Multi-Ion Space Plasma Research:
Two highlights

I. Plasma structures and boundaries in solar wind interaction with non-magnetized bodies

II. Origin of coherent large-amplitude waves in multi-ion space plasmas

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Multi-Ion Space Plasma Research:
I. Plasma structures and boundaries in solar wind interaction with non-magnetized bodies

Comet Hale-Bopp
Multi-Ion Space Plasma Research:

I. Plasma structures and boundaries in solar wind interaction with non-magnetized bodies

- Introduction:
  - History of Mars Plasma Research
- Two-fluid model of interaction
- Numerical results
- The MPB at Mars - a new type of plasma boundary
- Implications to ROSETTA, MARS-EXPRESS and CASSINI

Ion acoustic waves in an Ar-He plasma

Theory: Fried et al., 1971; Experiment: Tran and Coquerand, 1976

Left: experimental wave pattern for different concentration $\alpha$. The interference pattern for $\alpha = 30\%$ is due to the super-position of the two wave modes.

Right: phase velocity of the two ion-acoustic modes versus the concentration $\alpha$
Dust-acoustic waves in a Q machine
(Barkan et al., 1996)

Dust-acoustic waves (Rao, Shukla and Yu; 1990):

\[ v_{pb} = \sqrt{\frac{k(T_p + T_d)}{m_p n_p}} n_d Z^2 \]

Differential streaming between protons and \( \alpha \)-particles in the solar wind

Helios: Marsch et al., 1982
Ulysses: Neugebauer et al., 1994, 1996
Wind: Steinberg et al., 1996

\[ V_{\alpha p} = |v_p - v_\alpha| \]

Temporal variation of \( V_{\alpha p} \) for one week of Ulysses data (Neugebauer et al., 1996).
Solar wind interaction with Mars, Venus and comets

Solar wind parameters:
- \( v_p \approx 500 \text{ km/s} \)
- \( n_p \approx 5 \text{ cm}^{-3} \)
- \( B \approx 5 \text{ nT} \)
- \( T_e \approx 10 \text{ eV} \)

Dynamic solar wind and comet observation by Lasco on SOHO
The cometary plasma boundaries

BS: Bow Shock
MPB: Magnetic Pile-up Boundary
IP: Ionopause

Halley: \( Q \approx 10^{30} \text{s}^{-1} \)

SW proton cavity
cometosheath
magnetic pile-up region
magnetic cavity

ICB

Plasma boundaries at comets and Mars

Halley
BS
MPB
IP

MARS
Scientific aspects of solar wind - Mars interaction

Study of fundamental processes of plasma-plasma interaction which are relevant for many other situations: comets, moons (Titan), asteroids, Pluto, dust rings, etc.

Mars dehydration:
loss of water by solar wind - atmosphere coupling;
1-10 m of surface water in 4.5 billion years.

Space weather: generation of high energetic particles, especially by CMEs (no shielding by an intrinsic magnetic field).

Mars Express: ASPERA-3 will do global imaging and in-situ measurements of:
- Inflow — solar wind
- Outflow — planetary wind

using
Energetic neutral atom cameras and plasma (ion+electron) spectrometers

Solar wind scavenging of the martian atmosphere => dehydration
Scientific aspects of solar wind - Mars interaction

Study of **fundamental processes of plasma-plasma interaction** which are relevant for many other situations: comets, moons (Titan), asteroids, Pluto, dust, etc.

**Mars dehydration:**
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History of Mars Plasma Research

Our present view
Mars-2 observations in 1972
(Dolginov and Gringauz, 1972)

The spacecraft crossed the bow shock (BS) and the obstacle boundary (magnetopause = MP)

Variation of the magnetic field $B$ and the electron current $I_e$ at crossing the bow shock (BS) and the obstacle boundary (magnetopause = MP)
Obstacle boundary in classical MHD models

The solar wind dynamic pressure is balanced by

- **Ionospheric thermal pressure:**
  \[ \rho v^2 = n_e k T_e \]  
  (Ionopause)
  For \( T_e \approx 1 \text{ eV} \), a density of \( n_e \geq 10^4 \text{ cm}^{-3} \) is required. The ionosphere of Mars is not dense enough to reach such a density at about 500 km where the obstacle boundary is observed. Therefore, the observed boundary is not an Ionopause.

- **Intrinsic magnetic pressure:**
  \[ \rho v^2 = \frac{B^2}{2 \mu_0} \]  
  (Magnetopause)
  From the observed location of the obstacle boundary in a subsolar height of about 500 km a magnetic moment of Mars of about \( M \geq 10^{12} \text{ T} \cdot \text{m}^3 \) was estimated.

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History of the Mars magnetic moment 1965 - 2000

From position and shape of the obstacle boundary (MP) a magnetic moment of \( M \geq 10^{12} \text{ T} \cdot \text{m}^3 \) was estimated.
The Phobos-2 mission in 1989

The spacecraft approached Mars down to about 850 km during 4 elliptical orbits, nearly one month in a circular orbit, approached the Phobos moon up to 200 km.

It was equipped with important instruments for plasma research: magnetometer (MAGMA, FGMM), electron and ion spectrometers (ASPERA, TAUS), sounders for low- and high-frequency plasma waves.

Observation of the Ion Composition Boundary (ICB) by Phobos-2

Signatures of the ICB:
- SW proton density decreases
- electron density \( n_e \) sharply increases which -because of charge neutrality - means an abrupt increase of the planetary ion density: Protons are replaced by heavy ions.
Observation of the MPB/ICB in large distances by Phobos-2 (1989) (≥20 000 km)

Jump of the magnetic field:
- MPB

Change of ion composition:
- SW protons outside
- planetary ions (oxygen) inside
**Phobos-2 observations of the Ion Composition Boundary**

![Graph showing Ion Composition Boundary (ICB)](image1)

**Mars Global Surveyor - its contribution to Mars plasma research**

![Graph showing BS orbit and MGS orbit](image2)

**Most important:**
MGS went down to Mars up to about 150 km. The spacecraft carries a magnetometer and an electron spectrometer. It crossed the ionopause and from the measured magnetic field a moment of $M \approx 10^{11} \text{Tm}^3$ was determined. This value is more than one order of magnitude weaker than estimated before.
The Magnetic Pile-up Boundary at Mars and comet Halley

First attempts to find the ICB in two-ion fluid simulations

1D two-ion fluid simulations with lateral effects
First attempts to find the ICB in two-ion fluid simulations

Plasma boundaries at Mars discovered by the Phobos 2 magnetometers


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ABSTRACT. ....This boundary is interpreted as a multi-ion contact discontinuity where the protons are deflected by the Lorentz force arising from the relative motion between both ion fluids. The magnetic field penetrates the ICB.

Annales Geophysicae, 1990, 8 (10), 661-670.

Indication of three plasma boundaries from the Phobos-2 observations; 1D bi-ion fluid simulations with lateral effects

Further steps in two-ion fluid simulations

First theoretical evidence of an Ion Composition Boundary (ICB) in 2D simulations of solar wind massloading.

(The protonopause - an ion composition boundary in the magnetosheath of comets, Venus and Mars; Sauer et al., GRL)

Improved 2D two-ion fluid model (inclusion of thermal effects) showing the Magnetic Pile-up Boundary (MPB) at the same location as the ICB.

(The nature of the Martian obstacle boundary; Sauer and Dubinin, Adv. Space Res.)

Theoretical methods for describing multi-ion plasmas

**Linear theory:**
Dispersion of LF multi-ion waves (fluid and kinetic models)

**Numerical simulations:**
(1) 1D and 2D bi-ion fluid simulations
(2) 1D and 2D bi-ion hybrid code simulations

**Stationary nonlinear waves:**
Oscillitons - a new type of solitary structure, origin of coherent waves

The two-ion fluid Hall-MHD model

**Protons** (p) and **heavy ions** (h) are considered as separate fluids which are coupled by electromagnetic forces

Electrons are massless

Charge neutrality: \( n_e = n_p + n_h \)

No collisions

The system of basic equations consists of:
- 2 continuity equations
- 2 momentum equations
- Faraday’s law
- Energy equation for electrons
Solar wind flow through an heavy-ion cloud, simple model of electrostatic interaction

The interaction strongly depends on the \textbf{Mach number} of the incoming plasma flow.
Solar wind flow through an heavy-ion cloud: simple model of electrostatic interaction

Supersonic flow: $M_s = 2.0$

Subsonic flow: $M_s = 0.5$

The flow is accelerated within the cloud: Laval nozzle effect
Solar wind flow through an heavy-ion cloud: hybrid code simulations

**Sub-Alfvénic flow:**
\[ M_A = 0.1 \]

The flow is accelerated within the cloud.

Motschmann, Sauer and Roatsch, 1992

Fluid description in the mass-less electron approximation

\[
\frac{\partial}{\partial t} \left( n_p \mathbf{v}_p \right) + \nabla \cdot \left( n_p \mathbf{v}_p \mathbf{v}_p + \frac{P_p}{m_p} \right) = \frac{e n_p}{m_p} \left( \mathbf{E} + \mathbf{v}_p \mathbf{xB} \right)
\]

Ampere's law is used to eliminate \( v_e \):

\[
\nabla \times \mathbf{B} = -\mu_0 \mathbf{j}
\]

Electron-proton plasma:
\[
\mathbf{v}_e = \mathbf{v}_p - \frac{1}{\mu_0 e n_e} \nabla \times \mathbf{B}
\]

Charge neutrality: \( n_e = n_p \)

Two-ion plasma:
\[
\mathbf{v}_e = \frac{n_p \mathbf{v}_p + n_h \mathbf{v}_h}{n_e} - \frac{1}{\mu_0 e n_e} \nabla \times \mathbf{B}
\]

Charge neutrality: \( n_e = n_p + n_h \)
Equation of motion in single- and two-ion fluid description

Single-ion (proton) plasma

\[
\begin{align*}
\frac{\partial}{\partial t} \left( n_p m_p \mathbf{v}_p \right) + \nabla \cdot \left( n_p m_p \mathbf{v}_p \mathbf{v}_p + P_p \right) &= \\
&= - \nabla \left( P_e + \frac{B^2}{2 \mu_0} \mathbf{I} - \frac{BB}{\mu_0} \right)
\end{align*}
\]

Two-ion plasma

\[
\begin{align*}
\frac{\partial}{\partial t} \left( n_pm_p \mathbf{v}_p \right) + \nabla \cdot \left( n_p m_p \mathbf{v}_p \mathbf{v}_p + P_p \right) &= \\
&= \frac{n_e}{n_e} \left[ e \mathbf{n}_h (\mathbf{v}_p - \mathbf{v}_h) xB - \nabla \left( P_e + \frac{B^2}{2 \mu_0} \mathbf{I} - \frac{BB}{\mu_0} \right) \right]
\end{align*}
\]

gyro-radius effects

Magnetic field equation

Faraday’s law:

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0
\]

\[
\mathbf{E} = -\frac{1}{e n_e} \nabla P_e - \mathbf{v}_e xB
\]

Single-ion plasma

\[
\mathbf{v}_e = \mathbf{v}_p - \frac{1}{\mu_0 e n_e} \nabla \times \mathbf{B}
\]

Two-ion plasma

\[
\mathbf{v}_e = \frac{n_p \mathbf{v}_p + n_n \mathbf{v}_n}{n_e} - \frac{1}{\mu_0 e n_e} \nabla \times \mathbf{B}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \left[ \frac{1}{n_e} \left( n_p \mathbf{v}_p + n_n \mathbf{v}_n \right) xB - \frac{B \times \nabla B}{\mu_0} \right] = 0
\]

Hall term

charge neutrality: \( n_e = n_p + n_n \)
The two-ion Hall-MHD equations

Continuity and momentum equations of protons and heavies
\( p \rightarrow h, h \rightarrow p \)

\[
\frac{\partial}{\partial t} n_p + \nabla \cdot (n_p \mathbf{v}_p) = 0
\]

\[
\frac{1}{m_p} n_p \left( \frac{\partial}{\partial t} (n_p \mathbf{v}_p) + \nabla \cdot (n_p \mathbf{v}_p \mathbf{v}_p + P_p / m_p) \right) = \varepsilon n_h (\mathbf{v}_p - \mathbf{v}_h) \mathbf{x}_B - \nabla \left( (P_p + \frac{B^2}{2\mu_0}) \mathbf{I} - \frac{\mathbf{B} \cdot \mathbf{B}}{\mu_0} \right)
\]

Faraday's law

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot \left( \frac{1}{\mu_0} (n_p \mathbf{v}_p + n_h \mathbf{v}_h) \mathbf{x}_B - \mathbf{B} \cdot \mathbf{V}_B \right) = 0
\]

Electron energy equation

\[
\frac{\partial}{\partial t} P_e + \nabla \cdot (P_e \mathbf{v}_e) + (\gamma - 1) P_e \nabla \cdot \mathbf{v}_e = 0
\]

with
\[
\rho_a = n_p + n_h
\]
\[
\mathbf{v}_e = \frac{n_e \mathbf{v}_e + n_p \mathbf{v}_p}{n_e + n_p}
\]
\[
\mathbf{v}_h = \mathbf{v}_h + \frac{\mathbf{x}_B}{n_h \mu_0}
\]

2D hybrid simulation of solar wind - comet interaction

Magnetic field

Solar wind

Heavy ion source: weakly outgassing comet (Wirtanen at 3 AU)

Lipatov and Sauer, 1997
Comparison between two-ion fluid and hybrid code simulations

Interaction of the solar wind with a weak comet (Wirtanen at 3 AU)

M_A=10, Q_h=10^{26} \text{s}^{-1}

Bagdonat and Motschmann, 2003

Sauer et al., 1996

Plasma structures for three mass-loading regimes

weak comet: \( Q<10^{26}\text{s}^{-1} \)

increased p. rate: \( Q\geq 10^{26}\text{s}^{-1} \)

comet like G-S: \( Q\geq 10^{27}\text{s}^{-1} \)

Formation of a proton cavity

Sauer and Dubinin, 1999
Two-fluid modeling of solar wind interaction with the Martian exospheric plasma

A proton cavity is formed. At the boundary separating solar wind protons from exospheric oxygen ions (ICB = Ion Composition Boundary) the magnetic field piles up (MPB)

Sauer and Dubinin, 1999

Comparison between Phobos-2 observations and two-fluid modeling (elliptical orbit)
Comparison between Phobos-2 observations and two-fluid modeling (circular orbit)

Hybrid simulations: Formation of a proton cavity

Lipatov and Sauer, 1997
3D hybrid simulations of SW interaction with unmagnetized planets

Planetary ions are distributed over a sphere, no ionospheric profiles: Shimazu, 2001

Important results:

(1) Formation of an ICB

(2) Multiple shock-structure

(3) Plasma acceleration at the flanks

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3D hybrid simulations of solar wind - Mars interaction

(Bößwetter, Bagdonat, Motschmann - TU Braunschweig
K. Sauer - MPAe; 2004)

Main signatures of interaction are seen. Location of BS and MPB/ICB are in good agreement with the observations.
The Ion Composition Boundary (ICB) - a new type of plasma boundary

A shock is formed if the "supersonic" flow goes through the "sonic point":
\[ v = v_s \]

ICB

An ICB is formed if the "subsonic" two-ion flow becomes accelerated and goes through the "generalized sonic point":
\[ v = v_s (n_p, n_h, v_h, \beta_e, ...) \]

Formation of a proton cavity in a subsonic flow

heavy-ion cloud:
\[ n_s \leq 1.5 n_p^0 \]

proton flow
\( (M_s = 0.4) \)

Sauer et al., 1992
Plasma acceleration at the flanks of an impenetrable heavy-ion cloud

The subsonic plasma flow ($M_s = 0.4$) is accelerated and deflected by the heavy-ion cloud in regions where its density is about $0.2 n_{p0}$.

Two-fluid modeling of SW-heavy ion source interaction: $B=0$

Formation of a proton cavity

$M_s=4$

solar wind

heavy-ion source: $q=q_m \cdot \exp(-r^2/L^2)$
Observation of sharp boundaries in dusty plasmas under micro-gravity

(Annaratone et al., 2002)

Observation of sharp boundaries in dusty plasmas under micro-gravity

(Tsytovich et al., 2003)
Summary and conclusion

• The multi-fluid model is able to describe essential elements of solar wind interaction with non-magnetized bodies.

• The transition from very asymmetric plasma structures at weak comets to the magnetosphere of Mars with three well developed plasma boundaries (BS, ICB/MPB, IP) has been shown.

• The Ion Composition Boundary (ICB/MPB) at comets and Mars is a new type of plasma boundary which is formed in mass-loaded plasmas. It results from the momentum coupling between the two plasma populations at the “generalized sonic points“.

Summary and conclusion

The results have implications to future space missions:

• ROSETTA
  In-situ measurements near a (weak) comet at ~ 3AU.

• MARS/VENUS EXPRESS
  Plasma and neutral gas measurements with ASPERA-3.

• CASSINI
  New results about solar wind -Titan interaction.

• Beppi Colombo
  Mercury with its sodium atmosphere is an interesting multi-ion object.
Summary and conclusion

• The work was done in the project “Mars, Kometen, kleine Körper“
• ~25 publications in 2000-2003
• Low costs: ≤ 2 000 EU per annum
  (contacts to ISSI, CNRS, JPL)