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SMR 1161/10

AUTUMN COLLEGE ON PLASMA PHYSICS

25 October - 19 November 1999

Scaling Approach in the Solar and Heliospheric Plasma

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Contents

Turbosphere and Turbopause
around the Sun

regular mean flow velocity $\vec{V}(\vec{r},t)$
velocity fluctuations $\vec{V}_1(r,t)$

Turbosphere around the Sun – domain where $V < V_1$.

Numerous observations show the existence of the turbosphere with the subsonic, nearly sonic and trans-sonic regimes of the lateral and vertical motions.

Turbopause – the boundary, or the transition region where $V \approx V_1$.

The turbopause delimits the sites of dominant plasma heating near the Sun from the sites of the dominant solar wind acceleration.

This boundary is highly structured and time variable. It is not "a sphere around the Sun".

At sufficiently large distances from the Sun, in the developed supermagnetosonic solar wind flow, one has $v_1 < v$, as a rule.

The physical meaning of the turbopause is very simple and important: there are no down-flows outside the turbopause.

All observations in situ (numerous spacecraft during 40 years), direct measurements and remote-sensing methods (radio, optical) and many others like cosmic rays, geomagnetic and cometary manifestations of the solar wind, without any exceptions, convincingly demonstrate the absence of the heliospheric plasma domains with the bulk flow velocity directed to the Sun.

The global shape and the detailed space-time variations of the turbopause are poorly known

The fact, that the Sun is the source of the supersonic plasma escaping always and everywhere in the interplanetary space was understood many years ago before the space era. The term "<u>wind</u>" and reasonable values for this phenomenon were regularly used in the scientific literature.

(See e.g. K.O. Kiepenheur, 1953)

H. Bondi (1952) constructed the theory of the spherically symmetric flows based on the stationary solutions of the hydrodynamic (Bernoulli) equations for the polytropic gas in the gravity field of a star.

critical solutions (1) (2)

E. N. Parker (1958) proposed to describe the trans-sonic coronal expansion using the critical solution (2)

Critical solutions are unstable against the sound wave generation.

The solutions are twice eroded (v^2 in Bernoulli equations). $(1)^{\pm}$ $(2)^{\pm}$ + accretion − expansion

For the coronal expansion case $(2)^-$ the instability occurs in the region below the critical point R_* for the waves propagating

The space plasma is dynamical and radiative in many instances.

Because of this, it is interesting and useful to compare the relative importance of the kinetic energy and radiated (or absorbed) energy fluxes. The first is given by $\rho \frac{v^3}{2}$, the second is determined by atomic and radiative processes (Cox-Tucker approximations are often useful).

Let us introduce the dimensionless "velocity - emission" (Ve or V) number:

$$\mathbf{V_e} = \frac{\text{kinetic energy}}{\text{radiative energy gains (or losses)}}$$

$Ve \ll 1$ radiative zone of the Sun, active regions

$Ve \gg 1$ coronal holes, solar wind

$Ve \sim 1$ intermediate case

Another useful dimensionless parameter is the Faraday number – F, which is introduced as follows.

Let us consider the definition of the electric field $\vec{E}$ through the scalar potential φ and the vector potential $\vec{A}$:

$$\vec{E} = -\vec{\nabla}\varphi - \frac{1}{c}\frac{\partial \vec{A}(\vec{r},t)}{\partial t}.$$

Potentials are related to the electric charge density $\rho(\vec{r},t)$ and electric current density $\vec{j}(\vec{r},t)$:

$$\varphi = \int \rho(\vec{r}\,',t)\, R^{-1} d^3 r',$$

$$\vec{A}(\vec{r},t) = \frac{1}{c}\int \vec{j}(\vec{r}\,',t)\, R^{-1} d^3 r',$$

where

$$R = |\vec{r} - \vec{r}\,'|.$$

Let us introduce characteristic values j, ρ, l, t for the currents, charges, space scale and time scale.

In this case,

$$\boxed{F = \frac{j}{\rho c}\,\frac{l}{ct}}$$ Faraday number

$F \gg 1$: electric currents are strong,
dimensions are large,
processes are sufficiently fast,
electric charges are small

This case is very common in MHD →
– induction electric fields dominate over potential fields. This situation is well investigated in the solar physics.

$F \ll 1$: opposite situation
electrostatics.

This situation is very important: Double electric layers etc., accelerated particles. The charging of the solar and space plasma is poorly known. It is often neglected without sufficient grounds based on the "quasineutrality arguments", which are tenable only for sufficiently large volumes and can be violated in thin layers or small cavities especially for fast processes.

Length scales

l – the length scale of the problem,

$L = vt$ – the convective length scale, t – the characteristic time of the problem,

$r_{av} = n^{-1/3}$ – the average distance,

$r_0 = \frac{e^2}{mc^2}$ – the classical electron radius,

$\lambda_{e,i,o}$ – mean free paths,

r_d – Debye radius

$r_{i,e}$ – ion, electron Larmor radii

$r_b = \left(\frac{e}{B}\right)^{1/2}$ – the "magnetic" length

r – the heliocentric distance

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*)
$$\frac{(9)}{(8)} = \frac{\text{radiation}}{\text{Joule}} \simeq \frac{enl}{B}.$$

Hugill or Murakami numbers

$$H \sim Mu \sim \frac{enl}{B} \sim r_b^2 \, l \, r_{av}^{-3}$$

$H \gg 1$ radiation dominates $(n\uparrow l\uparrow B\downarrow)$

$H \ll 1$ Joule heating dominates $(n\downarrow l\downarrow B\uparrow)$

*) Remark: (9) and (8) numbers are related to the terms in the

$$V_e \sim Re_m M_A^2 H^{-2} G^{-1}(T_*)$$

$$T_* = T/E_{at} \qquad G(T_*) \sim 1 \text{ при } T_* \sim 1$$

Optically thin case – Priest, 1982.
Cox, Tucker.

The plethora of different MHD regimes is enormous.

Solar wind origin and hot corona problems

1) Evolutionary approach:
The mass loss is given → wind
(not accretion)

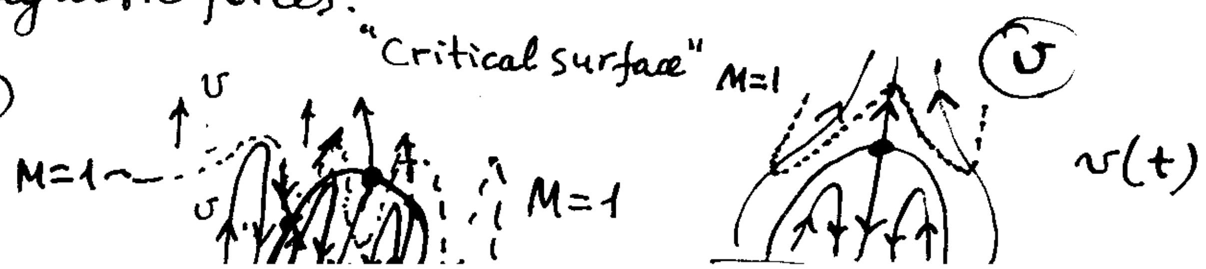
2) Solar atmosphere as an open system out of thermodynamical and mechanical equilibria

corona   wind

Physically correct answers: ① K.O. Kiepenheuer (1953)

Wind from the Sun 350 – 600 km/s
$1 - 10^3$ cm^{-3}
$M = 2 - 3{,}5$ ($v_T \sim 190$ km/s)
too high!!

activity – nonsteady state $\vec{B}$
magnetic forces.

3)


4) Kinetic or MHD problem?

It depends on $Kn = \lambda / \ell$

Knudsen number

Unsolved problem: What are space-time structures, which are responsible for the energy and mass supply to the solar corona and the solar wind?

What regimes dominate?

We know, why the solar corona is hot and why the solar wind blows. It is because of the lack of the mechanical and the thermodynamical equilibrium on the Sun and in the heliosphere. We know possible driving forces, energy and mass sources, but many quantitative and even qualitative questions are still not clear both in observations and in the theory.

The scaling approach to the structural solar wind and coronal heating problems is based on the dimensionless parameter analysis.

Additional approximation:

solar wind case, radiation neglected.

1) $p_r = Q = L = 0$.
Radiation transfer problem is not considered

2) Tenzor properties in $\eta_{ik}^{(\vec{B})}, \varkappa_{ik}, \sigma_{ik}$ are neglected.

3) Equation of the state: ideal gas with the constant mean atomic mass (no diffusion of components, no ionization changes)

Ordering:

$C_6^2 = 15$ independent binary regimes according to dimensionless parameters in the momentum equation:

$$\rho\left[\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}\right] = -\vec{\nabla}p + \frac{1}{4\pi}\left[[\nabla \times B] \times B\right] + F_{viscous} + F_{gravity}$$

①	②	③	④	⑤	⑥
S^{-1}	1	M^{-2}	M_A^{-2}	Re^{-1}	Fr^{-1}

Dimensionless parameters:

$S = \frac{vt}{\ell}$ Strouhal

$M = \frac{v}{c_s}$ Mach

$M_A = \frac{v}{V_A}$ Mach-Alfven

$Re = \frac{\rho v \ell}{\eta} = \frac{v\ell}{\nu} \sim M Kn^{-1}$ Reynolds

Knudsen $\frac{\lambda}{\ell}$

$Fr = \frac{v^2}{g\ell}$ Froude

Regimes

15 Binary C_6^2

Nonstationary $(S \lesssim 1)$

1 2 1) Inertial (force-free): $S \sim 1$, others $\gg 1$.

1 3 2) Gasdynamic $S \simeq M \ll 1$, others $\gg 1$

1 4 3) Cold MHD $S \simeq M_A \ll 1$, others $\gg 1$

1 5 4) Viscous $S \approx Re \ll 1$, others $\gg 1$

1 6 5) Gravity $S \simeq Fr \ll 1$, others $\gg 1$

Quasistationary $(S \gg 1)$

2 3 6) Bernoulli $M \sim 1$, others $\gg 1$

2 4 7) Cold MHD $M_A \sim 1$, others $\gg 1$

2 5 8) Viscous $Re \sim 1$, others $\gg 1$

2 6 9) Gravity $Fr \sim 1$, others $\gg 1$

3 4 10) Pressure balanced MHD $M \sim M_A \ll 1$, others $\gg 1$

3 5 11) Laminar Stokes $M \sim Re \ll 1$, others $\gg 1$

3 6 12) Gravity balanced gas $M \sim Fr \ll 1$, others $\gg 1$

4 5 13) Viscous MHD $M_A \sim Re \ll 1$, others $\gg 1$

4 6 14) Gravity MHD $M_A \sim Fr \ll 1$, others $\gg 1$

5 6 15) Sedimentation $Re \sim Fr \ll 1$, others $\ll 1$

More complicated regimes,

(not binary ones): $C_6^3 + C_6^4 + C_6^5 + C_6^6 = 20 + 15 + 6 + 1 = 42$

Total: $C_6^2 + C_6^3 + C_6^4 + C_6^5 + C_6^6 = 57$ momentum regimes

Nearly sonic and transsonic convective motions in the solar atmosphere related to the solar wind origin

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Abstract. Dissipative MHD regimes in the solar atmosphere are considered. Dimensionless parameters in the energy and momentum transport equations are analysed to understand the scaling relations between the dominant physical mechanisms in the solar atmosphere. The solar wind originates as a more or less regular tiny flow when the streamlines are temporary splitted from the powerful transsonic convective motions with ascending and descending nonstationary vortices in the solar atmosphere. There is no smooth quasistationary "critical surface" around the Sun where the sonic transition takes place.

Introduction

The lack of the thermodynamical and mechanical equilibrium in the solar atmosphere lead to the formation of the hot solar corona and supermagnetosonic plasma outflow from the Sun. The structures and processes involved in these phenomena are very complicated and encompass many orders of magnitude in space and time. The relative role of different scales is not clear from observational and theoretical points of view. The complexity of the solar corona and solar wind structures and processes prevents their sufficiently complete knowledge and description not only on the quantitative but on the qualitative levels as well.

Dimensional analysis of the governing equations may be helpful in this situation [Landau and Lifshits, 1982; Sedov, 1981]. Unfortunately such an analysis have not been done in a systematic way in the monographs on the solar physics and astrophysics [Kuiper, 1953; Thomas and Athey, 1961; Shklovsky, 1962; Parker, 1963; Spitzer, 1978; Michalas, 1978; Priest, 1982] nor in the current literature on the solar and stellar winds origin problem (see reviews [Pneuman, 1986; Abbot, 1988; Drake, 1988; Holzer, 1988]). The aim of this paper is an attempt to fill this gap and to obtain a new look at the solar wind origin problem.

The situation in this field seems to be somewhat analogous to the laboratory plasma studies where the importance of the detailed dimensional analysis and of the complete physical scaling was understood only recently. Early attempts to describe energy losses in tokomaks based on the restricted dimensional analysis and physical scalings neglecting the role of the radiation and macroscopic motions failed and a new scaling approach appeared [Katomtsev, 1975, 1990].

The approach adapted here is based on the MHD equations. Hence the most deepest and interesting questions about the solar corona and solar wind origin problem residing in kinetic physics are beyond the scope of this paper.

MHD approach

Let us consider dissipative MHD equations using the standard notations [Landau and Lifshits, 1982; Priest, 1982].

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho\vec{v}) = 0, \qquad (1)$$

$$\rho[\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}] = -\vec{\nabla}p + \frac{1}{c}[\vec{j}\times\vec{B}] +$$

$$+\eta[\nabla\vec{v} + \frac{1}{3}\vec{\nabla}(\vec{\nabla}\vec{v})] - \frac{\rho M_{\odot}G}{r^3}\vec{r} + \vec{F}_r, \qquad (2)$$

$$\frac{\partial}{\partial t}[\rho(u + \frac{v^2}{2})] + (\vec{\nabla}\vec{q}) = -L + A, \qquad (3)$$

where $\vec{F}_r$ is the force due to the radiation, L represents local energy gains and losses due to atomic processes (radiation, ionization, excitation etc.), $A = -\frac{\rho M_{\odot}G}{r^3}(\vec{r}\vec{v})$ is the work of external (gravity) forces. The energy flux $\vec{q}$ in Equation (3) is expressed as follows

$$q_i = \rho v_i(w + \frac{v^2}{2}) + v_k\sigma_{ik}' - æ\frac{\partial T}{\partial x_i} +$$

"Solar Wind Eight". AIP Press. 1996

$$+\frac{1}{4\pi}e_{ikl}B_k e_{lmn}v_m B_n + \frac{c}{4\pi\sigma}e_{ikl}j_k B_l, \quad (4)$$

where $\sigma'_{ik} = \eta(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_l}{\partial x_l})$ stands for the viscous tensor.

The electrodynamic and material equations (Ohm's law and the equations of the state) make the system (1-3) closed

$$\vec{j} = \frac{c}{4\pi}[\vec{\nabla} \times \vec{B}], \quad (5)$$

$$\vec{j} = \sigma(\vec{E} + \frac{1}{c}[\vec{v} \times \vec{B}]), \quad (6)$$

$$(\vec{\nabla}\vec{B}) = 0, \quad (7)$$

$$\frac{\partial \vec{B}}{\partial t} = [\vec{\nabla} \times [\vec{v} \times \vec{B}]] + \frac{c^2}{4\pi\sigma}\Delta\vec{B}. \quad (8)$$

We do not specify the equation of the state in the explicit way. It may be approximated by the ideal gas equation with the constant average mass of particles only with a limited accuracy in the photosphere and in the solar corona, but not in the chromosphere, where the ionization processes are very important and the ionization balance equations should be taken into account to calculate the effective average mass of particles in the one fluid MHD equations used here.

For the sake of simplicity of the discussion we will neglect tensor properties of the transport coefficients $\eta_{ik}(\vec{B})$, $æ_{ik}$, σ_{ik}. Diffusion processes are not considered and one-fluid approximation is used because of the same reason. Additional approximations (less realistic in the upper solar atmosphere) are introduced when the equation of the state is taken as for an ideal gas with the constant mean atomic mass (no diffusion, no ionization changes). Finally, we will neglect the radiation drag and pressure term in Equation (2) which is small indeed only in the upper solar atmosphere in comparison with other terms in momentum balance Equation (2).

MHD regimes

There is a large multitude of possible MHD regimes in the solar atmosphere. Physically distinguishable regimes may be characterized by the dimensionless parameters in the MHD equations. Let us consider the momentum and the energy equations.

a) Momentum equation

We present Equation (2) in the form appropriate to the dimensionless analysis neglecting the radiation term

$$\rho[\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}] = -\vec{\nabla}p + \frac{1}{4\pi}[[\vec{\nabla} \times \vec{B}]\vec{B}]$$

$$S^{-1} \qquad 1 \qquad M^{-2} \qquad M_A^{-2}$$

$$+\vec{F}_{viscous} + \vec{F}_{gravity} \quad (9)$$

$$Re^{-1} \qquad Fr^{-1}$$

There are six terms in this equation. The relative importance of the terms is estimated using dimensionless parameters $S = \frac{vt}{l}$, the Strouhal number, $M = \frac{v}{c_s}$, the Mach number ($c_s = \sqrt{\gamma\frac{T}{m}}$ is the sound velocity), $M_A = \frac{v}{V_A}$, the Mach-Alfven number ($V_A = \frac{B^2}{\sqrt{4\pi\rho}}$ is the Alfven velocity), $R_e = \frac{\varrho v l}{\eta} \approx \frac{vl}{\nu} \sim MKn^{-1}$ is the Reynolds number (ν is the kinematic viscosity, l is the characteristic scale length of the problem, $Kn = \frac{\lambda}{l}$ is Knudsen number, λ stands for the mean free path), $Fr = \frac{v^2}{gl}$, Froude number ($g = \frac{M_\odot G}{r^2}$ is the effective gravity acceleration). The second term (the dynamic pressure) was arbitrary chosen as a scale for comparison.

There is 57 physically different regimes which result when combining the five dimensionless parameters and the six possible dominant terms in momentum equation (9)

$$\sum_{i=2}^{6} C_6^i = 57.$$

We indicate here the fifteen simplest "binary" regimes when only two dominant terms are important in Equation (9). Only the essential characteristic dimensionless parameters will be written explicitly. All other dimensionless parameters are supposed to be extremely large ($\gg 1$).

First of all, there are the five nonstationary binary regimes, namely, 1) inertial (force-free) $S \sim 1$; 2) gasdynamic $S \sim M \ll 1$; 3) cold MHD $S \sim M_A \ll 1$; 4) viscous $S \sim R_e \ll 1$; 5) gravity dominated $S \sim Fr \ll 1$.

Next, there are the ten quasistationary regimes: 1) Bernoulli regime $M \sim 1$; 2) cold MHD $M)A \sim 1$; 3) viscous $R_e \sim 1$; 4) gravity $Fr \sim 1$; 5) pressure balanced MHD $M \sim M_A \ll 1$; 6) laminar Stokes $M \sim R_e \ll 1$; 7) barometric (gravity balanced gas) $m \sim Fr \ll 1$;

8) viscous MHD $M_A \sim R_e \ll 1$; 9) gravity MHD $M_A \sum Fr \ll 1$; 10) sedimentation $R_e \sim Fr \ll 1$.

b) Energy equation

Energy equation (3) may be written in the form convenient for the dimensional analysis

$$\frac{\partial}{\partial t}(\rho u + \rho\frac{v^2}{2}) + \frac{\partial}{\partial x_i}(\rho v_i w + \rho v_i\frac{v^2}{2}+$$

$$M^{-2}S^{-1} \quad S^{-1} \qquad M^{-2} \qquad 1$$

$$+v_k\sigma'_{ik} - æ\frac{\partial T}{\partial x_i}+$$

$$Re^{-1} \quad Re^{-1}M^{-2}Pr^{-1}$$

$$+\frac{1}{4\pi}e_{ikl}e_{lmn}v_m B_k B_n + \frac{c}{4\pi\sigma}e_{ikl}j_k B_l)$$

$$M_A{}^{-1} \qquad\qquad M_A^{-2}Re_m{}^{-1}$$

$$= -L + A. \tag{10}$$

$$V^{-1} \qquad Fr^{-1}$$

There are ten terms in this equation.The fourth term (the kinetic energy flux density) in Equation (10) was chosen to be of the order of the unity for the sake of comparisons between the terms. The relative importance of the all ten terms is indicated using independent dimensionless parameters, M, S, M_A, Fr and Re_m, Pr, V.

Here $Re_m = \frac{4\pi\sigma l v}{c^2}$ is the magnetic Reynolds number, $Pr = \frac{\nu}{\chi}$ is the Prandtl number, i.e. the ratio of the kinematic viscosity $\nu = \frac{\eta}{\rho}$ to the temperature conductivity $\chi = \frac{æ}{\rho}$. The Prandtl number is usually ~ 1 in the simple neutral gas mixtures with nearly equal molecular weights of the components. In the hydrogen plasma (Lorentz gas) $Pr \sim \sqrt{\frac{m_e}{m_i}} \sim \frac{1}{40}$.

The dimensionless number V^{-1} characterizes the relative role of the ninth term, i.e. the radiative gains (losses) due to the excitation, deexcitation, recombination, ionization and other atomic or ion-molecular processes ("reactions") in comparison with the forth term, i.e. the kinetic energy of the gas flow. It may be estimated by the order of magnitude as

$$V^{-1} \sim (\frac{E_{at}}{E_{kin}})(\frac{\tau}{\tau_r}) \tag{11}$$

where $E_{at} \simeq \frac{me^4}{\hbar^2}$ is the atomic energy scale; $E_{kin} \simeq \frac{mv^2}{2}$ is the kinetic energy of the mass flow (which may be subsonic or supersonic in the solar atmosphere); $\tau \sim \frac{l}{v}$ is the transit time through the scale length l; τ_r stands for the characteristic effective time scale of the radiation, excitation, ionization, recombination or other preponderant atomic and radiative processes.

Atomic and radiative processes dominate the flow in the case when $V \ll 1$. The flow of the gas is not essential in the bulk energy balance equation in this case (slow flows in the lower solar atmosphere).

Atomic and radiative processes are not essential in the energy transport when $V \gg 1$. In this opposite case the flow of the gas dominates in the energy balance (fast streams in the most upper solar atmosphere, solar wind).

There are several length scales which should be combined when obtaining dimensionless MHD parameters mentioned above. These length scales are: l is the scale length of the phenomena or structure under consideration; $l_t = vt$ is the convective length scale corresponding to the characteristic time of the phenomena; $r_{av} = n^{-1/3}$ is the average distance between the particles; $r_o = \frac{e^2}{mc^2}$ is the classical electron radius, $\lambda_{e,i,o}$ being the mean free paths of the charged and neutral particles, r_d is the Debye radius, $r_{i,e}$ is ion, electron Larmor radius, $r_b = (\frac{e}{B})^{\frac{1}{2}}$ is the electrodynamic "magnetic" length, r stands for the heliocentric distance and others. Not all of them are independent and some choice is possible. For example, the ratio of the ninth term to the eighth one in energy balance Equation (10), i.e. the radiative/Joule ratio is proportional to $\frac{enl}{B}$, which is known to be related to the Hugill (H) or Murakami (Mu) numbers defined in the literature [Kadomtsev, 1990]

$$H \sim Mu \sim \frac{enl}{B} \sim r_b{}^2 l r_{av}{}^{-3}. \tag{12}$$

The radiation dominates over the Joule heating when $H > 1$, i.e. in the dense plasma regions with a low magnetic field . The opposite situation takes place when $H < 1$, i.e. in the rarefied strongly magnetized plasma. The both opposite cases are frequently playing their important role in the local structures and processes in the solar atmosphere.

The scaling relations between the terms in the energy and momentum equations and relevant dimensionless parameters have not been studied in a systematic way for the solar atmosphere regions and processes. We indicate here the relation between V and H numbers.

The dimensionless number V may be expressed as

$$V \sim Re_m M_A^2 H^{-2} G^{-1}(T_*), \tag{13}$$

where H is the Hugill dimensionless number, and $G(T_*)$ is the function of the dimensionless temperature $T_* = \frac{T}{E_{at}}$. One has $G(T_*) \sim 1$ when $T_* \sim 1$. In the case of the optically thin atmosphere the function $G(T_*)$ may be represented by a sum of the radiative losses and gains using the known approximations described in the literature [Priest, 1982].

One may use V or H (or some other combination like the Murakami number) as an independent dimensionless parameter characterizing the role of the atomic and radiative processes in the plasma energy balance. We have seen that the choice of the parameter V as independent one is more natural for the problems of the solar and stellar wind origin when plasma flows are the main concerns.

The plethora of MHD regimes is enormous taking into account independent parameters appearing in the momentum and energy conservation equations, Maxwell equations and material equations. Most of these individual cases were observed or theoretically anticipated, but some of them have not been discussed in the literature.

Let us discuss briefly the relative importance of the different heating mechanisms in the upper solar atmosphere based on the dimensional analysis. The ratio of Joule/viscouse terms according to Equation (10) is equal to $M_A^{-2} Re Re_m^{-1}$. This ratio may be represented as $M_A^{-2}\sqrt{\frac{m_i}{m_e}}\frac{m_e c^2}{T}(n r_d^3)$ in the case of the fully ionized plasma. Estimates show that this ratio is very small ($\ll 1$) in the solar corona. Hence the solar corona is heated mainly by viscous friction [Shklovsky, 1962]. The Joule heating dominates locally in the denser and colder plasma with slower motions in the strong magnetic fields. Such conditions are met in the solar atmosphere locally in-between the corona and the photosphere. But the lower solar atmosphere is only weakly ionized and the Joule heating again is relatively unimportant here. The competition between the viscous heating, heat conduction and radiation takes place here.

Discussion and Conclusions

The view of the solar atmosphere as an open system out of the mechanical and thermodynamical equilibrium is very useful for a better understanding of many questions about the solar corona and the solar wind structures and processes.

Physically plausible and correct answers have been suggested a long time ago on this way to the general questions about the hot solar corona and wind origins (see for example excellent but partially forgotten classical review papers by K.O.Kiepenheuer and H.C.Van der Hulst in the monograph [Kuiper, 1953]). Naturally, many important details appear now more clear, and some unresolved questions remained when new ones arise.

It is interesting that a number of early and very tentative negative statements, which seems to be never precisely formulated nor proven or seriously tested, were not critically accepted and repeated during a long time by different authors and still appear in the current literature. We indicate here one example, namely, the prejudice that the velocities of the plasma flow across magnetic fields are slow compared with velocities along field lines was advocated by C.T.Cowling neglecting electric drifts (see, e.g., his article in the same monograph [Kuiper, 1953]. No strict theoretical arguments exist supporting this general rule, $v_\perp \ll v_\parallel$, in plasmas. Many counterexamples show that it is not the case in the laboratory and space plasmas (eruptive prominances on the Sun, solar wind streams in the heliosphere beyond 1 a.u., plasma flows in the magnetosphere during substorms). This rule is often absolutely not tenable in the stationary situations and is especially violated when induction electric fields $\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$ are present due to time variations of the magnetic field. The topology of the magnetic field (open-closed) is of the secondary importance and not relevant in this sense when induced and potential electric fields are present in the moving plasma. Magnetic zero points and field line topology are generally not invariant against moving coordinate system transformations when the electric field is not zero in the magnetic zero points. It is clear that the knowledge of the electric field in the solar atmosphere is very important in the solar wind origin problem but still not sufficiently elaborated. The leading role of the open magnetic configurations in the solar wind source regions is anticipated, but was not proven as yet cf. [Parker, 1992; Axford and McKenzie, 1992].

But the topology may be important in the sense, that electric drifts are faster in the low magnetic fields, i.e. around zero points of the magnetic field, when electric fields are more or less homogeneous. In the case of drifts under the influence of the inductive electric fields due to the magnetic field time variations one obtains in general faster flows when larger scales are involved in the rapid time changes. We hope that the study of the local nonstationary nearly sonic and supersonic convective motions in the solar atmosphere will allow to elucidate the role of parallel and perpendicular velocities.

The existing observational data lead us to the conclusion that the solar wind originates as a more or less regular flow when the streamlines are temporary splitting from the powerful transsonic convective motions with ascending and descending vortices in the solar atmosphere. There is no smooth quasistationary "critical surface" around the Sun where the sonic transition takes place.

Acknowledgements. The author is grateful to the Organizing Commettee for the local support, and to RFBR for the travel grant enabling the participation in the International Solar Wind 8 Confernce. The work was partially supported by the RFBR grant 95-02-06074-a.

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Turbosphere and Turbopause in the Solar Wind Formation Region

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Abstract. The MHD classification of the regimes is based on the relative values of the phase velocities versus the turbulent velocity dispersion σ and regular flow velocity V. Concepts of the turbosphere and the turbopause around the Sun are introduced as follows. In the solar atmosphere near the Sun one has $\sigma > V$. This domain may be termed as the turbosphere around the Sun. An opposite situation, $\sigma < V$, is characteristic for the fully developed supermagnetosonic solar wind flow sufficiently far from the Sun. The turbopause represents a transition region around the Sun, where the condition $\sigma \approx V$ is achieved. The turbopause delimits the sites of dominant plasma heating near the Sun from the sites of the dominant solar wind acceleration farther out.

INTRODUCTION

There is no standard generally accepted quantitative definition of the turbulent and laminar regimes. Instead, intuitive and descriptive concepts of turbulent and laminar motions prevail in the literature (see, e.g., [1]). Turbulent motions are more dynamical, complicated and irregular. Their theoretical description meets severe difficulties. Because of this, even a semi-semantic analysis of the role of the "turbulence" and mixing in space plasmas is not an easy problem (see, e.g. [2]). Many examples show that there are no "universal" turbulent states.

Multiscale dimensional analysis and observations indicate that the turbulence in the solar atmosphere is not fully developed. It is intermittent, inhomogeneous and anisotropic here. Laminar and turbulent structures coexist in the solar atmosphere in different proportions depending on the solar cycle phase. The permanent solar wind outflow from the Sun introduces a natural velocity scale for the description of the turbulent regimes in the solar atmosphere. This scale is the bulk or average flow velocity V, which is increasing with the heliocentric distance. The purpose of this paper is to present a classification of turbulent regimes in the solar atmosphere using this velocity scale.

LAMINAR AND TURBULENT STRUCTURES IN THE SOLAR ATMOSPHERE

Motions in the solar atmosphere are supported by the free energy of the thermal, electromagnetic, mechanical and gravitational forces. Numerous laminar and turbulent structures are formed here depending on initial and boundary conditions. The transitions between regular and irregular states are mediated locally and globally by the complicated non-linear dissipative mechanisms. The corresponding Reynolds numbers are useful dimensionless parameters, which delimit the laminar and turbulent behaviour. As a consequence, sufficiently small structures are strongly dissipative and appear as laminar entities in many instances (loops, threads, rays, jets etc.). At larger scales we often meet turbulent motions inside the chromosphere and corona. Turbulent motions are ubiquitous here but they are especially remarkable for most dynamical events like eruptions. The gravity and magnetic fields introduce an obvious anisotropy.

The mechanical Reynolds number Re can be estimated as follows

$$Re \sim \frac{\rho V l}{\eta} \sim \alpha M (Kn)^{-1}, \qquad (1)$$

where ρ is the mass density, V and l are the characteristic velocity and space scales of the structure under consideration, η is the corresponding component of the viscosity tensor in the magnetic field [3,4], $M \sim V/c_s$ is the Mach number, c_s is the sound speed, $Kn \sim \lambda/l$ is the Knudsen number, λ is the mean Coulomb free path length for protons, α is the factor depending on the geometry and the magnetic field strength. The factor $\alpha \sim 1$ along the magnetic field lines and $\alpha \sim O(\omega_{cp}\tau_p)^q >> 1$ across the magnetic field, where ω_{cp} is the proton cyclotron frequency, τ_p is the mean free time for proton Coulomb collisions, q = 1 or 2 for different viscosity components. A strong magnetic field means here $\omega_{cp}\tau_p >> 1$, i.e. "magnetised" protons. This condition is, as a rule, fulfilled in the upper solar atmosphere. Because of this, the turbulence is quasi-two-dimensional at the smallest hydrodynamic scales and mostly represented here by sheet-like and tube-like structures stretched along magnetic field lines.

One general comment is in order at this point about a hypothetical "universal statistics" in a theory of the so-called fully developed hydrodynamic turbulence with scaling differing from the well known self-similar exponents in the inertial range [5]. In reality the turbulence is far from being homogeneous, isotropic and statistically stationary in many instances. It is composed

"Solar Wind Nine". AIP Press. 1999

from different branches of convective and propagating perturbations. They are numerous even in the linear one-fluid MHD approximation. Several types can be indicated: potential entropy perturbations, solenoidal entropy perturbations (vortices), gravity waves, Alfven waves, fast and slow magnetosonic waves. Moreover, non-linear couplings between different modes and inside the modes make the analytical description practically intractable. The influence of the boundary and initial conditions, as well as the kinetic structures, introduce additional ample diversity of turbulent plasma states. The solutions of the governing non-linear dynamical equations are not unique, especially for marginally stable situations. Bifurcations appear even for a weak local non-linearity.

All this taken together restricts the applicability of the ideas of the universality in the theory of turbulence. Deviations from an expected self-similar fractal or multifractal behaviour are typically non-negligible. Nevertheless, these model approaches have their heuristic significance and the inferred scaling can be considered as useful intermediate asymptotic within the limits, which are not known apriori and should be attentively checked by experiments. The quantitative assessment of internal and external scales as well as estimates of the mentioned deviations is beyond the scope of available theoretical approaches that are based on dynamical equations and first principles. In summary, the impression of a broad diversity of possible turbulent regimes differing in their types, strengths, scaling and intermittence patterns seems to be more adequate view for applications in plasma physics [6]. The complicated phenomena in the solar atmosphere give a good example supporting this general view.

TURBULENCE LEVEL

It is natural to use characteristic velocities v_c of the propagating small amplitude linear wave perturbations (sound speed c_s, Alfven speed V_A, fast and slow mode speeds v_f and v_s and others) as scales for measuring the relative strength of different turbulent motions with velocity σ. Weak, moderate and strong turbulence regimes could be defined theoretically as the states with $\sigma < v_c$, $\sigma \sim v_c$ or $\sigma > v_c$ accordingly. The corresponding Mach numbers M are low, intermediate or high in comparison with 1 in a local reference frame co-moving with the bulk plasma velocity. Nevertheless, another terminology is often used in the literature: weak ($M < 1$), strong ($M \sim 1$), and super-strong or supersonic ($M > 1$) turbulence. A general theory of a weak turbulence is rather well developed especially in quasilinear approximations based on the hypotheses of the phase mixing. In the case of a strong turbulence non-linear effects are very important, which makes the theoretical description principally much more complicated. Shock waves and strong discontinuities are immediate signatures of a strong turbulence. We often meet all these situations in the solar atmosphere, especially in "perturbed conditions".

TURBOSPHERE AND TURBOPAUSE AROUND THE SUN

The concepts of the turbosphere and turbopause around the Sun are introduced as follows. The solar wind bulk velocity V increases with a distance from the Sun because of the density decrease and mass conservation in the solar atmosphere. The solar wind velocity somewhere near the Sun is negligible in comparison with turbulent motions and one has $\sigma > V$. Hence, this domain may be termed as the turbosphere around the Sun. The turbosphere encompasses the lower parts of the solar corona and the chromosphere. The nearly sonic and trans-sonic values $\sigma \sim$(1-10 km/s) are often seen in the turbosphere. The estimated radial expansion velocity V is of an order of 1 km/s at the density level $\sim 10^8$ cm^{-3} of the corona and rapidly decreases with depth in the atmosphere. It is about 1 m/s at the density level $\sim 10^{11}$ cm^{-3} of the middle chromosphere and only 10^{-3} cm/s at the density level $\sim 10^{16}$ cm^{-3} of the chromospheric bottom.

The corresponding residence or replenishment times estimated by the transit time across the height of the standard atmosphere are about several days-weeks for the coronal height and many years for the photosphere.

The Lagrangian fluid particle trajectory lengths L between radial distances r_1 and r_2 are estimated to be of an order of $L \sim k\frac{\sigma}{V}\Delta r$, where $\Delta r = r_2 - r_1$. The numerical geometry factor is equal to k =2 for one-dimensional vertical up-and-down motions controlled by the strong magnetic fields, $k = \pi$ for the circular vortices with the horizontal axis, $k >> 1$ for vortices with the vertical axis. There is no large sense to follow tangled and wavy trajectories close to the Sun because of dissipative limits, which destroy fluid particles. Nevertheless, the solar wind keeps the partial memory of the non-linear dissipative self-organisation processes near the Sun.

An opposite situation, $\sigma < V$, is characteristic for the fully developed supermagnetosonic solar wind flow sufficiently far from the Sun. The kinetic energy of the solar wind dominates everywhere above the turbosphere. The turbopause represents the transition region around the Sun, where the condition $\sigma \approx V$ is achieved. There are no turning points in the radial direction of the flow behind the turbopause, i.e., all zero points of the radial velocity are situated in the turbosphere. There are two different types of streamlines and trajectories in the turbosphere: with/without zero points of the radial velocity. There is only one type of these curves farther out in the solar wind: without zero points. The turbopause delimits the sites of the dominant plasma mixing and heating near the Sun from the sites of the dominant plasma acceleration farther out in the solar wind formation region.

The structure and position of the turbosphere and turbopause are space and time dependent. This dependence is strong and multiscale because of turbulent processes. An approximate equipartition between kinetic, thermal, magnetic and potential gravity energies is fulfilled at the turbopause. This situation is favourable for intensive fluctuations of plasma and magnetic field parameters with relative amplitudes comparable for all these degrees of freedom. Below the turbopause several regimes are possible. These regimes are known from observations as different morphological elements: coronal holes, coronal streamers, prominences, etc. Up-and-down flows associated with chromospheric spicules represent complicated regimes differing in two aspects: there is no essential outward expansion velocity, the radiation processes are very important in the energy balance. Thermal, gravitational, mechanical and electromagnetic forces support convective motions inside the turbosphere. This situation is different from the photosphere, where only the two first forces dominate, as a rule.

Telescopically unresolved nearly sonic and supersonic up-and-down motions in the solar atmosphere lead to the nonthermal spectral line broadening observed at the disc. Large amplitude Alfven perturbations in the low β plasma are especially effective in this respect at the tops of the coronal loops. The same perturbations are effective in the sense of the line broadening both for open and closed magnetic structures at the limb.

The plasma drifts produce numerous expanding loops in the solar corona across magnetic fields due to the induced electric fields

$$\vec{E}(r) = \frac{1}{4\pi c}\int \frac{\left[\vec{R}\times\vec{B}\right]}{R^3} d^3 r', \qquad (2)$$

where $\vec{R} = \vec{r} - \vec{r}'$.

The drift velocity

$$V = c\,\frac{\left[E\times B\right]}{B^2} \qquad (3)$$

can be estimated as $V \sim r/t$, where r and t are the characteristic space-time scales of the fields under consideration.

SOLAR WIND ORIGINS

The solar wind formation region is not a strictly defined volume around the Sun. In our context, this definition is not so relevant as the energy, momentum and mass flux patterns. The velocity field pattern is rather complicated. The low beta coronal plasma flow geometry is regulated here by the magnetic field structures, which form locally specific nozzles. Lagrangian fluid particle trajectories coincide with streamlines for stationary flows. It is not the case in the turbosphere as a rule. Maximal mass flow densities are attained at critical points, which are single or multiple along these curves. Collisional or turbulent mixing processes are effectively acting against the inertial, gravitational and magnetic ion mass separation. Because of this, only moderate changes are taking place in the ion composition of the hot corona and the solar wind. The opposite situation is met at higher levels behind the turbopause.

The anisotropy of the turbulence in the solar formation region is an important factor. Two limiting cases should be mentioned: 1) the locally isotropic turbulence; 2) waves propagating from the Sun. In the first case the turbulence dissipation is mainly responsible for an additional heating. The thermally driven expansion appears as a consequence of this process which presumably dominates inside the turbosphere. In the second case, the branching ratio between the heating and acceleration of the plasma by waves depends on many specific details of the local MHD and kinetic situation. For example, an additional supersonic acceleration by Alfven waves outside the turbopause in the coronal holes is a viable mechanism for producing fast solar wind streams.

The origins of the slow solar wind remain not clear. Several ideas were suggested. According to one point of view, rather small open magnetic configurations inside coronal streamers are thought to be sources of a slow solar wind. Another possibility is also discussed in the literature. Namely, it is supposed that the slow solar wind arises at a boundary between coronal streamers and the adjacent fast flows from surrounding large coronal holes. A viscous drag due to laminar and turbulent lateral interactions between coronal streamers and large holes could be important in this case. A streamer is considered more or less as a passive element. In this case, the energy for the acceleration inside the streamer is supplied from its lateral boundary. The third possibility is not excluded too: nonstationary magnetic fields at the bottoms produce electric drifts in the plasma as described by formulae (2,3). This mechanism is operating both for open and closed magnetic configurations inside and outside streamers. In this sense, the whole surface of the Sun can be considered as a source of the solar wind energy and mass. Quantitative assessments of these ideas are possible by future observations of vector velocity components in the solar wind formation region.

Continuous spectra of perturbations in the solar atmosphere have local features corresponding to the eigenmodes and regular convective structures evolving with time. Direct and inverse wave energy cascades coexist in this complicated open system with the energy.

momentum and mass flows. The relative importance of these processes in the solar corona is not sufficiently investigated and any conjectures about their role in the solar wind origin and coronal heating would be premature.

Moreover, the ideas that the quasi-stationary electric currents are the immediate driving agents of the solar wind acceleration and their dissipation provides the energy to heat the corona are still attractive because of their simplicity. Hence, the fourth mechanism of the solar wind acceleration could be related to the quasi-stationary Ampere forces. In this case, non-propagating convective structures are more important than waves in the energy, momentum and mass balance.

The open questions in the solar wind origin and coronal heating problems can be formulated as follows. What are space-time structures, which are responsible for the energy and mass supply to the solar corona and the solar wind? What regimes dominate inside these structures: MHD or kinetic?

The fact that the Sun is the source of the supersonic plasma, which is escaping always and everywhere in the interplanetary space was understood many years ago (see, e.g., [7]). The term "wind" and reasonable values for this phenomenon were regularly used in the scientific papers (see e.g. [7]). The beautiful poetic image of the "solar wind" ("solnechnyi veter" in Russian) can be found in the non-astrophysical context in the stories written in 1933-1939 during the immigration in France by the Russian writer, the Nobel prize laureate in literature, I.A.Bounine. As it often happens, unclear dreams were going ahead of the precise knowledge.

The theory of spherically symmetric flows describing the stationary hydrodynamic motions of the polytropic gas in the gravity field of a star was available in 1952. Multiple subsonic, supersonic and two critical trans-sonic branches have been found and analysed. One of the critical solutions was selected to describe the trans-sonic accretion near the star [8]. Nevertheless, the possibility of the trans-sonic coronal expansion [9], given by the second critical solution, was not indicated in [8]. Solutions of the governing Bernoulli equation in this theory are twice eroded and do not determine the velocity sign. Entropy growth arguments allow selection of the correct velocity direction for both critical branches describing acceleration or expansion, respectively.

It is interesting to note that critical solutions are unstable against the sound wave generation [10]. This means that the inhomogeneous coronal expansion could be one of the important free energy sources for waves inside the turbosphere around the Sun.

CONCLUSIONS

The concepts of the turbosphere and turbopause around the Sun are useful for the interpretation of the existing observations. They are adequate for the description of the nonstationary and non-linear multiscale structures in the solar wind formation region. The physical meaning of these newly introduced concepts for the solar wind problem is very simple: down-flows are possible only within the turbosphere. There are no down-flows outside the turbosphere.

ACKNOWLEDGMENTS

This work is supported by the RFBR 96-15-9670, 98-02-17660 and the Federal Program "Astronomy" 1.5.6.2 grants. The author is grateful to the Organising Committee chaired by Dr. S.R.Habbal for the financial support enabling the participation in the Solar Wind 9 Conference.

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"Trieste numbers" (T)

External, internal and linking parameters could play different roles when we consider physical processes inside a given volume.

Their relative importance is expressed by corresponding dimensionless numbers – "Trieste numbers"

$T_{\alpha\beta}$ $\{\alpha, \beta\}$: 1 – i, 2 – e, 3 – ℓ

"Triest numbers" are useful as a quantitative measure of the non-locality and the boundary condition influence on the physical process or structure.

For example: Let us consider any vector field $\vec{v}$ (velocity, electric current, magnetic field ...). It is composed of internal field lines ($\vec{v}_i$), external field lines ($\vec{v}_e$) and linking field lines ($\vec{v}_\ell$): $\vec{v} = \vec{v}_i + \vec{v}_e + \vec{v}_\ell$, which are situated inside, outside or crossing the boundary.
The ratio of terms (i, e, ℓ) – "$T_{\alpha\beta}$"
characterizes the openess degree of the system