Cassini observations of a Kelvin-Helmholtz vortex in Saturn’s outer magnetosphere

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We present Cassini observations of a plasma vortex in Saturn’s dayside outer magnetosphere. The vortex encountered took place on 13 December 2004 as Cassini was travelling toward the planet. The spacecraft crossed the magnetopause 3 times, before being immersed in the low-latitude boundary layer. During the transition between the boundary layer and the magnetosphere proper, the spacecraft observed deflected boundary layer plasma, a twisted magnetic field topology, and high-energy (>20 keV) directional electron fluxes. These observations are consistent with an encounter with a vortex on the inner edge of the boundary layer, an interface that is expected to be susceptible to the growth of the Kelvin-Helmholtz (K–H) instability due to its low magnetic shear. The size of the vortex is determined to be at least 0.55 R_S, and a simple model of the current system resulting from the formation of the vortex is proposed. The possible acceleration mechanisms responsible for the high-energy electrons are discussed. The identification of the structure provides compelling evidence of the operation of the nonlinear K–H instability at Saturn’s morning magnetospheric boundaries and has implications for our understanding of the transfer of energy and momentum between the solar wind and Saturn’s magnetosphere.


1. Introduction

The growth of the Kelvin-Helmholtz (K–H) instability at the boundary of a planetary magnetosphere has long been considered to be an important aspect of the solar wind–magnetosphere interaction. The instability operates at a fluid interface and can manifest itself in the form of waves that propagate along the interface itself, which may then evolve into vortices as the instability enters its nonlinear phase. In a space plasma environment, conditions are favorable for the growth of the K–H instability where there is a large velocity shear between plasma flows, combined with local magnetic fields throughout the shear layer that are approximately perpendicular to the relative flow direction, reducing the stabilizing effect of the magnetic tension force [Southwood, 1968]. The problem of the K–H stability of a planetary magnetopause was first discussed by Dungey [1955] and has since been the subject of numerous theoretical studies [Kivelson and Pu, 1984, and references therein].

Spacecraft observations of Earth’s magnetopause have revealed a structured boundary that exhibits significant spatial and temporal variability [e.g., De Keyser et al., 2005]. It has been shown that the boundary is typically in motion at speeds on the order of 10 km s⁻¹ and that the magnetopause current layer has a variable thickness [Berchem and Russell, 1982; Haaland et al., 2004]; furthermore, a region of mixed magneto sheath and magnetospheric plasma on the planetary side of the magnetopause at low latitudes has been identified. This region (hereafter referred to as the boundary layer) is characterized by tailward flows and a quasi-permanent magnetospheric feature [Freeman et al., 1968; Eastman and Hones, 1979]. The boundary layer is adjacent to the magnetopause current layer, and its highly variable
Figure 1. Schematic illustrating K-H waves on Saturn’s dawn flank magnetospheric boundaries. The equatorial cross-section of the magnetosphere is shown, as viewed from the north. The solar wind and magnetospheric plasma flows and the structure of the magnetospheric boundary region are indicated.

thickness is generally greater than that of the current layer itself [Eastman and Hones, 1979; Schopke et al., 1981].

[5] In this complex region of interaction between the solar wind and Earth’s magnetic field, it has been proposed that the Kelvin-Helmholtz instability can operate at both the magnetopause and the inner (planetward) edge of the boundary layer [e.g., Lee et al., 1981]. Indeed, the evaluation of the K-H instability criterion at both surfaces using in situ spacecraft observations implies that the dayside of the terrestrial magnetopause is generally stable, whereas the dayside boundary layer edge is often unstable [Ogilvie and Fitzenreiter, 1989]. Many of the examples of boundary waves identified on Earth’s magnetopause may have been driven by the K-H instability [e.g., Owen et al., 2004]; however, the most convincing evidence for the operation of the K-H instability in the nonlinear regime concerns the identification of boundary vortices. Fairfield et al. [2000] compared data taken by the Geotail spacecraft during a set of crossings of the distant flank magnetopause with simulation results presented by Otto and Fairfield [2000], showing that the magnetic and plasma signatures could be interpreted as spacecraft encounters with boundary vortices propagating tailward. Further convincing evidence was presented by Hasegawa et al. [2004], who demonstrated that observations made by the four Cluster spacecraft in the vicinity of the equatorial, dusk flank magnetopause are also consistent with the presence of boundary vortices.

[6] The growth of the K-H instability at Earth’s magnetopause and inner edge of the boundary layer is of considerable research interest, since it has been shown to promote the transport of solar wind mass, energy, and momentum into the magnetosphere [Pu and Kivelson, 1983; Miura, 1987; Fujimoto and Terasawa, 1994] and may provide the anomalous viscosity required to drive convection of magnetospheric plasma [Axford and Hines, 1961].

[7] Compared to its terrestrial counterpart, Saturn’s magnetosphere is far larger and possesses significant internal plasma sources, with the dominant motion of magnetospheric plasma being in the sense of corotation with the planet [Richardson, 1986; Eviatar and Richardson, 1986]. Figure 1 illustrates the structure of Saturn’s magnetospheric boundary and the major plasma flows. Spacecraft observations suggest that Saturn’s magnetosphere, like Earth’s, has a boundary layer [Lepping et al., 1981; McAndrews et al., 2008; Masters et al., 2009]. The dynamics of Saturn’s magnetopause include global expansion and contraction associated with variations in the dynamic pressure of the solar wind and, possibly, changes in the internal magnetospheric plasma configuration [Arridge et al., 2006; Achilleos et al., 2008]. Another aspect of the dynamics of Saturn’s magnetopause is the oscillation of the boundary at approximately the planetary rotation period [Clarke et al., 2006, 2009]. In addition, data taken by the Cassini spacecraft during magnetopause crossings have provided evidence for dayside reconnection [McAndrews et al., 2008].

[8] The plasma flow pattern illustrated in Figure 1 reveals a clear dawn-dusk asymmetry in the flow shear across the magnetospheric boundary region. The dawn flank boundaries are expected to be susceptible to the growth of the K-H instability, whereas the dusk flank boundaries are expected to be generally stable on the dayside [Pu and Kivelson, 1984; Galopeau et al., 1995]. Waves on Saturn’s dawn flank magnetopause were first identified by Lepping et al. [1981] using Voyager 1 observations; these authors suggested that the waves may have resulted from the growth of the K-H instability. Masters et al. [2009] analyzed Cassini data acquired during crossings of the predawn magnetopause, finding evidence for boundary wave phenomena. They concluded that the most plausible driving mechanism responsible for the wave activity was the K-H instability.

[9] The growth of the K-H instability at Saturn’s magnetospheric boundaries is also apparent in the results of three-dimensional magnetohydrodynamic (MHD) simulations of Saturn’s magnetosphere: Fukazawa et al. [2007a] reported that large-scale vortices form in their simulations when the interplanetary magnetic field (IMF) is northward, southward, or not included. In a further study, Fukazawa et al. [2007b] reported that for the case of northward IMF the boundary vortices formed on the dawn side, followed by the dusk side, in their simulations. They concluded that the vortices were similar to structures that develop in the nonlinear regime of the K-H instability and suggested that they induced local magnetic reconnection [e.g., Pu et al., 1990].
Galopeau et al. [1995] proposed that the growth of the K-H instability at the magnetopause can explain why the most intense source regions of Saturn Kilometric Radiation (SKR), Saturn’s auroral radio emissions, are on the morning side at high latitudes. In this scenario, the typically K-H unstable morning magnetopause produces MHD waves capable of accelerating electrons along magnetic field lines toward the planet. Furthermore, Fukazawa et al. [2007a] found that the strongest field-aligned currents generated in their simulations were the result of vortex formation, suggesting that such structures can produce auroral signatures. A similar coupling with the planetary ionosphere has been studied at Earth: it has been proposed that K-H vortices in the outer magnetosphere produce bright spots of ultraviolet (UV) auroral emissions [Lui et al., 1989; Vo and Murphree, 1995].

[10] In this paper, we present the first observations of a K-H vortex structure in Saturn’s dayside, outer magnetosphere. In section 2, we examine data taken during the magnetopause crossings made by Cassini in the postdawn sector during the inbound orbital pass that took place in December 2004. In particular, we analyze the magnetic field and plasma observations made by the spacecraft during its transition from the boundary layer into the magnetosphere proper. In section 3, we demonstrate that these observations are consistent with a spacecraft encounter with a plasma vortex on the inner (planetward) edge of the boundary layer. In section 4, we propose a simple model of the coupling between the vortex and Saturn’s ionosphere via field-aligned currents and discuss the possible acceleration mechanisms responsible for the high-energy electrons detected during the encounter. Finally, in section 5, we summarize our results and define the open issues concerning this topic.

2. Observations

[11] The coordinate system used throughout this study is the Kronocentric Solar Magnetospheric (KSM) system, which is Saturn-centered with the positive x axis pointing toward the Sun. The z axis is chosen, such that the x-z plane contains Saturn’s magnetic dipole axis, with the positive z axis pointing toward the north. The y axis completes the orthogonal set, with the positive y axis pointing toward dusk. The unit of distance is Saturn radii ($R_S$; 1 $R_S = 60,268$ km).

[12] The Cassini spacecraft has been in the Saturn orbit since 1 July 2004. The instruments mounted on the three axis stabilized orbiter allow us to study the planetary magnetospheric environment in detail [Blanc et al., 2002]; in this paper, we present data taken by three of these orbiter-mounted instruments. Magnetic field vectors are obtained from the fluxgate sensor of the dual-technique magnetometer (MAG) [Dougherty et al., 2004]. Thermal plasma properties are obtained from the Cassini plasma spectrometer (CAPS) [Young et al., 2004]. Data taken by two of the CAPS sensors are used: the electron spectrometer (ELS), which detects electrons with energies between 0.6 eV and 28.75 keV, and the ion mass spectrometer (IMS), which detects ions with energies between 1 eV and 50.28 keV per charge. High-energy particle fluxes are obtained from the magnetospheric imaging instrument (MIMI) [Krimigis et al., 2004]. Data taken by the low-energy magnetospheric measurements (LEMS) of the MIMI instrument, which detects directional flows of electrons with energies between ~20 keV and ~5 MeV, are used in this study.

[13] During the initial phase of Cassini’s orbital tour, the spacecraft explored the low-latitude morning magnetosphere, regularly crossing the magnetopause boundary [e.g., Dougherty et al., 2005]. We assessed the K-H stability of the morning magnetopause on the orbital passes that occurred between June 2004 (Saturn orbit insertion) and April 2006, comparing the typical magnetic fields measured in the magnetosheath and magnetosphere surrounding the crossings made on each pass. As mentioned in section 1, magnetic tension forces act to stabilize the boundary; thus, the ideal magnetic conditions for the growth of the K-H instability at Saturn’s magnetopause correspond to parallel or antiparallel fields perpendicular to the relative flow direction on either side. As the magnetospheric field is typically southward and steady at low latitudes, such conditions correspond to the cases of steady southward IMF (parallel fields) and steady northward IMF (antiparallel fields). These are the IMF orientations for which the simulations have shown vortex formation [Fukazawa et al., 2007a, 2007b]. The orbital pass during which the magnetosheath and magnetospheric fields were closest to being parallel or antiparallel was the inbound orbital pass that took place in December 2004. The IMF was steadily southward, close to parallel to the magnetospheric field. Consequently, this pass was selected for further analysis as one during which K-H vortices would be likely to form on the magnetopause.

[14] Figure 2 shows the equatorial projection of the spacecraft trajectory during part of the inbound pass. The first magnetopause crossing took place at a range of 22.9 $R_S$, a magnetic latitude of −1.6°, and a Saturn local time (SLT) of 10:06. Figure 3 shows Cassini observations made on 13 December 2004 during a 10 h period encompassing the boundary crossings. Data taken by MAG, ELS, and LEMS are shown, revealing the properties of the local magnetic field and electrons over the combined ELS-LEMS energy range. The periodic modulation seen in the ELS energy-time spectrogram (Figure 3e; particularly evident during the first 2.5 h of the day) results from the ~7 min sweep cycle (actuation) of the CAPS sensors [Young et al., 2004]. Throughout the period, a photoelectron population is evident at energies below ~10 eV. Despite the actuation of the CAPS sensors, the pointing constraints prohibited IMS from sufficiently resolving the local ion distributions to derive reliable ion moments during the interval.

[15] For the period shown in Figure 3, the spacecraft began in the magnetosheath before making three magnetopause crossings and ending the period in the magnetosphere. Such multiple crossings during an orbital pass occur when the boundary moves at a speed greater than that of the spacecraft. The intervals when the spacecraft was in the magnetosheath are shaded gray. The field elevation angles (Figure 3c) show that the magnetic field stayed predominantly southward throughout the period; the angular difference between the typical magnetosheath and magnetospheric fields was <10°. During the magnetosheath intervals, the field strength was generally lower, the thermal electron populations were colder and denser, and a lower flux of high-energy (>20 keV) electrons was measured, whereas during the magnetosphere
Trajectory of the Cassini spacecraft between 12 and 15 December 2004 projected onto the x-y plane of the KSM coordinate system. Black dots on the trajectory indicate the position of the spacecraft at the beginning of each day. The cross section of the Arridge et al. [2006] magnetopause model scaled to intersect the final magnetopause crossing position is shown, as well as the position of the vortex encounter at the planetward edge of the boundary layer.

Figure 2: Trajectory of the Cassini spacecraft between 12 and 15 December 2004 projected onto the x-y plane of the KSM coordinate system. Black dots on the trajectory indicate the position of the spacecraft at the beginning of each day. The cross section of the Arridge et al. [2006] magnetopause model scaled to intersect the final magnetopause crossing position is shown, as well as the position of the vortex encounter at the planetward edge of the boundary layer.

intervals the field strength was generally higher, the thermal electron populations were hotter and more tenuous, and a greater flux of high-energy (>20 keV) electrons was measured, with the LEMMS data revealing that the motion of the high-energy electrons was predominantly field aligned and bidirectional.

[16] The magnetosheath excursion between ~0400 and ~0500 universal time coordinate (UTC) is an exception to the above magnetosheath characterization: the magnetic field magnitude was comparable to that of the magnetosphere, with a number of field strength depressions, and the thermal electron number density was lower than that measured in the earlier magnetosheath interval. We interpret this region as a plasma depletion layer in the magnetosheath, adjacent to the magnetopause [e.g., Zwan and Wolf, 1976], within which the field strength depressions correspond to spacecraft encounters with mirror mode waves [e.g., Tsurutani et al., 1982; Joy et al., 2006].

[17] Following the third magnetopause crossing at ~0500 UTC, the spacecraft was immersed in the boundary layer, where the thermal electron number density was higher than that in the magnetosphere proper and where bidirectional energetic electron signatures confirm that Cassini was located on closed magnetospheric field lines. The vertical dashed lines in Figure 3 indicate the period during which the spacecraft made the transition from the boundary layer into the magnetosphere proper. This unusual transition has a clear signature in the LEMMS electron data.

[18] Data taken by MAG, ELS, IMS, and LEMMS during a shorter interval encompassing this transition are shown in Figure 4. The interval is divided into subintervals 1–4. During subinterval 1, the spacecraft was in the boundary layer. During subinterval 2, Cassini was immersed in a hotter, more tenuous electron environment, coincident with a strikingly higher intensity of superthermal electrons. The pitch angles of these high-energy particles were principally between 165° and 180°; thus, these electrons were predominantly traveling antiparallel to the local magnetic field (in the northward direction). During subinterval 3, Cassini was immersed in a colder, denser electron environment, similar to that encountered during subinterval 1; however, the distinctive high-energy electron distribution persisted. Finally, during subinterval 4, the spacecraft was in the magnetosphere proper, where the lowest electron number densities and highest electron temperatures encountered during the entire interval shown in Figure 4 were measured. The intensity of superthermal electrons in subinterval 4 was lower than that of the previous two subintervals, and the strong pitch angle asymmetry was no longer clear.

[19] To examine the magnetic field observations in more detail, the field perturbation vectors shown in Figure 4d were calculated. To determine these vectors, the average field for the entire interval shown in Figure 4 was subtracted from 5 min resolution field measurements. In Figure 4d, the projections of these perturbation vectors into the M-N plane of the boundary normal coordinate system are shown. This is a right-handed orthogonal system with three axes: the N axis points along the boundary normal direction (given by the prediction of the Arridge et al. [2006] model of Saturn’s magnetopause surface and directed away from the planet), the L axis is chosen such that the average magnetospheric magnetic field lies in the L-N plane, and the M axis completes the set [Russell and Elphic, 1978]. Thus, in Figure 4d, we are viewing the perturbation vectors from the north, looking along the nominal field lines, with down pointing into the magnetosheath and right pointing toward the subsolar region along the surface.

[20] There was a clear systematic variation of the perturbation vectors during the transition. The largest field perturbations (~2 nT) were measured during subintervals 1 and 4; these strongest field perturbations accounted for roughly a third of the total field magnitude (~6 nT). During subinterval 2, the field perturbation vectors all had a negative N component, whereas during subinterval 3, they all had a positive N component. During both subintervals 2 and 3,
the maximum field perturbation was \( \sim 1 \) nT. This distinctive variation of the field perturbations suggests that the spacecraft passed through a twisted magnetic field structure during the transition.

The final set of observations to examine were made by IMS and can provide some information about the bulk flow direction, even though full ion moments cannot be derived. The total field of view of the IMS sensor consists of

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**Figure 3.** MAG, ELS, and LEMMS observations for a 10 h interval encompassing the boundary crossings on 13 December 2004. (a) KSM components of the magnetic field. (b) Magnetic field magnitude. (c) Magnetic field elevation angle, defined as the angle between the field vector and the KSM \( x\)-\( y \) plane, with 90° and −90° corresponding to field vectors in the positive and negative \( z \) directions, respectively. (d) Electron number density (red) and temperature (blue; from the second moment of the ELS distributions in the spacecraft rest frame) derived from ELS anode 5. (e) Energy-time spectrogram of electron count rate averaged over all ELS anodes. (f) Energy-time spectrogram of electron intensity from LEMMS. (g) Pitch angle–time spectrogram of electron intensity from LEMMS, over the same energy range shown in Figure 3f. Spacecraft trajectory information is shown below the bottom. Shaded intervals correspond to when the spacecraft was in the magnetosheath. The pair of vertical dashed lines indicate the start and end of the vortex encounter.
Figure 4. MAG, ELS, IMS, and LEMMS observations for a 4 h interval encompassing the spacecraft encounter with a plasma vortex on the edge of the boundary layer. (a) KSM components of the magnetic field. (b) Magnetic field magnitude. (c) Magnetic field elevation angle, defined as the angle between the field vector and the KSM x-y plane, with 90° and −90° corresponding to field vectors in the positive and negative z directions, respectively. (d) 5 min resolution magnetic field perturbation vectors projected onto the M-N plane of the boundary normal coordinate system. (e) Electron number density (red) and temperature (blue; from the second moment of the ELS distributions in the spacecraft rest frame) derived from ELS anode 5. (f) Energy-time spectrogram of electron count rate averaged over all ELS anodes. (g) Energy-time spectrogram of ion count rate from IMS detector 7. (h) Energy-time spectrogram of electron intensity from LEMMS. (i) Pitch angle–time spectrogram of electron intensity from LEMMS, over the same energy range shown in Figure 4f. Spacecraft trajectory information is shown below the bottom. The four subintervals are numbered, and the transitions between subintervals are indicated by changes in the background shading (or vertical lines) in each panel.
a fan and is given by the combined fields of view of eight detectors [Young et al., 2004]. Figure 5 shows the data taken by all eight detectors and the pointing of each of them during the interval shown in Figure 4. The look directions describe continuous curves due to the actuation of the entire CAPS instrument, which is designed to improve the overall field of view.

During subinterval 1, the highest count rates were measured by detector 3, which was close to pointing into the anticipated direction of tailward magnetosheath flow (based on flow around a magnetopause surface that is axially symmetric about the planet-Sun line). This evidence for tailward flow in the boundary layer is in agreement with observations of the terrestrial boundary layer [e.g., Eastman and Hones, 1979]. During subinterval 2, the lower-density ion distribution was poorly resolved. During subintervals 3 and 4, the highest count rates were measured by detectors 6–8; these detectors were close to pointing into the anticipated direction of corotational flow. During subintervals 3 and 4, the measured spectra reveal a double-peaked distribution. These data suggest that the flow in the boundary layer–like region (subinterval 3) was distinctly different from the flow in the boundary layer region encountered earlier (subinterval 1).

In summary, on 13 December 2004 during Cassini’s passage from the boundary layer to the magnetosphere proper, the spacecraft passed in and out of different plasma regimes, recorded a twisted magnetic field topology, found evidence of deflections of the bulk flow, and detected a significant increase in the flux of superthermal electrons.

3. Interpretation

We propose that the unusual transition between the boundary layer and the magnetosphere proper observed on 13 December 2004 was caused by the passage of the spacecraft through a plasma vortex that had formed on the inner edge of the boundary layer as a result of the growth of the K-H instability. Given the inferred, close to antiparallel flow directions in the boundary layer and magnetosphere proper and the approximately parallel, southward magnetic fields on either side of the interface, the growth of the K-H instability at the inner edge of the boundary layer at this time is anticipated [e.g., Kivelson and Pu, 1984]. The proposed schematic structure of the vortex and the geometry of Cassini’s passage through it are illustrated in Figure 6.

This vortex encounter scenario provides an explanation for the different plasma regimes: the spacecraft was within the vortex during subintervals 2 and 3, and the environment sampled by Cassini during these subintervals corresponded to a region of deflected magnetospheric plasma and a region of deflected boundary layer plasma, respectively. A spacecraft encounter with a plasma vortex is also consistent with the observed behavior of the magnetic field. The circulating plasma would have dragged the field lines with it due to the frozen-in flux approximation, leading to the
application of a twist to the magnetic flux tubes and the observed field topology. The vortex encounter scenario also explains the variations in the inferred bulk flow direction. Figure 6 illustrates that in this scenario the boundary layer plasma encountered during subinterval 3 was flowing nearly parallel to the magnetospheric plasma flow, i.e., nearly in the direction of corotation, which is significantly different from the inferred tailward flow direction of the boundary layer plasma observed during subinterval 1. Hasegawa et al. [2004] have reported remarkably similar magnetic and plasma signatures in their analysis of magnetic field measurements made by the multiple Cluster spacecraft during encounters with vortices on Earth’s magnetopause.

Spacecraft excursions into different regions of Saturn’s outer magnetosphere can be caused by large-scale motion of the inner edge of the boundary layer in the normal direction or wave activity on the interface itself. However, following our above discussion, it is clear that both these cases cannot explain the observations made by Cassini on 13 December 2004, since they produce transitions between two distinct regimes of plasma properties, whereas on 13 December Cassini encountered more than two regimes. We conclude that the most plausible explanation of the observations is that Cassini encountered a plasma vortex on the inner edge of the boundary layer.

Further interpretation of the data taken during the transition can provide information about this phenomenon. Concerning the propagation and size of the structure, simulations suggest that K-H vortices propagate tailward at a speed greater than that of the spacecraft [Fukazawa et al., 2007a, 2007b]. In the absence of bulk flow measurements, we cannot determine the velocity (and thus scale) of the structure, and given the variability of the flow speeds previously measured in Saturn’s dayside outer magnetosphere, we are unable to make a reasonable assumption based on theory. However, since the field perturbations shown in Figure 4d reveal a clear positive-negative variation in the N component of the perturbation vector and the spacecraft velocity vector was closer to the negative N direction than either the positive or negative M directions in the rest frame of the planet, we deduce that the vortex propagated along the inner edge of the boundary layer at a speed greater than that of the spacecraft, as in the above-mentioned simulations. In this case, the size of the vortex must be greater than the distance traveled by the spacecraft while it was inside the structure (beginning of subinterval 2 to end of subinterval 3): 0.55 Rs.

The twisted magnetic field topology produced by the formation of the vortex must have been supported by a current system. If we assume that the vortex was propagating tailward, then the application of Ampère’s law to the magnetic field perturbation vectors shown in Figure 4d suggests that within the vortex there was a net southward field-aligned current (FAC), flanked by net northward FACs at the peripheries of the structure. By constructing a model of the expected vortex-induced current system, we can determine the region of the vortex sampled by Cassini by comparing the model with the observed FAC signatures.

Consider initially unperturbed magnetic field lines in the equatorial region of the outer magnetosphere, where a K-H vortex forms. Prior to the formation of the vortex, the field lines all point southward with a uniform field strength;
however, as the vortex evolves and plasma begins to circulate, the magnetic field lines are constrained to move with the flow due to the frozen-in flux approximation. In our model, the vortex is axially symmetric about the direction of the mean magnetic field. This results in the twisted magnetic field structure shown in Figure 7. The perturbation of the field lines that thread the structure is consistent with a clockwise sense of plasma circulation, as viewed from the north, in agreement with the 13 December vortex observations. By Ampère’s law, this twisted field topology in our model leads to FACs that flow into the vortex from the north and from the south. The nature of the field line perturbations in the vicinity of the vortex results in cross-field currents directed away from the center of the circulation, with return FACs at the edges of the structure. The “$J \times B$” forces act to resist the twisting of the magnetic field resulting from the plasma circulation; thus, there will be a competition between these forces and the forces related to the sheared flow. The comparison between this simple current system model and the observed FAC signatures requires that on 13 December 2004 the spacecraft passed through the vortex northward of the site of the most rapid circulation, where the main twist was applied to the field lines (see Figure 7).

Figure 7. Schematic illustrating the local current system produced as a result of the formation of the K-H vortex in Saturn’s morning, outer magnetosphere. The vortex, magnetic field lines, and electric currents are shown as viewed from within the equatorial plane, with north directed vertically upward. The sense of plasma circulation within the vortex is in a clockwise sense, when viewed from the north. The vortex is shown as a dark gray oval, magnetic field lines in the foreground (background) are shown as solid (dashed) black lines with arrow heads, and currents are shown as light gray block arrows.

[30] The double-peaked ion distributions observed by IMS during subintervals 3 and 4 suggest a mixed population of protons and water group ions. Although the time-of-flight capability of IMS does not confirm that such different species were present, a comparison of the energies of the two peaks of the distribution supports the case for multiple ion species. Assuming that the species were flowing at the same speed and using typical peak energies of $\sim 150$ eV and $\sim 2.4$ keV, the mass ratio is $\sim 16$. This is consistent with the presence of protons and water group ions. McAndrews et al. [2009] showed that such ion populations are present in Saturn’s magnetosphere at Saturn–centered distances similar to that of the spacecraft at the time of the vortex encounter presented here. In addition, observations [Hasegawa et al., 2004] and simulations [Fujimoto and Terasawa, 1994] of K-H vortices at Earth’s magnetopause have shown that such structures result in mixing of the plasmas either side of the boundary. The particle distributions measured by Cassini during the vortex encounter may thus correspond to a complex mix of boundary layer and magnetospheric populations.

[31] We note that during subinterval 4, an increase in the electron number density was observed by ELS at $\sim 0825$ UTC, coincident with an increase in the IMS detector 7 count rates and a double-peaked ion distribution. This dense feature does not appear to be directly associated with the vortex encounter, as there was no distinctive magnetic field signature, and the superthermal electrons associated with the earlier vortex encounter were not detected. The evidence of flow in the corotation direction implies that the dense feature was not caused by an excursion into the boundary layer, as the earlier observations of the pristine boundary layer suggest tailward bulk flow. Similar dense plasma features in Saturn’s outer magnetosphere were observed by the Voyager spacecraft and discussed by Goertz [1983], who suggested that they were flux tubes that had detached from the plasma sheet due to a centrifugally driven flute instability. We suggest that it is also possible that such features are related to K-H boundary vortices. It has been shown that reconnection can occur inside K-H vortices on Earth’s magnetopause [Nykyri et al., 2006], and simulations suggest that this process leads to injection of regions of magnetosheath plasma into the terrestrial magnetosphere [Nakamura and Fujimoto, 2005]. We suggest that a similar phenomenon could explain the origin of some of the dense plasma regions encountered by spacecraft in Saturn’s outer magnetosphere.

[32] Simulations of the growth of the K-H instability in space plasmas have suggested that in a highly rolled-up K-H vortex there is a balance between the centrifugal force exerted by the circulating plasma, the sum of the $J \times B$ forces, and the pressure gradient force, which results in a pressure minimum at the center of the structure [e.g., Miura, 1997]. The 13 December Cassini observations of a K-H vortex at Saturn do not reveal a clear pressure minimum during the encounter. However, there are various possible explanations for this: the vortex observed by Cassini may have been encountered at an early stage of its development when a pressure minimum had not yet formed or the spacecraft may not have passed close enough to the center of the structure to reveal the pressure difference between the center and the peripheries or the formation of a K-H vortex may not require a pressure minimum at the center of the structure.

[33] The presence of bidirectional, high-energy electrons before, during, and after the vortex encounter reveals that the spacecraft was on closed, magnetospheric field lines at all these times. The absence of a magnetosheath excursion during the encounter is consistent with our assertion that the
vortex formed on the inner edge of the boundary layer, not on the magnetopause. The lack of any encounters with K-H vortices on the magnetopause just prior to the encounter with a K-H vortex on the inner edge of the boundary layer can be accounted for in various ways: the magnetopause may have been relatively unperturbed, or waves may have been present on the magnetopause, or vortices may have formed on the magnetopause as well as on the inner edge of the boundary layer but were not encountered by Cassini as the spacecraft crossed the magnetopause. Given that this orbital pass was chosen because of the steady southward IMF orientation that should produce a highly K-H unstable magnetopause, it is likely that the magnetopause surface was K-H unstable at the time of the encounter. Figure 6 is consistent with a wave-like perturbation of the magnetopause boundary and simultaneously a vortex on the inner edge of the boundary layer.

[34] In this section, we have shown that observations made by Cassini on 13 December 2004 are consistent with a spacecraft encounter with a vortex on the inner edge of Saturn’s boundary layer that resulted from nonlinear growth of the K-H instability. We have provided an interpretation of the data taken during the encounter, which suggests that the size of the structure was at least 0.55 Rₜ, and has motivated the construction of a simple model of the local vortex-induced current system.

4. Discussion

[35] Although the vortex encounter scenario clearly explains most of the observations made by Cassini between 0500 and 0900 UTC on 13 December 2004, the distinctive signature in the LEMMS data has not been discussed. As we have seen, while Cassini was within the structure LEMMS observed a dramatic increase in the intensity of superthermal electrons (some with energies as high as 400 keV), with most of these particles travelling northward within 15° of the direction antiparallel to the local magnetic field. In this section, we discuss two mechanisms that could have produced this striking electron energization signature.

[36] The first potential mechanism is the field-aligned acceleration of magnetospheric electrons away from the planet above Saturn’s ionosphere, possibly associated with auroral emissions. The local current system constructed in section 3 (see Figure 7) implies FACs that are likely to close in Saturn’s northern and southern ionosphere, as shown in Figure 8. This global model predicts that the vortex footprint in the ionosphere in each hemisphere should have coincided with a region of upward-directed FAC, surrounded by a region of downward-directed FAC. These currents would have been predominantly carried by electrons. If the current system was sufficiently strong, field-aligned potentials would have developed in order to support the currents by accelerating charged particles. Such field-aligned potentials would have accelerated magnetospheric electrons toward the planet in the regions of upward-directed FAC (possibly leading to electron precipitation in the ionosphere and auroral emissions) and away from the planet in the regions of downward-directed FAC (which were observed by Cassini as high-energy, approximately field-aligned electron distributions in the equatorial, outer magnetosphere).

[37] This mechanism accounts for the asymmetry in the LEMMS electron pitch angle distributions as a seasonal effect. Since the electrons were predominantly travelling northward during the Cassini vortex encounter, this mechanism suggests that they originated from the antiplanetward acceleration region above the southern ionosphere that was associated with the region of downward-directed FAC. The vortex-induced current system shown in Figure 8 can be thought of as a circuit with resistors connected in parallel, where the resistors are the regions of the northern and southern ionosphere in which field-perpendicular currents flow. Since the magnetic field lines are equipotentials (away from the field-aligned acceleration regions), the potential differences across the ionospheric regions of field-perpendicular current must be the same in the north and the south. At the time of the encounter, southern summer conditions prevailed at Saturn, as the planet’s near-aligned rotation and magnetic dipole axes [Dougherty et al., 2005] were tilted antisunward by ∼23°. Therefore, a lower-impedance (higher conductivity) southern ionosphere caused by southern summer conditions could have resulted in more current flowing through the southern part of the system than the northern part, which would have led to greater field-aligned potentials above the southern ionosphere to support the larger current (assuming that the source populations are the same) and thus higher energy electrons originating from the southern acceleration zone than its northern counterpart.

[38] A north-south asymmetry in antiplanetward electron acceleration might explain why Cassini observed a greater flux of high-energy (∼20 keV) electrons travelling north than travelling south in the equatorial region where the spacecraft encountered the vortex. Finally, this vortex-ionosphere coupling mechanism potentially reveals why the greatest flux of high-energy electrons were detected by LEMMS just after the beginning and just before the end of the spacecraft’s passage through the vortex (see Figure 4). By this mechanism, the electrons were accelerated anti-
planetward along magnetic field lines that map to the edges of the structure and may have then drifted onto field lines just inside the edges of the structure due to the curvature of the magnetic field associated with the vortex.

[39] To some extent, we are able to test the plausibility of this mechanism. Since it involves acceleration of electrons into and away from the ionosphere, it suggests that the vortex may have produced a spot of auroral emission in one or both hemispheres; however, we are unable to confirm this as coincident auroral imaging was not carried out. Nonetheless, we can employ Knight’s theory [Knight, 1973] to speculate about whether or not the vortex produced an auroral signature in the Northern Hemisphere, since Cassini observed a signature of southward FAC inside the vortex that would have mapped, in our model, to the region of upward-directed FAC above the northern ionosphere (see Figure 8).

[40] The magnitude of the southward FAC inside the region of the vortex sampled by Cassini can be estimated using Ampère’s law, the magnitude of the magnetic field perturbations observed during the encounter (~1.4 nT), and the estimated size of the structure (~0.55 R_S). This leads to an estimated southward FAC density of ~0.03 nA m^2. Assuming that the FAC associated with the magnetic flux tube was conserved and using a dipole model of the magnetospheric field [Dougherty et al., 2005] to calculate the field strength at the altitude of Saturn’s auroral zone [Gérard et al., 2009], we can then infer that the upward-directed FAC density in the vicinity of the northern ionosphere was ~170 nA m^2. Using this model, the field lines that thread the vortex map to a latitude of ~78°; ultraviolet (UV) auroral emissions have been observed from similar latitudes [e.g., Clarke et al., 2005].

[41] We can now employ Knight’s theory to investigate whether the vortex-induced current system required field-aligned potentials. If the estimated current density above the northern auroral zone (~170 nA m^2) was greater than the maximum value that could be supported by the local electron population, then field-aligned potentials would have resulted, accelerating the electrons and increasing the current density to the required value. The minimum field-aligned potential (\(\Phi_{||}\)) predicted by Knight’s kinetic theory is

\[
e^{\Phi_{||}} = W_e \left( \left( \frac{j_e}{j_0} \right) - 1 \right)
\]

and the precipitating accelerated electron energy flux (\(E_e\)) is

\[
E_e = \frac{E_c}{2} \left( \left( \frac{j_e}{j_0} \right)^2 + 1 \right),
\]

where \(e\) is the elementary charge, \(W_e\) is the thermal energy of the unaccelerated source electron population, \(j_0\) is the required ionospheric FAC density (~170 nA m^2 in this case), \(j_e\) is the FAC density provided by the unaccelerated source electrons, and \(E_c\) is the energy flux of the unaccelerated source electron population [Knight, 1973; Bunce et al., 2008]. Knight’s approach assumes a full loss cone for the electron distribution and that the source electron population is isotropic. Here we use the typical electron distributions measured during the vortex encounter to calculate the necessary values (subinterval 2 in Figure 4: \(W_e \sim 160\) eV, \(j_e \sim 26\) nA m^2; \(E_c \sim 0.004\) mW m^2; subinterval 3 in Figure 4: \(W_e \sim 76\) eV, \(j_e \sim 71\) nA m^2, \(E_c \sim 0.005\) mW m^2). For the electron distributions measured during subinterval 2, Knight’s theory predicts that the vortex produced a field-aligned potential of ~0.9 kV and a precipitating electron energy flux of 0.09 mW m^2, whereas for subinterval 3, it predicts a potential of ~0.1 kV and an energy flux of 0.02 mW m^2.

[42] Therefore, the results of the application of Knight’s theory support the proposition that field-aligned electron acceleration occurred above the northern ionosphere, at least in the regions of upward-directed FAC. We note that if we equate 0.1 mW m^2 to 1 kR of UV emission [e.g., Bunce et al., 2008] then these calculations suggest that the vortex produced a UV auroral signature with an intensity between ~0.2 and ~0.9 kR in the north. This would have been below the detectability level of the Hubble Space Telescope and far less intense than the average main auroral emission [e.g., Clarke et al., 2005]. The Knight’s theory values should be treated as order of magnitude estimates, as we have likely underestimated the scale of the vortex. Consequently, the values of field-aligned potential and precipitating energy flux should be treated as upper limits.

[43] The presence of strong FACs associated with the vortex would be consistent with simulations of Saturn’s magnetosphere [Fukazawa et al., 2007a]. A similar relationship between K-H vortices and auroral emissions has been proposed at Earth to explain the occurrence of bright spots of terrestrial aurorae [Li et al., 1989; Vo and Murphy, 1995]. The seasonal effect proposed as an explanation of the pitch angle asymmetry of the superthermal electrons is in agreement with observations of the current system associated with Saturn’s main auroral emissions, which is generally stronger in the Southern Hemisphere under southern summer conditions [Talboys et al., 2009]. To conclude the discussion of this mechanism, we note that the antiplanetward acceleration of electrons associated with magnetosphere-ionosphere coupling has been observed at Earth, Jupiter, and Saturn [Marklund et al., 2001; Frank and Paterson, 2002; Tomás et al., 2004; Saur et al., 2006; Mitchell et al., 2009], and observations of such acceleration regions at Earth imply that these regions are above the altitude of the planetary ionosphere (where magnetospheric electrons are the source population). How such field-aligned potentials are maintained remains the subject of debate [e.g., Marklund et al., 2001].

[44] An alternative mechanism that may explain the increase in the flux of high-energy electrons measured by Cassini during the vortex encounter is magnetic reconnection induced by the formation of the structure. Vortex-induced reconnection has been observed at Earth’s magnetopause [Nikutowicz et al., 2002; Nykyri et al., 2006] and is the result of the strong field perturbations associated with the vortices. Although large magnetic shears were not observed by Cassini during the Saturn vortex encounter (implying that the local conditions were not favorable for reconnection), the reconnection process may have occurred at higher latitudes. As we have discussed, the plasma circulation within the vortex is likely to have produced perturbations of the field lines that extend to higher latitudes than the site where the primary twist was applied (see Figure 6). It is possible that the field lines that were affected by the vortex formation reconnected at higher latitudes, leading to the energetic, field-aligned electron beams that were detected during the encounter.
Two main features of the LEMMS observations may also be explained by this reconnection mechanism. If the field lines reconnected below the region of the vortex traversed by Cassini (at southern latitudes), then the spacecraft would have observed an increase in the northward flux of field-aligned, high-energy electrons, producing the clear asymmetry in the LEMMS electron pitch angle distributions that were measured. The strongest field perturbations measured by Cassini within the structure were present at its peripheries, implying that the field lines that threaded the edges of the vortex were more likely to reconnect at higher latitudes. This could explain why the greatest flux of high-energy electrons was detected by LEMMS just after the beginning and just before the end of the spacecraft’s passage through the vortex (see Figure 4).

Although we are unable to test the plausibility of reconnection as the mechanism responsible for the signatures recorded by LEMMS, we conclude that vortex-induced reconnection at higher latitudes also provides an explanation for the electron flux increase measured by LEMMS during the vortex encounter. We propose that both the vortex-ionosphere coupling mechanism and the vortex-induced reconnection mechanism are plausible.

5. Summary

In this paper, we have presented and analyzed observations taken by the Cassini spacecraft during the inbound orbital pass that took place in December 2004. This orbital pass was selected because the orientation of the magnetic field in the magnetosheath suggested that Saturn’s morning magnetopause was likely to have been unstable to the growth of the K-H instability at the time of the spacecraft crossings of the boundary. Multiple magnetopause crossings occurred on 13 December 2004, with a boundary layer region observed following the final crossing. We have demonstrated that the spacecraft subsequently encountered a vortex on the planetward edge of the boundary layer, which was associated with a twisted magnetic field topology, a significant increase in the flux of high-energy (>20 keV) electrons travelling predominantly antiparallel to the field, and a deflection of the bulk plasma flow.

Further interpretation of the data suggests that the vortex was at least 0.55 Rs across. A simple model of the currents associated with the vortical flow, consistent with the magnetic field observations, has been constructed. Possible acceleration mechanisms responsible for the high-energy electrons detected during the vortex encounter were discussed. We concluded that both a mechanism based on vortex-ionosphere coupling and a mechanism based on vortex-induced reconnection are plausible.

This discovery of a K-H vortex in Saturn’s dayside magnetosphere has implications for our understanding of the physics of the outer magnetosphere and solar wind influences on Saturn’s space environment. Our analysis confirms the predictions of theory [Pu and Kivelson, 1984] and simulations [Fukazawa et al., 2007a, 2007b] that the dawn flank magnetospheric boundaries can be K-H unstable; however, there are a number of open issues concerning this topic. It is unclear how often waves and vortices are present on Saturn’s magnetopause and inner edge of the boundary layer and whether the two interfaces are independently unstable. We note that the stability of the magnetopause is likely to be most sensitive to the orientation of the IMF, which could partly explain why vortex formation in MHD simulations has only been reported for cases of northward/southward IMF. In contrast, the magnetic fields either side of the inner boundary layer are generally steady and southward; therefore, this interface is expected to be particularly sensitive to the density and flow velocity in the boundary layer. In addition, the potential dawn-dusk asymmetry in boundary perturbations caused by the growth of the K-H instability has not yet been examined, as well as the importance of this instability for transport of solar wind mass, energy, and momentum into Saturn’s magnetosphere and how important this phenomenon is for magnetospheric dynamics. Finally, the question of whether or not the growth of the K-H instability influences both SKR and UV auroral emissions at Saturn remains unanswered and is deserving of further attention.

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