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INFRARED SPECTRA OF THE SATELLITES OF SATURN: IDENTIFICATION OF WATER ICE ON IAPETUS, RHEA, DIONE, AND TETHYS

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ABSTRACT

Spectra of Iapetus, Rhea, Dione, and Tethys, as well as the rings of Saturn, were obtained from 0.8 to 2.7 μ at a spectral resolution of 50 cm^{-1}. All four satellites show the characteristic absorption bands of water ice. Ice temperatures of ~80 K are measured for each satellite. The extent of the surface ice coverage is discussed, and from it geometrical albedos are estimated. Upper limits of 100, 20, 100, and 40 cm-amagat, respectively, are derived for a methane atmosphere. No spectroscopic evidence for any other ices, gases, or minerals is found.
Subject headings: infrared: spectra — planets: Saturn — planets: satellites

Because of their small size and faintness, the satellites of Saturn are difficult objects for astronomical observations, so our knowledge about their physical nature is limited. Increases in detector sensitivity coupled with the advantages of Fourier spectroscopy now, however, make spectral observations of these objects possible. About a year ago we succeeded in obtaining a spectrum of the brightest of the Saturn satellites, Titan. The spectrum shows the expected deep methane absorptions and will be analyzed in a separate paper.

Recently we have obtained low-resolution spectra of four more of Saturn's satellites: Iapetus, Rhea, Dione, and Tethys. The spectra were obtained at the Steward Observatory 2.29 m (90 inch) telescope on Kitt Peak during the period 1976 January 13 –18.The instrument used was a rapid-scanning Michelson interferometer developed in this laboratory and described in detail by Larson and Fink (1975*a*). Indium antimonide photodiodes with a cooled 2.7 μ, short-wave-pass filter were used as detectors. Our spectrometer uses two optical inputs providing first-order cancellation of a uniform sky background. Because the position of Saturn is not symmetric with respect to the two inputs, scattered light from Saturn is not completely canceled. We checked for the presence of scattered light by integrating on a patch of sky adjacent to the position of Tethys, near inferior conjunction, on a night when the sky was quite hazy. Almost no signal was acquired in the same time that Tethys would have given a recognizable spectrum. We conclude that possible scattered light contributions in our spectra are less than the noise level.

The satellite data are displayed in Figure 1, apodized to a spectral resolution of 50 cm^{-1}. A solar-type stellar comparison is superposed on each satellite spectrum as a dotted line. This comparison is an average of spectra of η Boo (GO IV) and ξ UMa (GO V) weighted to match the average air mass (1.11) of the satellites. At the bottom of the figure a spectrum of the rings of Saturn (1976 January 15, effective observing time 5 minutes) is included for comparison. Each satellite spectrum is the result of approximately one night of integration time. As expected, the brightest of the satellites, Rhea (see Table 1) gave the best-quality spectrum. Differences in the signal-to-noise ratio of the other three satellites are due to their relative magnitudes and the

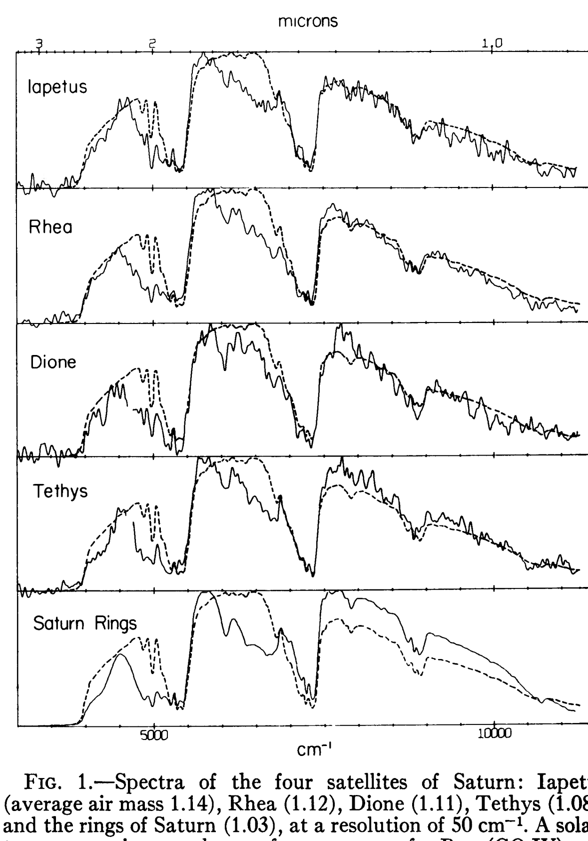

FIG. 1.—Spectra of the four satellites of Saturn: Iapetus (average air mass 1.14), Rhea (1.12), Dione (1.11), Tethys (1.08), and the rings of Saturn (1.03), at a resolution of 50 cm^{-1}. A solar-type comparison made up of an average of η Boo (GO IV) and ξ UMa (GO V) (average air mass 1.11) is superposed as a dashed line on each spectrum.

TABLE 1

PERTINENT PHYSICAL PARAMETERS AND RESULTS OF ANALYSIS FOR THE FOUR SATELLITES OF SATURN

Satellite	Mean Visual Opposition Magnitude*	Radius* (km)	Geometrical Albedo	Measured Ice Temperature	Fractional Ice Coverage	Estimated Geometrical Albedo	Upper Limit for CH_4 Atmosphere (cm-amagat)
Tethys	10.3	~500	...	77±15	>0.8	0.7	40
Dione	10.4	575	0.6*	67±25	0.5–0.7	0.6	100
Rhea	9.7	800	0.6*	87±15	>0.8	0.7	20
Iapetus	10.2–11.9	900	0.07–0.35†	75±15	>0.8‡	0.7‡	100
Rings of Saturn	...	...	...	78±5			

* From Morrison and Cruikshank 1974.
† Morrison *et al.* 1975.
‡ Bright side only.

changing transparency of the Earth's atmosphere on different nights.

Comparison of the four satellite spectra with the solar-type comparison shows that all four satellites have deep absorptions near 1.6 and 2.0 μ. The exact shape of these absorptions is clearly brought out in Figure 2, which contains ratio spectra of all four satellites and the rings of Saturn with the solar-type comparison. Included at the top of the figure is a laboratory water ice spectrum at a temperature of 90 K taken from Fink and Larson (1975). The close match of this laboratory spectrum to the satellite spectra leaves no doubt that water ice is present on all four satellites. The detection of water ice in the rings of Saturn is of course well established now (Kuiper, Cruikshank, and Fink 1970*a*, *b*, *c;* Pilcher *et al.* 1970*a*, *b*), and the high signal-to-noise ratio spectrum of the rings therefore serves as an ideal comparison for the satellites, since the temperature of the rings and the satellites should be closely matched. This close match is confirmed by the similar appearance of the temperature-dependent water ice feature at 6056 cm^{-1}. The calibration of its equivalent width versus temperature described in an earlier paper (Fink and Larson 1975) allowed us to determine the temperatures listed in Table 1. The limiting factor for the satellite ice temperature determination is the noise in their spectra, while for the rings of Saturn it is the uncertainty in the laboratory calibration. Within the uncertainties of the measurements the ice temperature of the rings (78 K) and the average for the four satellites (76 K) are the same, and agree with the calculated ice equilibrium temperature of 74 K, using a Bond albedo of 0.9 for the frost.

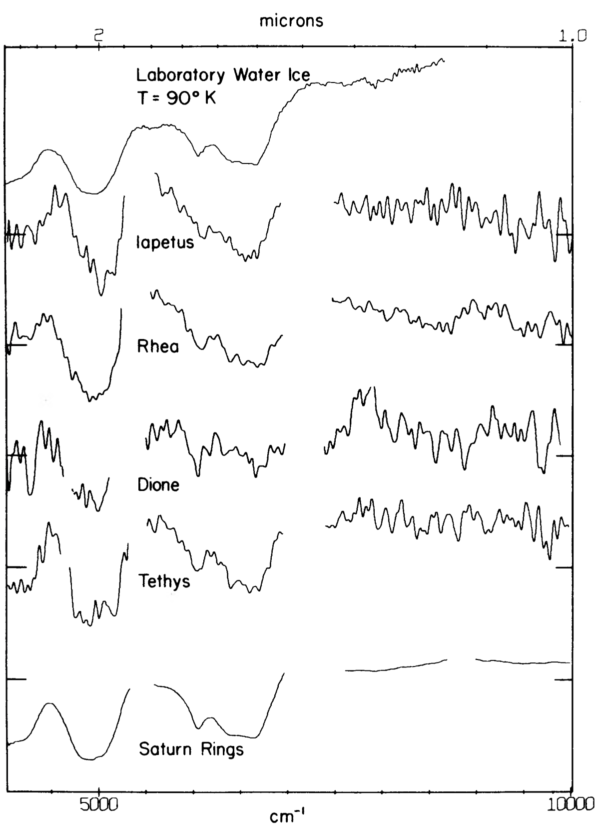

FIG. 2.—A laboratory water ice spectrum at a temperature of 90 K (*top*) and ratio spectra of the four satellites and the rings of Saturn, in Figure 1, with the solar-type comparison. The similarity of the absorption features in the spectra is quite clear. The ratio spectra are interrupted in regions of strong telluric absorption. Zero absorption levels are displaced as indicated on the side.

The depths of the water ice absorptions on Rhea, Tethys, and the rings of Saturn are about equal to those in the laboratory ice spectrum, which represents a completely frost-covered surface. While the depths of the ice absorptions may be affected to some degree by the ice texture and particle size, we feel that these effects are not overriding and an estimate of the frost surface extent is feasible. With this proviso and the assumption that the albedo of any non-ice constituent is not so low that it reflects negligible flux near 2 μ, we conclude that these two satellites have almost complete ice coverage. Despite its lower signal-to-noise ratio, Dione clearly shows weaker ice absorptions than the satellites Rhea and Tethys on either side of its orbit. Dione must therefore have a considerable fraction of non-icy material exposed on its surface.

The slightly weaker ice absorptions on Iapetus can be explained by the well-known orbital change in brightness of this satellite. Our observations were made at an orbital phase angle around Saturn of 339°, or a little more than halfway between greatest western elongation, when the satellite is brightest, and superior conjunction. The projected surface area of the bright side facing us is 68 percent, and the ratio of the albedo of the bright side to the dark side is 5/1 (e.g., see Morrison and Cruikshank 1974). Using these numbers, we calculated that the observed strengths of the ice absorptions on Iapetus can be synthesized from a bright side with a 100 percent ice cover, hence a spectrum similar to that of Tethys or Rhea, and a bare dark side, with a neutral reflectivity similar in appearance to the stellar comparison. Complete confirmation of this interpretation will require spectra of both the bright side and the dark side. Such spectra are entirely within our present instrumental capability if a large telescope such as the planned NASA infrared telescope or the KPNO 4 m telescope is used. For the other satellites no definite conclusion about the orbital phase variations of the ice absorptions could be made because of the limited orbital coverage resulting from only one night of observing time for each satellite and the modest signal-to-noise ratio.

It having been established that large portions of the satellites' surfaces are covered with water ice, it is possible to estimate their visual albedos. The Galilean satellites Europa and Ganymede are also ice covered and have more accurately determined geometrical albedos of 0.65 and 0.45 respectively, (Millis and Thompson 1975; Wamsteker 1975; Morrison, Morrison, and Lazarewicz 1974; and review by Morrison and Cruikshank 1974). Comparison of the depths of the ice absorptions in our spectra with those in spectra of the Galilean satellites (Pilcher, Ridgway, and McCord 1972; Fink, Dekkers, and Larson 1973) shows Rhea and Tethys to have slightly deeper ice absorptions than Europa while those of Dione are slightly less. All four of the Saturn satellites have deeper ice absorptions than Ganymede. On this basis we estimate geometrical albedos of 0.7 for Rhea and Tethys, and 0.6 for Dione. The bright side of Iapetus should also have an albedo of about 0.7 since we have shown above that it is substantially ice covered. Our albedo for Rhea is a little higher than the value of 0.6 derived by Morrison (1974), while for Dione our value agrees with the one by Morrison. For Tethys, no albedo has previously been reported.

The close agreement between our albedo estimates and the measured albedos indicates that the basic premises that were used in our estimates are reasonable. Instead of estimating an albedo, we therefore can conclude that the surface properties of Rhea and Dione, such as the texture and scattering properties of the ice and the reflectivity of the rocky materials, are similar to those of Europa and Ganymede. Our value of 0.7 for the bright side of Iapetus is considerably higher than the value of 0.35 derived by Morrison *et al.* (1975), but not so far different from the value of 0.48 recently reported by Veverka, Burt, and Elliot (1976). The remaining difference might be explained by a different texture of the ice on Iapetus, a large fraction of very dark material, or a slightly smaller radius than the one determined by Veverka. It appears that the unusual photometric properties of this satellite must be better understood before a definitive albedo or size can be determined.

Because of the unexpected detection of a deep methane atmosphere on Titan by Kuiper (1944), we have also examined our spectra for any traces of an atmosphere. At the present signal-to-noise ratio no unidentified absorptions can be discerned on any of our spectra. Since the vapor pressures of most gases (such as NH_3, CO_2, etc.) at the temperatures of the satellites are very low, we have limited ourselves to determining upper limits for methane, the most plausible constituent. By searching for the Q-branches of the methane bands at 4220, 4320, 4540, and 6006 cm^{-1} and employing an analysis similar to that described in our earlier papers on the Galilean satellites (Fink, Dekkers, and Larson 1973; Fink, Larson, and Gautier 1976), we obtain upper limits for Rhea of 20, Tethys 40, and Dione and Iapetus 100 cm-amagat of methane. The major error in these numbers comes from the uncertain saturation factor of the Doppler curve of growth which had to be used because of the presumed nonexistence of a satellite atmosphere. Saturation effects for these bands can thus be very large. However, if such were the case, the many weak lines in the complex spectrum of methane would start to contribute and therefore nullify the extreme saturations allowed by a purely theoretical curve of growth. Negative results for an atmosphere on Rhea, Tethys, and Dione were also obtained by Kuiper (1944), but the limit of his film sensitivity near 6600 Å would only permit searching for very weak methane bands; therefore, his upper limits, although not stated in his paper, must be of the order of 100 m-amagat.

The detection of water ice on the observed four satellites of Saturn is not, of course, completely unexpected. The stability of water ice over a planetologic time scale of a few billion years, on bodies near Saturn's orbit, can be demonstrated by a consideration of the vapor pressure of ice (e.g., see Kuiper 1952, p. 365). A number of avenues of investigation have therefore been used to supply indirect evidence for the possibility of water ice as a surface and bulk constituent. More than 50 years ago, Hepburn (1923) was able to estimate a size and therefore a density for the six inner satellites of Saturn, by assuming a reasonable albedo. The low densities which he derived by that method led him to suggest that these bodies might be made of water ice. Kuiper (1952) lent some support to these densities by difficult and therefore quite uncertain diameter measurements of the satellites Rhea, Dione, and Tethys. That the albedos chosen by Hepburn and Kuiper were approximately correct was verified by polarimetric measurements of Zellner (1972) and Bowell and Zellner (1973), and by combined visual and infrared photometric measurements by Morrison (1974). Spectrophotometry from 0.4 to 1.1 μ of the satellites Iapetus, Rhea, Dione, and Tethys by McCord, Johnson, and Elias (1971) showed a general flat reflectivity with a slight drop toward the infrared which is consistent with a variety of ice spectra. Infrared photometry of Rhea at 1.6 and 2.2 μ by Johnson, Veeder, and Matson (1975) supported this drop of the reflectivity toward the infrared, consistent with a surface of icy constituents. *JHKL* photometry measurements recently carried out by Morrison *et al.* (1976), for the same four satellites investigated in this paper, again supported ice as a likely surface constituent.

Since the surfaces and interiors of the major planets are not accessible to direct observation, one must look to their satellites for providing clues to their constitution and evolution. Direct spectroscopic evidence for water ice has already been reported for the rings of Saturn and for the Galilean satellites Europa and Ganymede. These results, together with our present detection of water ice on four of Saturn's satellites, provide important evidence for the correctness of the basic framework of current theories of the origin of our solar system.

Detailed calculations of condensation processes in the primitive solar nebula have been carried out by Lewis (1972, 1973). For satellites of the outer planets he proposes a condensate consisting of approximately 54 percent by weight water ice, 10 percent ammonia ice, 21 percent silicates, and 15 percent iron oxide. Lewis (1971) also discusses the consequences of radioactive heating on the evolution of a satellite formed from the above mixture. He calculates that bodies greater than about 900 km in radius should have largely, if not totally, melted at some time during their lifetime. For this situation he predicts a crust of pure water ice. Smaller bodies need not have completely melted and will remain relatively undifferentiated, preserving a surface more representative of the primitive condensate.

Since the radii of Tethys and Dione (see Table 1) are considerably below the limit that Lewis calculates to be differentiated, we looked closely for evidence of ammonia ice in our spectra. Calculations of the stability of ices in the solar system by Watson, Murray, and Brown (1963) and Lebofsky (1975) show that in addition to water ice, ammonia ice, and somewhat more marginally CO_2 ice, should be stable near Saturn's orbit. Ammonia ice has a strong absorption at 4400 cm^{-1} (2.27 μ) (e.g., Kieffer and Smythe 1974; Fink, Larson, and Gautier 1976) in a region where water ice has no absorptions. We estimate that we could clearly see the ammonia ice feature if its abundance were one-tenth that of the water ice, or about half the amount in Lewis's condensate. We do not, however, see evidence for this amount of ammonia ice on any of the four satellite spectra.

Although risks are involved in extrapolating observed surface properties to the bulk composition, our present results provide us with the only observable clues, and constitute the tightest constraints on the chemistry of Saturn's satellite system. From our negative result on ammonia ice we conclude that either the primordial condensate had a different composition than that of the assumed solar composition or satellites smaller than estimated by Lewis also differentiated. A factor of 2 uncertainty in the solar composition is not unlikely, although the chemical composition of the solar nebula is constrained by many other lines of evidence, and Lewis's extrapolation to the satellite composition is not extreme. Greater uncertainty surrounds the mechanism of differentiation in small solar system objects. Heating mechanisms effective early in the history of the solar system are not well understood. Recent observations of differentiated silicates in the asteroid Vesta (McCord, Johnson, and Elias 1971; Larson and Fink 1975*b*) suggest that there may have been an unexpectedly intense, but short-lived, heating episode shortly after the formation of these objects. Even with the reduced silicate component of the satellites of the outer planets, internal temperatures may have been sufficient to melt bodies with radii of about 100 km or less, thereby providing the pure water ice crust consistent with our observations.

A more definite interpretation of our observations cannot be reached until other puzzling aspects of Saturn's satellite system are better understood. Especially enigmatic is the concentration of ice on the trailing side of Iapetus and the origin and composition of the dark material on its leading side. Photometric studies of the other three satellites indicate that they are slightly brighter on their leading sides. The smaller amount of ice observed on Dione, whose orbit lies between the more completely ice-covered satellites Tethys and Rhea, is also unexpected. It appears that, as more knowledge about the physical nature of the satellites is acquired, similarities or progressive changes in their properties predicted by model theories simply do not exist, and each satellite acquires an individuality of its own.

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