# COMETOSHEATH STRUCTURES AND TAIL RAYS: OUTCOME OF BI-ION FLUID SIMULATIONS

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**Abstract.** Momentum coupling between the solar wind (SW) and the cometary plasma is a crucial element in the plasma dynamics around comets. A bi-ion fluid model is applied instead of one-fluid MHD normally used in 3D global simulations. This new approach accounts for the observational fact of spacecraft measurements at comets that in a region inside the bow shock beginning from about cometary distances, where the mass density of cometary ions and protons becomes comparable, complex interaction processes take place. They are manifested in pronounced plasma structures and additional plasma boundaries. An essential signature of the bi-ion fluid description consists in the occurrence of new (bi-ion) wave modes which may grow to large amplitudes due to a drift of protons relative to the heavies. In this way, a structuring of all plasma parameters results. Additionally, steepening of the underlying bi-ion waves and their phase bunching in multiple “Mach cones” are suggested to be responsible for cometary tail ray formation. Corresponding results of 2D bi-ion fluid simulations are presented.

## 1. Introduction

Tail rays which may extend up to several million kilometers constitute one of the most fascinating features of bright comets during their active phase near perihelion. The related mechanism for the large scale structuring of cometary ions, however, is one of the unsolved problems in the physics of solar wind–comet interaction. Photographs of comets reveal a very rich variety of structures classified in different categories (rays, streamers, plumes, arcades, disconnection events, kinks, helices etc., e.g., Fernandez and Jockers, 1983). Tail events were interpreted as a result of magnetic reconnection (Brandt, 1982). The occurrence of different types of condensations have been attributed to the Kelvin–Helmholtz instability (Ershkovich and Chernikov, 1973). Tail kinks were interpreted as a result of Rayleigh–Taylor instability associated with solar wind changes (Jockers, 1991). One of the most prominent features in photographs of comets is a series of long regular narrow rays (with a typical width of about 2000 km) emanating from the head and extending often over $10^7$ km. Comet Hale–Bopp also gives us some good examples of plasma structuring in the cometosheath (Bonev and Jokers, 1994; Larson et al., 1998). Although a number of explanations were proposed, no general consensus on the mechanisms responsible has been reached. One of the reasons for this is the lack of simultaneous ground-based and in-situ plasma and field measurements. Alfven

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(1957) has interpreted the phenomenon of rays as a manifestation of the magnetic field lines traced by cometary ions. Schmidt and Wegmann (1982) have attributed the formation of rays to changes of the interplanetary field direction. A new set of field lines, draping the cometary ionosphere, build a new ‘draping magnetosphere’ and forms a new sequence of ion structures. Effects of different types of discontinuities in the solar wind on cometary plasma tails were studied by Schmidt and Voigt (1989) using a time-dependent 3D MHD model. In the case of slight changes of the solar wind direction a gradual turn of the plasma tail towards the new direction was found. More systematic studies with the same model were done by Rauer et al. (1995). Another model considers non-stationary ion production which supplies field tubes travelling around the comet (Ip and Axford, 1982). Wave phenomena such as mirror waves were also proposed as a possible reason for tail ray formation (Russell et al., 1987; Raeder et al., 1990).

In this report, we suggest for discussion a mechanism of plasma structuring which is based on the concept of collisionless (electromagnetic) coupling between the proton and cometary ion fluids. A multifluid approach may fill the gap between the common one-fluid MHD theory which is presently used in 3D global simulations (e.g., Gombosi et al., 1997–1999) and hybrid code simulations (e.g., Omidi and Winske, 1987) which have technical limitations even for powerful computers. It benefits from both the inclusion of a more realistic coupling mechanism between the different particle species and the advantage of a continuum description. Multifluid theories have been known for a long time and have already been applied to different problems of solar wind massloading (e.g., Maroshnik, 1982; Chapman and Dunlop, 1986). In contrast to the one-fluid description which implies a ‘rigid’ velocity coupling between the particles involved, a coupling between different ion species in the multifluid model is provided by electromagnetic forces. Especially, the Lorentz force acts on the ions in the case when they begin to move relative to the electron fluid (which carries the frozen-in magnetic field). These macroscopic forces cause an ‘elastic’ momentum coupling which enables the different ion species to react differently. In 2D bi-ion MHD simulations it was shown that the dynamics of protons and heavy cometary ions becomes strongly coupled, leading to the generation of non-linear bi-ion waves associated with periodical structures in all plasma parameters (Sauer et al., 1996a,b,c).

## 2. 2D Bi-Ion MHD Simulations

*The model and numerical procedure:* Having in mind the interaction of the solar wind (SW) with a cometary heavy ion source, we study the behaviour of a magnetized plasma system consisting of two ion species: SW protons (subscript $p$) and heavy ions ($H_2O^+$, $OH^+$ or $CO^+$, subscript $h$). The two ion species – treated as separate fluids – communicate with each other only be means of electromagnetic forces (no collisions). The electrons are considered as a massless fluid with frozen magnetic field. The ions are assumed to be cold, thus no pick-up heating of the cometary ions and all effects which can arise from nonzero ion temperature are neglected. Under the restrictions above the system of bi-ion fluid equations can be written as (Sauer et al., 1994): Continuity and momentum equation for the solar wind protons

$$\frac{\partial}{\partial t} n_p + \nabla \cdot (n_p v_p) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(n_p v_p) + \nabla \cdot (n_p v_p v_p + P_p) =$$

$$\frac{1}{m_p}\frac{n_p}{n_e}\left[ e n_h (v_p - v_h) \times B - \nabla \left( \left( P_e + \frac{B^2}{2\mu_0} \right) I - \frac{BB}{\mu_0} \right) \right], \tag{2}$$

and for the heavy ions

$$\frac{\partial}{\partial t} n_h + \nabla \cdot (n_h v_h) = q_h \tag{3}$$

$$\frac{\partial}{\partial t}(n_h v_h) + \nabla \cdot (n_h v_h v_h + P_h) =$$

$$\frac{1}{m_h}\frac{n_h}{n_e}\left[ e n_p (v_h - v_p) \times B - \nabla \left( \left( P_e + \frac{B^2}{2\mu_0} \right) I - -\frac{BB}{\mu_0} \right) \right]. \tag{4}$$

The above equations are closed with Faraday's law

$$\frac{\partial B}{\partial t} - \nabla \times \left[ \frac{1}{n_e}(n_p v_p + n_h v_h) \times B \right] - \frac{B \cdot \nabla B}{\mu_0 n_e} = 0. \tag{5}$$

The electron pressure $P_e = n_e k T_e$ is calculated for isothermal conditions ($T_e$ = const), where the electron density follows from the quasi-neutrality condition, $n_e = n_p + n_h$, $q_h$ is the cometary production rate, $q_h = n_0 \nu_{ph}$ where $n_0$ is the cometary neutral gas density and $\nu_{ph}$ is the photo-ionization rate.

In the simulations a 2D version of the flux-corrected transport algorithm (Book et al., 1981) was used. A simulation box of 100 × 200 grid points was applied to solve the time-dependent problem of the initially undisturbed SW flowing along the $x$-axis onto an obstacle represented by a source of heavy neutrals which are being ionized at a given rate. The computation was carried on until a quasi-stationary state was reached.

*Non-stationary 1D simulation:* Basic elements of the momentum coupling between the SW and the cometary plasma can already be explained by considering a simple 1-D model of the proton flow interacting with a localized cometary source. The magnetic field is in the $Y$ direction, $B = B_y$. Results are shown in Figure 1.

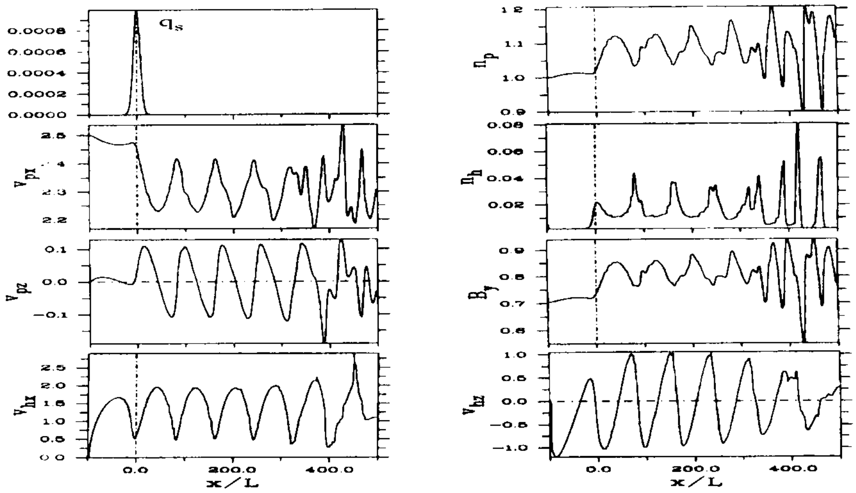

*Figure 1.* Variations of the magnetic field, velocity and the number density of the incoming protons and heavy ions along the $x$-axis in 1-D MHD bi-ion simulations.

Newly generated cometary particles, originating near the source, start to move on cyloid-type trajectories. When the heavy ions are near the rest, the massless electron fluid slows down to provide charge neutrality, $v_{ex} = n_p v_{px}/(n_p + n_h)$. Deceleration of the electrons results in a decrease of the motional electric field $E_z = -v_{ex}B_y$ that causes the proton flow to be deflected in the $+Z$ direction which is opposite to the direction of the motional electric field $E_z = -v_{ex}B_y < 0$:

$$\frac{\mathrm{d}v_{pz}}{\mathrm{d}t} = \frac{e}{m_p}(E_z + v_{px}B_y) \geq 0.$$

The deflection of protons is clearly seen in the third left panel from above showing $v_{pz}$. The arising Lorentz force $v_{pz}B_y$ decelerates the streaming protons which transfer momentum to the heavy ions. The bulk speed of heavies gradually exceeds the proton velocity. To supply a charge quasi-neutrality, the electrons begin to outrun the protons. An enhancement of the electron bulk velocity $v_{ex}$ and an increase of the motional electric field $E_z$ leads to a deflection of the proton flow in the $-Z$ direction. As a result, heavies transfer momentum back to the protons. Thus, the motion of both ion populations become oscillating and the exchange of momentum between the ion flows occurs in a periodical manner. The process of a relative gyration of both fluids becomes evident from the momentum equations given above. An essential difference of these equations to the classical one-fluid approach is the appearance of the Lorentz force, connected with a relative streaming of the ion fluids ($-\Delta v x B$). This force arises because either ion fluid in their reference frame senses the motional electric field $-\Delta v x B$ which is supplied by the differential ion streaming. Wave-like motion of protons and heavy ions give rise to a structuring in the cometary plasma. Peaks of the ion density occur in nodes of the waves. It is worth noting that due to the momentum exchange between the ion species the cycloidal trajectories of protons and heavies will be modified. Generally, at large distances from the comet, where the mass density of the cometary plasma is small, the shape of the cycloid is close to the ideal one which describes the motion of a test particle ($L = 2v_{\mathrm{SW}}/\Omega_h$, where $\Omega_h$ is the gyrofrequency of the cometary ions).

In our earlier studies is was found that the differential motion of the ion species becomes more complicated and a bunching on smaller scales occurs when the cometary mass density increases (Sauer et al., 1996c; Dubinin et al., 1998). Small scale structuring of $n_h$ gives rise to subsequent variations of the plasma parameters by the same manner as discussed above. Indications are also seen in Figure 1 where small-scale structures develop in large distances ($x/L \sim 300$).

*Results of 2D simulations:* For these simulations a production rate was taken which is approximately that of Grigg–Skjellerup ($Q_h \sim 10^{27}$ s$^{-1}$). The Mach number of the incoming solar wind is $M_A = 2$. The undisturbed magnetic field is in the simulation plane transverse to the flow direction. On Plate 1, the results are shown as color-coded spatial profiles of the heavy ion density $n_h$ (upper panel), the proton density $n_p$ (middle panel) and the total magnetic field $B_{\mathrm{total}}$ (lower panel). A structuring of the plasma parameters within the cometosheath is clearly seen. Maxima in the heavy ion density which are in the range of several percents of the proton density coincide with minima of the proton density and vice versa. In the outer regions of low cometary ion densities the magnetic field follows the proton density. In the region nearer to the comet, however, the proton density decreases and the heavy ion density increases, which means a replacement of protons by heavy ions. The non-stationary character of the structures seen on Plate 1 becomes evident by plotting the temporal evolution of the plasma parameters and the magnetic field in a selected point within the simulation box. This was done in Figure 2 taking a run with $M_A = 1.5$ (instead of $M_A = 2$). It is seen that the structures are moving with a velocity of about $0.7v_A$, where $v_A$ is the local Alfven velocity. This indicates a dynamic process of structuring rather than a steady-state pattern. Structures are moving away and new ones arise. Thus, Plate 1 represents only a snapshot of the interaction process.

Another run with higher Mach number ($M_A = 5$) and lower production rate ($Q_h \sim 10^{26}$ s$^{-1}$) was chosen mainly for studies of cometary tail rays (for technical reasons, there are limitations to extending the simulations on both the cometosheath and the tail). Figure 3 shows the cometary ion density profile for this case, where the magnetic field is out of the simulation plane (in the $Z$ direction). The resulting tail structures are thought to be formed by an interference of the excited bi-ion waves (e.g., Sauer et al., 1998). This means that they are considered as generalized Mach cones in the bi-ion plasma. The multiple character of the cones seems to be caused by the density inhomogenities in the source region. Because of our special conditions of a magnetic field which has no components within the $X, Y$-plane, any draping effects are excluded as an explanation for the observed ray pattern.

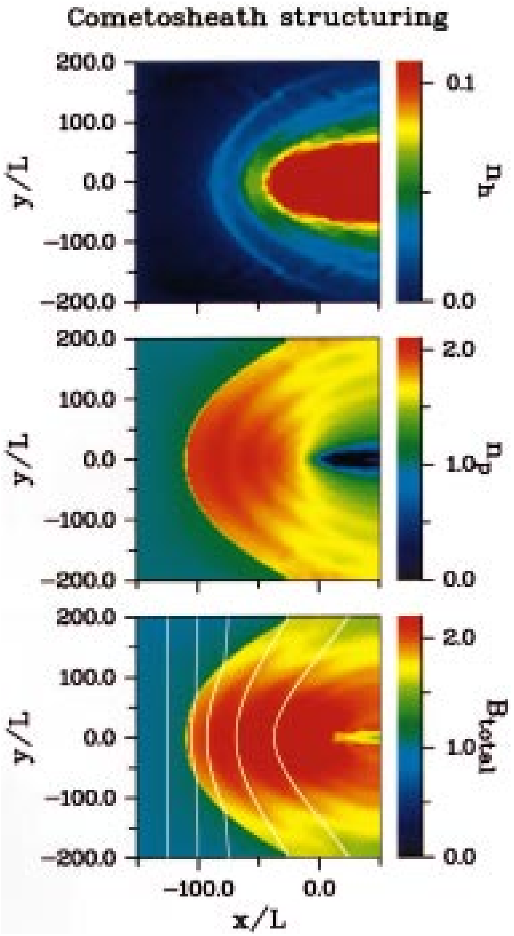

*Plate 1.* Cometosheath structuring seen in 2D bi-ion fluid simulations of SW interaction with a comet ($M_A = 2$, $Q_h \approx 10^{27}$ s$^{-1}$). From top to bottom: heavy ion density, proton density and magnetic field (magnitude and field lines). The structures are caused by bi-ion waves and are not aligned with the draped field lines. The distances are normalized to the proton skin length ($L \approx 100$ km).

## 3. Summary

The purpose of this contribution was not directly to compare ground-based observations of plasma structuring in the cometosheath and in the tail with results of bi-ion fluid simulations. Especially, for such bright comets as comet Hale–Bopp it was, the required grid sizes which are determined by the wavelength of excited bi-ion waves set strong limits to the production rates allowed. Our intention was rather to draw the reader's attention to a structuring mechanism which seems to be of basic importance in the solar wind-comet interaction. It consists in the generation of bi-ion waves in the coupling process between the two fluids of SW protons and cometary ions. In our simulations, periodical structures were seen with

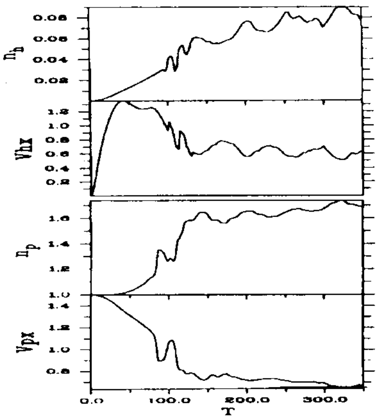

*Figure 2.* Temporal evolution of the densities and velocities of protons and cometary ions in the point (0, 75).

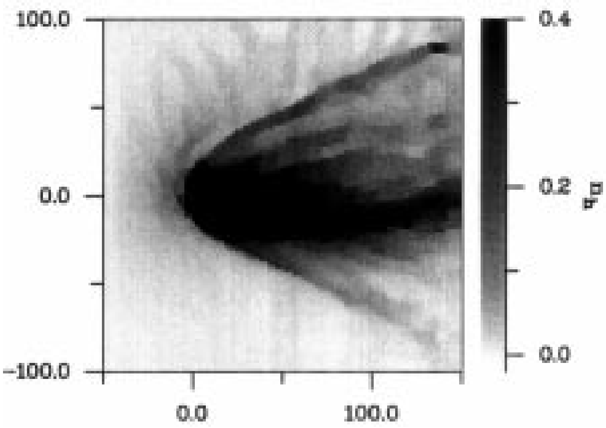

*Figure 3.* Two-dimensional distribution of cometary ions in the simulation run with $M_A = 5$.

scales ranging from about 2000 km (2D simulations) up to several $10^4$ km (1D studies). It should be pointed that the comet exerts a double function: ion source and obstacle. Due to a wide-ranging neutral gas atmosphere comets represent a largely extended source of heavy ions which become implanted into the solar wind. So, a bi-ion flow is created and somewhere inside the bow shock, where the mass density of heavies reaches that of the protons, both ion fluids participate equally in further mass-loading. This region is especially predestined for electromagnetic coupling processes which are accompanied by an excitation of bi-ion waves and related plasma structuring. It should also be mentioned that similar processes may appear near other objects in space which are surrounded by an extended exosphere/ionosphere, such as Mars and Venus where tail rays (Brace et al., 1987; Dubinin et al., 1991) and magnetosheath structuring (Dubinin et al., 1996) were discussed. Concerning tail rays, from our studies we suggest that some of these may be interpreted as multiple Mach-cones caused by the interaction of the bi-ion flow with cometary obstacle. Of course, our two-dimensional bi-ion fluid approach can only be considered as a first step in describing the main processes. Other studies, like the analysis of stationary non-linear solutions (bi-ion solitons etc.) and 3D bi-ion fluid simulations (Fischer et al., 1988) would be helpful towards a better understanding of the fascinating plasma phenomena at comets.

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