Hot flow anomalies at Saturn’s bow shock

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We present evidence for the occurrence of hot flow anomalies (HFAs) at Saturn’s bow shock. A survey of Cassini magnetic field and electron data taken upstream of the dawn flank bow shock is carried out in order to identify Kronian HFAs. Seventeen events are identified that were all associated with energization of the solar wind electrons and satisfied the majority of the conditions for HFA formation. The majority of the events possessed a central cavity of rarefied plasma; however, for two of the events the central cavity was over dense, possibly indicating that these examples were at an early stage of formation. For the event that occurred on 8 November 2004 the calculation of ion moments is possible, revealing an ion temperature increase by a factor of ~800 in the central region of the event that was associated with a significant deflection of the solar wind bulk flow. The spatial extent of the event was ~4.6 Saturn radii in the direction normal to the current sheet underlying the event. Pressure calculations imply that the heated central region was expanding at the time of the encounter. We conclude that the 8 November 2004 event was a spacecraft encounter with an HFA at Saturn’s bow shock and we propose that the other 16 events identified by the survey were also HFA encounters. These observations suggest that HFAs are a solar-system-wide phenomenon.


1. Introduction

Since their discovery at Earth’s bow shock in the mid-1980s [Schwartz et al., 1985; Thomsen et al., 1986] hot flow anomalies (HFAs) have been a topic of intense research. An HFA is a cavity of heated and deflected solar wind plasma that forms at the intersection between an interplanetary current sheet and a planetary bow shock under the appropriate conditions [Schwartz et al., 2000] (see the review by Schwartz [1995]).

Simulations [Burgess and Schwartz, 1988; Burgess, 1989; Thomas et al., 1991; Lin, 2002; Omidi and Sibeck, 2007] and further spacecraft observations [Paschmann et al., 1988; Schwartz et al., 1988; Thomsen et al., 1988; Thomsen et al., 1993] have contributed to our understanding of this formation process and revealed the importance of the motional electric field. If this field has a component directed toward a current sheet, on either side of the intersection between the current sheet and a planetary bow shock, then shock-reflected ions can be focused onto the current sheet and become trapped near the intersection region. Ion-ion instabilities then grow [Gary, 1991] and result in a population of heated plasma that expands along the current sheet and is labeled an HFA. The HFA formation process is illustrated in Figure 1. Although HFA formation is reasonably well understood, the process of the electron heating within an HFA remains unclear [Schwartz, 1995]. As well as being a potentially important space plasma phenomenon it has also been shown that HFAs can strongly perturb Earth’s magnetopause and modulate the terrestrial magnetosphere as a whole [Sibeck et al., 1998, 1999]. Schwartz et al. [2000] defined a set of conditions for HFA formation and estimated the occurrence rate of HFAs at Earth’s bow shock to be three per day.

Recent studies of HFAs at the Earth’s bow shock have utilized multispacecraft observations. A series of HFAs that were observed by the four Cluster spacecraft were studied by Lucek et al. [2004] and Tjulin et al. [2008]. Lucek et al. [2004] examined the plasma and magnetic signatures of the HFAs and concluded that the series was comprised of HFAs at different stages of development; whereas Tjulin et al. [2008] analyzed the low-frequency waves inside two of these HFAs and identified a wave number periodicity inside the more developed of the two events, which they suggested could be linked to the geometry of the cavity itself. A
survey of HFAs observed by the Cluster spacecraft was carried out by Facskó et al. [2008], who suggested that more HFAs occur during high speed solar wind streams, and most recently Eastwood et al. [2008] presented observations of a terrestrial HFA that were made by the five THEMIS spacecraft and discussed the importance of the electron firehose instability in producing the isotropic electron distributions observed inside HFA cavities [Thomsen et al., 1988].

[5] It has been suggested that HFAs should form wherever there is an appropriate interaction between a current sheet and a collisionless shock [Lucek et al., 2004], thus it is hypothesized that they also occur at the bow shocks of other planets. Öieroset et al. [2001] presented Mars Global Surveyor observations of hot diamagnetic cavities upstream of the Martian bow shock, and Masters et al. [2008a] (hereafter M08) presented Cassini observations of a similar phenomenon at Saturn’s bow shock; however, both of these studies used magnetic field and electron data only, and so were unable to demonstrate that ion heating and a deflection of the bulk flow were present during their respective events. Thus neither study was able to unambiguously identify an HFA. Interestingly, one of the two HFA-like events at Saturn’s bow shock reported by M08 was associated with a higher density in the central cavity than that of the surrounding solar wind. This is markedly different from the highly rarefied cavities typically associated with terrestrial HFAs. Thus the question of whether or not HFAs occur at other planetary bow shocks remains open, it is not clear how the different typical values of upstream density, upstream motional electric field strength, and bow shock Mach numbers that have been measured at the various planetary bow shocks (see the review by Russell [1985]) affect the interaction that results in terrestrial HFAs.

[6] In this paper we extend the work of M08 by carrying out a survey of Cassini data taken during the spacecraft’s orbital tour of Saturn. Since M08 identified two HFA-like events by examining the data taken upstream of the bow shock during Cassini’s first two orbits, we aimed to examine all of the dawn flank upstream observations in order to identify further events. In section 2 we outline the event selection criteria and show that all of the seventeen events identified satisfy most of the conditions for HFA formation [Schwartz et al., 2000]. We then present firm evidence that one of the events was a spacecraft encounter with an HFA at Saturn’s bow shock. Consequently, we suggest that all of the events were HFA encounters, and that HFAs are a solar-system-wide phenomenon.

2. Kronian HFA Survey

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

[8] The Cassini spacecraft achieved Saturn orbit insertion in July 2004 and during the initial phase of its orbital tour the spacecraft crossed the dawn flank bow shock on a number of occasions, before the orbits moved away from the bow shock and into the magnetotail by mid-2006 [Matson et al., 2002]. Cassini made a total of 303 bow shock crossings during this period; the last shock crossing of this set took place on 21 February 2006. Since the two HFA-like events identified by M08 occurred during Cassini’s first two orbits we set out to inspect data taken during all of the upstream solar wind excursions on the dawn flank to identify further events. Figure 2 shows Cassini’s trajectory during the period of interest projected into the x-y plane; the spacecraft stayed at low latitudes during this interval. Since the portions of the spacecraft trajectory where Cassini was downstream of the bow shock are shown in gray, and the portions where Cassini was upstream of the shock are shown in red, whenever there is a transition between the two colors a bow shock crossing occurred.

[9] Extensive observations of the solar wind magnetic field and plasma were made during the upstream excursions by the Cassini dual technique magnetometer (MAG) [Dougherty et al., 2004], plasma spectrometer (CAPS) [Young et al., 2004], radio and plasma wave system (RPWS) [Gurnett et al., 2004], and magnetospheric imaging instrument (MIMI) [Krimigis et al., 2004]. MAG provides high time resolution measurements of the local magnetic field, and the electron spectrometer sensor (ELS) of the CAPS instrument is able to measure electrons with energies between 0.6 and 28,250 eV. Accurate measure-
Unlike IBS, IMS uses time-of-flight analysis to resolve different ion species. RPWS radio wave observations can be used to measure the solar wind electron number density when it is possible to reliably identify the Langmuir frequency. Finally, the charge-energy-mass spectrometer (CHEMS) and low-energy magnetospheric measurements system (LEMMS) of the MIMI instrument are able to measure ions with energies between 3 and 220 keV, and between 0.03 and 160 MeV, respectively. LEMMS is also able to measure electrons in the energy range 0.015 to 5 MeV. CHEMS, like IMS, is able to resolve ion species.

To find further HFA candidates we began by inspecting the upstream ELS distributions to identify all the instances of electron energization. We looked for the same distinctive change in the solar wind electron distribution that was associated with the events presented by M08. The MAG observations made during each event identified were then examined and those without a clear rotation of the magnetic field across the event were excluded. Thus we reduced the list to only include the upstream events where electron energization associated with an interplanetary current sheet was observed. This led to the identification of 15 new events, in addition to the two events previously reported by M08; the positions of all 17 events are shown in Figure 2.

The magnetic field magnitude signatures of the events are shown in Figure 3. Although the signatures exhibit significant variability, intervals of elevated magnetic field strength generally flanked an interval where the field was often weaker, with an increase in field fluctuations. These magnetic field magnitude signatures are strikingly similar to those of terrestrial HFAs [Thomsen et al., 1986], where the flanking field enhancements typically correspond to compression regions driven by the expansion of the central cavity of heated plasma. A list of the events is presented in Table 1, giving the time and date of each event and the associated magnetic field (B) rotation. The field rotations were calculated by taking the average of the one second resolution magnetic field measurements that were made in a two minute interval immediately before and after each flanking field enhancement.

To determine the plasma parameters associated with the events we used a number of instruments. Surrounding the events, when Cassini was in the unperturbed solar wind, ELS was unable to measure the ambient electron distribution as it was obscured by the spacecraft photoelectron population [Ishisaka et al., 2001]. Consequently the only electron parameter able to be measured outside the events was the electron number density, derived by RPWS. Generally, the Langmuir frequency was well defined within 30 min before and after each event, revealing a relatively steady electron number density; the only exception to this was event eight. These external densities (n_e) are given in Table 1. Inside the events the ambient electron population could usually be differentiated from the spacecraft photoelectrons; thus, ELS observations were used to derive the electron number density and temperature inside the events where this was the case. These internal densities (n_e) and temperatures (T_e) are given in Table 1. For a number of the events the ambient electron and photoelectron distributions were not sufficiently separated in energy to allow these internal parameters to be reliably calculated. Temperatures
quoted in units of Kelvin throughout this paper assume a Maxwellian distribution; inside terrestrial HFA cavities highly Maxwellian electron and ion distributions have been observed [e.g., Thomsen et al., 1986]. The IBS and IMS sensors were only able to accurately measure the solar wind ion population during event 3, which will be analyzed in detail in section 3.

[13] These plasma parameters reveal that the majority of the events were associated with cavities of rarefied solar wind, although two of the events (one of which was
reported by M08) were associated with an over dense central region. The available internal electron temperatures suggest that the electron populations in the cavities were hotter than the typical solar wind electron temperature ($\approx 2.5 \times 10^4$ K calculated by M08), and a number of them were likely to have been significantly hotter. Furthermore, we note that CHEMS observations suggest that none of the events were associated with energetic ions of magnetospheric origin, a phenomenon which has been observed upstream of the bow shock [Krimigis et al., 2005].

We then considered the conditions for HFA formation, as outlined by Schwartz et al. [2000], to ascertain whether or not the newly identified events were further spacecraft encounters with HFA-like phenomena. First, we determined the orientation of each underlying current sheet by calculating the vector product of the average fields on either side of each event. Spacecraft observations [Sibeck et al., 1999] and simulations [Thomas et al., 1991] both suggest that the current sheets that result in HFAs correspond to tangential discontinuities in the magnetic field, thus we used this vector product for each event as the normal to the underlying current sheet [Schwartz et al., 2000]. For all the events it was found that the orientation implied that the current sheet intersected the bow shock. As an indicator of the orientation we calculated the cone angle in each case as the angle subtending the current sheet normal and the sunward direction, where the current sheet normal was constrained to have a positive sunward component. The cone angle associated with each event is given in Table 1. Current sheets with high cone angles are anticipated to track across the shock surface relatively slowly as they are convected with the solar wind flow, compared to those with low cone angles.

We then inferred the shock angle ($\theta_{bs}$) on either side of each event, given as the angle between the shock normal and the upstream magnetic field. To do this we used the nominal position of the bow shock determined by Masters et al. [2008b] and assumed that the magnetic field observed on either side of each event was the same as the magnetic field on either side of the intersection between each underlying current sheet and the bow shock at that time. Using the calculated current sheet normal we traced the current sheet to its intersection with the shock to determine the model bow shock normal at the intersection, and then used the measured magnetic fields to calculate $\theta_{bs}$ on either side. The inferred shock angle before (pre) and after (post) each event is shown in Table 1. We then calculated the motional electric field ($E$) on both sides, using the appropriate magnetic field ($B$) and assuming that the solar wind velocity ($v_{sw}$) was $[−500, 0, 0]$ km s$^{-1}$ [Crary et al., 2005] ($E = −v_{sw} \times B$). The combination of the motional electric field vectors and the appropriate current sheet normal suggested whether or not the electric field on either side of each event had a component directed toward the current sheet itself. Table 1 indicates whether a toward component was present before (pre), after (post), both before and after (both), or neither before nor after (neither) an event. Finally, Schwartz et al. [2000] derived an expression for the ratio of the speed at which a current sheet tracks across the shock surface to the speed of a shock-reflected, gyrating ion. This expression is given in equation (1), where $V_{tr}$ is the speed at which the region of intersection between the current sheet and the shock surface tracks across the shock surface, $V_g$ is the gyrospeed of a shock-reflected ion, $\theta_{cs:sw}$ is the angle between the current sheet normal and the solar wind velocity, $\theta_{cs:bs}$ is the angle between the model bow shock normal and the solar wind velocity, and $\theta_{tr:bs}$ is the angle between the current sheet normal and the model bow shock normal

$$\frac{|V_{tr}|}{V_g} = \frac{\cos \theta_{cs:sw} - \cos \theta_{cs:bs} \sin \theta_{tr:bs} \sin \theta_{cs:sw}}{2 \cos \theta_{cs:sw} \sin \theta_{tr:bs} \sin \theta_{cs:sw}}. \tag{1}$$

They suggested that when this ratio is below one the tracking speed of the current sheet is sufficiently slow to allow shock-reflected ions to be focused onto the current sheet and produce an HFA. We calculated this speed ratio using the value of $\theta_{bs}$ calculated on both sides of each event, the lower of the two ratio values for each event are given in Table 1.
It is clear that all of the identified events were associated with large magnetic field rotations, with an average of 75.3°. For higher cone angles a current sheet will track more slowly across the shock surface, and thus the speed ratio will be lower. We note that many of the cone angles of these Kronian events are lower than the smallest value of ~40° of the set of terrestrial HFAs discussed by Schwartz et al. [2000], although the speed ratio is a better indicator of whether or not the tracking is speed enough for an HFA to form. Almost all of the speed ratios are below one, as required for HFA formation, however we note that the highest speed ratio of any of the events reported by Schwartz et al. [2000] was ~0.6, whereas 10 of our 17 Kronian events are associated with speed ratios greater than this value. For the majority of the events the shock geometry on at least one side of the encounter was predicted to be quasi-perpendicular (θ_Bn > 45°), which suggests the presence of gyrating ions adjacent to the current sheet-bow shock interface; however it has also been suggested that a quasi-parallel shock geometry (θ_Bn < 45°) is also important for an HFA to result from the interaction [Omidi and Sibeck, 2007]. Importantly, the motional electric field on at least one side of each event has a component directed toward the underlying current sheet, with the exception of one event. This is true for the speed ratio; the values are all below one with the exception of one event. This event is not the same one that violates the motional electric field pointing condition. Schwartz et al. [2000] examined 30 terrestrial HFAs to define the conditions for HFA formation and found that two events violated the motional electric field pointing condition, which suggests that a small number of events that each violates one of the conditions are not unusual. All of these Kronian events satisfy the majority of the conditions for HFA formation and are examples of an HFA-like phenomenon.

As mentioned earlier in this section, only during the newly identified event that occurred on 8 November 2004 (event 3) was the pointing of the IBS and IMS sensors appropriate for the calculation of reliable solar wind ion moments throughout the entire duration of the event. In section 3 we examine this event in detail and proceed to unambiguously identify it as an HFA at Saturn’s bow shock.

3. The 8 November 2004 Event

On 8 November 2004 Cassini was moving away from Saturn on the outbound pass of its second orbit. The spacecraft last crossed the bow shock on 7 November 2004 at 1243 UTC; on 8 November 2004 the spacecraft was in the solar wind. The event occurred at ~0955 UTC when Cassini was 62.0 Rs from the center of the planet, at a Saturn local time of 5.45 h, and at a magnetic latitude of ~13.5°. Given that the event occurred within the limits of bow shock location, as shown in Figure 1, and that it occurred 6.2 Rs from the closest point on the surface that describes the nominal bow shock position, it is possible that the bow shock was in close proximity to the spacecraft at the time of the event. Figure 4 presents Cassini observations made during a 1 h 10 min interval centered on the event.

The magnetic field magnitude shown in Figure 4a illustrates that both before and after the event the field strength was between 0.3 and 0.4 nT, and that the event was associated with two field strength increases to a value between 1.0 and 1.5 nT, flanking an interval with field strengths as low as ~0.1 nT. The intervals of field enhancement have been labeled A and C, and the interval of field depression has been labeled B; these three intervals comprise the event. As mentioned in section 2, the typical field magnitude signature of a terrestrial HFA is qualitatively similar, the field enhancements have been shown to correspond to compression regions caused by the expansion of the heated solar wind plasma, and the region of field depression has been shown to correspond to the (effectively diamagnetic) cavity of heated plasma itself [Thomsen et al., 1986]. The field elevation angle (θ_y) (Figure 4b) is defined as the angle between the field vector and the x-y plane; the field azimuthal angle (θ_x) (Figure 4c) is defined as the angle between the projection of the field vector into the x-y plane and the negative x direction (antisunward), with θ_x increasing in the direction of planetary rotation. The field rotation of 101.4° from the beginning of interval A to the end of interval C is clear in these two field angles, which suggests that the event was coincident with what was once an IMF discontinuity. To calculate the orientation of the boundaries of the event we applied minimum variance analysis [Sonnerup and Schreible, 1998] to the magnetic field vectors that were measured during each boundary traversal, however, the results were unreliable because of eigenvalue ratios significantly below 10.

The ELS time-energy spectrogram of electron count rate (Figure 4g) confirms the expectation that outside the event the ambient electrons could not be resolved from the spacecraft photoelectrons, observed below energies of ~10 eV. However, the spectrogram shows that this was not the case during most of interval B (inside the event) when the two populations were separated in energy. This separation is similar to, but more pronounced than, that observed during the two events that were presented by M08. As a result, the ambient electron population was well resolved in the ELS measurements during most of interval B, making the calculation of reliable electron moments possible; during this interval RPWS was unable to accurately resolve the Langmuir frequency. Thus before and after the event only measurements of the electron number density from RPWS were available, whereas during most of interval B the calculation of the electron number density and temperature from ELS was possible.

A further consideration regarding the plasma data is that during the interval shown in Figure 4 the CAPS sensors were actuating, thus the ELS, IBS, and IMS sensors were oscillating about a fixed position. This actuation made it possible to calculate ion moments at specific times when the solar wind ion distribution was well resolved by IBS or IMS. Because of these pointing considerations the measurements of the ion moments outside the event were made by IMS, whereas the measurements inside the event were made by IMS. The temporal modulation of the trapped spacecraft photoelectron population, shown in Figure 4g, was caused by the actuation of the ELS sensor. The presence of this actuation-induced modulation suggests that the spacecraft potential is not uniform over the spacecraft surface and does not reflect a modulation in the ambient solar wind electron distribution (although one may exist).
Before and after the event the properties of the solar wind plasma were similar. The electron and ion number densities (Figure 4d) were typically $0.10 \text{ cm}^{-3}$ and $0.05 \text{ cm}^{-3}$, respectively. Some of the difference between the electron and ion densities may be due to the ionized helium content of the solar wind that we were unable to resolve with IMS. The average ion temperature was $4.3 \times 10^3 \text{ K}$ ($0.4 \text{ eV}$) and the solar wind flow was approximately anti-sunward with a steady speed of $\sim 360 \text{ km s}^{-1}$.

The event itself was associated with a dramatic change in the properties of the solar wind plasma. During intervals A and C a single plasma parameter was measured by RPWS. Although this electron number density measurement was among the highest in the overall interval it is clearly not strong evidence that intervals A and C are compression regions, although this possibility is not ruled out by the observations. However, during interval B the electron and ion number densities fell to average values of $0.008 \text{ cm}^{-3}$ and $0.006 \text{ cm}^{-3}$, respectively, indicating that Cassini was in a region of highly rarefied solar wind. The average electron temperature during interval B was $3.5 \times 10^5 \text{ K}$ ($30.2 \text{ eV}$), more than 10 times larger than the value of $2.4 \times 10^4 \text{ K}$ ($2.1 \text{ eV}$) that was calculated for the unperturbed solar wind at Saturn orbit by M08. The most

**Figure 4.** MAG, RPWS, ELS, IBS, and IMS data for a 1 h 10 min interval centered on the 8 November 2004 event. (a–c) Magnetic field in spherical polar coordinates (MAG). (d) Electron and ion number densities (RPWS, ELS, IBS, and IMS). (e) Electron and ion temperatures (ELS, IBS, and IMS). (f) KSM components of the bulk flow velocity (IBS and IMS). (g) Time-energy spectrogram of electron count rate from ELS anode 5.
significant change was in the ion temperature; in interval B the ion temperature reached $3.7 \times 10^6$ K (319.1 eV) which is $\sim$800 times greater than the value measured in the solar wind before or after the event. Coincident with the measurement of increased ion temperature the solar wind speed decreased to $\sim$220 km s$^{-1}$, and the flow rotated away from the nominal flow direction by $\sim$50$^\circ$. To examine this flow deflection in the solar wind rest frame we subtracted the nominal solar wind velocity vector from the deflected flow vector, and found that in this frame the deflected flow made an angle of $\sim$70$^\circ$ with the calculated current sheet normal, and an angle of $\sim$4$^\circ$ to the model-predicted bow shock surface normal [Masters et al., 2008b]. Thus the deflected flow was away from the bow shock and, within likely errors, along the plane of the current sheet.

[24] To investigate the dynamics of this heated, deflected cavity of solar wind we calculated the typical magnetic and particle pressures both outside the event and inside the heated cavity (interval B). Because of the paucity of plasma observations we were unable to examine the pressures inside the potential compression regions (intervals A and C). When calculating the particle pressures we assumed that the plasma was comprised of protons and electrons only. In addition, we noted that in their study of Saturn’s ring current Sergis et al. [2007] showed that a significant proportion of the particle pressure can reside with the energetic particles. Consequently we included this energetic particle contribution when calculating particle pressures. High-energy protons were observed surrounding and during the event by the CHEMS and LEMMS sensors; although there is an overlap of the CHEMS, LEMMS, IMS, and IMS energy ranges the high-energy ions observed by CHEMS and LEMMS were not simultaneously observed by IMS or IMS.

[25] Using the typical magnetic and particle pressures outside and inside the heated cavity we then calculated the plasma $\beta$ (the ratio of the particle pressure to the magnetic pressure) and the sum of the two pressures for each case. Outside the event the plasma $\beta$ was of the order of 1, whereas when Cassini was inside the cavity during interval B it increased to the order of 1000, because of the plasma heating and reduced magnetic field strength. The sum of the particle and magnetic pressures outside the event was $\sim$0.0002 nPa, whereas inside the cavity it was $\sim$0.0060 nPa. Since the sum of these two pressures inside the cavity was $\sim$27 times greater than the sum of the pressures outside the cavity, we conclude that the cavity of heated plasma was expanding because of the resulting pressure gradient force when it was encountered by Cassini. Furthermore, the sum of the magnetic and particle pressures inside the cavity was equal to approximately half the dynamic pressure of the nominal solar wind, which is consistent with the observed flow deflection. This expansion could drive fast mode shocks, as has been observed at terrestrial HFAs [Fuselier et al., 1987].

[26] Since the ion observations inside the cavity were made by IMS, the ion composition can be examined. The IMS measurements do not suggest the presence of heavy ions (e.g., water group ions), and, as mentioned in section 2, the CHEMS observations reveal that the event was not associated with energetic ions leaked from the magnetosphere [Krimigis et al., 2005]. These data are consistent with the proposition that the cavity contained heated plasma of solar wind, rather than magnetospheric, origin.

[27] Using the time duration of the event, and the measured nominal solar wind flow direction, we calculated the spatial scale of the heated cavity, in the direction of the current sheet normal, to be $\sim$4.6 $R_S$. Using the magnetic field and ion parameters measured inside the cavity, we calculated that the proton gyroradius was $\sim$0.5 $R_S$, thus the spatial scale of the cavity was equivalent to $\sim$9 proton gyroradii. Although the spatial extent of this cavity is considerably larger than that of a typical terrestrial HFA cavity in units of km, we note that in units of proton gyroradii its scale is comparable [Thomsen et al., 1986]. Overall, the characteristics of this event are qualitatively the same as those reported for terrestrial HFAs [e.g., Thomsen et al., 1986] and it satisfies all of the conditions for HFA formation (see Table 1) [Schwartz et al., 2000]. Crucially, we have been able to demonstrate that this event was associated with dramatic ion heating and a deflection of the bulk flow. Consequently, we conclude that this event is a spacecraft encounter with an HFA upstream of Saturn’s bow shock.

4. Summary and Discussion

[28] In this paper we have presented the results of a survey of data taken by the Cassini spacecraft in the solar wind upstream of Saturn’s bow shock. During Cassini’s dawn flank solar wind excursions between June 2004 and February 2006 we identified 17 HFA-like events that were encountered by Cassini, two of which were previously reported by M08. All of the events were associated with electron heating and evidence of an interaction between an interplanetary current sheet and Saturn’s bow shock. During the event that occurred on 8 November 2004 we were able to derive reliable ion moments that revealed that the event showed the extreme ion heating and bulk flow deflection found at an HFA. Thus we conclude that the 8 November 2004 event was a spacecraft encounter with an HFA at Saturn’s bow shock. Given the similarities between this event and the other 16 events, in the absence of ion data, we propose that all of the events were HFA encounters.

[29] Following this identification it is necessary to address three outstanding questions regarding HFAs at Saturn’s bow shock: 1. How frequent are Kronian HFAs? 2. Do the characteristics of Kronian HFAs differ from those of terrestrial HFAs? 3. Can Kronian HFAs perturb Saturn’s magnetopause? To address the first question we calculated how long Cassini spent in the solar wind during the overall interval considered in this study. We then used the range of bow shock positions deduced by Masters et al. [2008b] to define the region of space in which the shock could be observed, and then subtracted the time spent by Cassini outside this region. Using the resulting time duration, and the total number of identified HFAs, we estimated the occurrence rate for Kronian HFAs as one HFA every 15 days. Naturally, this represents a lower bound of the occurrence rate due to the limited spatial sampling of the spacecraft.

[30] To address the second question we note that two observational differences between Kronian and terrestrial HFAs are revealed by this study, the first is that the speed
ratio associated with 10 of the 17 Kronian events is higher than the largest value associated with the terrestrial HFAs reported by Schwartz et al. [2000]. As discussed in section 2, this ratio is related to the cone angle of the underlying current sheet: for larger cone angles the speed ratio will be lower. Thus this difference may be due to a change in the average orientation of tangential discontinuities in the solar wind between Earth and Saturn orbit, caused by the evolution of the interplanetary magnetic field with radial distance from the Sun [Lepping and Behannon, 1986; Jackman et al., 2008]. This might explain the typically lower cone angle of the current sheets that result in Kronian HFAs, compared to those that lead to terrestrial HFAs. As we have seen, the lower cone angles associated with the Kronian events does not appear to prevent HFA formation, as anticipated since the speed ratios are mostly below one. A detailed study of discontinuities in the solar wind at Saturn orbit, combined with a consideration of the importance of the greater scale of Saturn’s bow shock compared to that of Earth, would have implications for the comparison between Kronian and terrestrial HFAs, and should be addressed in future research.

The second difference between Kronian and terrestrial HFAs is that two of the 17 Kronian HFAs were associated with an over dense central cavity, whereas terrestrial HFAs generally involve significant plasma rarefaction. It is possible that the two over dense Kronian events are examples of HFAs at an early stage of formation, where the focusing of plasma onto the current sheet had produced a dense region that has not yet been heated and expanded.

[31] Because of the lack of simultaneous observations of a Kronian HFA and Saturn’s magnetopause we are unable to address the third question concerning the magnetopause perturbation, which remains an open question. The effect of various parameters on the process of HFA formation also remains unresolved. We have shown that the current sheet-bow shock interaction at Saturn can produce events that have the same characteristics as the HFAs that can result from the solar wind bow shock at Earth; however, the precise effect of changes in the parameters of the interaction (e.g., the strength of the motional electric field) is still unclear, and may only be resolved by future simulations. Preliminary simulations of the interaction of a tangential discontinuity with Saturn’s bow shock suggest the formation of cavities of solar wind plasma that have the same characteristics as terrestrial HFAs (N. Omidi, private communication, 2008), which is in agreement with the observations presented in this paper.

[32] The event presented in section 3 is the first confirmed HFA at a bow shock other than that of the Earth. These observations suggest that HFAs are a solar-system-wide, rather than a purely terrestrial, phenomenon. Future studies of HFAs at the bow shock of Saturn, and potentially other planets, may shed further light on the process of HFA formation and evolution that would not be possible through the consideration of solely terrestrial events.

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