primarily to a single-component, corotating, isotropic Maxwellian, and the best fit of the data to the three parameters above is found by numerically integrating the sensor responses over the two half-cones as functions of ion velocity and for various species, $M/Q$.

An example of these measurements and analyses is shown in Fig. 5 for 1219 UT, ERT, on 1 September 1979. The corresponding Saturn-centered radial distance of the spacecraft is 6.3 $R_S$. Figure 5a shows the positive-ion phase space densities as a function of ion velocity if the dominant responses of the analyzer are due to protons. These measurements are indicated as solid dots and the measurements for the two half-cones are indicated by $\pi/2 \leq \phi < 3\pi/2$ and $3\pi/2 \leq \phi < 2\pi$, $0 \leq \phi < \pi/2$, respectively, where $\phi$ denotes the clock roll angle of the spacecraft. In general, the velocity distribution function $n(v)$ is a monotonically decreasing function of velocity within the range sampled by the analyzer. Background counting rates were subtracted from the analyzer responses in computing the velocity distribution. Peak analyzer responses are approximately a factor of 80 above background rates. For the half-cone $3\pi/2 \leq \phi < 2\pi$, $0 \leq \phi < \pi/2$ the average responses for three energy passbands are used to improve counting statistics.

Also shown in Fig. 5a are the results of the fit of these data to a corotating Maxwellian distribution of protons. The corresponding temperature and density are $2 \times 10^6$ K and 24 $cm^{-3}$. The method for finding the best fit requires that the half-cone with best counting statistics, $\pi/2 \leq \phi < 3\pi/2$, be used to determine $T$ and $N$ at low velocities, $\lesssim 4 \times 10^7$ cm $sec^{-1}$. It is easily seen that the assumption of protons ($M/Q = 1$) provides a poor fit to the entire set of measurements. This procedure is repeated for each species $M/Q$ = 2, 4, 8, 16, and 32. The best fit for this series of observations is $M/Q = 16$ with $T$ and $N$ equal to $7 \times 10^5$ K and 51 $cm^{-3}$, as shown in Fig. 5b. In fact, considering that this is only a three-parameter fit to the observations, the agreement is excellent, excluding only the high-velocity tail of the distribution, which may be due to either a nonthermal component of the distribution or another species. The current accuracy for assessing the $M/Q$ value of these ions is $\pm$ 4—that is, 16 $\pm$ 4—in our preliminary analysis. Although we have labeled these ions $O^+$, any positive ion, such as $OH^+$, within this $M/Q$ range can be equally well identified as the dominant ion. The elimination of $H^+$ as the ion species would seem to preclude the solar wind or the Saturn ionosphere as the main source of magnetospheric plasmas at 6 $R_S$. The $O^+$ or $OH^+$ could be produced by dissociation of ice on the rings or satellites. Heavier ions such as $S^+$ and $Na^+$, found in the magnetosphere of Jupiter and presumably associated with the Io volcanoes (7), do not appear to be a dominant constituent of the Saturn plasmas examined to date. This preliminary analysis will be followed by a comprehensive report covering the entire series of measurements of Saturn magnetospheric plasmas.

*Conclusions.* It is concluded that, like Earth and Jupiter, Saturn has a detached, strong, bow shock wave and a magnetopause. From the preliminary results it appears that Saturn's magnetosphere, like that of Jupiter, is very responsive to changes in the solar wind dynamic pressure, but on a scale size perhaps one-third of that at Jupiter. Also, Saturn's outer magnetosphere, like Jupiter's, is inflated by corotating plasma. The corotating plasma was not observed by this experiment during either of the Pioneer Jupiter encounters, presumably because of the much less favorable viewing directions and much higher backgrounds resulting from the more intense energetic charged particle environment at Jupiter.

It is interesting to note that the character of Saturn's magnetosphere should be drastically altered (expanded because of the reduction in solar wind dynamic pressure) when Saturn is near solar alignment with Jupiter such that Jupiter's long magnetospheric tail, observed by the Pioneer 10 plasma analyzer at the orbit of Saturn in March 1976 (8, 9), engulfs Saturn. This may be just the situation for the Voyager 2 encounter with Saturn in August 1981 (10).


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3 December 1979


# Saturn's Magnetic Field and Magnetosphere


Abstract. *The Pioneer Saturn vector helium magnetometer has detected a bow shock and magnetopause at Saturn and has provided an accurate characterization of the planetary field. The equatorial surface field is 0.20 gauss, a factor of 3 to 5 times smaller than anticipated on the basis of attempted scalings from Earth and Jupiter. The tilt angle between the magnetic dipole axis and Saturn's rotation axis is < 1°, a surprisingly small value. Spherical harmonic analysis of the measurements shows that the ratio of quadrupole to dipole moments is < 10 percent, indicating that the field is more uniform than those of the Earth or Jupiter and consistent with Saturn having a relatively small core. The field in the outer magnetosphere shows systematic departures from the dipole field, principally a compression of the field near noon and an equatorial orientation associated with a current sheet near dawn. A hydromagnetic wake resulting from the interaction of Titan with the rotating magnetosphere appears to have been observed.*


The similarity of Saturn to Jupiter and the somewhat tentative observations of decametric radio bursts from Saturn led to the expectation that the planet would have a relatively strong magnetic field. However, Pioneer 11 reached a distance of only 23.7 $R_S$ before the first bow shock crossing was observed. This is shown in Fig. 1, which presents an overview of the encounter as evident in the magnitude of the ambient magnetic field. Knowledge of the solar wind pressure (1), which was



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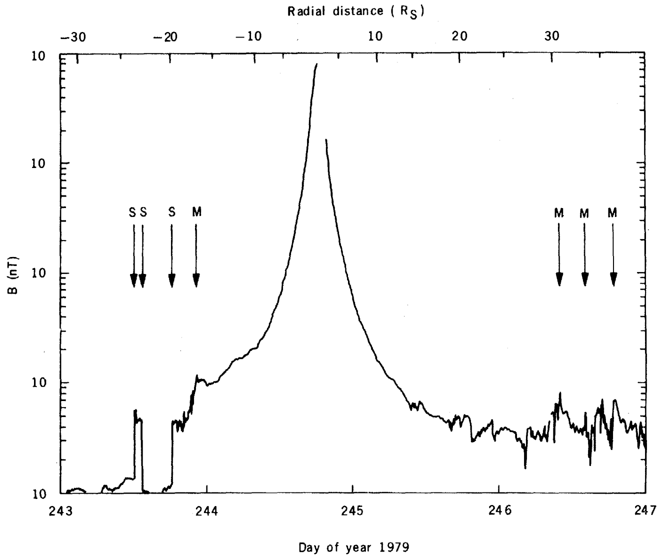


Fig. 1. The observed field magnitude near Saturn. The field is plotted on a logarithmic scale as a function of time with distance in planetary radii at the top. Multiple shock crossings (*S*) and a single magnetopause crossing (*M*) are seen inbound and multiple magnetopause crossings outbound. Outbound shocks are not shown.

exceptionally high, and comparing the bow shock location for Earth and Jupiter with that for Saturn, suggested an equatorial surface field of approximately 0.3 gauss, very nearly the field strength at the Earth's surface. After a pair of additional shock encounters, Pioneer crossed the Saturn magnetopause at 17.4 $R_S$, a location that was also consistent with a planetary field of the same magnitude. The field just inside and throughout the magnetosphere had a southward orientation at the equator, establishing that the polarity of the field was the same as Jupiter and opposite that of the Earth. As Pioneer proceeded inward to periapsis, the observed field strength increased from 10 to 8200 nT ($10^{-5}$ gauss = 1 nanotesla). The field strength then gradually decreased as the spacecraft traveled outbound until multiple magnetopause crossings were observed between 30.1 and 40.3 $R_S$, followed by multiple bow shock crossings which began at 49.4 $R_S$ and continued to beyond 65 $R_S$. The essential features of the prograde Pioneer trajectory are that the inclination was low (essentially equatorial within ± 6° latitude) with periapsis at 1.35 $R_S$, and that the inbound and outbound legs occurred near the noon and dawn meridians, respectively.

The increase in field magnitude, *B*, with decreasing distance provided clear evidence that the field was that of a dipole. Figure 2 is a log-log plot of *B* against *r*, which shows very clearly the inverse cube (straight line) dependence that extended both inbound and outbound from 10 $R_S$ to periapsis. Extrapolation of the inverse cube straight line to Saturn's surface implies an accurate value for the equatorial field of 0.2 gauss. Beyond 10 $R_S$, Fig. 2, especially the portion representing the inbound trajectory, shows the characteristic enhancement of the field above the dipole field value associated with compression of the magnetosphere by the solar wind. The field gradually increases to a value that is about two times the dipole field strength at the magnetopause. Close inspection of Fig. 2 shows that, inbound, the field between 6 and 10 $R_S$ was slightly lower than the dipole field value, a result that presumably indicates the presence of a ring current in the middle magnetosphere. There is a data gap between 1.35 $R_S$ inbound and 2.28 $R_S$ outbound caused by an occultation of the spacecraft. Data were stored in an onboard memory during approximately half of this interval but they require special data

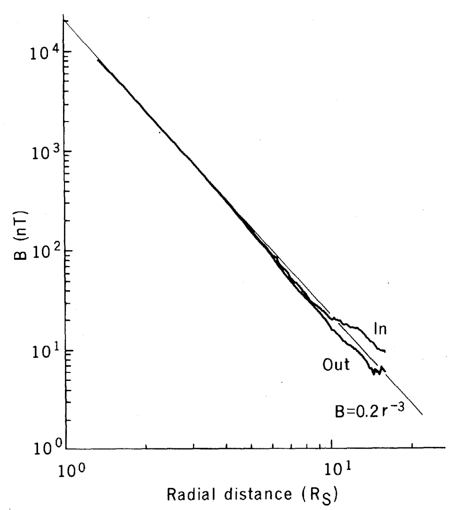


Fig. 2. The logarithm of the field magnitude plotted as a function of the logarithm of radial distance. Inside 10 $R_S$, both inbound and outbound, the measurements coincide with an inverse cube decrease characteristic of the dipole field. Beyond 10 $R_S$, significant departures can be seen.

processing and are not yet available.

The measurements acquired within 8 $R_S$ of Saturn were analyzed to obtain a precise description of the planetary field and its equivalent multipole source. If such an analysis is to be successful, stringent requirements must be imposed on the accuracy with which the vector components of the field are determined. Throughout the Pioneer mission we have taken great care to preserve the accuracy of the measurements. The vector helium magnetometer is an ultrastable instrument capable of achieving a relative accuracy of better than 1 percent (*2*). The sensor is mounted at the end of a long boom to eliminate the influence of magnetic fields associated with the spacecraft and other experiments. The instrument operates on one of eight ranges with full-scale values from ± 4 nT to ± 1.5 gauss. It upranges and downranges automatically and avoids a significant digitization uncertainty at the low end of the range. Large numbers of measurements are available since, at the nominal encounter bit rate, field measurements were obtained 2.7 times each second. One advantage of this high rate is that it allows complete reconstruction of the sinusoid generated on two magnetometer axes as the spacecraft rotates, and therefore provides an inflight determination on each operating range of any magnetometer zero offsets that might adversely affect the absolute accuracy. Finally, an inflight calibration was activated by ground command approximately every 2 weeks for the 6½ years between encounter and the launch in April 1973. The calibration data showed no evidence of change and established that the relative error remained smaller than 1 percent from the beginning to the end of this interval.

In our preliminary analysis we inverted each field measurement to obtain the equivalent dipole source vector that would have produced that field (*3*). A particularly interesting aspect of the results was the apparent absence of any evidence of rotation of these source vectors. Since Saturn is known to be rotating fairly rapidly, this result implied that the tilt angle between the magnetic dipole and the rotation axis of Saturn must be very small compared to the value of about 10° which is characteristic of Earth, Jupiter, and Mercury.

Subsequently, the measurements were used to carry out a spherical harmonic analysis of the type that has conventionally been used to characterize the magnetic fields of Earth and Jupiter (*3*). The computer program allows a choice of the order of the harmonics both internal and external to the spherical shell in which a least-squares fit is obtained to the data. For most purposes, it appears that the most useful analysis is based on two internal orders (dipole plus quadrupole) and one external order (equivalent to a uniform field in the spherical shell), denoted as (2, 1), which is presented below. In Fig. 3 the model is compared with the observations and shows very clearly the high level of agreement between the two that was achieved. The cronographic longitude system that was used is based on a rotation axis, period, and zero meridian provided by the project (*4*).

The interior spherical harmonic coefficients (in gauss) corresponding to the fit are: $g_1^0 = 0.203$, $g_1^1 = 0.000$, $h_1^1 = 0.000$; $g_2^0 = 0.015$, $g_2^1 = 0.000$, $h_2^1 = 0.001$, $g_2^2 = 0.000$, $h_2^2 = 0.002$. The exterior terms (in nanoteslas) are: $\bar{g}_1^0 = 0.0073$, $\bar{g}_1^1 = 0.000$, $\bar{h}_1^1 = 0.071$. These values are sufficiently small to be consistent with zero.

These results indicate that Saturn's field has a surprisingly high degree of axial symmetry. The results imply a dipole moment, $M$, of 0.2 gauss $R_S{}^3$ and a surprisingly small tilt angle consistent with 0.0°. The ratio of the quadrupole to dipole moment is 0.07, a value that is smaller than those for Earth and Jupiter. The components of the quadrupole moment associated with an axial quadrupole can be eliminated by computing a magnetic center or offset from the center of Saturn (*3*). The offset so derived has a magnitude of 0.04 $R_S$, principally in a polar direction. Although there is some uncertainty as to the magnitude and direction of the offset, it is likely that Saturn's field has an offset, that is significantly different from zero.

The values of $M$, the offset, and the oblateness of Saturn (the polar radius is 0.9 times the equatorial radius) can be used to compare the surface field strength at the equator (0.20 gauss), the north pole (0.63 gauss), and the south pole (0.48 gauss). The last two values are significantly different than would be implied by the usual doubling at the poles of the equatorial field for a simple centered dipole and a spherical planet.

The dipole moment, which is 600 times larger that the dipole moment of Earth and 30 times smaller than that of Jupiter, is substantially smaller than had been anticipated. Various methods that are based on scaling the magnetic fields of the planets consistently lead to moments corresponding to an equatorial surface field of ≃ 1 gauss (*5*). In particular, Saturn provides a useful check of the so-called "magnetic Bode's law" which attempts to relate the magnetic moments and angular momenta of the planets (*6, 7*). On this basis, Saturn's moment is about five times smaller than would be predicted by this model. However, the field strength is reasonably consistent with values inferred from radio emissions thought to originate at Saturn (*8, 9*), particularly if those estimates are taken to refer to the polar rather than the equatorial regions.

The most surprising result is undoubtedly the small angle of tilt between $M$ and Saturn's rotation axis. It has generally been supposed, on the basis of observations of the other planets, that a tilt angle of 10° to 20° might be fundamental to planetary dynamos. Thus, Saturn provides a first and excellent counter example showing that such a tilt angle is not required. Clearly, any dynamo theories that require a tilt or a precession of the dipole moment around the spin axis are in serious difficulty. Another aspect of this property worth commenting on is the difficulty it poses for investigators attempting to measure accurately the rate of rotation of Saturn's interior using the magnetic field observations. Absence of a tilt angle supresses evidence of the rotation, although some evidence may remain and this objective will be pursued in subsequent analyses.

The relatively small ratio of quadrupole to dipole moments implies that Saturn's magnetic field is also very regular or uniform compared to the other planets. In fact, much of the irregularity can be removed by displacing the dipole from the center of the planet, in which case a very uniform dipole field is obtained. It is customary to relate the degree of field irregularity to the relative size of the core within which the dynamo is operating. The weakness of the quadrupole moment at Saturn is consistent with the source being well below the visible surface. This result agrees with recent models of the interiors of Saturn and Jupiter that reveal that the metallic hydrogen core, within which the dynamo is presumed to operate, extends only from about 0.2 to 0.5 $R_S$ inside Saturn as compared to the corresponding values of 0.2 to 0.75 $R_J$ for Jupiter (*10, 11*). The reason is that the pressure at which me-

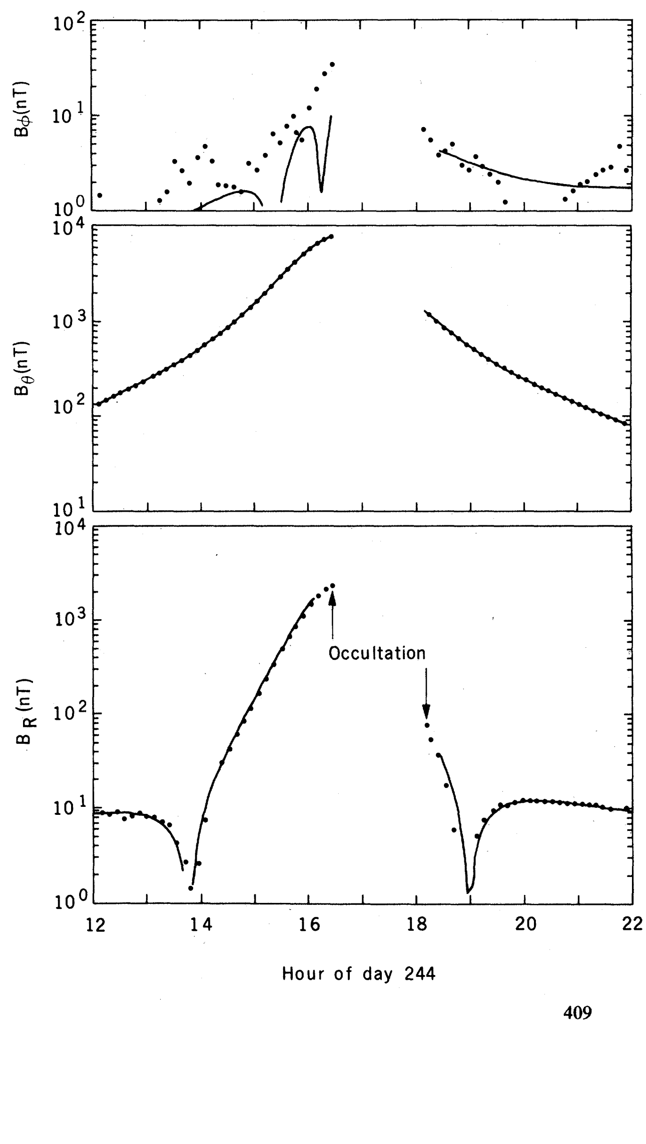


Fig. 3. A comparison of the measured field (dots) with the field computed from a spherical harmonic fit (curve). In general, there is excellent agreement between the measured and computed field components which are shown here in chronographic coordinates. Note that the discrepancies in the upper panel are actually very small, typically 10 nT or less.

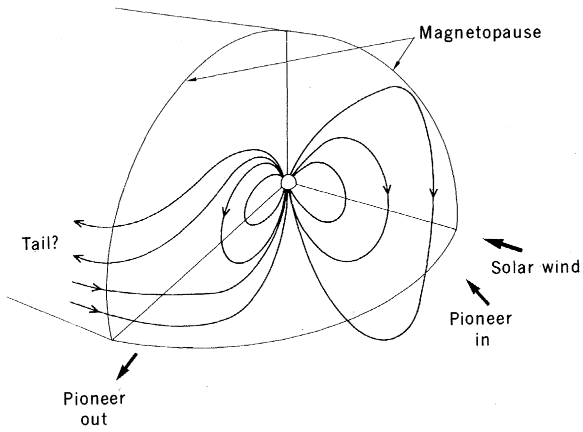


Fig. 4. A schematic representation of the magnetospheric field along the inbound (noon) and outbound (dawn) portions of the flight path. In the outer magnetosphere, the dipole field is compressed near noon and swept back more or less parallel to the equator and the magnetopause near the dawn meridian.

tallic hydrogen forms occurs at significantly greater depths inside Saturn. The smaller dimension of Saturn's core is also qualitatively consistent with the significantly weaker dipole strength (*12*).

Beyond about 10 $R_S$, both inbound and outbound, the observed field shows systematic departures from the dipole field associated with plasma currents either interior to the magnetosphere or at the magnetopause. This departure inbound is distinctly different from that outbound (Fig. 4). Such differences are to be expected because of major differences in local time, with the inbound observations being made near local noon and the outbound measurements near the dawn time sector. With only a single spacecraft it is difficult, if not impossible, to distinguish spatial variations, that is, magnetospheric structure, from time variations, that is, magnetospheric dynamics.

The principal features of the outer magnetosphere near noon, as mentioned above, are a compression of the dipole field and the apparent presence of a distributed ring current. There is no evidence in these data for a magnetodisk or current sheet similar to that seen in the Jovian dayside magnetosphere by both Pioneers 10 and 11 (*3*). Near dawn, in contrast, the field in the outer magnetosphere departs from being principally north-south to being equatorial. Accompanying this change in orientation is the observation of polarity reversals, with the field switching abruptly from outward to inward and vice versa. Several such reversals are seen and are a clear indication that the spacecraft has penetrated an extended current sheet lying in or near the magnetic equator.

One possible explanation for this current sheet is that it is associated with the formation of a magnetotail much like those associated with Earth and Jupiter (*13*). An alternative possibility is that, at the time it was observed, the current sheet extended from dawn around into the dayside magnetosphere and was part of a magnetodisk encircling Saturn. Since no such structure was seen when Pioneer was inbound, this interpretation would require a major change in the structure of the magnetosphere between the inbound and outbound observations. However, such a hypothesis should be given serious consideration since there is evidence that the magnetosphere was, in fact, inflated during the outbound passage. By analogy with Jupiter, it would be expected that a decrease in the external pressure as the solar wind stream passed Saturn would allow the magnetosphere to expand and would be favorable to the formation of a magnetodisk current (*14*).

In the two time zones, significant differences were also observed in the field and plasma properties on the two sides of the magnetopause. On the basis of pressure balance calculations in which we assumed that the inward pressure, $p$, of the shocked solar wind in the magnetosheath was equal to $B^2/8\pi$, we determined that inbound, the field strength was clearly adequate to withstand $p$. Outbound, however, the first few magnetopause crossings revealed that the magnetic field in the magnetosheath was comparable to what it was inside the magnetosphere, a situation that has been observed near dawn at Earth. Such observations imply that the major contribution to the pressure inside is associated with plasma internal to the magnetosphere. In other respects, the magnetopause crossings at Saturn appear to be very similar to those typically observed at Earth and at Jupiter with the field rotating as the boundary is crossed from its orientation in the magnetosheath to an orientation characteristic of the planetary field or vice versa.

Finally, a hydromagnetic wake associated with Titan appears to have been observed just prior to the near approach of Pioneer to the satellite. A disturbance consisting of waves of relatively large amplitude was observed for an interval of about 2 hours centered approximately on the time at which Pioneer crossed the Titan $L$ shell. This timing is to be expected because the interaction of Titan with the corotating magnetosphere would tend to curve the wake so as to conform approximately to the circular $L$ shell.


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