Cassini Magnetometer Observations During Saturn Orbit Insertion

M. K. Dougherty,1* N. Achilleos,1 N. Andre,2 c S. Arridge,1 A. Balogh,1 C. Bertucci,1 M. E. Burton,3 S. W. H. Cowley,1 G. Erdos,1 G. Gianpietri,1 K.-H. Glassmeier,1 K. K. Khurana,3 J. Leiser,1 F. M. Neubauer,1 C. T. Russell,1 E. J. Smith,1 D. J. Southwood,3 b T. Tsurutani1

Cassini's successful orbit insertion has provided the first examination of Saturn's magnetosphere in 23 years, revealing a dynamic plasma and magnetic environment on short and long time scales. There has been no noticeable change in the internal magnetic field, either in its strength or its near-alignment with the rotation axis. However, the external magnetic field is different compared with past spacecraft observations. The current sheet within the magnetosphere is thinner and more extended, and we observed small diamagnetic cavities and ion cyclotron waves of types that were not reported before.

The first in situ observations from Saturn's magnetosphere in 23 years were obtained during Cassini's Saturn orbit insertion on 30 June 2004. The magnetometer instrument (J) (MAG) obtained data on upstream waves, bow shock, magnetosheath, magnetopause, magnetospheric currents, and waves, as well as the planetary magnetic field. These data are consistent with measurements made on earlier missions, provide more detail of some parameters such as the planetary magnetic field, including its possible secular variation, and reveal some features in the external field not previously reported.

The solar wind controls the size of the magnetosphere and the dynamics of its outer reaches. Because the solar wind speed is supersonic, the deflection of the solar wind occurs via a standing bow shock that compresses and heats the solar wind, forming the magnetosheath. The inner edge of the magnetosheath, the magnetopause, marks the outer boundary of the region controlled by the planetary magnetic field. Saturn's bow shock is of intrinsic interest because it is expected to be much stronger than that of Earth. The magnetopause is important because it controls the coupling of the solar wind flow to the magnetosphere, principally, we expect, through the process known as reconnection [2]. The locations of both boundaries are determined by the dynamic pressure of the solar wind and the combined plasma and magnetic pressure of the magnetosphere.

The boundaries were observed to be very dynamic. We measured a total of 17 bow shock and 9 magnetopause crossings (Fig. 1) on the inbound and outbound passages. Bow shock crossings were identified by large increases in the magnetic field magnitude where the solar wind was compressed and decelerated. As Cassini approached Saturn near 08:00 local time (LT), it crossed the bow shock on seven separate occasions, starting at 09:45 universal time (UT) on 27 June 2004 at a distance of 49,154 km [1, Rs = 60,268 km (L)].

The last inbound bow shock crossing occurred at 05:38:30 UT on 28 June 2004 at a distance of 40,554 km. At least 10 crossings of the bow shock were observed on the outbound leg in the magnetometer data, with the earliest bow shock crossing observed on 7 July 2004 at a radial distance range of 56,54 km and the final bow shock crossing occurring on 14 July 2004 at 85 km. Saturn's bow shock is expected to be a strong quasi-perpendicular shock. A large over-shoot in the magnetic field magnitude is a consistent feature of the shock crossings and is a typical feature of supercritical stationary bow shocks [4]. These observations afford us the opportunity to study bow shocks at high Mach numbers, which are rarely observed on Earth. Indeed, the Mach number can be inferred from the amplitude of the over-shoot BBn [3]. The average value for the bow shocks observed is ~1.5, consistent with a fast magnetosonic Mach number as high as 1.5.

On the Saturnian side of the bow shock lies the magnetosheath, where the magnetic field is very turbulent and dominated by wave activity. The entrance into the magnetosphere was preceded by multiple crossings of the magnetopause on 28 June and 29 June 2004. On the outbound pass, the spacecraft exited the magnetosphere near 05:00 LT. The first excursions into the inner magnetosphere were characterized by the presence of mirror mode structures. The multiple crossings of these plasma boundaries reveal the dynamic character of Saturn's outer magnetosphere in response to variations in the solar wind ram pressure.

Before the Cassini arrival at Saturn, there had been three previous flybys: Pioneer 11 (6) and Voyagers 1 and 2 (7, 8). The spatial coverage of these flybys was limited, with the inbound trajectories all being in the noon sector and outbound Pioneer 11 and Voyagers 1

*To whom correspondence should be addressed.

E-mail: m.dougherty@imperial.ac.uk

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10.1126/science.1095740
exciting the dron meridian (Fig. 2). The inbound Cassini trajectory occurred at an earlier local time, and its outbound passage was similar to that of Voyager 2, exciting at high southern latitudes. A measure of the variability in the position of the different plasma boundaries can be assessed by comparing the locations of the Cassini crossings with their nominal position as deduced from the previous observations (9, 10). The Cassini inbound crossings occurred further from Saturn than their average expected locations, revealing an expanded magnetosphere at the time of the inbound encounter (Fig. 2) with the first magnetopause crossing occurring a day earlier than expected. The state of the magnetosphere during the outbound part of the orbit was very different. The magnetopause and bow shock crossings were located inside their respective average surfaces, in agreement with a magnetosphere in a compressed regime. This regime is consistent with predictions (11) from upstream magnetic observations during the approach to Saturn. The entry into the magnetosphere was identified from the dropping of the magnetic field, which is compatible with a dipole. In addition, an expansion of the magnetosphere occurred during the outbound passage of Cassini, with the magnetopause moving back out over the spacecraft and with the last bow shock occurring close to the expected nominal distance at 85R₉.

In situ measurements of the internal magnetic field at Saturn have been obtained from the three previous flyby missions. The Cassini mission as an orbiter will provide a much more complete three-dimensional sampling of the magnetic field over the next 4 years. Until more complete measurements of the Saturnian magnetosphere are obtained during future orbits, the insertion observations (Fig. 3) can essentially be treated as a single flyby. In particular, for the inversion of the internal field we used only data within 85R₉ and assumed an axisymmetric field configuration up to degree 3. Exponential terms were also included by adding an axisymmetric ring current whose presence was revealed by analysis of previous data. Previous analyses led to the SPV and Z3 models (12, 13), which included terms corresponding to a uniform external field in a source-free region. However, we have found that such a uniform field is not adequate for describing the field in and near the ring current, and therefore we have used the more realistic Connerney model adapted to Saturn (14, 15).

Precise knowledge of the gain and pointing of the magnetometer is important for the accurate inversion of the measurements to obtain the internal magnetic field. We performed extensive ground calibration before launch, checked the calibrations during the Earth flyby, and monitored the calibrations since launch with the magnetic field produced by coils both remote from and near the sensor. We estimate the uncertainty in presently 0.1% in gain and 0.1° in pointing. The magnetic field data were analyzed by using a standard singular value decomposition of the inversion matrix. Only zonal terms up to degree 3 are included in addition to the four-disk parameters (namely, total current, inner and outer radii, and thickness). The internal field coefficients are shown (Table 1) alongside those from past models.

The quantity \(\epsilon_{QCD}\), where \(\epsilon_{QCD}\) is the quadrupole moment and \(\epsilon_{QCD}\) the dipole moment, can be interpreted as a northward displacement of the dipole by 0.037R₉. The comparable results for the SPV, Z3, and GD (13) models are 0.037R₉, 0.038R₉, and 0.037R₉, respectively. The implication is that the magnetic and rotational equators do not coincide. However, the relatively large centrifugal moment cannot be explained by this effect. After accounting for the uncertainties associated with the estimated parameters, we were not able to determine any secular change in the internal field radial coefficients. Also, we noticed that the azimuthal field component was barely visible near closest approach, which confirms the near-axial symmetry of the field. Although we have not considered the azimuthal component in our analysis because of the limited spatial sampling of the insertion trajectory, a previous study (11) has revealed the likely presence of a small azimuthal field.

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of internal origin, in accordance with theoretical constraints.

In the inner magnetosphere, the larger contribution to the external field was from the ring current, whose magnitude was as large as ~20 nT at the point where Cassini crossed the inner boundary of the disk (r ~ 6Rₖ). The estimated inner radius and current density of the disk are in very good agreement with our previous estimates; however, there are indications that the disk is thinner (half-thickness < 2Rₖ) as well as more elongated (outer radius > 2Rₖ) than in the past.

As in the case of the Earth and Jupiter, the magnetic field at Saturn is generated by three different current systems: in the core, in the magnetospheric plasma, and from the solar wind interaction with the planetary magnetic field. Subtracting the planetary magnetic field model allows us to examine the contribution of the various currents flowing inside the magnetosphere and on its boundaries. This difference field (ΔB = Bₚ - BI) shown at radial distances greater than 2Rₖ can be seen in Fig. 4 in the black trace. Overlain on this figure are two different models of the external field in Saturn's magnetosphere. The blue trace is the best fit of Cowley's model as described above, and the red trace is a new global magnetospheric model that models the external field, i.e., considering the internal field to be a fixed, known quantity.

In this global model, we retain the Cowley current disk to model the equatorial azimuthal current and used parameters obtained from the Voyager 1 flyby. The model also includes fields to represent the effect of magnetopause currents, which are modeled by the source-surface method (16) used in the Tsyganenko models of the terrestrial magnetosphere (17-19). We shield the field so that it is tangent to the magnetopause boundary at all points over that surface, which is represented by a prolate semi-ellipsoid (20) for the nose region and a cylinder for the tail. The field due to the shielding of the dipole is represented with use of cylindrical harmonics and that due to the shielding of the disk with use of Cretinskii harmonics. These representations allow the model to have an analytical dependence on the tilt angle between the dipole axis and the solar wind flow and on the solar wind dynamic pressure. The magnetopause standoff distance, a function of the dynamic pressure, was set to be consistent with the location of the final inbound magnetopause crossing.

The global model does not fit the observed data well, and the current disk model suggests that the current disk field has changed compared with that of the Voyager 1 epoch. The magnitude of the azimuthal field in the outer magnetosphere caused by magnetopause currents is larger than that estimated from the model. This has also been seen in the previous flyby data sets (15) and may hint at further dynamical processes. At present, the model does not include a magnetopause current, which means we are underestimating the field in the tail region. Neither model accurately accounts for both the inbound and outbound observations simultaneously. This feature of the magnetosphere has been noted in modeling studies and indicates an equatorial current disk that has local time structure and asymmetry. However, the compression of the magnetosphere during the Cassini flyby probably also affected the equatorial current distribution.

When Cassini was immersed within the plasma sheet, changes in the magnetic field
configuration associated with an enhanced level of small-scale magnetic fluctuations. Outside of these regions, the Cassini spacecraft was located in the outer high-altitude magnetosphere, a region with less plasma that is similar to the field regions of the Earth's magnetosphere. The plasma sheet crossings occurred at distances approximately 15RE inbound and 12RE outbound and are associated with sharp transitions in the magnetic field. The observed field fluctuations reveal a dynamic system associated with plasma crossings, transport processes, and related wave generation. Closer to the planet, the field is more dominated by the internal source. Onboard Cassini, we have again observed the plasma sheet at high latitude, possibly caused by a dynamic solar wind-driven motion of the sheet. The field at these latitudes and distances is also lat-like, with a more extended configuration.

On both the inbound and outbound legs of the pass, near but inside the orbit of Dione at 6.27RE, MAG measured diurnally driven geomagnetic activity in which some of the magnetic pressure was replaced by increased plasma pressure. On each leg, the internal depression was largest. Such diurnally driven events were not reported for the Voyager and Pioneer flybys.

The lateral size of the depressions occurred at 21:05 UT on 19 June 2004 at a radial distance of 3.5RE, a local time of 19:45 UT, and a latitude of 90°, while the Cassini spacecraft was at 15.08 UT. The maximum depth of the magnetic depression in the 93-kT background field was produced by a plasma pressure energy density of 0.5 eV cm⁻³. If produced by 1-keV electrons, a plasma density of about 0.3 electrons cm⁻³ would be required. On the outbound leg at 01:02 UT, 5.5RE, 01:53 UT, and -90° latitude, a similar depression was seen at an 115-kT background field, corresponding to a plasma energy density of 300 eV cm⁻³. This was the outer boundary of a cold plasma torus, we conclude that the source of the cold ions would be the inner and the ion electrons outside, for cold torus region would be produced close to the computer, where the field-aligned current system needed to enhance containment of the plasma close. Similar to the two largest and highest latitude field regions were relatively strong waves polarized in the direction transverse to the field. These waves were probably incompressional waves with the normal mode of the ionosphere. The plasma sheet crossings were accompanied by a narrow band of left-hand cyclotron wave propagating only close to the direction of the magnetic field at the H₂O-gene frequency. Although seen on both sides of the depressions and at both legs, this narrow band of ions cyclotron waves makes a small contribution to the total wave power. The water group ion cyclotron waves are proportionately associated with a ring from the 150 ring, but we do not have any obvious source for the strong farward traveling wave that started around the equator. These are associated with the existence because their amplitude decrease with distance from the center.
be maintained by the ionosphere. The resulting slippage in the ionosphere heats the ionospheric electrons, producing high beta conditions along the entire flux tube.

Quite distinct from the waves surrounding the cavities was a 100-mi-long burst of ion cyclotron waves (from 06:10 to 07:50 UT on 30 June 2004) unlike any seen on Voyager and Pioneer that appeared 5 hours after the Cassini engine stopped firing. These waves were limited to the frequency band expected for the singly ionized products of the engine exhaust H₂O, N₂, CO, and CO₂. We do not expect these waves to be present (except for H₂O that may be associated with the icy satellites’ environments) in the natural plasma. We note that Cassini’s engine deposited over 850 kg of fuel in the Saturnian magnetosphere and, as it ionized and traversed the magnetosphere, it would produce a cloud of ions with energy predominantly transverse to the magnetic field, that is, a ring beam. The energy of these pickup ions at the locations where the waves were seen is comparable to that of the pickup ions in the Io torus. This may be the first detection of artificially induced plasma waves in a magnetosphere other than that of Earth.

References and Notes
5. The ratio β0 is an enhancement of the overshoot magnetic field strength normalized by the magnetosphere field strength away from the overshoot.
20. The decay of the magnetosphere is approximately exponential, but this is not the case in the tail, which is nearly circular in cross section. The decay is approximately exponential if the tailward half of an ellipse is replaced with a cylinder. Thus, the boundary is a composite surface composed of a half-ellipsoid and a cylinder. The latter is appropriate at the semi-minor axis of the polar ellipse (from pole to nearest point).
24. The KSM (Krupp Solar Magnetic) coordinate system has Saturn at the origin, with the x-axis directed toward the Sun, 2 defined such that Saturn’s rotation and magnetic axes lie in the XZ plane (with p of pointing close to northward), and P lying in Saturn’s equatorial and magnetic equatorial plane.
25. The reference for the ONY model is [12] for the 23 model, [14] and the Q2 model [15].
26. We wish to acknowledge the Cassini Project and operates team from the Jet Propulsion Laboratory, as well as the many people at our home institutions for their designs, engineering, and software support over many years on behalf of this investigation. The contributions to the ONY team have been supported by the Particle Physics and Astronomy Research Council in the UK, the Deutsche Zentrum für Luft- und Raumfahrt in Germany, and NASA in the U.S.

6 October 2004; accepted 7 December 2004