Power Aspects of Processes at the Piston Shock Region

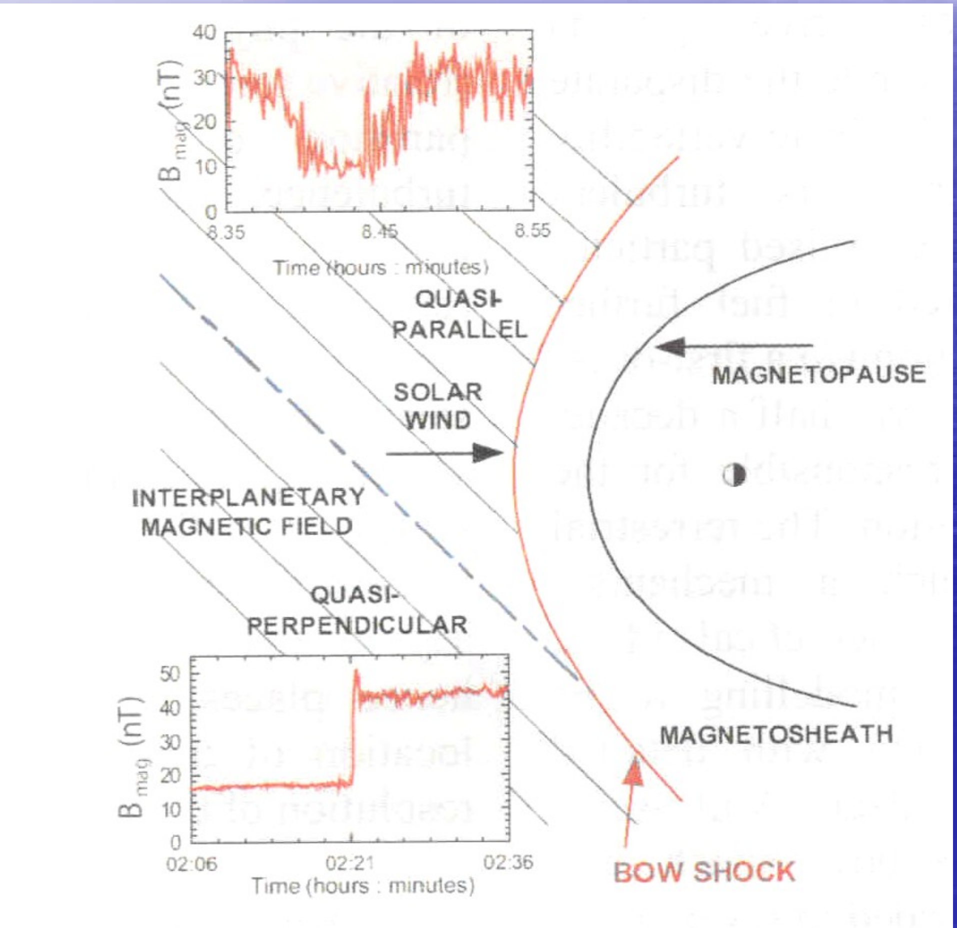
P.A. Sedykh

Irkutsk National Research Technical University. 83, Lermontov str., 664074, Irkutsk, Russian Federation;
e-mail: pvlsd@mail.ru

Introduction

Identifying blast-wave shocks, which can arise during CME formation, is a much more complex problem. The difference from piston shocks is that a blast-wave shock originates from the explosions that frequently accompany CME formation, and further propagates freely without any CME piston effects. Earth's bow shock (BS) is a piston shock. Behind the bow shock front there is a flow of the modified solar wind plasma: transition layer, which also carries the modified magnetic field of solar wind. Velocity and density of plasma as well as parameters of magnetic field of this current can be estimated if the form of the bow shock front and of magnetopause are considered to be known. In this paper we assumed them to be paraboloids of rotation. In this paper we have determined potential distribution along magnetopause from the balance condition of substance coming into transition layer from the solar wind on one side and leaving through the gap between magnetosphere and the bow shock front and through magnetopause on another. To a first approximation this distribution differs from potential distribution at the BS front only in a constant multiplier. We used the established potential distribution as a boundary condition while solving the problem on potential distribution in the magnetosphere. The first solution harmonic turned out to coincide in the form with the boundary condition on magnetopause. We have constructed the full solution for electric field in the magnetosphere having limited ourselves to the first harmonic and corotation field. We have obtained necessary equations to model processes in the region of bow shock.

Interest to research the processes in BS has strongly increased recently (research within the framework of projects – GEOTAIL, CLUSTER-II, THEMIS; interplanetary shocks - in SPECTR-R). Bow shock is a powerful transformer of the solar wind kinetic energy into the gas dynamic and electromagnetic energy.

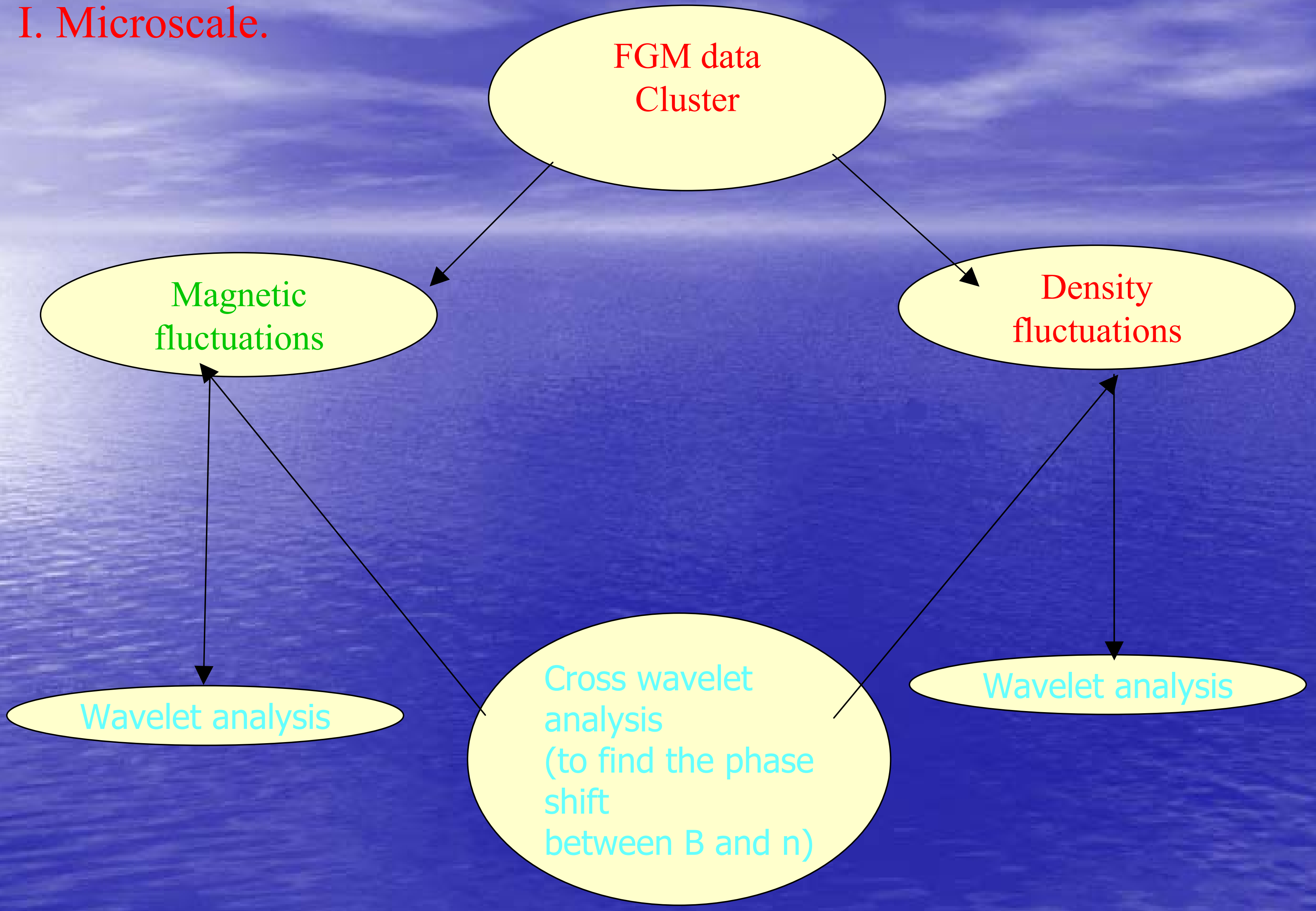


[Balogh, A., Schwartz, S.J., Bale, S.D., Balikhin, M.A., Krasnoselskikh, V.V. (2005). Cluster at the bow shock: Introduction. Space Sci. Rev., 118, P. 155-160]

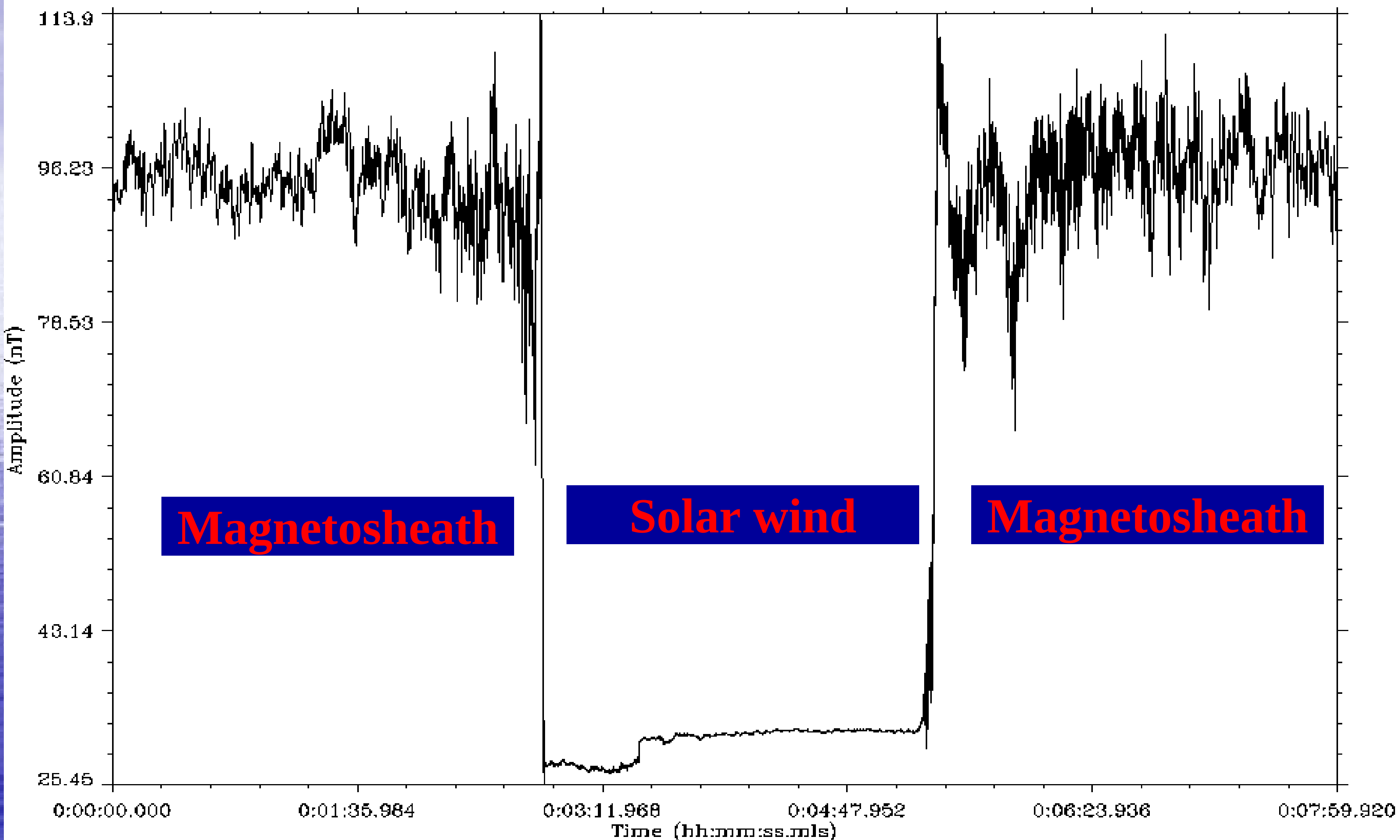
- The solar wind energy also feeds the ion acceleration process, the generation of waves in the region of bow shock, and the energy necessary to build up the foreshock. The suggested mechanism of electric power generation at the bow shock front is physically completely clear and does not require introduction of any hypothetical properties of plasma such as additional viscosity or electroconductivity and at the same time meets all necessary requirements to a power source for magnetospheric processes.
- Leonovich (2012) [Leonovich, A.S. (2012). Wave mechanism of the magnetospheric convection. Planetary and Space Science., 65, P. 67–75.] succeeded in indicating that oblique magnetosonic waves, penetrating into the magnetosphere and bringing their momentum into this region, are generated in the shear flow at a supersonic flowing of the magnetosheath plasma past the magnetopause. Leonovich A.S. presented an original wave mechanism of magnetospheric convection. But I think that fast magnetosonic waves entering the magnetosphere from the magnetosheath excite slow magnetosonic waves at the resonance magnetic shells inside the magnetotail. Resonant oscillations interact with the background plasma transferring their momentum to it, and, as a result, the wave mechanism might be associated with Bursty Bulk Flows generations, but not with generation of large-scale mangetospheric plasma convection.
- In the study [Santolik, O., Sedykh, P., Wang, X., Amar, Kakad, Rongxin, Tang, Xuzhi, Zhou, Zongying, Huang. Case studies of wave phenomena in the Earth's bow shock region. 3rd Regional COSPAR Workshop, Beijing, 2004, 10-14.] it was interesting to see the Poyting flux value and to estimate the ratio of the energy flux carried by the waves to the kinetic energy flux of the incident solar wind.

- The scientific objectives in our study were the following: 1. Origin and propagation characteristics of two type of wave phenomena observed close to the bow shock(a) narrow-band waves below the local electron cyclotron frequency (at frequencies near 0.5 of the electron cyclotron frequency); b) low-frequency waves (at frequencies comparable or less than the proton cyclotron frequency)).
- 2. Two types of wave phenomena observed close to the bow shock.
- 3. Major free energy source responsible for excitation of these waves:
- a) Mechanism and the parametric study of their generation
- Wave propagation
- Polarization - wave mode recognition
- Energy flux
- Spatial-temporal structure

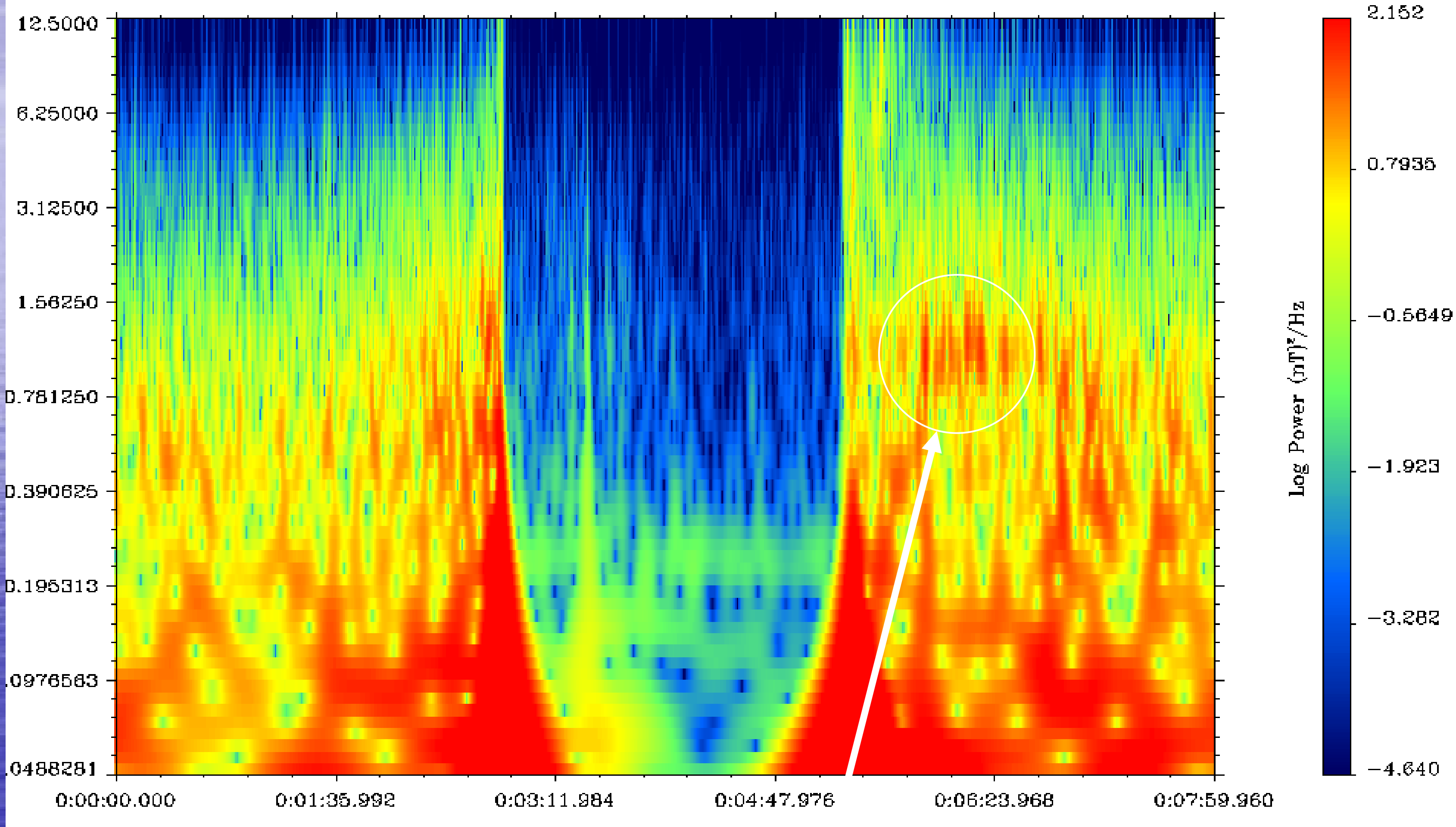
I. Microscale.



Magnetic field profile



Magnetic field wavelet power



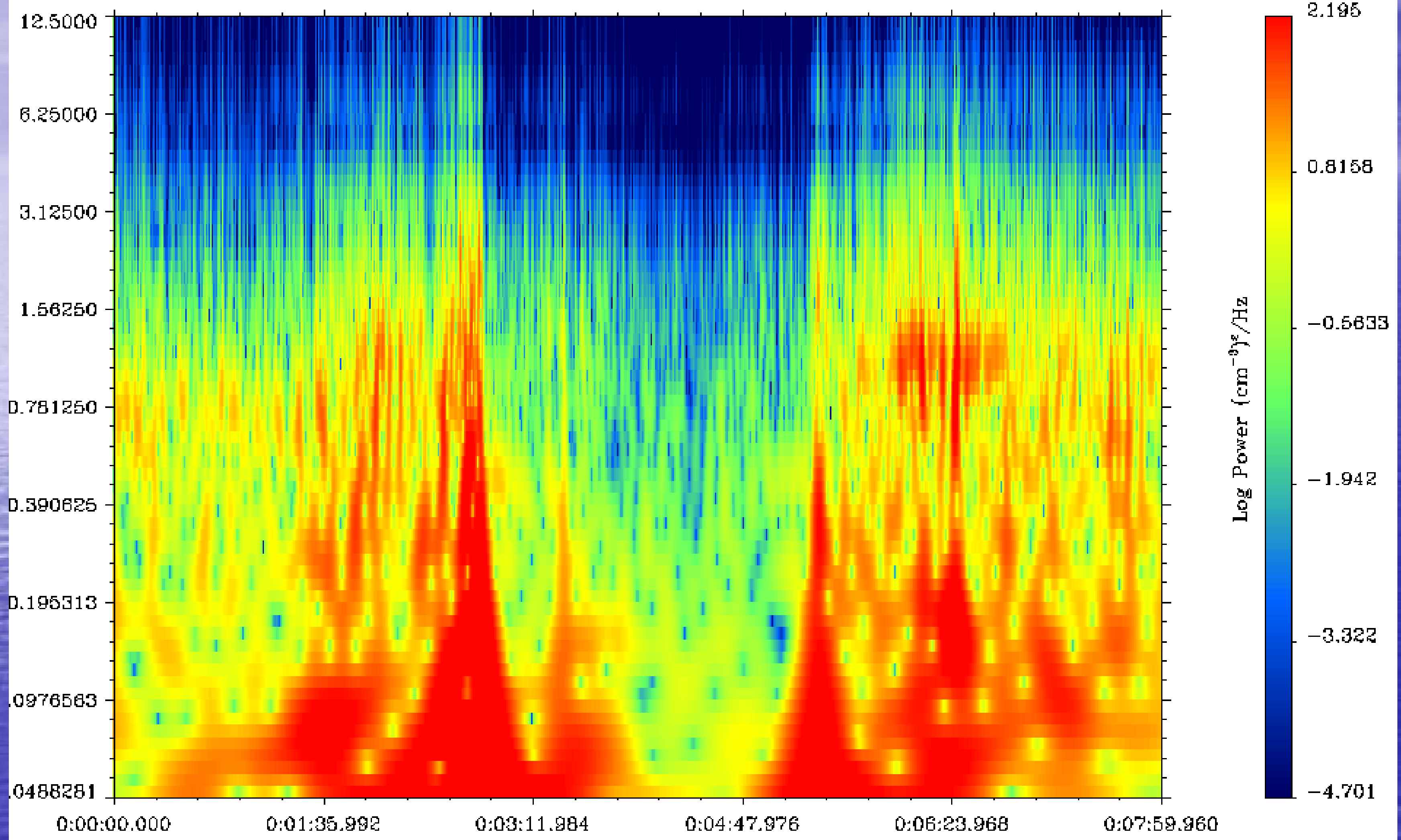
Scale: frequency (Hz)

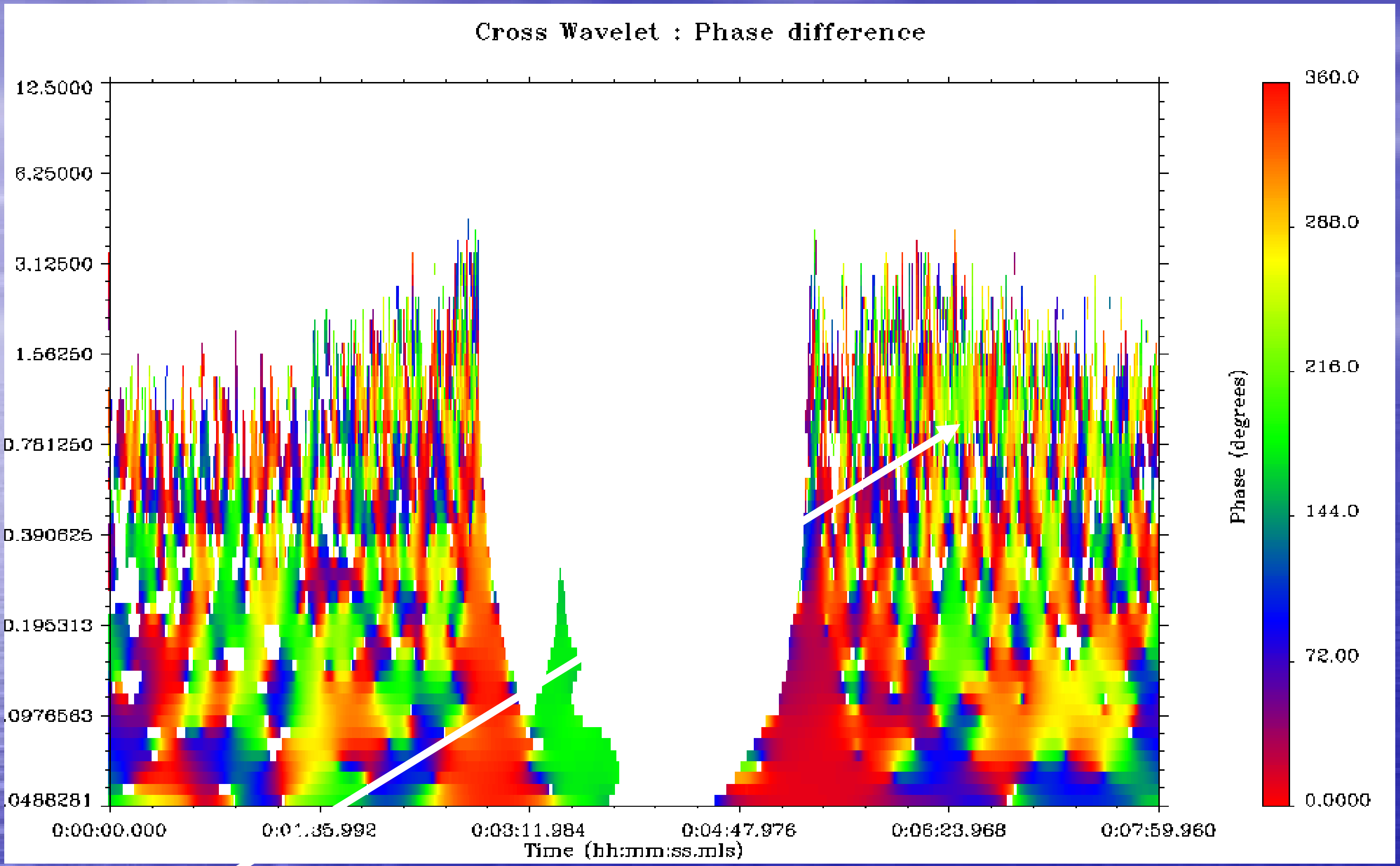
Time

Poynting flux: ~1.2 % of the kinetic energy flux of the incident solar wind

Density fluctuations - wavelet power

Scale: frequency (Hz)



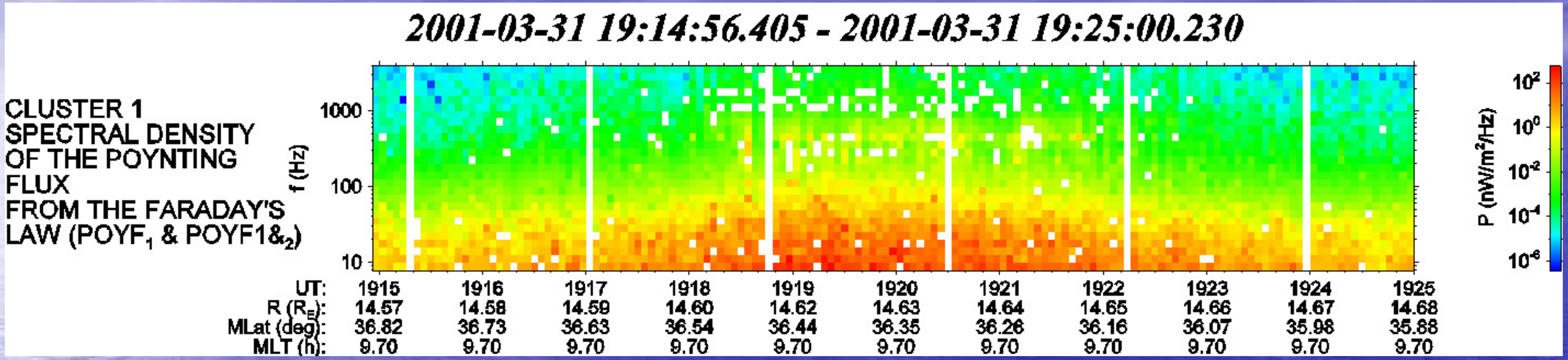


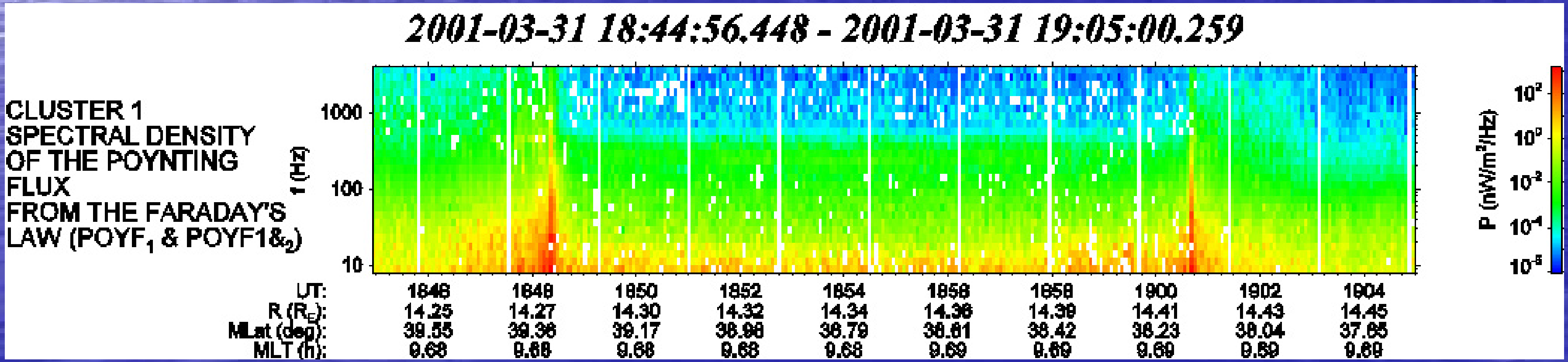
180 degrees: Slow mode or mirror mode

polarization of the magnetic field: (1) high degree (2) wave vector along Z_{GSE} = perpendicular to the plasma flow: slow mode

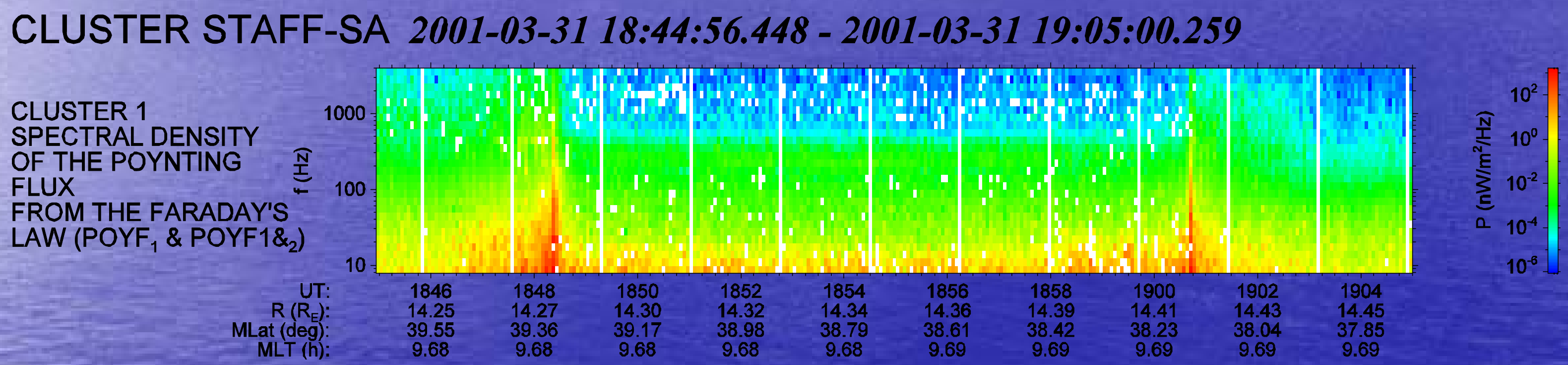
- We have observed bursts of electromagnetic waves in the upstream region of the bow shock, and also in the downstream region (very near to the bow shock). The waves in the downstream region had a frequency ranging from 300 Hz to 1000 Hz. They were all right-hand circularly polarized and propagated parallel to the ambient magnetic field. So we concluded that the waves are whistler mode waves. Because of their parallel propagation, the waves could be excited by the electron cyclotron resonance. Cold plasma theory was used to estimate the phase velocities. Also, based on wave parameters of the waves, we calculated the electron cyclotron resonant velocity (energy). It showed that the waves mainly interact with several hundred eV and several keV electrons. It was also interesting to see the Poyting flux value and to estimate the ratio of the energy flux carried by the waves to the kinetic energy flux of the incident solar wind. We concluded that only a very small portion of the solar wind energy dissipates into the whistler waves, typically 0.1%. As a comparison, we focused on the waves of similar frequency in the upstream region. The waves showed almost the same properties as downstream waves, except for lower frequencies, from 150 Hz to 300 Hz. So the whistler waves upstream may also be excited by electron cyclotron resonance. Different frequencies were due to the lower magnetic field value and lower densities in the bow shock upstream region. Also, we calculated a Poyting flux value and an estimation of the percentage of energy. We concluded that those 150 Hz to 300 Hz waves can carry even less energy.

We can clearly see that only a very small portion of the solar wind energy dissipates into the whistler waves, typically 0.1%.





- Also a Poyting flux value is calculated and an estimation of the percentage of energy is done.



- It seems that those 150 Hz to 300 Hz waves can carry even less energy.

TRANSFORMATIONS OF PARAMETERS OF THE SOLAR WIND AT TRANSITION THROUGH THE BOW SHOCK FRONT AND MAGNETOSHEATH

One can note that modeling of processes of energy transfer from the solar wind into the magnetosphere is very important, because the data from multisatellite magnetospheric missions for these purposes would be a very expensive project. Therefore there arises a necessity for modelling processes of near-Earth space. A selection and applying of correct initial system of equations are also very important.

The process of energy transfer from the solar wind into the magnetosphere, or rather, to convecting magnetospheric plasma, appears to be rather complicated.

The Poynting vector (for the case of the solar wind-magnetosphere interaction) is defined as:

$\mathbf{S} = c\,[\mathbf{E}\mathrm{x}\mathbf{B}]/4\pi$,

where **E**, **B** represent the electric and magnetic fields, respectively; c- is the speed of light.

On one hand: $\mathbf{S} = c\,[\mathbf{E}\mathrm{x}\mathbf{B}]/4\pi = \mathbf{V}B^2/4\pi$, where - is a mass velocity of plasma (in the direction of electric drift);

On the other hand: $\mathbf{S} = c[\mathbf{E}\mathrm{x}\mathbf{B}]/4\pi = \mathbf{V}B^2/4\pi = 2\mathbf{V}PB$, because PB is a magnetic pressure ($P_B = B^2/8\pi$); , (in the stationary case $\mathbf{E} = -\mathbf{grad}(\Phi)$); $\mathbf{curl}(\Phi\mathbf{B}) = \Phi\mathbf{curl}(\mathbf{B}) + [\nabla\boldsymbol{\Phi}\times\mathbf{B}]$; $j = (c/4\pi)\mathbf{curl}(\mathbf{B})$, $\mathbf{div}(\mathbf{S}) = \mathbf{div}(\Phi\mathbf{j})$, because it is well known $\mathbf{div}(\mathbf{curl}) = 0$.

The gas kinetic energy flux will be:

$$\vec{S} = \vec{V}(\gamma \cdot P_g + \frac{1}{2}\rho V^2)$$

Pg – is a gas pressure, **V** – is a mass velocity of plasma, ρ – is a density of plasma; γ – is the adiabatic exponent.

We restrict ourselves to the stationary case. In the stationary case, the terms with partial derivatives (∂E/∂t) and (∂B/∂t) are zero, whereas the electric field is potential: **E**=-**grad**Φ; Φ is the electric potential. It is known that [**grad**Φx**B**]=**curl**(Φ**B**) – Φ**curl**(**B**). Hence **S**=Φ**j**–(c/4 π)**curl**(Φ**B**). The integral over the entire magnetosphere surface (s) is:

the integral **S**ds=[Φ**j**–(c/4 π)**curl**(Φ**B**)]ds =Φ**j**ds.

The integral Φ**j**ds≠0, if Φ≠const.

The energy flow within the closed surface is defined by the electric current normal component and potential distribution along the surface. The density of the electric current component normal to the surface is expressed in terms of surface current divergence.

We shall follow [Whang, Y.C. (1987). Slow shocks and their transition to fast shocks in the inner solar wind. J. of Geophys. Res., Vol. 92, №5. P.4349-4356] in the approach to BS description.

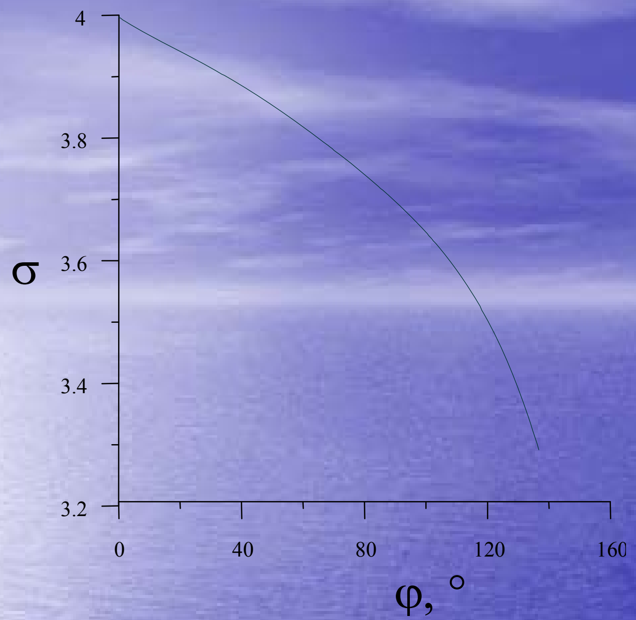
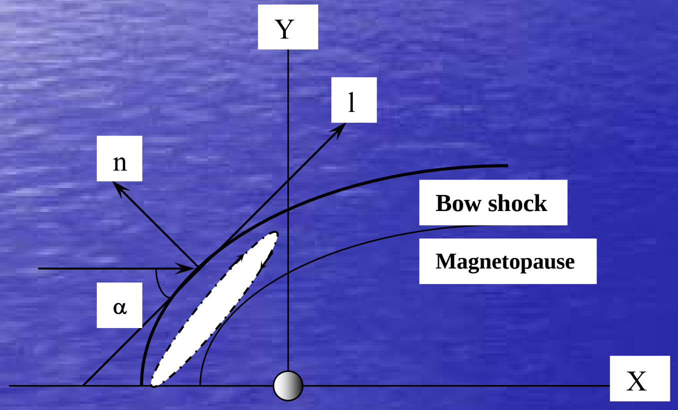
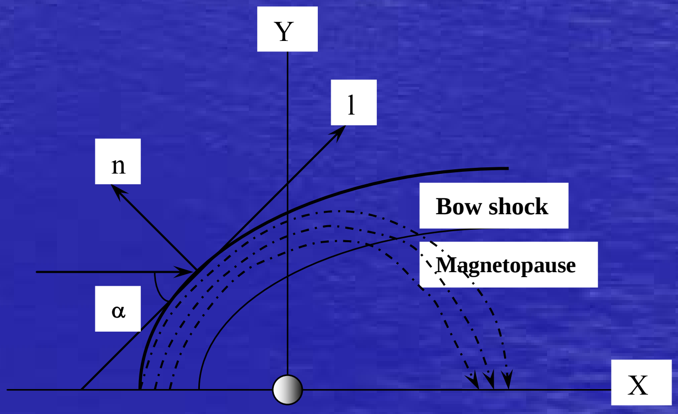


Fig. Value of transition coefficient $\sigma = B_{lt}/B_{0t}$ as a function of the angle φ for the equatorial section (calculated values).





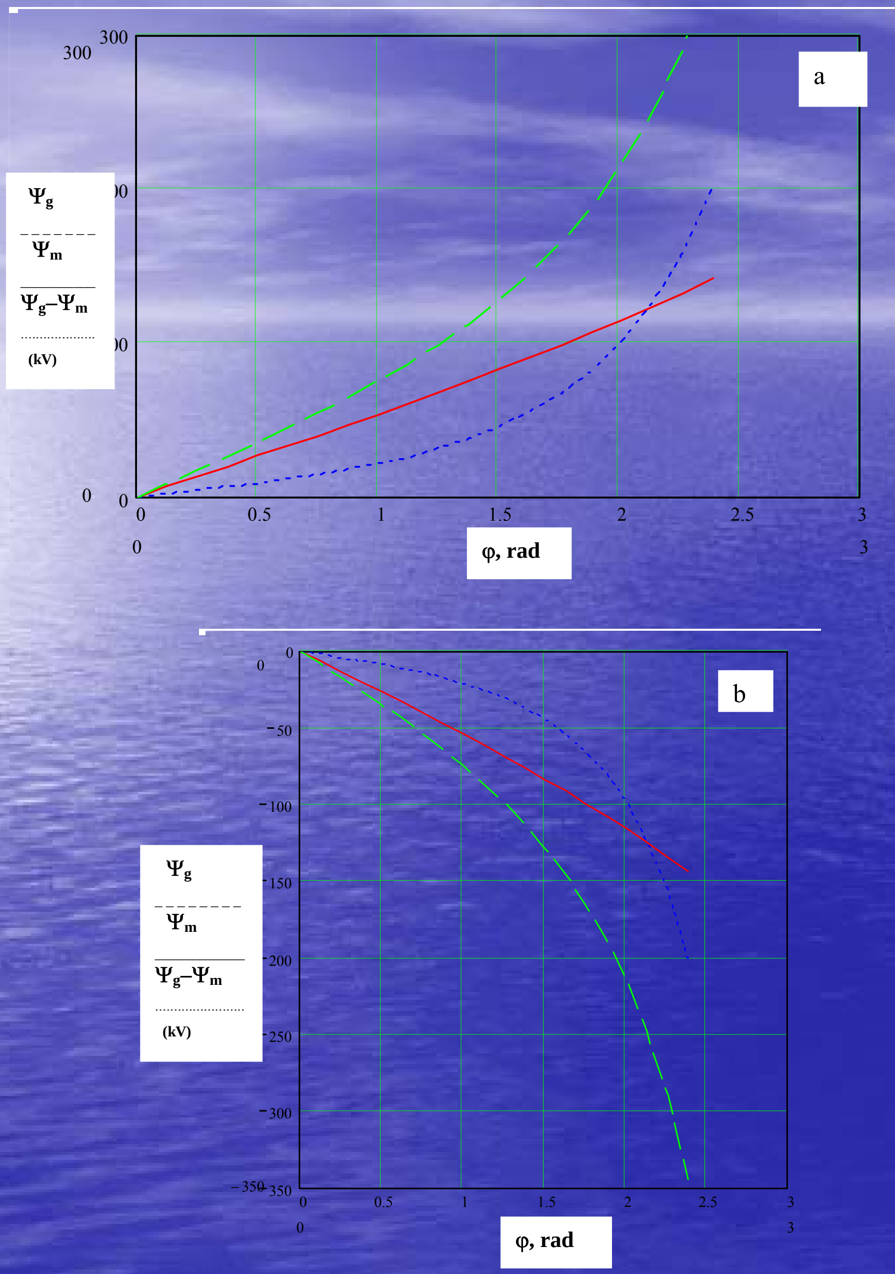


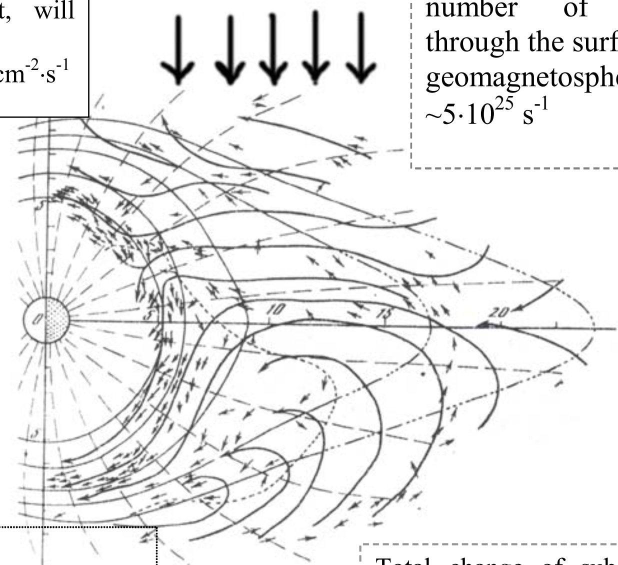
Fig. Results of calculation of change of electric potential $\Psi_g(\varphi)$ - at the bow shock front, $\Psi_m(\varphi)$ - on the magnetopause and the differences $\Psi_g - \Psi_m$ (when IMF B_z=-2nT); φ - in rad : (a) B_z=2 nT, (b) B_z=-2nT

The BS front is a source of electric power. There is a potential difference between the BS front and the magnetosphere, unequivocally associated with the velocity of the transition layer plasma flow. Thus, the magnetopause potential is functionally related to SW parameters. The power consumed by the magnetosphere is spent on the compressor work and consists of active and reactive power. The active part covers losses in the ionosphere (ohmic, primarily), the reactive part returns to the magnetospheric compressor.

The flow of the number of particles, transferable by the electric current, will be:
$j_{3h}/2e$? $10^5 \div 5 \cdot 10^5$ $cm^{-2} \cdot s^{-1}$

$j_{3h} \sim 10^{-4}$ CGSE ($\sim 3.3 \cdot 10^{-10}$ A/m^2)

The total flow of the number of particles through the surface of the geomagnetosphere: $\sim 5 \cdot 10^{25}$ s^{-1}



Total change of substance in the Earth's magnetosphere: ~12 hours – 2.5 days

S=Φ
$\sim 10^{-4}$ CGSE ($\sim 3.3 \cdot 10^{-10}$ A/m^2);
When $E_{sw} \sim 5 \cdot 10^{-9}$ CGSE and volume $\sim 4 \cdot 10^{30}$ cm^3 : Energy flux
$S \sim 10^{18}$ ergs/s ($\sim 10^{11}$ Watt).

Fig. Transportation of energy and plasma from the solar wind into the geomagnetosphere.

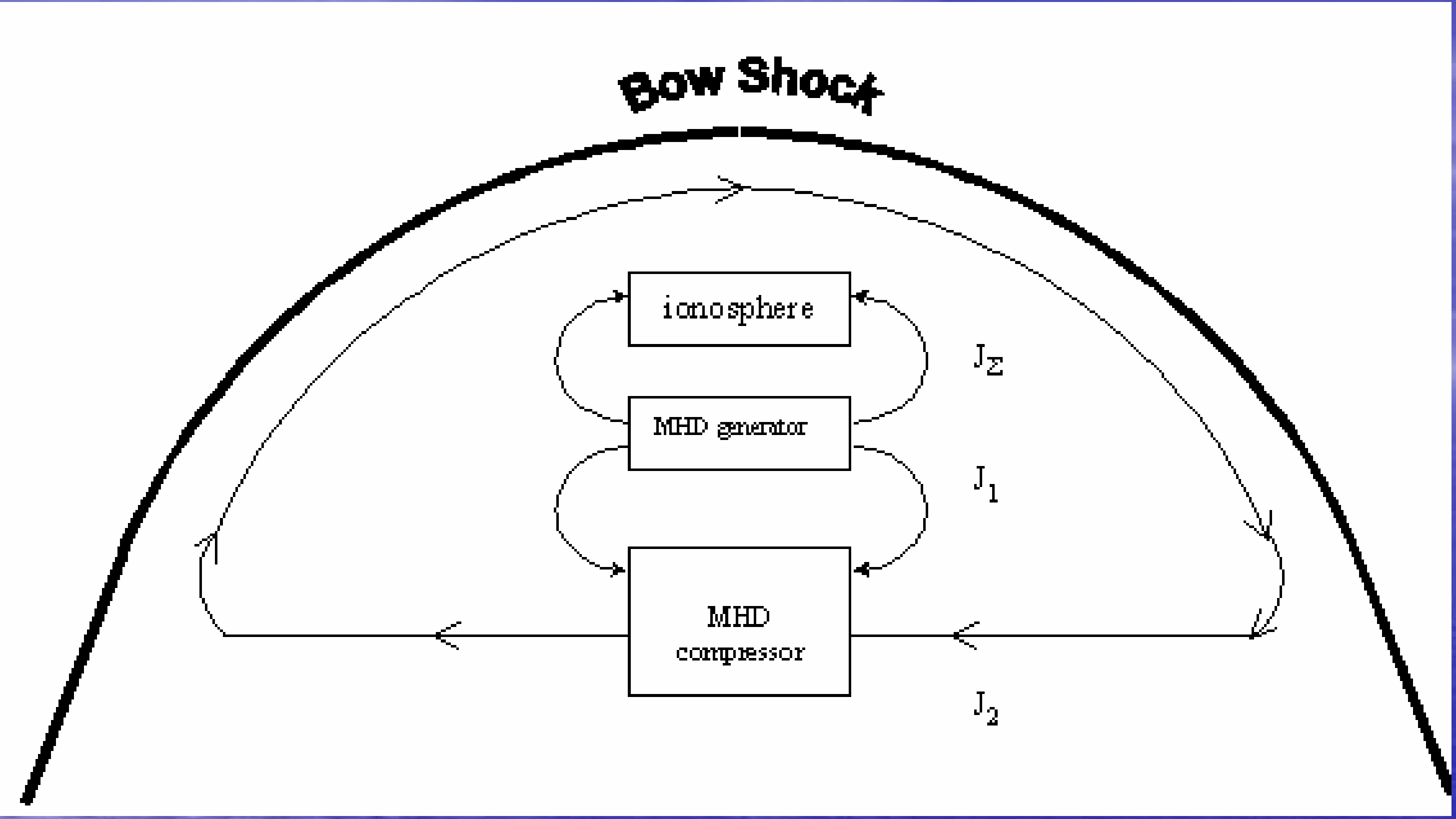


Fig. The simplified scheme of layout of the functional blocks in the magnetosphere:

I - MHD generator that converts solar wind kinetic energy to electromagnetic energy;

II - MHD compressor that converts electric energy to gas pressure;

III - secondary MHD generators that convert compressed gas energy to electric current feeding electrojets in the ionosphere.

CONCLUSION

The suggested mechanism of electric power generation at the bow shock front is physically completely clear and does not require introduction of any hypothetical properties of plasma such as additional viscosity or electroconductivity, and at the same time meets all necessary requirements to a power source for magnetospheric processes.

The bow shock front is the main converter of solar wind kinetic energy into electromagnetic energy. When passing through the bow shock front the intensity of the tangential component of the SW magnetic field and the plasma density increase several fold. Therefore, among other things, the BS front is a current sheet. The electric current is diverging in this layer, that is, the front is the generator of the electric current. Since plasma with magnetic field passes through the front, electric field arises in the front reference system. Thus, the BS front is a source of electric power. This electric power is distributed between two sinks - the transition layer (magnetosheath) and the magnetosphere. The transition layer may only conditionally be classed as a sink, because in a certain mode the transition layer can act as a generator (source). The power consumed by the magnetosphere is spent on the magnetospheric MHD compressor work (a region of the magnetosphere operating like MHD-compressor) and consists of active and reactive power. The active part covers losses in the ionosphere (ohmic losses, primarily), the reactive part returns to the magnetospheric MHD-compressor. The power produced by the generator at the BS front does not appear to depend on power consumed by the magnetosphere, but then a necessity arises for a “power accumulator”, in which the power produced by the BS, but not consumed by the magnetosphere, can be dumped. The transition layer is a viable candidate for this role.

References

- Leonovich, A.S. (2012). Wave mechanism of the magnetospheric convection. Planetary and Space Science., 65, P. 67–75.
- Ponomarev E.A., Sedykh P.A. From the solar wind to the magnetospheric substorm.// Chinese Journal of Space Sciences. 2005. 25(5). P. 390-398.
- Ponomarev E.A., Sedykh P.A., Urbanovich V.D. Bow shock as the power source for magnetospheric processes.// Journal of Atmospheric and Solar-Terrestrial Physics, Elsevier Science. 2006, Vol.68, Issue 6, P.685-690.
- Ponomarev E.A., Sedykh P.A., Urbanovich V.D. Generation of electric field in the magnetosphere, caused by processes in the bow shock.// Journal of Atmospheric and Solar-Terrestrial Physics, Elsevier Science. 2006 Vol.68, Issue 6. P.679-684.
- Sedykh P.A. On the role of the bow shock in power of magnetospheric disturbances.// Sun & Geosphere. Special issue of ISWI /United Nations/NASA/JAXA/AGU/ESA/; ISSN 1819-0839. 6(1), P.27-31, 2011.
- Sedykh P.A. Bow shock. // Advances in Space Research, Elsevier Science. DOI: 10.1016/j.asr.2014.03.015, JASR11746, 2014.
- Sedykh P.A. Transformation of solar wind energy into the energy of magnetospheric processes.// Acta Geodaetica et Geophysica. Springer; DOI: 10.1007/s40328-013-0036-2, Volume 49 Number 1, 2014.
- Sedykh P.A. Bow shock: Power aspects. Nova Science Publishers, Inc., NY 11788 USA. P.67, 2015.

Thank you for your attention!