Dark Material on Planetary Satellites and Rings

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General

Material of low albedo covers the surfaces, and in some cases *constitutes* the surfaces, of many planetary satellites. The low mean densities and water ice absorption bands detected in the spectra of some of these bodies show that they are fundamentally icy, but other bodies contain substantial fractions of rocky material. If we define three arbitrary albedo categories ranging from very low to very high, we find that there are many examples in each group. Table I, which is not intended to be exhaustive, illustrates this point.

Table I.

	Geometric Albedo	
0.02 – 0.2	**0.2 – 0.5**	**0.5 – 1.0+**
The Moon	Ganymede	Europa
Phobos/Deimos	Callisto	Enceladus
Himalia	Hyperion	Mimas
Elara	Miranda	Tethys
Phoebe	Ariel	Dione
Nereid	Titania	Rhea
Some small satellites of Jupiter, Uranus, and Neptune	Oberon	Triton
Rings of Jupiter, Uranus, and Neptune	Charon	Rings of Saturn
Leading side	⇐⇐ Iapetus ⇒⇒	Trailing side

Few generalizations can be made from Table I, but the cratering records on planetary satellites suggest that older surfaces have lower albedos than young surfaces (which may have been covered recently with erupted materials).

Dark material of some sort seems to be present on all planetary satellites, but to greatly varying degrees. Some are completely covered with a uniform layer, while others show a patchy distribution and only a partial covering. Other satellites have very high albedos throughout most of their spectrum, except in the ultraviolet wavelengths, indicating the presence of some quantity of strongly UV absorbing material mixed with their otherwise high-albedo surface material (H_2O ice, except in the case of Io). Apart from the Earth's Moon, there seem to be threads of similarity among satellites that are colored and darkened to various degrees. It is important to determine whether or not the dark material on these other satellites has a common composition and origin, or if it comes from a variety of sources through different chemical and/or dynamical pathways.

Many planetary satellites have unique properties or special interactions with their environment. Io's volcanism, Titan's dense atmosphere, and Triton's atmospheric exchange with surface volatiles are examples. Saturn's satellite Iapetus is also unique in that its leading hemisphere (in the direction of its orbital motion) is coated with very low-albedo material, while the trailing hemisphere is nearly pure H_2O ice of high albedo.

We approach the question of the identity of the dark material by first noting the two basic types of known natural materials of very low reflectivity. The first type includes shocked meteorites, meteoritic impact melts, various terrestrial minerals, and the carbon-rich rocky materials such as carbonaceous meteorites (including urelites). The second type includes the solid (and mostly refractory) organic materials, such as kerogen and solid oil bitumens, the organic residues from carbonaceous meteorites, hydrogen cyanide polymer, and the suite of synthetic organics produced by energy deposition in mixtures of simple gases and ices containing C, H, and N (the tholins). Other materials, notably mafic (ferromagnesian-rich, dark-colored minerals) volcanic lavas, cover the Moon and Mercury, and parts of Venus and Mars (and perhaps Io), imparting low albedo. In fact, mafic lavas are the *only* dark materials positively and unambiguously identified on a planetary surface.

Small Satellites

The giant planets each have several small satellites with dimensions less than ~100 km. Voyager discovered many of these objects in orbits close to each planet, but telescopic observations have revealed small bodies in more distant orbits. Each of the four giant planets has one or more "irregular satellites" in inclined (sometimes retrograde), elliptical orbits that suggest that they were captured from some unknown reservoir of such bodies.

The small, inner satellites of Jupiter have low albedos in the range 0.03 – 0.1, while the small inner satellites of Saturn have much brighter surfaces with albedos 0.5 – 0.9 (Thomas et al. 1986). The inner satellites of Uranus and Neptune are very black, with albedos of order 0.05 - 0.07 (Thomas et al. 1989, 1995). The small, dark satellites of the planets are similar in photometric properties to the low albedo asteroids, although specific exceptions exist. These small, dark objects are unlikely to be covered with mafic volcanic lavas, and the cause of their low albedo is more likely related to the presence of carbonaceous materials, at least on their surfaces, but perhaps throughout their bulk makeup. The small satellites of Saturn appear to be fundamentally different because of their high albedos and very low mean densities (0.27 – 0.65 g/cm^3); indeed the larger Saturn satellites (excluding Titan) are distinct among giant planet satellites because of their low mean densities (1.0 – 1.49 g/cm^3). Their high albedos may be an indication of their youth.

The distant, irregular satellites of the giant planets that have been studied have very low albedos. Color studies of the outer Jovian satellites by Luu (1991) show they are diverse, but have close similarities to low-albedo asteroids in the outer main belt and the Trojan populations, specifically the C and D classes. In the absence of more specific information, it is reasonable to assume that whatever causes C and D asteroids (and their various subtypes) to be black or red-black, is also responsible for the albedos and colors of the outer satellites of Jupiter.

Saturn's outermost satellite, Phoebe, has an average albedo of 0.08, but some regions are a bit darker and some slightly brighter (Simonelli et al. 1999). Overall, Phoebe has photometric properties similar to those of a C-class asteroid. Brown (1998) and Owen et al. (1999) have found weak water ice absorption bands in the near-IR spectrum of Phoebe. Likewise, Neptune's outermost satellite Nereid has a low albedo, but weak H_2O ice bands are detected in its spectrum (M. E. Brown et al. 1998, R. H. Brown et al. 1999).

It therefore appears that in sufficiently cold environments, objects with spectral similarities to C- and D-class asteroids can contain and retain water ice. In the asteroid zone, however, water ice is not stable in the long term, and if those objects ever contained water ice, it has been lost from the surface layers. Some low-albedo asteroids show spectral evidence for the presence of hydrous silicates in their surface layers, perhaps a result of the hydration of native minerals by the migration of water liberated from entrained ice by the heat of the Sun.

Low-Albedo Material on Mid-Size Satellites

The Uranian satellite Umbriel (diameter 1170 km, albedo 0.21) is the darkest of the mid-size satellites, but Titania (0.27) and Oberon (0.23) are only slightly brighter (Miner 1998) The images from Voyager do not give clear clues to the reason for the low albedos, but all five of the mid-size Uranian satellites show clear and strong spectral features of H_2O ice. The dark material that lowers their albedos is evidently a material that is mixed with the ice at a granular level. Carbonaceous dust deposited on the satellites from an external source could, in principle, produce the observed effect. Such dust may be the same material as that found in the rings of Uranus.
Alternatively, the dark material may be an organic residue of the processing of surface ices (H_2O plus a carbon-bearing component) by solar radiation and/or energetic particles from the Uranian magnetosphere. In modeling the spectra of the Uranian satellites in the wavelength interval 0.22 – 2.45 μm Roush et al. (1999) have found that organic solids, notably an ice tholin (Khare et al. 1993) provide the observed absorption in the ultraviolet (0.22 – 0.5 μm) and a suitable match to the spectra overall. The ice tholin was produced by plasma irradiation of an ice mixture of H_2O and C_2H_6 (6 : 1) (Khare et al. 1993). The identification of this particular material is not unique; other organic solids with strong absorption in the ultraviolet might also provide satisfactory fits.

Saturn's satellite Rhea has high albedo (0.76 on the leading hemisphere; Buratti et al. 1998) in the visible spectral region and into the near infrared. The spectrum shows strong ~~absorption bands of H_2O ice, but a decrease in reflectance toward the ultraviolet ($\lambda < 0.5$~~

absorption bands of H_2O ice, but a decrease in reflectance toward the ultraviolet ($\lambda < 0.5$ μm), indicative of another surface component. The ultraviolet reflectance is consistent with the presence of an organic solid mixed at a granular level with H_2O ice, as well as trace amounts of O_3 trapped in the surface ice (Noll et al. 1996). Spectrum modeling of Rhea over the very broad wavelength region 0.2 – 3.5 μm is fully consistent with the presence of an organic solid material mixed with the surface H_2O ice of this satellite, and in fact the high reflectance of Rhea at 3.5 μm requires a material other than H_2O ice. The organic solid found to fit the Rhea spectrum is the same ice tholin used by Roush et al. (1999) in modeling the Uranian satellites. Again, the identification is not unique, but is indicative of the role that refractory organic solid seem to play in providing coloring (and darkening) agents in the ices of the satellites of the outer planets.

All of the other mid-size satellites in the Saturn system have ultraviolet absorption that is not characteristic of pure H_2O ice; modeling with organic solids and other materials is in progress.

Saturn's satellite Iapetus is a noteworthy special case of dark material in the Solar System. The hemisphere centered on the apex of the satellite's orbital motion (the leading hemisphere) is (except at the extreme polar regions) covered with a material of albedo 0.05, while the opposite hemisphere is primarily H_2O ice with an albedo of 0.6. The identity and method of emplacement of the dark material have been subjects of wide discussion (e.g., Cruikshank et al. 1983, Bell et al. 1985, Wilson and Sagan 1995, and Vilas 1996), but no consensus has been reached on either point.

A new study of Iapetus (Owen et al. 2000) extends the range of the observed spectrum to 4.0 μm. The spectrum of the leading hemisphere shows a small amount of H_2O ice absorption, and a red slope between 0.4 and 2.5 μm. In addition, the new data clearly define a strong absorption band between 2.7 and 3.6 μm. The band is not entirely due to H_2O ice, because ice absorbs strongly at 3.6 μm, whereas Iapetus is relatively bright (reflectivity ~0.1) at that wavelength. The spectrum is modeled with a mixture of H_2O ice, amorphous carbon, and a tholin produced by plasma discharge in a gas consisting of N_2 and CH_4 (99.9 : 0.1). This particular organic solid is not regarded as unique, but represents a refractory residual material produced by energy deposition in simple ices and gases (see below). The high reflectivity of Iapetus at 3.6 μm places an important constraint on candidate materials to explain the dark material on Iapetus' leading hemisphere.

The Rings of Saturn

The rings of Saturn have very high albedo, and the spectrum shows strong bands of H_2O ice, long known to be the principal constituent. Voyager images showed that there is locally variable color to the rings when viewed in multiple wavelengths in the spectral region from 0.34 – 0.56 μm. An analysis of the ring colors by Cuzzi and Estrada (1998) found that meteoroid bombardment explains the regional variations of ring composition and accounts for the fact that the A and B ring particles are redder and brighter than the particles in the C ring and the Cassini division. Their models showed that silicate minerals cannot account for the combination of steep spectral slope and high absorptivity, but that organic material in the form of tholin (specifically the Titan tholin of Khare et al. 1984) provide a satisfactory match. Neutral material with the low albedo of elemental carbon was also incorporated into the Cuzzi and Estrada models to explain the lack of redness of the darker ring components.

Since the publication of the Cuzzi and Estrada (1998) paper, new observations have been made of Saturn's rings with the Hubble Space Telescope at smaller angles of ring inclination (hence smaller phase angles of the constituent particles). The new data show a less red color for the various ring components, indicating a strong phase angle effect on the color. Cuzzi (personal communication 1999) indicates that while the rings are a bit less red than they appeared in the Voyager observations, tholin is still favored over silicates in the models, because of the implausibly large amount of silicates required (a quantity that would appear to violate the measured radar reflectivity of the rings).

The rings of the other giant planets appear to consist of particles some 10^{-4} to 10^{3} cm in dimension, depending on the ring system. Because the particles in these rings have very low albedo (0.05 - 0.15) with varying degrees of neutral to red color (Burns 1999), they may be directly related in composition to the dark material constituting the small satellites noted above. The red color of the particles in some ring systems (in addition to the Saturn system) is suggestive of the presence of organic solids.

The Case for Macromolecular Organic Material

Models of the spectra and the photometric properties of planetary satellites and rings point toward the need for a component that absorbs in the ultraviolet and is capable of imparting a color to the scattering surfaces of these bodies that is, to varying degrees, red. Rigorous scattering models require the complex optical indices (n and k) of the modeled constituents for the radiative transfer calculations that yield synthetic spectra for comparison with observational data. Very few materials have been measured for n and k in the spectral region (and with the spectral resolution) that matches the observational data acquired from spacecraft and ground-based telescopes. Insofar as a few organic solids, the tholins, have been measured and chemically characterized, these materials have proven to be a suitable and plausible component of the successful models calculated to date. This success may be fortuitous, but probably it is not. The mechanisms for energy deposition in simple ices and gases are prevalent in planetary environments, and the existence of the requisite raw materials is well established.

Several kinds of tholin have been made and analyzed, and various kinds have been referenced in this paper. The starting mixtures, both in the form of gases and solids, have been the principal variables, while the energy source has typically been a plasma discharge producing ultraviolet light and charged particles. Table II is a summary of four tholins produced at Cornell University, having demonstrated relevance to planetary environments. Other laboratories are now producing tholin materials.

Table II Tholins

Name	Starting Mixture	Energy Source	References
Titan tholin	Gaseous N_2:CH_4 (9:1)	Plasma discharge	Khare et al. 1984, McDonald et al. 1994
Triton tholin	Gaseous N_2:CH_4 (99.9:0.1)	Plasma discharge	McDonald et al. 1994
Ice tholin I	H_2O:C_2H_6 (6:1)	Plasma discharge	Khare et al. 1993, McDonald et al. 1996
Ice tholin II	H_2O:CH_3OH:CO_2:C_2H_6 (80:16:3.2:0.8)	Plasma discharge	McDonald et al. 1996

The organic solids called tholins, which are macromolecular complexes of polymers, polycyclic aromatic hydrocarbons, nitriles and nitrogen heterocyclic compounds (when N is included in the starting mixture), should be regarded as an *intermediate* product of the irradiation of simples ices and gases. As Thompson et al. (1987) showed when they irradiated a methane clathrate (CH_4 + H_2O), the initial reddening of the material eventually progressed to an overall darkening as the carbon was more completely dehydrogenated. Continued energy deposition in tholins is expected to remove hydrogen and other atoms, eventually resulting in a residue of mostly elemental carbon.

The genesis and study of organic residues from energetic processing of gases and ices is in progress in France, Germany, Italy, the Netherlands, the United States, and elsewhere, so there is hope that continued experimentation will provide even better and more constraining model fits that tell us more about the true nature of the processes and the chemical components of volatile materials in the outer Solar System.

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