt at solving the variable-reflectivity riddle.

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ORIGIN AND EVOLUTION OF ORDINARY CHONDRITE METEORITES,  
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About 85% of the meteorites that hit the earth's surface are rocks called chondrites, which are aggregates of materials that formed 4.6 billion years ago from a cloud of dust and gas. These rocks are important for what they can tell us about the origin of the solar system and because they probably resemble the rocks from which the earth formed and its inhabitants evolved. The great majority of chondrites (90%) have very similar chemistry and mineralogy: these 'ordinary' chondrites are pieces of three unidentified asteroids that were removed and transported to earth by collisions among asteroids and comets. Chondrites are named after their major constituent: millimeter-sized spherules called chondrules, which formed from molten droplets in a cloud of dust and gas.

A small fraction of the chondrites (15%) are made of materials that have never been heated above 600°C; these chondrites have been studied intensively for clues to the origin of the solar system. But the great majority of chondrites, including 95% of the ordinary chondrites, are largely made of ingredients that were heated to temperatures between 600 and 900°C. To decipher their history, we need to understand how these rocks were heated inside asteroids and how their mineral textures and compositions were affected. Then we can hope to understand how their ingredients were formed from the primordial cloud of dust and gas - the 'solar nebula'.

Did the baked chondrites form from asteroidal material that resembled the unbaked chondrites? This question has caused much argument among meteorite researchers during the past 20 years because it is not possible to reproduce in the laboratory a process whereby asteroids many miles in diameter were heated for several million years. Differences in the composition and texture of unbaked and baked chondrites are small relative to the range of properties of all meteorites, so that this question cannot be answered without a detailed understanding of chondrite properties and their origins.

A major complication in unravelling the history of the ordinary chondrites and other old planetary materials is that their parent bodies suffered intense bombardment from comets and other asteroids, especially during the first half billion years of their history. This bombardment fractured and mixed the rocks so much that most meteorites are mixtures of materials from various

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parts of their parent asteroids. About 85% of our samples of asteroids that were once molten are mixtures or 'breccias' of this kind. For the ordinary chondrites it is probable that a similar high proportion are breccias of materials that were baked to various extents. Unfortunately, these breccias are more difficult to identify because the fracturing and mixing process did not greatly change the appearance or composition of chondritic rocks: they were originally diverse mixtures of materials that formed in various parts of the solar nebula. The unbaked and half-baked materials in the chondritic asteroids were easily crumbled and mixed so that only a very small proportion of ordinary chondrites are not breccias of materials with diverse thermal histories. The mixing of material and redistribution of volatile elements during impact heating makes the origin of the ordinary chondrites much more difficult to decipher. Many meteorite researchers have analyzed samples of ordinary chondrites without realizing that they were not studying pure unbaked or baked material. Naturally this has caused much confusion.

Chondrules that were moderately or strongly heated are made of silicate minerals with rather uniform compositions. By contrast, unbaked chondrules are made of silicates with highly variable iron concentrations. Did the heating process homogenize the silicate minerals, or did baked and unbaked chondrules form in different ways in the solar nebula? One group of meteorite researchers has claimed that silicates in baked chondrules have uniform compositions because these chondrules cooled slower in the nebula causing their minerals to homogenize during crystallization. We have found evidence that strongly favors the alternative view that heating in asteroids caused homogenization of mineral compositions.

We have identified one type of chondrule that always contains silicates with low concentrations of iron in chondrites that lack baked material. By studying compositions of silicates in this variety of chondrule in a whole range of chondrites, we have found that the iron concentrations of these silicates vary in a way which is consistent with homogenization during asteroidal heating, and inconsistent with homogenization during crystallization in the nebula. We can make this distinction because the two major silicate minerals in chondrules called olivine and pyroxene tend to crystallize with similar iron concentrations. However, they exchange iron at different rates so that chondrules which contain olivines with high and uniform iron concentrations but pyroxenes with low and variable iron concentrations must have achieved

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these compositions during heating, not crystallization. Because pyroxenes would take thousands of years to homogenize, it is much more likely that this occurred during slow asteroidal heating, and not during rapid nebular heating.

Subtle differences in the chemical compositions of baked and unbaked ordinary chondritic material have also caused considerable controversy over their origins. Volatile elements are more abundant in unbaked chondrites and they may have been partly lost during slow heating inside asteroids or redistributed during impact heating. However, it is doubtful whether all the chemical differences were caused by heating. Carbon is much more abundant in unbaked than baked chondrites and it is unlikely that loss of carbon monoxide during heating could be the sole cause. We know of some rare baked chondrites that are rich in carbon but we have not identified carbon-poor chondrites composed of unbaked material. If carbon concentrations were controlled by nebular processes, how were nebular and asteroidal processes linked so that all C-poor chondrites were heated in asteroids?

According to the simplest explanation, asteroids were heated by the decay of radioactive atoms such that material at the core was hotter than material at the surface. Carbon and volatile elements condensed from the solar nebula after nebular temperatures had fallen below 300°C. Chondritic material that condensed above this temperature accreted to form the cores of the ordinary chondrite parent asteroids, whereas material that condensed below this temperature accreted on the surface. Thus no C-rich and all C-poor material was baked. There are a number of difficulties with this scheme. Why weren't C-rich and C-poor materials mixed during accretion of planetesimals to make the ordinary chondrite parent bodies? There is evidence for mixing of baked and unbaked material during heating so it would seem to be difficult to preserve chemical differences during accretion. Perhaps the heating source was a hot sun instead of radioactive atoms, or perhaps we misunderstand the chemical changes produced by heating.

Answers to these questions require more detailed laboratory studies of meteorites and the processes which formed them, and exploration of the asteroids themselves. The proposed flyby of asteroid Amphitrite by the Galileo spacecraft in 1986 should show whether the abundant S-type asteroids, such as Amphitrite, are the parent bodies of ordinary chondrites. It will also provide important clues to the nature of impact and heating processes which must have drastically affected most asteroids and planetesimals.

## MINERALOGICAL STUDIES OF LUNAR METEORITES AND THEIR LUNAR ANALOGS.

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The first lunar meteorite had been recovered from Yamato Mountains by JARE (Japanese Antarctic Research Expedition) party in 1979, but the sample (Yamato 791197) was kept in refrigerated stock room at National Institute of Polar Research in Tokyo, Japan before it was characterized. Meanwhile, a small unusual meteorite collected from Allan Hills, Antarctica (ALHA81005), by the U.S. party, was recognized as a 'lunar meteorite', a meteorite brought from the moon (e.g. 1). Now all lunar and planetary scientists and meteoriticists believe that ALH81005 is of lunar origin (1). Subsequently, Yamato 791197 and another sample recovered in 1982, Yamato 82192 have been described as second and third lunar meteorites by Yanai and Kojima (2) and by Yanai et al. (3). All these samples are solidified soils of lunar highland, what lunar scientists called regolith breccia. The closest precedents have been proposed to be the Apollo-16 and Lunar-20 regolith (1).

In the previous studies on lunar meteorites, scientists have made effort to prove they are of lunar origin. No extensive study has been undertaken to find and compare them with closest lunar analogs of lunar meteorites among lunar samples collected by the Apollo missions. In order to locate the impact location of the lunar meteorites, or to find that all lunar meteorites are derived from the same meteorite impacts on the lunar surface, or that they are pieces of a single meteorite fall over the Antarctic continents, we have to study regolith breccias recovered by the Apollo missions. This kind of lunar rocks have been very poorly characterized up to date, because many lunar scientists are more interested in pristine, crystalline rocks which formed primary lunar crust in the earliest history of the solar system.

Comparisons of three lunar meteorites are also extremely important, because they inform us about portions of the Moon's crust never sampled by either the U.S. Apollo or the Soviet Lunar missions. Those missions provided samples from only a tiny region near the center of the near side, comprising about 4.7% of the entire lunar surface (personal communication, Dr. P. H. Warren). Thus, the probability that meteorite such as Y791197 originated from outside of the Apollo-Lunar sampling area is about 95%; and we can be virtually certain that careful study will provide important new clues to the Moon's composition, origin and evolution. If all three lunar meteorites were different, each sample would be worth while one lunar mission.

In 1979, we studied an Apollo 16 regolith breccia, 60016,97, which is one of the few highland regolith breccias studied by mineralogists and petrologists. We investigated, chemical compositions and textures of a mineral called pyroxene, and reported that it contained almost all types of pyroxenes known in lunar highland rocks. Lunar meteorite, ALH81005 also show similar trends. Because there was more glass in the matrix of ALH 81005 than 60016, we investigated another samples which resembles more lunar meteorites. NASA scientists informed us that 60019 may be a better candidate to be studied (Dr. D. McKay, personal communication, 1984). We also investigated ALH81005 by analytical transmission electron microscope (ATEM),

which is capable of analysing the chemical composition, texture and atomic arrangements of a region as small as 800 Å. We tried to see whether the glass matrix was produced by an impact which produced this breccia or by an impact which excavated this sample to leave the Moon to come to Earth.

Yamato 791197 has been briefly described by Yanai and Kojima (2). Now, international consortium studies on this lunar meteorite are underway. The first result will be presented at the 10th Anniversary Symposium on the Antarctic Meteorites, which will be held at the end of March, 1985, in Tokyo. Only preliminary comparison will be made.

Among the polished thin sections we examined, large areas of lunar regolith breccias 60019, 14, 75, 80 and 91 are similar to lunar meteorites ALH81005 and Y791197. They are characterized by brown glass matrix, varieties of lithic and mineral fragments and glassy components of lunar highland regoliths. A lunar light matrix breccia, 60016 has smaller amounts of such glass matrices than 60019, but the clast materials are similar. Because smaller amounts of glass will help us to study clast materials, we investigated 60016, extensively.

60016,97 consists of the fine-grained comminuted constituents of the regolith such as rock, mineral and glass fragments, glass spherules with mineral fragments, glassy agglutinates. These are agglomerated to a coherent rock by sintering of hot glass or by shock lithification. Some portions of the glass matrix clasts with plagioclase and mafic mineral fragments are more similar to the lunar meteorite than the over all PTS. Large lithic clasts with mafic minerals are less abundant than ALH81005. Abundance of large clasts in ALH81005 is also higher than that of Y791197 (2). A clast with hedenbergite (Hd) and Plagioclase in Y791197 (2) (4) should be compared with Hd in 14321, 993 (5), and spinel-plagioclase clast with spinel troctolite. These are uncommon rock types on the Moon.

The glass bulk compositions of the breccia matrices and matrices of glassy clasts of 60016 and ALH81005 were obtained by a broad beam (40 microns) microprobe analyses (average of 5 to 10 points) and are plotted in  $Al_2O_3$  vs. CaO (wt. %) diagram and in the Silica-Olivine-Plagioclase pseudoternary system. Two groups distribute in a similar region. Because glasses were produced by heating of fine-grained fragmental materials of lunar highland rocks, similarity in glass compositions suggests that they were derived from similar source materials.

Pyroxene is a silicate mineral, with various amounts of calcium, magnesium and iron. Their compositional variations are plotted in so called "pyroxene quadrilateral, which is a portion of triangle with these three components at the corners. This mineral is probably a mineral which gives us the most valuable information on the components of lunar highland regoliths, because their compositions and inversion and exsolution textures are often unique signatures of certain rock types.

The chemical compositions of all pyroxene grains analysed by electron microprobe are plotted in a pyroxene quadrilateral and were compared previously with those of pyroxenes in nonmare pristine rocks compiled by Ryder and Norman (6). They are also compared with those of ALH81005 (7) and Y791197 (2). The compositions are distributed over a wide range in the quadrilateral, covering almost all known pyroxenes in nonmare pristine rocks. Pyroxenes of rapidly cooled KREEP basalts and of the most Mg-rich troctolites are not present. The olivine compositions of 60016 studied previously (6) also show that they represent those of the above rock type.

The distribution of the plagioclase compositions of large fragments in

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the matrix of the entire PTS, fragments in the glassy clasts of 60016 are also similar but some plagioclases in glassy clasts show higher potassium contents. The number of ALH81005 plagioclase is too small to compare them with 60016, but the variation within 60016 is larger than within ALH81005.

The study of glass in the lunar meteorites suggests that the glass was not produced by a meteorite impact which excavated the mass into the orbit towards the Earth. The glass had been devitrified on the lunar surface before the excavation, and new glass was not produced by the last impact. This conclusion was obtained by the following facts.

The ATEM study of suevite-like glass veins in ALH81005, revealed that apparently glass-like materials are fine recrystallized plagioclase. The plagioclase show a texture called twinning. The fact indicates that the glass is devitrified in ATEM scale. No true glass was found in portions of ALH81005 we examined. Olivine and pyroxene crystals distribute as islands, showing poikilitic anorthosite-like texture. The size of the olivine crystal is about a few microns. Some pyroxenes show fine exsolution texture, indicating spinodal decomposition in the Ca-rich areas. The tweed-like texture turns into exsolution by coarsening of certain lamellae. This indicates rapid cooling within a surface regolith breccia. Some of the features observed in ALH81005 are similar to those of breccias observed by Christie et al. (8).

The compositional and textural variation of lithic clasts and pyroxene types in 60016 and lunar meteorites is larger than in all other lunar breccia types. This variation may be due to the intense impact gardening of the regolith materials. In order to locate the impact location of the lunar meteorites or to find all lunar meteorites are derived from the same impact or are pieces of a single fall, we have to study more lunar regolith breccias, employing the exsolution-inversion textures and the compositions of pyroxene as signature of the nonmare pristine rocks. Such approach has been successful in studying howardites and polymict eucrites (9). Our study presented here is a first step to do such investigation. Our experience with Apollo lunar samples has taught us that data obtained on different samples from a single stone are often not suitable for comparison, because most highland rocks are heterogeneous mixtures of fragments of older rocks. Discoveries of three lunar rocks may activate renewed interests in lunar regolith breccias, which have not been studied extensively in the last fifteen years.

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## DUST DEVILS ON MARS

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Large columns of dust have been discovered rising above plains on Mars. Between 1 and 6 kilometers in height and up to one kilometer in width, the storms are nevertheless such small features in images obtained by the NASA Viking orbiters that they have escaped notice until recently. The Viking orbiters photographed Mars between 1976 and 1980, and the thousands of pictures that were obtained are still being analyzed.

Mars is dry and dusty, and the storms are probably analogous to terrestrial dust devils, but their size indicates that they are more similar to tornadoes in intensity. They occur at locations where the soil has been strongly warmed by the sun, and where the surface is smooth and fine grained. These are the same conditions that favor dust devils on Earth. Warm gas from the lowest atmospheric layer converges and rises in a thin column, with intense swirl developing at the edge of the column. In desert regions on the Earth dust devils usually reach heights of only a few hundred meters and although they are interesting phenomena, the vortices are not of great importance.

On Mars the situation is different. In the absence of liquid water, wind erosion is a major geological force, and transport of dust and soil by wind is the major process that changes the face of the planet. The newly discovered storm systems may produce wind speeds in the same class with tornadoes, and can clearly lift large quantities of

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dust from the surface. Geologists have been puzzled by many long markings on the surface of Mars where layers of dust appear to have been scoured away, and it now seems likely that these markings are the tracks of dust vortices, much as the track of a tornado leaves a long narrow arc of destruction across the Earth.

Only a small fraction of the Viking images were obtained at sufficiently close range to reveal features like these, but the storms appear not to be rare in those that were taken near midday and at low latitudes, where the sun is high in the sky and surface heating is intense. In particular, there are vortices visible during four different days in the northern hemisphere summer. In one area a mosaic of images shows 97 vortices in a three day period. This represents a density of vortices of about one in each 900 square kilometers. Thus these vortices, or dust devils, may be important at some seasons in moving dust or starting other dust storms. The atmospheric conditions implied by the presence of dust devils will be useful in guiding further studies of the general characteristics of martian climate and weather.

Dust devil activity on Mars was first predicted in 1964 by J.A. Ryan (now at California State University, Fullerton). At that time it was thought that the global dust storms known to occur every few years on Mars might be caused by fields of small dust devils. It is now known from spacecraft observations that these huge storms are truly global phenomena, caused by planetary scale wind fields. Furthermore, the newly discovered vortices were observed in northern summer on Mars, whereas the global dust storms begin during southern summer.

ORIGIN OF MESOSIDERITES AS A NATURAL CONSEQUENCE OF PLANET FORMATION. John T. Wasson and Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA.

Of the three basic types of meteorites that fall to Earth (stone, iron and stony-iron), the stony-irons are rarest. There are two main groups of stony-iron meteorites: pallasites, which are mixtures of metallic iron and olivine, and mesosiderites, which are mixtures of metallic iron and basaltic silicates. Although there is general agreement that pallasites formed at the boundary between a silicate (olivine) mantle and a metallic core of a once-molten asteroid, it has proven much more difficult to reach agreement on the origin of mesosiderites.

Basalts are formed by partial (generally 5-10%) melting of mantle rocks followed by the squeezing ("extrusion") of the liquid out onto the surface of the planet, where it solidifies.

Because bodies with basaltic crusts are expected to have olivine-rich silicate mantles and metal-rich cores, models of mesosiderite origin calling for the basalt and metal to originate in the same body have been hard-pressed to explain the scarcity of olivine in these stony-iron meteorites.

Mesosiderite textures show these meteorites to be mixtures of metal grains and nuggets with millimeter-to-centimeter-size angular fragments of basaltic silicates. This "breccia" texture clearly indicates that mesosiderites formed on an asteroid surface that was subjected to intense meteorite bombardment. Some mesosiderites exhibit clear evidence of impact-melting.

Basalts like those that make up the silicate portions of the mesosiderites are common in the inner solar system. Mercury, Venus, Earth, Moon and Mars all have basalt exposed at their surfaces. The large asteroid Vesta is covered with basalt and certain groups of stone meteorites are made up of basalt and very little metallic iron. The meteoritic basalts are very old; they formed about 4.3 to 4.4 billion years ago. Plausibility arguments indicate that heat sources capable of melting asteroid-size bodies in such a brief period would have been nonselective; they would have melted all bodies of similar or larger size at that distance from the Sun. Within one particular radial distance from the Sun, it seems likely that almost all of the asteroid-size bodies were melted; we do not know this radial distance, but the presence of basalts on Vesta (orbital radius of 2.4 AU) suggests that it may have extended out past the orbit of Mars to about 2 AU from the Sun. The mesosiderites formed in this broad region where nearly every asteroid-size body melted.

We follow a common picture of planet formation that calls for bodies to gradually grow as a result of low-velocity collisions. According to this picture, asteroids (typical radius of

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100 km) are intermediate products of this process.

We suggest that the asteroid parent body of the mesosiderites also formed in the inner solar system, perhaps just within the orbit of Mars. At this location, the gravitational influences of Jupiter and Earth (the largest terrestrial planet) are relatively small and many of the asteroids remained in low-inclination, nearly circular orbits. However, as a result of close planetary encounters, some bodies that formed near Earth or Venus were gravitationally perturbed into non-circular orbits; a few such bodies passed through the mesosiderite region at high relative velocities, colliding with and destroying a few of the native asteroids. Olivine-rich silicate mantles shattered into small pieces, but the stronger metal cores remained as large fragments.

Much of the debris remained in circular orbits and accreted to (i.e., was collected by) the basaltic regoliths of intact native asteroids at low relative velocities, perhaps 1 km/s. The small pieces of the olivine mantles formed a more-or-less uniform diluent in the indigenous basalt; examination of mesosiderites and the closely related howardite meteorite regolith breccias shows them to contain about 2% of a foreign olivine component. The large core fragments that collided with the crust greatly enriched restricted regions of the surface in metal. These localized regions were the mesosiderite progenitors; they accounted for only about 1% of the surface area of the parent bodies.

Because mesosiderites are tough, durable objects, they preferentially survived the rigors of impact-ejection from their parent body, erosion by collisions with space debris, and ablation and fragmentation during passage through the Earth's atmosphere. These selection biases account for the enhancement (by a factor of 30) of mesosiderites among meteorite falls compared to the metal-poor basaltic howardites.