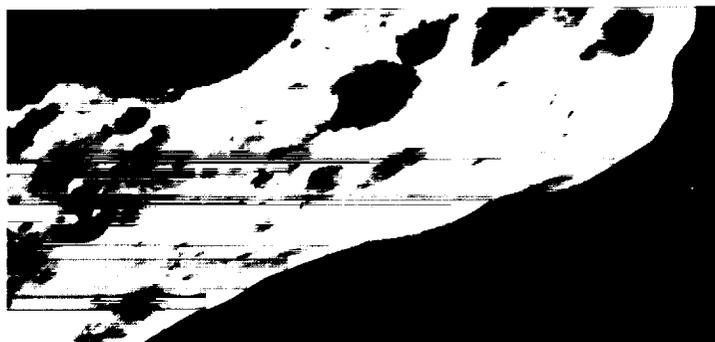


# Organic Material: V 9 3 - 1 8 5 5 5 Asteroids, Meteorites, and Planetary Satellites

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**I**nfrared telescopic observations in *in situ* spacecraft investigations over the last two decades have shown that many planetary satellites, asteroids, and comets have surfaces containing very dark material that is either neutral (black) or red in color. Awareness of the presence of this very dark material probably originated with the 1971 discovery of the very low geometric albedo (0.03) of asteroid 324 Bamberga, determined from its easily detectable thermal radiation. Further infrared observations showed that many other asteroids in the main belt have low geometric albedos, and in 1975 it was established that dark asteroids are very common, particularly in the outer parts of the main belt. That the Trojan asteroids and the outer satellites of Jupiter are similarly very dark was first shown by infrared observations in 1977.

  
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Most of the smallest planetary satellites, including the majority of the objects accompanying Mars, Jupiter, and Uranus, have surfaces of very low albedo, as revealed by spacecraft encounters and continued telescopic observations. The outer Jovian satellites and the two satellites of Mars are comparable in size and have low albedos and colors that are similar to the C-type (dark and neutral) asteroids. The small, inner satellites of Uranus discovered by Voyager are also low in albedo. The small, inner satellites of Saturn are an exception to the above examples because they lie in the range of geometric albedos from about 0.4 to 1.1. Phoebe, the outermost known satellite, has an albedo of 0.06 and therefore resembles the asteroids rather than the ice-covered satellites of the Saturnian system.

Saturn's large satellite, Iapetus, is an extraordinary object having a bimodal surface distribution of high and low albedo material. The hemisphere of Iapetus centered on the apex of its orbital motion has a very low albedo of 0.04 and is red, while the trailing hemisphere of the satellite has an albedo of about 0.5 and is composed of water ice.

Although comets are not the focus of this paper, the possible relationship of comets to asteroids, meteorites, and interplanetary dust (see below) requires that we discuss them briefly in the context of their dark-matter component. Evidence has been steadily accumulating that at least some, if not all, comet nuclei have surface deposits of low-albedo material. Telescopic observations of comet Halley on its approach to perihelion gave indications that its nucleus has a dark red surface of low albedo. The direct images of the nucleus of this comet by the Giotto and two Vega spacecraft unambiguously confirmed the pre-encounter deduction, showing that the nucleus has albedo 0.04-0.05.

Comet Halley contains high-molecular-weight organic molecules that have been detected both by direct sampling at the comet by the Vega and Giotto spacecraft and from ground-based telescopes. While the identification of the specific organics is difficult, the presence of aromatics, aliphatics, and amorphous heavy molecules can be reasonably concluded. Furthermore, the presence of these heavy organics, which often tend to be black, is entirely consistent with the low albedo of the comet

nucleus derived from direct observations. Indeed, the formation of a nonvolatile crust of low albedo from cometary ices appears to be an inescapable consequence of ion irradiation of the outer few meters of the nucleus.

Beyond the direct observations of the nucleus of comet Halley, the accumulating telescopic data on other comets are giving a similar picture of the widespread occurrence of dark nuclei. Many periodic comets have nuclear albedos of 0.10 or less, with the majority studied so far, less than 0.07.

Except for Iapetus, the objects noted so far have relatively uniform surface properties of color and albedo. There are several other planetary satellites, and probably asteroids, with surfaces that include some fraction of dark material. For example, the five large satellites of Uranus have reflectance spectra indicating the dominance of water ice on their surfaces, but their albedos are too low for water ice, ranging from Umbriel at about 0.17 to Ariel at about 0.39. The dark material mixed with the water ice of the Uranian satellites is a neutral color, but its albedo remains unknown.

Pluto has a nonuniform brightness distribution across its surface, with a wide, circumplanetary dark band of relatively low albedo at the equator. Models of Pluto's surface constrained by the rotational lightcurve and the secular change in brightness due to changing observing aspect predict large surface areas of lower and higher albedo, as well as two polar caps. Charon, the satellite of Pluto, has an albedo of 0.4 (compared to Pluto's albedo of 0.6, both in the blue spectral region). We return to these two objects below.

It appears that dark matter occurs throughout the outer solar system, particularly on small bodies, but also mixed with other surface components on larger ones. At the present time, we know only that this low-albedo material can be reddish in color (reflectance increasing at longer wavelengths) or neutral. This simplistic observation may well belie a tremendous diversity in molecular or mineral composition.

Cosmic material of low albedo that is available to us for study on Earth consists of meteorites of certain classes and interplanetary dust particles collected from the stratosphere, the Greenland ice sheets, and the sea floor. It is natural to consider the possible connections of these materials to the comets and the asteroids, as mechanisms for their delivery to the Earth have been established and can be readily understood. Interplanetary dust particles are discussed elsewhere in this volume, but here we discuss the carbonaceous meteorites in the context of their organic content.

## Carbonaceous Chondrites

Meteoritic organic matter occurs primarily in those meteorites termed carbonaceous chondrites that have the additional property that their chemical compositions are similar to that of the Sun. The two properties are related at least to the extent that preservation of organic molecules would have been aided by a history that led to minimal chemical fractionation. Nonetheless, it is important to note that even carbonaceous chondrites have not been immune to geochemical processing during their evolution and that the episodes of localized heating, impact brecciation, irradiation by solar flares and galactic cosmic rays, and aqueous mineralization recorded in them may well have altered their organic components and may even have been implicated in the origin of those components.

The molecular and isotopic composition of meteoritic organic matter has been the subject of numerous studies, but considerable work remains to be done, particularly by application of recently developed analytical techniques to issues that were studied at lower sensitivity and resolution in the 1960s and early 1970s. The principal objective of such studies is to discriminate between the different hypothetical origins that have been proposed for the organic matter. Variables used for that purpose have generally involved the molecular and isotopic distributions within specific classes of compounds, e.g., as a function of C number within homologous series. Patterns observed so far are difficult to fit within a single mode of synthesis and suggest instead multiple origins for the organic species now found in meteorites.

**T**he salient properties of meteoritic organic matter include the following:

By far the dominant organic fraction is an insoluble macromolecular component, resembling terrestrial kerogen, that consists of polycyclic aromatic moieties distributed in a three-dimensional network with short aliphatic bridging units and side chains (fig. 9-1).

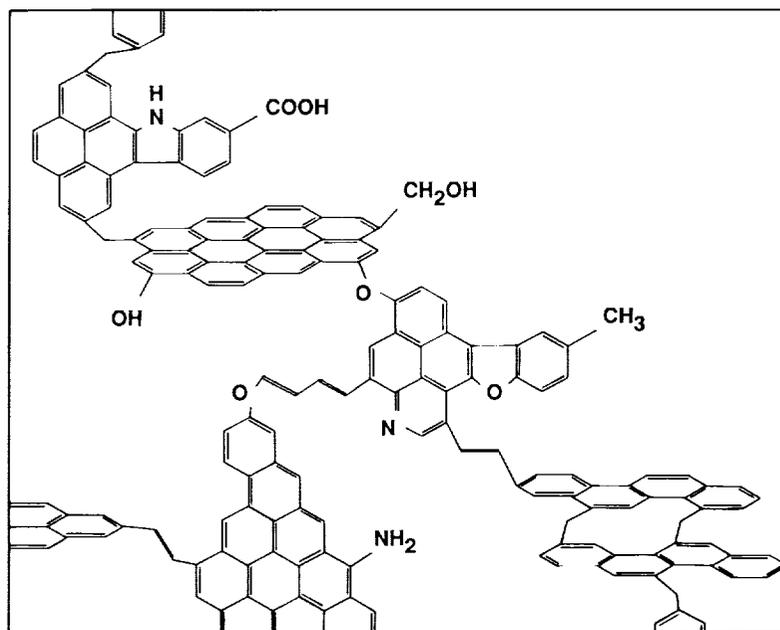


Figure 9-1. Schematic representation of the structure of kerogen-like material in carbonaceous chondrites. Note the three-dimensional array of aromatic moieties with aliphatic bridging units and side chains.

The soluble organic fraction contains many different classes of compounds, some of which, e.g., carboxylic and amino acids, reveal considerable, perhaps complete, structural diversity and a predominance of branched-chain molecules, whereas others, e.g., aliphatic hydrocarbons, do not.

**T**he stable isotopes of C, H, and N are not distributed uniformly throughout the organic matter but show variations, some of which are probably related to the mode

of formation of the organic molecules, whereas others probably reflect admixture of material from different sources. An example of the first kind is shown in figure 9-2, which shows the distribution of the C isotopes among the homologous series of alkanes and monocarboxylic acids: the systematic decrease in  $^{13}\text{C}/^{12}\text{C}$  with increasing C number clearly reflects a synthesis in which higher homologs were made from lower by progressive

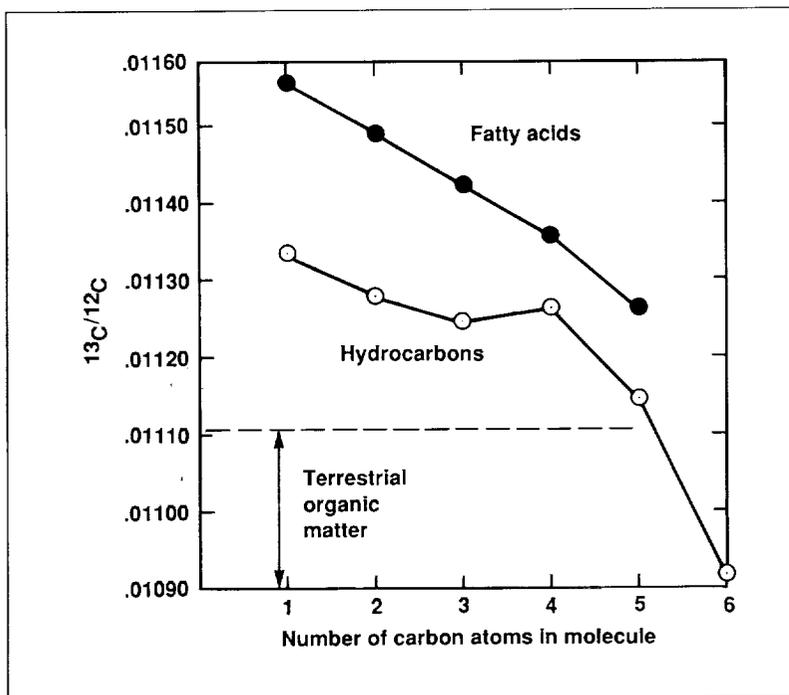


Figure 9-2. Distribution of carbon isotopes among the homologous series of alkanes and monocarboxylic acids in the organics of the Murchison meteorite. The systematic decrease in the isotope ratio with increasing C number reflects a synthesis in which higher homologs were made from lower by progressive addition of single C atoms.

addition of single C atoms. The effects of mixing discrete isotopic components are illustrated in figure 9-3, which shows C and H isotopic compositions of moieties identified within the kerogen-like material: the different components cannot be readily derived one from another by isotopic fractionation and are therefore believed to come from different sources.

**H**ydrogen in the kerogen-like fraction and in amino and carboxylic acids is considerably enriched in D relative to terrestrial H, and even more so relative to primordial solar-system H. These enrichments greatly exceed those that could be generated by known solar system processes and are therefore generally attributed to fractionation during ion-molecule reactions at very low temperatures in interstellar clouds (fig. 9-4).

The mode of synthesis is not the only interesting issue potentially addressable by the meteoritic record. The location and timing of that synthesis are also usefully, if not rigorously, constrained by the chondritic data. Thus, it now seems most likely that carbonaceous chondrites, like all other chondrites, are fragments broken off asteroids so that, given the apparently primordial zoning within the asteroid belt, a formation location for those meteorites inside the orbit of Jupiter is indicated. An origin for their organic matter in the inner solar system is thereby suggested, but the observed D enrichment mentioned above seems to require operation of a presolar mechanism, i.e., isotopic fractionation in interstellar molecular clouds. It is not known whether the interstellar H survived entry into the primordial solar system within the organic molecules or in some other form from which it was subsequently recycled into locally produced organic matter. For example, meteoritic amino acids are

## Asteroids

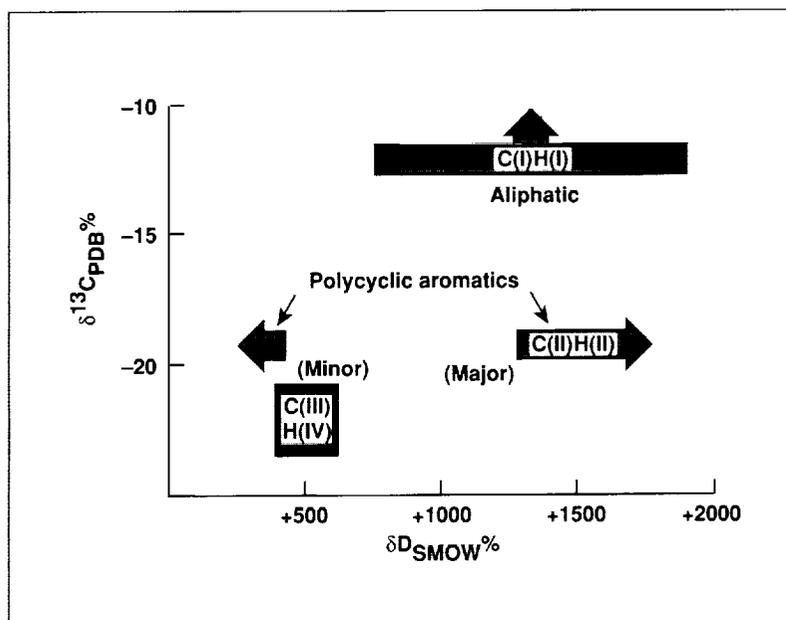


Figure 9-3. Isotopic composition of different moieties present within kerogen-like material in the Murchison carbonaceous meteorite. The values of the  $^{13}\text{C}/^{12}\text{C}$  and  $\text{D}/\text{H}$  ratios are expressed in the delta notation as variations, in parts per thousand, relative to terrestrial standards: Pee Dee Belemnite in the case of  $\text{C}$ , Standard Mean Ocean Water in the case of  $\text{H}$ .

commonly believed to have been synthesized by the Strecker cyanohydrin reaction during aqueous activity in asteroid surface regions, and the precursor molecules for that synthesis have all been observed in interstellar clouds and, in the early solar system, could plausibly have had such an origin.

Radiometric dating places the epoch of aqueous alteration and impact-induced turnover on the parent asteroids within, at most, a few tens of Myr after solid formation in

the solar nebula, and since it is most unlikely that the organic matter was introduced after that epoch, very early organic synthesis is indicated. This is obviously consistent with either interstellar, nebular, or planetesimal production of the organic matter.

The albedos of the asteroids have been determined largely from infrared radiometric observations at 10 and 20  $\mu\text{m}$  from Earth-based telescopes, and at 25  $\mu\text{m}$  from the Infrared Astronomical Satellite (IRAS). On the basis of a modest sample of about 180 asteroids, ground-based radiometry established a bimodal distribution of asteroid geometric albedos, with peaks in the distribution at 0.04 and 0.15. The IRAS data base has yielded reliable albedos for over 1800 asteroids; in the sample of objects of diameter  $>40$  km, both the bimodality and the median values of the two peaks are clearly confirmed, but in the sample with diameter  $<40$  km, the distribution of albedos is more nearly Maxwellian with the peak at 0.05 (fig. 9-5).

Telescopic observations have been used to classify the low-albedo asteroids into three basic categories according to their colors in the photovisual spectral region (0.3-1.05  $\mu\text{m}$ ). In this classification scheme, the C asteroids are usually neutral over most of the spectral region, with a downturn in reflectance toward the violet end of the spectrum. In the near-infrared (1-2.5  $\mu\text{m}$ ) the C-types are neutral to slightly reddish (a small upward slope in reflectance toward longer wavelengths). No discrete spectral absorp-

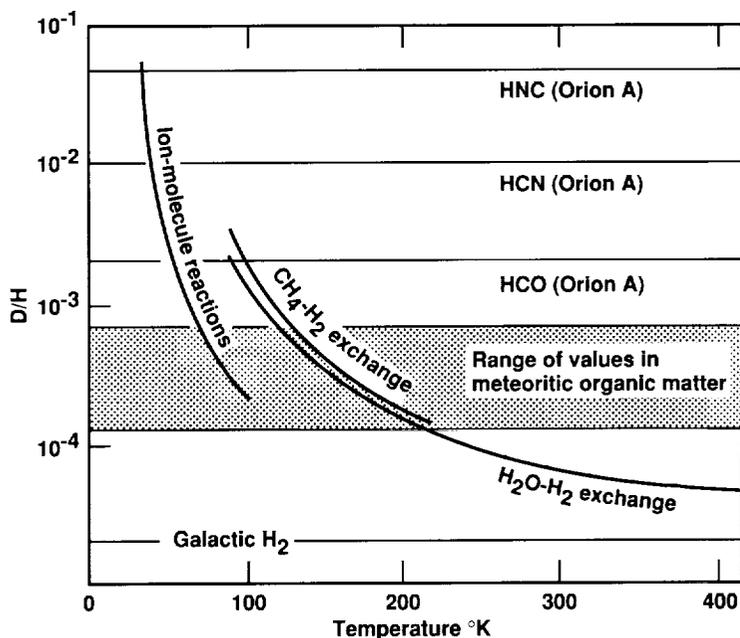
tion bands are seen in the C-type spectra in this region, but farther into the infrared some of the asteroids in this category have a distinct absorption band at 3  $\mu\text{m}$  attributed to  $\text{H}_2\text{O}$  and OH in hydrated silicates in the regolith. Some of the C-types have no bound water, and there appears to be considerable variability among them, with several degrees of hydration represented. The pres-

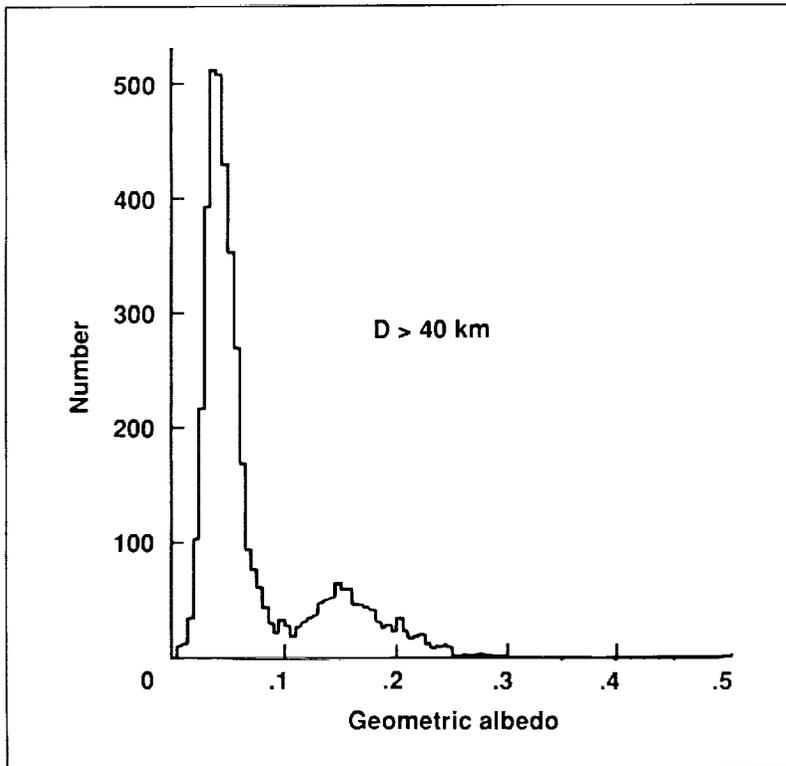
ence of the 3- $\mu\text{m}$  hydrated silicate band appears correlated with the strength of the violet downturn in reflectance, such that the "wet" C-types fit into a subclass called G.

The D-type asteroids are distinguished from the C-types by their significantly redder slopes both in the photovisual and near-infrared regions; the D-types include the reddest known asteroids. Hydrated silicates have not yet been found in asteroids of this class, but the D-types are difficult to observe because of their low albedos and their tendency to lie in the outer reaches of the asteroid system.

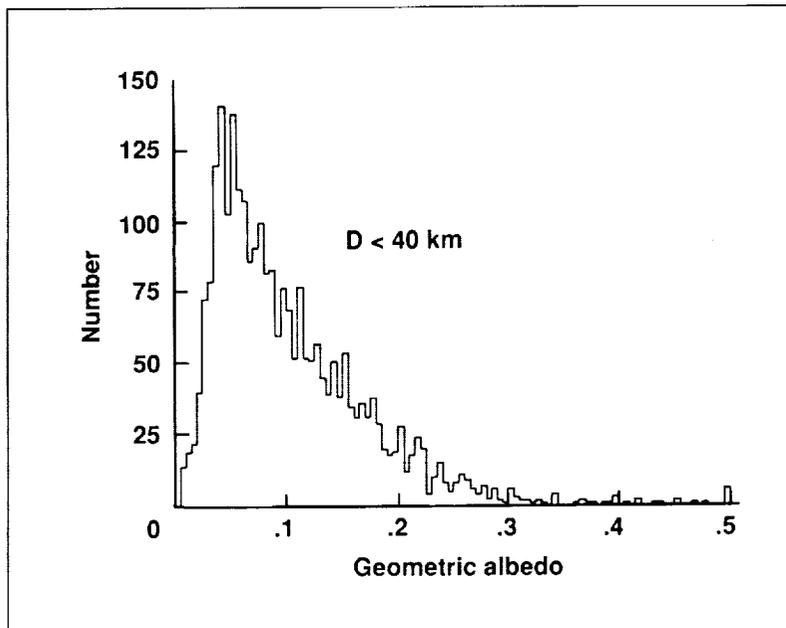
The P-type asteroids are similarly of low albedo, and may represent a transition between the C and D types. They have similar absorption in the UV and featureless red-sloping reflectance throughout the near-infrared. There is currently no information on the presence of hydrated silicates; as in the case of the Ds, they are very faint and difficult to observe.

Figure 9-4. Deuterium fractionation, relative to galactic  $\text{H}_2$ , caused by exchange reactions and ion-molecule reactions, compared with D/H values observed in meteoritic components and in the Orion interstellar cloud.





(a)



(b)

Figure 9-5. (a) Histogram showing the distribution of the number of asteroids of diameter  $>40$  km with geometric albedo. These data were derived from measurements of the thermal radiation of the asteroids with the Infrared Astronomical Satellite (IRAS). The distribution is bimodal, with the greatest number at about 0.05. (b) The same plot as in (a), but for asteroids of diameter  $<40$  km. The bimodality of the distribution is gone, but the peak still lies at about 0.05. This and figure 9-5a are adapted from E. F. Tedesco et al., "IRAS Observations of Asteroids," in *Comets to Cosmology*, Andrew Lawrence, ed., Springer-Verlag, 1988.

The distribution of the asteroid types with distance from the Sun has proved to be of some significance, once bias-corrected samples could be studied. A number of studies of the heliocentric distribution of various types that culminated in the appearance of a clear pattern are shown in figure 9-6. The middle of the asteroid main belt is at about 2.7 AU; inside this distance most of the asteroids are of the high-albedo classes, particularly the S-types (median albedo 0.15). Beyond 2.7 AU, there is a

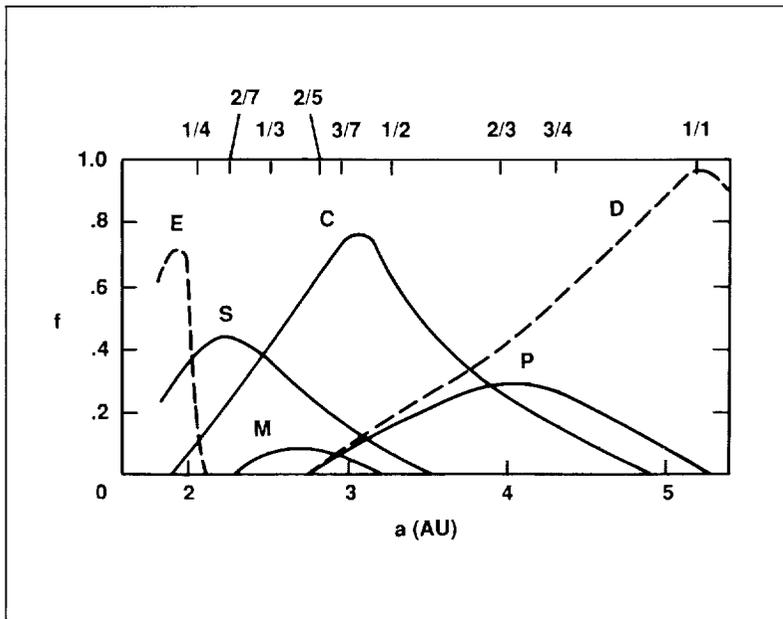
dramatic increase in the number of low-albedo objects; the C-types dominate the outer half of the main belt, and as they decline beyond 3 AU, the redder objects of the P and D classes increase toward their peak in the Hilda group at 4.0 AU. Color variations among the reddish types have been noted.

Two clear trends have emerged from this work. First, the low-albedo asteroids dominate the region beyond about 3 AU, and second,

there is a strong trend toward increased redness of the spectral reflectances with increasing distance from the Sun.

Various investigators have suggested that the dominance of the low-albedo bodies and the increased redness in the outer portions of the asteroid system are results of a temperature gradient in the solar nebula that is preserved in the present distribution of the asteroids that formed at different distances from the Sun. The appearance of dark bodies at about 3 AU could represent the onset of formation in the solar nebula of carbon-rich minerals and macromolecular carbon compounds (organics) that color the materials of which the asteroids are composed. Alternatively, 3 AU could mark the inner limit in the solar nebula at which such organic compounds formed elsewhere could survive.

Figure 9-6. The distribution of a bias-corrected sample of asteroids by taxonomic type with distance from the Sun. This figure shows that the C-type objects peak in their distribution at about 3 AU, while the peaks for the P- and D-types are at larger distances. Types E, S, and M are higher-albedo objects not addressed in this paper.  $f$  is the estimated fraction of asteroids at a given distance in each class.



The possible presence of complex organics in the outer solar system bodies in the form of kerogen-like material, which compose the bulk of the organic matter in the carbonaceous chondrites (up to 70% in the CI meteorites such as Orgueil) was noted in 1980. Kerogen itself is a mixture of complex molecules which, in the case of terrestrial petroleum deposits, consists of a waxy substance that adheres to carbonate grains. At temperatures of about 750 K, the kerogen is altered to liquid petroleum. In the meteorites, it is intermixed with clay mineral grains and constitutes a very opaque, black component. Kerogen, or kerogen-like material, therefore, appears to be a plausible cause of the very low reflectivities of various solar-system objects, in part because few other natural substances are so black, and in part because the widespread occurrence of complex organic molecules is an acceptable working hypothesis, given its presence in interstellar space and the most primitive meteorites, and the relative ease of its genesis in plausible planetary environments.

One serious drawback to the kerogen hypothesis is that, by itself, kerogen, as prepared, for example, from coal tar has the wrong colors, although it is extremely low in albedo. For example, the photovisual reflectance of the very red D-type asteroids could be simulated by a synthetic mixture of clays and kerogens, the clays giving the red color and the kerogens the low albedo. The Trojan asteroid 624 Hektor was matched by a mixture of 85% montmorillonite clay and about 8-15% kerogen, plus some magnetite or carbon black. In part because the term kerogen carries a connotation of origin in terrestrial petroleum deposits, it is perhaps advantageous to substitute the term "macromolecular carbon" in the context of meteorite and related studies.

In laboratory reflectance spectra of carbonaceous chondrites the presence of bound water is revealed by a broad absorption band at 3  $\mu\text{m}$ . On the long-wavelength portion of the featureless slope of this band, at 3.4  $\mu\text{m}$ , there is superimposed a weak band complex assigned to the stretching mode in C-H in the organic compounds in the meteorite.

The 3.4- $\mu\text{m}$  absorption band of C-H was sought in the reflectance spectra of asteroids that were selected on the basis of their bound-water band and their low albedo (i.e., the G-types). Tentative identification of the C-H band was made in asteroid 130 Elektra, based on the data shown in figure 9-7. In the laboratory spectra of carbonaceous meteorites, the C-H band is weak because of the high opacity of the finely granulated sample. This is true for pulverized samples of the bulk meteorite as well as for the concentrated insoluble organic residue remaining after removal of the other components. Similarly, the band is expected to be very weak in the diffuse reflectance spectra of an asteroid, making its detection quite difficult. The intrinsic weakness of the band, plus the inherent difficulties in registering the spectrum of a weak astronomical source in the 3- $\mu\text{m}$  region, account for the uncertainties in the detection of C-H in 130 Elektra.

The importance of establishing the presence of organic molecules in the regoliths of asteroids is multifold. It is certainly connected with the general problem of the origin of specific kinds of meteorites, but it also bears on the chemistry of the solar nebula on the outer edge of the zone

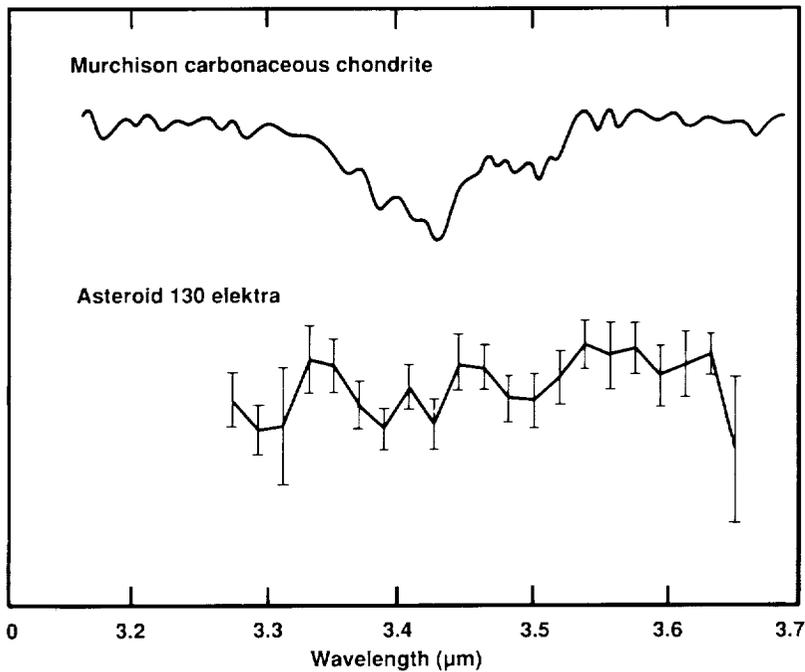


Figure 9-7. The reflectance spectrum of the G-type asteroid 130 Elektra in the region of the 3.4- $\mu\text{m}$  C-H stretch band, with a laboratory spectrum of the Murchison carbonaceous meteorite for comparison. Effects of continuum slope due to sample and asteroid temperature as well as the strong band of bound water in each material have been removed. The correlation of the absorption features in the asteroid spectrum with the main feature in Murchison is taken as preliminary evidence for the presence of C-H on an asteroid. Adapted from D. P. Cruikshank and R. H. Brown, *Science*, vol. 238, 1987, p. 183.

of terrestrial-planet formation. In the broader sense, the question of the origin of macromolecular carbon molecules in the interstellar medium and incorporation into the solar nebula, versus the genesis of this material near the forming Sun is of great interest. The confirmed

detection of organic molecular material on asteroids will be only the first step, to be followed by the identification of the species and the study of the space distribution of organic-bearing asteroids.

## Low-Albedo Planetary Satellites

The odyssey of the Voyager spacecraft through the outer solar system has resulted in the discovery of a number of previously unknown planetary satellites, typically small and close to their parent planets. Together with low-albedo satellites known from telescopic discoveries, there are some 24 of these bodies of a few tens of kilometers in dimension. The impending encounter of Voyager 2 with the Neptune system carries the potential for the discovery of more of these small bodies.

The similarity in size, low albedo, and density (where known) of some of these satellites to dark asteroids has invited comparison and speculation on commonality of origin. The two satellites of Mars are often regarded as asteroidal in nature, though skepticism has been expressed on the issue of dynamical capture into their present circular orbits. The outer Jovian satellites are often compared with the Trojan asteroids (which share

Jupiter's orbit at the Lagrangian points). Dynamical considerations of the origin of planetary satellites show that asteroids or comets might be captured by planets under certain circumstances. Indeed, the only known way to acquire such retrograde satellites as Saturn's Phoebe and four of the outer satellites of Jupiter appears to be through dynamical capture. Thus, at least some of the small, dark planetary satellites may have originated in a way similar to the asteroids, though the details seem to be unique for each body.

In discussing the possibility of organic materials as the darkening component of the surfaces of asteroids, and particularly planetary satellites, it is worth bearing in mind the fairly low albedo of our own Moon. The overall geometric albedo of the Moon is 0.12, but that of the darkest lunar maria is about 0.07. Samples returned from the Moon attest to the fact that the regolith on the lunar maria has no organic component, and the low albedo is attributed to the dark minerals and texture of the regolith. It is very difficult to make natural surfaces with an albedo half that of the lunar maria without resorting to some other component, and macromolecular carbon compounds are a plausible choice.

The physical evidence for a possible macromolecular carbon component of planetary satellites consists of broad-band photometric measurements of the colors of these objects (0.3-3.5  $\mu\text{m}$ ), and in some cases actual spectra over limited wavelength intervals. The limiting factor in obtaining spectral data is the faintness of small planetary satellites, even when observed with the largest telescopes and most sensitive spectrometers. Spacecraft sent to the planets with small dark satellites have not carried spectrometers suitable for studies of their small dark satellites, with the result that only color data (from space and from the Earth) and imperfect spectra (from the Earth) exist. An added inconvenience is the absence of strong diagnostic spectral features in accessible spectral regions, owing partly to the nature of organic molecules themselves and to the intrinsic weakness of most spectral features of low-albedo solids seen in diffuse reflectance. The most promising spectral band is that of CH at 3.4  $\mu\text{m}$  seen in some carbonaceous chondrites, and possibly in asteroid 130 Elektra, as noted above. This band has not been observed on any planetary

satellite (except Titan), though attempts have been made to detect it on Iapetus, as we discuss below.

The striking bimodal distribution of a very low-albedo surface unit and an expanse of water ice or frost on Saturn's satellite Iapetus has commanded special attention in the search for organic material on bodies in the outer solar system. Data from Voyagers 1 and 2 confirmed the pattern of distribution of the dark material that had been derived from telescopic studies showing that the dark covering on the leading hemisphere of the satellite is centered on the apex of the orbital motion. Such a geometry argues strongly for a method of emplacement of the dark material that depends in some way on the influx of material from space, though the details are unclear.

There are two main ideas concerning the origin and composition of the dark material on Iapetus. In one, dark material is emplaced by deposition from a source outside the orbit of Iapetus, or it results from a process of impact concentration to the surface of dark material already present and distributed in the upper layers of the satellite. In another model, black macromolecular carbon is formed *in situ* from methane clathrate by solar UV bombardment. The former model appears to be favored in view of the telescopic data and the spacecraft images showing the manner in which the surface deposits relate to topography on Iapetus.

The dark hemisphere of Iapetus, which is seen from the Earth face-on for an interval of about 48 hours once during each 80-day orbit of the satellite around Saturn, is sufficiently bright to permit low-resolution spectrophotometric observations in the photovisual and near-infrared spectral regions. Such data have been compared with laboratory samples of candidate materials, with concentration on materials of very low albedo and red color.

It is important to remember that very small quantities of dark, opaque powder can have a strong effect on the albedo of the material in which it is incorporated. For the case of the dark hemisphere of Iapetus, for example, it has been demonstrated that the abundance of water ice on that hemisphere could range from less than a few weight percent to as much as 95 weight percent. Finely divided dark material, such as charcoal, lampblack, magnetite, or macromolecular carbon, is extremely effective in reducing the overall albedo of the mixture and in quenching the strong ice absorption bands normally seen in the near infrared.

**W**hen fully corrected for the effects of the minor contamination of the dark hemisphere with relatively pure water frost in the polar regions, the reflectance of Iapetus between 0.3 and 2.5  $\mu\text{m}$  is relatively smooth and strongly upward sloping toward longer wavelengths (that is, it is red), as seen in figure 9-8. Comparisons were made using this spectrum of Iapetus and laboratory data for the organic component of the Murchison CM carbonaceous chondrite, and an insoluble coal-tar kerogen. Neither the Murchison organic extract nor the coal-

tar kerogen had the correct spectral reflectance, but mixtures of the kerogen with clay were produced and a good match in both spectral reflectance and albedo was achieved. An organic-clay mixture with about 10 weight percent kerogen produced the best match, as shown in figure 9-8.

The 10 newly discovered small satellites of Uranus all orbit very close to the planet. Only one, Puck, was imaged at sufficient resolution by Voyager 2 to show surface relief and its slightly non-spherical shape. The albedos are all very low, in the range of 0.04-0.06, and comparison is often made with the particles in the Uranian rings, which are also quite black. Furthermore, the ices of the five major satellites all appear to be contaminated to some degree with neutral material of low albedo which may have the same origin. Whether or not this material has any relationship to macromolecular carbon

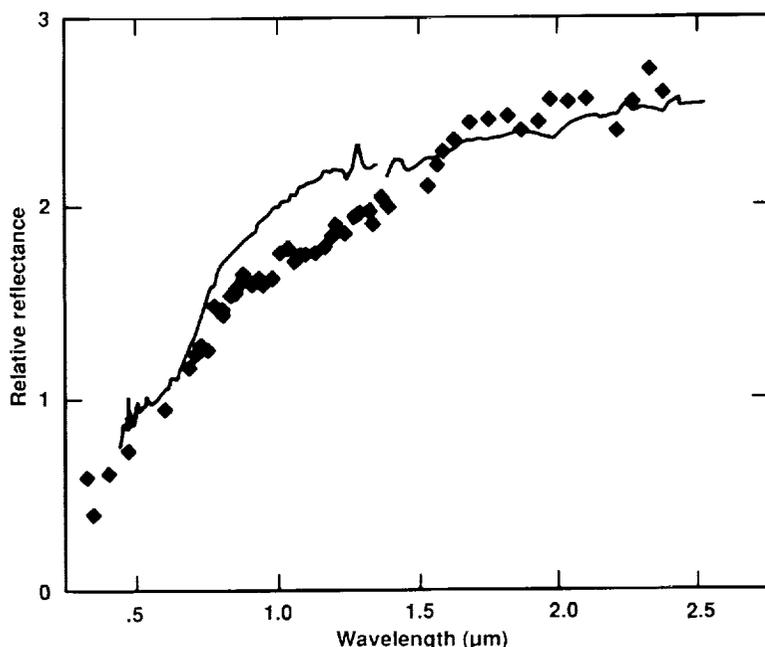


Figure 9-8. Spectral reflectance of the low-albedo hemisphere of Saturn's satellite Iapetus (data points) in comparison with the reflectance of a laboratory sample of 90% clay plus 10% organics (line). The general shapes and absolute values of the spectra are very similar over this broad wavelength range. From J. F. Bell et al., *Icarus*, vol. 61, 1985, p. 192.

cannot be established at this time, but it has been shown that irradiation of surface ices by the ion and electron fluxes observed by Voyager at Uranus can darken the surfaces if those ices contain some carbon. While the presence of water ice on the larger Uranian satellites is well established, the telescopic search for other substances, such as CH<sub>4</sub>, NH<sub>3</sub>, CO, and CO<sub>2</sub> has so far only given a faint hint of NH<sub>3</sub>.

## Pluto, Charon, and Triton

The low temperatures at the surfaces of the outermost planets and satellites permit methane and some other simple hydrocarbons to exist as solids, though the vapor pressures are sufficiently high that a certain mobility (sublimation and recondensation) is expected in seasonal cycles. Methane has been found on Pluto and Triton, and there is

strong evidence for condensed nitrogen on Triton. Water ice has been found on Pluto's satellite Charon, which has led to some early models of the escape of original methane from the satellite.

While neither solid methane nor condensed nitrogen (solid or liquid) are quite neutral in the photovisual region of the spectrum (0.3-1.0 μm), both Pluto and Triton are notable for their yellow-red colors. Pluto's surface is clearly non-uniform in albedo and color distribution, with a concentration of relatively darker material at the equator and high-albedo deposits at the poles. There is some suggestion of surface variegation on Triton, but the issue is confused by an apparent change in both the spectrum and the photometric lightcurve that occurred sometime in the early 1980s.

# Laboratory Studies

Numerous laboratory studies in the last few years are pertinent to the outstanding questions of the nature and origin of the very dark material on surfaces of some solar system bodies. The experimental work falls into two general categories: (a) spectroscopic and photometric studies of natural materials in various mixtures, including extracts from meteorites, and (b) similar observations of synthetic materials produced or altered through the effects of irradiation by ions, protons, electrons, ultraviolet, or gamma rays.

Radiation-processed ices and organic materials have been studied in several laboratories. Organic residues from carbon-containing gases or ices have been produced by electrical discharges, UV radiation, high-energy ions, and fast protons. Some preliminary planet-related experiments with gamma-irradiated mixtures of nitrogen and methane have also been done in the laboratory. In addition, direct studies of meteoritic organics in the context of the interstellar and planetary occurrence of this material have moved steadily forward.

Ices of planetary significance ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{NH}_3$ , etc.) all show diagnostic spectral features in diffuse reflectance, and a number of these solids have been identified on cold planetary bodies. Similarly, hydrous clays and igneous rock-forming minerals of planetary significance (pyroxene, plagioclase, orthoclase, and olvine) are identified on planets, asteroids and satellites through their spectral absorption features. The laboratory work has stressed spectral regions where actual astronomical data exist or can be obtained within the constraints of flux level and transparency of the Earth's atmosphere. Extension of the laboratory data into spectral regions from which spacecraft data will eventually come has only begun.

New work is in progress on combinations of ices and minerals, which must occur because the overall albedos of some icy bodies are too low and the colors are incorrect for pure ices. Laboratory work is being undertaken in support of the computation of synthetic spectra of pure minerals and ices and, most significantly, combinations of these materials in a range of grain sizes and surface textures, through knowledge of the theory of scattering from planetary surfaces and detailed knowledge of the

optical properties of the candidate materials. Eventually, this computational technique can be extended to mixtures of organic solids with ices of planetary interest.

Work on organic compounds with application to planetary problems is being undertaken in the context of cometary nuclei and solids in the interstellar medium. Coloration and darkening of methane clathrate and other ices has been produced by charged-particle irradiation. Yellow and brown organic products are generated when otherwise white ices of various combinations of water, methane, and ammonia are irradiated for times that are relatively short in terms of equivalent exposures in space. Similar experiments have been conducted with the production of non-volatile colored organic material from irradiation of methane ice. UV irradiation of ices containing methane and other simple hydrocarbons can produce more complex molecules, in particular a variety of polycyclic aromatic hydrocarbons, which show spectral features giving a close match to infrared bands in the interstellar medium and in some interplanetary dust particles.

In some cases these experiments produce very low-albedo material that is a plausible constituent of the dark planetary surfaces and meteorites discussed in this review, and in other cases, colored material of possible relevance to the yellow surfaces of Pluto and Triton are formed. The relative ease with which complex organics are produced from the simple raw materials found in many places in the outer solar system virtually ensures a significant role for them in the surface chemistry of the comets, asteroids, planetary satellites, and some planets. The current production of stable and complex hydrocarbons in the atmospheres of the outer planets has been appreciated for quite some time.

## Summary

Low-albedo bodies in the solar system appear to come in a range of colors, with Iapetus being very red and the outer satellites of Jupiter being nearly neutral (nearly flat reflectance curves). This statement also applies to the asteroids in the outer parts of the main belt and in the Trojan groupings, and it is now accepted that the surfaces of many comet nuclei are extremely low in albedo. Macromolecular carbon, which is found in meteorites and interplanetary dust particles, is a plausible low-albedo constituent of these dark asteroid, comet, and satellite surfaces; indeed, the presence of organic matter in cometary dust has been established.

Insofar as the asteroids are the source bodies of the carbonaceous meteorites, the presence of organic material on at least some classes of asteroids is a certainty. Telescopic searches for the CH spectral signature strongly suggest its presence on dark, hydrous asteroids, but confirmation and further exploration are

needed. More information is needed on the relationship between carbonaceous chondrites and specific asteroids or classes of asteroids. Major questions remain about the origin of the meteoritic organic matter, particularly concerning the role played by presolar, interstellar processes. This issue will be greatly clarified by detailed analysis of the organic population of comet nuclei, in which interstellar molecules should be preserved. In that connection, the Comet Rendezvous Asteroid Flyby (CRAF) and Comet Nucleus Sample Return Missions will be of prime importance.

Solid organic matter is presently being synthesized in the atmospheres of the methane-bearing planets and satellites of the outer solar system, and probably on the solid surfaces of Pluto and Triton. Photochemical smog is continuously produced in the atmospheres of Titan and the giant planets, and the presence of methane frost or ice on the yellow-colored surfaces of Pluto and Triton virtually ensure the alteration to more complex organic solids by the action of UV and the galactic cosmic ray flux.

More generally, we wish to know which chemical processes have been effective at synthesizing organic molecules from simple inorganic gases, and what factors have controlled the extent of chemical, pre-biotic evolution on different solar system bodies. For example, chemical evolution led to the emergence of life on Earth but not, apparently, on the carbonaceous chondrite parent asteroids. Were some components of the "primordial soup," present on Earth, missing on the asteroids, and if so, which?

## Additional Reading

The text and references for this article were up to date at the time of writing in 1988. Many additional papers on related topics have been published since that time; references to two of them are cited here.

Anders, E.: Organic Matter in Meteorites and Comets: Possible Origins. *Space Science Reviews*, vol. 56, 1991, p. 157.

Cruikshank, D. P.; Allamandola, L. J.; Hartmann, W. K.; Tholen, D. J.; Brown, R. H.; Matthews, C. N.; and Bell, J. F.: Solid C≡N Bearing Material on Outer Solar System Bodies. *Icarus*, vol. 94, 1991, p. 345.

### *Other Reading*

Allamandola, L. J.; Sandford, S. A.; and Wopenka, B.: Interstellar Polycyclic Aromatic Hydrocarbons and Carbon in Interplanetary Dust Particles and Meteorites. *Science*, vol. 237, 1987, p. 56.

Clark, R. N.; Fanale, F. P.; and Gaffey, M. J.: Surface Composition of Natural Satellites. In *Satellites*, J. A. Burns and M. S. Matthews, eds., University of Arizona Press, Tucson, 1986, p. 437.

Cruikshank, D. P.: Dark Matter in the Solar System. *Adv. Space Res.*, vol. 7, 1987, p. 109.

Cruikshank, D. P.; and Brown, R. H.: Satellites of Uranus and Neptune, and the Pluto-Charon System. In *Satellites*, J. A. Burns and M. S. Matthews, eds., University of Arizona Press, Tucson, 1986, p. 836.

Cruikshank, D. P.; and Brown, R. H.: Organic Matter on Asteroid 130 Elektra. *Science*, vol. 238, 1987, p. 183.

Hartmann, W. K.; Tholen, D. J.; and Cruikshank, D. P.: The Relationship of Active Comets, "Extinct" Comets, and Dark Asteroids. *Icarus*, vol. 69, 1987, p. 33.

Hayatsu, R.; and Anders, E.: Organic Compounds in Meteorites and Their Origins. *Topics in Current Chemistry*, vol. 99, 1981, p. 1.

Kerridge, J. F.; and Matthews, M. S., eds.: *Meteorites and the Early Solar System*. University of Arizona Press, Tucson, 1988.

Lewis, R. S.; and Anders, E.: Interstellar Matter in Meteorites. *Scientific American*, vol. 249, p. 66.

Thompson, W. R.; Murray, B. G. J. P. T.; Khare, B. N.; and Sagan, C.: Coloration and Darkening of Methane Clathrate and Other Ices by Charged Particle Irradiation: Applications to the Outer Solar System. *J. Geophys. Res.*, vol. 92, 1987, p. 933.



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