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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

K. Sauer*

Max-Planck-Institut für Aeronomie, KatlenburgLindau, Germany

*** in close cooperation with E. Dubinin (MPAe) and partly with A. Lipatov and J. McKenzie**

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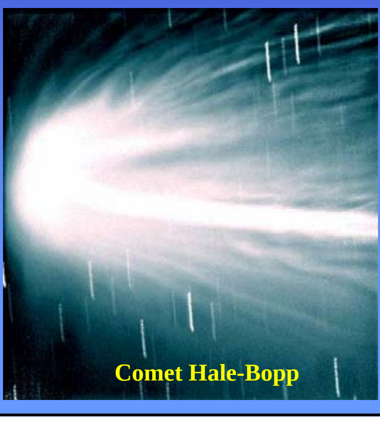
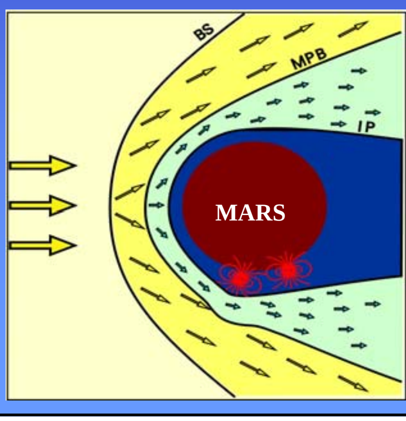
Multi-Ion Space Plasma Research:

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



Comet Hale-Bopp



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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**

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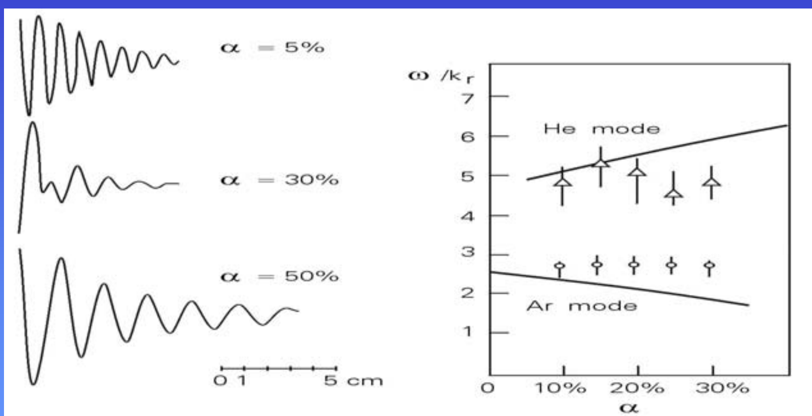
Ion acoustic waves in an Ar-He plasma

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



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

Right: phase velocity of the two ion-acoustic modes versus the concentration α

Dust-acoustic waves in a Q machine
(Barkan et al., 1996)

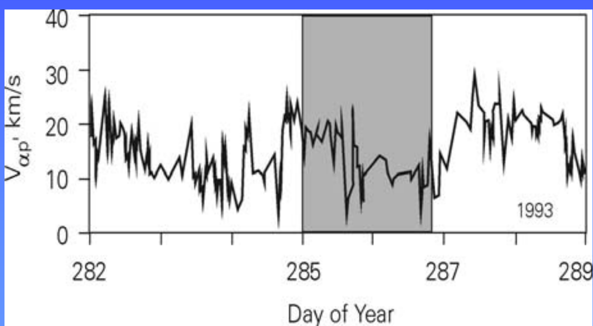
Dust-acoustic waves (Rao, Shukla and Yu ;1990):

$$v_{ph} = \sqrt{\left(\frac{k(T_e + T_i)}{m_d} \frac{n_d}{n_p} Z^2\right)}$$

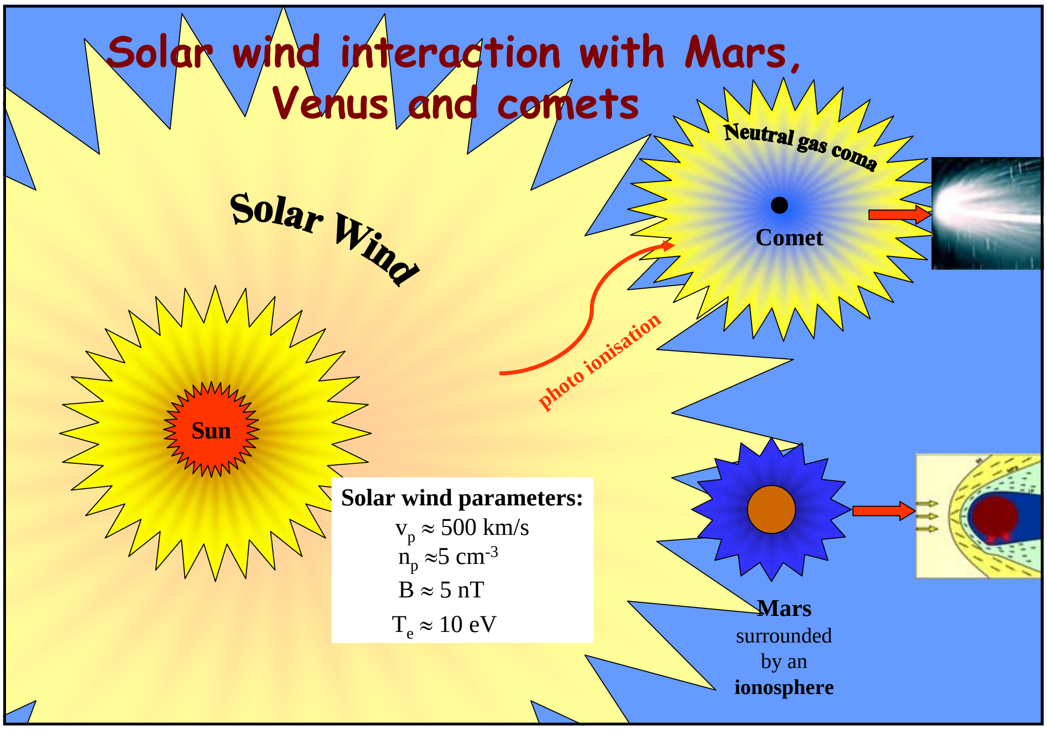
Differential streaming between protons and α-particles in the solar wind

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

$V_{\alpha p} = |\mathbf{v}_p - \mathbf{v}_\alpha|$



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
Neutral gas coma
Comet
photo ionisation
Sun
Solar wind parameters:
v_p ≈ 500 km/s
n_p ≈5 cm^-3
B ≈ 5 nT
T_e ≈ 10 eV
Mars
surrounded
by an
ionosphere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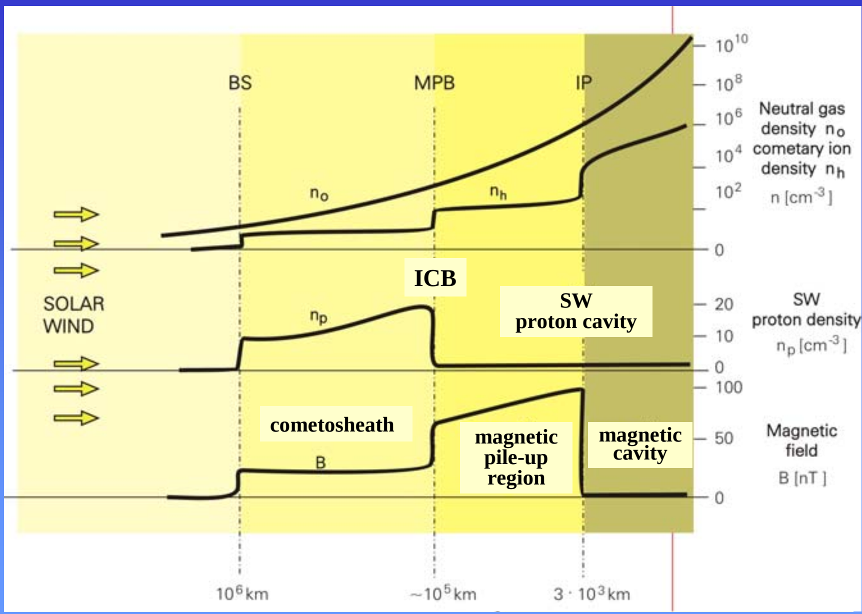
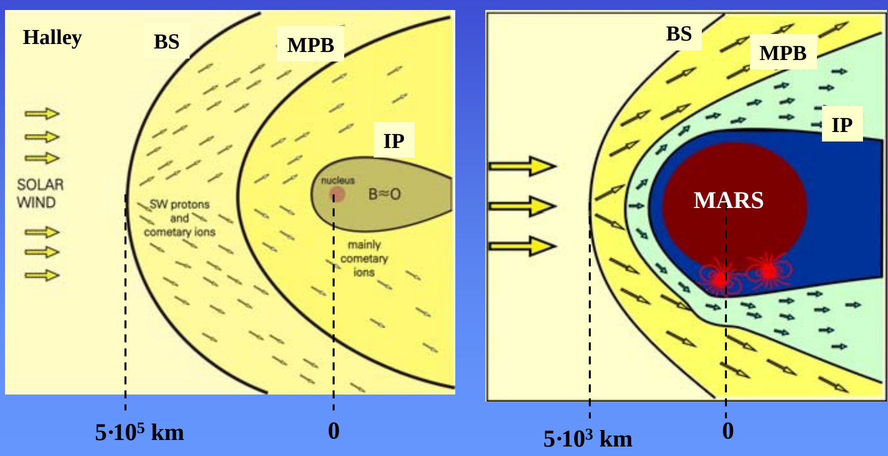
Dynamic solar wind and comet observation by Lasco on SOHO
C3 1996/04/30 01:35

The cometary plasma boundaries



Plasma boundaries at comets and Mars



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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).

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Solar wind scavenging of the martian atmosphere => dehydration

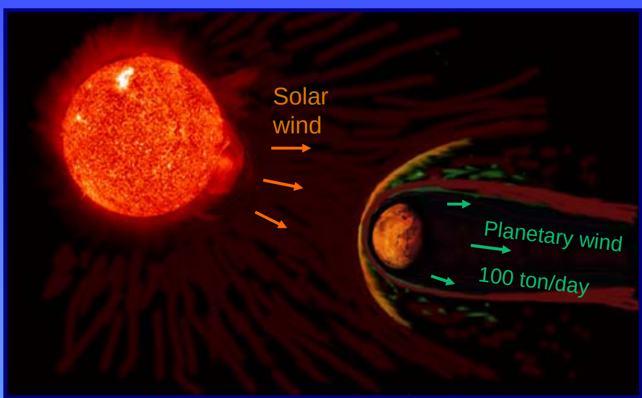
Mars Express: ASPERA-3 will do global imaging and *in-situ* measurements of:

Inflow — solar wind

Outflow — planetary wind

using

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



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Mars dehydration:
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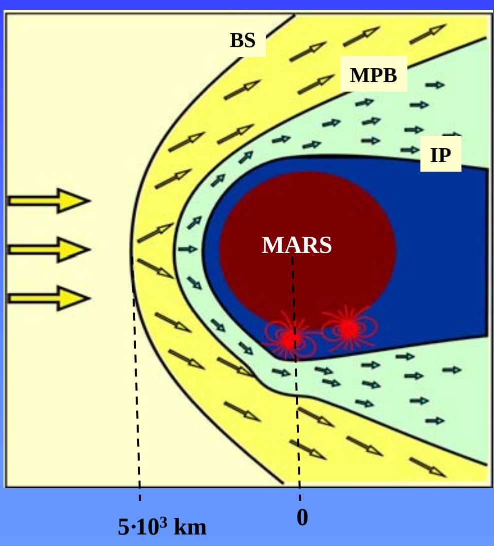
History of Mars Plasma Research



Our present view

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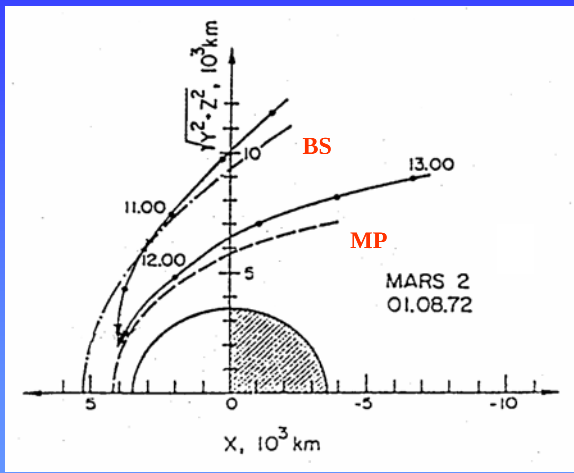
Mars-2 observations in 1972

(Dolginov and Gringauz, 1972)



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

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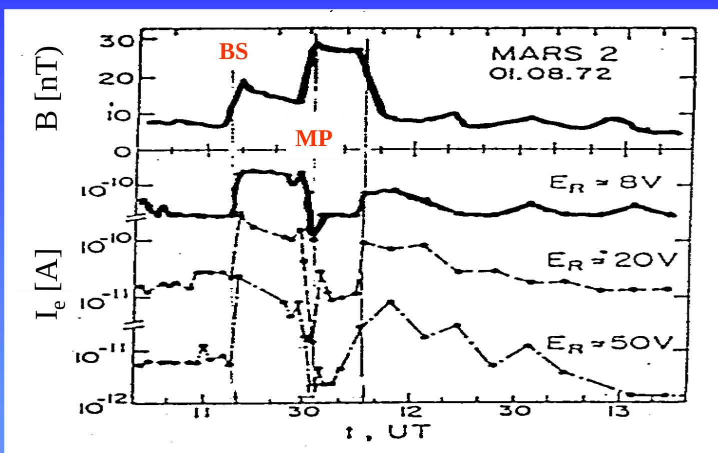
Mars-2 observations in 1972

(Dolginov and Gringauz, 1972)



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 $T_e \approx 1$ eV, a density of $n_e \geq 10^4$ 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:

$\rho v^2 = B^2/2\mu_0$

(Magnetopause)

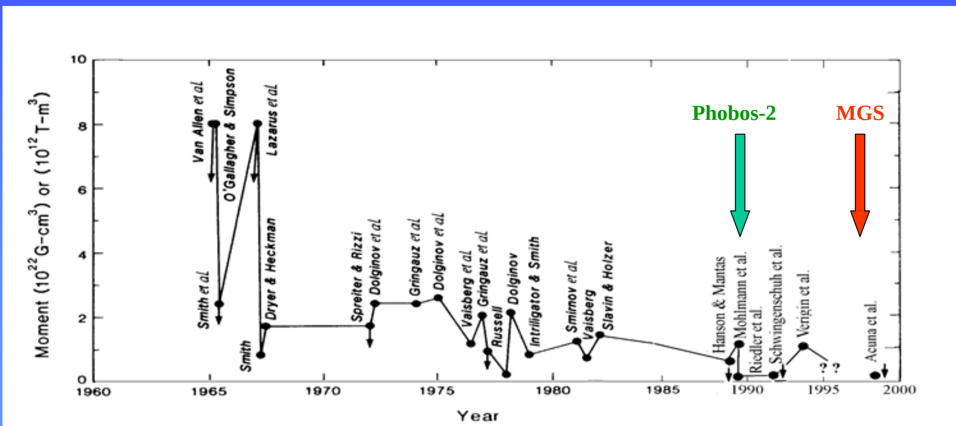
From the observed location of the obstacle boundary in a subsolar height of about 500 km a magnetic moment of Mars of about

$M \geq 10^{12}$ T·m^3

was estimated.

History of the Mars magnetic moment 1965 - 2000

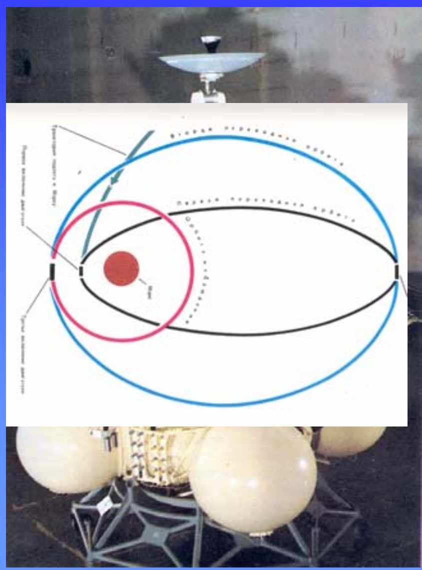
From position and shape of the obstacle boundary (MP) a magnetic moment of $M \geq 10^{12}$ T·m^3 was estimated.



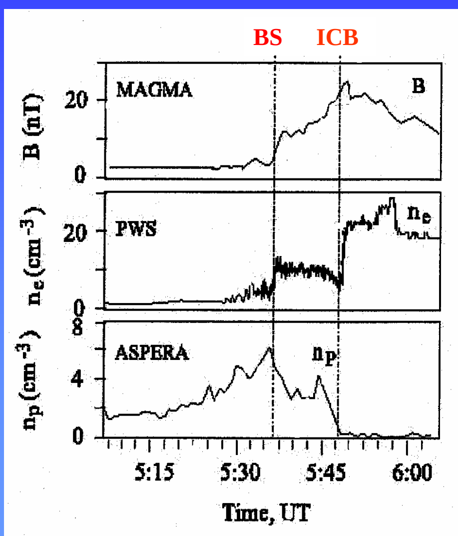
The Phobos-2 mission in 1989

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:

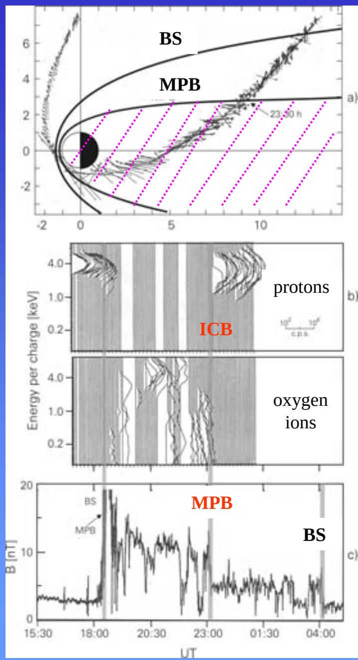
- SW proton density decreases
- electron density n_e sharply increases which -because of charge neutrality - means an abrupt increase of the planetary ion density: Protons are replaced by heavy ions.

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



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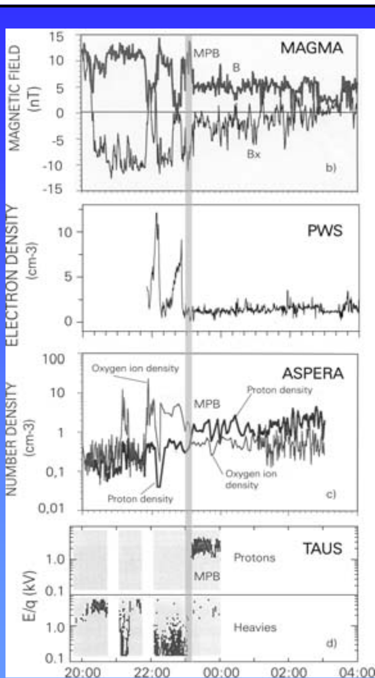
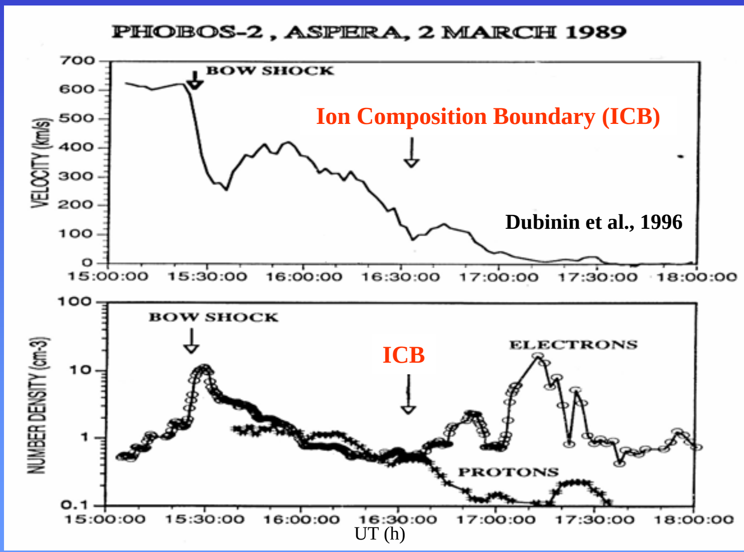
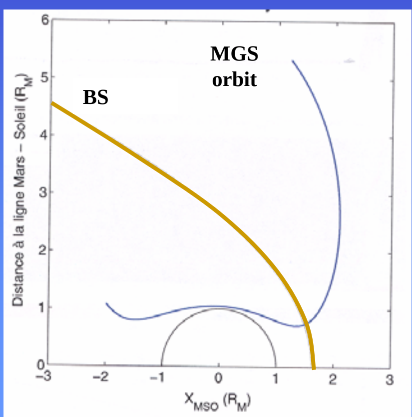


Phobos-2 observations of the Ion Composition Boundary



Mars Global Surveyor -

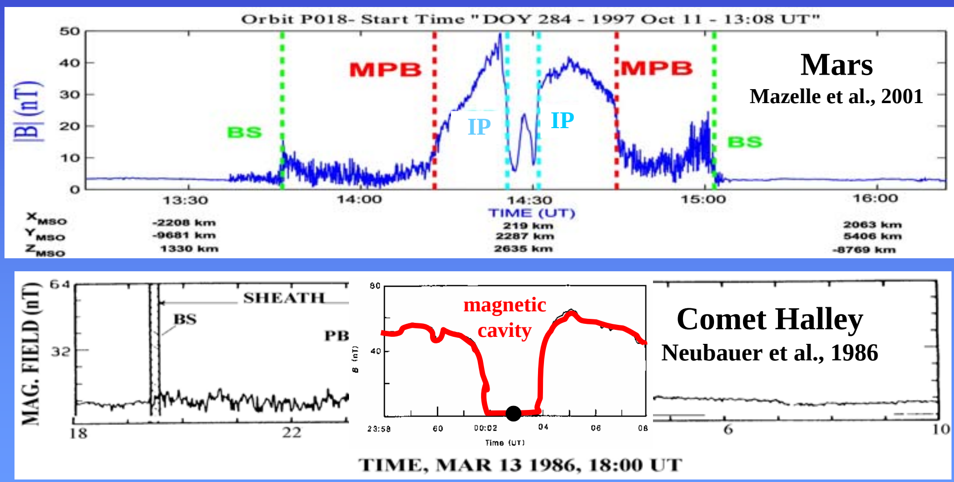
its contribution to Mars plasma research



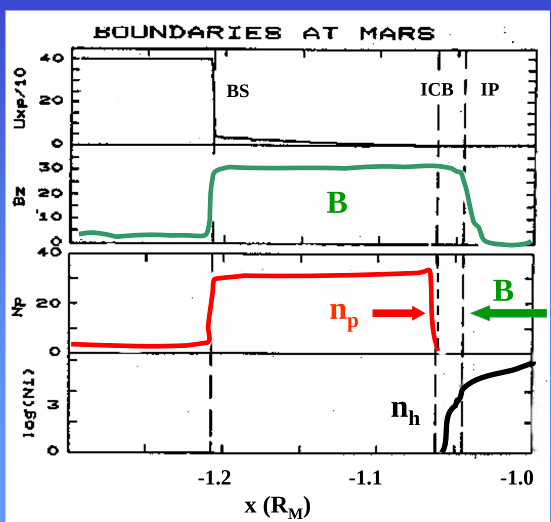
Most important:

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 $\approx 10^{11}$ T·m^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

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

1990

Plasma boundaries at Mars discovered by the Phobos 2 magnetometers

K. SAUER (1), TH. ROATSCH (1), U. MOTSCHMANN (1), D. MÖHLMANN (1), K. SCHWINGENSCHUH (2), and W. RIEDLER (2)

(1) *Institut für Kosmosforschung, Akademie der Wissenschaften der DDR, Rudower Chaussee 5, Berlin, DDR-1199*
(2) *Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Inffeldgasse 12, Graz, A-8010, Austria*

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

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Further steps in <u>two-ion</u> fluid simulations

1994

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*)

1999 (after MGS)

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.)*

2001-2003

Joint Phobos - MGS ISSI workshops: Mars book (Kluwer) + *Space Science Review* will be published in spring of 2004.

Theoretical methods for describing multi-ion plasmas

<u>Linear theory:</u>
Dispersion of LF multi-ion waves (fluid and kinetic models)

<u>Numerical simulations:</u>

(1) 1D and 2D bi-ion fluid simulations

(2) 1D and 2D bi-ion hybrid code simulations

<u>Stationary nonlinear waves:</u>
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 mass less

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

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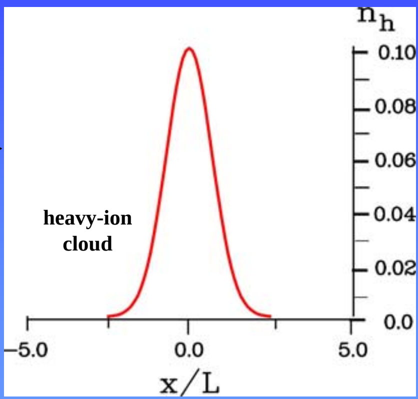
Solar wind flow though an heavy-ion cloud, simple model of electrostatic interaction

Situation at t=0:

solar wind

no magnetic field



cold ions, warm electrons:

$$\frac{\partial}{\partial t} n_p + \frac{\partial}{\partial x}(n_p v_{px}) = 0$$

$$\frac{\partial}{\partial t}(n_p v_{px}) + \frac{\partial}{\partial x}(n_p v_{px}^2) = \frac{e\, n_p}{m_p} E_x$$

$$\frac{\partial}{\partial t} n_h + \frac{\partial}{\partial x}(n_h v_{hx}) = 0$$

$$\frac{\partial}{\partial t}(n_h v_{hx}) + \frac{\partial}{\partial x}(n_h v_{hx}^2) = \frac{e\, n_h}{m_h} E_x$$

$$E = -\frac{1}{e\, n_e} \frac{\partial}{\partial x} p_e \qquad m_e = 0$$

$$\frac{\partial}{\partial t} p_e + \frac{\partial}{\partial x}(v_{ex} p_e) + (\gamma - 1) p_e \frac{\partial}{\partial x} v_{ex} = 0 .$$

$$n_e = n_p + n_h \qquad v_{ex} = (n_p v_{px} + n_h v_{hx})/n_e$$

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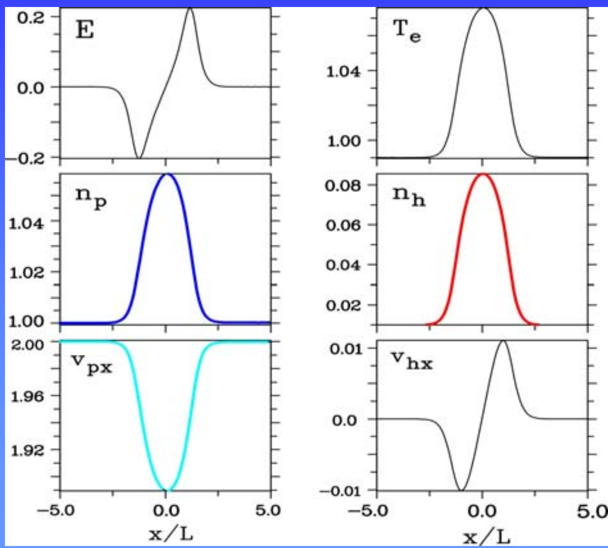
Solar wind flow though an heavy-ion cloud, simple model of electrostatic interaction

The interaction strongly depends on the **Mach number** of the incoming plasma flow

Solar wind flow though an heavy-ion cloud: simple model of electrostatic interaction

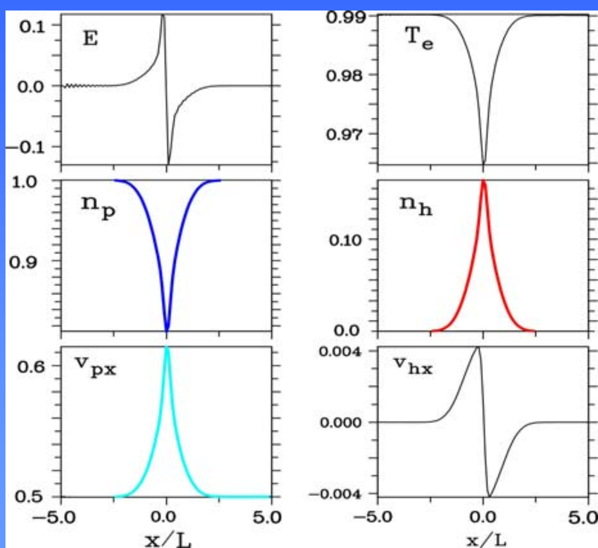
Supersonic flow:
$M_s = 2.0$



Solar wind flow though an heavy-ion cloud: simple model of electrostatic interaction

Subsonic flow:
$M_s = 0.5$

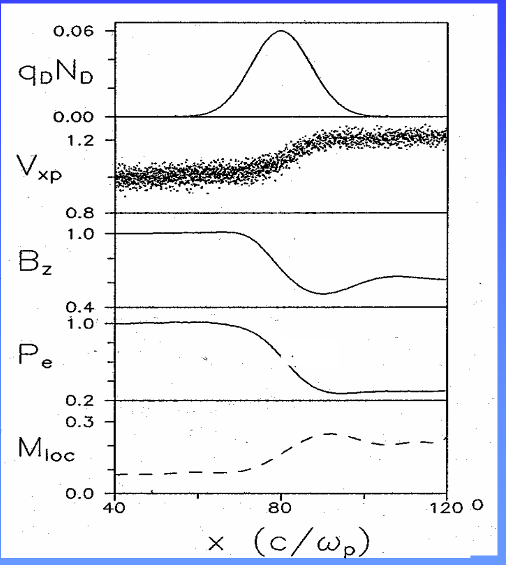
The flow is accelerated within the cloud: Laval nozzle effect



Solar wind flow though an heavy-ion cloud: hybrid code simulations

Sub-Alfvenic 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

$$\frac{\partial}{\partial t}(n_p \mathbf{v}_p) + \nabla \cdot (n_p \mathbf{v}_p \mathbf{v}_p + \frac{P_p}{m_p}) = \frac{e\, n_p}{m_p}(\mathbf{E} + \mathbf{v}_p \mathbf{x} \mathbf{B})$$

$$\mathbf{E} = -\frac{1}{e\, n_e} \nabla p_e - \mathbf{v}_e \mathbf{x} \mathbf{B}$$

approximation of mass-less electrons: $m_e=0$

Ampere‘s law is used to eliminate v_e

$$\nabla \mathbf{x} \mathbf{B} = -\mu_0 \mathbf{j}$$

$\mathbf{j} = -e\, n_e v_e + n_p v_p + n_h v_h$

Electron-proton plasma

$$\mathbf{v}_e = \mathbf{v}_p - \frac{1}{\mu_0\, e\, n_e} \nabla \mathbf{x} \mathbf{B}$$

charge neutrality: $n_e = n_p$

Two-ion plasma

$$\mathbf{v}_e = \frac{n_p \mathbf{v}_p + n_h \mathbf{v}_h}{n_e} - \frac{1}{\mu_0\, e\, n_e} \nabla \mathbf{x} \mathbf{B}$$

charge neutrality: $n_e = n_p + n_h$

Equation of motion in single- and two-ion fluid description

Single-ion (proton) plasma

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

Two-ion plasma

$$\frac{\partial}{\partial t}(n_p m_p \mathbf{v}_p) + \nabla\cdot(n_p m_p \mathbf{v}_p \mathbf{v}_p + P_p) = \frac{n_p}{n_e}\left[e\, n_h(\mathbf{v}_p - \mathbf{v}_h)\mathbf{x}\mathbf{B} - \nabla\left(\left(P_e + \frac{B^2}{2\mu_0}\right)\mathbf{I} - \frac{\mathbf{BB}}{\mu_0}\right)\right]$$

gyro-radius effects

charge neutrality: $n_e = n_p + n_h$

Magnetic field equation

Faraday's law:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \mathbf{x}\, \mathbf{E} = 0$$

$$\mathbf{E} = -\frac{1}{e\, n_e}\nabla p_e - \mathbf{v}_e \mathbf{x}\mathbf{B}$$

single-ion plasma

$$\mathbf{v}_e = \mathbf{v}_p - \frac{1}{\mu_0\, e\, n_e}\nabla \mathbf{x}\mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\mathbf{x}\left[\mathbf{v}_p \mathbf{x}\mathbf{B} - \frac{\mathbf{B}\cdot\nabla\mathbf{B}}{e\, n_e\, \mu_0}\right] = 0$$

Hall term

two-ion plasma

$$\mathbf{v}_e = \frac{n_p \mathbf{v}_p + n_h \mathbf{v}_h}{n_e} - \frac{1}{\mu_0\, e\, n_e}\nabla\, \mathbf{x}\mathbf{B}$$

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

charge neutrality: $n_e = n_p + n_h$

Hall term

The two-ion Hall-MHD equations

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

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

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

Faraday's law

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

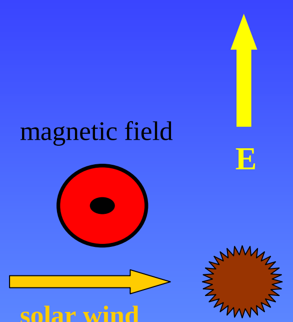
Electron energy equation

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

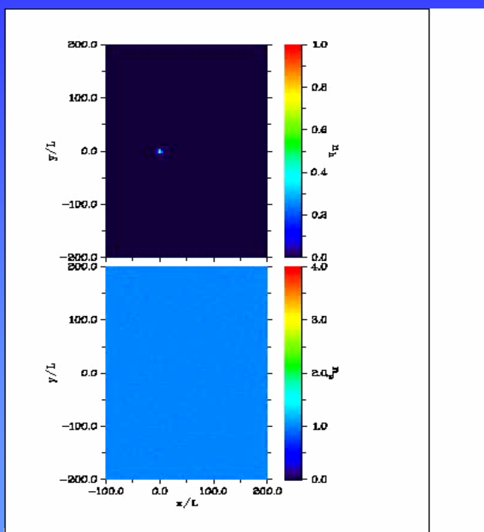
with

$$n_e = n_p + n_h , \qquad \mathbf{v}_e = \frac{n_p \mathbf{v}_p + n_h \mathbf{v}_h}{n_e} - \frac{\nabla \mathbf{x} \mathbf{B}}{n_e \mu_0}$$

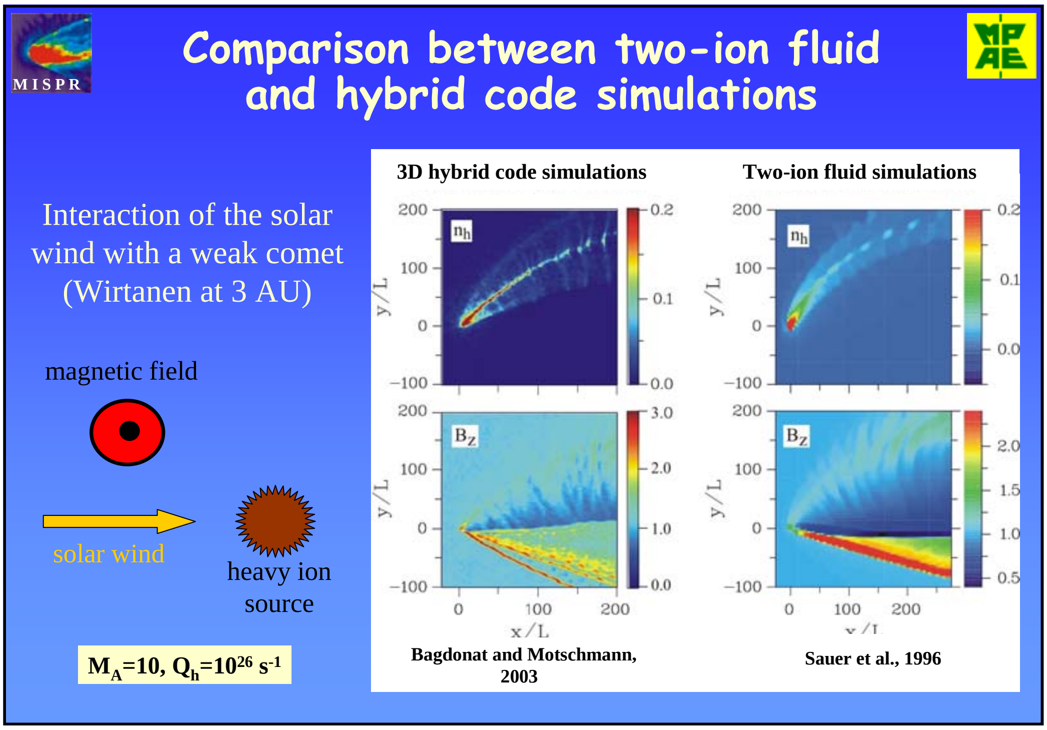
2D hybrid simulation of solar wind - comet interaction



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



Lipatov and Sauer, 1997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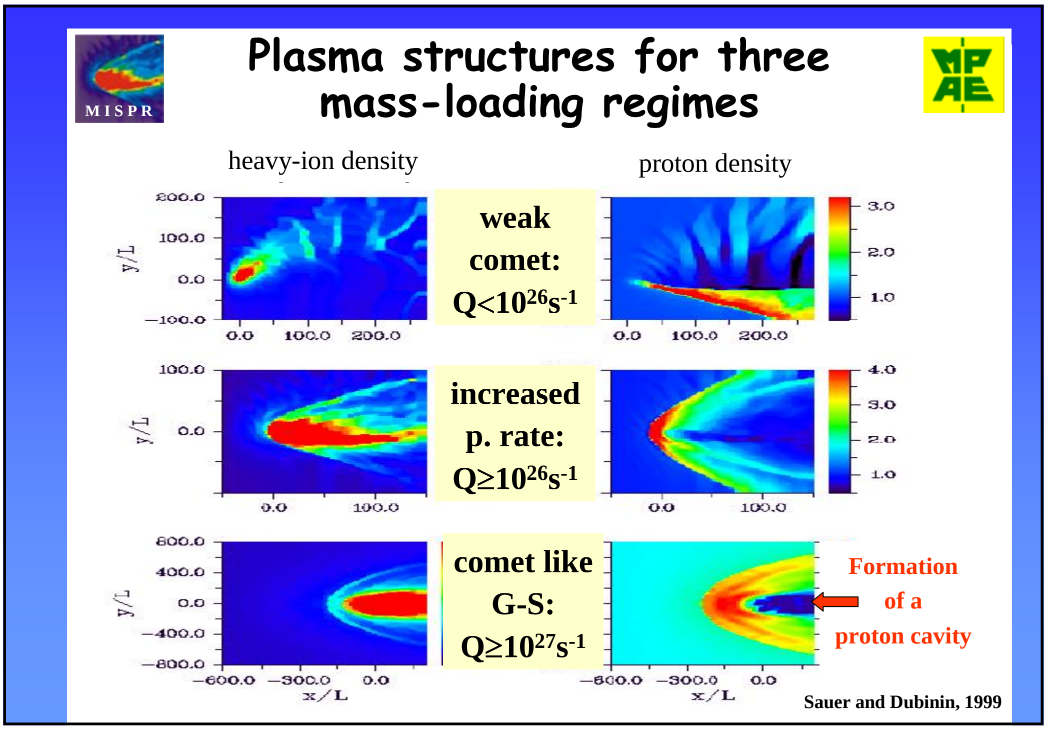
Comparison between two-ion fluid and hybrid code simulations
Interaction of the solar wind with a weak comet (Wirtanen at 3 AU)
magnetic field
solar wind
heavy ion source
M_A=10, Q_h=10^{26} s^{-1}
3D hybrid code simulations
Two-ion fluid simulations
n_h
B_z
y/L
x/L
Bagdonat and Motschmann, 2003
Sauer et al., 1996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Plasma structures for three mass-loading regimes
heavy-ion density
proton density
weak comet: Q<$10^{26}$$s^{-1}$
increased p. rate: Q≥$10^{26}$$s^{-1}$
comet like G-S: Q≥$10^{27}$$s^{-1}$
Formation of a proton cavity
y/L
x/L
Sauer and Dubinin, 1999

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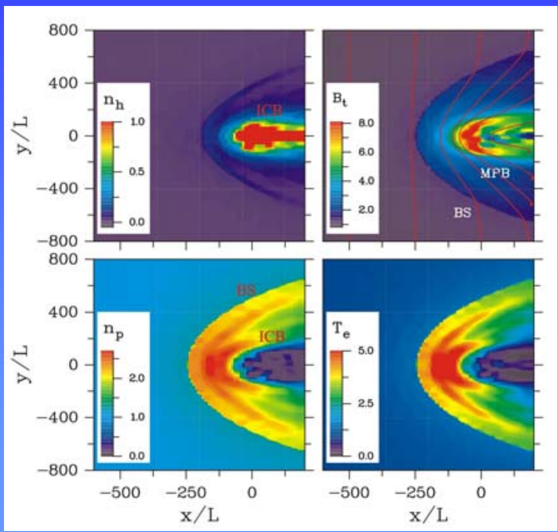
Two-fluid modeling of solar wind interaction with the Martian exospheric plasma



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

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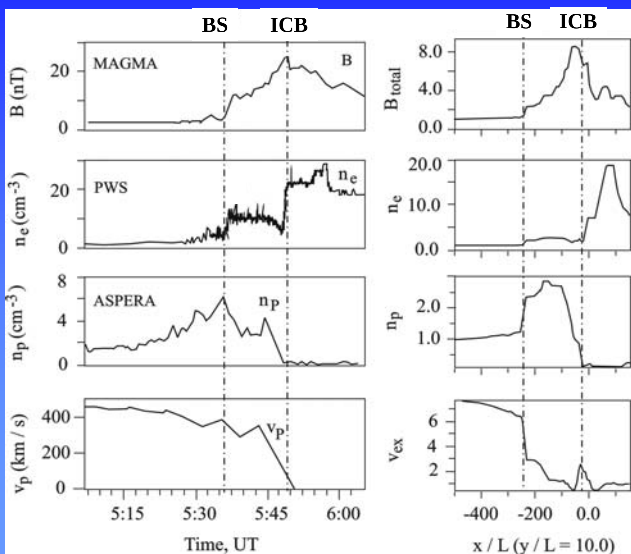
Comparison between Phobos-2 observations and two-fluid modeling

(elliptical orbit)

Phobos-2 observations | 2-fluid modeling



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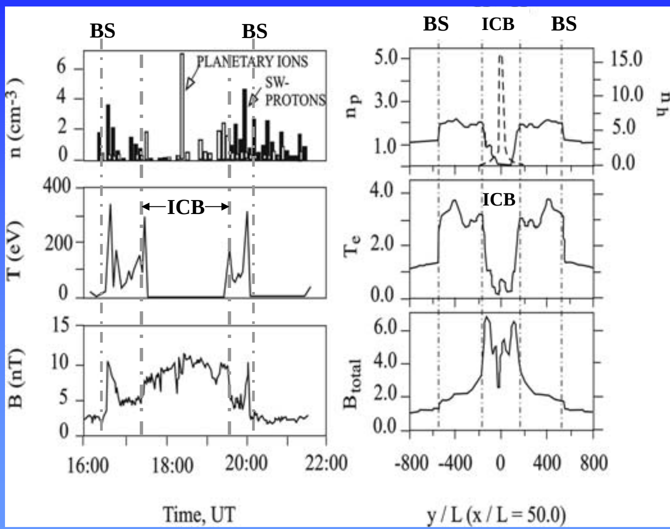
Comparison between Phobos-2 observations and two-fluid modeling (circular orbit)

Phobos-2 observations **2-fluid modeling**



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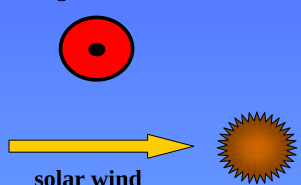
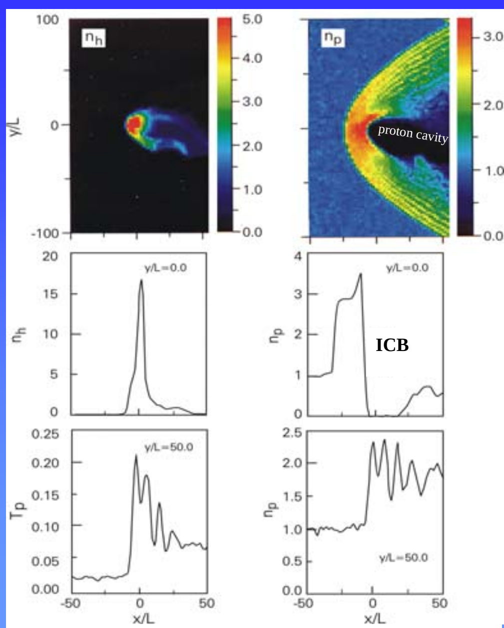
Hybrid simulations: Formation of a proton cavity

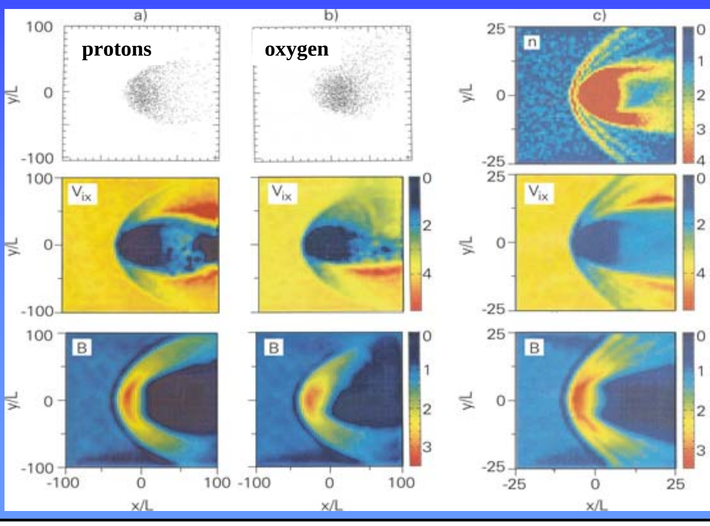




Lipatov and Sauer, 1997

3D hybrid simulations of SW interaction with unmagnetized planets

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



Important results:

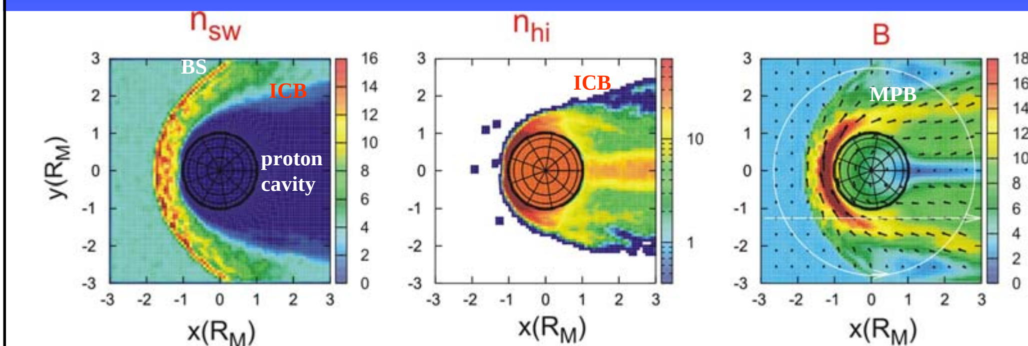
(1) Formation of an ICB

(2) Multiple shock-structure

(3) Plasma acceleration at the flanks

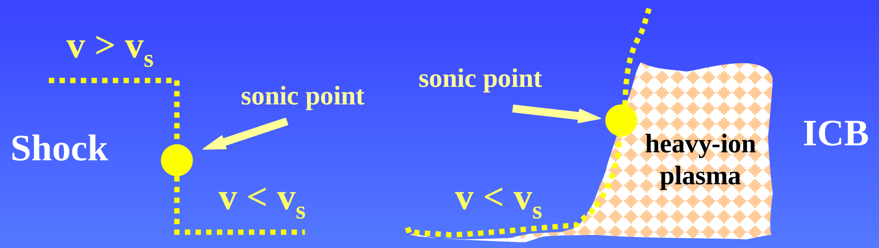
3D hybrid simulations of solar wind - Mars interaction

(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

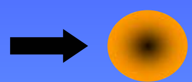


A <u>shock</u> is formed if the "<u>supersonic</u>" flow goes through the "sonic point": $v = v_s$

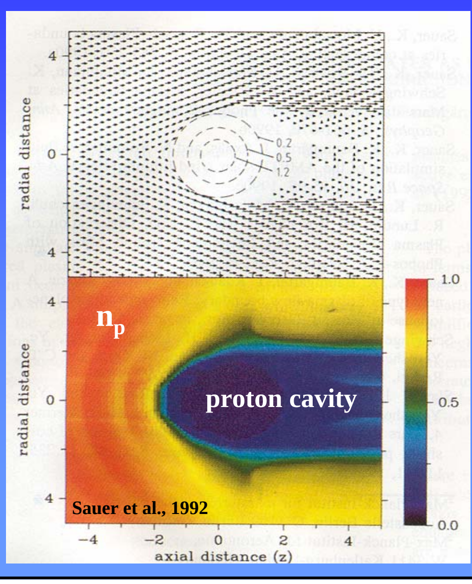
An <u>ICB</u> is formed if the "<u>subsonic</u>" two-ion flow becomes accelerated and goes through the "generalized sonic point": $v = v_s(n_p, n_h, v_h, \beta_e, \ldots.)$

Formation of a proton cavity in a subsonic flow

heavy-ion cloud: $n_h \leq 1.5\ n_{p0}$



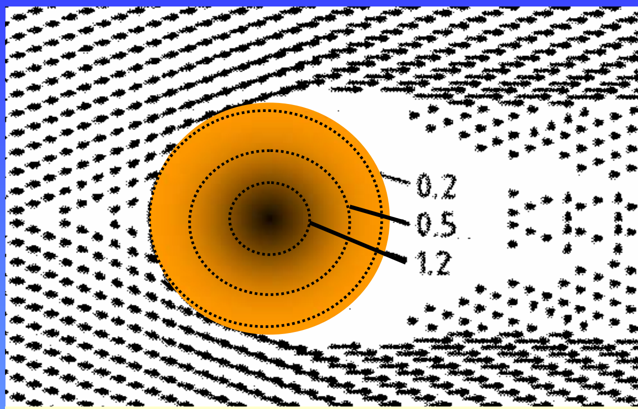
proton flow ($M_s = 0.4$)



Plasma acceleration at the flanks of an impenetrable heavy-ion cloud

heavy-ion cloud

proton flow (M_s= 0.4)



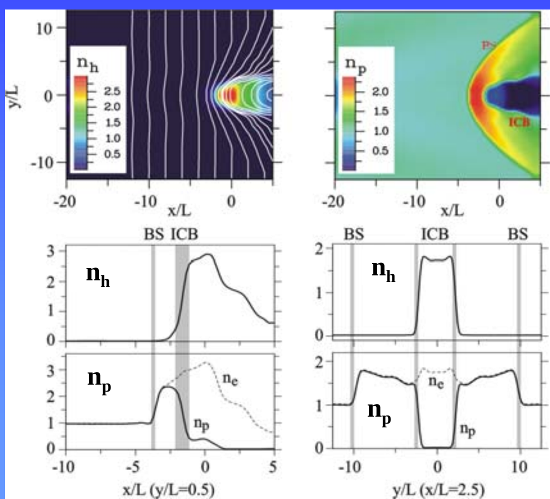
The subsonic plasma flow (M_s = 0.4) is accelerated and deflected by the heavy-ion cloud in regions where its density is about 0.2 n_{p0} .

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

M_s=4

solar wind

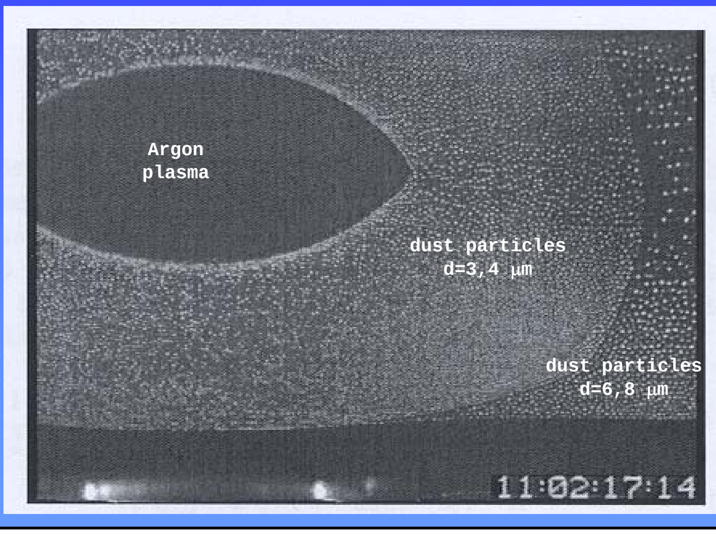
heavy-ion source: $q=q_m \cdot exp(-r^2/L^2)$



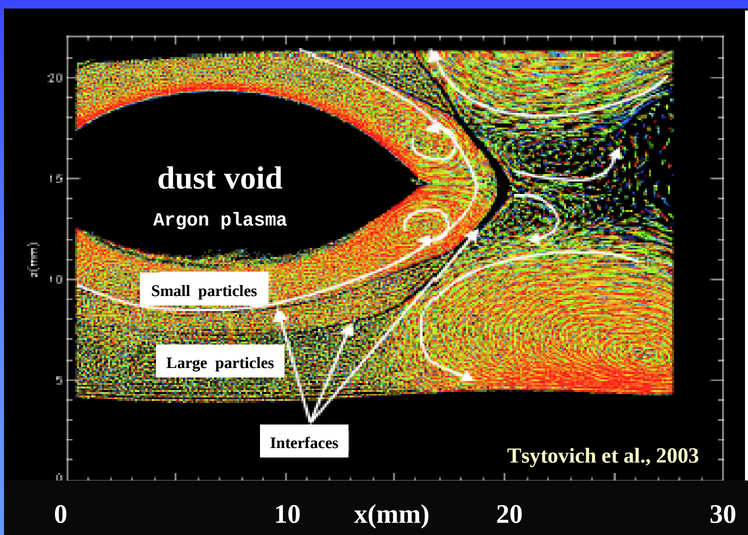
Formation of a proton cavity

Observation of sharp boundaries in dusty plasmas under micro-gravity

(Annaratone et al., 2002)



Observation of sharp boundaries in dusty plasmas under micro-gravity



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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“.

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Summary and conclusion

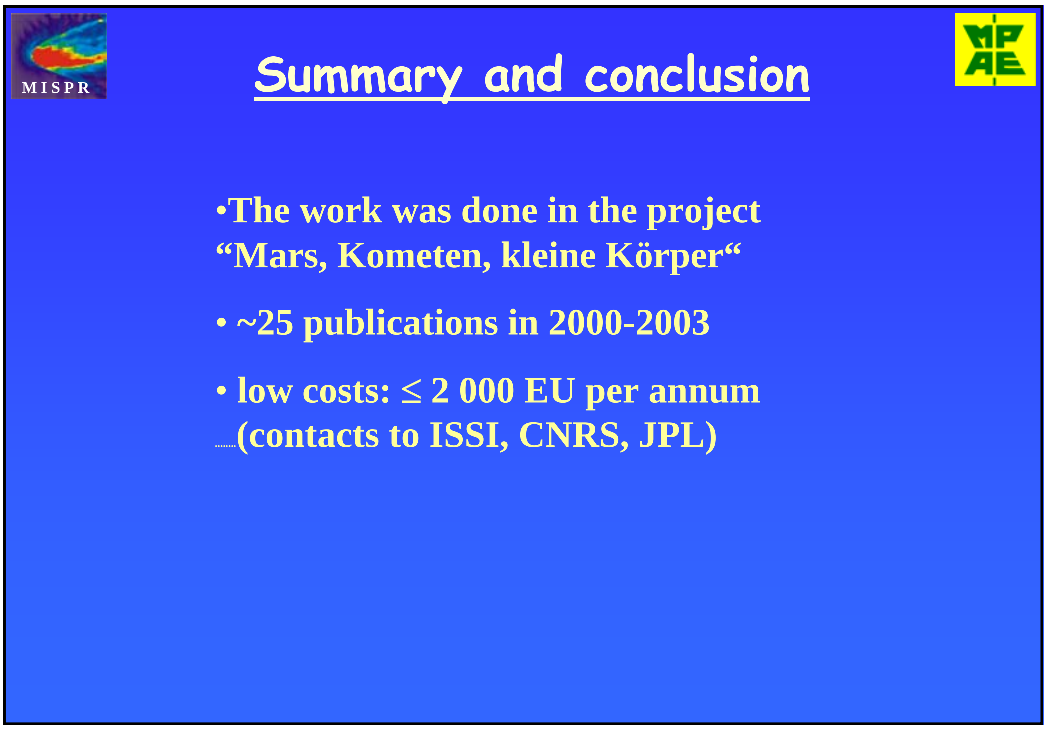
The results have implications to future space missions:

•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.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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)
MPAE