Solar Activity and its Magnetic Origin
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Solar wind and solar energetic particles: origins and effects

Igor S. Veselovsky[1,2]

[1]Institute of Nuclear Physics, Moscow State University, Moscow, 119992, Russia
email: veselov@dec1.sinp.msu.ru

[2]Space Research Institute (IKI), Russian Academy of Sciences, Moscow, 117997, Russia

Abstract. The paper reports about several actual problems of the solar wind and solar energetic particle studies. Primary focus is on unsolved questions. The clear and sharp boundary in the phase space between solar wind plasma particle populations and "solar energetic particles" does not exist. Because of this separate consideration of "solar energetic particles" has only limited applicability and needs some reservations, which should be clearly stated and not forgotten to avoid possible errors and misinterpretations, which sometimes happen in the literature. In any case, the solar wind particles often serve as a big reservoir for acceleration (or cooling) of less abundant energetic particles. Solar wind and solar energetic particles are just two selected populations (big and small) in their joint distribution functions. It is very difficult and even impossible in many instances to have demarcation between particle populations in the energy space or indicate their ultimate "origins" in the coordinate space. It is because of the absence of localized "accelerators", "heaters" or "sources" of particles. All these three categories mentioned above often have very limited physical meaning, but sometimes they can be useful and localized in the momentum and coordinate space. We are still too far from complete knowledge and understanding of many relevant questions in this regard.

Keywords. Solar wind, solar energetic particles

1. Introduction

Let us clarify and refine first of all definitions and basic physical properties of the solar wind and energetic particles. Solar wind and energetic particles represent major and minor populations of the particle distribution functions $f_{i,e}(\vec{r}, \vec{v}, t)$ for ions and electrons in the heliosphere. There is no strict and well defined boundaries between both populations in the phase space $(\vec{r}, \vec{v})$. These particles are intermixed every time and everywhere in the heliosphere in the way that the solar wind can be associated with the main body of the ion distribution functions. It is peaked around several hundred volts or keV domains for typical and perturbed solar wind bulk velocities which are nearly the same for different kinds of ions. The position of peaks in the energy space E_i is roughly proportional to the ion mass, $E_i \sim m_i$. Thermal energies of solar wind ion populations are usually one-two orders lower. Hence, the peaks are sharp. Their width is usually of the order of ten eV in the solar wind.

Distribution functions of electrons in the solar wind have approximately Maxwellian cores with energies of the order of ten eV or so and the tails or shoulders (strahl, halo shapes) extending at higher energies as well some distortions at lower (less investigated) energies. The electron distribution cores are highly skewed by the presence of heat fluxes transported away from the Sun mainly along the magnetic field. Heat fluxes transported by ions are much lower than those transported by electrons in the solar wind. See more details and references about solar wind distribution functions and kinetics of ions and electrons in the review paper by E. Marsch at this meeting.

2. Solar wind bulk parameters

Local Maxwellian distribution functions are often used as approximations allowing the calculation of their first lower moments: density n, bulk velocity $\vec{V}$, temperature T, heat flux q for each kind of particles in the solar wind (ions and electrons). The main ion components of the solar wind are protons and alpha-particles (more than 90 % and about 4 % in average number densities accordingly). All other ion components termed as minor ions are less abundant. The solar wind ion composition is variable, but roughly corresponds to the average solar composition.

The Debye radius in the solar wind at the Earths orbit is about 10 m. Hence, the solar wind can be usually considered as a quasineutral plasma at larger scales. Quasineutrality condition approximately holds and means $\sum kq_k n_k = 0$, where q_k and n_k stay for electric charge and number density of all components: ions (i) and electrons (e). We should stress that this condition does not mean the total absence of electric fields in the plasma. Electric and magnetic fields exist and play important roles in the solar wind dynamics and in the ion composition variations. These variations are rather large and regulated in a complicated way by different ion separation and mixing phenomena competing in the collisional solar atmosphere as well as in collisionless coronal and heliospheric structures and processes. Nevertheless, observations show that protons are more abundant than all other ions every time and everywhere in the solar wind. The content of alpha particles can drop or rise, but was never observed to be higher than 2030 % in the number density. It happens after eruptions on the Sun. He^+ ions are also seen sometimes after such events associated with the cool prominence material erupted in the interplanetary space. The well known three-part coronal mass ejection structure consisting of the dense cool plasma, concentric dark cavity and bright coronal loops can be observed. This core can be identified with the eruptive prominence or missing in some instances of propagating disturbances in the corona and in the heliosphere.

The solar wind density varies roughly as a square of the heliocentric distance because of the super-magnetosonic radial plasma expansion. The plasma density out-flowing from coronal holes is lower than from coronal streamers.

Bulk velocities of all ion components in the solar wind are nearly equal to the proton bulk velocity, but they can slightly differ by an order of 10 % or so due to dynamical kinetic effects. Alpha-particle bulk velocities are usually higher than proton bulk velocities. This means some additional acceleration mechanisms for them. Opposite situations are rare and can be observed under perturbed conditions in the solar wind. It is important to note that the magnetic field in the solar wind every time has all three components which are not vanishing and not directed along the velocity vector. It is because of the presence of electric fields and E cross B drifts. Plasma flows along and across magnetic fields are superimposed.

Bulk velocities of electrons in the solar wind are poorly known because of severe difficulties with their measurements. Bulk velocities of electrons are generally small in comparison with their thermal velocities in the solar wind plasma. Our experimental knowledge is usually not sufficient for calculation of electric currents $\vec{j}$ in the solar wind starting from distribution functions of all charged particles and their moments according to the simple formula

$$\vec{j} = \sum_k q_k n_k \vec{V}_k,$$

where n_k and V_k are bulk density and bulk velocity of the particles with charge q_k. Unfortunately, only indirect measurements of electric currents in the solar wind are possible at present time. It can be done using magnetic field measurements and recalculations by

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formulae of standard electrodynamics $rot\vec{B} = \frac{4\pi}{c}\vec{j}$ etc. The lack of needed information about the electric currents in the solar wind strongly hinders our correct understanding and interpretation of many dynamical plasma processes. The same comment is true for electric fields $\vec{E}$ and electric charges q in the solar wind, which are present but not measured. The quantity $q = \sum n_k q_k$ was never directly measured in the solar wind, but the knowledge of the functions $q(\vec{r}, t)$ and $\vec{j}(r, t)$ would be of fundamental importance for better descriptions, which are not available as yet.

The thermal state of the solar wind plasma depends on its origin places in the solar corona and subsequent dynamics in the heliosphere. The ions can be hotter or cooler than electrons. Many interesting features of this kind are more or less understood and can be explained based on available theoretical models. For example, the ion temperature can be roughly proportional to the mass number of corresponding ions (in the case of rare collisions and cyclotron heating or kinematic mixing of ion beams), or nearly independent of ion mass number and equal for all ions in the case of frequent collisions. Ion temperatures along and across magnetic field can be equal or essentially different in the solar wind because of different mechanisms operating in the solar corona and on the way in the heliosphere. These mechanisms are collisional and collisionless in their physical nature depending on the situation in cooler, denser or hotter, rarefied regions respectively.

The main part of the energy, mass and momentum transported by the solar wind belongs to the protons radial motion away from the Sun. The heat transported by this motion (convective heat) is only of secondary importance as well as the heat transported by the heat conduction (third momentum of the distribution function). The heat conduction is dominated by electrons, when the viscosity determined by the ions in the situations for transports along the magnetic field in the solar wind. All details of this kind are not always clear in observations and need careful analysis, but they can be a valuable source of information about the solar wind kinetics, which is regulated by self-consistent electric and magnetic fields.

Suprathrmal particles represent some not well definite buffer zone in the velocity space and occupy an intermediate position between the major solar wind particle population and energetic particles, which are minor. Demarcation between populations in the phase space not always has some clear physical meaning. It looks often arbitrary and artificial. Solar energetic particles and heliospheric energetic particles are difficult or even impossible to consider as separate populations in any real situations when acceleration and propagation processes accompany each other in space and time. Nevertheless, sometimes one can indicate clear acceleration and heating sites in solar flares, coronal mass ejections, propagating shocks, thin layers and other features on the Sun and in the heliosphere. Potential and inductive electric fields play the role together with the magnetic field and ambient plasma context resulting in a very complicated and dynamical pattern. In the opinion of the present author, there is no typical or universal geometry and parameters of accelerators on the Sun and in the heliosphere. This geometry is complicated, dynamical and variable from case to case, which leads to the lack of any realistic universal scenarios, contrary to opposite statements in the literature dealing with so called standard models of solar flares and coronal mass ejections. Sometimes, only in rare situations, we are able to elucidate the dominant space-time scales and configurations. But it is not possible to do as a rule in most cases, which are clearly multi-scale in their nature and look as turbulent events. Correct deterministic description of such cases is practically impossible due to mentioned reasons. Only statistical and scaling methods can be really applied in such cases. Similarly, we can conclude that it is very difficult to present a consistent view of the solar wind and energetic particles based on simplistic classifications not using appropriate dimensionless parameters and their scaling.

Magnetic fields in the heliosphere play an important self-consistent role in the plasma and particle dynamics. The corresponding electromagnetic problems are non-local. Magnetic fields are non-potential and supported by electric currents on the Sun and in the heliosphere. Radial electric currents provide the couplings between different layers and form complicated global and local electric circuits. Closing currents flow across magnetic fields. Field-aligned electric currents and electric currents across the magnetic field produce global and local spiral magnetic field patterns. The largest element of this kind is the main heliospheric current sheet. It is situated near the heliomagnetic equatorial plane, which is inclined and rotates around the solar rotation axis with a period of 22 years. The current sheet separates heliospheric domains -magnetic sectors of opposite polarities. The current sheet is planar near the solar activity minimum and warped during perturbed periods. The thickness of the current sheet forming sector boundaries can be small, several ion Larmor radii, in quiet conditions and large and dynamical during active periods especially associated with sporadic coronal mass ejections. Magnetic flux ropes (non-potential magnetic flux tubes) in the heliosphere are laminar or turbulent depending on the boundary conditions on the Sun. The superposition of corotating and/or several sporadic perturbations usually leads to powerful heliospheric perturbations and complicated geomagnetic storms. The free magnetic energy of heliospheric electric currents is the key factor of the non-local electromagnetic solar terrestrial connections producing geomagnetic storms. A simple approximate empirical rule holds $D_{St} \sim 6\,B_z$ between the geomagnetic D_{St} index and the southward interplanetary magnetic field B_z. The northward magnetic field is not so geoeffective, because magnetosphere acts as a non-linear rectifier.

It would be not correct to consider the heliospheric plasma neglecting self-consistent magnetic fields, but sometimes it can be approximately done under restrictive assumptions and using inverse square magneto-sonic Mach number as a small parameter. It would be equally misleading if one attempts to reduce solar activity exclusively to the magnetic activity of the Sun. The magnetic activity of the Sun has powerful non-magnetic drivers in interiors. They can be associated with solar radiation variations as well as heat and gravity free energy sources, which are not specified at the moment and need more investigations.

3. Some astrophysical and geophysical effects of the solar wind

Solar wind plays an important role in the heliophysics. It forms the outermost plasma environment of the Sun, the solar corona and the heliosphere. The free energy of the solar wind feeds dynamical plasma processes in a broad range of space-time scales from smallest kinetic structures up to largest bulk inhomogeneities and variations encompassing many orders of magnitude in space and time. It drives the electric currents and magnetic fields here.

The solar wind is an evolutionary astrophysical phenomenon. Its origins can be ultimately related to the current state of the solar evolution and the lack of precise mechanical and thermodynamic equilibrium on the Sun, when the mass of the Sun as a star slowly diminishes. This phenomenon and the solar activity can be not described by the so called standard model of the Sun. The mass losses of the contemporary Sun are mainly due to the diminishing of its rest mass via electromagnetic radiation, i.e. white light. All other losses of the rest mass are relatively small. It is interesting to note that the energy losses of the Sun in the white light (solar constant) is about five-six orders higher than the energy losses via solar wind. The average speed of the solar wind is roughly three orders of magnitude below the speed of light. The corresponding ratios of momentum or dynamical pressures of the solar light and solar wind are of an order of 10^2–10^3. Hence, losses of the rest mass of the Sun could be of the same order or even larger for the solar wind, if compared with the light using reasonable estimates ($n \sim 5$ cm^3, $V \sim 500$ km/s) for the solar wind and 1366 W/m^2 for the light at the Earths orbit ($\sim 10^1$ erg/cm^2). An accuracy of the estimates is rather low especially for the solar wind total energy momentum and mass fluxes because of strong variations of its parameters in space and time. We do not know if this approximate equality of rest mass losses via the light and via the solar wind is accidental or not. In the second case, there should be some physical relation between luminosity and average wind for stars of solar type. We are not aware of detailed works in this direction.

The evolutionary role of the solar wind for the Sun as a star is usually assumed to be small based on the very simple estimates of the corresponding mass loss via the contemporary solar wind $\dot{M} \sim 10^{12}$ g/s. This value is negligible, $\dot{M} \ll M_\odot/\tau$, where $M_\odot = 10^{33}$ g is the mass of the contemporary Sun, $\tau \sim 10^{17}$ s being the life time of the Sun (billions of years). It is not known, when the formation of the Sun as a star due to presumed accretion processes was completed and the solar wind arose. This time moment in the past history of the transition from the accretion to the wind is to be established in the realistic scenario of the Sun formation and evolution.

According to generally accepted views, the solar activity (variability of the Sun) is due to internal processes inside the star. We do not know primary origins of solar cycles and energy driving chains, but all parameters of the solar electromagnetic and particle emissions including the solar wind and energetic particles are varying with cycle. According to the point of view of the author, the magnetic energy of the Sun could be the sequence, but not the cause of the variability of the solar constant. This hypothesis needs further investigations. The initial ideas about solar cycles caused by planetary motions around the Sun are now not so popular as in past, but they are finally not disproved. In this regard, it would be interesting to now examples of solar-type stars without planets, but with cycles of activity. If such stars will be found, it can convince that planets could be not necessary for producing stellar activity cycles. There exist also ideas about the outer interstellar or heliospheric origins of the solar activity. The estimated travel time of Alfv?n waves through the size of the heliosphere is of the order of the solar cycle duration. External electric currents can have impacts on the Sun and induce solar cycles according to these ideas, but the quantitative side is not clear. The free magnetic energy reservoir of the heliosphere and the interstellar medium is rather big and could be sufficient for this, but the real situation is not clear. We do not know internal magnetic fields in the Sun. Their estimates are not certain and not reliable.

The solar wind plays an important role when shaping the outer solar corona seen as bright coronal streamers and rays (slower outflows in denser, cooler regions) or coronal holes (faster outflows of more tenuous, hotter plasma). This shaping process continues up to outermost boundaries of the heliosphere. The kinetic energy of the inhomogeneous solar wind drives electric currents and magnetic fields in the heliosphere. Many non-linear processes and features like discontinuities and shock waves arise in a self-consistent manner. The solar wind flow evolves in space and in time, but partially keeps and transports the memory of the boundary condition near the Sun. Binary and collective collisions between particles partially smear-out this memory and lead to the new self-organization processes in the heliosphere. For example, propagating shocks can be formed due to the velocity profile evolution not only in the corona and in the inner heliosphere, but also in the distant regions of the heliosphere up to its termination and boundaries with the interstellar medium.

The solar wind and heliospheric magnetic fields control the formation and dynamics of planetary magnetospheres and comet tails. The variability of the solar wind is one of factors regulating the space weather conditions, geomagnetic perturbations and magnetic storms. Fastest solar wind streams and other strong perturbations can lead to the essential impacts on the functioning o technical systems and scientific measurements in space.

4. Solar energetic particles: terrestrial impacts

Solar energetic particles penetrate in the magnetosphere and influence on the upper atmosphere and the ionosphere in many ways. Energetic solar protons produce an additional ionization in the D-region and corresponding black-outs in the short-wave radio-communication. The same protons play their role in the chemistry of the upper atmosphere: they destroy ozone molecules, influence on the nitric oxide balance. Radiation damages of materials in space by solar energetic protons and ions are essential especially for semiconductors and dielectrics (solar panels, microelectronics, optical glasses). They can be also a risk factor during the men's flight in space and even for aircraft crew and passengers crossing polar region of the Earth during storms in space weather. Relativistic electrons accelerated inside the magnetosphere during geomagnetic storm appear sometimes at the geostationary orbit with severe consequences for communication satellites. Seed particle populations of this kind strongly correlate with high speed solar wind streams from coronal holes. Many technical and biological effects are complicated and not completely investigated.

5. Conclusions

Let us summarize our main points. 1) The solar wind originates as a more-or less regular super-magnetosonic flow of the plasma parcels in the solar corona after their long time and turbulent wanderings in vertical and horizontal directions in the lower solar atmosphere. Two domains can be indicated in this regard: 'turbosphere' near the Sun and more laminar faster outflow behind some imaginary surface around the Sun, – 'turbopause', which is not spherical and not stationary boundary or transition region between these two domains. 2) There is no sharp and strict delimitation in velocity and coordinate space between the solar wind and energetic particles. The heating/cooling and acceleration/deceleration processes are distributed in a broad range of space and time scales. Simplistic dynamical models are of limited applicability first of all because of the complicated geometry, though physical principles are clear in many instances. Hence, there is no tenable 'universal' or 'standard' scenario for the solar wind and energetic particle acceleration. The dispersion from case to case is too big for any unambiguous unification which does not use explicitly dimensionless scaling. 3) There are many important unsolved questions, mentioned and not mentioned in the text.

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