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# **PHYSICAL PROPERTIES OF THE SATELLITES OF SATURN**

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## **ABSTRACT**

The photometric and bulk parameters of the known and suspected satellites of Saturn are presented in updated tables and are compared. The surface compositions of all the satellites are discussed in terms of modern photometry and spectroscopy; most if not all of the inner bodies have water frost surfaces, but the outer three satellites have surfaces of unknown composition. The few reliable mass values of some inner satellites, together with the best current values for the satellite radii, suggest mean densities representative of bulk compositions dominated by frozen volatiles, though Titan may have a substantial volume fraction of silicates. The special case of Iapetus is considered in the light of new studies of its two distinct faces and polar cap.

## **INTRODUCTION**

In spite of a superficial resemblance, the satellite system of Saturn is quite distinct from that of Jupiter, and is, in fact, unique in the Solar System. This review includes a cursory discussion of the dynamics of the satellite system, but concentrates on the current stage of understanding of the compositions, masses, bulk densities, and interior structures of the known and suspected objects orbiting Saturn outside the confines of the rings. The atmospheric composition and structure of Titan is left for other papers in this collection, though the photometric and bulk properties of this largest of the satellites are included in the scope of this review.

### SATURN'S FAMILY OF SATELLITES

The search for and discovery of satellites of Saturn has occupied astronomers for over three centuries, and the result of these endeavors is a retinue of at least ten, and probably more, objects orbiting the planet outside the confines of the ring system. The search continues to this date and is currently concentrated on the region between Mimas and the outer extremity of the rings.

The population of satellites of Saturn includes (1) the small bodies of unknown number that appear to exist just outside the rings, (2) six satellites, of which Titan is by far the largest, lying in circular orbits in the plane of the rings, (3) two irregular satellites, including Hyperion in an eccentric orbit at very nearly the 4:3 commensurability with Titan, and Iapetus with an inclined but nearly circular orbit, and (4) Pho be in a highly inclined retrograde orbit. In this paper we consider the physical properties of all these bodies.

Before examining the details of the Saturn satellites, we must first consider the evidence for the existence of the most recently discovered members of the family, those orbiting just exterior to the rings. From photographic observations made at the time of the 1966 passage of the earth through the ring plane, Dollfus (1967 a, b) announced the discovery of a probable satellite (Janus, S 10) near the extremity of the ring system, and the presence of a new object was confirmed by Texereau (1967) and Walker (1967). Fountain and Larson (1978) have studied some of the original photographs by Dollfus, Texereau, and Walker, plus data acquired at the Lunar and Planetary Laboratory at the time of ring-plane passage (Figure 1), and have shown evidence for a small object in addition to Janus, though no name has so far been proposed for it. Aksnes and Franklin (1978) analyzed the available photographs independently and concluded that the orbital characteristics of Janus should still be regarded as questionable, as should those of the Fountain/Larson object because unique orbits cannot be computed from the sparse observations available. While Fountain and Larson (1978) suggest even another object in addition to Janus and S 11, Aksnes and Franklin find the evidence unconvincing. The latter authors conclude that whatever the exact identities and orbits of the objects might be, ". . . the efforts of Dollfus, Fountain and Larson have seemingly established the important fact that the region just outside ring A may well contain several bodies in nearby orbits - a sort of highly attenuated, large-particle 'ring' near the Roche limit."



Figure 1. Photographs of Saturn and several satellites at the time of the passage of the earth through the ring plane in 1967. The upper photograph shows (tick mark) the possible S 11. The other satellites in order, left to right, are Enceladus, Kona, Tethys (in planet's glare), and Titan (17 December 1967, 0230 UT). The lower photograph (18 December 1967, 0249 UT) shows S 10, Janus on the left, Enceladus, S 11 (tick mark) and Tethys. From Fountain and Larson (1978).

In spite of the uncertainties attached to the existence and nature of S 11 and Janus, they are listed in Tables 1 and 2 with their provisional orbital parameters and brightnesses, though these quantities are subject to large revision at the time of the next observing opportunity, that is, when the earth again intersects the ring plane in 1980.

Aksnes and Franklin (1978) have also reanalyzed the evidence for the satellite that was reported early in this century by Pickering (1905, 1908) and named Themis. The evidence does not withstand careful scrutiny and detailed comparison with deep photographs of the background star fields, and Aksnes and Franklin (1978) conclude that while the space where Themis was reported is likely on dynamical grounds to contain a satellite (4:3 resonance with Titan), Pickering's object does not exist.

Table 1. Orbital Data for the Satellites of Saturn

Satellite	Orbital Radius		Period (Days)	Eccentricity	Inclination(°)
	(10 <sup>3</sup> km)	(Planetary Radii)			
11 No name	151.3	2.93	0.69378*	0	0
10 Janus	159.5	2.65	0.74896	0	0
1 Mimas	186.	3.09	0.942	0.0201	1.5
2 Enceladus	238.	3.97	1.370	0.0044	0.0
3 Tethys	295.	4.91	1.888	0.0000	1.1
4 Dione	377.	6.29	2.737	0.0022	0.0
5 Rhea	527.	8.78	4.518	0.0010	0.4
6 Titan	1222.	20.4	15.95	0.0289	0.3
7 Hyperion	1481.	24.7	21.28	0.1042	0.4
8 Iapetus	3560.	59.3	79.33	0.0283	14.7 <sup>†</sup>
9 Phoebe	12930.	216.	550.4	0.1633	150.

<sup>†</sup> Variable

\* Eastern elongation 1966 Oct 29.596 ET

Data from Morrison and Cruikshank (1974) except those for S 11, which come from Fountain and Larson (1978).

## THE DYNAMICS OF THE SATELLITE SYSTEM

Recent studies of the dynamics of the system of Saturn's satellites have explored old and new ideas in great detail and need not be repeated here. The review by Greenberg (1977) clarified the question of orbital resonances in the Saturn system as they pertain to orbital evolution, while the review by Kovalevsky and Sagnier (1977) considered details of the orbital motion of these and the other natural satellites. Burns (1977) considered the effects of tides and of accretion drag in the evolution of satellite orbits, while Peale (1977, 1978) has recently addressed the nature and evolution of the Titan-Hyperion commensurability.

The 1:2 resonance in the Mimas:Tethys orbital periods and the 1:2 resonance in the Enceladus:Dione pair have permitted mass determinations of these four bodies,

Table 2. Light Curve Data for Saturn's Satellites

Satellite	Sources	$\frac{dV}{d\alpha}$	Light Curve Amplitude $\Delta V$	$\theta_{\min}$	$\theta_{\max}$	Remarks
11 (No name)	1	-	-	-	-	No information
10 Janus	1, 2, 3	-	-	-	-	No information
1 Mimas	4, 5	-	-	-	-	No information
2 Enceladus	6	~0.08 (?)	0.4	~90° (?)	~270° (?)	More data needed
3 Tethys	6, 7, 8, 9, 10	~0.02	~0.15	~270°	~90°	Confirmation needed
4 Dione	6, 7, 8, 9, 10	~0.01	~0.4	~290 ± 30°	~120 ± 30°	Not well determined
5 Rhea	7, 8, 9, 10, 11, 16	0.05	0.2	270 ± 5°	90° ± 50°	Well established
6 Titan	9	~0.005	<0.02	-	-	
7 Iapetus	9, 10, 12, 13	~0.05** ~0.03	1.9*	90°	270°	Well established
8 Hyperion	14, 15	-	0.05 - 0.10	30°, 210°	120°, 300°	Needs confirmation
9 Phoebe	14, 15	-	~0.3	270°, 0°	90°, 180°	More data required

Source Code

- |                                |   |
|--------------------------------|---|
| 1. Fountain and Larson (1978)  | 12. Millis (1973)                         |
| 2. Dollfus (1967)              | 13. Morrison <i>et al.</i> (1975)         |
| 3. Aksnes and Franklin (1978)  | 14. Andersson (1978)                      |
| 4. Franz (1975)                | 15. Andersson, Degewij and Zellner (1978) |
| 5. Koutchmy and Lamy (1974)    | 16. Franklin and Cook (1974)              |
| 6. Franz and Millis (1975)     |   |
| 7. McCord <i>et al.</i> (1971) |   |
| 8. Blair and Owen (1974)       |   |
| 9. Noland <i>et al.</i> (1974) |   |
| 10. Harris (1961)              |   |
| 11. Blanco and Catalano (1971) |   |

\*Depending on polar axis tilt at epoch of observation.

\*\*Larger value corresponds to dark face ( $\theta = 90^\circ$ ) and smaller value corresponds to bright face ( $\theta = 270^\circ$ ).

though the precision is low. Titan dominates the pair Titan:Hyperion so that only the effect of the largest satellite on the smallest can be observed, resulting in a mass value for Titan alone.

The motion of Iapetus is affected about equally by the sun and Saturn, and is also influenced by massive Titan. The retrograde orbit of Phoebe is slightly perturbed by the sun and departs slightly from an ellipse.

## PHOTOMETRY OF THE SATURN SATELLITES

The goals of photometric studies of a planetary satellite are (1) to search for clues to the surface composition and the microstructure of the body, (2) to determine the rotation period from the periodicities in the light curve induced by zonal brightness (albedo) inhomogeneities, (3) to draw inferences on the distribution of albedo features that may be related to the satellite's rotational history or that can lead to a rudimentary map of the surface, and (4) to determine either the body's radius or surface geometric albedo when the other parameter is known.

The first goal is most satisfactorily met by spectrophotometry or spectroscopy, and the results of this work for the Saturn satellites will be discussed below. In this section we consider the results of photometric studies of the rotation of satellites and the changes in global brightness related to changing solar phase angle.

Photometric studies of those satellites that lie at sufficient angular separation from Saturn to permit precise measurements from ground-based telescopes have shown orbital phase angle variations in the brightness (V-mag) ranging from less than 2 percent (Titan) to a factor of more than five (Iapetus) with a sinusoidal or near sinusoidal pattern having the same period as the orbital period (with the possible exception of Hyperion noted below). These observations have been reviewed by Morrison and Cruikshank (1974) and Veverka (1977) in the context of similar measurements of satellites of other planets, and the patterns are similar for the four Galilean satellites of Jupiter, though the amplitude of the variation in V of Iapetus is uniquely high.

The measurement of orbital phase angle ( $\theta$ ) variations in the brightness of satellites must necessarily be made over a period of many days, during which time the solar phase angle ( $\alpha$ ) varies. For dark objects, or dark portions of spotted satellites, the solar phase coefficient is different from that of bright surfaces or parts of surfaces. The solar phase curve at the V wavelength (0.56  $\mu\text{m}$ ) has a linear portion at  $\alpha > 5^\circ$ , of about  $dV/d\alpha = 0.02 \text{ mag deg}^{-1}$  for both dark and bright surfaces,

but for  $\alpha < 5^\circ$ ,  $dV/d\alpha$  is somewhat larger for dark surfaces and nearly unchanged for bright surfaces. This is, of course, a qualitative description of the opposition effect, or brightness surge seen on airless bodies having irregular surface micro and macrostructures when viewed at small phase angles. The opposition effect is dependent on albedo, and to some degree, on color of the satellite, asteroid, and planetary surfaces. Veverka's (1977) discussion of this property of satellite surfaces observed from the Earth is especially lucid and relevant in the present context.

With a sufficient quantity of observations the effects of changing  $\alpha$  and  $\theta$  can be separated, though for the outer planets where the observable range of  $\alpha$  is small, the distinction of the two effects is more difficult. Saturn's satellites are observable over a range of about  $6^\circ$ , so that the establishment of the exact magnitude of the opposition surge on top of the normal linear phase coefficient requires a large number of high-quality data. As noted below, the only Saturn satellites for which the solar phase functions are adequately known are Titan, Rhea and Iapetus.

The question of the information content of the solar phase function has recently been reviewed by Veverka (1977). Borrowing freely from Veverka's study, we note that the phase function depends on (1) the effective scattering phase function and albedo for the single particles comprising the surface, (2) the shadowing function of a surface element determined by small-scale texture, and (3) the large-scale shadowing function resulting from surface topography, such as craters and mountains. While unique surface properties cannot be derived directly from the observed phase function, satellites with the roughest surface structures on both micro and macro scale would be expected to have the largest phase coefficients, and for those surfaces in which multiple scattering is significant (such as frosts) the phase coefficient is less than for a surface in which single scattering dominates. The nonlinear opposition effect is most pronounced in low-albedo pulverized surfaces where shadowing and single scattering are dominant. Bright powders also show an opposition effect, but it is less than in dark powders, and is most pronounced at extremely small phase angles. Various analytical models of the opposition effect and phase functions of pulverized materials are reviewed in some detail by Veverka (1977).

Adequate determinations of the orbital phase angle variations or rotation curves, in various colors, have been obtained for Tethys, Dione, Rhea, and Iapetus (e.g., Noland *et al.*, 1974); observations of the innermost satellites are especially difficult because of the proximity to the bright rings and planet, while the faint outer satellites can be measured only with very large telescopes. Figure 2 (from Noland

et al. 1974) shows the  $\gamma$  (5470 Å) curves for two satellites after removal of the solar phase function; the ordinates are plotted in stellar magnitudes, where

$$0.4 (m_1 - m_2) = \log \frac{\text{Brightness}_2}{\text{Brightness}_1} .$$

All those satellites for which the orbital phase curve has been satisfactorily observed show a rotation period synchronous with the period of revolution around the planet, as is expected from rotational dynamics. Hyperion may be an exception inasmuch as the scanty data available suggest a double maximum and minimum in one revolution around Saturn, but this can also be explained as a shape factor (asteroids commonly show double maxima and minima in one rotation). This cannot be regarded as a firm conclusion because of the very few data available (Andersson 1974, Degewij et al., 1978). The rotation of Phoebe may not be synchronous with the revolution period, but there are no data relevant to this problem. The 550.4-day period of

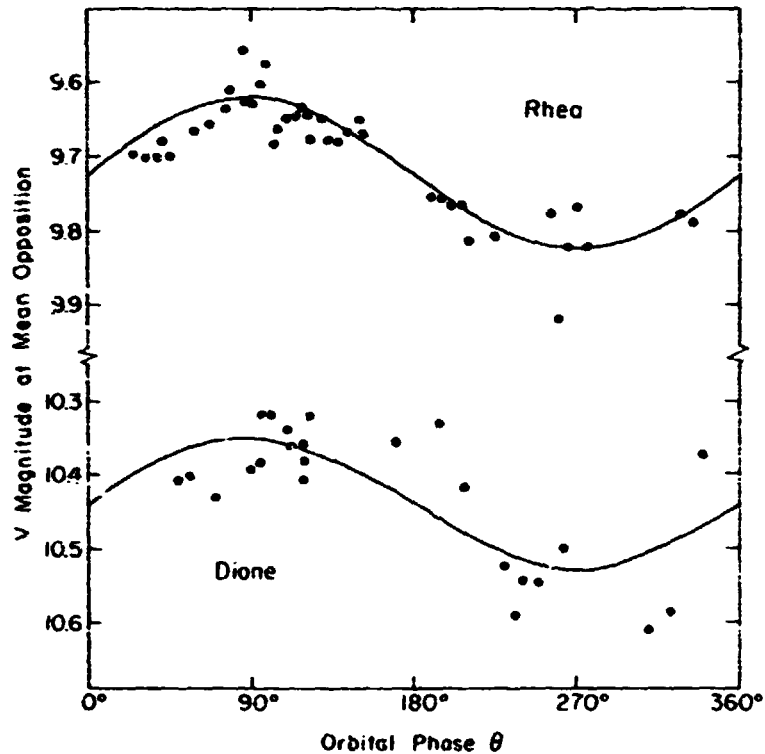


Figure 2 Orbital photometric variations of Rhea and Dione in the  $\gamma$  band. The solid curve for Rhea is given by  $y = 9.72 - 0.10 \sin \theta$ , and for Dione by  $y = 10.44 - 0.09 \sin \theta$ . The dependence of the magnitude on solar phase angle was removed by using phase coefficients of 0.025 and 0.009 mag deg<sup>-1</sup>, respectively. From Morrison and Cruikshank (1974), adapted from observations by Noland et al. (1974).



Phoebe makes an observational study of the rotation quite difficult unless the rotation period of the satellite is on the order of several hours, as is expected if it is not synchronously locked to the motion around Saturn. The innermost satellites (S11, Janus) can be observed only under very rare conditions, as noted earlier, and Mimas and Enceladus can normally be observed only at elongations, so the observational confirmation of the virtually certain synchronous rotation will be difficult to achieve.

The nonuniformities in the brightness and color of a satellite that yield the lightcurve often show a symmetry with respect to the leading and trailing hemispheres of a synchronously rotating body. "Leading" is used in the sense of the hemisphere in the direction of the satellite's orbital motion around the planet; the leading hemisphere is that viewed from Earth at eastern elongation ( $\theta = 90^\circ$ ) of the satellite with respect to its primary. The leading-trailing asymmetry is clearly seen in photometry of the Galilean satellites of Jupiter and of Iapetus, as well as several other satellites of Saturn. In Table 2 are given lightcurve data for the Saturn satellites as well as the best available values for  $dV/d\alpha$ . In the Table,  $\theta_{\min}$  corresponds to the orbital phase angle where the satellite is faintest, and  $\theta_{\max}$  to maximum brightness. For many of the satellites these parameters are not well known because of a paucity of data.

A significant point is that some satellites have darker trailing hemispheres and others have darker leading hemispheres. Iapetus is the prime example of the latter, as noted below, and Enceladus may share this property, though to a much lesser degree. Tethys, Dione, and Rhea appear to have darker trailing hemispheres, though corroborating data are needed. The leading-trailing asymmetries have led to interesting speculation on their causes, but there are still no adequate explanations, especially for the great contrast in the two hemispheres of Iapetus. The Galilean satellites of Jupiter also exhibit significant rotational curves, but the alignment with the leading and trailing hemispheres is most distinct for Europa.

The rotation curve of Titan, as noted above, shows an extremely small amplitude at the wavelengths at which it has been observed, presumably owing to the satellite's cloudy, or at least deep, atmosphere. It is possible that the methane atmosphere of Titan exhibits zonal inhomogeneities, as does the atmosphere of Neptune (Cruikshank 1978), and that the rotational curve can be determined from observations with filters centered in strong methane absorption bands in the near infrared. The required studies should be performed in order to ascertain if the inhomogeneities exist, if they change on an observable time scale, and to determine if the atmosphere rotates with the same period as the (presumably) synchronously rotating solid satellite.

## SURFACE COMPOSITIONS OF THE SATELLITES OF SATURN

Multi-color photometry (see Table 3) of the satellites of Saturn, has yielded information on their surface compositions. Leaving aside variations in the colors as a function of  $\alpha$  and  $\theta$ , broad- and narrow-band photometry in the spectral regions where compositional information occurs as a result of absorption in the constituents of the surfaces, has, in the past few years, led us to a fairly satisfactory understanding of the surface compositions of four of the inner satellites plus the bright hemisphere of Iapetus. UVB and other visible region photometry (Harris 1961, McCord *et al.*, 1971, Noland *et al.*, 1974), though carefully done, gave only clues to the composition of the inner satellites (Tethys, Dione, Rhea, and Iapetus) because the relevant compositional information lies further into the infrared. Broadband UVB photometry of the more difficult satellites, Hyperion and Phoebe, has also been accomplished (Andersson 1974, Degewij *et al.*, 1977) with significant results, but the infrared work on these bodies is in its infancy, chiefly as a result of their faintness.

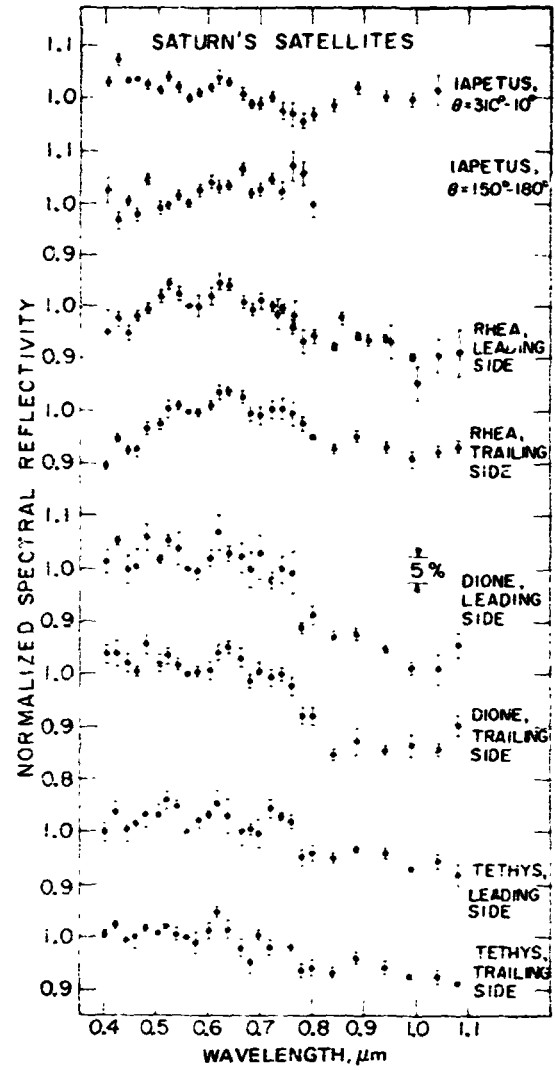
Narrow-band photometry of four satellites obtained by McCord *et al.* (1971) is shown in Figure 3, where the data are presented normalized to intensity equal 1.0 at wavelength  $0.56 \mu\text{m}$ ; this normalization was necessary at the time the data were acquired because the diameters and geometric albedos of the satellites were not known. While some variations are seen from satellite to satellite, and there may even be broad absorption features, notably at about  $0.57 \mu\text{m}$  or longer wavelengths for some objects, the spectra are largely uninterpretable. They do show, however, that the sharp brightness decrease in the violet seen on many other solar system bodies (e.g., Mars, Mercury, the Moon, the Jovian satellites, and the rings of Saturn) is largely absent on the satellites for which data were obtained. This is significant because the rings of Saturn, now known to be similar in composition to Tethys, Dione, and Rhea, do show the steep violet absorption, and questions arise as to the differences among these surfaces.

In Figure 4 are shown photometric results in the near infrared where solid surfaces of ices and mineral assemblages show stronger and more diagnostic absorptions than in the visible region of the spectrum. The simplest interpretation of Figure 4 comes from the comparison of the Saturn satellites with the Jovian satellites, two of which (Europa and Ganymede) are known to have partial covers of water ice (cf. Morrison and Cruikshank 1974 and Morrison and Burns 1977). The photometry of the Saturn satellites closely mimics that of Ganymede, from which it was concluded

Table 3. Colors of the Satellites of Jupiter and Saturn

Satellite	$V_0$	U-B	B-V	J	J-H	J-K	J-L
J1 Io	5.0	1.3	1.15	$3.7 \pm 0.1$	$0.35 \pm 0.01$	$0.43 \pm 0.02$	$0.43 \pm 0.03$
J2 Europa (L)	5.3	0.5	0.89	$4.1 \pm 0.1$	$-0.31 \pm 0.02$	$-0.66 \pm 0.03$	$-2.90 \pm 0.04$
J2 Europa (T)				$\pm$	$-0.37 \pm 0.02$	$-0.91 \pm 0.04$	$-3.25 \pm 0.05$
J3 Ganymede (L)	4.6	0.53	0.81	$3.6 \pm 0.1$	$-0.10 \pm 0.03$	$-0.18 \pm 0.04$	$-2.08 \pm 0.14$
J3 Ganymede (T)					$-0.07 \pm 0.02$	$-0.14 \pm 0.03$	$-1.58 \pm 0.04$
J4 Callisto	5.6	0.55	0.88	$4.4 \pm 0.1$	$0.27 \pm 0.01$	$0.34 \pm 0.02$	-0.67
S1 Mimas	12.9	-	$0.65 \pm 0.1$	-	-	-	-
S2 Enceladus	11.8	-	0.62	$10.6 \pm 0.1$	$-0.16 \pm 0.05$	$-0.33 \pm 0.07$	$> -0.66$
S3 Tethys	10.3	0.34 - 0.32	0.74	$9.3 \pm 0.1$	$-0.20 \pm 0.05$	$-0.36 \pm 0.07$	$> -0.46$
S4 Dione	10.4	0.27 - 0.30	0.71 - 0.82	$9.6 \pm 0.2$	$-0.20 \pm 0.05$	$-0.32 \pm 0.07$	$> -0.42$
S5 Rhea	9.7	0.35	0.76	$8.6 \pm 0.1$	$-0.05 \pm 0.05$	$-0.29 \pm 0.07$	$-1.89 \pm 0.18$
S6 Titan	8.4	0.75	1.30	-	-	-	-
S7 Hyperion	14.2	0.33	0.78	$13.0 \pm 0.1$	$0.15 \pm 0.05$	$-0.03 \pm 0.07$	$> 0.55$
S8 Iapetus (L)	10.2	$0.38 \pm 0.03$	$0.78 \pm 0.02$	$10.3 \pm 0.1$	$0.20 \pm 0.03$	$0.28 \pm 0.04$	$-0.82 \pm 0.25$
S8 Iapetus (T)	11.9	$0.29 \pm 0.03$	$0.69 \pm 0.01$	$9.4 \pm 0.1$	$-0.11 \pm 0.02$	$-0.24 \pm 0.03$	$> -1.35$
S9 Phoebe	16.5	0.30	0.63	-	-	-	-
S10 Janus	14	-	-	-	-	-	-

Figure 3. Spectrophotometric data for several Saturn satellites, normalized at 0.56 microns. From McCord et al. (1971).



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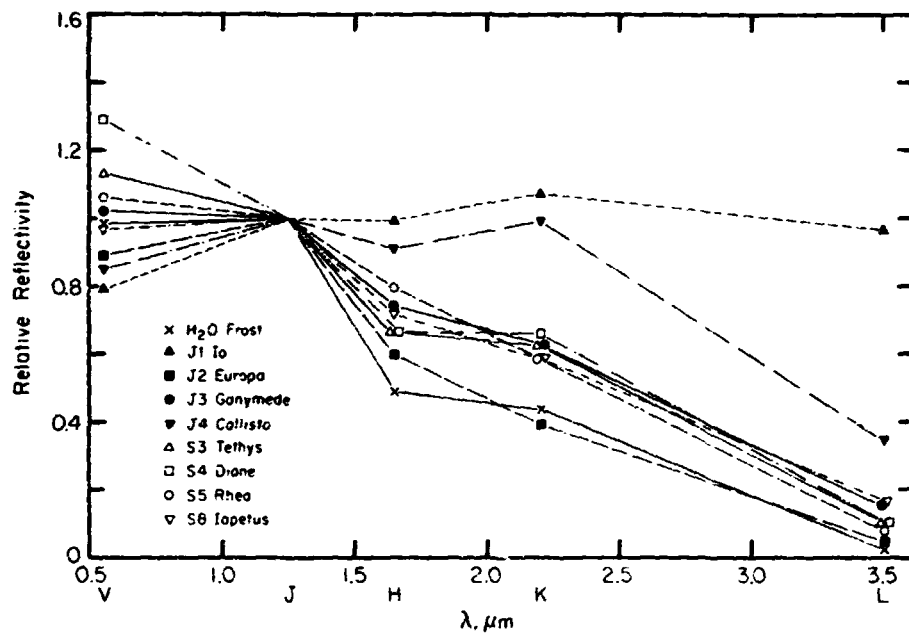


Figure 4. Infrared reflectances of several satellites of Saturn and Jupiter's Galilean satellite. From Morrison et al. (1976).

(Morrison *et al.*, 1976), that Tethys, Dione, Rhea, and the bright hemisphere of Iapetus have at least partial coverings of water frost at a low temperature presumably in equilibrium with the solar insolation.

This conclusion was reached nearly simultaneously (but published first) by Fink *et al.* (1976), who obtained the remarkable first infrared spectra of the same satellites. Their spectra, together with a stellar comparison, are shown in Figure 5, and in Figure 6 are shown the ratios of the satellite spectra to the comparison. Those deep absorptions at 1.6 and 2.0  $\mu\text{m}$  in the spectra of Iapetus, Rhea, Dione, and Tethys are clearly a result of water ice absorption, as shown by the laboratory comparison and the accompanying spectrum of Saturn's rings.

Thus, the presence of water ice is clearly established on the surfaces of Rhea, Dione, Tethys, and the bright hemisphere of Iapetus. The fact that Rhea, Dione, and Tethys show relatively small variations of brightness with  $\theta$  (Figure 2) suggests that the areal distribution of water frost or ice is more or less uniform.

Although fully satisfactory infrared spectra have not yet been obtained for the other satellites or the dark hemisphere of Iapetus, JHK photometry of Enceladus, Hyperion, and darker Iapetus has given some interesting results. The spectrum of Iapetus (Morrison *et al.*, 1976) is similar to that of Callisto. The reflectivity of Enceladus is shown in Figure 7 in comparison with data for ice-covered Rhea, plus four other satellites (Cruikshank *et al.*, 1977). The similarity of Enceladus to Rhea has led Cruikshank *et al.*, to conclude that this small satellite is similarly water-frost covered, a result corroborated by a new spectrum (1.9-2.6  $\mu\text{m}$ ) of Enceladus obtained by Cruikshank (1979) in 1973.

The reflectance of Hyperion appears to be quite another problem. As shown in Figure 7 it resembles not Enceladus and Rhea, but two satellites of Uranus and Neptune's Triton. As pointed out by Cruikshank *et al.* (1977), the reflectance characterized by Hyperion and the others does not appear to represent volatiles, and these objects constitute a class different from the groups into which most of the other satellites of the solar system fall. The reflectance class, of which Hyperion is a member, is shown in relation to the other recognized classes in Figure 8 (from Cruikshank *et al.* 1977), and the membership and probable natures of these classes are described in Table 4.

Cruikshank and C. B. Pilcher succeeded in obtaining a low-resolution infrared spectrum of Hyperion with the Kitt Peak 4-m telescope in 1976, in the region 1.4 - 2.6  $\mu\text{m}$  (see Figure 9), but the reflectance of the satellite, while bearing

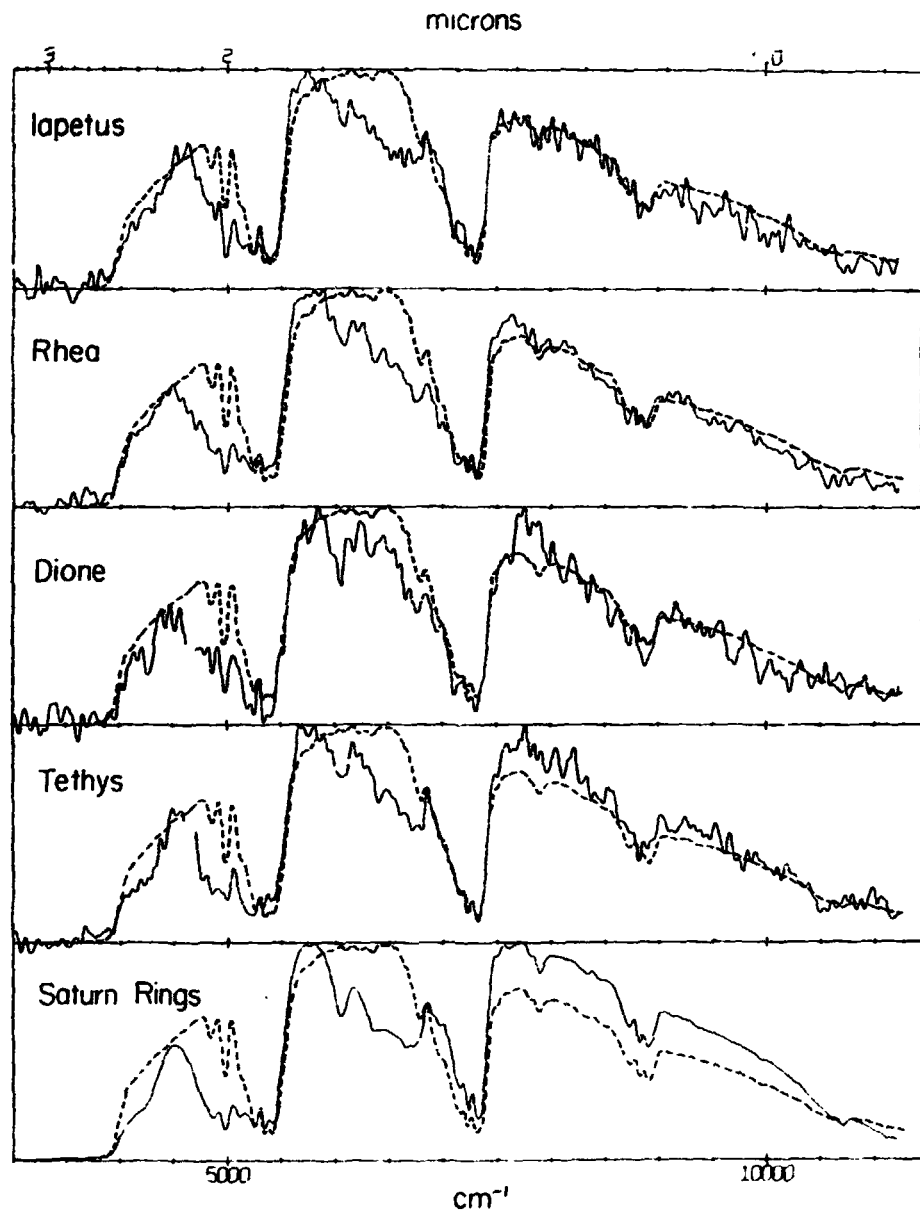


Figure 5. Near infrared spectra of Saturn's satellites and the rings, showing residual absorptions attributed to water frost or ice. From Fink et al. (1976)

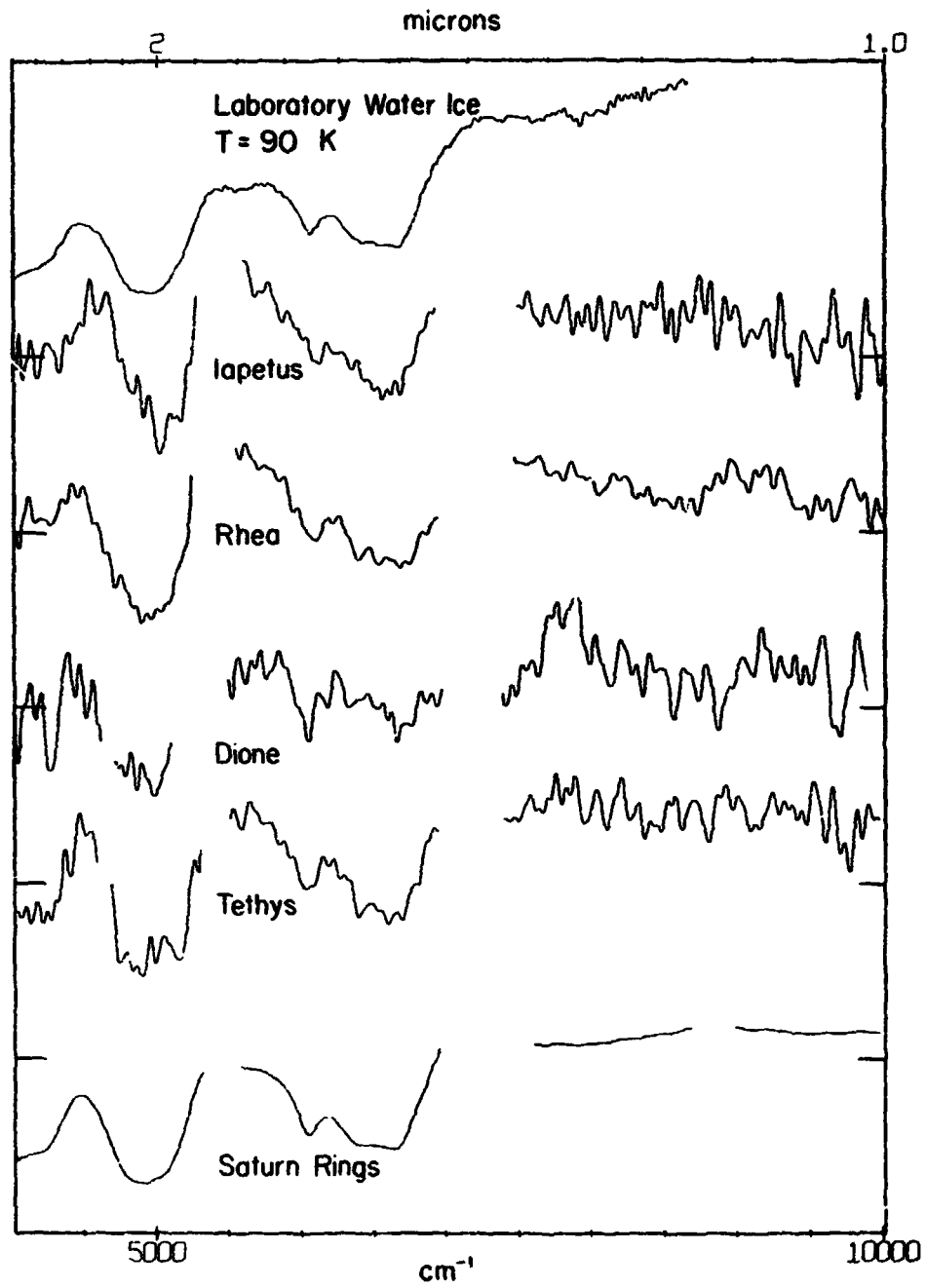


Figure 6. Ratio spectra of the satellites and rings of Saturn showing absorptions attributed to water frost or ice. From Fink et al. (1976).

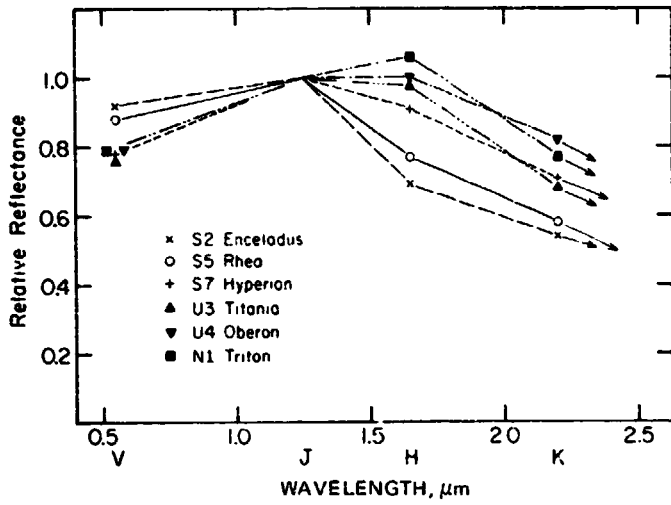


Figure 7. Infrared reflectance spectra of three satellites of Saturn, Triton, Titania, and Oberon. From Cruikshank et al. (1977).

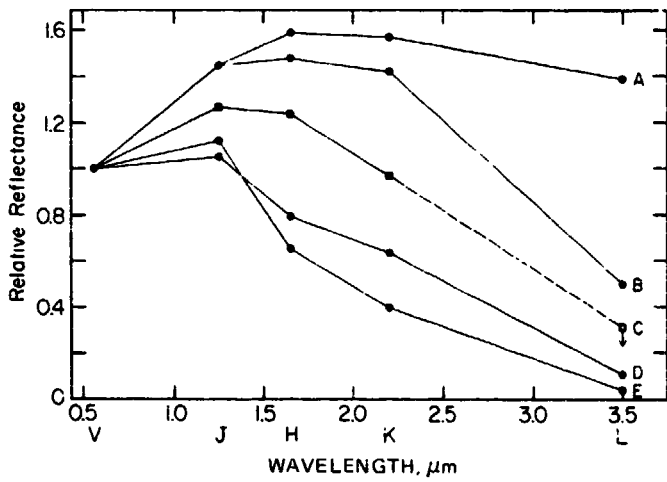


Figure 8. Reflectances, normalized at V, of five categories of solar system bodies. The categories and their members are identified in Table 4.



Table 4. Reflectance Classes of Solar System Bodies

Group	Members of Group	Surface Composition	Average Reflectance Relative to J ( $\lambda = 1.25 \mu\text{m}$ )			
			$a_V$	$a_H$	$a_K$	$a_L$
A	Io	Evaporite salts ?	0.69	1.10	1.08	0.96
B	Callisto	Rock	0.69	1.02	0.99	0.35
C	Hyperion, Titania, Oberon, Triton	?	0.79	0.98	0.77	<0.25
D	Ganymede, Enceladus, Tethys, Dione, Rhea, Iapetus (trailing)	H <sub>2</sub> O ice (frost) + neutral material	0.94	0.75	0.60	0.11
E	Europa, Rings of Saturn	H <sub>2</sub> O ice (frost)	0.88	0.58	0.35	0.04
F	Pluto	CH <sub>4</sub> ice (frost)	0.92	0.94	0.57	<0.36
-	Asteroids 88, 511	[C-type asteroids]	-	1.16	1.23	-
-	Asteroids, 5, 6, 7, 116, 433	[S-type asteroids]	-	1.13	1.09	-
-	Asteroid 64	[E-type asteroid]	-	1.08	1.09	-

a superficial resemblance to water frost, is not immediately identifiable. In particular, the upturn in reflectance at the extreme long wavelength end of the spectrum, if real, is atypical of water frost, and in fact precludes the presence of a substantial H<sub>2</sub>O frost component on the surface. Additional data are needed, not only for Hyperion, but for Triton and the other two members of the class of which they are members in common. The Hyperion spectrum resembles that of volatiles rather than asteroids or any known meteorites (Gaffey 1976), but the identification from a spectrum of such low resolution and insufficient precision is not easy. UVB photometry of Hyperion (Degewij *et al.* 1977) shows this satellite to be distinct from the dark asteroids, including Trojans.

The only relevant data on Phoebe's surface composition are contained in UVB photometry obtained by Degewij *et al.* (1977) (Figure 10). In a UVB color plot Phoebe clusters together with Himalia and Elara (J6 and J7), which are very dark objects (Cruikshank 1977). As is seen in the figures, Phoebe and the Jovian satellites form a small group quite separate from the Trojans (also very dark; Cruikshank 1977) and other asteroids of low albedo, and fall generally within the field in the UVB color plot occupied by C-type asteroids.

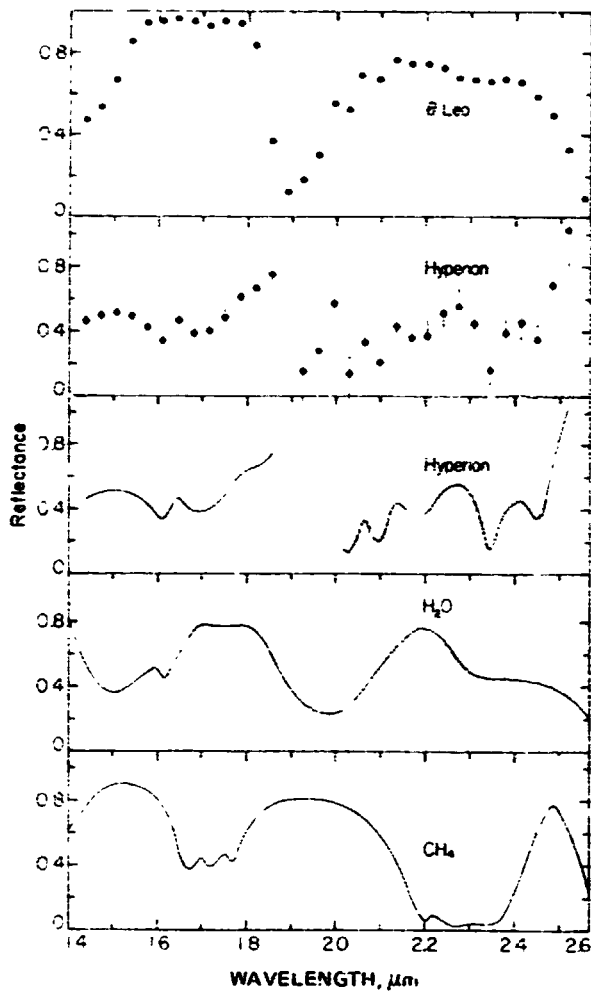


Figure 9. Preliminary infrared spectrum of Hyperion ratioed to Theta Leo. The second panel from the top shows the individual data points with error bars, and the third panel is a "maximum interpretation" version of the same data. Reflectance spectra of water and methane ices are also shown. From Cruikshank and Pilcher (in preparation).

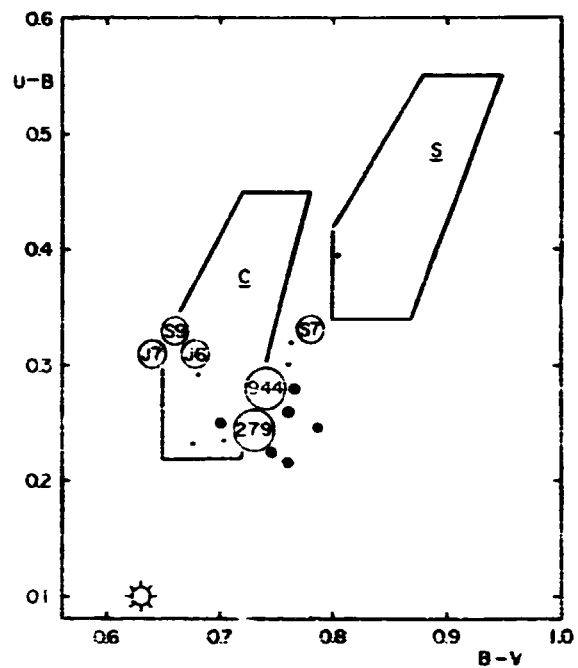


Figure 10. This U-B, B-V color plot shows several solar system objects known or suspected to be very dark. Hyperion (S 7) and Phoebe (S 9), are shown with Himalia (J 6) and Elara (J 7), Trojan asteroids (large dots), and Hilda asteroids (small dots) plus 279 Thule and 944 Hidalgo. From Degeus et al. 1977.

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The compositions of Mimas, Janus, and the possible S11 are completely unknown from direct observations, though inferences might be made on the basis of the known frost composition of the rings and the satellites nearby these three bodies. Mimas and Janus lie in a region of special interest because of the great difference in reflectance between the rings and satellites Tethys, Dione, and Rhea, specifically the violet turn-down in the ring spectrum, as noted above. Lebofsky and Fegley (1976) suggest that the violet absorption in the ring spectrum results from solar ultraviolet irradiation or trapped particle bombardment of polysulfide or other impurities in the ring frost, with the implication that such impurities do not occur in the frosts of the satellite surfaces, or that the bombarding particles in the vicinity of Saturn (either past or present) do not extend spatially outward to the neighborhood of the satellites. Spectrophotometric observations of Mimas and Janus are thus of special interest in order to ascertain (1) if they are composed of water frost, and (2) if the frost shows radiation damage similar to the rings.

#### DIAMETERS AND ALBEDOS

In terms of observations made from Earth, the diameter and surface geometric albedo of a satellite or asteroid are inextricably related by

$$5 \log r = V_o - V_v - 2.5 \log p_v + 5 \log (R \cdot \Delta),$$

where  $r$  is the radius of the object,  $V_o$  is the  $V$ -mag of the Sun (usually taken as  $-26.77$ ),  $p_v$  is the visible geometric albedo,  $R$  is the distance of the satellite from the Sun, and  $\Delta$  is its distance from the Earth (or observer).  $V_o$  is reasonably well known for most of the satellites, but the computation of  $r$  or  $p_v$  requires knowledge of one or the other.

With the largest telescopes in the finest seeing conditions, the disks of the satellites of Saturn are occasionally discernable, and in 1954 Kuiper published his measurements of the diameters of Enceladus, Dione, Tethys, Rhea, Titan, and Iapetus, made with a visual diskmeter on the Hale 5-m telescope. Other measurements of the diameters of the Saturn satellites have been made by more or less direct means. In 1974, Elliot *et al.* (1975) observed the occultations of several satellites by the dark limb of the moon and measured the time required for extinction of the light from the satellites with a high-speed photometer. The lunar occultation technique gives the highest intrinsic accuracy of the methods so far used, but the interpretation

of the results depends on a model of the brightness distribution across the surface of the occulted object, a model dependent on both the spatial distribution of dark and bright materials (frost and rock, for example) and the limb darkening/brightening of the disk. The identification of water frost on the surfaces of several of the satellites has aided in establishing the limb brightening coefficients used in modeling the brightness distribution (e. g. Veverka *et al.*, 1978). Double-image micrometric measurements have also been made with large telescopes (Dollfus 1970) using rare moments of excellent seeing and image definition when the disks of the satellites are discernible. In addition, photometric measurements of the thermal fluxes of six satellites have been used to derive "radiometric" diameters. All of these results are collected in Table 5 together with similar determinations of the radii of the Galilean satellites and Triton for comparison.

Beyond the measurements of the type described above, none others have been successfully applied, though the techniques of speckle interferometry and fringe interferometry can in principle be used for further independent determinations.

Diameters of planetary satellites can be calculated from *assumed* values of  $p_V$ . For example if we allow that the surface of Enceladus is covered with water frost, as deduced from the infrared photometry, we can assume that the albedo lies in the range of that of other ice-covered satellites, such as Europa, Ganymede, Rhea, etc., or about 0.40 - 0.65. The radius is then in the range 295 - 375 km. The frost-cover assumption may be quite valid for Janus, S11, and Mimas by analogy with the rings and the next several satellites, but it is not valid for Titan, Hyperion, the dark side of Iapetus, or Phoebe.

The photometric/radiometric method of radius determination in fact yields the geometric albedo if certain assumptions are made about the infrared emissivity of the surface and the phase integral of the satellite. The radius is then computed from  $p_V$  and  $V_0$ . The sensitivity of the photometric/radiometric method to uncertainties in the values of various parameters has been discussed by Morrison (1977). Assembled in Table 6 are the "accepted" radii and corresponding values of  $p_V$  for several of the Saturn satellites. For the remaining satellites, the radii are calculated from assumed albedos, and these values are enclosed in parentheses. In this table,  $V(1,0)$  corresponds to the V-mag at unit distance from the sun and earth and seen at  $\alpha = 0^\circ$ , with no allowance for an opposition surge in brightness at small phase angles, but with the  $dV/d\alpha$  indicated in Table 2.

Table 5. Various Determinations of Satellite Diameters

Object	Kuiper Diskmeter Radius (km)	Occultation Radius (km)	Radiometric Radius (km)	Double Image Radius (km)	Accepted Radius (km)
Enceladus (S2)	275	-	-	-	-
Tethys (S3)	410	520 ± 60 <sup>(1)</sup>	-	-	520 ± 60
Dione (S4)	410	415 ± 75 <sup>(1)</sup>	575 ± 100 <sup>(6)</sup>	-	500 ± 120
Rhea (S5)	820	790 ± 45 <sup>(2)</sup>	800 ± 125 <sup>(6, 7)</sup>	-	800 ± 100
Titan (S6)	2290	2915 ± 25 <sup>(1)</sup>	2800 ± 150 <sup>(8)</sup>	2425 ± 150 <sup>(12)</sup>	2900 ± 200
Hyperion (S7)	-	-	112 ± 15 <sup>(9)</sup>	-	112 ± 15
Iapetus (S8)	670	725 ± 100 <sup>(2)</sup>	835 <sup>+50</sup> <sub>-75</sub> <sup>(10)</sup>	-	725 ± 100
Io (J1)	1650	1820 ± 5 <sup>(3)</sup>	-	1750 ± 75 <sup>(13)</sup>	1820 ± 10
Europa (J2)	1420	1500 ± 100 <sup>(4)</sup>	-	1550 ± 75 <sup>(13)</sup>	1500 ± 100
Ganymede (J3)	2460	2635 <sup>-15</sup> <sub>-100</sub> <sup>(5)</sup>	-	2775 ± 65 <sup>(13)</sup>	2635 ± 25
Callisto (J4)	2290	-	-	2550 ± 75 <sup>(13)</sup>	2500 ± 150 <sup>(14)</sup>
Triton (N1)	1900	-	≤ 2630 <sup>(11)</sup>	-	2200 ± 500

Notes:

- (1) Elliot *et al.* (1975). The values given are those computed for a Lambert limb-darkened model. The uniform-disk model yields radii 10-15 percent smaller than those given here. The values tabulated here are rounded off from those actually given by Elliot *et al.*
- (2) Yeager *et al.* (1978)
- (3) O'Leary and van Flandern (1972). See also Taylor (1972) and discussion in Morrison and Cruikshank (1974).
- (4) Based on mutual occultations of the Galilean satellites (Aksnes and Franklin, 1974; Vermillion *et al.* 1974).
- (5) Carlson *et al.* (1973).
- (6) Morrison (1974).
- (7) Murphy *et al.* (1972).
- (8) W. M. Sinton, private communication (1975). See also Low and Rieke (1974).
- (9) Cruikshank (1978b).
- (10) Morrison *et al.* (1975).
- (11) Cruikshank *et al.* (1978).
- (12) Dollfus (1970).
- (13) Dollfus (1970), Morrison and Cruikshank (1974).
- (14) Cruikshank and Stockton (1978).

Table 6. Bulk Parameters of the Satellites of Saturn

Satellite	V(L, 0)	$\rho_V$	R(km)	M( $10^{23}$ g)	$\bar{\rho}$
1 Mimas	+3.3	(0.6)	(180)	0.37 ± 0.01	~1.5
2 Enceladus	+2.2	(0.6)	(300)	0.84 ± 0.03	~1
3 Tethys	+0.7	0.8	520 ± 60	6.2 ± 0.11	~1.1
4 Dione	+0.88	0.6	500 ± 120	11.6 ± 0.3	~1.5
5 Rhea	+0.16	0.6	800 ± 100	-	~1
6 Titan	-1.20	0.21	2900 ± 200	1399 ± 2	1.4
7 Hyperion	+4.6	0.47	112 ± 15	-	-
8 Iapetus	0.6/2.3	0.35/0.05	725 ± 100	-	-
9 Phoebe	+6.9	(0.05)	(120)	-	-
10 Janus	+4	(0.6)	(100)	-	-
11 -	+4	(0.6)	(100)	-	-

Values in parentheses are estimated on the basis of an assumed ice or frost-covered surface.

#### MASSES AND MEAN DENSITIES

The masses of five of the satellites in the resonance pairs Mimas: Tethys, Enceladus:Dione, and Titan:Hyperion, have been determined from observations of the mutual gravitational interactions. The values in Table 6 are from the review by Duncombe *et al.* (1974). While Duncombe *et al.* give mass values for Rhea, Hyperion, Iapetus, and Phoebe taken from the literature, they cannot be considered reliable enough for inclusion in the table; this conclusion was adopted by Morrison and Cruikshank (1974) in their review, and more recently by Morrison *et al.* (1977) in an updated consideration of the same material.

Mean densities of the satellites are calculated from the adopted radii and masses, but only for Tethys, Dione, and Titan can these densities be given much credence. The formal calculations of density of Enceladus gives a value less than 1.0, which is considered unlikely. A composition of mostly frozen volatiles is consistent with mean densities on the order of 1 - 1.5 g cm<sup>-3</sup>, as noted below, but for most of the Saturn system of satellites these basic parameters are still largely unknown. If masses are required for dynamical computations, the best values might be calculated from an assumed mean density of 1 - 1.5 g cm<sup>-3</sup> using the estimated radii

given in the table, at least for the inner satellites. Hyperion, Iapetus, and Phoebe may be exceptions, but there is no relevant information presently available.

### THE SPECIAL CASE OF IAPETUS

The problem of the large range of brightness of Iapetus between eastern and western elongations was solved by Murphy *et al.* (1972), who showed that thermal emission was maximum when the visible brightness was at a minimum, that is, the visible and thermal "lightcurves" are anticorrelated. The brightness variations are therefore a result of nonuniform albedo rather than a shape factor, and subsequent work by Morrison *et al.* (1975) provided a detailed (but unique only to first order) solution to the distribution of dark and bright areas on the satellite surface. From a new analysis of early and recent photometry of Iapetus, plus observations of the thermal flux throughout an orbit, Morrison *et al.* (1975) derived an albedo distribution map, shown in Figure 11, that satisfactorily accounts for the visual lightcurve seen at various aspects. The distribution of albedo shown in Figure 11 is not unique in that (small) variations may occur across the bright face and across the dark face. In order to reproduce the observed lightcurves, a polar cap of bright material intruding

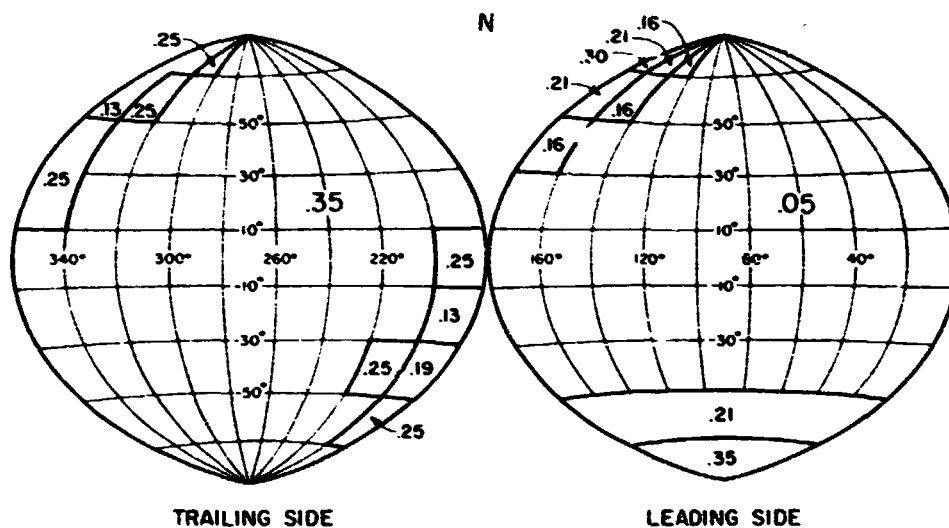


Figure 11. Model albedo distribution for Iapetus, shown on an Astoff equal-areas projection. Each area is labeled by its visual geometric albedo. The coordinate system is defined such that the longitude on the satellite is equal to the orbital longitude, measured prograde from superior geocentric conjunction, and the axis of rotation is assumed normal to the satellite's orbital plane. Longitude increases to the east as seen from the earth, and north is at the top. From Morrison *et al.* 1975

on the dark face was necessary, as were darker limbs on the bright face. The average geometric albedo of the bright face must be about 0.35 and that of the dark face about 0.05 in order to yield the observed thermal fluxes, and the phase integral for the bright side must lie in the range 1.0 - 1.5. An artistic rendition of the albedo map is shown in Figure 12. The thermal (20  $\mu$ m) observations at different orbital phase angles (Morrison *et al.*, 1975) are shown in Figure 13, together with model curves for two values of the phase integral, and the visual light curve from three different observers is shown in Figure 14.

A new analysis of the occultation lightcurve of Iapetus by Veverka *et al.* (1978) corroborates the Morrison *et al.* (1975) model requiring approximately, but not exactly, a two-hemisphere albedo distribution. Veverka *et al.*, suggest that the dark hemisphere shows no limb darkening (similar to the moon), but that the bright hemisphere exhibits limb darkening according to the Minnaert relationship (Veverka *et al.*, equation 2). With the limb darkening coefficient and the time duration of the occultation, Veverka *et al.*, compute the diameter of the satellite, and then the albedo of the bright hemisphere (Elliot *et al.*, 1978). The diameter is that given in Tables 5 and 6, while the geometric albedo is  $p_V = 0.54^{+0.20}_{-0.16}$ . The dark hemisphere is then  $p_V = 0.11^{+0.04}_{-0.03}$ . Both values are appreciably higher than those derived by Morrison *et al.* (1975). The higher albedo derived by Veverka *et al.*, and Elliot *et al.* for the dark hemisphere does not appear to be sufficiently low to produce the infrared thermal flux measured by Morrison *et al.* (1975), though the bright hemisphere albedos derived in both studies are adequately included in the range expected for water frost.

The question of the polar cap has been further studied by Millis (1977) who has continued the photoelectric photometry of Iapetus in recent years as the aspect angle changes. The inclination of the satellite's orbit to the ring plane, though it amounts to less than 15°, results in a small change in aspect from year to year such that in the interval 1970 to the present the south pole is tilting out of view. As a result, the integrated brightness of the dark (leading) side has decreased in the past few years, as shown in Millis' photometry in Figure 15. Concurrently, the thermal flux of the dark side is increasing (Cruikshank 1979, in preparation) as less bright material is exposed.

We noted earlier that the composition of the material on the bright face of Iapetus is at least partially water frost. The composition of the dark material on the leading face is unknown, but its reflectance from broadband filter photometry in the near infrared appears to resemble that of Callisto. Callisto's surface mineralogy is not yet understood, but the presence of bound water has been revealed by infrared



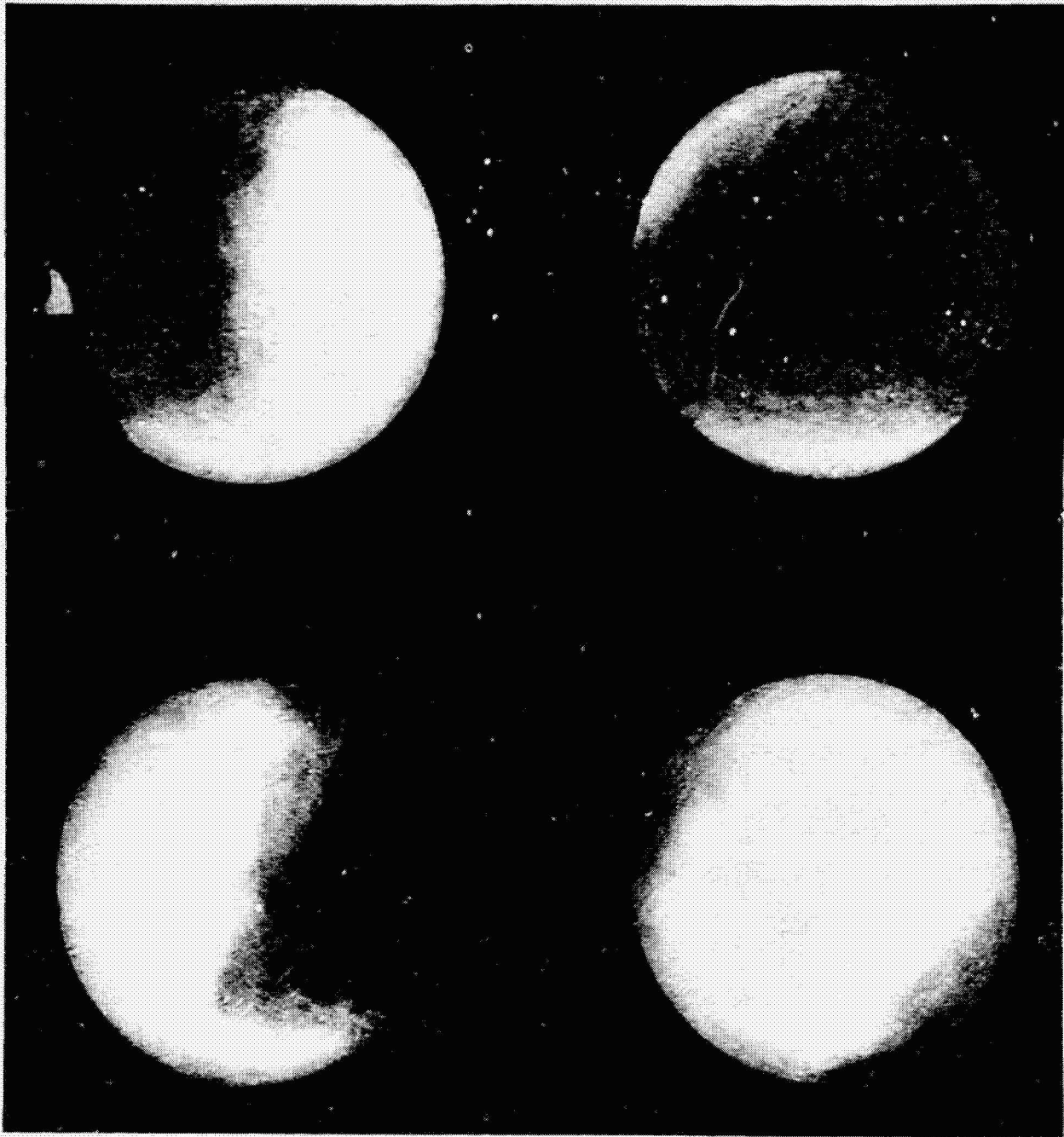


Figure 12. Artistic representation of the surface of Iapetus as seen with linear resolution about 0.02 arcsec, based on the computed albedo distribution model shown in Figure 11. The longitudes of the central meridian (equal to the orbital longitude) for these four views are (u.l.)  $0^\circ$  (superior geocentric conjunction), (u.r.)  $90^\circ$  (eastern elongation), (l.l.)  $180^\circ$  (inferior conjunction), (l.r.)  $270^\circ$  (western elongation). Note that these drawings illustrate only one of a range of similar albedo distributions that are consistent with the available data. From Morrison et al. (1975).

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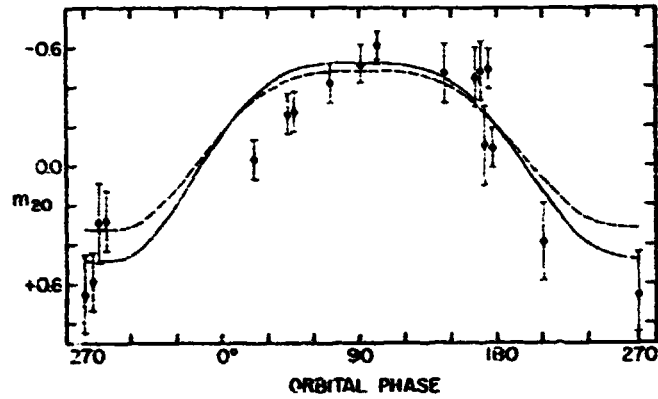


Figure 13. Brightness variations of Iapetus at 20 microns as a function of orbital (rotational) phase, compared with two theoretical curves calculated from the albedo distributions in Figure 11. The solid curve provides the best fit and corresponds to a phase integral for the bright material  $q = 1.3$ . The dashed line is for  $q = 1.1$ . From Morrison et al. (1975).

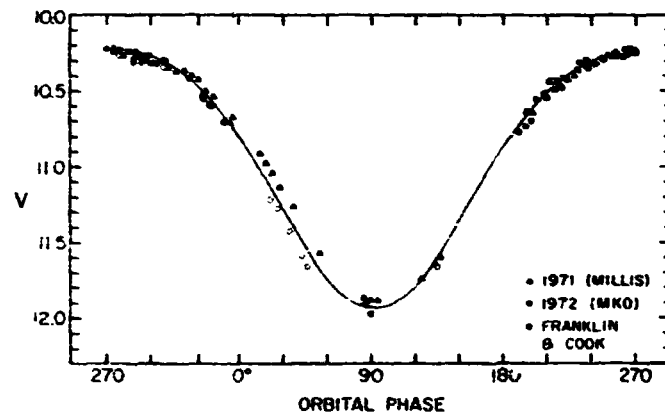


Figure 14. The visible light curve of Iapetus from 1971-1973 compared with the theoretical curve generated from the albedo distribution shown in Figure 11.

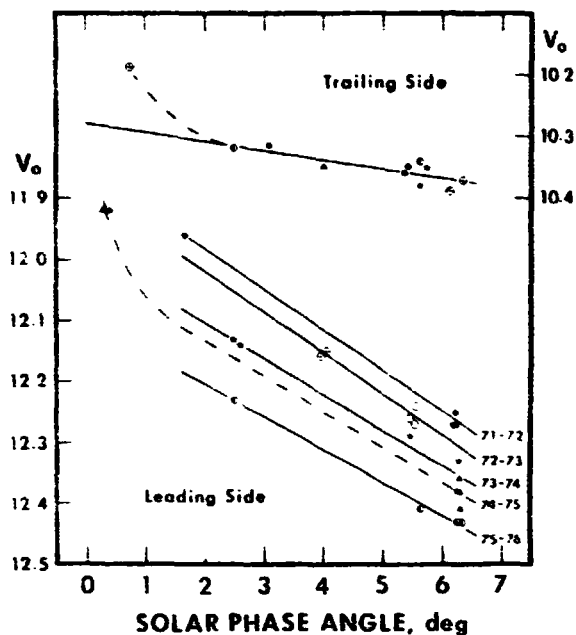


Figure 15. *V*-photometry of the leading and trailing sides of Iapetus versus solar phase angle for a number of different apparitions. The decrease in brightness of the leading (dark) side of the satellite each successive year since 1971-1972 is attributed to the gradual tilting of the polar cap out of the angle of view from the earth. From Millis (1977).

spectrophotometry near  $3 \mu\text{m}$  (Lebofsky 1977, Pollack *et al.*, 1977, and Cruikshank *et al.*, 1977). This absorption also occurs in certain dark asteroids (Pallas and Ceres) but not in Vesta (Cruikshank and Gaffey 1978, in preparation). The bound water band should be sought on Iapetus, and this problem is within present observational capabilities with narrow-band filters. Discrete mineral absorptions should also be sought, but it should be noted that such observations must be made at the exact time of eastern elongation so that the feeble light from the dark surface materials is not contaminated with the bright reflected light from the ice and snow. This requirement places a rigid constraint on an already difficult observational problem, but with persistence it can be solved.

A rare eclipse of Iapetus by Saturn and its rings in January 1978 afforded an opportunity to observe for the first time since the invention of the bolometer the change in brightness temperature of the satellite with changes in solar insolation. Portions of the event were successfully observed at  $20 \mu\text{m}$  in Hawaii, California, and Arizona, though the results are in a very preliminary state at this time. The Hawaii observations (Cruikshank and Becklin 1978) are shown in Figure 16; the changing  $20\text{-}\mu\text{m}$  flux occurred as Iapetus passed through the shadow of Ring A and into full sunlight;

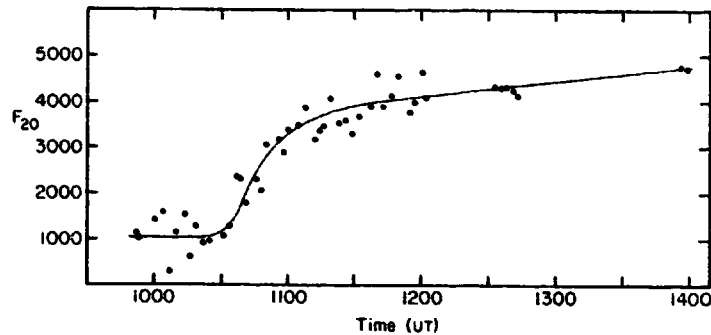


Figure 16. Thermal observations at 20 microns of the reappearance of Iapetus from the shadow of Saturn's Ring A, 8 January 1978. This preliminary curve shows the increase in thermal flux following reheating of the satellite surface by sunlight after reappearance from the shadow. From Cruikshank and Becklin (in preparation).

emersion from the ring shadow was predicted (by Alan Harris) at 1100 UT, but the satellite surface had clearly begun to warm up starting at about 1030 UT. This suggests that the outer extremities of Ring A are partly transparent, a result known earlier from observations of stellar occultations. There is evidence that the thermal response of the uppermost surface layer(s) of the regolith of Iapetus is almost instantaneous, indicating, as in the case of the Galilean satellites (Morrison and Cruikshank 1973, Hansen 1973) that the thermal conductivity and the thermal inertia are extremely low. Detailed models of the Iapetus data may put realistic constraints on the presence of atmospheric gases on this satellite because of the strong effect of an atmosphere on the thermal conductivity of the dendritic surface microstructure presumed to exist on Iapetus.

The reason for the stunning asymmetry in the distribution of frost, hence the brightness, on the leading and trailing faces of Iapetus is not understood. Hypotheses proposed have included both preferential deposition of frost on the trailing hemisphere and preferential removal of frost from the leading hemisphere, but neither can be satisfactorily modeled, especially in view of the more nearly uniform distribution of bright (or dark) materials on the other satellites. A more recent hypothesis suggests that dark material generated from impacts on Phoebe might preferentially accumulate on the leading face of Iapetus as the particles spiral toward Saturn, but this, too, requires detailed modeling. In this context, the determination of the nature (at least albedo) of the surface of Phoebe is of interest.

## ATMOSPHERES

Except for Titan, nothing is known about the presence of atmospheres on the satellites of Saturn, but the Fink *et al.* (1976) spectra would have shown methane or ammonia had either gas been present in even very small amounts. Water frost has a finite vapor pressure, and water vapor will dissociate in the presence of solar ultraviolet light with spectroscopically identifiable oxygen as one byproduct. Searches for oxygen surrounding the icy Galilean satellites have so far been negative, however, and the reduced vapor pressure at the lower temperature of the Saturn satellites, plus the lesser solar ultraviolet flux, makes the detection from earth of oxygen around Rhea, for example, unlikely.

## INTERIOR STRUCTURES OF THE SATELLITES

The principal studies of the interior structures and thermal histories of small bodies in the outer solar system have been those of Lewis (1971a, b, 1972) and Consolmagno and Lewis (1976), who have described equilibrium and disequilibrium models of condensation from the solar nebula. In the most recent exposition of this work, Consolmagno and Lewis (1977) have shown that for condensation at  $T = 160$  K or less, a body will have a bulk composition consisting of C1 chondritic material and water ice in roughly equal proportions if the process is slow enough to permit maintenance of chemical equilibrium with the surrounding solar nebula. If condensation occurs too fast, disequilibrium occurs and the body is built up of layers that do not interact chemically with one another. Such a body will have a high-density core surrounded by a mantle of ice and ammonium hydrosulfide, with an ultimate crust of ammonia ice.

The total mean densities of both types of satellite will be about the same, and within the range of the probable densities of the Saturn satellites, except Titan. The higher mean density of Titan suggests a larger volume fraction of silicate material.

The thermal histories of the small satellites depend on their compositions because of the different melting temperatures of various ices. If only C1 material and water ice are present, satellites less than 650 km in radius will probably not melt, and bodies as large as 1000 km will melt and differentiate only slightly. In models where ammonia compounds are present, smaller bodies will melt because of the lowered melting temperature, and satellites of 700 to 1000 km radius will be significantly

differentiated with a core of silicates, a mantle consisting of water ice and an ammonia-water solution, plus a crust of water ice a few hundred kilometers thick.

The thermal history of Titan is much more complex because of its greater size (with higher internal pressure) and possible larger volume fraction of silicate minerals. Melting occurs early in the history of a satellite this large, and accelerates as energy is released by the gravitational settling of denser fractions. The thermal histories of large bodies are perhaps more properly termed cooling histories, and the formation of different pressure phases of the ices in the interiors of these objects, plus the chemical interactions of the different constituents has only begun to be studied.

#### SUMMARY

It is useful at this point to summarize our understanding of each satellite individually; we consider them radially outward from Saturn.

1. S 11 If it exists, S 11 is probably an icy satellite with high albedo and radius several tens of kilometers. It may be, as Aksnes and Franklin suggest, just one member of a family of extended ring particles near the Roche limit. Verification of its existence will probably await the next passage of the earth through the ring plane, or perhaps spacecraft imagery.

2. Janus If Janus really exists, it is probably indistinguishable from S 11 and any other members of the ring-tip family of satellites, but additional data are clearly required.

3. Mimas By inference and analogy, the surface, and perhaps the bulk composition, of Mimas is dominated by water frost. Mimas is less than half the size of the largest asteroids.

4. Enceladus The only relevant data indicate that Enceladus is a frost-covered satellite, though there is a suggestion of a leading-trailing asymmetry in the same sense as that observed on Iapetus. If correct, there may exist a further clue to the puzzling case of Iapetus. Enceladus is about the same size as Mimas, but there is marginal evidence that its mean density is a bit greater, though still in the range of total volatile composition.

5. Tethys Another icy satellite, Tethys is about the same size as the largest asteroids, though its albedo is much higher. The frost appears uniformly distributed around the body.

6. Dione Dione is indistinguishable from Tethys at the present level of precision of the relevant data.

7. Rhea Frost dominates the surface of Rhea, and the albedo is uniformly high around the satellite. It is larger than the largest asteroids, but is still only half the size of Titan and the Galilean satellites. The mass, hence the density, is unknown, but frozen volatiles probably are the bulk compositional constituents.

8. Titan Titan dominates the satellite family in terms of diameter and mass, and exerts a measurable gravitational force on other bodies in the system. Its opaque atmosphere controls its photometric properties, and we know nothing of its surface. The mean density of Titan is uncertain, but is probably less than  $2 \text{ g cm}^{-3}$ , suggesting that the interior contains only a very small fraction of silicates in addition to the presumed condensed volatiles. Titan presents an interesting contrast to the icy satellites interior to it.

9. Hyperion Apparently another non-icy satellite, Hyperion exists in a gravitational relationship with Titan, and its orbital (and rotational) history may have been controlled by the larger body. Sketchy evidence appears to show a compositional similarity between the surface of Hyperion and satellites of Uranus and Neptune, but the nature of the material has not yet been deciphered. Hyperion is very small.

10. Iapetus One of the great puzzles of the solar system is the asymmetry in the distribution of frost on the surface of this satellite; the leading face may be dark, and the trailing hemisphere is largely covered with water frost. Iapetus is comparable in size with the largest asteroids, and it is the first satellite outward from Saturn whose orbit is inclined significantly to the ring/satellite plane. Thermal eclipse data appear to indicate a very low density upper surface layer.

11. Phoebe Marginal evidence suggests that Phoebe's surface is dark, in which case material removed by impacting space debris may be the source of the dark material on Iapetus. Phoebe moves retrograde in its large orbit, at a high inclination to the ring plane. There is no evidence on the question of surface composition.

Ground-based observational techniques have not been exhausted in the study of the satellites of Saturn. Infrared spectra can be obtained for all members of the system with the exception of Janus and S 11, with instruments in existence or under development, thus giving us the possibility of studying the composition of Mimas, Hyperion, the dark side of Iapetus, and Phoebe. The largest telescopes and most sensitive detectors are required, however, so progress on these problems will be slow.

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## DISCUSSION

D. MORRISON: Since you mentioned the recent Iapetus eclipse, I think it would be appropriate to read into the record the abstract of a preprint that I received from K. Aksnes and F.A. Franklin of a paper entitled Mutual Phenomena of Saturn's Satellites in 1979-1980. (This paper has since appeared in *Icarus* (1978), 34, 194-207.)

"Using two sets of orbital elements and the radii of the Saturnian satellites 1 (Mimas) through 7 (Hyperion), we predict that from Oct. 1979 until Aug. 1980 nearly 300 mutual eclipses and occultations involving these bodies will occur. To allow for the expected errors in the satellite ephemerides, we repeat these calculations in order to obtain the additional events that occur when all satellite radii (save Titan's) are increased by 1000 km. A third listing predicts eclipses of satellites by (the shadow of) the ring. Photometric observations of a large number of these events will add much precise information to our knowledge of the Saturnian system at a critical time."

D. CRUIKSHANK: These eclipses and occultations will be tough to observe.

G. SISCOE: Are the leading faces of all the satellites interior to Titan brighter than the trailing faces?

D. CRUIKSHANK: No, they're not. There is some marginal evidence that Enceladus is oriented the same way that Iapetus is, namely, that the face in the leading direction is darker than the trailing face. That conclusion was based on insufficient photometric data that are intrinsically very difficult to get.

In the case of Mimas, we have no data whatever. But it is interesting to speculate about the difference between the reflectance of the icy satellites and the reflectance of the rings, specifically short of 500 nm. The rings, as you know, drop off toward the UV, while the satellites are flat. Where does the transition occur? Does it occur at the edge of the rings? Does it occur with S-11 or Janus or Mimas? It would be very interesting to find out.

I might point out that a lot of these problems that still remain on the satellites of Saturn are soluble. We can get better spectra and better photometry, but it takes big telescopes with sensitive detectors.

D. MORRISON: There also will be a much improved opportunity in the next couple of years because of the rings being on edge. The scattered light problem will be substantially less for the inner satellites.

J. CUZZI: In the spectra of Callisto and Ganymede, can you resolve the rock component from the ice component? Also, do you see less reddening in the outer Galilean satellites than you do in Io and Europa? In the Saturn system you see the Saturn satellites having flat spectra and the rings being red, and I wondered if a similar effect was seen in the Galilean satellites.

D. MORRISON: There are such major compositional differences from one Galilean satellite to another that such a systematic effect is probably masked. That's why it's interesting to talk about the ensemble of the rings and the satellites for Saturn. As far as we know, they all have surfaces with about the same composition - mainly water ice. It is a more homogeneous sample, at least to first order.