During the Saturn encounter, the carrier signal strength margin was only about 18 dB above threshold. For this reason, the signal could only be followed to a level at which the closest approach distance of the ray corresponded to a pressure level of less than 120 mbar. It may be possible to extend the depth of penetration somewhat but certainly not to a great extent.

A profile of the temperature in the atmosphere of Saturn for a hydrogen fraction by number of 94 percent is shown in Fig. 3. The three separate curves represent initial temperatures at the top of the measurement of 50, 100, and 150 K. It is apparent that the depth of signal penetration was sufficient to carry measurements below the temperature minimum at the tropopause and slightly into the convective region of the atmosphere. The reason for choosing a hydrogen fraction of 94 percent becomes clearer upon examination of Fig. 4. The temperature-pressure structure of the Saturn atmosphere as determined from the Pioneer Saturn exit data is plotted alongside the temperature structure obtained from the Pioneer Saturn infrared radiometer experiment (*9*), as well as several models produced from Earth-based observations (*10*). The dots surrounding the Pioneer Saturn occultation profiles represent the effects of different assumptions with respect to the initial temperature. It should be noted that these are not error bars and should not be so interpreted. The actual error bars or uncertainty limits have not yet been established and they depend more on the subtleties of drift function fit than on the initial temperature assumptions.

The profile derived from the Pioneer Saturn radio occultation with the assumption of 94 percent hydrogen and 6 percent helium practically overlies the profile determined from the infrared radiometer measurements. The infrared radiometer profile has been derived assuming a helium fraction of 15 percent, and it will change somewhat as the helium fraction is varied. The location of the temperature minimum in the radio occultation profile is highly dependent on the composition. For instance, for 15 percent helium that minimum occurs at a temperature of about 91 K, and for 100 percent hydrogen it moves to about 79 K. This sensitivity to composition will eventually allow a good estimate of the ratio of hydrogen to helium to be made after several iterations with the Pioneer Saturn infrared radiometer results. Although it is premature at this stage of analysis to derive a helium fraction, it is obvious that the percentage of helium by number cannot be higher than about 10 percent or lower than about 4 percent. Such a helium fraction is also consistent with the modeling of the interior structure of Saturn based on the mass and gravity coefficients derived from the celestial mechanics experiment (*4*). The structure in the temperature profile above the minimum is probably real, and the ledge at 10 to 30 mbar may represent heating by a layer of particles.

The analysis of data from the Pioneer Saturn radio occultation is continuing, and more information on the structure of the ionosphere and upper neutral atmosphere will be provided from the analysis of entry occultation data. These results will provide further clarification of the preliminary findings reported here, and in November 1980 radio occultation results at two frequencies will become available from the Voyager 1 flyby of Saturn. These results will most likely provide a deeper penetration into the neutral atmosphere.

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References and Notes

1. J. Dyer, *Science* **207**, 400 (1980).
2. A. Berman and R. Ramos, *IEEE Trans. Geosci. Electron.*, in press.
3. R. Woo, W. Kendall, A. Ishimaru, R. Berwin, *Jet Propul. Lab Tech. Mem. 33-644* (1973).
4. J. D. Anderson, G. W. Null, E. D. Biller, S. K. Wong, W. B. Hubbard, J. J. MacFarlane, *Science* **207**, 449 (1980).
5. A. J. Kliore and P. M. Woiceshyn, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976), p. 238.
6. G. Fjeldbo and V. R. Eshleman, *Planet. Space Sci.* **16**, 1035 (1968); A. J. Kliore, in *Mathematics of Profile Inversion*, L. Colin, Ed. (Publ. TMX-62, 150, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 3-2.
7. J. H. Waite, Jr., S. K. Atreya, A. F. Nagy, *Geophys. Res. Lett.* **6**, 723 (1979).
8. V. R. Eshleman, G. L. Tyler, G. E. Wood, G. F. Lindal, J. D. Anderson, G. S. Levy, T. A. Croft, *Science* **204**, 976 (1979).
9. A. P. Ingersoll, G. S. Orton, G. Münch, G. Neugebauer, S. C. Chase, *ibid.* **207**, 439 (1980).
10. A. Tokunaga and R. Cess, *Icarus* **32**, 321 (1977); J. Caldwell, *ibid.* **30**, 493 (1977); L. Wallace, *ibid.* **25**, 538 (1975); D. Gautier, A. Lacombe, I. Rivah, *Astron. Astrophys.* **61**, 149 (1977).
11. We thank the Pioneer Project personnel at NASA/Ames Research Center, especially C. F. Hall, the project manager, and R. Hogan, J. Wolfe, and J. Dyer of his staff, for providing leadership in this important phase of the mission. We also express our gratitude to the personnel of the NASA-Jet Propulsion Laboratory (JPL) Deep Space Network, especially to R. B. Miller, A. Bouck, T. Howe, J. Wackley, and W. Hietzke for their help in acquiring the data, and to the JPL Pioneer navigation team led by W. Kirhofer and including W. Blume, S. K. Wong, E. Biller, and A. Lubeley for providing orbital data. Special thanks are due to P. Laing and D. Cain for adapting the prediction software and C. Conrad for help with data reduction. We also thank D. O. Muhleman, A. P. Ingersoll, and G. S. Orton for some useful discussions. The work described above represents the results of one phase of research at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100. A.J.K. dedicates this report to the 400th anniversary of the University of Vilnius, Lithuania, the celebration of which took place while this work was in preparation.

3 December 1979

Pioneer Saturn Celestial Mechanics Experiment

Abstract. *During the Pioneer Saturn encounter, a continuous round-trip radio link at S band (~ 2.2 gigahertz) was maintained between stations of the Deep Space Network and the spacecraft. From an analysis of the Doppler shift in the radio carrier frequency, it was possible to determine a number of gravitational effects on the trajectory. Gravitational moments (J_2 and J_4) for Saturn have been determined from preliminary analysis, and preliminary mass values have been determined for the Saturn satellites Rhea, Iapetus, and Titan. For all three satellites the densities are low, consistent with the compositions of ices. The rings have not been detected in the Doppler data, and hence the best preliminary estimate of their total mass is zero with a standard error of 3×10^{-6} Saturn mass. New theoretical calculations for the Saturn interior are described which use the latest observational data, including Pioneer Saturn, and state-of-the-art physics for the internal composition. Probably liquid H_2O and possibly NH_3 and CH_4 are primarily confined in Saturn to the vicinity of a core of approximately 15 to 20 Earth masses. There is a slight indication that helium may likewise be fractionated to the central regions.*

A continuous round-trip coherent radio link at S band (~ 2.2 GHz) was maintained between the Pioneer spacecraft and stations of the Deep Space Network (DSN) during the period from 17 August to 4 September 1979. When the spacecraft passed behind Saturn, which started about 62 seconds after closest approach on 1 September, radio contact with Pioneer was lost and consequently there is a 97-minute gap in the round-trip data shortly after closest approach. Nevertheless, by analyzing the Doppler shift in the radio carrier frequency outside of occultation, one can measure trajectory perturbations on the spacecraft and de-

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Table 1. Ring model used in the preliminary analysis of Pioneer Saturn data. Values of GM correspond to a total mass of 10^{-6} Saturn mass. Other values of total mass are obtained by scaling each GM proportionately.

Ring	Inner radius* (km)	Outer radius* (km)	GM† (km^3 sec^{-2})
C	72,600	91,800	1.3
B	91,800	98,406	2.4
B	98,406	105,746	6.1
B	105,746	117,000	20.9
A	121,800	129,356	4.8
A	129,356	137,400	2.5

*Radii are derived from a review by Cuzzi (*8*).
†Masses are derived from surface densities which are assumed proportional to the optical thicknesses of Cook *et al.* (*7*).

termine values for various gravitational parameters (*1*). This is the essence of the celestial mechanics experiment.

Time variations in the solar electron density along the ray path, as Pioneer Saturn approached conjunction on 10 September, produced an increasingly noisy S-band Doppler signal. The sun-Earth-spacecraft angle at encounter was about 8° of arc. After conjunction, when the spacecraft was far enough from the sun in angular separation, more precise Doppler tracking was resumed, but we have not analyzed these later data in sufficient detail to report on them at this time. Instead, preliminary results are given for a trajectory which fits the reduced Doppler data from 1 July to 4 September 1979 in a weighted least-squares sense.

Before 17 August the tracking was not continuous, but the amount of data is sufficient for an accurate determination of the trajectory. During the period when the data were continuous, the DSN received Doppler tracking data at 64-m antennas in California (Goldstone), Australia, and Spain. The raw data are in the form of accumulated phase measurements from a cycle counter. The data reduction consists of a conversion of the phase measurements to frequency data by differencing two successive phase readings and then dividing by the time interval between readings. For data taken near Saturn encounter, we used a sample time of 10 seconds to construct frequency data. Outside of the encounter region, the sample time was increased because there are no high-frequency components of interest in the gravitational field once the near-encounter region has been sampled.

The noise on the data can be characterized by the unbiased estimate of the standard error on the Doppler residuals after the fit. This varies from day to day but is typically 0.05 Hz (3 mm/sec) at the 10-second sample rate near encounter. Outside of the conjunction region, the Pioneer data are more accurate by about one order of magnitude than near conjunction. Unpredictable plasma variations produce low-frequency components (~ 10^{-4} Hz) in the power spectrum of the data (*2*), and they represent the most important error sources in the gravitational results from Pioneer Saturn. Our evaluation of these errors is incomplete, and therefore relatively large error estimates have been attached to the preliminary results. Improvements are expected with subsequent analysis, but plasma effects will remain as the limiting error source.

Gravitational field of Saturn and its rings. The close approach of Pioneer Saturn to a distance of 1.35 equatorial radii (R_S) from the center of the planet provides an excellent opportunity to determine the character of the external gravitational field. The higher order moments, in particular, J_2 and J_4 in the usual Legendre expansion of the planetary field, yield important boundary conditions on the interior mass density distribution (*3*), and knowledge of the mass of the rings can contribute to an understanding of their constituents. Pioneer Saturn offers the first dynamical data on a body that actually penetrates the sphere defined by the outer ring boundary, in contrast to the satellites which are all outside of this sphere as expected from a calculation of Roche and accretion limits for low-density material (*4*). Indeed, Pioneer Saturn penetrates well within the sphere defined by the inner boundary of the B ring, so that, if the rings are sufficiently massive, they should be detectable in the Doppler data taken on the day of encounter. In fact, the rings are not detectable in the following sense. If the rings are ignored, then it is possible to fit the Doppler data with the remaining gravitational model for the planet, satellites, and solar perturbations, such that there are no systematic Doppler residuals after the fit that could be attributed to the rings. As a result, the best preliminary estimate of the total mass in the rings is zero with a standard error of 3×10^{-6} Saturn mass (M_S).

The only recent attempt to determine the mass of the rings from satellite dynamics is that of McLaughlin and Talbot (*5*). They found that it is impossible to disentangle the ring mass from the higher order planet harmonics, particularly J_4, but by imposing a theoretical dependence between J_2 and J_4 based on a polytropic interior for Saturn they were able to determine a total ring mass of $(6.2 \pm 2.4) \times 10^{-6}$ M_S. However, as they point out, this result is highly model-dependent. Nevertheless, their conclusion that the satellite data contain information on the ring mass is important. Because of the different orbital characteristics for an inner satellite and the Pioneer Saturn flyby, there are probably orthogonalities in information from the two sources. We would expect that a future combination of Pioneer data and results from satellite dynamics will decrease the current ring mass uncertainty by more than $1/2^{1/2}$. By the same argument, even better results should become available when Voyager flyby data are added in the next few months.

Table 2. Determinations of Saturn gravitational harmonic coefficients J_2 and J_4 normalized to an equatorial radius of 60,000 km. All uncertainties are standard errors.

Source	$J_2 \times 10^2$	$J_4 \times 10^3$
Jeffreys (*9*)	1.651 ± 0.002	−1.00 ± 0.07
Kozai (*10*)	1.6445 ± 0.0013	−1.05 ± 0.07
Pioneer Saturn (preliminary)*	1.646 ± 0.005	−0.99 ± 0.08

*Determined with J_6 fixed at a value of 0.84×10^{-4}, J_8 fixed at -0.11×10^{-4}, and the total mass of the rings fixed at 10^{-7} M_S.

Because the rings are so fundamental to a description of the gravitational field of Saturn, we include here a brief description of the model being used in the Pioneer analysis. It is a series of annuli of constant areal density in the equatorial plane of Saturn, with each annulus defined by an inner and outer radius and by a mass M multiplied by the gravitational coefficient G. The acceleration on the Pioneer spacecraft is determined for each annulus by differencing the attraction from two disks having respective radii equal to the inner and outer radii of the annulus. The accelerations are evaluated with elliptic integrals, which avoid the singularities of the usual Legendre expansions on the spheres defined by ring boundaries (*6*). For the preliminary analysis we have divided the rings into six annuli in accordance with the optical thicknesses given by Cook *et al.* (*7*). It is assumed that the surface density of each annulus is proportional to the optical thickness. Then one determines the mass of each annulus by multiplying the surface density by the surface area. The results, normalized to a total mass of 10^{-6} M_S, are given in Table 1. The radii of the inner and outer boundaries of the A, B, and C rings are taken from a review by Cuzzi (*8*).

With the preceding model for the rings, we have obtained a number of least-squares solutions for the harmonic coefficients J_2 and J_4. The total mass in the rings has been varied from 0 to 10^{-6} M_S, and in addition solutions for the ring mass have been attempted with one degree of freedom (total mass) and two degrees of freedom (total mass plus the ratio of the mass in the B ring to the mass in the A ring). In this way, a correlation between J_4 and the total ring mass has been found which must be taken into account in assigning error estimates to J_4. In addition, uncertainties in the ephemeris of the Saturn system with respect to the sun and Earth are significant in determinations of J_2 and J_4. Therefore, the current estimate of the two harmonics is affected systematically by both the ring mass and the planet ephemeris. Values for the two coefficients and realistic error estimates are given in Table 2 along with other determinations from satellite dynamics (*9, 10*). Because of the systematic errors in the Pioneer Saturn determination at the present time, the assigned errors are comparable in magnitude to those from satellite dynamics. In the future, this situation will change and the spacecraft results, particularly with the addition of Voyager data, will be superior. This is especially the case for J_4, which is the parameter to improve for purposes of limiting the class of acceptable interior models. The solutions in Table 2, exclusive of Pioneer Saturn, assume a zero ring mass. The Pioneer determination is based on an assumed ring mass of 10^{-7} M_S, or on values of GM for the six annuli that are ten times smaller than given in Table 1. The Pioneer values of the Saturn harmonics are determined with fixed values of J_6 and J_8 of 0.84 $\times 10^{-4}$ and -0.11×10^{-4}, respectively (*11*). All other harmonics are assumed zero, consistent with hydrostatic equilibrium. The mass of the planet is a free parameter in the solution. The satellite masses are fixed at the values given in the next section except for Iapetus, Rhea, and Titan, which provide three more free mass parameters.

Satellite masses. Masses for a number of satellites can be determined from their gravitational attraction on Pioneer Saturn. The closest approach distances are shown in Table 3 along with estimates of the masses of the satellites from studies of their mutual perturbations (*12*) and from Pioneer Saturn. A good determination of the masses of Titan, Rhea, and Iapetus is possible with Pioneer Saturn. The other satellite masses cannot be improved, and their masses are fixed in the fits to the data.

A preliminary fit to the Doppler data yields a value of GM for Rhea of 143 ± 50 km^3 sec^{-2}, whereas the GM of Iapetus is 188 ± 50 km^3 sec^{-2}. The respective values of the masses are (3.8 ± 1.3) × 10^{-6} and (5.0 ± 1.3) × 10^{-6} M_S, and the corresponding mean densities, including radius uncertainties (*13*), are 1.0 ± 0.5 and 1.8 ± 0.9 g cm^{-3}. The uncertainties in the mass determinations are realistic and reflect considerations of systematic error from the gravitational field of Saturn and its rings, as well as uncertainties in the planetary and satellite ephemerides. Future improvements will be made both from additional analysis of Pioneer Saturn data and from the upcoming Voyager encounters. Our preliminary mass of Rhea is in good agreement with the determination of McLaughlin and Talbot (*5*), who give a value of (4.8 ± 0.8) × 10^{-6} M_S from satellite dynamics.

The preliminary value of the GM for Titan is 8989 ± 100 km^3 sec^{-2} or (2.370 ± 0.027) × 10^{-4} M_S. The value differs significantly from the most recent 1958 value of Message (*14*) of (2.4622 ± 0.0013) × 10^{-4} M_S, but it is consistent with some older determinations which, like those of Message, use the motion of Hyperion. In particular, the 1911 analysis of Eichelberger yields a value of (2.397 ± 0.049) × 10^{-4} M_S (*15*). Also, our value is barely consistent with the 1953 determination of Jeffreys [(2.412 ± 0.019) × 10^{-4} M_S] from the motion of the orbital plane of Iapetus (*16*). Subsequent Pioneer analysis may yield a more accurate mass for Titan, but it is more probable that data from a second flyby by Voyager will be needed before the discrepancies between various determinations are resolved. In view of the preliminary nature of the Pioneer result, it is premature to adopt an updated mass for Titan at this time. The best current estimates of densities for the Saturn satellite system are given in Table 3. The overall low densities of the satellites, taken together with an indication of low total mass in the rings, suggest that ices comprise most of the material surrounding Saturn.

Table 3. Closest approach distances of Pioneer Saturn from satellites along with estimates of radius (*13*), mass, and density. Masses for Rhea, Iapetus, and Titan are from this work. Other satellite masses are from Kozai (*12*). All uncertainties are standard errors.

Satellite	Closest approach (km)	Radius (km)	Mass ($M_S \times 10^{-6}$)	Density (g cm^{-3})
Mimas	103,400	180	0.066 ± 0.002	1.5
Enceladus	225,200	300	0.13 ± 0.06	0.7
Tethys	331,700	520 ± 60	1.10 ± 0.03	1.1 ± 0.4
Dione	291,100	500 ± 120	1.85 ± 0.06	2.0 ± 1.4
Rhea	345,600	800 ± 100	3.8 ± 1.3	1.0 ± 0.5
Titan	363,073	2,900 ± 200	237 ± 3	1.32 ± 0.27
Hyperion	674,000	112 ± 15	?	?
Iapetus	1,039,000	725 ± 100	5.0 ± 1.3	1.8 ± 0.9
Phoebe	9,453,000	120	?	?

Because of the sensitivity of the Pioneer Doppler system, it is reasonable to ask whether the satellite 1979 S 2, which was detected by three separate particle experiments (*17–19*), might also be evident in terms of its gravitational effect on the Pioneer trajectory. The gravitational perturbation in velocity by a small body of this type is given by the formula (*20*)

$$\Delta v = \frac{GM}{vr}$$

where v is the flyby velocity at distance r. Because of the near coincidence of the decrease in respective proton and electron intensities as the spacecraft probably passed through the satellite's magnetic flux tube, Simpson *et al.* (*18*) infer that the spacecraft encountered the satellite at a distance of ~ 2500 km. At the time of the disappearance of flux, the geometry of the encounter was such that the spacecraft flyby velocity with respect to the satellite was 17 km sec^{-1} and the velocity perturbation occurred at an angle of 46° of arc with respect to the Earth-spacecraft line of sight. Certainly, any perturbation of magnitude 0.1 Hz (twice the root-mean-square noise or 6.7 mm sec^{-1}) would have been discernible in the Doppler data. However, no obvious anomalous effect appears in the data. Using the formula above and accounting for the cosine of 46°, we conclude that the mass of the satellite is less than 6.2 × 10^{21} g, if it was at a distance of ~ 2500 km at closest approach. If 1979 S 2 has a density of 1.0 to 1.5 g cm^{-3}, which is typical of the Saturn system, then the upper limit on its mass implies an upper limit on its radius of 100 to 115 km. This is near the lower bound of the radius estimates from the particle data (*17–19*), and hence the radius of 1979 S 2 is probably in the range of 85 to 115 km. An alternative explanation of our failure to detect the satellite is that the spacecraft passed

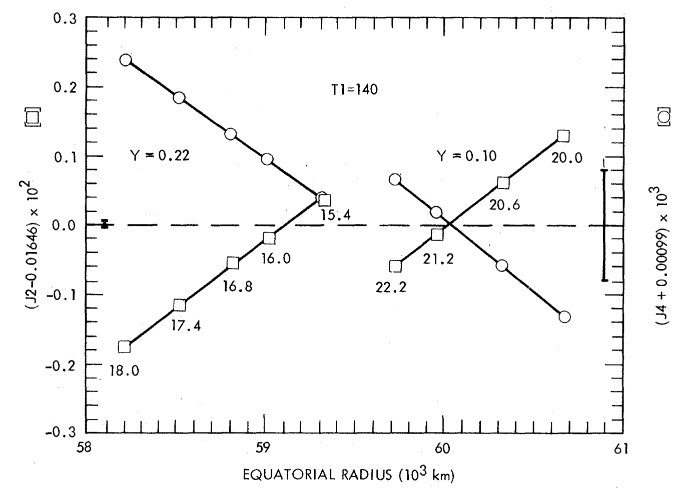

Fig. 1. Calculated values of the equatorial radius and gravitational harmonics J_2 and J_4, normalized to an equatorial radius of 60,000 km for a series of Saturn interior models with total core mass (in Earth masses) as independent variable. Results are shown for a solar composition helium abundance by mass ($Y = 0.22$) and a helium-poor abundance ($Y = 0.10$) in the envelope. The starting temperature T_1 at 1.0 bar is 140 K. The error bar at the right represents the error in J_4 from Pioneer Saturn, and the error bar at the left represents the error in J_2.

a few degrees of longitude to the west of the satellite at a considerably greater distance (~ 12,500 km), as suggested by Van Allen (*17*) and Blume (*21*).

Saturn interior. Although the development of interior models for Jupiter and Saturn has progressed in parallel (*22*), more observational and theoretical difficulties exist for Saturn than for Jupiter. A major theoretical problem is the uncertainty in the equation of state for a mixture of molecular hydrogen (H_2) and helium in the envelope. For Saturn, this region comprises almost one-half of the outer radial dimension of the planet, whereas for Jupiter, where it is less important, this region comprises less than 20 percent of the same dimension. The first detailed Saturn models which used a sufficiently accurate equation of state in the molecular region were those of Slattery in 1977 (*23*), and hence any models published prior to this should be considered rough approximations.

Pioneer Saturn can resolve some of the observational difficulties with Saturn, and current interior models can be improved from the theoretical point of view. We are in the process of computing new Saturn models which fit the observations and which use the most recent equations of state for the interior (*24*). The models consist of a hydrogen-helium envelope, a liquid outer core of ices (H_2O, CH_4, NH_3), and a liquid or solid, or both, inner core of rock (MgO, SiO_2, FeS, FeO). For preliminary models, the hydrogen and helium are assumed to be well mixed by convection at all levels in the envelope. The equation of hydrostatic equilibrium is solved for the rotating planet, and the planetary figure and gravitational moments are calculated to the third order in the ratio of the centrifugal-to-gravitational acceleration. Fourth-order calculations are in progress.

The observational constraints on the models are the following:

1) The temperature T_1 at the 1-bar level in the atmosphere, which from the Pioneer Saturn infrared data is ~ 140 K (*25*), the starting temperature for the adiabatic models.

2) The mass of the planet, which is known to one part in 10^4 from planetary and satellite dynamics (*26*).

3) The equatorial radius of Saturn, which is assumed equal to 60,000 km at the 1-bar level (*27*).

4) The gravitational moments J_2 and J_4 from the Pioneer Saturn flyby, which are important because they provide observational constraints on the interior mass distribution through the rotational response of the planet (*3*). The third-order theory which we presently use for models calculates J_4 to an accuracy of ~ 2 percent and the so far undetected J_6 to ~ 15 percent.

5) The period of rotation of the body of Saturn. Unfortunately, visual and spectroscopic observations of Saturn tell us little about the rotation of the body of the planet. Moreover, the fact that the axis of the magnetic dipole of Saturn is aligned closely with the spin axis (*28*) means that a rotation rate will be difficult or impossible to extract from the Pioneer magnetometer data. The rotation period must be considered a free parameter in the Saturn models within reasonable uncertainty limits of $10^h30^m \pm 30^m$.

The two important independent variables in the interior models are (i) the amount of heavy elements in the envelope and (ii) the total mass of material in the core. The gravitational moments are sensitive to the total core mass but relatively insensitive to how it is distributed. Thus the ratio of ices to rock is not determined by observation but by the estimated relative abundances in the solar system (*29*).

A series of preliminary Saturn models are shown in Fig. 1 for various values of the core mass (in Earth masses) and two helium mass fractions Y, which correspond to a solar composition model ($Y = 0.22$) and a helium-poor model ($Y = 0.10$). The calculations assume a rotation period of 10^h30^m and a temperature at 1 bar of 140 K. Values of J_2 and J_4, normalized to an equatorial radius of 60,000 km, are plotted versus the physical equatorial radius of the models. The zero line corresponds to the preliminary values of J_2 and J_4 from Pioneer Saturn. Although the determination of J_4 and the calculation of models, especially for a helium-poor envelope, are preliminary and subject to later revision, we nevertheless conclude that the envelope of Saturn may be depleted in helium relative to the solar abundance. We can produce an acceptable model which has a solar hydrogen:helium fraction in the envelope, but only by assuming adiabatic temperatures in the interior which correspond to an initial temperature of 160 K at 1 bar. This higher value does not appear to be consistent with the Pioneer infrared radiometer value of ~ 140 K. However, a low helium abundance is consistent with results from the radio occultation experiment (*27*).

A major conclusion that we draw from this initial study is that H_2O and possibly NH_3 and CH_4 are primarily confined in Saturn to the vicinity of the ~ 15 to 20 Earth mass core, if they are present in solar proportions to rock. If, on the contrary, this core were composed mainly of rock, then the solar composition complement of water, $\gtrsim 15$ Earth masses, would have to be distributed in the outer layers of Saturn, contrary to observation. We cannot yet conclude that helium is likewise fractionated to the central regions, although there is a slight indication that this may be so.

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References and Notes

1. See J. D. Anderson [in *Experimental Gravitation*, B. Bertotti, Ed. (Academic Press, New York, 1974), p. 163] for a general discussion of Doppler tracking with associated data reduction and analysis techniques.
2. See J. W. Armstrong, R. Woo, and F. B. Estabrook [*Astrophys. J.* **230**, 570 (1979)] for an evaluation of Doppler noise as a function of the angular separation of a Viking spacecraft from the sun.
3. W. B. Hubbard, V. P. Trubitsyn, V. N. Zharkov, *Icarus* **21**, 147 (1974); V. N. Zharkov and V. P. Trubitsyn, *ibid.*, p. 157; W. B. Hubbard, *ibid.*, p. 157.
4. R. Smoluchowski, *Nature (London)* **280**, 378 (1979).
5. W. I. McLaughlin and T. D. Talbot, *Mon. Not. R. Astron. Soc.* **179**, 619 (1977).
6. A theoretical model for the gravitational attraction of a disk was provided by F. T. Krogh, E. W. Ng, and W. V. Snyder of the Jet Propulsion Laboratory (in preparation).
7. A. F. Cook, F. A. Franklin, F. D. Palluconi, *Icarus* **18**, 317 (1973).
8. J. Cuzzi, in *The Saturn System*, D. M. Hunten and D. Morrison, Eds. (Publication NASA CP-2068, National Aeronautics and Space Administration, Washington, D.C., 1978), p. 73.
9. H. Jeffreys, *Mon. Not. R. Astron. Soc.* **114**, 433 (1954).
10. Y. Kozai, *Publ. Astron. Soc. Jpn.* **28**, 675 (1976).
11. These values of J_6 and J_8 are taken from Saturn interior models of W. L. Slattery [*Icarus* **32**, 58 (1977)] and were normalized to an equatorial radius of 60,000 km.
12. Mass estimates are taken from the most recent work of Kozai (*10*). We have converted the quoted probable errors to standard errors for consistency with the other uncertainties given in this work.
13. These radii are adopted by D. Cruikshank, in *The Saturn System*, D. M. Hunten and D. Morrison, Eds. (Publication NASA CP-2068, National Aeronautics and Space Administration, Washington, D.C., 1978), p. 217. Radii for Rhea (800 ± 100 km) and Iapetus (725 ± 100 km), from which we derive our density estimates, are based on work by R. E. Murphy, D. Cruikshank, and D. Morrison [*Astrophys. J.* **177**, L93 (1972)]; D. Morrison [*Icarus* **22**, 51 (1974)]; J. L. Elliot, J. Veverka, and J. Goguen [*ibid.* **26**, 387 (1975)]; D. Morrison, T. J. Jones, D. P. Cruikshank, and R. E. Murphy [*ibid.* **24**, 157 (1975)]; and J. Veverka, J. Burt, J. L. Elliott, and J. Goguen [*ibid.* **33**, 301 (1978)].
14. P. J. Message, *Trans. Int. Astron. Union* **10**, 111 (1958).
15. W. S. Eichelberger, *Publ. U.S. Nav. Observ.* **6** (appendix 2B), 1 (1911).
16. H. Jeffreys, *Mon. Not. R. Astron. Soc.* **113**, 81 (1953).
17. J. A. Van Allen, M. F. Thomsen, B. A. Randall, R. L. Rairden, C. L. Grosskreutz, *Science* **207**, 415 (1980).
18. J. A. Simpson, T. S. Bastian, D. L. Chenette, G. A. Lentz, R. B. McKibben, K. R. Pyle, A. J. Tuzzolino, *ibid.*, p. 411.
19. W. Fillius, W. H. Ip, C. E. McIlwain, *ibid.*, p. 425.
20. J. D. Anderson, in *Physical Studies of Minor Planets*, T. Gehrels, Ed. (Publication NASA SP-267, National Aeronautics and Space Administration, Washington, D.C., 1971), p. 577.
21. W. H. Blume *et al.*, in preparation.
22. W. C. De Marcus, *Astrophys. J.* **63**, 2 (1958); P. J. E. Peebles, *ibid.* **140**, 328 (1964); W. B. Hubbard, *ibid.* **155**, 333 (1969); M. Podolak and A. G. W. Cameron, *Icarus* **22**, 123 (1974). In their pioneering work, De Marcus and Peebles assumed cold hydrogen and helium interiors for Jupiter and Saturn. After the discovery of the infrared excess for Jupiter [F. J. Low, *Astron. J.* **71**, 391 (1966)], Hubbard considered hot interiors, with the helium soluble in the hydrogen and mixed thoroughly by convection. Heavier elements were added by Podolak and Cameron, who concluded that both Jupiter and Saturn are enriched in heavy elements with respect to solar abundances.
23. See Slattery (*11*). Monte Carlo calculations were carried out for the two-body interactions H_2-H_2, H_2-He, and He-He from a density of 0.005 to 0.3 g cm^{-3}, where three-body interactions become significant. The method of calculation is described in W. L. Slattery and W. B. Hubbard, *Icarus* **29**, 187 (1976). Similar conclusions on the structure of Saturn were reached by M. Podolak, *ibid.* **33**, 342 (1978).
24. The perfect gas law is used in the atmosphere; with a starting temperature T_1 at the 1-bar level, an adiabat is calculated with quantum mechanical corrections [W. B. Hubbard, *Astrophys. J.* **182**, L35 (1973)] to a density level of 0.005 g cm^{-3}. The Monte Carlo calculations of the equation of state are used from this point to a density level of 0.3 g cm^{-3}. The remainder of the molecular hydrogen region is determined by interpolation between 0.3 g cm^{-3} and about 1.3 g cm^{-3} (2-Mbar level) where a phase transition between molecular and metallic hydrogen is assumed. The equation of state for the metallic region is well known [D. J. Stevenson, *Phys. Rev. Sect. B* **12**, 3999 (1975); H. E. De Witt and W. B. Hubbard, *Astrophys. J.* **205**, 295 (1976)]. Equations of state for a core of rock and ices and the relative solar abundances of various constituents have been discussed elsewhere [A. G. W. Cameron, *Space Sci. Rev.* **15**, 121 (1973); M. Podolak and A. G. W. Cameron, in (*22*); W. B. Hubbard and J. J. MacFarlane, *J. Geophys. Res.*, in press].
25. Before Pioneer Saturn, estimates of T_1 ranged from 90 to 150 K [R. L. Newburn and S. Gulkis, *Space Sci. Rev.* **3**, 179 (1973); V. N. Zharkov, A. B. Makalkin, V. P. Trubitsyn, *Sov. Astron. AJ* **18**, 768 (1975)]. The value from the Pioneer infrared data [A. P. Ingersoll, G. S. Orton, G. Münch, G. Neugebauer, S. C. Chase, *Science* **207**, 439 (1980)] places a tight observational constraint on the Saturn interior models.
26. The mass of the Saturn system has been determined from perturbations on the orbit of Jupiter. A value of 3498.5 ± 0.5 for the ratio of the mass of the sun to the mass of the Saturn system is given by M. E. Ash, I. I. Shapiro, and W. B. Smith [*Science* **174**, 551 (1971)], and a value of 3498.1 ± 0.4 is given by W. J. Klepczynski, P. K. Seidelmann, and R. L. Duncombe [*Celestial Mech.* **4**, 253 (1971)]. The value used in the Jet Propulsion Laboratory 1979 planetary development ephemeris (DE 108) was determined independently from planetary data and is given by 3497.99 (E. M. Standish, personal communication). By subtracting the known satellite masses from the system mass and assuming a value of 1.9888×10^{33} g for the mass of the sun, we arrive at a value of 5.684×10^{29} g for the mass of Saturn. The product of G multiplied by the mass of the Saturn system will be determined in the future from the Pioneer Doppler data to higher accuracy than presently available. This will be important to future studies on planetary motions, where it will no longer be necessary to carry the Saturn system mass as an unknown parameter in fits to the planetary dynamical data.
27. The equatorial radius is not well determined from ground-based observations, but the radio occultation data will yield a value in the future. Analysis of the data to date [A. J. Kliore, G. F. Lindal, I. R. Patel, D. N. Sweetnam, H. B. Hotz, T. R. McDonough, *Science* **207**, 446 (1980)] indicates that 60,000 km is a good assumption for now. Also, see T. Gehrels *et al.*, *ibid.*, p. 434.
28. E. J. Smith, L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett, *Science* **207**, 407 (1980); M. Acuña and N. F. Ness, *ibid.*, p. 444.
29. A. G. W. Cameron, *Space Sci. Rev.* **15**, 121 (1973).

30. We acknowledge the outstanding support for our experiment by Pioneer Project personnel at the NASA Ames Research Center under the direction of C. F. Hall. The experiment would have been impossible without a dedicated effort by personnel of the NASA-JPL Deep Space Network under the leadership of R. B. Miller. We thank L. A. Brown, B. N. Casey, E. L. Lau, and A. Lubeley for assistance in data reduction; W. Blume for assistance with trajectory characteristics; and W. Kirhofer for his encouragement and support as leader of the Pioneer navigation team. We are grateful to J. G. Williams and C. F. Yoder for their reviews of the manuscript. The work of the JPL experimenters represents the results of one phase of research at the Jet Propulsion Laboratory under NASA contract NAS 7-100. W.B.H., J.J.M., and J.D.A. acknowledge support from the Caltech President's Fund.

3 December 1979