and B). Titan and its atmosphere measurably absorbed the ENA emission from Saturn's magnetosphere (Fig. 3B). In Fig. 3C, which corresponds in time with the first increase in the integrated ENA flux (black curve), a hint of the halo emission seen in the October Titan encounter is evident. Later (Fig. 3D) the characteristic halo emission is quite evident, including the dark region in the lower atmosphere where the neutral density is too high for survival of the magnetically trapped ions (*2*, *3*).

By 11:27 universal time (UT) (Fig. 3E) the peak of the ENA emission was no longer within the 90°-by-120° FOV. The ENA intensity increased all the way to the edge of the FOV. The emission was considerably more intense: The color in this image is scaled to a peak value of 20 cm^{-2} s^{-1} sr^{-1} keV^{-1}, four times the peak in the preceding images.

Beginning in Fig. 3F, the orientation of the INCA FOV relative to Titan changed, and Titan's limb remained in the FOV for the remainder of the observation. The peak intensity in the images also rose (note the rescaling of the color bar). As shown in the last several images, a qualitative change occurred: The peak emission, which in Fig. 3, D to F, remained well above the limb, moved closer and closer to the limb until the time of Fig. 3, I to K, and then it appeared at a much lower apparent altitude.

With the use of the currently accepted range for the Titan exospheric density profile (*5*, *6*), we calculated the altitude at which we expect to find the maximum emissions by using the same approach outlined in Amsif *et al*. (*2*) and Dandouras *et al*. (*3*). Because the density profile was slightly different than that assumed in (*2*) and (*3*), the predicted altitude of the peak was a bit lower (1400 km versus 1700 km). Emissions are expected to fall steeply below that altitude, because the mean free path for the ions and ENAs rapidly shortens in the dense lower atmosphere (scale height of roughly 150 km). The observed peak in emission for the October encounter, at an altitude of ~2000 km for the tangent point of the line of sight, was higher than the predicted ~1400 km. In the 13 December encounter, the peak emission moved from about the same tangent point altitude (~2000 km) to an apparent altitude much lower than can be easily explained (~1000 km) toward the end of the encounter (Fig. 4). The model we used to predict the location of the peak intensity did not include the complex and important physics of the interaction between the ionosphere of Titan and the corotating, magnetized medium in which Titan is immersed. Treated as noninteracting, the magnetic field close to Titan has the same magnitude and direction as the field that intercepts Titan, and the ion interaction with the exosphere can be described by simple geometry (*3*).

In actuality, the highly conducting ionosphere interacts strongly with the flowing, magnetized medium about it, and magnetic flux piles up on the upstream side and drapes about Titan into a long tail on the downstream side, quite analogous to a comet tail in the magnetized solar wind. This Alfvénic interaction creates much higher magnetic field strengths than in the unperturbed medium as well as far different vector directions of the field. The trapped, gyrating ions are controlled by that field close to the moon, executing much more complex motions than those predicted by the simple noninteracting model. Consideration of effects of the actual measured magnetic field on ion trajectories during each flyby suggests that the unexpectedly high altitude for the peak emission during each Titan approach may be explained by the departure of these near-Titan magnetic field characteristics from the model used by Amsif *et al*. (*2*). Images taken after closest approach on 13 December (with the peak ENA emission occurring at anomalously low apparent altitude) will likewise require a more sophisticated treatment.

The energetic neutral atom images of Titan thus have revealed unexpected aspects of the interaction between the trapped energetic plasma and the exosphere of an outer planet moon. As is often the case, simple models are not adequate to describe all of the features found in the images. The Cassini MIMI images reveal the structure of ENA emission from the Saturn magnetosphere–Titan exosphere interaction to be quite complex. The emission is sensitive to quantitative details of the electromagnetic interaction of Titan's atmosphere and ionosphere, with the fast flowing corotating magnetosphere surrounding them. Magnetohydrodynamic and kinetic effects lead to extreme departures of the magnetic field direction and strength from the nominal conditions in the unperturbed medium, and the ENA images affirm that improved models of the interaction are required to represent that complexity.

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REPORT

Titan's Magnetic Field Signature During the First Cassini Encounter

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The magnetic field signature obtained by Cassini during its first close encounter with Titan on 26 October 2004 is presented and explained in terms of an advanced model. Titan was inside the saturnian magnetosphere. A magnetic field minimum before closest approach marked Cassini's entry into the magnetic ionopause layer. Cassini then left the northern and entered the southern magnetic tail lobe. The magnetic field before and after the encounter was approximately constant for ~20 Titan radii, but the field orientation changed exactly at the location of Titan's orbit. No evidence of an internal magnetic field at Titan was detected.

We report results from the Cassini magnetometer experiment obtained during the first close encounter [closest approach (CA) altitude: 1174 km] of Cassini with Saturn's moon Titan on 26 October 2004. This was the first opportunity to investigate Titan's environment with in situ measurements since the Voyager 1 flyby in 1980. With its extended neutral atmosphere, Titan orbits Saturn at a distance of 20.3 Saturn radii (R_S) and an orbital period of 15.95 days. For most of its orbit Titan is inside Saturn's magnetosphere (*1*), which is populated by neutral atoms and plasma from several potential sources (Saturn atmosphere and rings, icy satellites, Titan, solar wind) and at least partially corotates with the planet. Because Titan's orbital period is much larger than Saturn's rotational period (10.7 hours), Titan is embedded in a flow of magnetized plasma with a relative velocity on the order of 100 km/s (*2*). The magnetic field data measured as Voyager 1 flew by Titan placed an upper limit on Titan's internal magnetic field of 4.1 nT at the equatorial surface (*3*), which is approximately equal to the magnetospheric field at Titan's orbit. Thus, the interaction of Titan with Saturn's magnetosphere is of an atmospheric type, like, for example, the interaction of Venus with the solar wind, but has some unique features. At times of high solar wind dynamic pressure, when the magnetopause is pushed toward Saturn, Titan can leave the magnetosphere on the subsolar part of its orbit and interact with magnetosheath plasma or even the solar wind. In addition, the ionospheric properties on the side of Titan that faces the oncoming plasma flow vary with saturnian local time (SLT). The Voyager data also showed that the magnetospheric plasma properties are different from those of other plasmas in the solar system [trans-sonic, trans-Aflvénic, $\beta \approx 10$ (*3*, *4*)].

Cassini's magnetometer experiment is described in (*5*). Throughout the encounter, 32 vectors per second were measured by the flux gate magnetometer. At its first close encounter (T_A), Cassini passed through the northern part (with respect to the equatorial plane) of the streaming plasma wake of Titan, heading toward Saturn (Fig. 1). The closest approach occurred on 26 October 2004 15:30:04 SCET UTC (*6*) at an altitude of 1174 km above Titan. At this time Titan was near the saturnian magnetopause at 10:36 SLT (fig. S1), with the declination of the Sun relative to Titan's orbital plane $\alpha_{sol} = -23{:}23°$ (south summer). At about 12:15 on 25 October and at a radial distance of $\sim 28\ R_S$, Cassini finally crossed the saturnian bow shock and entered the magnetosheath, where strong compressional waves were observed (Fig. 2). The bow shock crossing was closer to Saturn than it was at Saturn orbit insertion (*7*), indicating that the magnetosphere was now more compressed. At about 10:40 on 26 October, 4 hours before CA and at a distance of about 39 Titan radii (R_T), Cassini finally crossed the saturnian magnetopause; thus, Titan was well inside the magnetosphere during T_A (Fig. 2). Cassini observed the magnetic field disturbance generated by Titan's interaction with the magnetospheric plasma between 15:10 and 15:50, centered about CA (15:30:04). The inbound magnetic field ($\vec{B}_{in}$) between 12:20 and 14:50, covering a distance of more than $\sim 20\ R_T$ in Titan's rest frame, was notably steady (Fig. 2), with a mean value of $\vec{B}_{in} = (0.72, 2.38, -5.60)$ nT (*8*), implying that the magnetic field was rotated toward Saturn by an angle of $\theta_{x,in} = 23.8°$. The angle between the Saturn-Sun line and Titan's orbital plane was $\|\alpha_{sol}\| = 23.2°$. The rotation toward Saturn was likely produced by Chapman-Ferraro currents in the near magnetopause. In the period after the encounter from 16:10 to 18:40, the outbound magnetic field ($\vec{B}_{out}$)

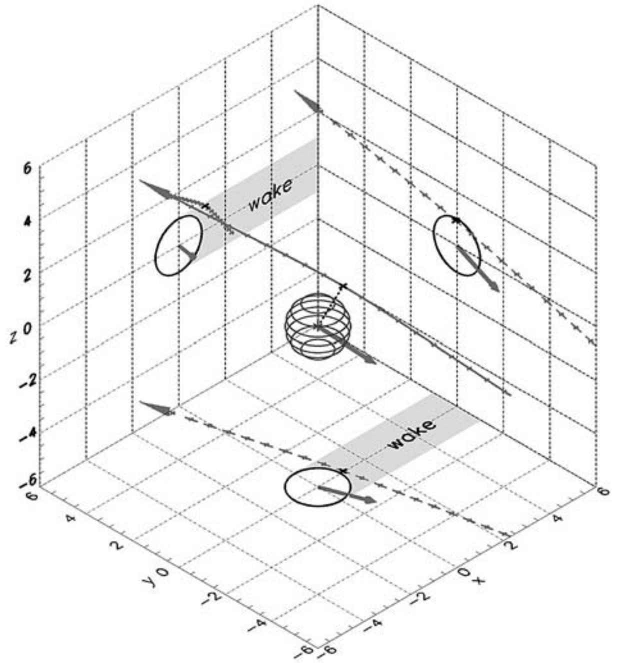
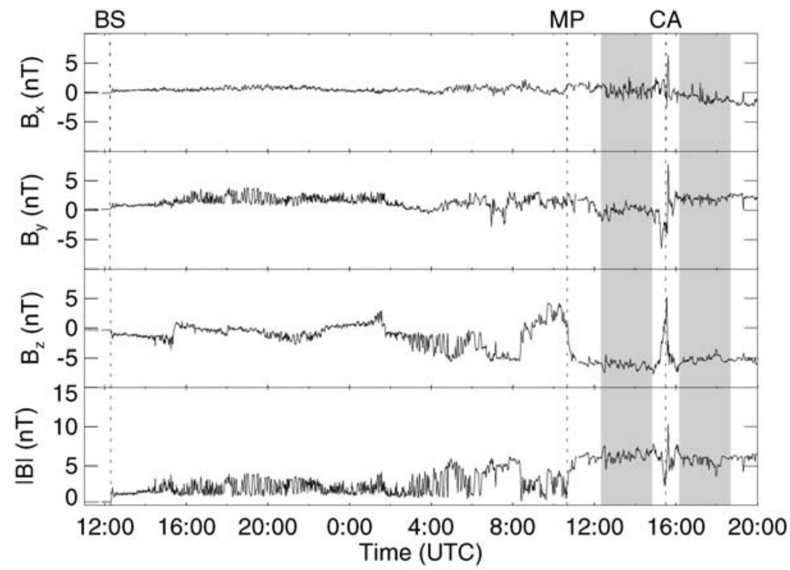


Fig. 1. Geometry of Cassini's T_A encounter. The Titan interaction coordinate system (TIIS) is centered at Titan with the *x* axis pointing in the direction of Titan's orbital motion, the *y* axis pointing toward Saturn, and the *z* axis being perpendicular to the orbital plane. Under ideal conditions, the incident plasma flow is along the *x* direction and the ambient saturnian magnetic field points in the –*z* direction. Cassini's trajectory and the projections on the three planes are shown. The drawn vector with its origin in Titan's center indicates the direction to the Sun. The wake with respect to an ideal corotating plasma flow is also indicated.



x(KSM)	21.97	21.40	20.80	20.15	19.46	18.71	17.91	17.01	16.06
y(KSM)	-14.91	-13.59	-12.24	-10.86	-9.46	-8.04	-6.58	-5.13	-3.79
z(KSM)	10.43	10.26	10.07	9.86	9.63	9.37	9.08	8.74	8.28
r (R_S)	28.5	27.3	26.1	24.9	23.7	22.4	21.1	19.8	18.5

Fig. 2. MAG data leading up to the Cassini T_A encounter (CA). The coordinates are in the Kronocentric Solar Magnetospheric (KSM) coordinate system (*x* is in the solar direction, *z* is in the plane formed by *x* and the saturnian dipole axis, and *y* completes the system). At 12:15 on 25 October 2004, Cassini crossed the bow shock (BS) at a saturnian distance of about 28 R_S. The magnetic field in the magnetosheath showed strong wave signatures. After several magnetopause crossings, Cassini finally entered the saturnian magnetosphere at 10:40 on 26 October 2004 at a distance of 21.6 R_S from Saturn's center (MP). The shaded areas mark periods of steady field inbound and outbound of the encounter.

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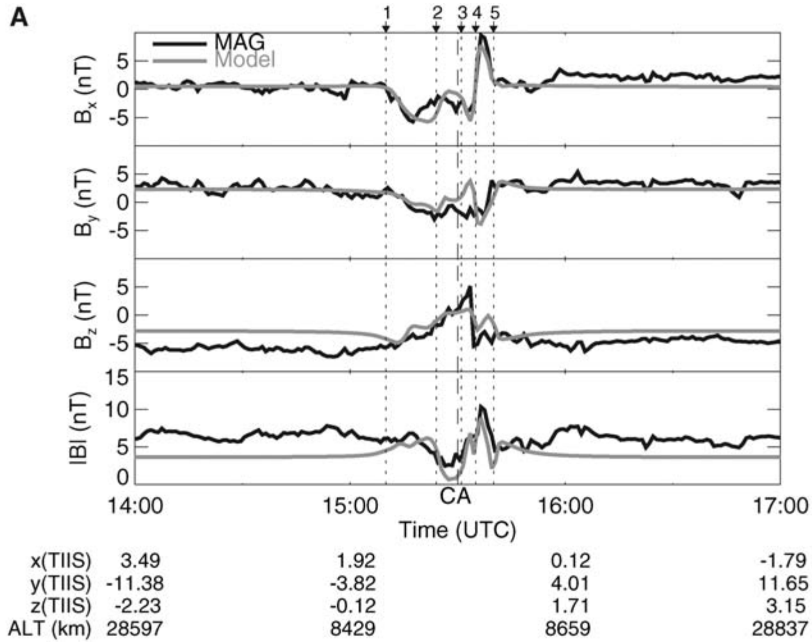

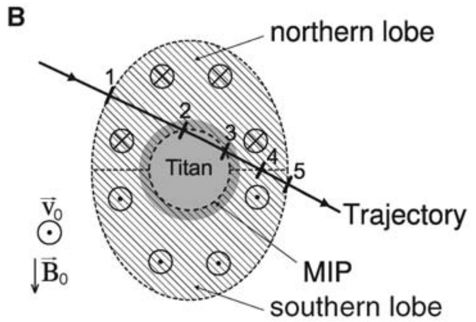

Fig. 3. (**A**) Magnetic field measured by the Cassini MAG instrument within a 3-hour interval centered at CA (15:30:04 UTC) (black line) plotted with the magnetic field along Cassini's trajectory obtained by a model (*11*). The magnetic field signature caused by Titan's interaction was observed between 15:10 and 15:50. The main features of the signature—a minimum of B 2 min before CA and an abrupt change of sign of B_x after CA—are well reproduced by the model. The magnetic field after the encounter is rotated with respect to the field before the encounter. (**B**) Schematic drawing of the magnetic field on a cut through the wake as obtained by the model (*11*). Titan is in gray. The hatched oval illustrates the magnetic wake. In the upper (northern) lobe the magnetic field points toward Titan, and in the lower (southern) lobe the field points away from Titan. Cassini's trajectory as it crosses the wake is drawn as a bold line. The numbers along the trajectory mark the borders between different regions traversed by Cassini [the positions are also marked in (A)]. Between positions 1 and 2, Cassini was in the northern lobe with the magnetic field pointing toward Titan $B_x < 0$. Between positions 2 and 3 Cassini dipped into the magnetic ionopause (MIP). In this region the field was at a minimum and the ionospheric electron density was at a maximum (*19*). After entering the northern lobe again for a short time (between positions 3 and 4), the polarity reversal layer (*22*) separating the northern and southern lobe was crossed and Cassini entered the southern lobe with $B_x > 0$ (between positions 4 and 5). The results of the model (*11*) that were used to generate this schematic are shown in the supporting online material (*15*).

was again steady but at a different orientation $\vec{B}_{\text{out}} = (1.99, 3.53, -3.93)$ nT and rotated more toward Saturn ($\theta_{x,\text{out}} = 41.9°$). The magnetic field changed at the position of Titan by $\Delta\vec{B} = (1.59, 1.03, 1.75)$ nT, with the magnitude remaining nearly constant ($\Delta B < 0.6$ nT). It might appear that Titan marks a boundary between two different magnetospheric regions, although no similar feature was observed by Voyager 1, and this feature may be a temporal coincidence.

Titan's large-scale magnetic interaction can be qualitatively described in terms of magnetic field line draping—a feature that has been observed, for example, at the solar wind interaction with comets (*9*). The basic idea is that a magnetized plasma streaming around a conducting obstacle leads to a draping of the frozen-in magnetic field around that obstacle [see figure 3 in (*10*)]. A quantitative description of the magnetic field topology—especially near the obstacle—is quite complicated because it involves details of the incident plasma flow and of the obstacle, which in the case of Titan consists predominantly of the neutral atmosphere and the ionosphere and their interdependence.

A three-dimensional resistive magnetohydrodynamic (MHD) model has been developed to describe Titan's interaction with the saturnian magnetospheric plasma (*11*, *12*). The model includes a static neutral atmosphere consisting of the two major species N_2 and CH_4 with radial distributions following (*13*). Ionospheric plasma is produced by photoionization and impact ionization by photoelectrons and magnetospheric electrons. The incident solar extreme ultraviolet (EUV) flux is parameterized using the EUVAC model (*14*) at solar minimum conditions. Elastic and inelastic collisions of magnetospheric electrons with the neutral gas and heat conduction along the magnetic field lines are included (*15*). The three-dimensional (3D) ionosphere generated has a dayside peak electron density of 7200 cm^{-3} at an altitude of 900 km. The nightside peak density is lower by an order of magnitude and is located at higher altitudes. We applied the model to T_A conditions (*16*) and assumed that the incident plasma properties were similar to the properties deduced from data measured during the Voyager 1 encounter (*3*).

For a comparison with the magnetic field data measured by the Cassini magnetometer (MAG) instrument during T_A, the coordinate system of the model was rotated with respect to the TIIS frame (defined in Fig. 1) in order to obtain the least-mean-square fit of the data by the model between 15:10 and 15:50. This was necessary because in the basic model it was assumed that the incident magnetic field was in the $-z$ direction. In the rotated frame the plasma velocity does not deviate from the ideal corotation direction in the equatorial plane (<1°) but has a small northward component (~10°). During the Voyager 1 encounter, the plasma velocity deviated from corotation by more than 20° in Titan's orbital plane (*17*, *18*). The incident magnetic field is rotated Saturnward (41.7°), which is inside the range between $\vec{B}_{\text{in}}$ and $\vec{B}_{\text{out}}$, and has a small x component (fig. S2). In the rotated frame (where the incident magnetic field is aligned with the $-z$ axis), the trajectory had to be adjusted appropriately. Whereas in TIIS the trajectory has a small northward component, it is southbound in the rotated frame (Fig. 3B). The model reproduces the observed magnetic field structure very well (Fig. 3A).

Titan's magnetic field signature in the interval between 15:10 and 15:40 is explained in terms of results from the model. At 15:10 the magnetic field changed direction and pointed toward Titan ($B_x < 0$ in Fig. 3A). At this point, Cassini entered the northern magnetic tail lobe (Fig. 3B). Two minutes before CA (15:28), the magnitude of the magnetic field as measured by Cassini showed a minimum and the ionospheric electron density, measured by the Langmuir probe of the plasma wave experiment (RPWS) (*19*) onboard the spacecraft, as well as in the model, was at a maximum. There are two reasons for the discrepancy between the location of the plasma density peak and CA: (i) Cassini travels along its trajectory from the dayside to the nightside of Titan. At CA, the optically thick atmosphere has absorbed most of the ionizing EUV. (ii) As predicted by the model, the ionization rate by magnetospheric electrons is an order of magnitude lower than the photoionization rate. Both effects cause the peak location to shift from CA toward Titan's dayside, i.e., toward times before CA. The reduction of the magnetic field magnitude is a consequence of shielding currents flowing in a layer that we call the magnetic ionopause, which separates the upper magnetized ionosphere from the lower non- or weakly magnetized ionosphere. The presence of this layer has been predicted by 1D models (*20*, *21*) for the side of Titan facing the streaming plasma. Our model (*11*) successfully describes the 3D structure of this layer and explains the observed magnetic field minimum. After the minimum, the magnetic field increased and was orientated toward Titan, indicating that Cassini was still in the northern lobe. About 5 min after CA, B_x changed sign abruptly. This point marks the transition from the northern into the southern magnetic lobe (Fig. 3B), which occurs as a rotation of the magnetic field at nearly constant field magnitude (*22*). Cassini left the southern magnetic lobe at 15:39 and returned into the unperturbed saturnian magnetic field. The good agreement between the modeled (*11*) and measured magnetic field signature of Titan implies that the signature can be explained without imposing any internal magnetic field.

This conclusion is consistent with the upper limit derived from Voyager 1 (*3*). However, the geometry of the T_A trajectory was not favorable for detecting an internal field. In addition, the occurrence of the magnetic field minimum before CA indicates the existence of a magnetic ionopause at Titan, implying that the lower ionosphere is non- or weakly magnetized. The model also shows that the plasma velocity vector derived from the rotation angles in order to obtain the best fit aligns nearly perfectly with the corotation direction in the equatorial plane, with a small northward component. From the similarities between model and MAG data, we suggest that the incident flow plasma conditions were not substantially different from Voyager 1 conditions.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/308/5724/992/DC1
SOM Text
Figs. S1 to S3
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