IDENTIFICATION OF A DYNAMIC ATMOSPHERE AT ENCELADUS WITH THE CASSINI MAGNETOMETER

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Abstract

The Cassini magnetometer has detected the interaction of the magnetospheric plasma of Saturn with an atmospheric plume at the icy moon Enceladus. This unanticipated finding made on a distant flyby was subsequently confirmed during two follow-on flybys, one very close to Enceladus. The magnetometer data are consistent with local outgassing activity via a plume from the surface of the moon near to the south pole, as confirmed by other Cassini instruments.

Interest has been high in Cassini’s observation of Saturn’s moon Enceladus because of its possible contribution to the material in the E ring. The first data were obtained during a flyby on 17 February 2005 (day 48) with a closest approach altitude of
1265km. Magnetometer observations (1) from this flyby revealed clear perturbations of the magnetic field, indicating that the nearly corotating plasma flow from Saturn with its frozen-in magnetic field was slowing down near Enceladus and being deflected around it. In addition enhanced ion cyclotron wave activity at the water group gyro-frequency during the flyby points to Enceladus as a major source of ions for the magnetospheric plasma. A second flyby on 9 March 2005 (day 68) at an altitude of 500km confirmed both the draping and ion cyclotron wave signatures although clear differences between the two passes were observed. This discovery of significant atmospheric/ion pick-up acting as an obstacle to the flow of magnetospheric plasma around Enceladus led to a decision to decrease the altitude of the third Cassini flyby on 14 July 2005 (day 195) to 173km enabling a more detailed understanding to be gained of this exotic interaction by numerous onboard instruments (2-6). We describe the observations from these three flybys and present their interpretation below.

The three Cassini flybys of Enceladus have distinct and complementary trajectories (Fig. 1). Data are shown in the (ENIS) coordinate system aligned with the expected direction of the corotation flow (7). The first flyby was above Enceladus on average about 4.7 Re above the orbital plane (8). The second flyby was below the moon at about 1.5 Re and the third flyby made a south to north cut as the spacecraft flew by at closest approach of about 0.7 Re. On the last two flybys Cassini moves inbound towards Saturn from upstream of Enceladus (as measured relative to the corotational flow) whereas on the first flyby it moves outbound. All passes move in the direction of corotation (with increasing X in the ENIS system).
The magnetic field of Saturn at Enceladus is 325 nT due southward at the orbit of Enceladus. The perturbations that are observed during the three flybys are slight tilts of the field and a small compression of the southward field. It is most convenient for discussion to display only the perturbed field in the three directions (see Fig. 1): $B_X$ in the direction of the rotating planet; $B_Y$ towards Saturn and $B_Z$, northward. The magnetic field perturbation on the first pass, day 48 of 2005, extends over a broad region from about 5 Re inside Enceladus’ orbit to about 8 Re outside. The negative X-component of the perturbed magnetic field is consistent with a slowdown of the flow below the spacecraft. The positive-Y deflection on the Saturn side and the negative-Y deflection of the field direction on the anti-Saturn side indicate there is some deflection to the flow to either side of Enceladus. This signature indicates that the magnetospheric plasma that corotated with Saturn was slowed and deflected by an obstacle to the flow. Such an obstacle could be provided by an atmosphere in which ionization leads to mass loading of the magnetized plasma near Enceladus. At Enceladus one does not expect induction processes to be significant since the background magnetic field has at most small deviations from axial symmetry. For a permanent dipole, in order to explain the first flyby observations a surface field of order ~ 1000nT would be necessary, either as a result of remanent magnetization or a dynamo field. Neither of these scenarios are plausible when taking into account the small size of Enceladus and its assumed internal structure and chemistry. This was subsequently confirmed when the second flyby observations were clearly inconsistent with the existence of a permanent dipole.
Hence if we assume an atmospheric interaction is causing the first flyby observations then we may expect a scenario (Fig. 2) where Alfven wings (9, 10) above and below the conducting obstacle are generated via currents which are driven through the atmosphere by the motional electric field of the incident plasma combined with the electric conductivity of the atmosphere, due to elastic collisions or ion pick-up. The pick-up process is connected with mass loading and has a decelerating effect on the plasma. Initial modelling suggests the current flowing in the pick-up region to be of order $10^5$ A. Pick-up is also the mechanism which excites ion cyclotron waves. The electromagnetic coupling interaction between Jupiter and its volcanic moon Io is a well known example of this type of interaction between a large moving conductor with a magnetized plasma (11, 12), although at Io the currents linking the moon to Jupiter are up to 10 times larger. Ion mass loading decelerates the plasma as slow-moving, Enceladus-derived plasma is added to the faster moving magnetospheric plasma. Since the slowing is greatest where the mass loading is greatest we would a priori expect the greatest slowing in Enceladus’ orbital plane. Since the upstream field is directed southwards, the $B_X$ or along-flow component of the draped field will be negative (positive) in any plane above (below) the mass loading region (Fig. 2). In addition, above and upstream of the mass loading region, draping will produce a positive $B_Y$ component on the Saturnward side and a negative perturbation on the side facing away from Saturn upstream of Enceladus as the flow is decelerated to the sides of Enceladus. Finally the field would be compressed in front of the obstacle where the magnetized plasma flow has slowed. This compression would appear mainly in the $B_Z$ component. On the first flyby, with the Cassini spacecraft above Enceladus, we see as expected a negative $B_X$, with the change in the $B_Y$ perturbation
(from negative on the negative Y side and positive on the positive Y side) indicating flow being slowed and diverted around Enceladus. Moreover the field is compressed as expected from an upstream flyby.

The far-field signature of the Alfven wing current system which was observed by Cassini (without actual penetration of the current carrying wing) cannot provide detailed information of the size of the wing or of the atmospheric source. Even for a strong atmospheric interaction the necessary diameter of the atmospheric volume producing the perturbations is by necessity larger than the body of the satellite and needs to be at least of order ~4 Re. A recent plasma model (13) predicts an even larger volume. This work suggests that a sputtering produced atmosphere at Enceladus would not be sufficient to produce the observed magnetic field perturbations and hence an additional atmospheric source must have been operating. A region of about 8 Re is affected in front of and to the side of the moon, consistent with a large but weak interaction region. The magnetic field perturbations are also consistent with the conductor/atmospheric volume being south of the spacecraft trajectory and downstream of it.

The second and third flyby data sets are not as easily explained by the simple guidelines used above. The second pass on day 68 is below Enceladus (Fig. 1) and the region of strongly perturbed field is noticeably smaller and occurs inside of about 3.5 Re. If the interaction was symmetric around Enceladus so that the source of the slow down was above the spacecraft then the perturbation vectors should be reversed relative to those of day 48. Outbound from about Y = 3 Re this is true. However inbound before Y
The implications of these findings, linked with the clear evidence from Voyager observations of endogenic geological activity (14) and speculations of out-gassing or geyser type activity led to the next Enceladus flyby being substantially decreased in altitude to enable an extremely close flyby of 173 km to take place on day 195. In the ENIS co-ordinate system, with the largest perturbation occurring in the $B_X$ component, a sharp corner is seen in the minimum before closest approach (Fig. 3). These sharp gradients in the field suggest the spacecraft may have crossed a current boundary during this time, perhaps even an entry into the atmospheric plume/ionosphere? The data on this encounter needs to be visualized in three dimensions since the trajectory moves very rapidly in $Z$ during the encounter. It can clearly be seen (Fig. 1) that the perturbation vectors are almost identical to those of day 68 despite the rapid motion in $Z$. The $B_X$ perturbation is that of a slow down in the flow below the spacecraft (while Cassini is in turn well below the orbital plane of Enceladus). Hence the out-gassing source must by necessity be at high southern latitudes well below the orbital plane. This is consistent with the realization that a neutral atmosphere at Enceladus is not strongly gravitationally
bound for normal temperatures and will be even weaker for the high temperatures
detected by observations (2, 3) in the tiger stripes (4) near the south pole. However this is
not the complete story since the By perturbation is that of a deflection in Y around
Enceladus but above Cassini. In other words the perturbation in B_Y is 90° to what one
would expect for a simple draping type signature.

Ion cyclotron waves oscillating near the gyro-frequencies of water-group ions
have been observed on nearly every Cassini orbit between 3.5 – 7 Rs (15). During the
three close encounters of Enceladus however the waves change in character as the
spacecraft approaches the moon. Near the orbit of Enceladus the water-group waves
nominally have amplitudes of ~0.25nT. On each of the three flyby days the wave
amplitude begins to increase above the background some 35 Re away. On the first flyby,
the amplitude rose to 0.72nT at closest approach and continued increasing outbound from
Enceladus. On the second flyby, the closest approach amplitude was 0.34nT and on the
third flyby, the wave amplitude increased to a maximum of 0.55nT but decreased to
0.32nT at closest approach.

Since wave growth increases as the pick-up rate and the background flow speed
increase, the observed decrease on day 195 may be due either to a decrease in the pick-up
rate or in the velocity of the pick-up. However since we expect the pick-up rate to
monotonically increase as Enceladus is approached; we believe the decrease in wave
amplitude signals a slow down in the plasma flow near the moon. The subsolar latitude
on Enceladus is about 20° south, but it has been shown (16) that charge exchange and
electron impacts, not photoionization would be the dominant forms of ionization (by two orders of magnitude). Therefore any variation of wave amplitudes between the different flybys is more easily attributed to variations in the moon’s neutral cloud morphology, the background plasma and the spacecraft location relative to the flow than to any photoionization effects. The energy of an Enceladus pick-up ion varies as the square of the relative velocities between the plasma and the neutrals, with about half of the energy of the pick-up ion being available for wave generation (17). Thus by measuring the electromagnetic energy flux of the ion cyclotron waves, we can estimate the energy flow into the picked up ions and hence the mass addition rate. For example, with the wave amplitude on the first flyby, the production rate near Enceladus can be estimated to be about eight times larger than that which is observed in the E ring far from the moon. This mass addition rate varies between flybys, both near and far from Enceladus.

The Cassini magnetometer data from the three recent flybys of Enceladus is consistent with the other Cassini instrument analyses of the existence of an out-gassing plume near the south pole of the moon (Fig. 4). The magnetic field observations from the first flyby are most readily interpreted in terms of an atmospheric interaction in which ions are picked up and the flow is slowed down and deflected around Enceladus. In the second and third flybys, the major perturbations which are observed are compatible with a source south of the spacecraft; and the narrower extent of the perturbed region is consistent with an out-gassing plume close to the south pole of Enceladus, with neutrals being ejected radially away. The Bx signature is consistent in all three flybys but more concentrated in extent in the second two flybys as one might expect if the plume is
expanding away from cracks in the surface of the moon. The $B_z$ perturbations simply reflect the compression in the magnetic field, with the field compressing in order to slow and deflect the flow. The $B_y$ perturbations in the latter two flybys are rather more difficult to interpret and will require detailed modelling work to better understand them.

The magnetic field measurements together with the UVIS occultation observations (5) from all three flybys suggest appreciable temporal variations in the atmospheric plume on the time scale of months. The field results are consistent with the plume location obtained from other observations (2, 3, 6) with the source being the “tiger stripes” or cracks on the surface close to the south pole (4).

Initial numerical simulations based on (13) quantitatively confirm the qualitative conclusions we have described in this paper. The simulations clearly indicate that the cause of the field perturbations is an atmospheric plume originating near the south pole of Enceladus. They also show that the neutral atmosphere which is generated is a dynamic one. The first flyby requires a spatially broadly distributed atmosphere on the scales of $R_e$; and since the flyby was well north of Enceladus itself, the observations were unable to place constraints on the latitudinal extent of the atmosphere. The last two flybys were much closer to Enceladus and hence able to be much more constraining, indicating the source of the magnetic field perturbations being an atmospheric plume near the south pole of Enceladus. In addition, the last two flybys are inconsistent with the broadly distributed neutral cloud and suggest the existence of a much narrower plume, confirming the dynamic nature of the atmosphere. The dynamic nature of the Enceladus neutral cloud
is also consistent with the large variation of neutrals observed remotely (18). This significant neutral source from Enceladus may go some way towards answering one of the outstanding questions regarding our understanding of Saturn’s magnetosphere, what is the missing source of the large densities of water and its derivatives that are observed.

References & Notes

2. J. Spencer et al., this issue.
3. R. H. Brown et al., this issue.
4. C. Porco et al., this issue
5. C. Hansen et al, this issue.
6. H. Waite et al., this issue.
7. The Enceladus Interaction co-ordinate system is defined with X in the direction of co-rotational flow; Y is positive towards Saturn and Z is along Saturn’s spin axis.
8. An Enceladus radius is defined as Re = 250 km.
15. A Saturn radius is defined as Rs = 60, 268km.


**Figure 1a:** The three flyby trajectories in the (X,Y) plane of ENIS co-ordinate system, where X is along the direction of co-rotational flow and Y is positive towards Saturn, arrows denote the flyby direction. Overlain on the trajectories are the residuals of the magnetic field (after the background magnetic field has been removed from the data). The scale of the residuals have 4.5 nT equivalent to 2 Re.

**Figure 1b:** The three flyby trajectories in the (X,Z) plane of ENIS co-ordinate system, where X is along the direction of co-rotational flow and Z is along Saturn’s spin axis, arrows denote the flyby direction. Overlain on the trajectories are the residuals of the magnetic field (after the background magnetic field has been removed from the data). The scale of the residuals have 4.5 nT equivalent to 2 Re.

**Figure 2:** A schematic showing the expected draping behaviour of magnetic field lines, denoted by B in the vicinity of a large conducting obstacle. The figure on the left is in the (X,Z) plane of the ENIS co-ordinate system, and the figure on the right in the (Y,Z) plane. The inflowing corotating Saturn plasma (with velocity V) is slowed down with the field being draped around the obstacle. The dashed region of the field lines are where they are moving through the conducting body.

**Figure 3:** The magnetic field data from the close flyby on day 195 in the ENIS co-ordinate system. The x, y, z components of the magnetic field and the field magnitude are shown. The clear perturbation in the magnetic field due to the interaction with Enceladus are clearly visible. Details of the spacecraft trajectory are listed beneath the plot where X, Y, Z are defined in the text and R is the radial distance of the Cassini spacecraft away from Enceladus.
Figure 4: A schematic (where Saturn and Enceladus are not to scale) showing the corotating Saturn magnetic field and plasma being perturbed by the neutral cloud being produced by a polar plume generated close to the south pole of Enceladus. This scenario fits the second two flyby observations, whereas the first more distant flyby arose from a stronger and more extensive source, implying a temporally changing atmosphere.