8. A NEM MÁGNESES BOLYGÓK MAGNETOSZFÉRÁJA

Szegő Károly

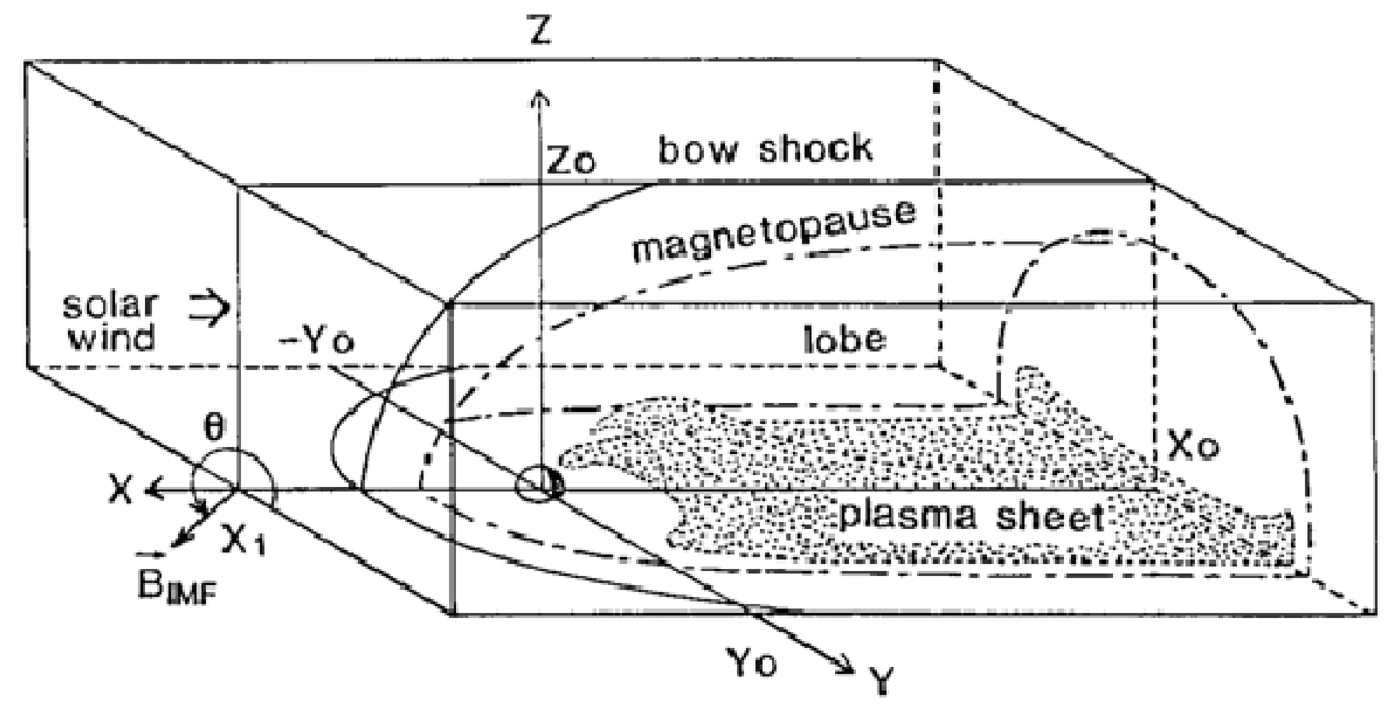
INDUKÁLT MAGNETOSZFÉRÁK

- **Az áramló napszél (és a benne hordozott mágneses tér) és a testek ionoszférájának (=vezető réteg) kölcsönhatása indukálja a magnetoszférát.**
- **Példák: Vénusz, Mars, Titán**
  az utóbbi esetben szubszónikus plazma áramlik, amely protonokból és oxigén ionokból áll, ezért lökéshullám nem alakul ki.

A BOLYGÓK ÉS AZ ÁRAMLÓ MÁGNESES PLAZMA

- **AZ ÉGITESTEK AKADÁLYT JELENTENEK A SZUPERSZÓNIKUSAN ÁRAMLÓ NAPSZÉLBEN.**
- **A KÖLCSÖNHATÁS JELLEGE AZ AKADÁLY MINŐSÉGÉTŐL FÜGG.**
- **A MEGZAVART TARTOMÁNY: A TEST PLAZMAKÖRNYEZETE**
- **HA AZ AKADÁLY**
  - **ELEKTROMÁGNESESEN SEMLEGES: CSAK GEOMETRIAI KERESZTMETSZETE SZÁMÍT**
  - **VEZETŐ VAGY MÁGNESES: ELEKTROMÁGNESES KÖLCSÖNHATÁSBA LÉP AZ ÁRAMLÓ NAPSZÉL PLAZMÁVAL, EZ VEZET A MAGNETOSZFÉRA KIALAKULÁSÁRA**
- **A PLAZMAKÖRNYEZET SZERKEZETE BONYOLULT, AZ UTÓBBI ESETBEN LEGALÁBB KÉT SZAKADÁSI FELÜLET ALAKUL KI:**
  - **LÖKÉSHULLÁM, MERT A PLAZMA MÁSKÉPP NEM TUD SZUBSZÓNIKUS SEBESSÉGRE LASSULNI**
  - **TANGENCIÁLIS SZAKADÁS: A NAPSZÉL KÖRÜLFOLLYA AZ AKADÁLYT**
- **AZ ALÁBBIAKBAN A TEST ÉS A NAPSZÉL KÖLCSÖNHATÁSÁVAL FOGLALKOZUNK.**

A NAPSZÉL ÉS AZ AKADÁLY SEMATIKUS KÖLCSONHATÁSA



Dependence of the location of the Martian magnetic lobes on the interplanetary magnetic field direction

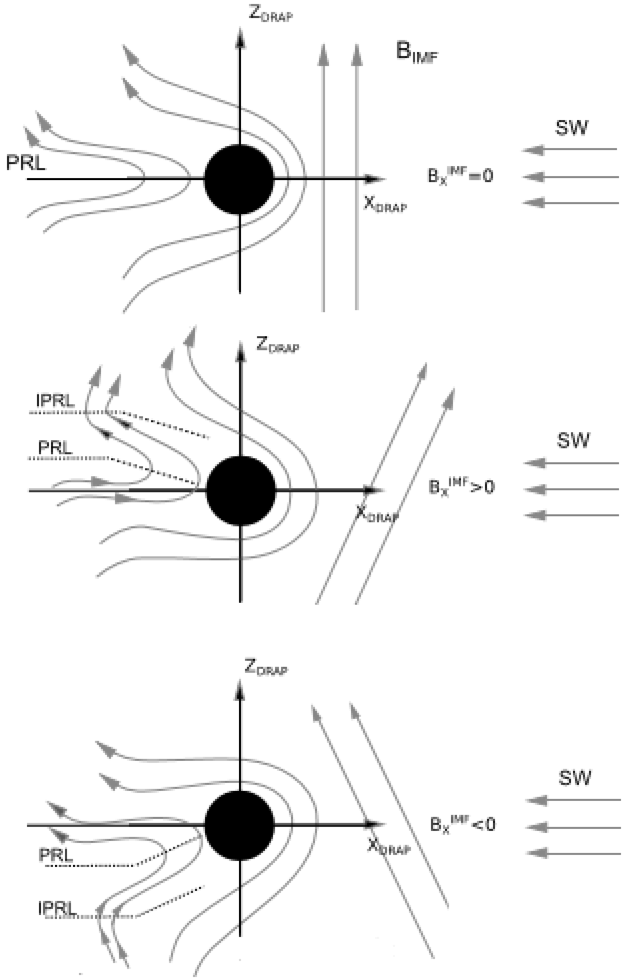


Figure 1. Scheme of an induced magnetosphere for different IMF orientations seen from the DRAP coordinate system. In all panels the solar wind flows antiparallel to the *X* axis and the *Z* component of the IMF is positive. The PRL is located between both magnetic lobes (where $B_{XDRAP} = 0$). (top) $B^{IMF}_{XDRAP}=0$, (middle) $B^{IMF}_{XDRAP} > 0$, and (bottom) $B^{IMF}_{XDRAP} < 0$. The PRL is located at $Z = 0$, in the northern and the southern hemisphere, respectively. Figure based on *Simon et al.* [2013]. For the computation of the location of the IPRL, the reader is referred to *Romanelli et al.* [2014].

Romanelli, N., C. Bertucci, D. Gómez, and C. Mazelle (2015), Dependence of the location of the Martian magnetic lobes on the interplanetary magnetic field direction: Observations from Mars Global Surveyor, J. Geophys. Res. Space Physics, 120, 7737–7747, doi:10.1002/2015JA021359.

An induced global magnetic field looping around the magnetotail of Venus

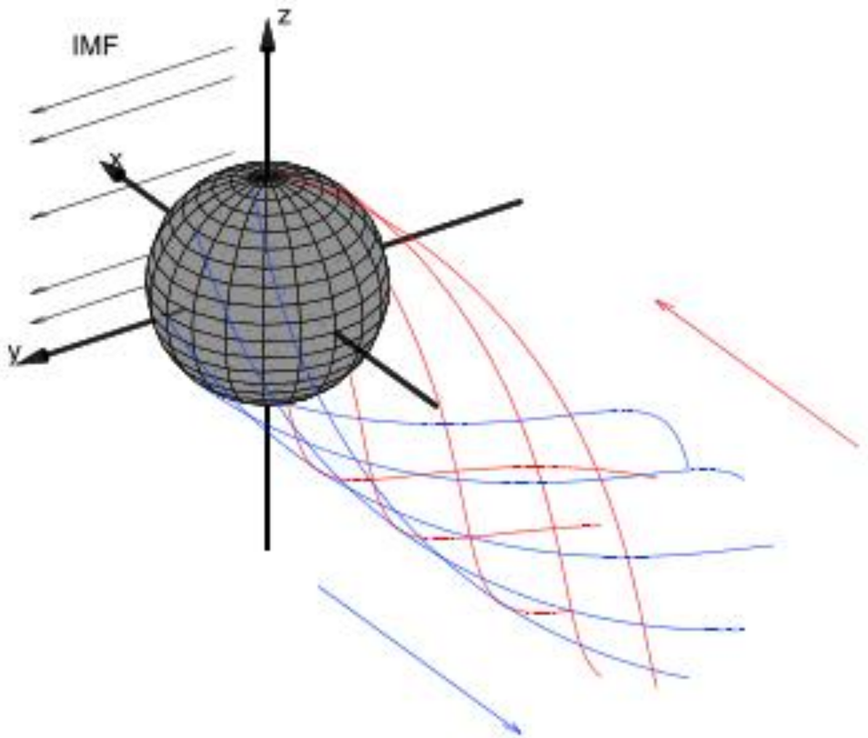


Figure 8. Schematic illustration of the nightside magnetic field lines combining the looping field and the draped IMF together. Red lines represent the magnetic fields with sunward components ($B_x > 0$), blue lines with antisunward components ($B_x < 0$).

Chai, L., et al. (2016), An induced global magnetic field looping around the magnetotail of Venus, J. Geophys. Res. Space Physics, 121, 688–698, doi:10.1002/2015JA021904.

GEOMETRIAI AKADÁLY: A HOLD

A HOLD FELÜLETE ABSZORBEÁLJA A NAP-SZELET, DE A MÁGNESES TÉR ÁTDIFFUNDÁL.

A MÁGNESES TÉR DEFORMÁLÓDIK, ENNEK SZÖGÉT A MÁGNESES PERTURBÁCIÓRA JELLEMZŐ V_A ÉS u_{SW} ARÁNYA HATÁROZZA MEG.

A PLAZMA “BEFOLYIK” AZ AKADÁLY UTÁNI TÉR-RÉSZBE, NAGYJÁBÓL A HANGSEBESSÉGGEL.

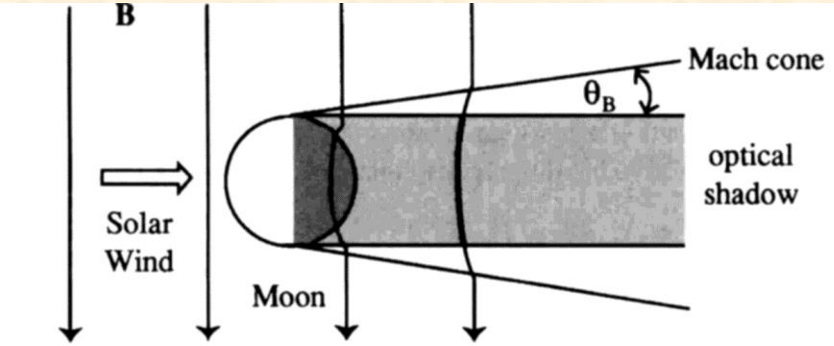


Figure 7.23. Schematic drawing of interplanetary magnetic field lines in the vicinity of the Moon. The magnetic disturbance propagates away from the shadow at the Alfvén speed, such that the edge of the disturbed field forms an angle of θ_B with respect to the solar wind direction.

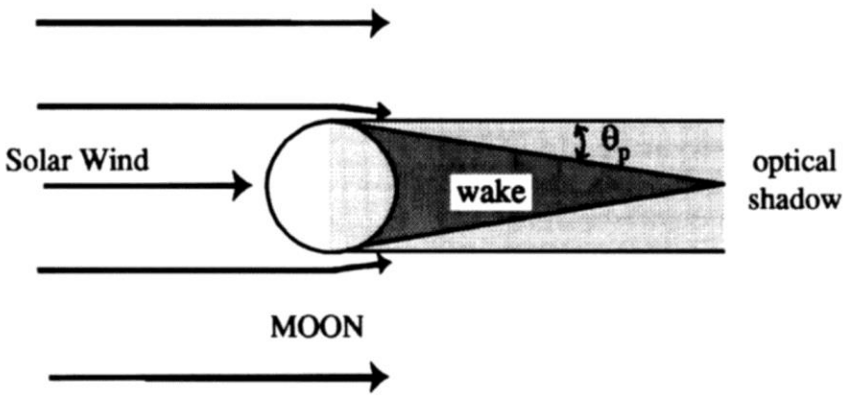
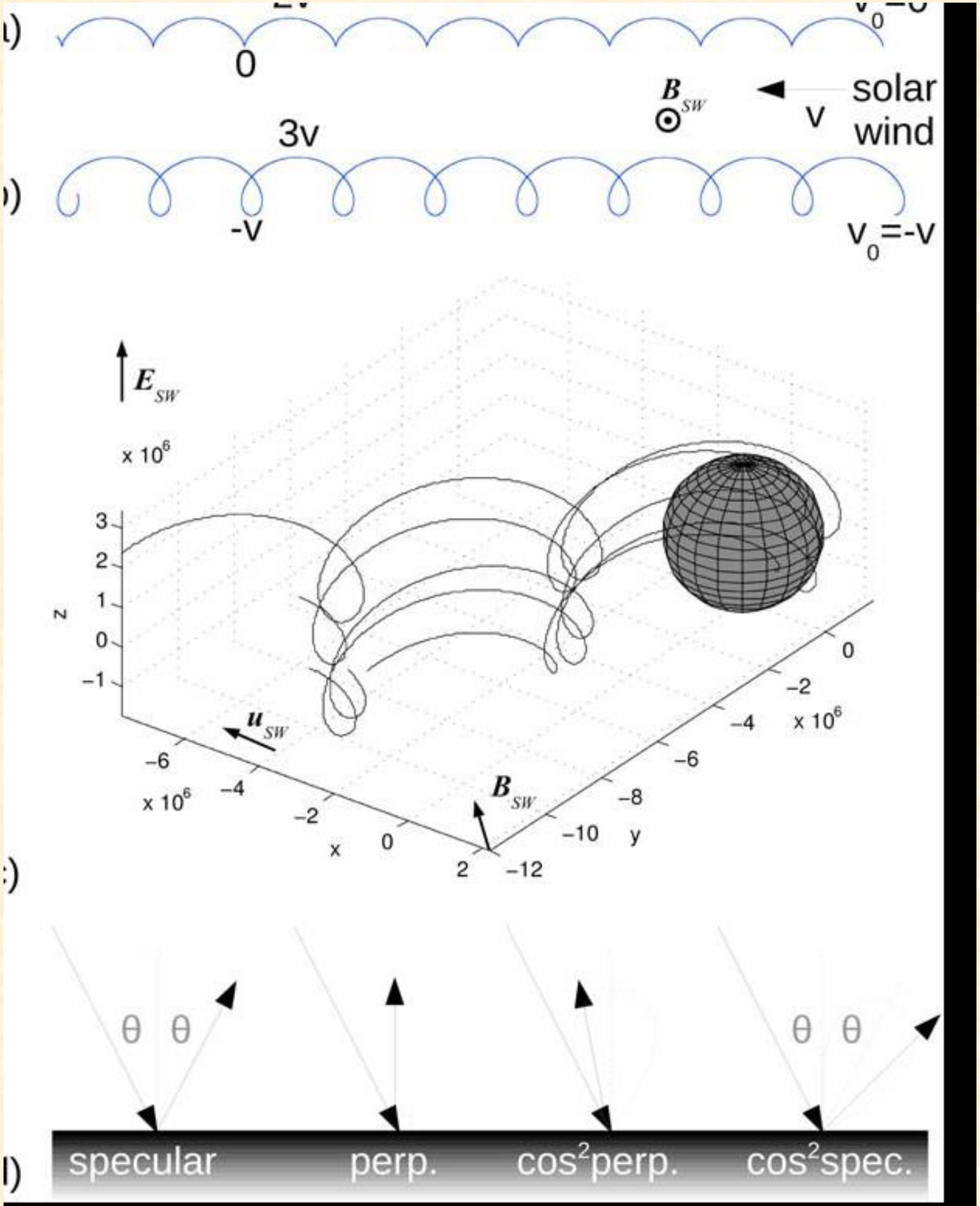


Figure 7.24. Schematic of the lunar plasma wake. The solar wind is absorbed on the ramside of the Moon but tends to flow back into the wake region at roughly the sound speed. The angle of the edge of this inflow is θ_p.



VISSZAVERT PROTONOK

(a) A felső ábra a pickup ionok pályáját mutatja zérus kezdeti sebesség mellett. A napszél sebességét a nyíl mutatja, a napszél mágneses tere a lapra merőleges. A napszél által indukált „convectional electric field” Esw = v × Bsw. Az ion sebesség 0 és 2v között változik.

(b) Olyan ion pályáját mutatja, amely –v kezdeti sebességgel rendelkezik.

(c) A Hold felszínére merőlegesen kilőkődött ionok pályája.

(d) Különböző visszaverődési modellek.

MÁGNESES ANOMÁLIÁK A HOLDON

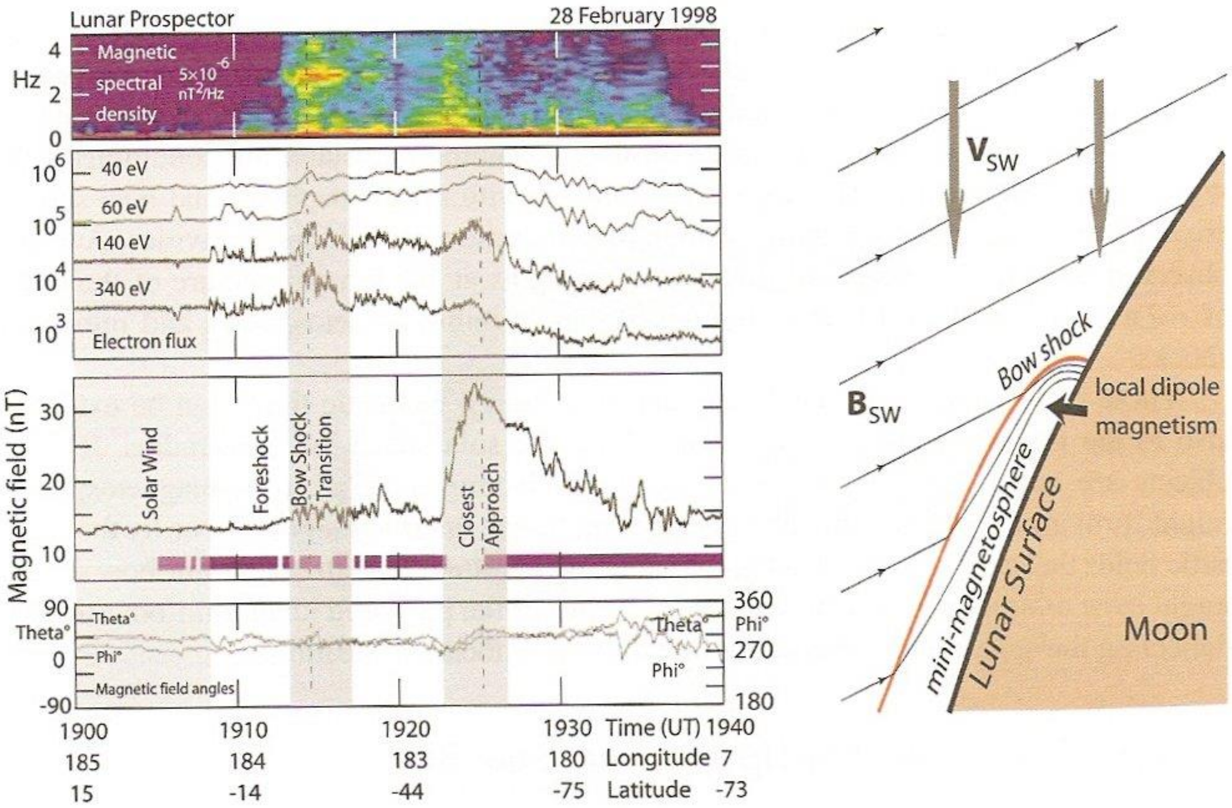


Figure 10.11: The passage across a mini-magnetosphere close to the lunar surface by the Lunar Prospector on 28 February 1998 [after *Lin et al*, 1998]. The spacecraft passes from the solar wind into a region similar to the electron foreshock with energetic electron beans emanating from the lunar direction along the magnetic field to the spacecraft. Afterwards a shock-like discontinuity is crossed which has the character of a detached bow shock which shields a strong magnetic field from a local crustal magnetism on the Moon. The low frequency wave spectrum shows the magnetic fluctuations that are related to the foreshock and bow shock. Four energy channels of electrons are shown. The *two bottom panels* give the magnitude and *two angles* of the magnetic field. The field reaches 30 nT. On the *right* the model of the mini-magnetosphere with its mini-bow shock is sketched.

“VEZETŐ GÖMB” AKADÁLY: NEM MÁGNESES BOLYGÓK

- A BOLYGÓK IONOSZFÉRÁJA JÓ VEZETŐ, IDEÁLISAN VEZETŐ GÖMBKÉNT FOGHATÓ FEL
- A VEZETŐBE A MÁGNESES TÉR NEM HATOL BE, AZ ÁRAMLÁS FELÜLETRE MERŐLEGES SEBESSÉGE IS NULLA
- AZ AKADÁLY FELSZÍNE NYOMÁSEGYENSÚLYI FELÜLET
  - BELÜL: KINETIKUS NYOMÁS
  - KÍVÜL: MÁGNESES NYOMÁS A NAP-BOLYGÓ EGYENES MENTÉN
  - A FELSZÍN KÖZELÉBEN B || AZ AKADÁLY ÉRINTŐJÉVEL ÉS AZ ÁRAMLÉSI SEBESSÉGGEL

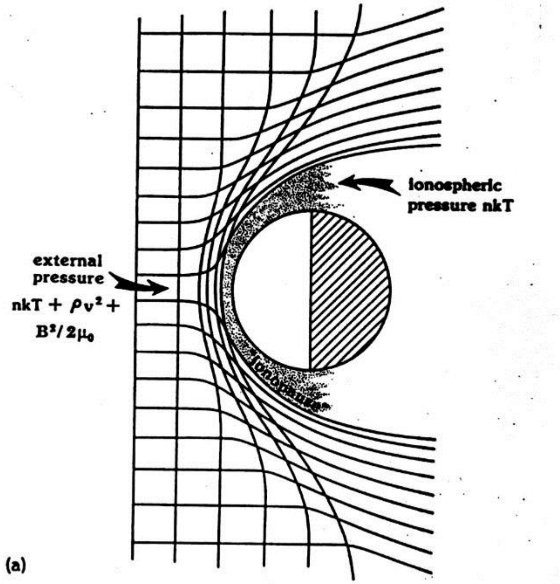


FIG. 8.7. Illustration of pressure balance between the solar wind and the thermal pressure of the ionosphere, which determines the height of the ionopause. The observed variability of the solar-wind pressure is indicated by the histogram on the right. ((a) From Luhmann, 1986; (b) and (c) from Luhmann et al. 1987.)

VENERA 9 & 10

- **Az első két szonda, amely a napszél és Vémusz kölcsönhatását vizsgálta, a Venera 9 és 10 volt. [Vaisberg et al., 1995]**
- **Vénus orbit pályára álltak: 20 and 23 October 1975.**
- **Fő feladat: a leszálló egység támogatása, a Vénucs csóvájának vizsgálata.**

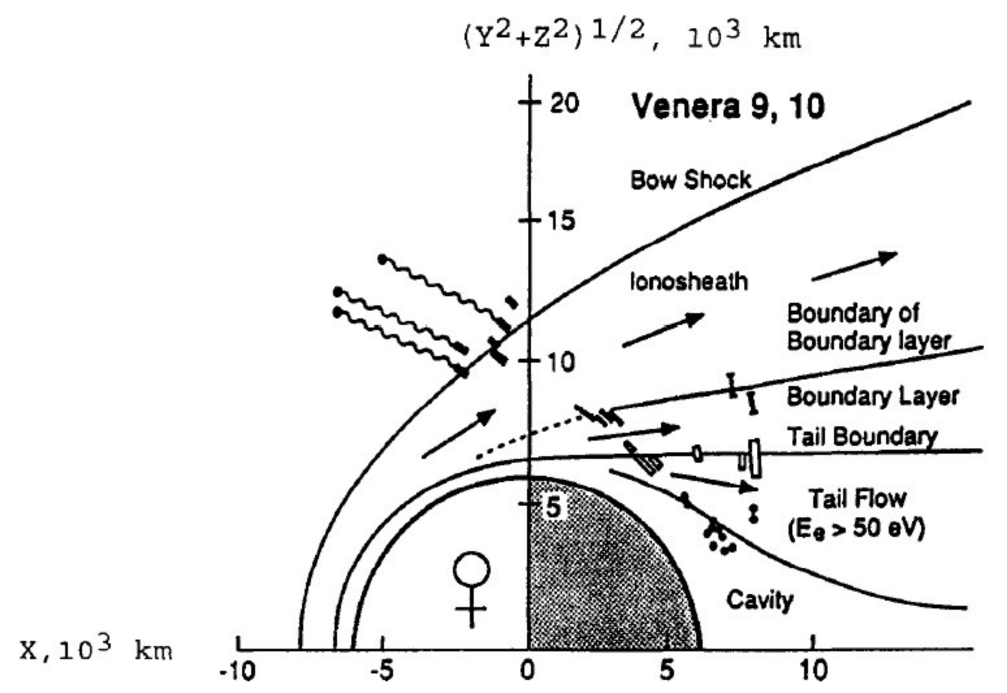


Fig. 1. The plasma boundaries behind the terminator in Venus-centered cylindric coordinate system with X-axis directed to the Sun, as observed on Venera 9 and 10 /1/.

A VÉNUSZ PLAZMAHATÁRAI/TARTOMÁNYAI

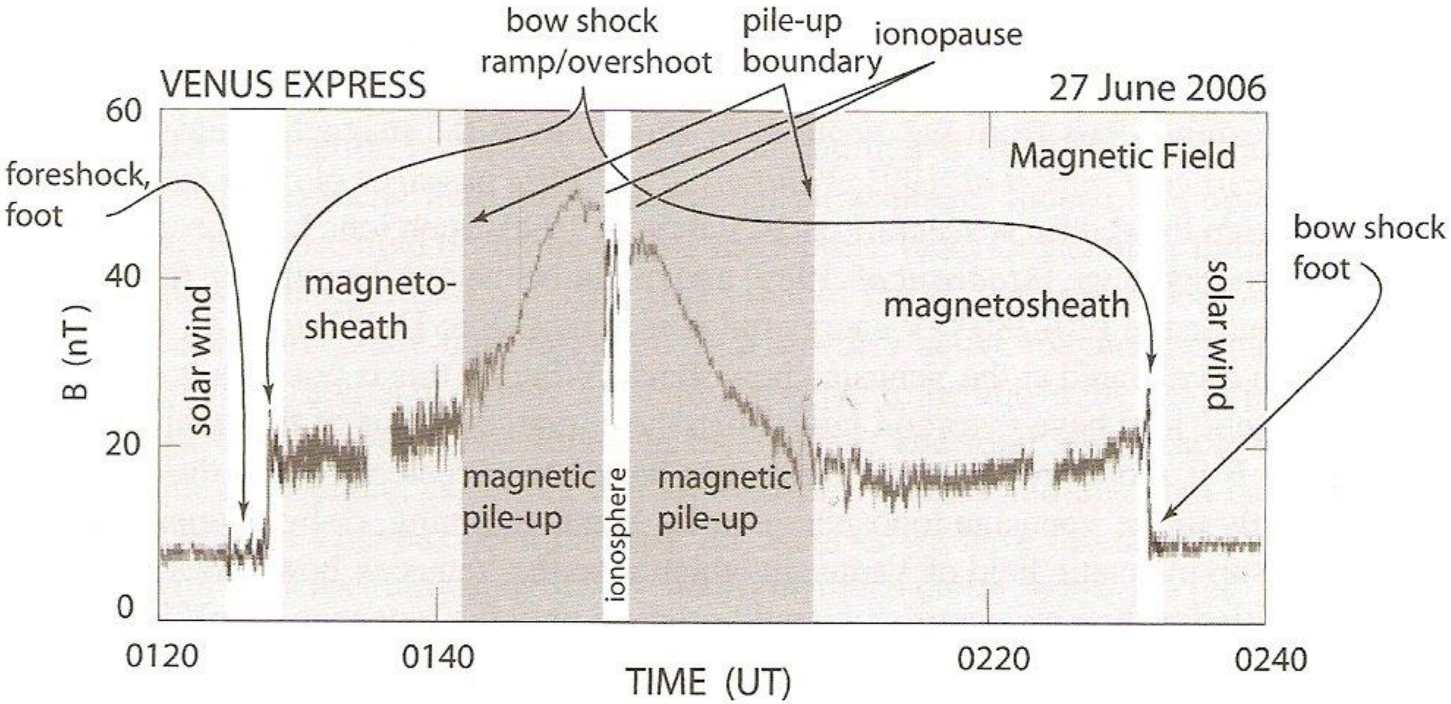


Figure 10.14: Recent magnetic field recordings during a Venus Express passage of the Venusian bow shock [data taken from *Zhang et al*, 2008], showing the various different regions and magnetic boundaries in the environment of Venus. During inbound the spacecraft detected a weak foreshock exhibiting magnetic fluctuations, a short foot region, a quasi-perpendicular bow shock ramp and overshoot, entered a disturbed magnetosheath and passed the magnetic pile-up boundary until reaching the ionopause. On the outbound path no foreshock was detected except for a short shock foot.

A MARS PLAZMATARTOMÁNYAI

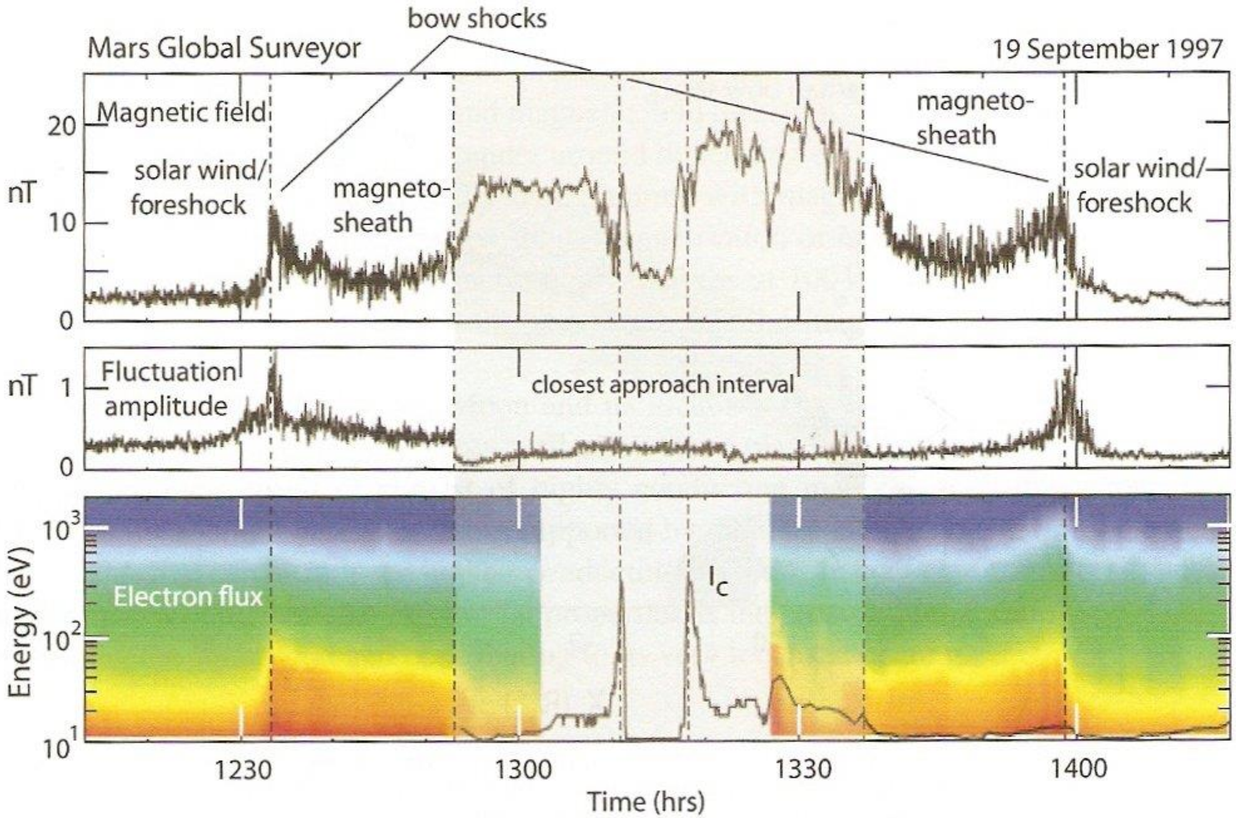


Figure 10.13: The Mars Global Surveyor passage near the red planet on 19 September 1997 as seen in the magnetic field, ultra low frequency magnetic fluctuations and electron flux measurements [data taken from *Acuña et al*, 1998]. Contact with the bow shock is preceded by increased magnetic fluctuations and increasing electron energy. Two shock crossings (inbound and outbound) are seen as steep magnetic transitions, peaked fluctuation levels and high electron thermal spreads, followed by a broad magnetosheath. The obstacle here is not the magnetic field but the thin Martian atmosphere. The *black line* in the electron spectrogram is the Langmuir probe current which is a measure of electron densities and temperatures close to the planet.

PIONEER VENUS ORBITER MÉRÉSEI SOLAR MIN/MAX

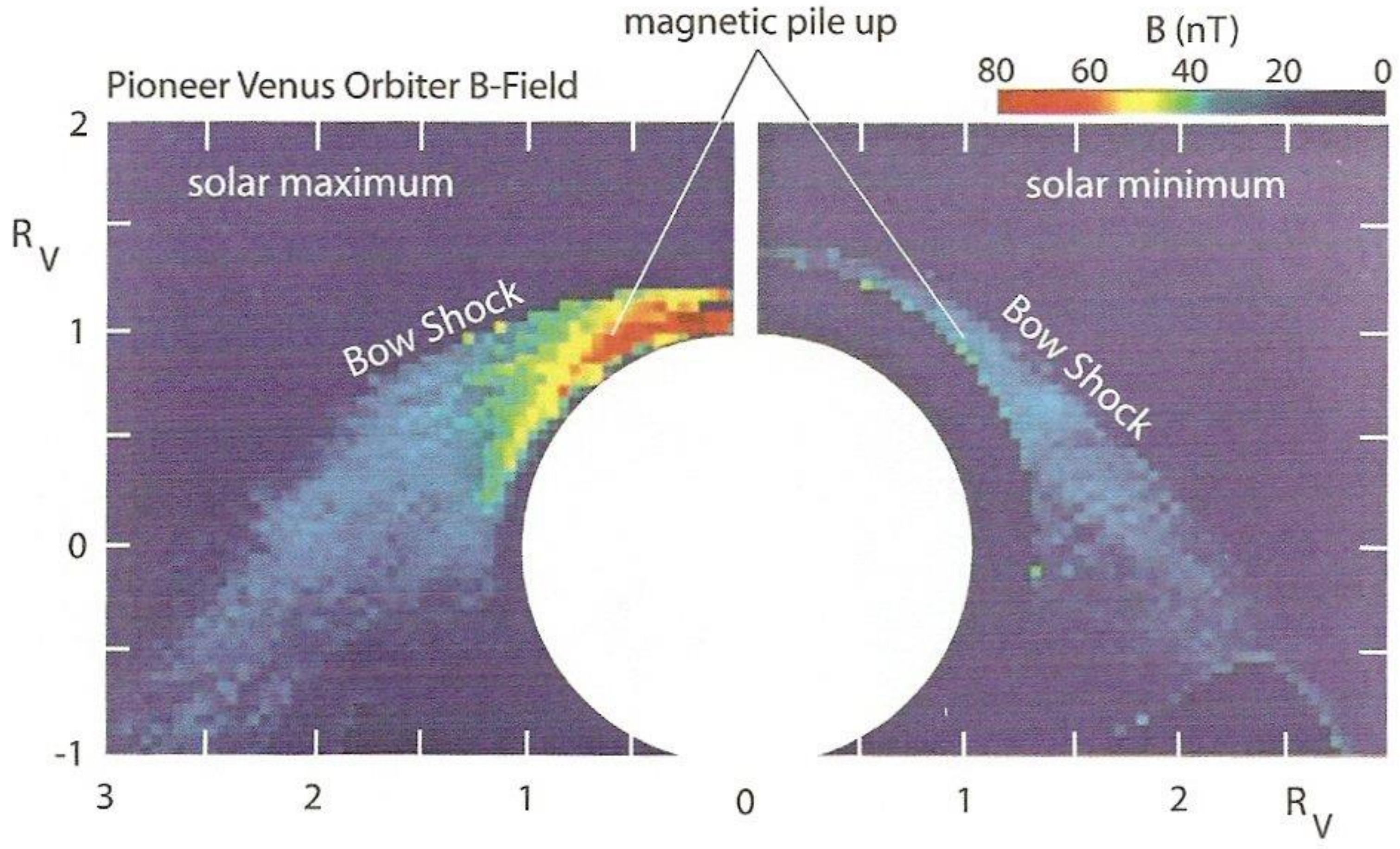


Figure 10.15: The Pioneer Venus Orbiter magnetic field measurements near Venus during solar maximum and solar minimum, showing the control of the magnetic pile up region and bow shock position with solar activity [data taken from *Kallio et al*, 1998, courtesy American Geophysical Union]. At high solar activity the pile up is much stronger and the bow shock stand-off distance smaller than at low solar activity.

PLAZMAOSZCILLÁCIÓK

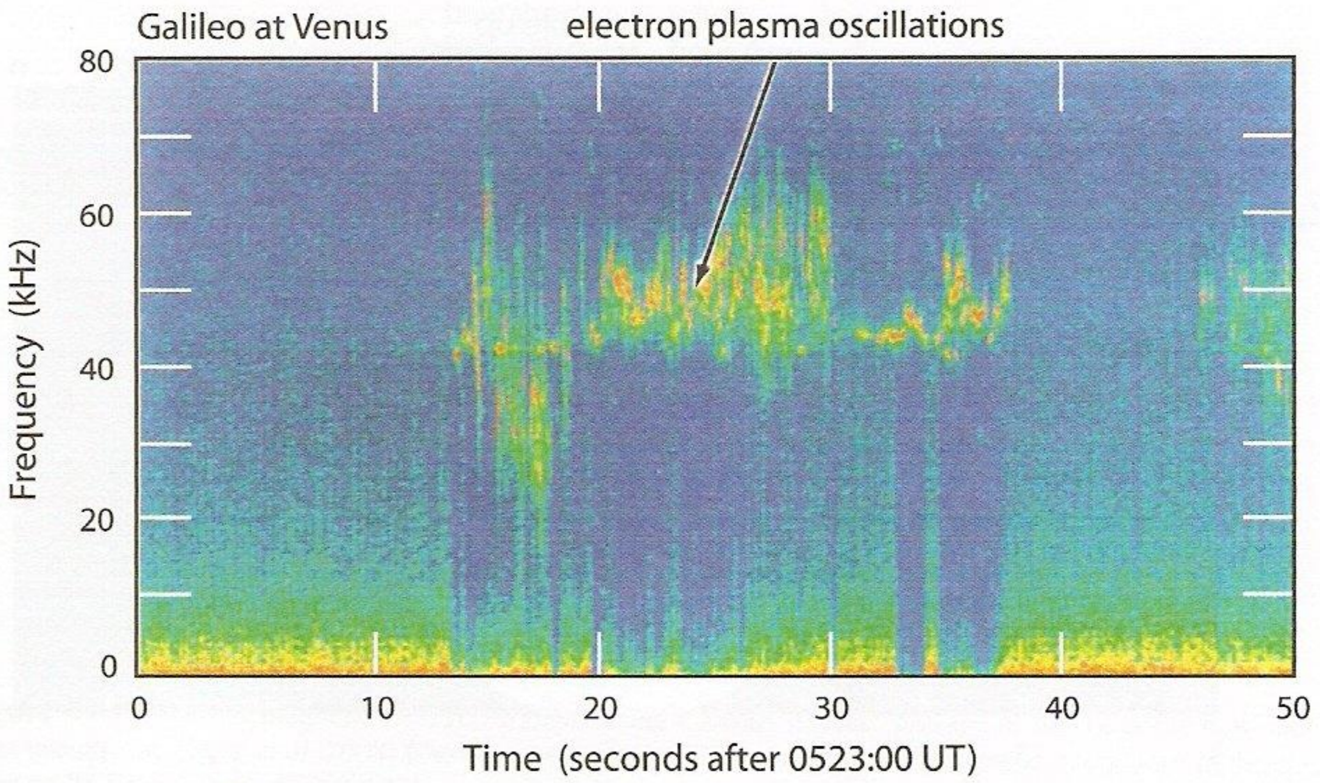


Figure 10.16: Galileo observations of electron plasma waves in the Langmuir mode as are excited by electron beams emitted from the Venusian bow shock into the electron foreshock. Intensification of the waves occurs when the spacecraft crosses the tangential magnetic field line [after *Gurnett et al*, 1991]. Note the high time variability which indicates wave localisation. The disappearance of the low frequency ion acoustic waves in response to the Langmuir waves is also of interest.

A Pioneer Venus Orbiter misszió főbb eredményei
Brace et al., Adv. Space Res. 1995

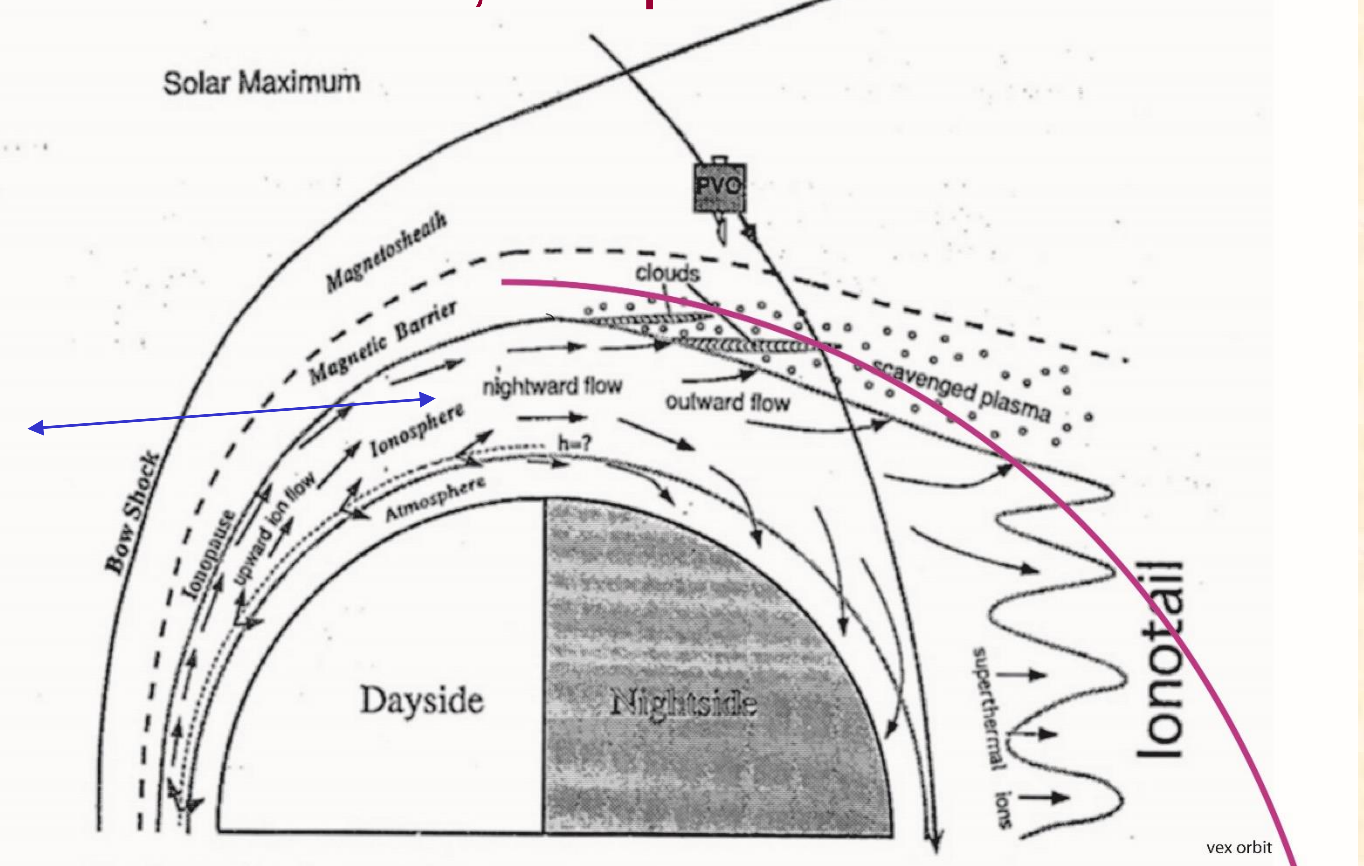
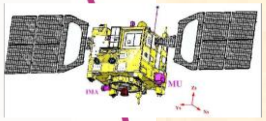
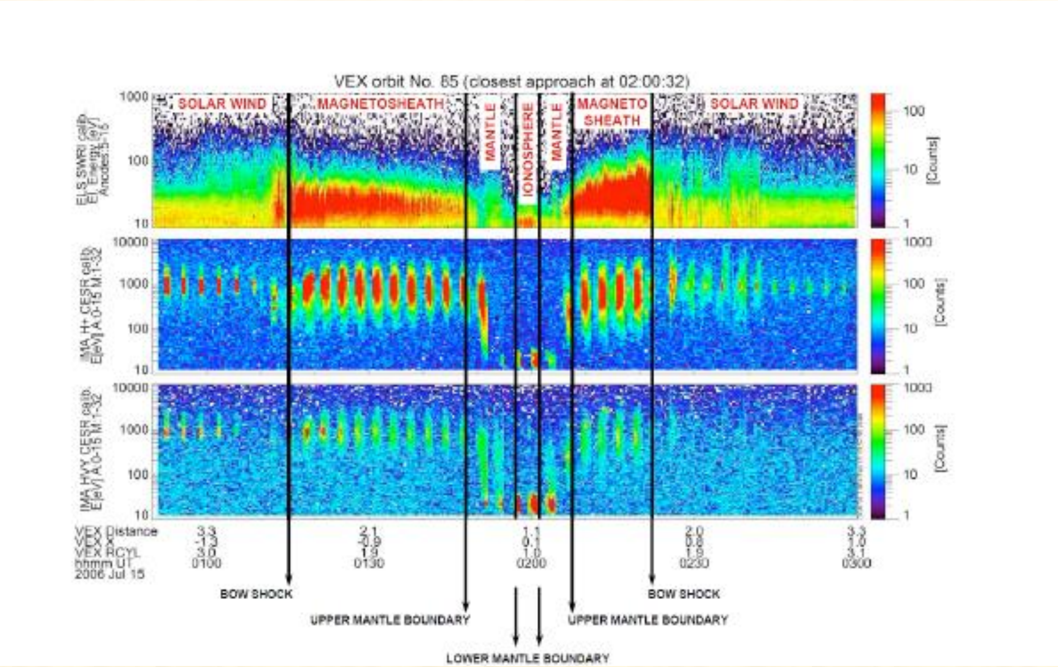


Fig. 2. An illustration of the nightward ion flow scenario at solar maximum based on measurements made along PVO trajectories such as the one shown. The transterminator O^+ flow is supplied by upward and nightward flow from the dayside, followed by subsidence to form the nightside ionosphere. Any excess flow drifts tailward to replace ions that escape in the form of clouds and other recognizable plasma features found above the ionopause. Superthermal ions observed in the ionotail may also be energetic enough to escape. The ionospheric level, h, from which upward flow begins depends upon Psw through its control of h_{ip}. At times of low Psw the nightward flow may be limited by the amount of O^+ that can be drawn from the dayside ionosphere, thus limiting the maximum ion escape rate and reducing the maximum flux available to maintain the nightside ionosphere.



KISÉRLETI EREDMÉNYEK 1.



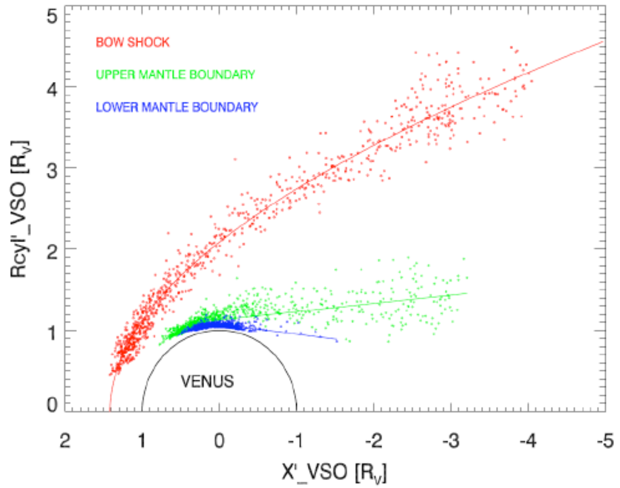
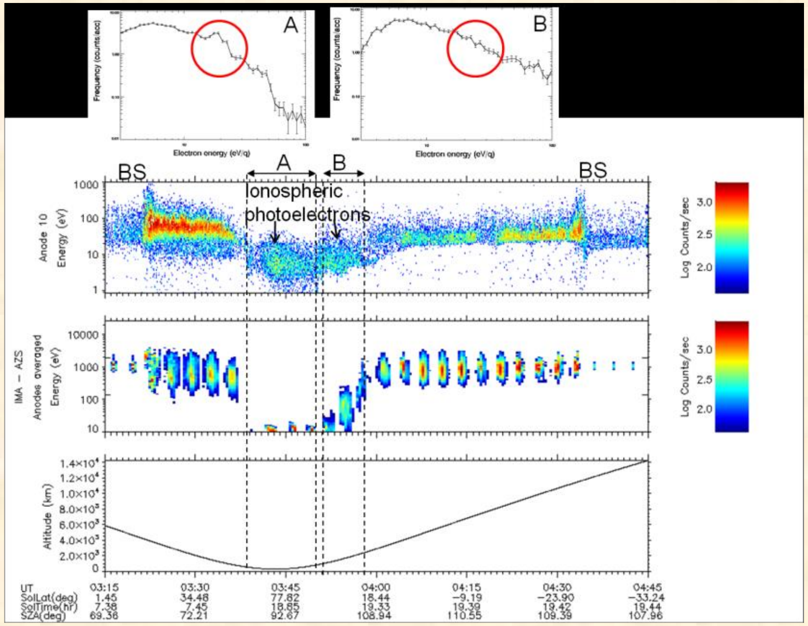
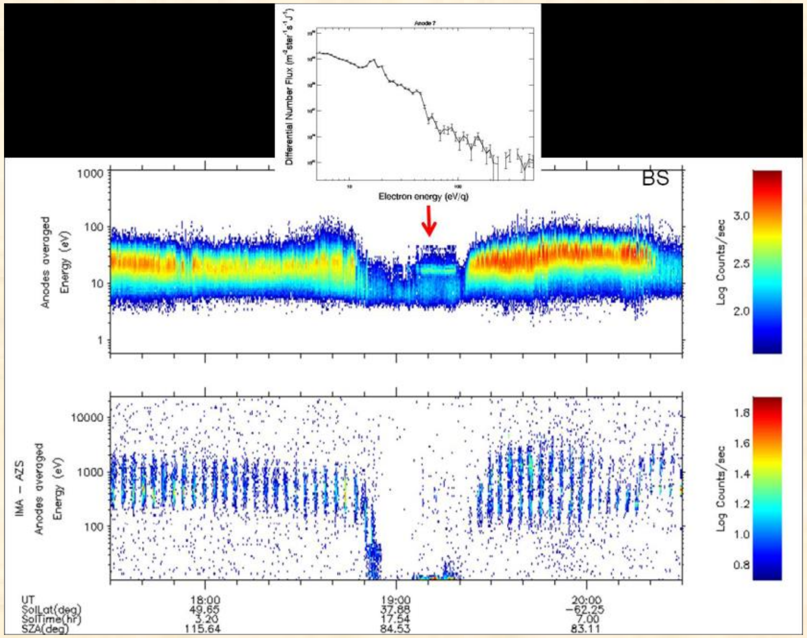


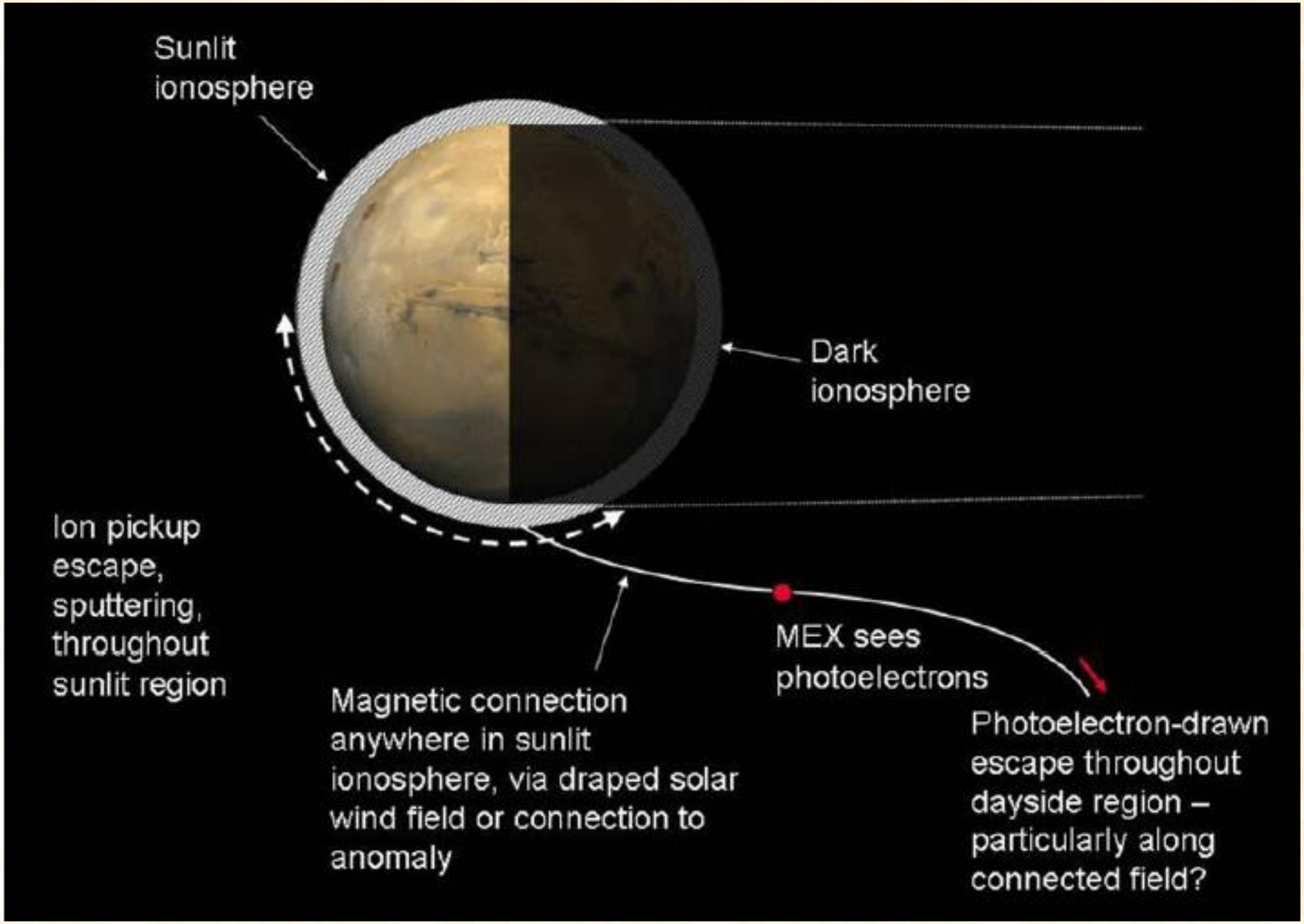
Figure 27. Axisymmetric bow shock (BS), upper (UMB) and lower (LMB) mantle boundary fits derived using the first 19 months of ASPERA-4 observations in an aberrated VSO coordinate system. The BS crossings (red circles) were fitted to a conic function. The UMB (green diamonds) and LMB (blue triangles) crossings were fitted by a circle on the dayside and by linear regression on the nightside [from Martinecz et al., 2008].

IONOSZFÉRIKUS FOTOELEKTRONOK A VÉNUSZNÁL ÉS A MARSNÁL

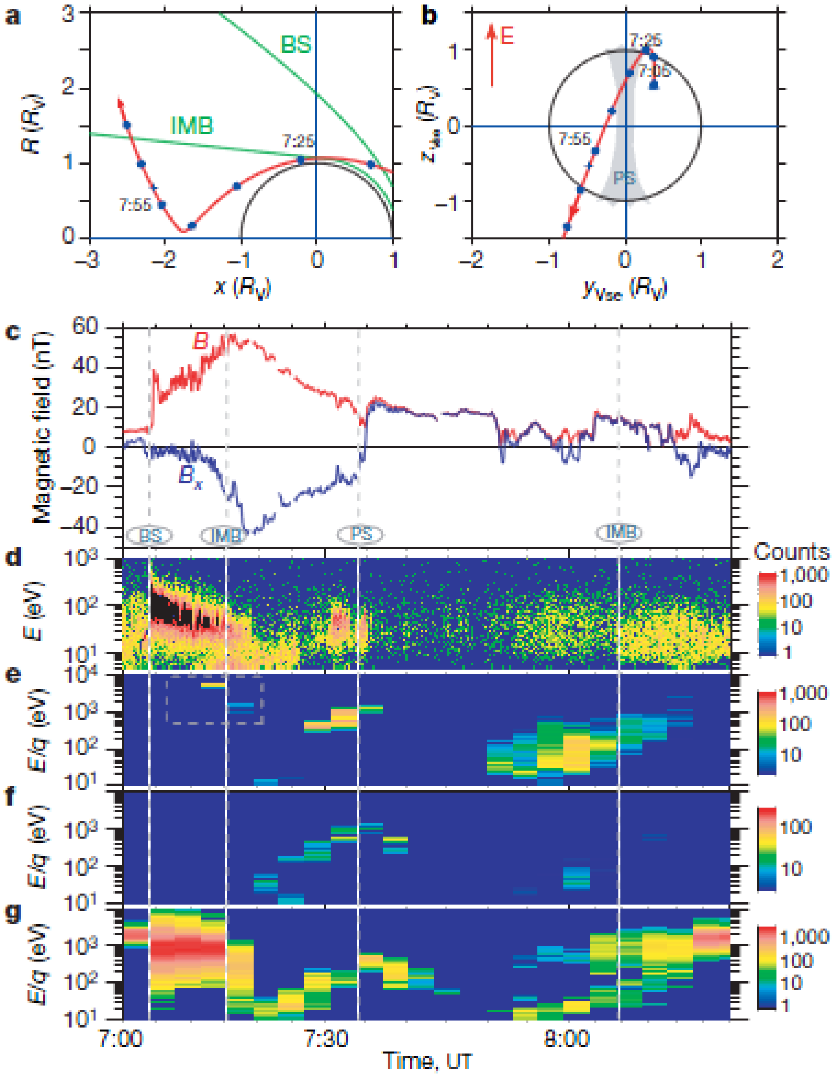




A FOTOELEKTRONOK MEGFIGYELÉSE



KÍSÉRLETI EREDMÉNYEK 2.



Venus Express orbit, and plasma and magnetic field measurements on 2006 December 12.

a, The Venus Express orbit in cylindrical coordinates, with x pointing towards the Sun, and R being the distance to the x axis (in Venus radii, RV=6,051 km). The green lines are the averaged positions of the bow shock (BS) and induced magnetosphere boundary (IMB), and the red line is the Venus Express orbit.

b, The Venus Express orbit in the Venus–solar–electrical coordinate system (Vse). In this system x points to the Sun, and z is in the plane containing the convection electric field E52Vsw3B (where Vsw is the velocity of the solar wind, B is the interplanetary magnetic field and3denotes the vector cross product); y completes the orthogonal coordinate system. The plasma sheet (PS) is identified by the grey area. The direction of the convection electric field is labelled E.

c, The magnetic field magnitude (red line) and Bx component (blue line).

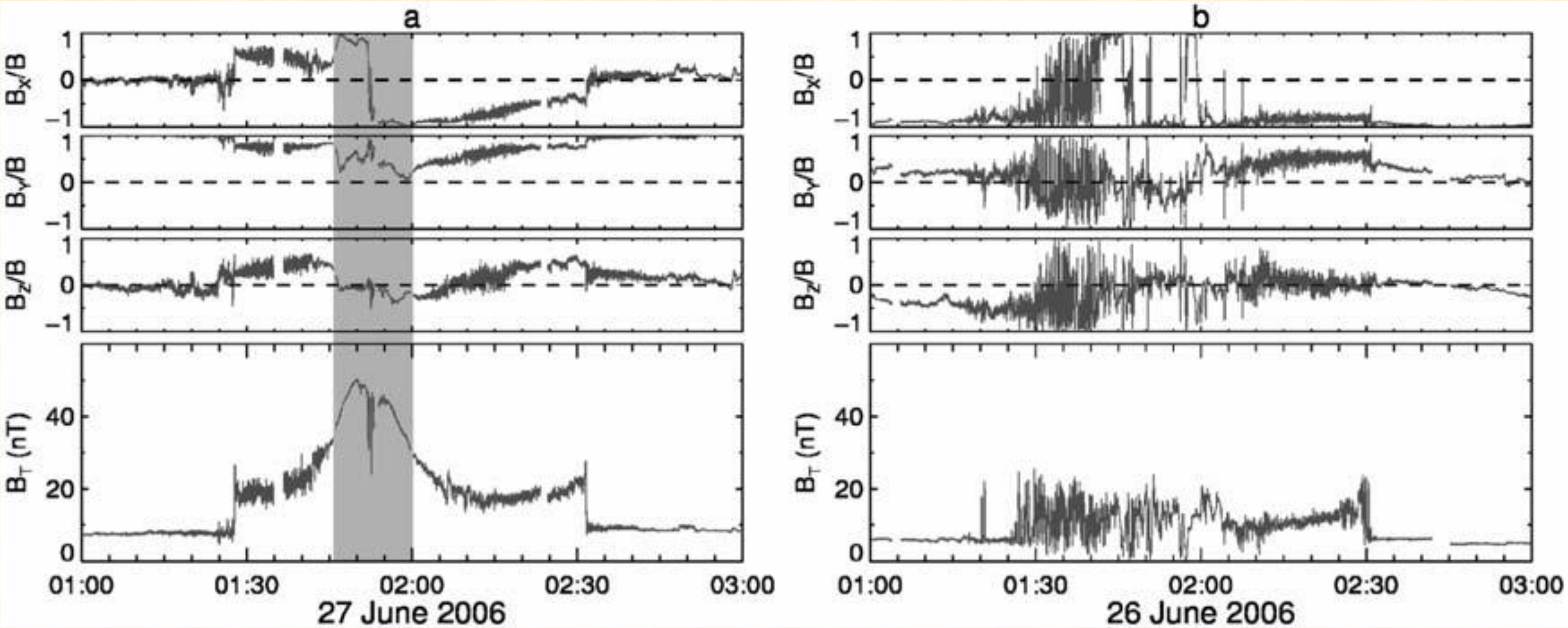
Energy–time spectrograms

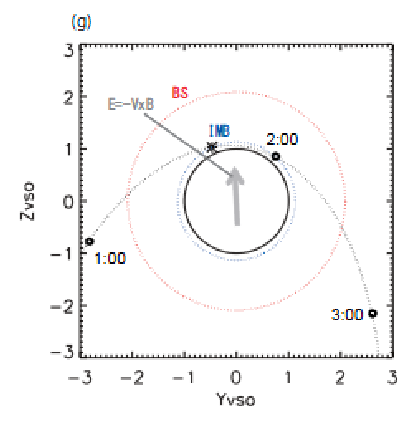
(d) electrons

(e), O+ ions

(g) protons

ELTÉRŐ A KÖLCSÖNHATÁS B ÉS A NAPSZÉL IRÁNYA KÖZÖTTI SZÖGTŐL: A MÁGNESES TÉR (MÉRÉS)





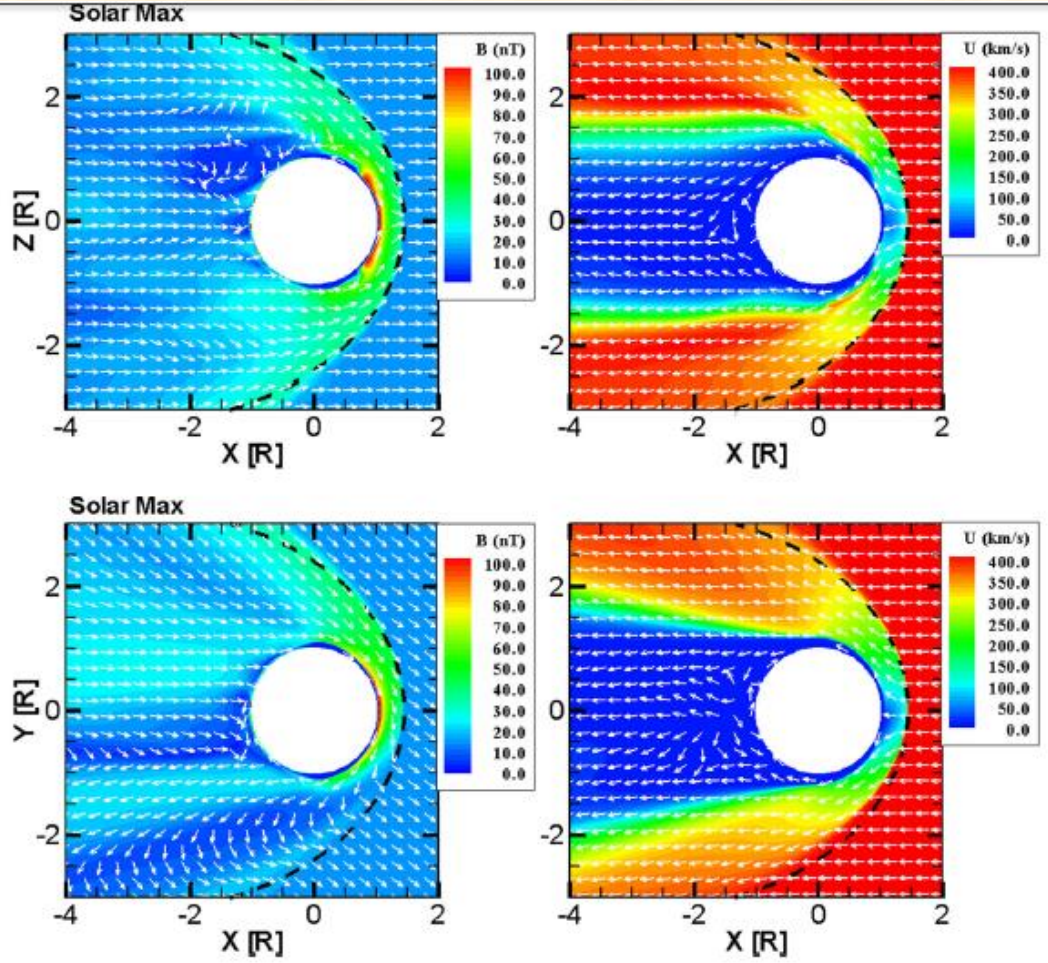


Figure 2. The contour of magnetic field and plasma flow speed in meridian (*XZ*) plane and equatorial (*XY*) planes for solar maximum case. The color plots show the magnitudes; the white arrows show the direction of the magnetic field (left panels) and plasma flow (right panels) projected in the corresponding planes. The black dashed line is the average bow shock location at solar maximum condition from *Zhang et al.* [1990].

MODELLEZÉS 1.

Ma,Y. J., A. F. Nagy, C. T. Russell,R. J. Strangeway, H. Y.Wei, and G.Toth (2013), A global multispecies single-fluid
MHD study of the plasma interaction around Venus, J. Geophys. Res. Space Physics, 118, 321–330, doi:10.1029/2012JA018265.

MODELLEZÉS 2.

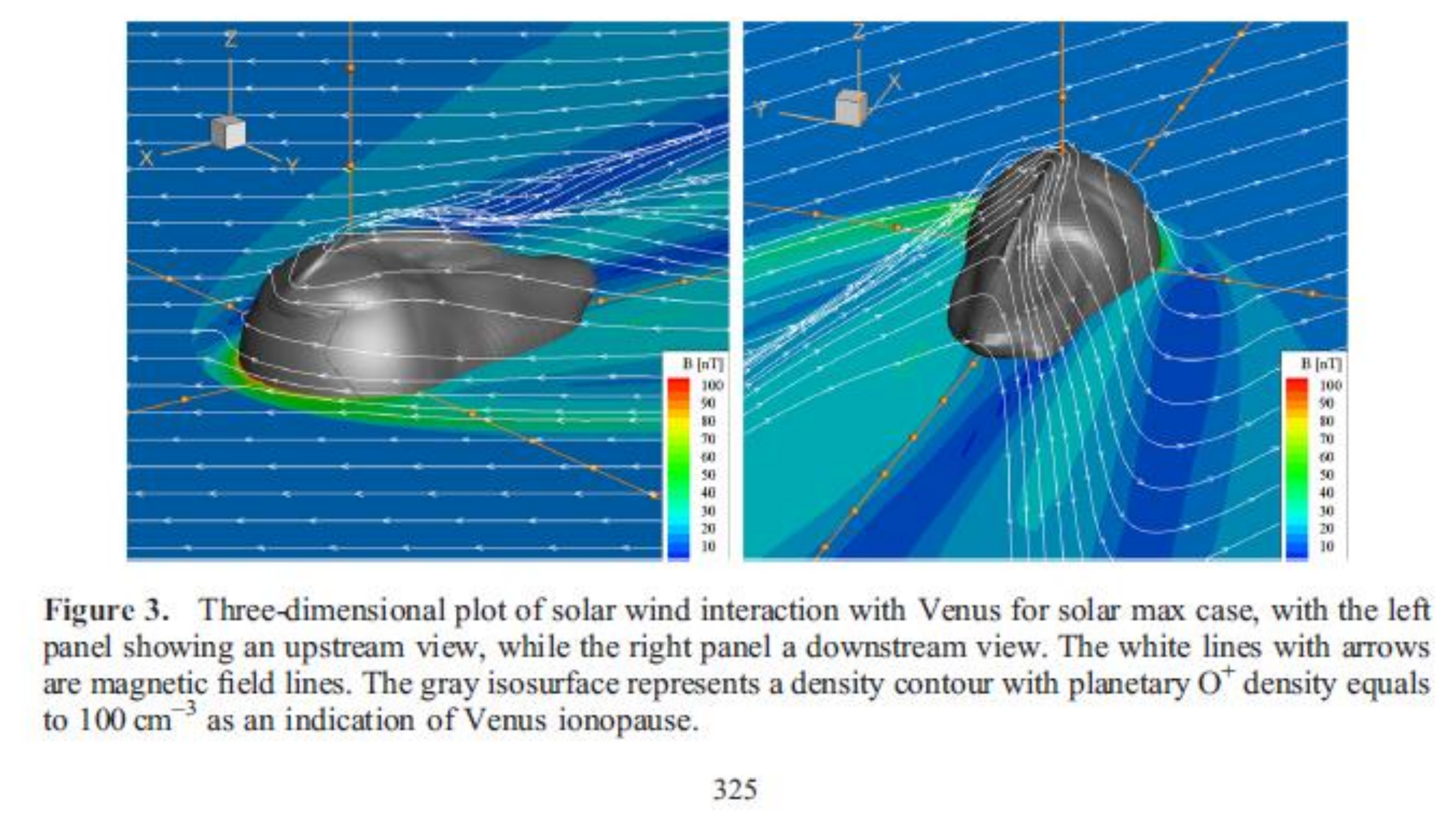


Figure 3. Three-dimensional plot of solar wind interaction with Venus for solar max case, with the left panel showing an upstream view, while the right panel a downstream view. The white lines with arrows are magnetic field lines. The gray isosurface represents a density contour with planetary O^+ density equals to 100 cm^{-3} as an indication of Venus ionopause.

325

MODELLEZÉS 3.

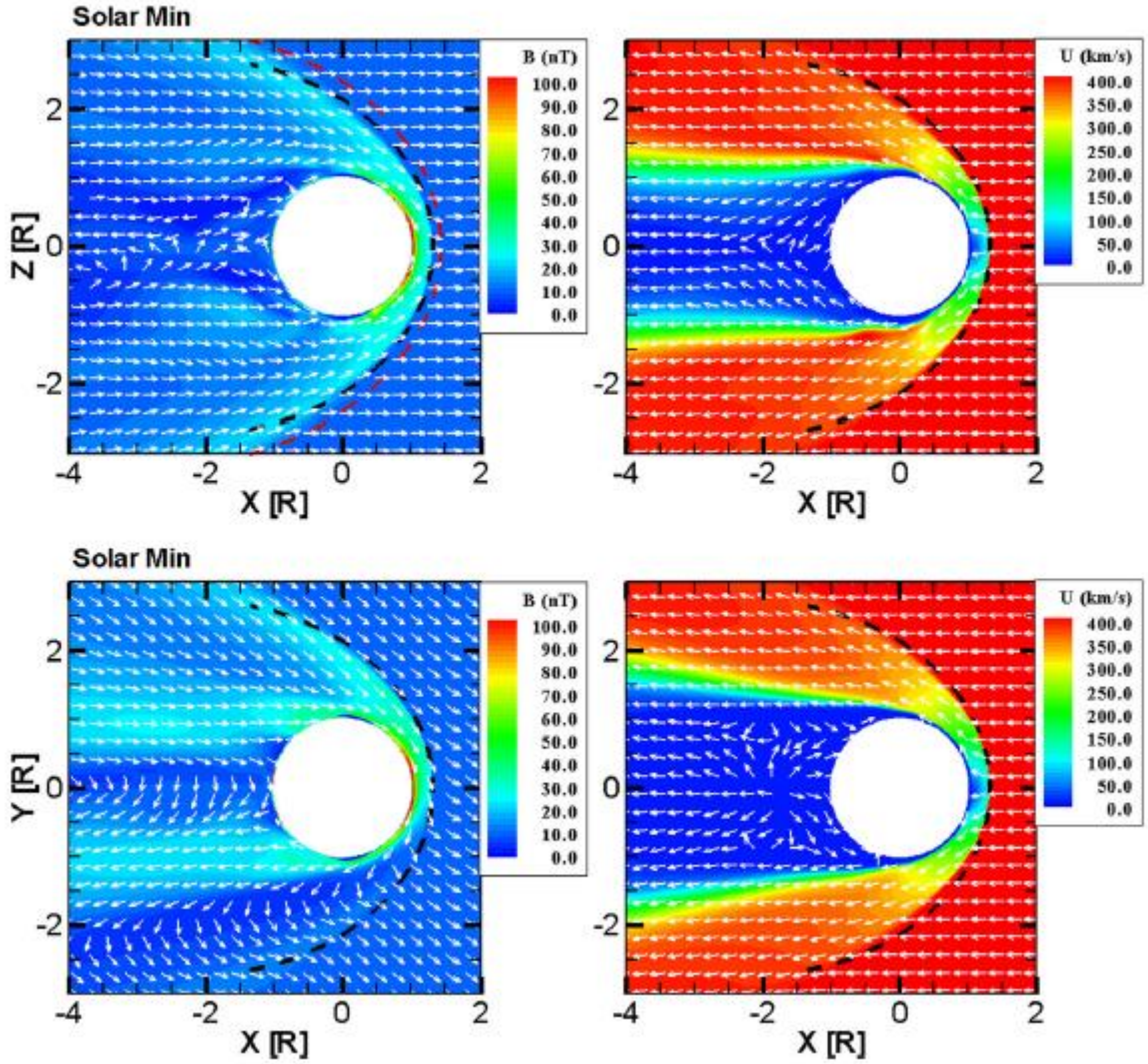


Figure 4. Same as Figure 2 but for solar minimum case. The black dashed line represents the mean bow

The extension of ionospheric holes into the tail of Venus

Collinson, G. A., et al. (2014), The extension of ionospheric holes into the tail of Venus, J. Geophys. Res. Space Physics, 119, 6940–6953, doi:10.1002/2014JA019851.

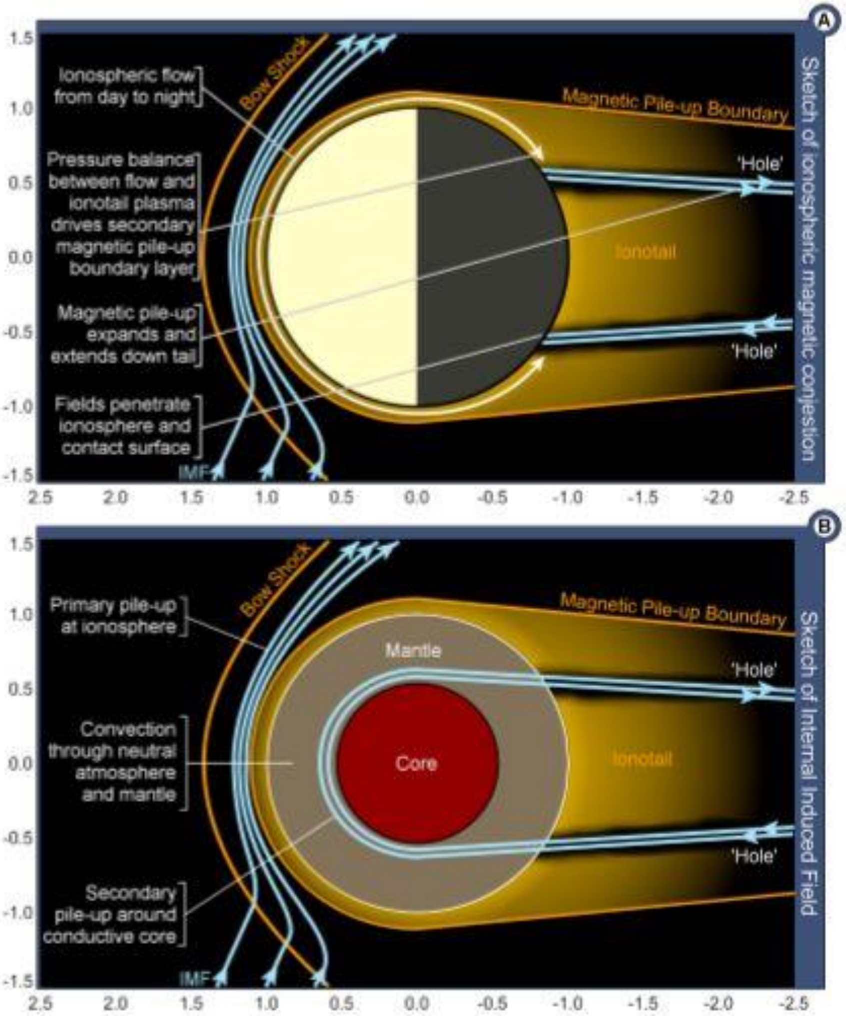
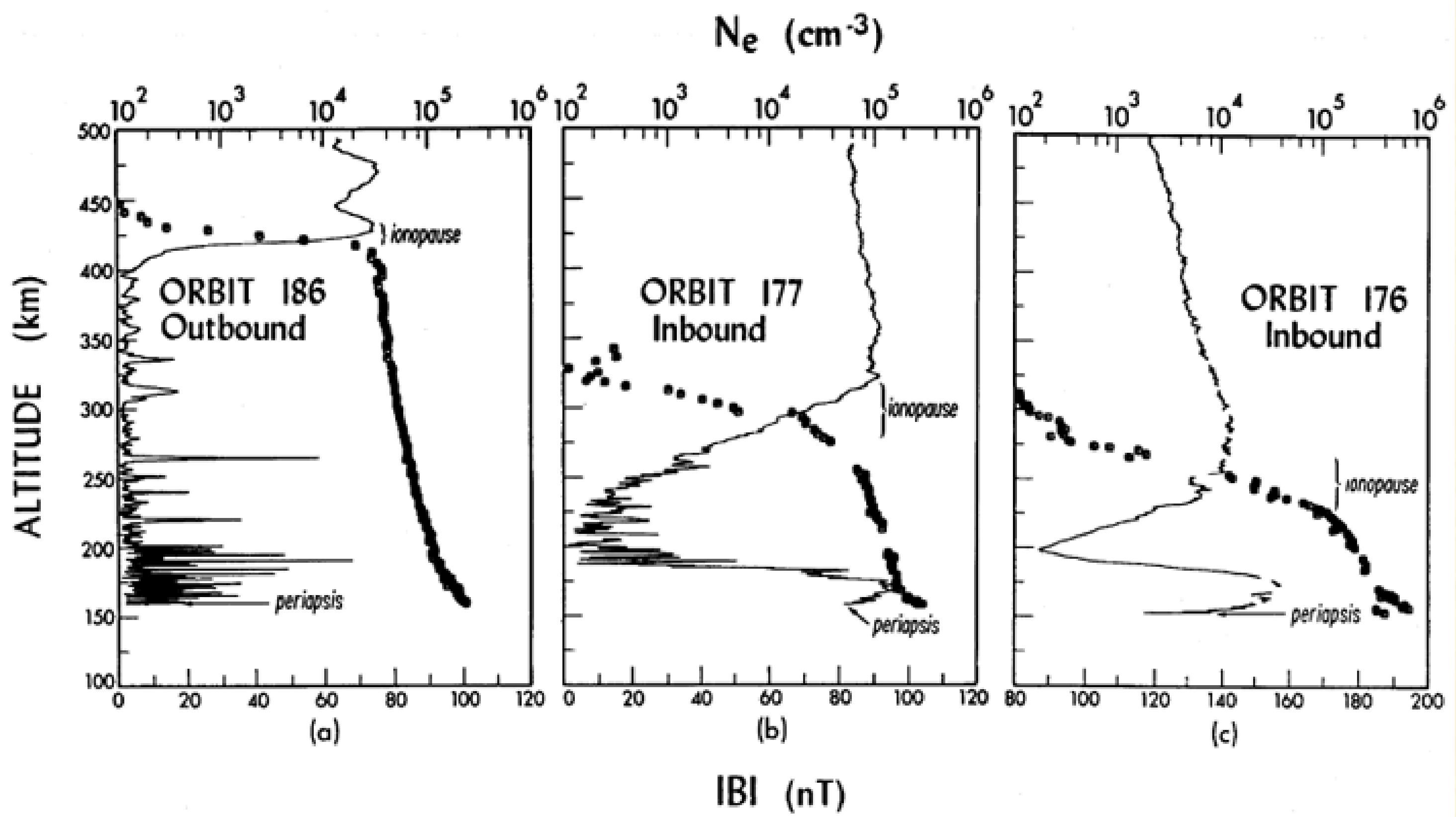


Figure 8. Sketch showing two theories to try and explain the formation of ionospheric holes. (a) Theorized pileup between day-to-night flow of ionospheric plasma and tail plasma. (b) The theorized pileup of interplanetary magnetic field at the core/mantle boundary, resulting in the formation of enhanced magnetic flux tubes, which under favorable nightside conditions results in localized plasma depletion.

A VÉNUSZ IONOSZFÉRA SZERKEZETE



A MÁGNESES REKONNEKCIÓ

A PLAZMA MOZGÁSA

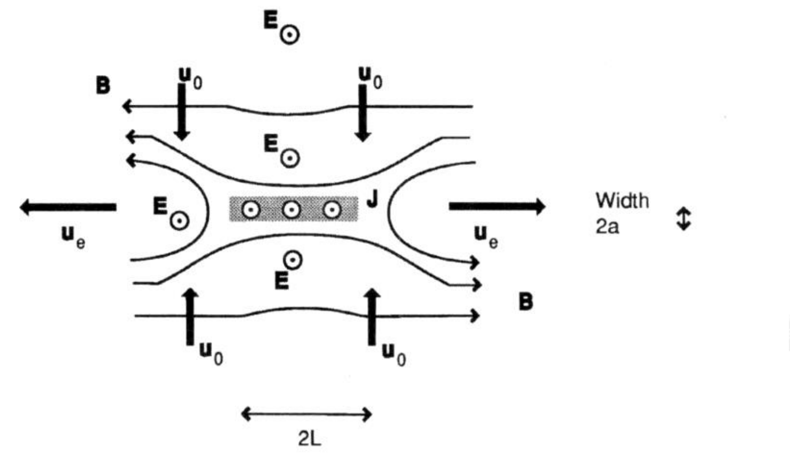


Figure 4.26. Schematic for steady-state magnetic reconnection. The hatched area with length $2L$ and width $2a$ is the magnetic diffusion region where $R_m < 1$. The x-line is a point at the center of this region and goes in and out of the page.

AZ ENERGIAMÉRLEG

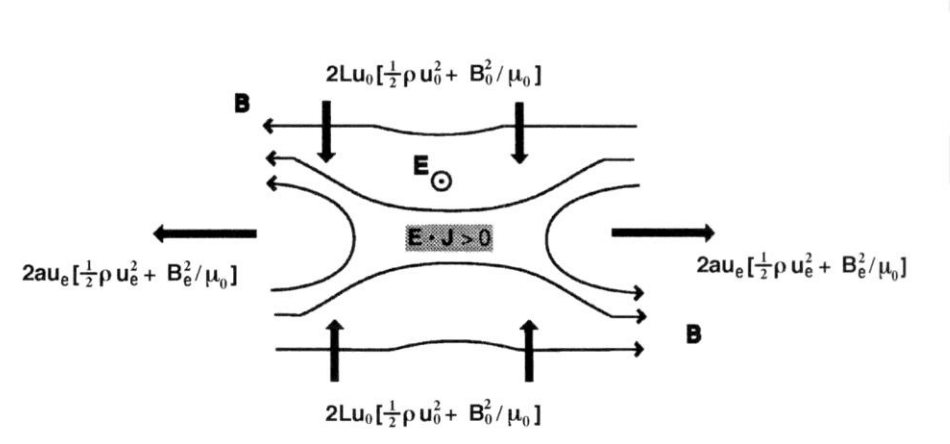
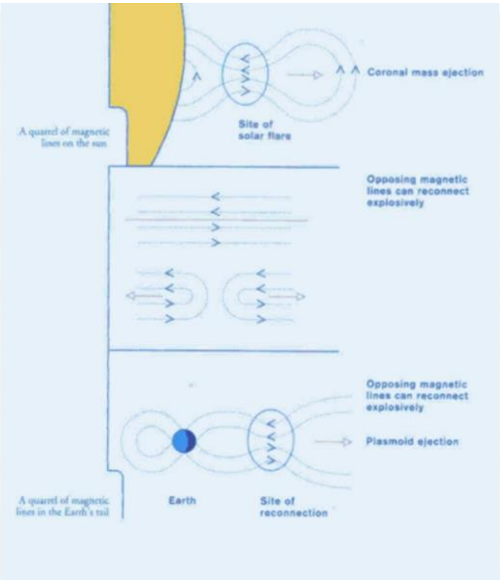


Figure 4.27. Energy balance for diffusion region surrounding the x-line. Energy input and outflow rates are indicated. Magnetic energy is converted into kinetic energy in the diffusion region. Thermal energy is neglected for simplicity.

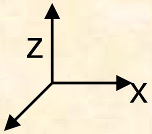
A REKONNEKCIÓ EREDMÉNYEKÉPP A PLAZMA MÁGNESES ENERGIÁJA KINETIKUS ENERGIÁVÁ ALAKUL.

EZ LEJÁTSZÓDIK MIND A FÖLDI CSÓVÁBAN, MIND A NAP ANYAGKILÖVELLÉSEI ESETÉBEN.



A CSÓVA

- A BOLYGÓKÖZI TÉR ERŐVONALAINAK ÁTHALADÁSA SPECIÁLIS PLAZMASTRUKTÚRÁT EREDMÉNYEZ: A CSÓVÁT.
- E TÉRSÉGBEN ELLENTÉTES IRÁNYBA MUTATÓ MÁGNESES ERŐVONALAK ALAKULNAK KI, EZT SZÜKSÉGSZERŰEN EGY ÁRAMLEPEL VÁLASZTJA EL.



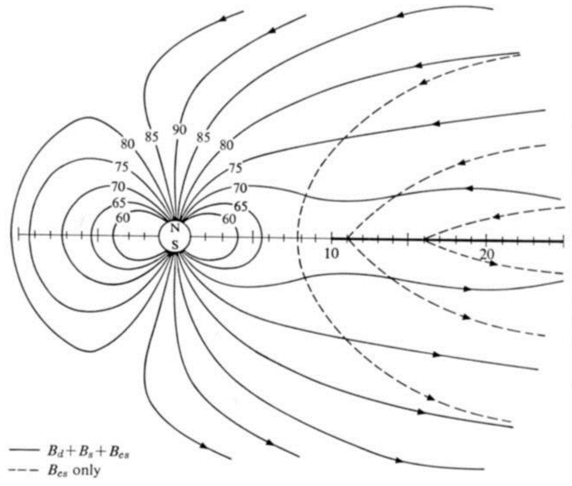


FIGURE 7.18 Geomagnetic field model used to explain the behavior of trapped particle distributions. The dashed lines are the magnetic field of the current sheet B_{cs}. The solid lines represent the superposition of the sheet field and the dipole B_d and a surface magnetopause field B_s. (From Williams and Mead, 1965)

- A FENTI KOORDINÁTA RENDSZERBEN A TÉR LEÍRHATÓ

  $B_x=B_o$ ha $z>L$
  $B_x=B_o\, z/L$ ha $L>z>-L$
  $B_x=-B_o$ ha $z<-L$

  vagy: $B_x=B_o \tanh(z/L)$
- Ekkor $J_y \sim B_o\, \mathrm{sech}^2(z/L)$
- L az áramlepel vastagsága

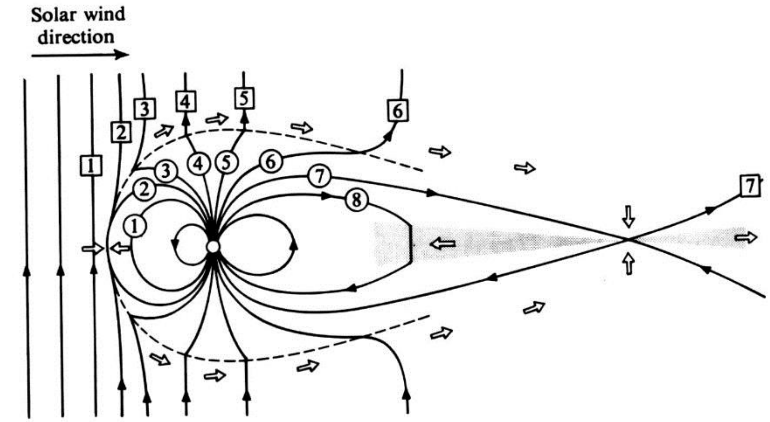


FIGURE 7.19 Evolution of merged magnetic field lines being swept back to form a tail (originally proposed by J. Dungey in 1961).

A CSÓVA 2.

- A CSÓVÁBAN A RÉSZECSKÉK MOZGÁSA MEGLEHETŐSEN KAOTIKUS, EZT ILLUSZTRÁLJA A MELLÉKELT PRÓBARÉSZECSKE KÖZELÍTÉS

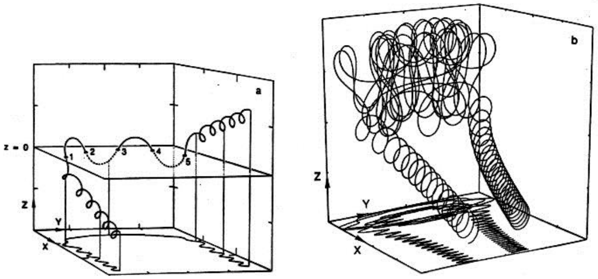


Fig. 2. (a) A Speiser orbit and its *x*-*y* projection. The crossing points at $Z = 0$ are indicated. $\hat{H} = 500$ and $b_n = 0.1$. The *z* axis is expanded by 1.2. (Adapted from *Chen and Palmadesso* [1986].) (b) A stochastic orbit. The *x* axis is compressed by ~10.

- A PLAZMA MOZGÁSA, AZ ÁRAMLEPELBEN VÉGBEMENŐ DISSZIPÁCIÓ A MÁGNESES TERET ENERGETIKAILAG KEDVEZŐBB ÁLLAPOTBA JUTTATJA: EZ A MÁGNESES REKONNENCIÓ

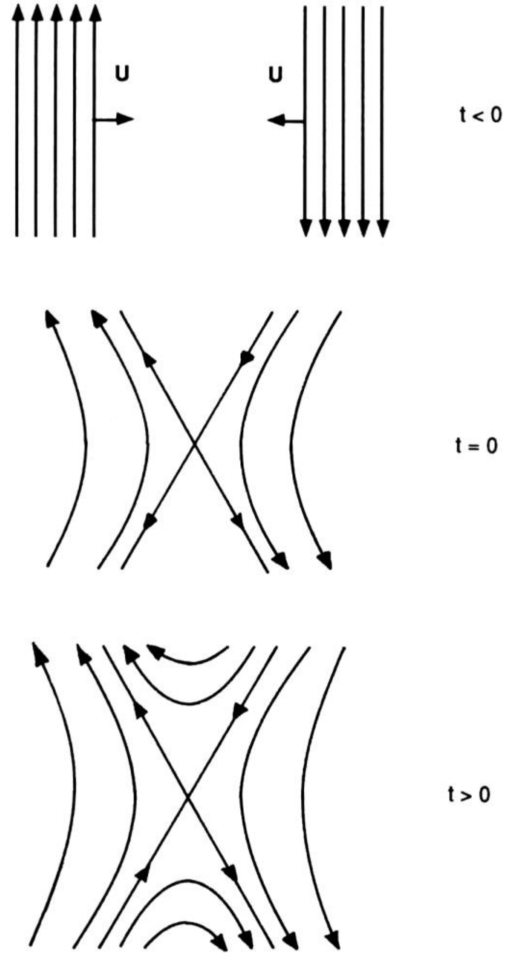
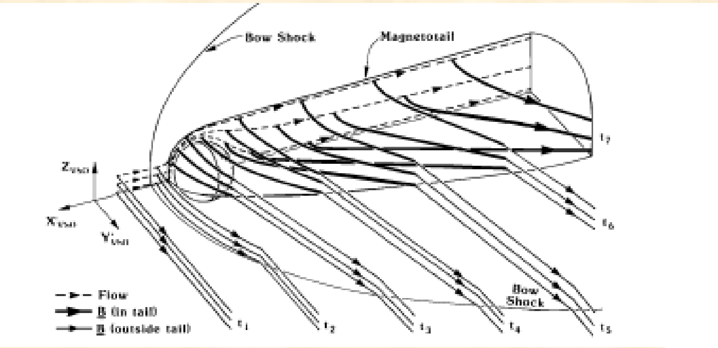


FIGURE 7.20 A schematic diagram to show how merging of the magnetic field works.

FIELDS AND PARTICLES IN THE TAIL
Russell, 1999; McComas et al., 1986



The momentum equation

$$\rho(\partial u/\partial t + \mathbf{u}\nabla\mathbf{u}) = -\nabla p + \mathbf{j}\times\mathrm{B} + \rho F_{\mathrm{g}}/m_{\mathrm{p}}$$

$$-\nabla B^2/2\mu_0 + (B\,.\nabla)B/\mu_0$$

$$\hat{\mathrm{b}}\hat{\mathrm{b}}\,.\nabla B^2/2\mu_0 \quad -\mathrm{n}B^2/\mu_0 R_{\mathrm{c}},$$

Curvature force or magnetic tension

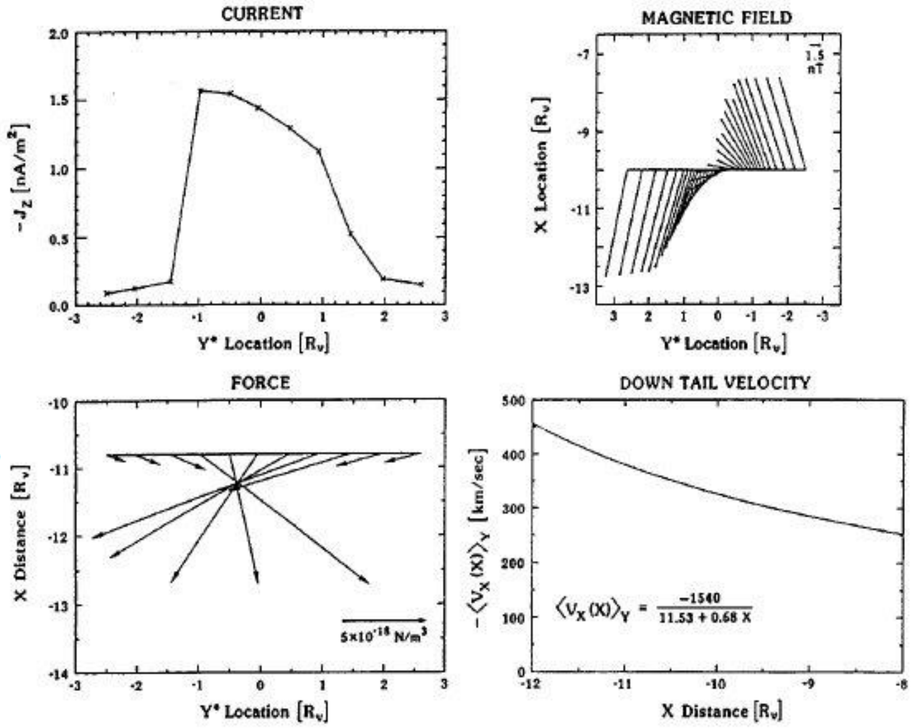


Fig. 11. Force balance in the Venus magnetotail (McComas *et al.* 1986). Upper right panel shows the average magnetic field configuration at $10R_V$ behind Venus. Upper left panel shows the electric current as a function of crosstail position at this point. The lower left panel shows the $\mathbf{j}\times\mathbf{B}$ force on the tail plasma as a function of crosstail position at $10R_V$ downtail. The lower right panel shows how this force accelerates the bulk velocity of the plasma with increasing downtail distance.

IONOK A TERMINÁTOR MÖGÖTT

MARS VÉNUSZ

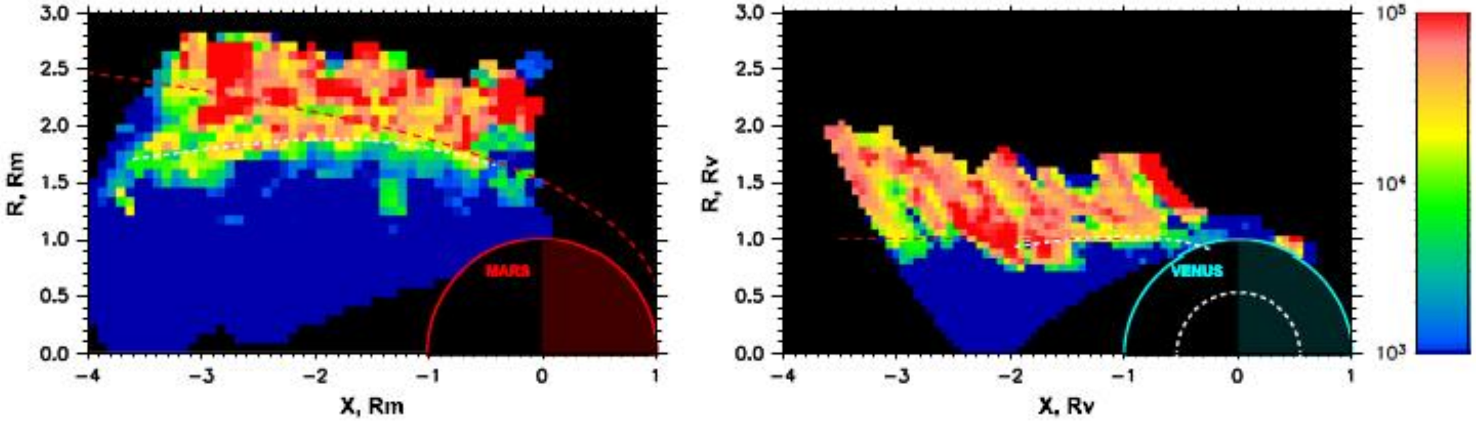
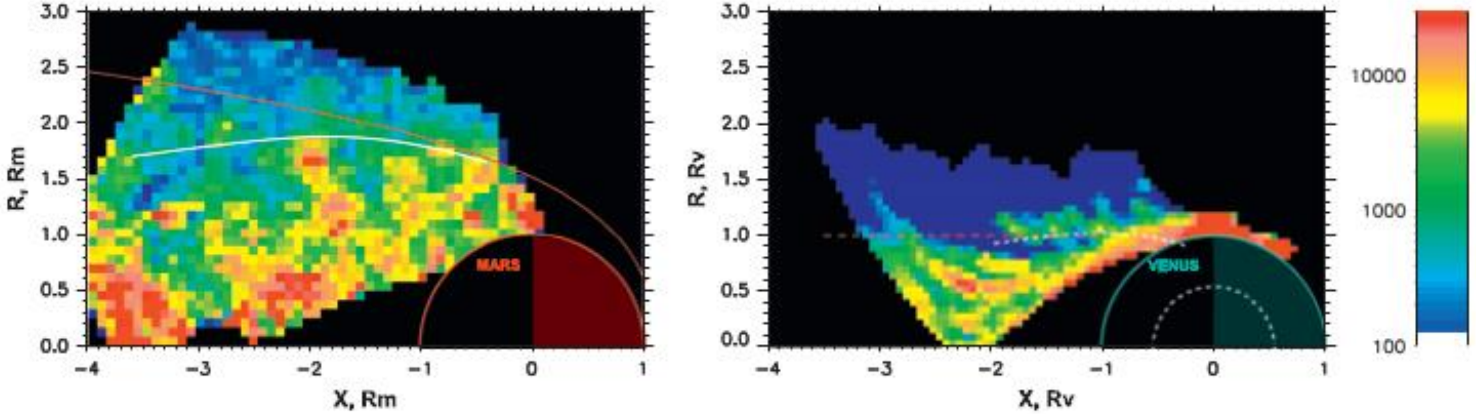
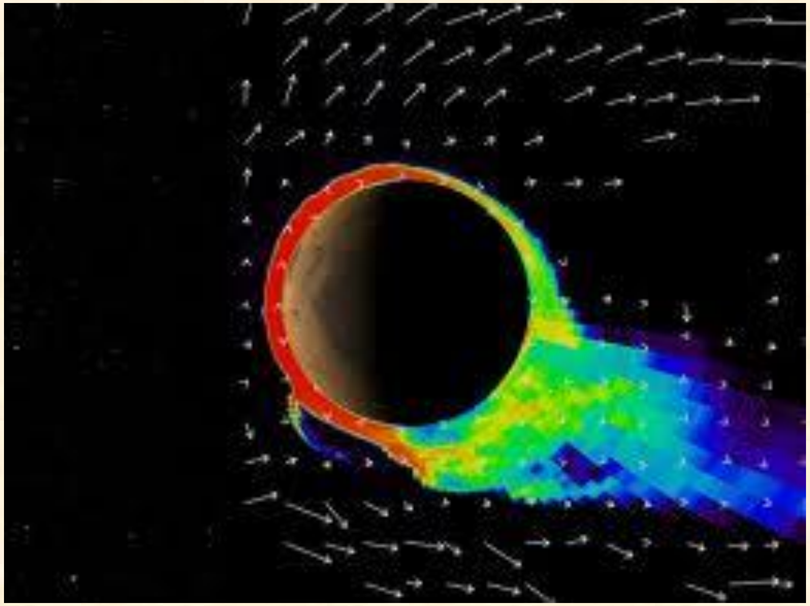


Fig. 1. Spatial distribution of the proton flux with energy greater than 300 eV in cylindrical coordinates: X connects the planet center and the Sun; $R = \sqrt{Y^2 + Z^2}$. All scales are in planet radii. The color scale is shown in arbitrary units. Blue color indicates zero flux, and black color shows the absence of the measurements. Left panel shows the Martian wake, and right panel shows the Venusian one. Red dashed curve in the left panel shows the theoretical position of the magnetosphere boundary after Kallio (1996). Similar dashed line in the right panel shows the wake boundary at Venus. White dashed curves are explained in the text.



A NAPSZÉL ÉS A VÉNUSZ KÖLCSÖNHATÁSA ANYAGVESZTÉSHEZ VEZET A CSÓVÁN KERESZTÜL



FENT: EGY MODELL A NAPSZÉL ÁLTAL ELRAGADOTT ANYAGRA

OLDALT: A VENUS EXPRESS SZONDA MÉRÉSEI A VÉNUS CSÓVÁJÁBAN

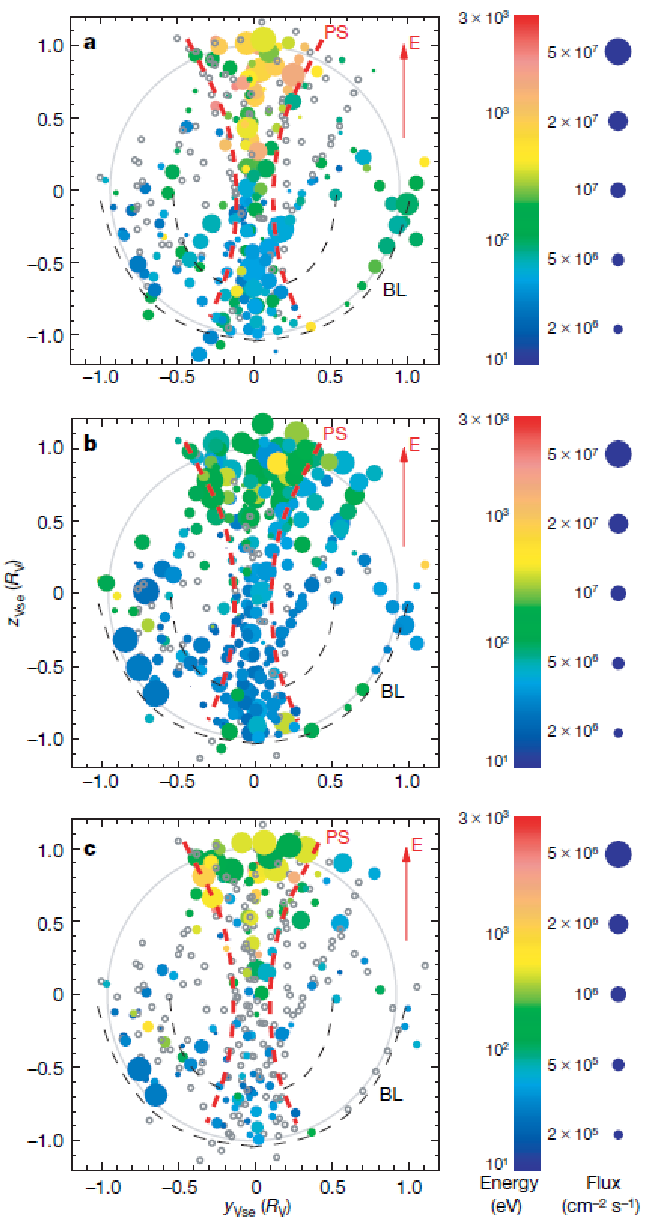
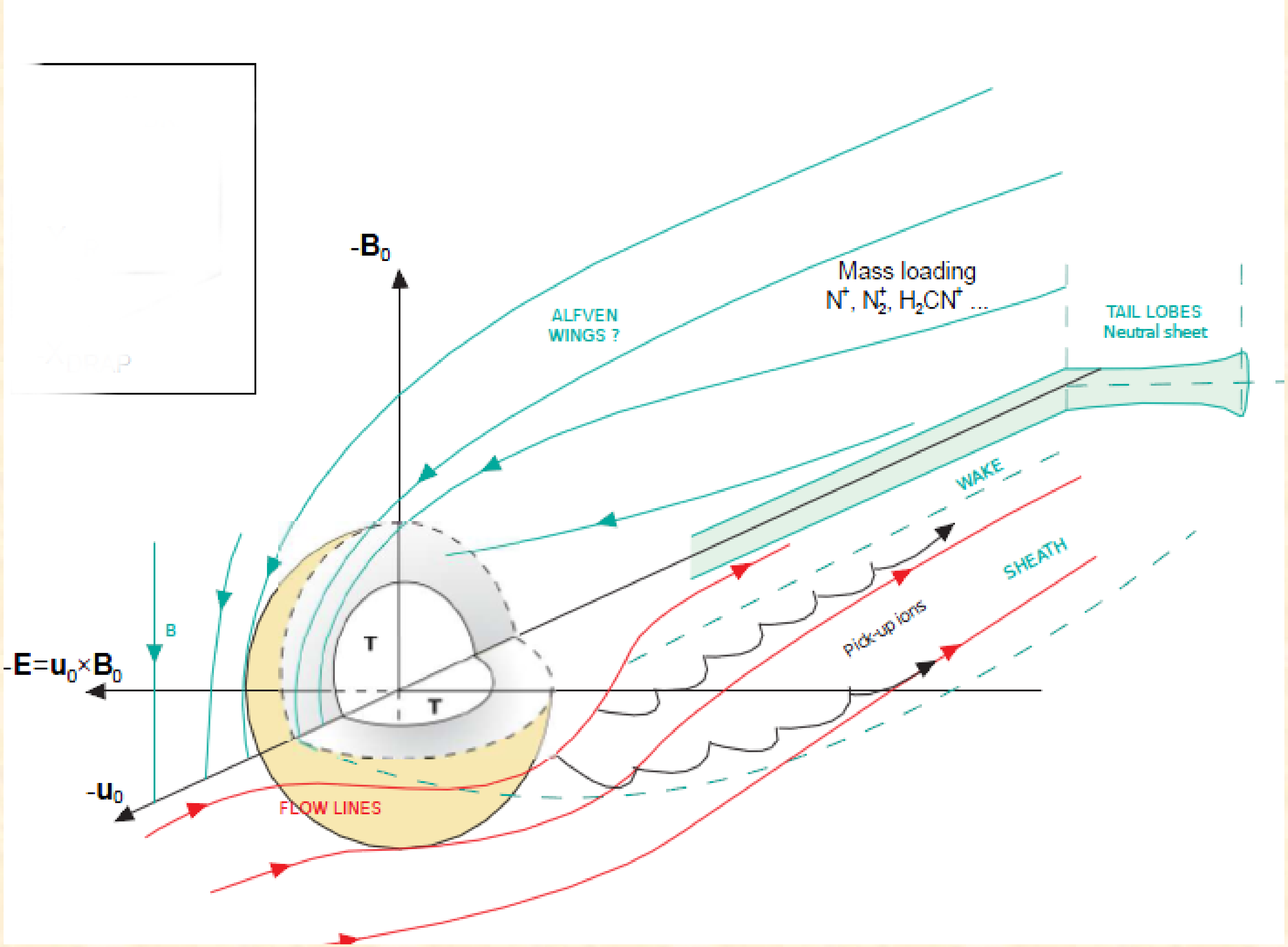


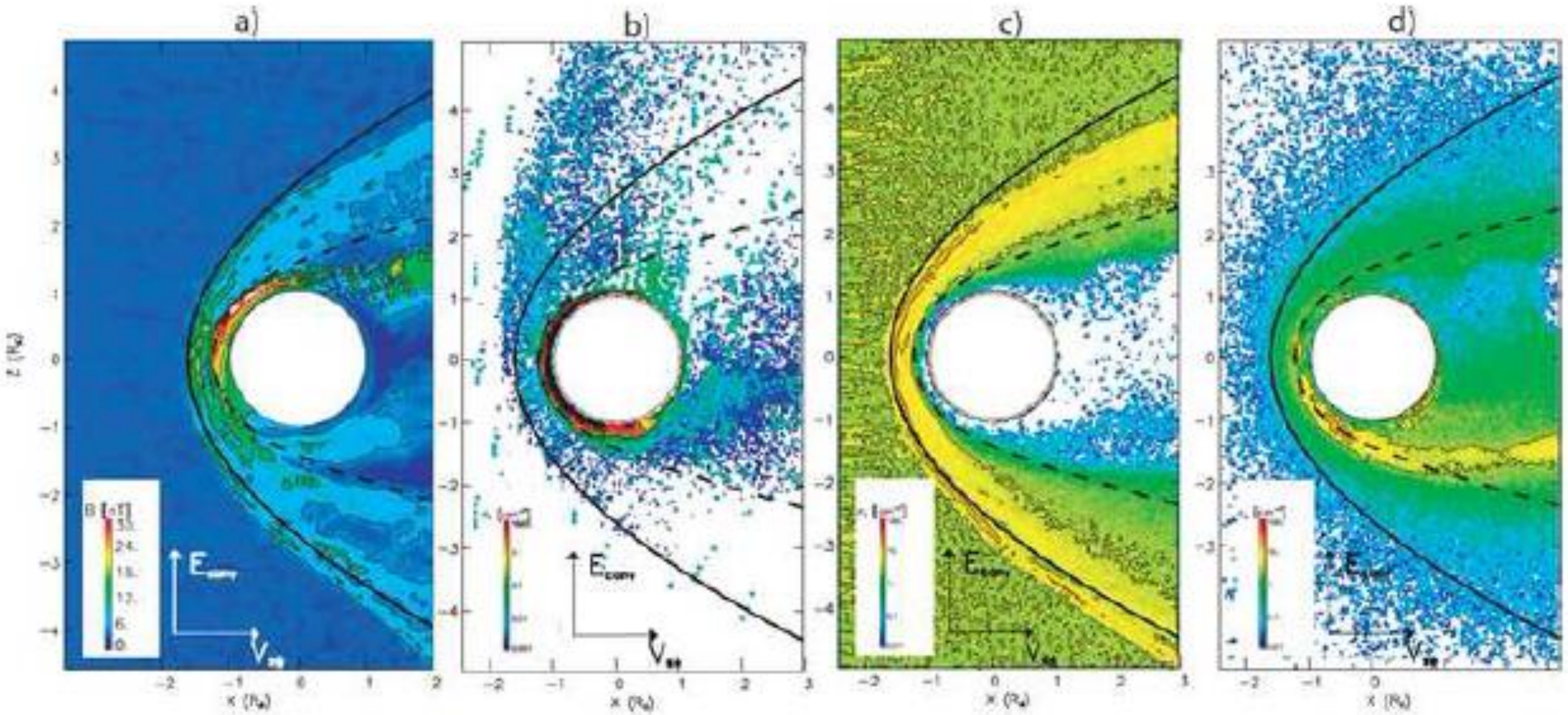
Figure 3 | Spatial distribution of the escaping plasma. The measured O^+ (**a**), H^+ (**b**) and He^+ (**c**) flux distributions in the tail region from 33 orbits

A Titán esete: nem szimmetrikus ion pályák

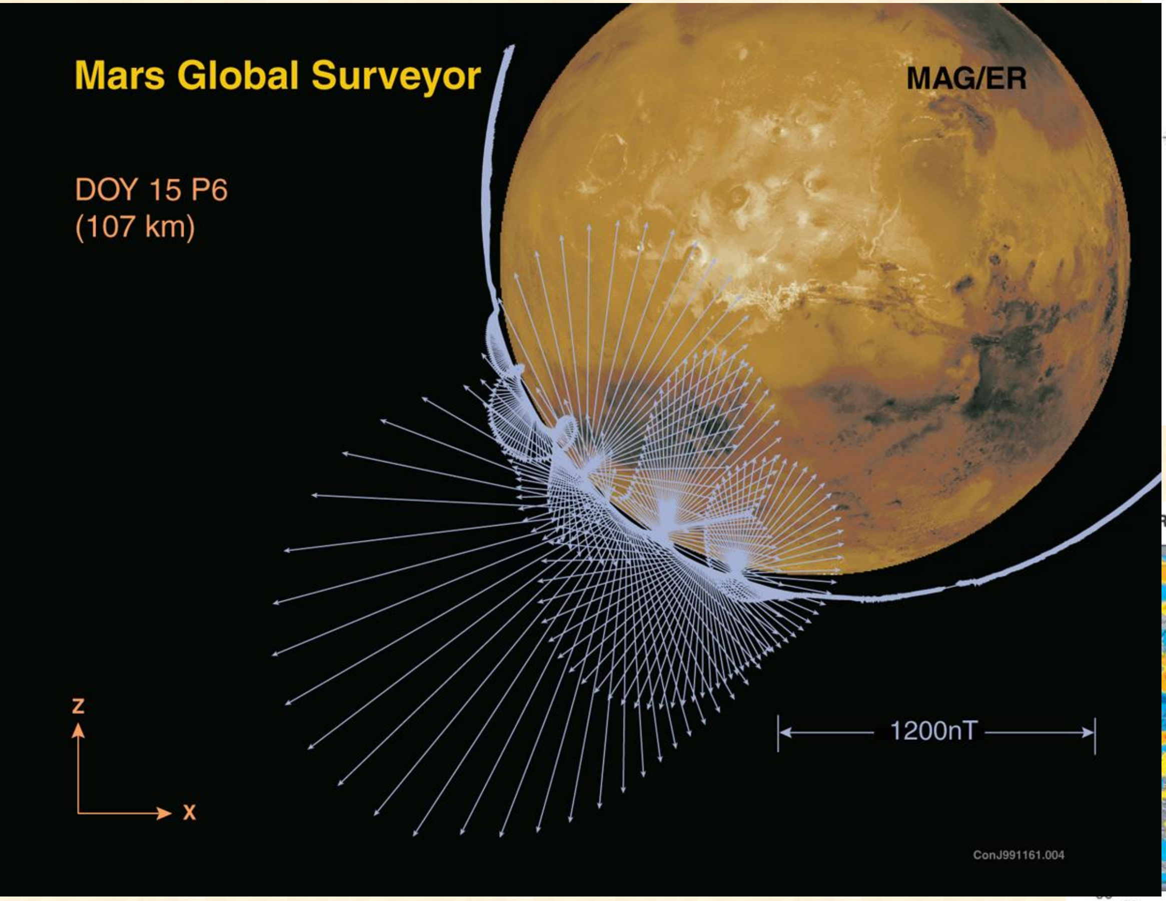


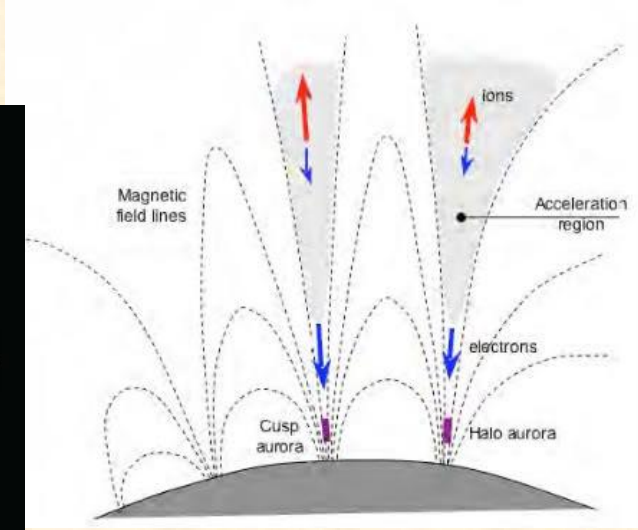
Nem szimmetrikus eloszlások (szimuláció)

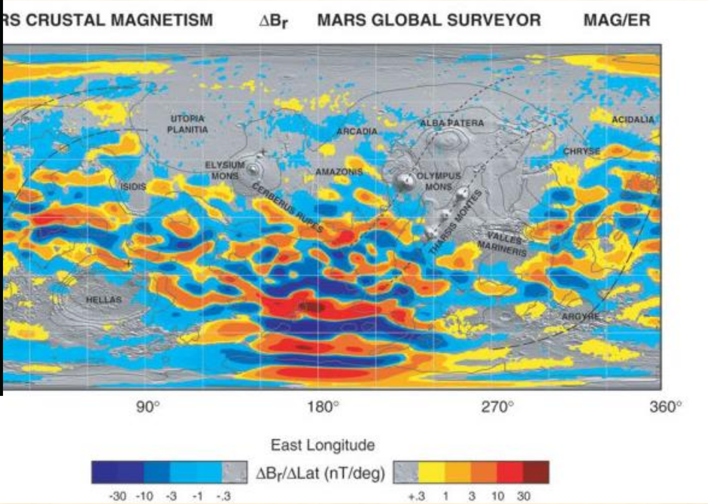
B **O+** **napszél** **bolygó protonjai**



A MARS MARADÉK MÁGNESESSÉGE

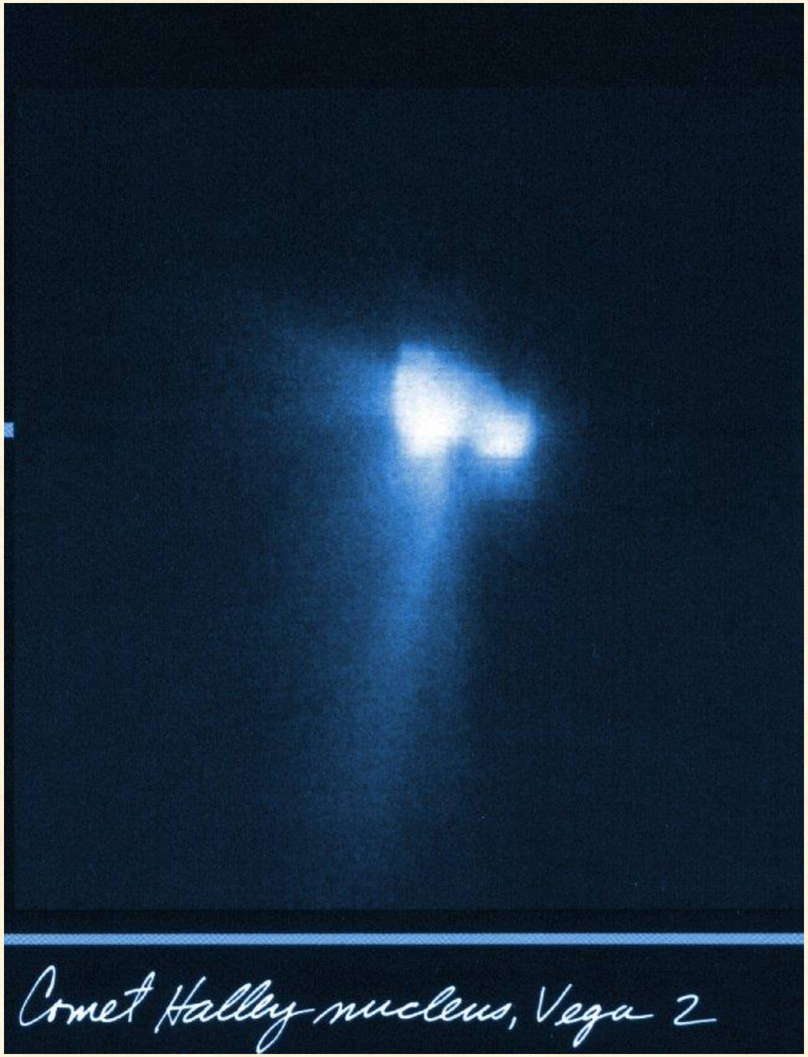






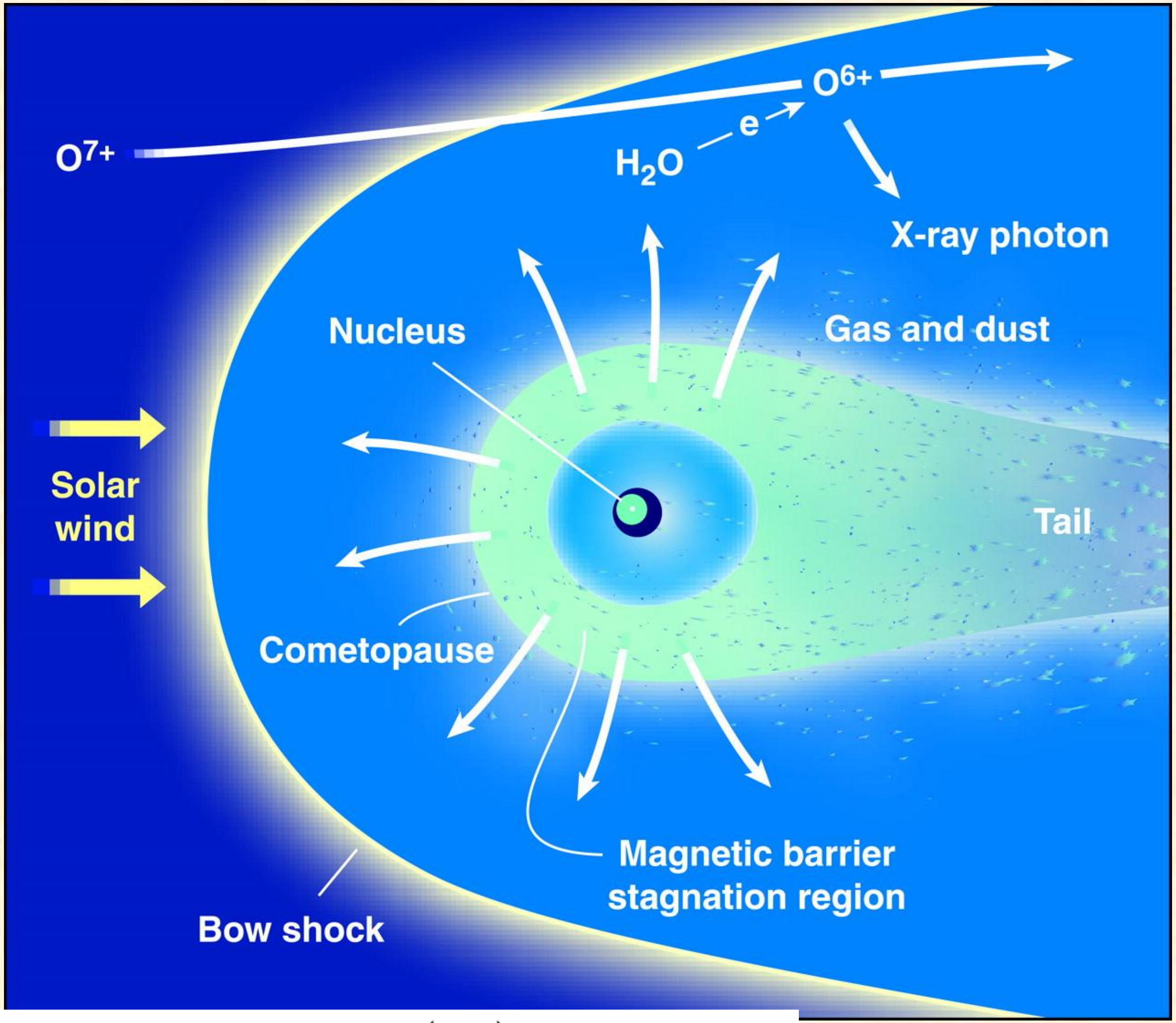
ÜSTÖKÖSÖK: SZERTEÁRAMLÓ IONOK

- **A SZÉTÁRAMLÓ IONOK HATALMAS KÖLCSÖNHATÁSI ZÓNÁT EREDMÉNYEZNEK:**
  A ZAVAROK AZ ÜSTÖKÖSTŐL TÖBB MILLIÓ KILOMÉTERRE IS ÉSZLELHETŐEK!
- **A KIÁRAMLÓ ANYAG LASSAN BELEÉPÜL A NAPSZÉLBE, E FOLYAMAT: MASS LOADING**
- **SPECIÁLIS AKADÁLY, RÉSZLETEIVEL NEM FOGLALKOZUNK**



Comet Halley nucleus, Vega 2

Scheme of the solar wind/comet interaction



$$n_n = \frac{Q}{4\pi r^2 V_n} \exp\left(\frac{-r}{V_n \tau_i}\right), \quad (5)$$

Published by AAAS

A HALLEY ÜSTÖKÖS PLAZMAKÖRNYEZETE

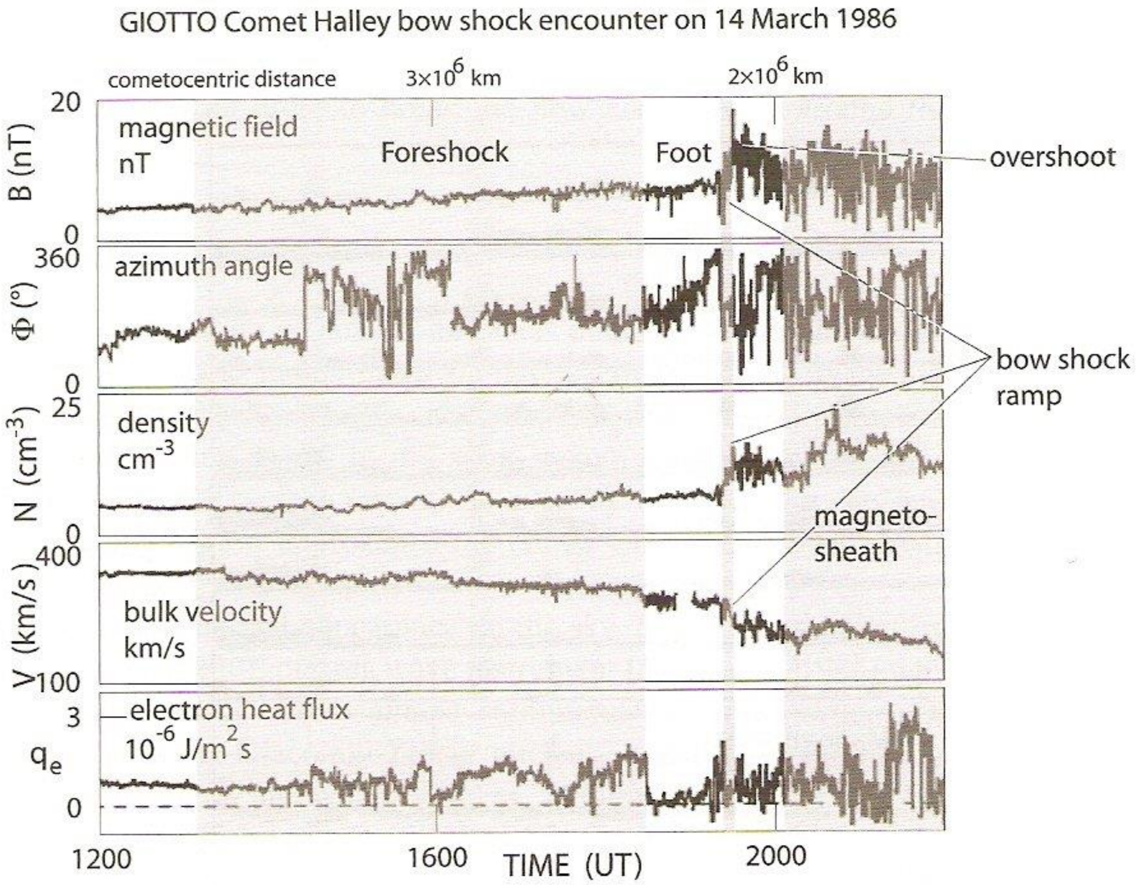


Figure 10.18: Giotto passage across the Halley bow shock on 14 March 1986 [data taken from *Larson et al*, 1992, courtesy American Geophysical Union]. Proving the existence of a cometary bow shock. The spacecraft entered the foreshock at about 1400 UT just before an interplanetary discontinuity passed over it which is seen in the turning of the magnetic field. After 1600 UT it was again in the foreshock, entering the foot region with the continuously increasing magnetic field and crossed the shock ramp at about ~1930 UT. The shock compression factor was about 2, and the shock was oblique, neither parallel nor perpendicular.

Ellenőrző kérdések

1.Rajzold le, hogyan hat kölcsön a napszél a nem mágneses, de ionoszférával rendelkező testekkel! Értelmezd a határfelületeket, tartományokat! (segítség: 4.dia)
2. Rajzold le egy vezető gömb napszéllel való kölcsönhatása során kialakuló tartományokat! Hol alakul ki a határfelület, minek a függvényében? (segítség: 10.dia)
3. Milyen plazmatartományok alakulnak ki a Marsnál (illetve Vénusznál)? (segítség: 13.dia)
4. Mi mozgatja a csóvában a részecskéket? Mik azok a pick-up ionok? (segítség: 30.dia)