Upper limits on Titan’s magnetic moment and implications for its interior

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Measurements from the Cassini spacecraft reveal a largely magnetized ionosphere of Titan whose low-altitude fields could be from the interior of Titan or from penetrating external fields. We use the Cassini magnetic field measurements obtained during 25 Titan flybys to examine the upper limit of Titan’s internal magnetic moment. The radial component of the magnetic field near the Titan surface (from 950 to 1100 km) is used to calculate the permanent dipole moment. The calculated upper limit of the permanent dipole moment is 0.78 nT × R\text{s}^3, that is, for the z, y, and x directions (0.46, 0.55, 0.29, respectively) nT × R\text{s}^3, with an error of ~0.5 nT in each component. This value is not significantly different from zero, but it is also a factor of 5 lower than the previous upper limit from Voyager observations. This small (possibly zero) magnetic moment of Titan indicates that the interior of the moon does not support a magnetic dynamo, in agreement with the results of recent gravity study which suggest an incompletely differentiated interior. The induced moment of Titan is examined to test the existence of a subsurface ocean. The data obtained thus far are not sufficient to provide definitive evidence of the existence and depth of a subsurface ocean. This situation will be improved with the addition of measurements after Saturn’s equinox when the external inducing field changes significantly.


1. Introduction

Titan, with a radius of 2575 km and density of 1.88 g/cm\textsuperscript{3}, orbits Saturn in its outer magnetosphere at 20 Saturn radii (R\text{s}). It has a dense atmosphere primarily composed of molecular nitrogen and methane, with minor amounts of additional hydrocarbon and nitrile species. For the majority of the time the environment surrounding Titan is the subcorotating plasma of the outer magnetosphere of Saturn. For short periods, Titan may be located in the Saturnian magnetosheath [Bertucci et al., 2008; Wei et al., 2009], or even in the solar wind, when Titan is close to noon and the magnetosphere is highly compressed.

The early measurements from Voyager 1 found that Titan has, at most, a weak intrinsic dipole magnetic field [Ness et al., 1982; Neubauer et al., 1984]. Thus, the interaction between Titan’s dense atmosphere and the flowing plasma resembles the interaction of the solar wind with unmagnetized planets. Since the magnetospheric plasma flow encountering Titan is submagnetosonic, unlike Venus and Mars, there is no bow shock in front of Titan. During the interaction, the upstream fields are compressed and draped around Titan while the plasma flow slows down and deflects [Ness et al., 1982; Kivelson and Russell, 1983; Backes et al., 2005; Wahlund et al., 2005; Neubauer et al., 2006; Wei et al., 2007].

Figure 1a shows an illustration of the Titan interaction with the Saturnian magnetospheric plasma along its orbit. The orbital phase of Titan affects the Titan interaction, not only because the upstream plasma conditions vary with Saturnian local time (SLT), but also because the upstream flow varies relative to the solar direction. Since Titan’s ionosphere is primarily produced by photoionization, it has a significant day-night asymmetry.

Figures 1b–1e show simulation results of the Titan interaction at 18 SLT and 06 SLT using a three-dimensional (3D), magnetohydrodynamic (MHD) model [Ma et al., 2006], which assumes a southward upstream field and the expected corotating flow. In the day-night meridian the simulated magnetic field strength is shown in Figures 1b and 1d and the total plasma mass density is shown in Figures 1c and 1e. The coordinate system is the Titan Interaction System (TIIS) [Dougherty et al., 2004], in which the x-axis is in the nominal corotation direction, the y-axis points from Titan to Saturn, and the z-axis is northward, completing the right-handed coordinate system. For the 18 SLT case shown in Figures 1b and 1c, the upstream flow encounters the dayside ionosphere, slows down, and diverts...
around Titan. The magnetic fields that are frozen in the flow pile up and drape around it, forming a magnetic tail stretched in the downstream direction. For the 06 SLT case shown in Figures 1d and 1e, the upstream flow encounters the nightside ionosphere, which is much weaker than that at 18 SLT (see Figure 1e). Thus, the interaction is similar to the 18 SLT case, except that the upstream fields can penetrate to lower altitudes and may magnetize the ionosphere and even penetrate to the neutral atmosphere below it. Whether the upstream fields can penetrate to low altitudes or penetrate below the surface is an important issue, because that would induce currents in any possible conductive layers inside the ionosphere.
Titan. It also affects the estimate of Titan’s internal moments by adding “noise” to the intrinsic or induced fields. We consider these effects in our study when discussing the permanent and induced moments of Titan in later sections.

The Saturnian magnetospheric field near the Titan orbit is not in the “ideal” dipolar southward direction according to Cassini spacecraft observations. It often has a significant component in the radial direction, either toward or away from Saturn. Titan has been generally below the bowl-shaped magnetodisk [Arridge et al., 2008] during the initial portion of the Cassini mission when the rotation axis is away from the Sun, so the field has been generally toward Saturn. There is also a small component of the magnetic field in the corotation direction. We notice that, generally, the upstream field near the noon sector is almost in the southward direction with very small components in the other two directions. While the upstream field near the midnight sector often has significant components toward Saturn and in the corotation direction, Saturn’s field near midnight usually stretches away from Saturn and relaxes periodically [Russell et al., 2008].

Measurements from the Voyager 1 spacecraft during its Titan flyby provided an upper limit of Titan’s internal field of 4.1 nT × R_{Ti}³. The Voyager pass was in the downstream wake region of the corotation flow with CA of 4006 km. The estimate of Titan’s internal field was obtained by: (1) assuming the hypothetical dipole moment was antiparallel to the magnetic moment of Saturn; (2) attributing the magnetic flux calculated from observation along the trajectory to the total flux through one hemisphere of Titan; and (3) assuming the size of the tail lobe to have a somewhat arbitrary extension of ±5 R_{Ti} in the ±z direction [Neubauer et al., 1984]. This estimate gave an upper limit to the internal moment of Titan based on the observations available then.

The Cassini mission, which has multiple flybys passing much closer to Titan, can improve significantly on this value. The Cassini Titan passes are at lower altitudes (with a CA as low as 950 km) than the Voyager pass (with a CA of 4006 km), but also because there are now over 50 Cassini Titan flybys passing over many different regions of Titan.
above the surface and at several different LT in the Saturn magnetosphere. Thus, the Cassini measurements allow us to isolate effects due to differing flyby geometries and changing plasma environment and to estimate a much more robust upper limit to Titan’s intrinsic field.

During Cassini’s Titan passes, the observed magnetic fields at low altitudes near CA do not usually approach zero (see Figure 2 for example), but have an average of about 4 nT in altitudes below 1100 km. The sources of such fields could be external or internal. There are three potential sources of magnetic fields in the low altitude Titan ionosphere. The largest component is the magnetic field that is induced in the ionosphere of Titan. This magnetic field is carried by the plasma in the collisionless, Saturnian magnetospheric plasma that “corotates” with Saturn (but at a somewhat slower angular speed). At low altitudes where the plasma is collisional, this field diffuses into the ionosphere slowly and produces a draped field pattern with a field sufficiently strong to largely balance the dynamic pressure of the flow. This field stretches out in the downstream direction, but is largely horizontal. The easiest way to understand this is to visualize isochrons of the magnetic field when the external field changes direction. Such a directional discontinuity will pass Titan in a few minutes, but the lower ionosphere will not experience the change for several hours. The ratio between the two time scales determines how horizontal the field is (with the exception of the tailward region where the field is both weak and radial). This field is not the subject of this report and will be treated as a source of noise that is to be minimized.

A second induced magnetic field source is the current that flows in the conducting interior of Titan in response to the field changes that it experiences. These currents act to exclude the exterior field (as does the ionosphere). They experience only the field changes that the low-pass filter of the ionosphere allows to penetrate to the conducting interior.

We are very interested in this field because its strength depends on the size of this conducting region as well as on the strength of the magnetic field at the bottom of the ionosphere. We assume herein that the field measured at the lowest altitudes by Cassini is the “external” field which these interior current systems exclude according to Lenz’ law. The interior conductor could be a global ocean or a metallic core (either fluid or solid).

A third source of field is the “permanent” field of Titan due to induced currents associated with long term immersion in Saturn’s (weak) dipolar field at Titan, plus any internal dynamo generated field, or any remnant magnetism-associated field. Just as currents in the conducting-interior flow to exclude the changing external field, any field that exists long enough to diffuse into the conductor will remain fixed over shorter-time scales as currents flow to maintain these fields when the external fields change (until diffusion occurs). Diffusion times in conductors of the size of Titan’s interior conducting region should have diffusion times of thousands of years or more. We cannot distinguish this long-term induced field from a dynamo-generated magnetic field maintained by convective motions that compete with this same diffusion, or from remnant fields in the cold outer layers of the moon.

In this paper, we use the magnetic field measurements near closest approach from 25 low-altitude Titan flybys to estimate the magnetic moments of Titan. Then, we discuss the possible sources that contribute to the estimated moments, and their implications for the interior of Titan.

### 2. Cassini Trajectories Past Titan

Cassini magnetometer data below 1100 km altitude, obtained over ~6 minutes around CA, are used in the

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**Table 1. List of Titan Flybys for Studying Internal Field**

<table>
<thead>
<tr>
<th>Tour</th>
<th>Date</th>
<th>CA Time</th>
<th>Distance (R&lt;sub&gt;Ti&lt;/sub&gt;)</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>B&lt;sub&gt;x&lt;/sub&gt; (nT)</th>
<th>B&lt;sub&gt;y&lt;/sub&gt; (nT)</th>
<th>B&lt;sub&gt;z&lt;/sub&gt; (nT)</th>
<th>SLT (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T05</td>
<td>2005106</td>
<td>19:11:46</td>
<td>1.39</td>
<td>74.46</td>
<td></td>
<td>177.89</td>
<td>0.15</td>
<td>3.74</td>
<td>3.62</td>
</tr>
<tr>
<td>T16</td>
<td>2006200</td>
<td>00:23:26</td>
<td>1.37</td>
<td>85.42</td>
<td></td>
<td>129.82</td>
<td>-1.34</td>
<td>4.56</td>
<td>3.50</td>
</tr>
<tr>
<td>T17</td>
<td>2006250</td>
<td>20:16:52</td>
<td>1.39</td>
<td>22.56</td>
<td></td>
<td>32.14</td>
<td>-0.36</td>
<td>-1.73</td>
<td>1.40</td>
</tr>
<tr>
<td>T18</td>
<td>2006266</td>
<td>18:58:49</td>
<td>1.37</td>
<td>70.98</td>
<td></td>
<td>90.88</td>
<td>-2.67</td>
<td>-1.13</td>
<td>-1.32</td>
</tr>
<tr>
<td>T19</td>
<td>2006282</td>
<td>17:30:08</td>
<td>1.38</td>
<td>60.81</td>
<td></td>
<td>90.88</td>
<td>-4.36</td>
<td>-5.45</td>
<td>-0.41</td>
</tr>
<tr>
<td>T20</td>
<td>2006298</td>
<td>15:58:08</td>
<td>1.40</td>
<td>6.14</td>
<td></td>
<td>44.76</td>
<td>-1.46</td>
<td>-1.54</td>
<td>4.38</td>
</tr>
<tr>
<td>T21</td>
<td>2006346</td>
<td>11:41:32</td>
<td>1.39</td>
<td>43.47</td>
<td></td>
<td>-175.81</td>
<td>-1.20</td>
<td>-2.20</td>
<td>-3.13</td>
</tr>
<tr>
<td>T22</td>
<td>2007013</td>
<td>08:38:23</td>
<td>1.39</td>
<td>30.71</td>
<td></td>
<td>90.80</td>
<td>-1.25</td>
<td>-6.45</td>
<td>0.47</td>
</tr>
<tr>
<td>T25</td>
<td>2007053</td>
<td>03:12:25</td>
<td>1.39</td>
<td>30.46</td>
<td></td>
<td>71.00</td>
<td>0.42</td>
<td>0.03</td>
<td>3.10</td>
</tr>
<tr>
<td>T026</td>
<td>2007069</td>
<td>01:49:01</td>
<td>1.38</td>
<td>31.71</td>
<td></td>
<td>89.40</td>
<td>-0.12</td>
<td>0.29</td>
<td>2.07</td>
</tr>
<tr>
<td>T027</td>
<td>2007085</td>
<td>00:23:27</td>
<td>1.39</td>
<td>40.93</td>
<td></td>
<td>89.39</td>
<td>0.78</td>
<td>-0.93</td>
<td>1.65</td>
</tr>
<tr>
<td>T028</td>
<td>2007100</td>
<td>22:58:01</td>
<td>1.39</td>
<td>50.18</td>
<td></td>
<td>89.36</td>
<td>0.80</td>
<td>0.13</td>
<td>0.41</td>
</tr>
<tr>
<td>T029</td>
<td>2007116</td>
<td>21:32:59</td>
<td>1.38</td>
<td>59.40</td>
<td></td>
<td>89.30</td>
<td>0.82</td>
<td>0.09</td>
<td>-2.50</td>
</tr>
<tr>
<td>T030</td>
<td>2007132</td>
<td>20:09:59</td>
<td>1.37</td>
<td>68.63</td>
<td></td>
<td>89.19</td>
<td>0.74</td>
<td>-0.53</td>
<td>-0.20</td>
</tr>
<tr>
<td>T032</td>
<td>2007164</td>
<td>17:46:12</td>
<td>1.38</td>
<td>84.51</td>
<td></td>
<td>88.98</td>
<td>-0.43</td>
<td>-0.93</td>
<td>-1.51</td>
</tr>
<tr>
<td>T36</td>
<td>2007275</td>
<td>04:42:43</td>
<td>1.38</td>
<td>-59.71</td>
<td></td>
<td>-20.22</td>
<td>1.41</td>
<td>5.38</td>
<td>-1.79</td>
</tr>
<tr>
<td>T39</td>
<td>2007334</td>
<td>22:57:55</td>
<td>1.38</td>
<td>-70.17</td>
<td></td>
<td>-87.43</td>
<td>-4.80</td>
<td>-4.05</td>
<td>0.80</td>
</tr>
<tr>
<td>T40</td>
<td>2008005</td>
<td>21:30:20</td>
<td>1.39</td>
<td>-11.57</td>
<td></td>
<td>-41.81</td>
<td>0.96</td>
<td>1.36</td>
<td>2.00</td>
</tr>
<tr>
<td>T042</td>
<td>2008085</td>
<td>14:27:48</td>
<td>1.39</td>
<td>-27.08</td>
<td></td>
<td>-67.73</td>
<td>0.40</td>
<td>-1.78</td>
<td>0.13</td>
</tr>
<tr>
<td>T043</td>
<td>2008133</td>
<td>10:01:58</td>
<td>1.39</td>
<td>18.13</td>
<td></td>
<td>-48.58</td>
<td>0.20</td>
<td>1.56</td>
<td>2.10</td>
</tr>
<tr>
<td>T048</td>
<td>2008340</td>
<td>14:25:45</td>
<td>1.37</td>
<td>-10.26</td>
<td></td>
<td>-89.97</td>
<td>1.30</td>
<td>1.63</td>
<td>1.63</td>
</tr>
<tr>
<td>T049</td>
<td>2008356</td>
<td>12:59:52</td>
<td>1.38</td>
<td>-44.02</td>
<td></td>
<td>-147.94</td>
<td>-0.50</td>
<td>1.16</td>
<td>-1.35</td>
</tr>
<tr>
<td>T050</td>
<td>2009038</td>
<td>08:50:53</td>
<td>1.38</td>
<td>-33.89</td>
<td></td>
<td>142.71</td>
<td>-0.62</td>
<td>0.41</td>
<td>-1.37</td>
</tr>
<tr>
<td>T051</td>
<td>2009086</td>
<td>04:43:37</td>
<td>1.37</td>
<td>-30.47</td>
<td></td>
<td>-145.91</td>
<td>1.84</td>
<td>-3.86</td>
<td>-2.45</td>
</tr>
</tbody>
</table>

*From left to right, the columns are flyby number, date of the pass, time of closest approach, radial distance, latitude, longitude, B<sub>x</sub>, B<sub>y</sub>, and B<sub>z</sub> of CA, and SLT.*
intrinsic field study. Because the exobase altitude is typically at 1400 km and the ionosphere density peak is typically around 1200 km in the dayside [Ågren et al., 2009], the upstream fields should be largely shielded from penetrating into the region below 1100 km if the ionosphere thermal pressure is strong enough to withstand the total pressure of the upstream plasma flow. Thus, these low-altitude data are better suited for studying any possible internal moments of Titan.

There are 25 such passes (Table 1): T5, T16–T21, T23, T25–T30, T32, T36, T39, T40, T42, T43, and T47–T51. Figure 3 shows the trajectories of these passes. Seven of these passes occurred when Titan is near 0200 SLT, 7 passes near 1400 SLT, 5 passes near 1100 SLT, 5 passes near 1000 SLT and 1 pass near 0500 SLT. Their CA altitudes vary from 950 to 1030 km. The magnetic field magnitudes observed at these altitudes varies from 0.5 to 11.6 nT with a median of 3.6 nT.

These low-altitude fields may be due to external or internal sources. In the dayside ionosphere of Titan below 1100 km and above 950 km, the conductivity becomes increasingly less important and the diffusion process in the plasma becomes increasingly more important. In the nightside ionosphere, the diffusion process becomes even more significant. At these altitudes, the time for diffusion of the magnetic field into the plasma is several hours [Ma et al., 2009]. This is true whether the field sources are external or internal, while the latter may be due to a permanent, intrinsic magnetic moment generated by a dynamo or to an electromagnetic-induced moment inside Titan due to excitation by external-inducing fields.

In the next section, we examine whether the observed low altitude fields are generated by a permanent dipole moment and estimate the upper limit of the moment, that is, test the third source discussed in the introduction. After that, we discuss the possibility of these observed fields being from an internally induced dipole moment, that is, test the second source discussed in the introduction. We also consider and discuss the effects of the upstream fields penetrating into these low altitudes when estimating the internal moments.

3. Internal Moment Estimate Using all Three Components

When calculating the internal moments, we need to consider the effects from the penetrating upstream fields. We have learned from the Venus-solar-wind interaction that if the ionospheric thermal pressure is strong enough to balance the upstream pressure (at an altitude where the...
plasma is collisionless), the upstream fields are shielded from penetrating below the ionopause; but, if the ionospheric pressure is weaker than the upstream pressure, the upstream fields can penetrate into the collisional lower ionosphere. In the Titan case, the upstreamside ionosphere, which withstands the incoming flow, has its strongest pressure when Titan is near 18 SLT and its weakest pressure near 06 SLT. It would be ideal if we could predict the fields which penetrate from the external fields and subtract them from the observed fields to calculate the internal moments. However, the prediction can hardly be accurate because of the uncertain upstream field orientation and plasma flow direction during each flyby, and the complexity caused by time variations in those upstream parameters. Due to the finite diffusion time in the lower ionosphere, it may take hours for a change of upstream field to diffuse down to low altitudes. Thus, the observed low-altitude fields may not be caused by the current upstream field, but by the upstream field of hours ago. Such fields are called “fossil fields” by Neubauer et al. [2006] and such fields add to the difficulty of predicting the low-altitude field due to penetration of these external fields.

Using data at the lowest possible altitudes helps minimize the effects from the penetrating external fields. As a first approximation, we assume that all the fields at low altitudes can be modeled as arising from an internal dipole moment. If this approximation is true, the calculated moments will have small standard deviations from orbit to orbit. They should be related to the upstream field orientations, if they are due to induced moments inside Titan. If these low-altitude fields are only due to the penetrating external fields or to a “fossil field” record, they should be badly approximated by a dipole field model and have varying orientation and magnitude from pass to pass. Although the following analysis is made under the assumption that the low-altitude fields are due to internal sources, the consistency and the standard deviations of calculated moments will tell us whether they are internal or external.

Under the assumption that the fields at low altitudes are predominantly generated by an internal dipole moment, we can calculate the source which is a vector sum of \( g_{10} \) (dipole moment along the \( z \)-axis), \( g_{11} \) (dipole moment along the \( y \)-axis), and \( h_{11} \) (dipole moment along the \( x \)-axis). The values of \( g_{10}, g_{11}, \) and \( h_{11} \) can be inverted from the observed magnetic field and position data in the 25 Titan flybys as in

\[
\begin{pmatrix}
B_x \\
B_y \\
B_z
\end{pmatrix} = r^{-5} \begin{pmatrix}
3xz & 3xy & 3z^2 - r^2 \\
3yz & 3y^2 - r^2 & 3yx \\
3z^2 - r^2 & 3zy & 3zx
\end{pmatrix} \begin{pmatrix}
g_{10} \\
g_{11} \\
h_{11}
\end{pmatrix}.
\]

Figure 3. (continued)
Figure 4 shows the median values of the calculated $g_{10}$, $g_{11}$, and $h_{11}$ moments for each of the 25 passes, and each error bar is bounded by the upper and lower quartiles of the calculated moments in that pass. Median and quartiles are more reliable than mean and standard deviation in this calculation because the former two minimize the effects from large outliers. We see in Figure 4 that there is a large standard deviation for the inverted values of $g_{10}$, $g_{11}$, and $h_{11}$ on several passes, such as T16 and T36. Also, the median values are not consistent from pass to pass, since they have both positive and negative values even for passes at similar SLT, such as T19, T20, and T21, which are near 0200 SLT. This large variability indicates that the field is not principally generated by a permanent internal moment, but may be caused by varying external fields inducing horizontal (draped) fields and currents in the ionosphere.

By looking at the components of the observed magnetic field vector, we notice that these low-altitude fields are larger and more variable in the two horizontal components than in the radial component. The altitude profile of T17 is shown as an example (Figure 5). It shows the altitude variation of magnetic field strength $B_T$, the radial component $B_R$, the local eastward component $B_E$, and the local northward component $B_N$. For both inbound and outbound of the pass, the radial component is less variable than the two horizontal components ($B_N$ and $B_E$). This is understandable since the “induced” ionospheric currents principally flow in horizontal layers at low altitudes and they affect the radial component much less than they affect the two horizontal components. This is similar to the ionosphere of Venus where the field lines are nearly horizontal because of the slow vertical transport of flux at low altitudes. The strong correlation of the horizontal field with the interplanetary magnetic field was first noted by Phillips and Russell [1987] when they mapped the Venus field. A similar result was obtained recently for the Moon by Purucker [2008], who used the radial component of the lunar field to construct his field model.

### 4. Internal Moment Estimate Using Radial Component

Although there is ambiguity in deciding the source of these low-altitude fields, we notice that the induced field, from ionospheric currents or the Titan interior by short-term change in the inducing field, should affect the two horizontal components much more than they affect the radial component in the low-altitude regions. Furthermore, the horizontal fields change with varying external conditions, while the radial component (if from a permanent internal dynamo) should be consistent from pass to pass. Thus, we use the observed greater stability of the radial field to esti-
mate the permanent intrinsic moment and we consider the results as an upper limit of the intrinsic moment because of the effects from the external and induced fields.

[23] Recalling that $B_r = r^{-1} (xB_x + yB_y + zB_z)$, we use equation (1) to show that $B_r = 2r^{-4} (z \cdot g_{10} + y \cdot g_{11} + x \cdot h_{11})$. With this equation we use three measurements of the radial fields, i.e., $B_{r1}$, $B_{r2}$, and $B_{r3}$, along with their corresponding positions, to uniquely calculate the three moments $g_{10}$, $g_{11}$, and $h_{11}$, as is shown as

$$
\begin{bmatrix}
B_{r1} \\
B_{r2} \\
B_{r3}
\end{bmatrix}
= 2r^{-4}
\begin{bmatrix}
z_1 & y_1 & x_1 \\
z_2 & y_2 & x_2 \\
z_3 & y_3 & x_3
\end{bmatrix}
\begin{bmatrix}
g_{10} \\
g_{11} \\
h_{11}
\end{bmatrix}.
$$

In this inversion, the three measurements should be taken close to the pole of each of the axes of $g_{10}$, $g_{11}$, and $h_{11}$, so that the radial component of the fields contain contributions from the moments on each of the $x$, $y$, and $z$ axes. This is because only the radial component is used in this inversion and the radial component of a dipole field maximizes near the polar region of the dipole axis and minimizes to zero near the equator.

[24] In Figure 3 we can see the trajectories of each pass. The passes containing data taken near the $z$-axis contribute most to the determination of $g_{10}$, data near the $y$-axis to $g_{11}$, and data near the $x$-axis to $h_{11}$. To estimate the permanent internal fields, we can use all the data from 25 passes to do one inversion, by sorting the data into three groups and using one $B_r$ from each of the three groups for one calculation with equation (2). The calculated $g_{10}$, $g_{11}$, and $h_{11}$ are shown in Figure 6. Their medians are shown in the right of each panel with error bars bounded by the upper and lower quartiles. The horizontal axes in this figure have no physical meanings but are just sequence numbers of the 2509 calculations. The majority of the calculated moments are in the range of $-20$ to $20$ nT $\times R_{Ti}^3$, but there are several outliers as high as thousands of nT $\times R_{Ti}^3$, which are not considered real, but are considered numerical. The calculation requires the

Figure 5. Altitude profile of magnetic field strength $B_T$, the radial component $B_r$, the eastward component $B_E$ (in the direction of the cross product of the radial direction and the $z$ direction in Dougherty et al.’s [2004] Titan Interaction System (TIIS), and the local northward component $B_N$ (in the direction of $B_r$ across $B_E$), for both inbound and outbound Titan flyby T17.
determinant of the matrix 
\[
\begin{bmatrix}
\frac{2z_1}{r^4} & \frac{2y_1}{r^4} & \frac{2x_1}{r^4} \\
\frac{2z_2}{r^4} & \frac{2y_2}{r^4} & \frac{2x_2}{r^4} \\
\frac{2z_3}{r^4} & \frac{2y_3}{r^4} & \frac{2x_3}{r^4}
\end{bmatrix}
\]
to be nonzero so that its inverse matrix can be stable. The large moment outliers are due to the determinant of the above matrix approaching zero, which generates unstable numerical results. If such strong moments existed locally, we would have observed large field in some regions in the ionosphere, while the maximum field in the ionosphere below 1100 km is only 11.6 nT.

[25] Since there are many ways to sort the data into 3 groups (Figure 6 shows one way of sorting), we randomly sort the data into 3 groups for 10,000 times and test the statistical fluctuation caused by the ways of sorting. For each sort we obtain the medians of the moments. For the 10,000 calculations, the average of the medians for \(g_{10}, g_{11}, \) and \(h_{11}\) are 0.46, 0.55, 0.29, respectively, with standard deviations of 0.04, 0.04, 0.03, respectively, in nT \(\times R_{Ti}^3\) units. These small standard deviations of the averaged moments show that the calculation is not sensitive to way of sorting the data into 3 groups. The vector sum of the averaged moments leads to a total moment of 0.78 nT \(\times R_{Ti}^3\). Compared with the moments in Figure 4, the calculated moments using only the radial component are much less scattered, thus more reliable. This agrees with our assumption that the radial component of the field is the component least affected by changing external conditions.

[26] If we use half of the difference between the upper and lower quartiles as the size of the error in each moment for one calculation, we obtain averaged error sizes of 2.27, 2.56, and 2.57 nT for \(g_{10}, g_{11}, \) and \(h_{11}\), respectively. Since we have only 25 passes, then there are 24 degrees of freedom. Thus, the probable error of the mean is estimated to be 0.46, 0.52, and 0.52 nT. The average probable error obtained from this estimation is about 0.5 nT and is comparable to the size of the calculated moments, thus the moments obtained are not statistically different from zero which implies a zero permanent internal moment at Titan.

[27] So far, we have treated the errors in our calculation from the induced fields and penetrating external fields as “noise” around the permanent fields, represented by error bars around the medians of moments. This treatment could be useful for the penetrating external fields since they are the draped fields near Titan so they have random variations. For the induced fields, this treatment may not be useful if their time scale is longer than the duration of the data we have so far. For example, the Saturnian magnetospheric field around Titan always has a southward component, which may induce currents inside Titan to generate a \(g_{10}\) moment, mimicking a permanent field. We will discuss such long time scale-induced and short time scale-induced fields in the next section.

5. Induced Moment Test

[28] As discussed above, the external–inducing fields have two time scales. The magnetic field that is principally in directions radially toward and away from Saturn varies as the magnetosphere stretches and compresses. These components reverse when Titan crosses the magnetosphere current sheet, which can happen due to solar wind flow changes or internal magnetospheric causes such as a tilt of the dipole or a reconfiguration of the magnetotail. This variable field will magnetize the ionosphere, which acts as a low-pass filter, and this filtered field is applied to the outer layers of any contiguous electrically-conducting ocean. It is the counterpart of the time-varying field that was used to sound the electric conductivity of the interior of Europa.
Kivelson et al., 1997] and Callisto [Khurana et al., 1997; Neubauer, 1998], which are not as strongly filtered by a thick conducting ionosphere. In contrast, the very long-term average of magnetospheric magnetic field could last millennia, if not eons, before it “flipped” and should create a uniform north-south magnetic field within Titan. We cannot distinguish the long-term field from that generated by an internal dynamo or from crustal magnetization.

To determine the short-term induced field in the interior, we surveyed the field orientation in Titan’s environment near 20 $R_S$ using over four years of Cassini observations during Titan flybys (Figure 7). These ambient fields are obtained by averaging over two 1-hour intervals before and after closest approach around the strongly draped field region.

The ambient magnetic field could produce magnetic induction in both the ionosphere and the interior of Titan. As discussed in the first section, the induction has three time scales, from minutes or hours in the ionosphere to thousands of years, or more, in the interior. The short-term exterior field changes can only cause a response in the ionospheric-induced currents, while changes in the averaged fields at the two longer time scales may diffuse into Titan and induce currents in any conducting layers. Field components in the direction of corotation and from Titan-to-Saturn are expected to change sign every 14 years when Titan moves from below the equatorial current sheet to above the current sheet and vice versa. However, the north-south component would be southward for thousands of years or more.

From Figure 7, we find the averaged north-south field is 2.8 nT during the 4 year Cassini observing time. The field varies from negative to positive in both $x$ and $y$ directions in the TIIS coordinates, but both components were mostly in positive values during these 4 years (i.e., pointing from Titan to Saturn and in the corotation direction), which shows that Titan at this time is below the current sheet of Saturn. The “constant” southward field may lead to a negative $g_{10}$ moment in the calculation of average value about 1.4 nT $\times R_{Ti}^3$, if there is an average of 2.8 nT southward field inside Titan (assuming a conductive layer close to the surface). In Figure 6, the calculated $g_{10}$ moments from just the radial fields are positive (the opposite sign to the southward ambient field) and the $g_{11}$ and $h_{11}$ moments are mostly positive (the same sign as the majority of ambient fields). If the moments estimated with the radial fields are actually due to the magnetization of the Titan interior by the penetration of external fields into the moon interior, the $g_{11}$ and $h_{11}$ moments should
be positive and $g_{10}$ should be negative. When Titan moves to above the current sheet of the Saturnian magnetosphere, the external field in $x$ and $y$ will reverse. Thus, we can apply the same calculation to the data obtained above the current sheet to average away the effects from induced internal moments along $x$ and $y$ axes. Such data will be obtained in the Extended Cassini Mission since Titan started to move above the current sheet in August 2009. For the $g_{10}$ component, the calculated positive value may indicate Titan has a permanent moment along the positive $z$ axis, countering the moment generated from interior magnetization by the external field in negative $B_z$. However, calculated permanent moments (i.e., 0.46, 0.55, and 0.29 nT $\times R_T^2$) are not statistically significant from zero. Thus at this stage, we cannot determine the existence of permanent moment in $g_{10}$ or the long-term induced field. It requires the results from data above the current sheet to examine the long-term induced field by checking if $g_{11}$ and $h_{11}$ reverse. If $g_{11}$ and $h_{11}$ reverse when Titan is above the current sheet, we could believe that there is also a long-term induced field in the interior causing negative $g_{10}$, thus the obtained positive $g_{10}$ indicates a permanent moment in positive $g_{10}$.

[32] We can do an initial test of the possibility that the fields observed near Titan during each pass are from short-term induced moments inside Titan, by applying a simple model to the data which considers the fields observed near Titan to be the sum of a constant external field ($B_{x0}$, $B_{y0}$, $B_{z0}$) and an internal dipole moment ($Ig_{10}$, $Ig_{11}$, $Ih_{11}$). The assumptions are that the induced moment response time is not much larger than the time scale of the external field variations, that the induced moment is antiparallel to the external field, and that the sum of the two fields cancel each other in the radial direction on the conductive surface. Thus, we can obtain the orientation and strength of the induced moment, expressing by the external field ($B_{x0}$, $B_{y0}$, $B_{z0}$). The field lines in such a situation are illustrated in Figure 8. Under the above assumptions, the observed fields can then be expressed as

$$
\begin{pmatrix}
B_x \\
B_y \\
B_z
\end{pmatrix} = \begin{pmatrix}
B_{x0} \\
B_{y0} \\
B_{z0}
\end{pmatrix} + r^{-5} \begin{pmatrix}
3xz & 3xy & 3x^2 - r^2 \\
3yz & 3y^2 - r^2 & 3yx \\
3z^2 - r^2 & 3zy & 3zx
\end{pmatrix} \begin{pmatrix}
Ig_{10} \\
Ig_{11} \\
Ih_{11}
\end{pmatrix}
$$

$$
= \begin{pmatrix}
0 & 0 & 1 \\
0 & 1 & 0 \\
1 & 0 & 0
\end{pmatrix} \begin{pmatrix}
B_{x0} \\
B_{y0} \\
B_{z0}
\end{pmatrix} - \frac{m^3}{r^5} \begin{pmatrix}
3xz & 3xy & 3x^2 - r^2 \\
3yz & 3y^2 - r^2 & 3yx \\
3z^2 - r^2 & 3zy & 3zx
\end{pmatrix} \begin{pmatrix}
Ig_{10} \\
Ig_{11} \\
Ih_{11}
\end{pmatrix} + \frac{1}{2} \begin{pmatrix}
B_{x0} \\
B_{y0} \\
B_{z0}
\end{pmatrix}
$$

$$
= \begin{pmatrix}
-3xz & -3xy & 2r^5/m - (3z^2 - r^2) \\
-3yz & -3yx & 2r^5/m - (3x^2 - r^2) \\
2r^5/m - (3z^2 - r^2) & -3zy & -3zx
\end{pmatrix}
\begin{pmatrix}
1/m^3 & 1/m^3 & 1/m^3 \\
1/m^3 & 1/m^3 & 1/m^3 \\
1/m^3 & 1/m^3 & 1/m^3
\end{pmatrix} \begin{pmatrix}
B_{x0} \\
B_{y0} \\
B_{z0}
\end{pmatrix}
$$

$$
= \frac{1}{2} \begin{pmatrix}
B_{x0} \\
B_{y0} \\
B_{z0}
\end{pmatrix}
$$

The reason we assume the inducing fields ($B_{x0}$, $B_{y0}$, $B_{z0}$) to be unknown is that although we have the measured ambient field around Titan during each pass (in Figure 7), the actual inducing field (which is at the conductive surface) can be very different from the more distant fields because it represents "fossil" fields penetrating into the surface of Titan that act as inducing fields.

[33] In (3), the factor $m$ is decided by the depth of the conductive layer, e.g., $m = 1$ when the conductive layer is on
the surface and \( m = 0.5 \) when it is at 0.5 \( R_{Ti} \). From (3), we can invert the values of \( B_{x0} \), \( B_{y0} \), \( B_{z0} \) for each pass by selecting a certain value of \( m \). Figure 9 shows the inverted \( B_{x0} \), \( B_{y0} \), \( B_{z0} \) values for \( m = 0.8 \). If we use half of the difference between the upper and lower quartiles as the size of error in \( B_{x0} \), \( B_{y0} \), and \( B_{z0} \) for each pass, we can obtain the total error for each pass by normalizing the three errors in each component. For each \( m \) value, the error size is estimated by the average of total errors of the 25 passes. Figure 10 shows the error size versus \( m \) values, from which we see that the \( m = 0.8 \) has the least error. However, the error only decreases by 2.3% from \( m = 0 \) to \( m = 0.8 \), thus we do not consider this result as strong evidence of the existence of a conductive layer inside Titan.

By comparing Figures 4 and 9, we can see that the induced field model fits the data better, because the error bars are much reduced in each flyby. It indicates the existence of a conductive layer (or subsurface ocean) inside Titan, but this can hardly be deemed definitive evidence because this calculation is simplified without removing of the ionospheric induced fields, which cannot be accurately modeled for each flyby.

6. Discussion

The accuracy of the permanent, dipole moment calculation is affected by external conditions, which depend on whether Titan is located below or above Saturn's current sheet and the external conditions of the observations. So far, the data available for this study were obtained only when Titan was below the current sheet and over a limited number of SLT sectors. Additional data could improve this study when Titan orbits above the current sheet of Saturn or at other SLT sectors where the external field orientation is quite different. Instrument error is another factor for the accuracy governing the result. We believe from occasional solar wind measurements that the accuracy of the zero level,
obtained from spacecraft rolls inside the magnetosphere, is much better than 0.5 nT.

[36] We note that, there could also be some small radial component from the short-term induced fields at low altitude that may appear as “noisy background” of the radial field from the permanent dipole moment. Thus, we consider the calculated 0.78 nT \times R_{1}^{3} dipole moment to be only an upper limit to Titan’s permanent internal field. The observed low-altitude fields have greater, and more variable, horizontal components which may arise from inducing current in the interior or in the ionosphere of Titan. The radial field does not vary like the horizontal fields from pass-to-pass, so it is more probably from a source internal of Titan that has long time scales. In short, our analysis shows, at most, a weak permanent field at Titan, which is not statistically different from zero. This weak or zero internal permanent field has little effect on the interaction between Titan and the corotating plasma, or on the plasma environment around Titan.

[37] The conclusion that Titan has at most a very small and possibly no internal permanent field puts constraints on the interior of Titan and its evolution in the past. Titan’s closest companion object in size, the Jovian moon, Ganymede, does have an intrinsic magnetic field. Thus, the internal structures of Titan and Ganymede should be different. Table 2 shows some parameters of Titan and Ganymede in which we see that the two objects resemble each other in many aspects. The generation of Ganymede’s magnetic field is thought to be dynamo action in a molten iron core or a conductive water layer, by considering the direction of the dipole axis aligned with the rotation axis [Kivelson et al., 2002], considering gravity results [Anderson et al., 1996], and analyzing the Doppler shift of radio signals [Schubert et al., 1996], although the remnant magnetization, paramagnetism, and magnetoconvection can be alternative mechanisms. Ganymede’s internal structure is considered to be strongly differentiated with a metallic core surrounded by a silicate mantle and an icy outer layer [Anderson et al., 1996; Schubert et al., 1996; McKimnon, 1997]. Either the molten iron core or an outer layer with salty water can be the source of its magnetic dynamo. It is also possible, but not conventionally held, that the Ganymede field is an amplification of Jupiter’s imposed field at the Ganymede orbit [Sarson et al., 1997]. If the interior of Titan and Ganymede were indeed similar, our findings would support the amplification hypothesis.

[38] There is no consensus on the internal structure of Titan. Theoretical models of Grasset et al. [2000] show that the possible existence of both a deep liquid layer and an iron core depends on the composition of chondrites and the primordial amount of volatiles included in ices. Two extreme cases of primordial conditions are used to study the evolution of Titan and they lead to two possible present internal structures of Titan in which either a solid silicate core or a liquid iron core is possible. A recent gravity field study shows that Titan’s moment of inertia is about 0.34, which implies incomplete differentiation, either in the sense of imperfect separation of rock from ice or a core in which a large amount of water remains chemically bound in silicates [Iess et al., 2010]. The much smaller intrinsic field at Titan may indicate that a magnetic dynamo is not able to be generated inside Titan. Thus, the weak intrinsic field is consistent with Titan’s core having low conductivity or weak heat convection; however, we cannot exclude other reasons which may prohibit a strong field in the core to diffuse out [Christensen, 2006].

[39] Does Titan have a subsurface ocean? Rappaport et al. [2008] show that direct evidence for the presence of Titan’s subsurface ocean can be provided by radio science determination of Titan’s Love number k2, which can be obtained with enough accuracy from five flybys (T11, T22, T33, T45, and T68). Thus, after the data from the last flyby is obtained, they will be able to detect the presence or absence of Titan’s ocean. The existence of Titan’s subsurface ocean can also be revealed by magnetic field measurements if the ocean is salty and conductive, which creates a detectable induced field in the space near Titan. Our results on testing the induced moment inside Titan indicate that there is, possibly, a conductive layer inside Titan at a reasonable depth. However, the result is from a simplified model which is insufficient to provide definitive evidence for the existence of a subsurface ocean.

[40] When Titan moves above Saturn’s current sheet at equinox, we will be able to improve our study on the intrinsic and induced moments of Titan. For the estimated permanent dipole moment of Titan, we can average the calculated moments when Titan is below and above the current sheet. This is because when Titan is below the current sheet, its ambient field is usually in the corotation direction and from Titan-to-Saturn. If the time scale of such fields is longer than our observation time scale and the diffusion time scale such that they penetrate into the surface of Titan, we cannot tell from our calculation whether they are permanent dynamo-generated fields or long-term induced fields inside Titan. When Titan moves above the current sheet, the ambient field in these two directions will reverse; thus, by averaging the calculated moments using data from below and above, the current sheet can minimize the effects from the long-term induced field in two such directions to mimic a permanent field. For the induced field in the north-south direction, its effects will still exist after averaging, but since this field exists for a very long time scale, it probably penetrates into the surface of Titan and magnetizes the interior, becoming part (or all) of Titan’s permanent field. If the calculation from the data above Saturn’s current sheet gives us reversed moments along the x and y axes from our current calculation, we will have greater confidence to say that Titan does have a conductive layer in its interior and we may further estimate the strength of the induced moment and the depth of the conductive layer.

### Table 2. Observed Properties of Titan and Ganymede

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Titan</th>
<th>Ganymede</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (km)</td>
<td>2575</td>
<td>2640</td>
</tr>
<tr>
<td>Mean Density (g/cm³)</td>
<td>1.88</td>
<td>1.94</td>
</tr>
<tr>
<td>Distance from planet (planetary radii)</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Distance from planet (km)</td>
<td>1,221,850</td>
<td>1,070,000</td>
</tr>
<tr>
<td>Orbital period (days)</td>
<td>15.9</td>
<td>7.2</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.029</td>
<td>0.002</td>
</tr>
<tr>
<td>Ambient magnetic field (nT)</td>
<td>about 5</td>
<td>about 100</td>
</tr>
<tr>
<td>Orbital average field along</td>
<td>about –3</td>
<td>about –78</td>
</tr>
<tr>
<td>rotation axis (nT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrinsic dipole moment</td>
<td>0.78</td>
<td>719</td>
</tr>
</tbody>
</table>

(\text{nT} \times R_{1}^{3}/(\text{nT} \times R_{2}^{3})$)
For the estimation of internally induced moments by way of this paper, we may improve it by using the data obtained near 6 SLT with a low-altitude approach (so far, only T5 is near 6 SLT and with a CA of 1000 km). Because the upstream flow encounters the nightside ionosphere near 6 SLT, the upstream fields have a greater chance to penetrate into a lower altitude, or below the surface, and induce currents inside Titan (if a conductive layer exists).

7. Conclusion

The analysis of magnetometer data near Titan’s surface shows at most a weak internal dynamo–generated field with an upper limit of 0.78 nT × R^3_{Ti}, that is, (0.46, 0.55, 0.29) nT × R^3_{Ti} in the z, y, and x directions, respectively, with an error of ~0.5 nT in each component. Titan’s weak internal field indicates that the interior of Titan may not sustain the generation of a magnetic dynamo or even sustain a simple amplification of the external magnetic field. For our results on testing the induced moment inside Titan, the least error of our model fitting occurs when m = 0.8, but the accuracy of these calculations is not sufficient to provide definitive evidence for the existence of a subsurface ocean. Both studies will be improved when Titan moves to above Saturn’s current sheet after equinox and different inducing fields are applied.

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References


