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Hybrid simulation of comet Shoemaker-Levy 9 interaction with Jovian bow shock

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Abstract. The interaction of the solar wind with comet Shoemaker-Levy 9 leading to the formation of the cometary magnetosphere and its interaction with the Jovian bow shock is simulated using a one dimensional hybrid code. The mass loading of the solar wind by the cometary ions leads to the formation of a bow shock behind which the plasma density is $2-3 \text{ cm}^{-3}$ and the electron temperature is 4 eV . The interaction of this system with the Jovian bow shock yields local enhancements of the magnetic field and the plasma density by factors of 4-5 and the electron temperature by 2-3.

Introduction

The spacecraft encounters with comets Halley and Giacobini-Zinner have shown the transition region at the comet solar wind interaction to be distinct from the planetary cases. This region was found to be dominated by turbulence, mainly at the MHD frequencies corresponding to the gyrofrequencies of the water group ions. Consequently, the magnetic moments of the cometary ions are no longer adiabatic invariants and their interaction with the solar wind plasma is essentially kinetic [Galeev et al., 1985; Sharma et al., 1988; Omid and Winske, 1991; Tsurutani, 1991]. On the other hand the planetary bow shocks are collisionless in nature and the kinetic behavior of ions is again an essential feature. In both the cometary and planetary cases, it is thus essential to incorporate the plasma kinetic behavior because of its leading role in the dissipation and acceleration processes. The need for a kinetic description is further accentuated in the cometary case by the large gyroradius of the cometary ions. In fact, the highly resolved observations during the spacecraft encounters show many localized wave and particle spectra characteristics of interactions with scale lengths shorter than the relevant ion gyroradii [Neugebauer, 1990]. The earlier hybrid simulations [Galeev et al., 1985; Omid and Winske, 1991] of the comet - solar wind interaction at 1 AU are for a comet with a single nucleus. To model the comet Shoemaker-Levy 9 (SL9) encounter with Jupiter we first simulate the solar wind interaction with a fragmented comet at 5 AU. Then the encounter of the resulting cometary magnetosphere with the Jovian bow shock is simulated. The enhancements in the plasma and field variables in these cases and their consequences are presented.

Interaction of Solar wind with a comet with fragmented nucleus

The interaction of a comet with the solar wind gives rise to the mass loading of the latter by the heavy cometary ions, leading to the bow shock and cometary tail. In the case of a comet with a fragmented nucleus, there are 3 different cases of the interaction depending on the distance between the cometary nuclear fragments, L_n and the characteristic size of the coma, L_c . These cases are: a) $L_n \gg L_c$, in which case the interaction among the fragments are weak and the cometary magnetosphere reduces to that of a single nucleus; b) $L_n \approx L_c$, corresponding to the strong interaction case; and c) $L_n \ll L_c$, where the system of fragments can be considered to be one big comet. The case (c) is similar to the rigid spherical impactor and the case (a) to the cylindrical impactor [Sekanina, 1993]. Since the full length of the fragment train of comet SL9 close to the impact is $2.4 \times 10^6 \text{ km}$ [Scotti and Melosh, 1993] with 20 fragments, $L_n \approx 10^5 \text{ km}$. The size of a single fragmented nucleus is less than 5 km , so that $L_c \leq 10^5 \text{ km} \approx L_n$. The relevant scenario is thus the case b) and we shall consider this case of strong interaction with two nuclear fragments, with the second fragment located in the subsonic flow region downstream. The second fragment may disturb the flank of the bow shock formed in front of the first fragment and form another shock due to the mass loading in the second coma. The conditions for the ionization of the atmosphere of the second and subsequent nuclei will also be significantly affected.

In order to use a one-dimensional (1-D) hybrid (particle ions and fluid electrons) code to study the solar wind flow near the comet we choose a stream line that is at a distance D from the solar wind - comet axis (z -axis). In the actual 3-D case the central stream line contains the stagnation point and 1-D simulations that include the central stream line do not yield a quasi-stationary state. The interaction of the comet with the flanks of the Jovian bow shock can be quasi-perpendicular, oblique or quasi-parallel. We consider the quasi-perpendicular case in which the magnetic field is nearly perpendicular to the shock normal and has only the B_y component. Initially the undisturbed supersonic solar wind fills the computational grid. At the right boundary the unperturbed field is specified, and solar wind protons are injected with a given velocity distribution. At the left boundary where the flow becomes subsonic, free boundary conditions are applied. The distribution of cometary ions depends on the position z_c of the nucleus along the z axis:

$$Q = \frac{qGe^{-q(z-z_c)/w_c}}{4\pi w_c((z-z_c)^2 + D^2)},$$

where the evaporation rate G of the cometary molecules depends on the solar irradiation and the surface area of the

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Paper number 94GL01295

0094-8534/94/94GL-01295\$03.00

nucleus. For comets near Earth the distance from the nucleus to the bow shock, L_{sh} , and the distance from the nucleus to the stagnation point, L_{st} , vary in the ranges $500 \text{ km} < L_{sh} < 10^6 \text{ km}$ and $5 \text{ km} < L_{st} < 5 \times 10^4 \text{ km}$, and $10^{26}/\text{s} < G < 10^{30}/\text{s}$. At Jupiter (5 AU) we have solar irradiation and density of solar wind plasma reduced to about 1/25 of the values at 1 AU.

The relevant physical variables that characterize the interaction region are the Alfvén Mach number M_A given by the ratio of the solar wind flow speed w_0 to the local Alfvén speed v_A , and the ratio β of the plasma to the magnetic energy densities. In the different simulations discussed here, the dimensionless parameters were assigned values typical of the solar wind at the Jupiter's orbit and in the outer part of the coma [Acuna et al., 1983; Bagenal, 1992]: $M_A = 6$, the proton $\beta_p = 0.5$, the electron $\beta_e = 2$, $q = 10^{-6}/\text{s}$, the initial neutral speed $w_c = 1 \text{ km/s}$, $w_0 = 350 \text{ km/s}$, the solar wind magnetic field $B_{sw} = 1 \text{ nT}$, the normalized cometary ion Larmor radius $R_{ci} = 1.32$ ($= w_0/\Omega_{ci} = 1.7 \times 10^4 \text{ km}$), the normalized proton Larmor radius $R_{cp} (= 0.266 = 3500 \text{ km})$, the size of the computational box $D_z = 10.0$, $D = 2.0$, the location of the fragments are $z_c = 2.0$ and $= 5.0$. All lengths are normalized by $L = R_{ci}/0.266 = 1.3 \times 10^4 \text{ km} = 0.18 R_J \approx L_{sh}/2$, and time by the proton gyroperiod T_{cp} . To minimize the run time of these simulations the ratio of the cometary ion and proton masses is taken to be 5. At the orbit of Jupiter the solar wind $M_A = 20 - 30$ but since we consider the processes at the flank of the bow shock we take $M_A = 5$ in our simulations. In a typical simulation run we use 2000 cells, 100 particles per cell and a time step of $0.0075 T_{cp}$. The results of one such run is shown in Fig. 1, which shows the profiles of the density of protons N_p (a), the density of cometary ions N_i (b), the magnetic field B_y (c), and the electron temperature T_e (e) at time $t = 12.0 T_{cp} = 2.4 T_{ci}$, where T_{ci} is the cometary ion gyroperiod. These profiles of the basic parameters are typical for many of our current simulations using values of $D = 0.5 - 3.0$. They clearly show the electron-proton subshock in front of which is the "foot" associated with the outflow of part of the cometary ions due to their large gyroradii. At the first electron-proton jump the Alfvén and magnetosonic Mach numbers decrease to 3.8 and 1.6 respectively. The jump in B_y reaches the value 3.8, and that of T_e reaches 4.0 at the electron-proton subshock and 2.0 - 2.5 in the downstream region. Behind the first subshock $M_A = 2.5$, the magnetosonic Mach number $M \geq 1$, and the bulk proton velocity $v_p = 0.6$, as the second electron-proton jump is formed. The jump in the magnetic field is 4.3, while T_e goes up by a factor of 4.0. The second electron-proton subshock is formed near the maximum of the cometary ion density. Fig. 1 also shows the formation of the long cometary tail. In our case the length of the cometary tail is approximately 5.0 in the normalized units. The typical parameters of solar wind at Jupiter are $N_e \approx 0.4 \text{ cm}^{-3}$, $B_0 = 0.5 - 2.0 \text{ nT}$ and $T_e \approx 0.4 \text{ eV}$. At the front of the shock, as shown in Fig. 1, these parameters jump to 4 - 5 times these values. For the case where the parameter D has small values, say, 0.5, the jump in T_e can double, yielding values exceeding 4.0 eV.

Interaction of comet Shoemaker-Levy 9 with Jupiter

At the encounter, the cometary magnetosphere will interact with the flank of the Jovian bow shock. To simulate

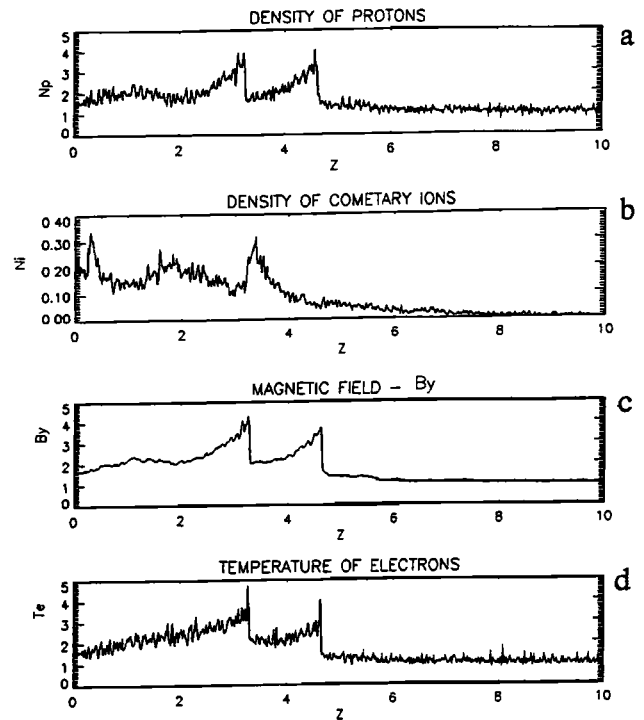


Figure 1. The interaction of the solar wind with two cometary nuclei (at $z_c = 2.0$ and $= 5.0$, corresponding to a separation of $4 \times 10^4 \text{ km} \approx 0.5 R_J$) for $M_A = 6$ with the flow to the right. Profiles of the proton (a) and cometary ion (b) densities, the magnetic field (c) and the electron temperature (d) are shown at $t = 12.0 T_{cp} = 2.4 T_{ci}$.

this interaction we use a reference frame in which the solar wind is at rest. At the start of the simulations we impose a strong discontinuity in the plasma density, the electron temperature and the magnetic field near the left boundary of the grid. This results into a shock wave that moves to the right towards the comet and a rarefaction wave in the opposite direction. At the left boundary the solar wind fields and plasma parameters are specified. At the right boundary reflecting boundary conditions are used as before. The cometary ion source is then introduced as described earlier.

In these computations the parameters values as in the previous section are used and also $R_{ci} = 0.33 - 0.66$ and $R_{cp} = 0.066 - 0.133$. The cometary nucleus now moves with a speed $V_n = 0.5$ so that $z_c = 10.0 - V_n t$. The initial jumps of magnetic field and density at the discontinuity were $B_2/B_1 = N_2/N_1 = 20$. As before we consider the processes at the flank of the bow shock and take $M_A = 5$ in our simulations. With these parameters the Jovian bow shock moves with a velocity $U_J = 0.47$ along the computational grid. When the two bow shocks are far away from each other, at the Jovian shock the value of the magnetic field overshoot is $B_2/B_1 = 3.1$ and the jump in proton density $N_2/N_1 = 5.5$. In the incoming flow $M_A = 4.7$ and $M = 1.3$, and $T_{e2}/T_{e1} = 3.5$. The cometary bow shock (proton-electron subshock) moves in the opposite direction with velocity $V_n = 0.5$. The jumps in the field and plasma parameters are $B_2/B_1 = 3.5$, $N_2/N_1 = 4.5$, $T_{e2}/T_{e1} = 2.4$, $M_A = 5.0$ and $M = 2.5$. The proton and cometary ion densities, the magnetic field and the electron temperature profiles when the shocks are $6600 \text{ km} \approx 0.1 R_J$ apart are shown in Fig. 2.

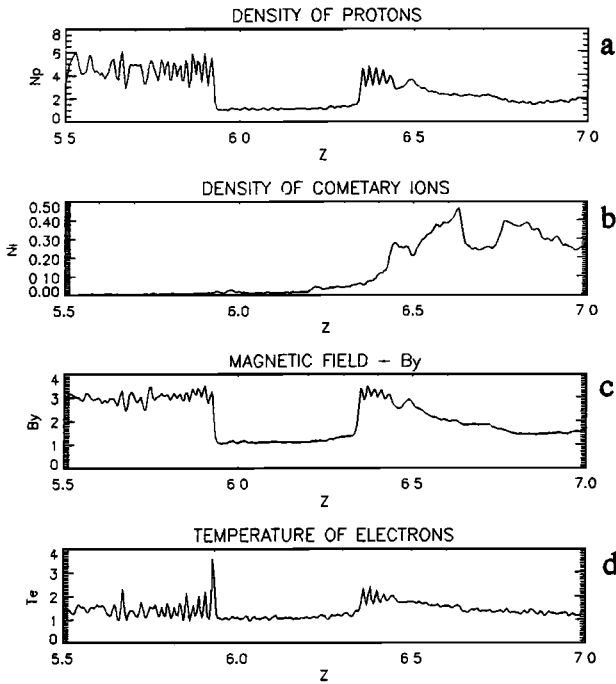


Figure 2. The cometary magnetosphere and Jovian bow shock before collision at time $t = 9.0 T_{cp} = 1.8 T_{ci}$. The Jovian bow shock is weakly mass loaded by the cometary ions. Shown are N_p (a), N_i (b), B_y (c) and T_e (d). The separation of the two bow shocks is $\approx 6600 \text{ km} \approx 0.1 R_J$.

There are three main stages in the interaction of the magnetospheres of the comet and Jupiter, viz. the mass loading of the Jovian bow shock, the collision of shock fronts, and the traversal of the cometary nucleus downstream of the Jovian bow shock. When the cometary nucleus is within L_c of the Jovian bow shock, the mass loading becomes significant and the pick up cometary ions form a ring distribution in velocity space perpendicular to the local magnetic field. At the collision of two bow shocks, shown in Fig. 3, the profiles of the magnetic field, the density of protons and the electron temperature have two nearly equal peaks. At this stage B_y increases by a factor of about 8, while T_e increases by a factor of 5. In the hybrid simulations of two equal supercritical electron-proton shocks with $M_A = 8$ [Cargill and Goodrich, 1987], enhancements of the magnetic field by a factor of 15 with an overall symmetry about the interaction region was obtained. In the present case $M_A = 5$ and also the mass loading plays an important role, resulting in an asymmetric interaction where the gyroradius of the heavy cometary ions determines the characteristic scale size. In the next stage of the interaction, shown in Fig. 4, the B_y and N_p profiles become irregular and broader, the ramp of the cometary ion density profile increases, and its peak moves closer to the nucleus.

Predictions and Conclusion

Based on the current understanding of the planetary and cometary bow shocks, the interaction at the encounter of comet Shoemaker-Levy 9 with Jupiter is expected to be dominated by ion kinetic processes. The encounter is further complicated by the nucleus of comet SL9 being fragmented into about 20 pieces. The plasma physical aspects of the encounter have been simulated in two parts using 1-D dimen-

sional hybrid code to delineate the observable predictions. In the first part of the comet - solar wind interaction has shown many new features arising from the fragmented cometary nucleus. The solar wind mass loading by the fragmented nucleus may result in multiple shocks with a set of jumps in the plasma densities and temperatures, and the magnetic field, and it results in an extended shock transition region. The separation between the shock regions is of the same order as that between the fragments of the nucleus. For comet SL9 with the nucleus fragmented into 20 pieces that approach Jupiter in a line, the predicted values may be obtained from the case of two fragments simulated here. Thus the plasma in the coma will be characterized by electron temperature of 2 – 4 eV with embedded magnetic field of 2 – 4 nT in a region which extends 10^4 km by 10^6 km .

Simulations of the collision of the shock fronts of the comet SL9 with Jupiter show very thin peaked structures. For the typical parameters of solar wind at Jupiter the width of this peak is about one proton gyroradius $\approx 10^3 \text{ km}$. The plasma parameters have the typical values: $T_e = 6.0 \text{ eV}$, $N_p = 5 \text{ cm}^{-3}$, and $B_0 = 4 - 16 \text{ nT}$. These values represent enhancements of nearly one order of magnitude over the ambient values. In the next stage the transition region begins to broaden to the size of $1.5 \times 10^5 \text{ km}$, forming a turbulent region with wide oscillations in the plasma and field parameters. The size of the coma decreases rapidly during this stage due to the sharp increase in the solar wind proton density downstream of the Jovian bow shock and the cometary ion density near the nucleus increases by a factor of 3. We have considered here only the quasi-perpendicular case and in the other cases, viz. the oblique and quasi-parallel cases, we expect broader scale sizes of the transition region and stronger level of turbulence. However the parameters at the electron-proton subshock is expected to be of nearly the same

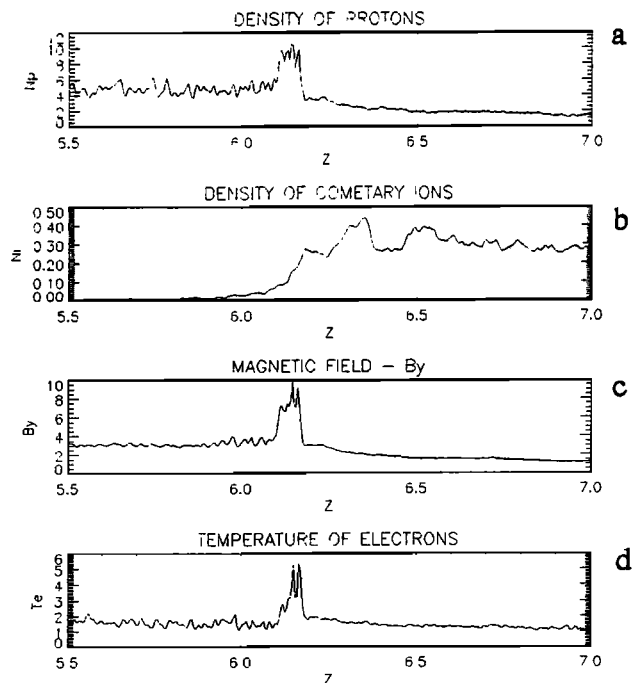


Figure 3. The collision of the cometary magnetosphere and Jovian bow shock at $t = 10.5 T_{cp} = 2.1 T_{ci}$. The densities of protons (a) and cometary ions (b), the magnetic field (c) and the electron temperature (d) are all peaked at the collision.

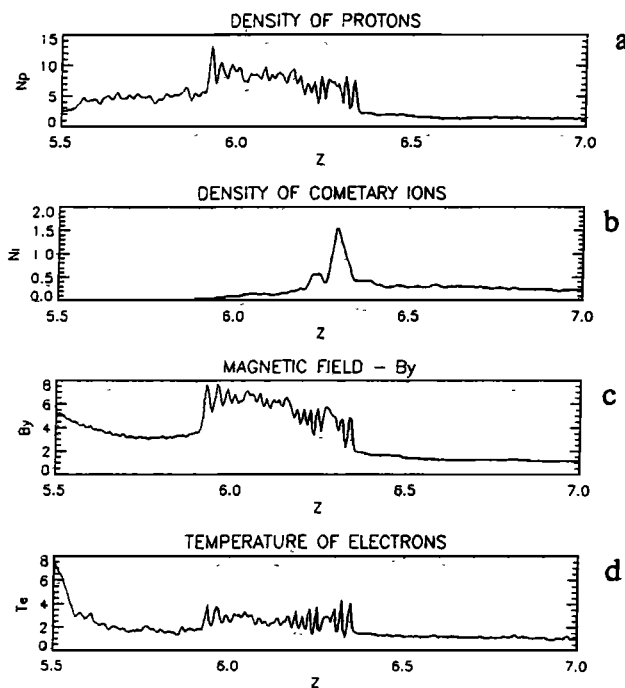


Figure 4. The broad region of interaction between the cometary magnetosphere and Jovian bow shock at time $t = 12.0 T_{ep} = 2.4 T_{ci}$. The regions of the densities of protons (a) and of cometary ions (b), the magnetic field (c) and the electron temperature (d) are expected to extend over a much wider region due to the multiple nuclei.

in all cases. The processes discussed here are predicted to take place when the comet SL9 enters the Jovian bow shock at $\approx 70 R_J \approx 5 \times 10^5 km$ on way to the crash.

The main observable characteristic of the plasma at the interaction will be the radiation whose intensity can be estimated based on the electron temperature and density, and the cometary ion and neutral densities. For example, ground based observations of H_2O^+ ion emission at 6198 Å at comet Halley [Ip et al., 1988] yielded localized enhancement in the H_2O^+ density, confirming earlier spacecraft observations [Neugebauer, 1990]. This radiation was also observed at the smaller comet Tuttle 1980h and should be observable at comet SL9. The radiation intensity is proportional to the number density of the excited ions, which in turn is proportional to the product of the electron and ion densities. Thus, based on the enhancements of 3 in the cometary ion density and 4 in the electron density seen in these simulations, the intensity of this and other similar radiation should go up by a factor of about 10 at 70 R_J from the crash.

Acknowledgments. This work was supported by NASA and NSF grants. We acknowledge many fruitful discussions with G. M. Milikh, K. Papadopoulos and R. Z. Sagdeev. The computations were performed at the UMD Advanced Visualization Laboratory.

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(Received February 21, 1994; revised April 14, 1994; accepted April 22, 1994)