frontiers in
PHYSICS

SPECIALTY GRAND CHALLENGE ARTICLE
published: 21 August 2013
doi: 10.3389/fphy.2013.00006

Space physics—grand challenges for the 21st century

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Reviewed by:
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Keywords: space science, solar wind, heliosphere, magnetospheres, reconnection, turbulence, ionosphere, aurora

INTRODUCTION

The birth of Space Physics occurred explosively in October 1957 with the launch of Sputnik 1 into low Earth orbit. Since then, *in-situ* observations and measurements of the matter outside Earth became possible by instrumentation on board a fleet of artificial spacecraft following Sputnik 1 in quick succession. Half a century later we are now in possession of a pretty complete overall knowledge of the state of matter in interplanetary space. A multitude of spacecraft monitored the space far out, most recently up to the bounds of the heliosphere accumulating a huge amount of data and discovering a large number of effects which are completely alien to the laboratory. The era of discoveries and their theoretical interpretation is ongoing; it has even accelerated, being supported by the modern means of massive data acquisition and analysis, computing, numerical methods and numerical simulation techniques. Nevertheless, though we witnessed an enormous progress in our knowledge and understanding of the phenomena occurring space, quite a number of the originally raised fundamental questions remain only partially answered or even unanswered altogether. They have become much more detailed than before as our knowledge and understanding has penetrated deep into the microscopic state of the phenomena, but the phenomena themselves have just been monitored without bringing them to their ultimate solution. In the following we list a few of the questions that still await their final answer and thus challenge the future of space physics. Our list will necessarily remain incomplete and be biased by our own preferences, though.

ORIGIN OF THE SOLAR WIND

Parker (1958) developed a stationary fluid theory of supersonic outflow from the solar corona, being accelerated and passing through a critical point to supersonic velocities. The mechanism of acceleration was hypothetical and remains unknown until today. Any material to leave the Sun must be accelerated to speeds large enough for overcoming the gravitational attraction at the solar surface, i.e., >620 km/s. Thermal models won't do, as has been understood early. In fact, the average radial solar wind speed at a distance of 1 AU is $\gtrsim 400$ km/s, occasionally reaching 1000 km/s and more. Various kinds of plasma waves, plasma turbulence including residual collisions have been invoked for the ultimate acceleration mechanism (for a review see Burgess et al., 2013); however, none of the proposals comes up for the quasi-steadiness, persistence and comparatively large number of particles accelerated from the solar corona into the solar wind. Other ideas called for microflares (Gold, 1964) or even nanoflares (Parker, 1972) in the lower corona or upper chromosphere, i.e., small reconnection events that occur almost continuously and contribute a continuous upward flow of matter. However, the evidence for such models is sparse and, in addition, the ultimate flare mechanism remains as well unknown, which implies that the problem is only shifted to another unexplained phenomenon.

In this respect the observations of the Ulysses mission have become important, which surrounded the Sun on a unique orbit almost perpendicular to the ecliptic plane. Ulysses confirmed that the solar wind is a two-state phenomenon (McComas et al., 1998) finding that the fast solar wind originates in coronal holes at polar latitudes (Balogh and Smith, 2001), where it is accelerated in the lower corona to high speeds, large momentum and energy content on open magnetic field lines. Conversely, the slow solar wind originates from regions where the coronal magnetic field appears closed, as revealed by composition studies (von Steiger et al., 2000). Its much higher variability in all parameters points to an altogether different origin than the fast wind, possibly by quasi-stationary reconnection of open magnetic field lines migrating along the coronal streamer belt (Fisk et al., 1998a). Coronal mass ejections (CMEs), cases of sometimes extreme solar outbursts with large amounts of matter ejected into space, preferentially also occur from these regions. The reason for such enormous mass ejections is not fully known (for reviews see Kunow et al., 2007). It may be related to the action of reconnection in the deeper layers of the coronal magnetic field, which destabilizes large coronal loops. Reconnection is assumed to be the dominant energy release mechanism of flares, as it already was in the micro-flare model. Possibly reconnection, maybe in combination with other phenomena like plasma heating to high temperatures etc., is indeed the primary driver of the solar wind. However, the origin of the solar wind remains one of the great mysteries of space physics and poses a challenge for this century. Possibly all three phenomena, CMEs, flares, and the acceleration of the solar wind are just different facets of the same problem.

THE HELIOSPHERE AND ITS BOUNDARIES

The solar wind, when flowing radially out at supersonic velocity, punches a huge hole into the surrounding local interstellar medium (LISM), the heliosphere (for reviews see Linsky et al., 2009). Before the solar wind encounters the LISM it has to become subsonic, which requires a shock transition, the heliospheric termination shock. Dynamic pressure balance is reached still further out, at a radial distance of 100–200 AU. At such large distance far out of the extent of our planetary system solar radiation and gravity play no role anymore on the behavior of matter. Somewhere at this heliocentric distance we expect the boundary of the heliosphere, the heliopause (for reviews see Izmodenov and Kallenbach, 2006). The problem is not so much this distance; the two Voyager spacecraft are on their way to cross it in two angularly widely separated locations within the next decade. Voyager 1 may well have crossed it at 120 AU in 2012, as it encountered a sudden drop in density coincident with an increase in cosmic rays, yet as there was no magnetic signature whatsoever this transition represents another challenge to our understanding. The big questions are on the nature and shape of this boundary; which role galactic and solar cosmic rays play in it; what the dominant processes are that cause its structure; what effects the interaction between the solar wind and the interstellar magnetic fields have on the heliopause; whether or not a bow wave is produced upstream in the interstellar gas as it approaches with a speed of ~30 km/s. Will the boundary be dominated by magnetic effects, i.e., mainly by magnetic reconnection, or will it be more like the interaction of a neutral atmosphere (the interstellar gas) with a plasma (the solar wind), resulting in an ionopause-like structure that is naturally much more diffuse than a magnetic boundary?

The Voyagers already crossed the termination shock at 84–94 AU (Decker et al., 2005, 2008; Burlaga et al., 2008; Stone et al., 2008). The two crossings—Voyager 1 in December 2004 at ~94 AU and Voyager 2 in August 2007 at ~84 AU—brought much surprise and new problems for hard contemplation. As usual, researchers put immediately forward a number of explanations, but none of them is completely satisfactory. The termination shock has always been thought of as the strongest shock wave in the entire heliosphere, but the observations seem to indicate otherwise. It was also believed to be the main place of particle acceleration, but again there is little indication for the truth of this notion. The two Voyagers, on their way out into the interstellar medium, are now in the heliosheath between the termination shock and the heliopause (or perhaps even beyond), which is thought to be a turbulent region. However the encountered turbulence has some unexpected characteristics. It seems as if the penetrating neutral interstellar gas changes the composition of the solar wind, mainly due to its ionization by charge exchange with solar wind ions. Moreover, the assumed spiral structure of the solar wind magnetic field may become dissolved or at least distorted by processes like magnetic reconnection, permitting interstellar matter to flow in freely. Neither of these processes is understood yet. One may argue that their spatial remoteness from the Sun (and us) should waive any interest in them. This is, however, not so. The solar wind and heliosphere with its boundaries are the only stellar wind and asterosphere in the entire universe accessible to *in situ* observation. They play the role of the only available testing ground for our theories and hypotheses about the matter around other stars, which makes them of vital interest for intense exploration.

SPACE WEATHER

In the planetary system the solar wind encounters the planets with their magnetic fields, which it compresses and shapes into planetary magnetospheres. The largest and most prominent of these is Jupiter's magnetosphere, and because of Jupiter's relatively fast rotation it resembles the inaccessible, remote magnetospheres of pulsars, making its investigation of utmost importance for astrophysics.

The best-explored magnetosphere is certainly the one of Earth with its Radiation Belts, three tori around Earth with a banana-shaped cross section that are filled with very dilute energetic particles. The explanation of their stability (Kennel and Petschek, 1966) generated enormous interest, not least because atmospheric nuclear explosions were realized to be capable of refilling them after slow gradual depletion over decades. Natural refilling occurs to a much lesser degree during geomagnetic storms, the large and substantially more important magnetospheric disturbances of which the radiation belts are just a tiny tertiary effect. The dynamics of a geomagnetic storm is still not fully understood, even though storms have been known since two centuries from ground observations of the geomagnetic field. This lack of understanding relates to the lack of understanding of the main interaction processes between the solar wind and the magnetosphere, which create the outer magnetospheric boundary, called the magnetopause, and the extended magnetotail pointing in anti-sunward direction. The gross structure of the magnetosphere has been explored already; nevertheless, the processes inside it are barely understood. Understanding, however, becomes urgent with human technology having evolved to its present state. Large geomagnetic disturbances are capable of inducing currents that destroy power grids and worse. Realizing this potential danger (see Baker et al., 2008a) has created the field of Space Weather (see, e.g., Koskinen and Huttunen, 2006; Koskinen, 2011). Its aim is to monitor and understand the causes and evolution of major violent magnetospheric disturbances with all their effects. It requires monitoring and understanding the external drivers of storms: the generation of CMEs, which in its turn requires understanding of solar coronal physics, the propagation of solar flare and CME effects across interplanetary space, and their interaction with and effects on the magnetosphere. It also requires complete understanding of the magnetospheric intrinsic processes causing the storm: the stability of the magnetosphere, the release of excess energy added to the magnetosphere by an external disturbance, heating, acceleration and ejection of matter as well as the generation of electromagnetic variations in Earth's environment. While much progress has been made in many of these problems individually, we are far from seeing the big picture; this remains one of the grand challenges of space physics in the twenty-first century.

BOUNDARIES

Among the ubiquitous types of boundaries in space three are most prominent: magnetopauses, ionopauses, and shocks;

all three of them separate different types of ionized media and, therefore, carry currents. Magnetopauses are formed in the interaction of the solar wind and planetary magnetospheres with a transverse thickness is of the order of the ion gyroradius. They can, to some extent in lowest approximation, be described as magnetohydrodynamic (MHD) discontinuities that separate magnetized flows of different properties and magnetic fields.

Research in magnetopause structure has been one of the first in space physics, but the internal structure of magnetopauses is still barely understood. Since they cannot be rigid in screening the solar wind from the magnetospheres, processes such as diffusion based on anomalous collisions or ion viscosities and magnetic reconnection have been invoked to come up for the transport of matter across them. Numerous spacecraft crossings of Earth's magnetopause accumulated an enormous data pool, even allowing for some kind of reconstruction of sections of the magnetopause from two-dimensional data based on Grad-Shafranov equation theory (for reviews see Sonnerup et al., 2008; Hasegawa, 2012). But the understanding of the internal magnetopause physics is still in its early stages. The coming decades with many more multi-spacecraft missions in sight is expected to settle this most urgent problem. Although purely diffusive processes for matter transport across magnetopauses can probably be ruled out at present and transport is attributed to magnetic reconnection, no convincing model or theory has yet been produced. Moreover, the stability of magnetopauses with respect to tangential flows provides another unsolved problem. Kelvin-Helmholtz instability should arise in fast shear flows causing mixing of media to both sides, flow vortices and vortices in the magnetic field which are equivalent to local currents. These will necessarily become unstable once the transverse size becomes of the order of the gyroradius. The result will be turbulent structures and anomalous diffusion. It is clear that these nonlinear problems can be treated only by combination of observations at the smallest scales with numerical simulations.

For nonmagnetized planets with atmospheres such as Venus the equivalent of the magnetopause is an ionopause caused by the interaction of the solar wind with the atmosphere. It is more diffuse than a magnetopause, of smaller radius, more inhomogeneous, and more strongly curved. Its width is of the order of the collisional or charge-exchange ionization scale. Due to mixture of different gas and plasma components, phenomena inside and near ionopauses are even more complicated than in magnetopauses.

Since the solar wind flows with supersonic—actually super-Alfvénic—velocity relative to the planets and their magnetospheres or atmospheres, where the solar wind becomes decelerated on the short scale of the ion gyroradius, shock waves must form upstream of the obstacles. These shocks are part of the collisionless solar wind and serve as the fronts where the velocity drops from solar wind to magnetosonic values. Such shocks occur everywhere under similar conditions throughout the Universe, from the fronts of CMEs to those remote objects such as supernovae, cosmic jets, stellar wind outflows causing asterospheres, galaxies, clusters of galaxies, etc. Their physics, at least for nonrelativistic shocks, has been studied at the only continuously accessible example in space, Earth's bow shock wave. The importance of shocks lies not just in retarding the flow but also in heating the plasma by converting kinetic energy into heat, in particle acceleration and the production of radiation. The latter two effects can be observed remotely in the form of cosmic rays and various forms of electromagnetic radiation.

ATMOSPHERIC COUPLING

One particularly important field of research in space weather is the coupling between a magnetosphere and the atmosphere of a planet. It includes the boundary between the magnetosphere and the neutral atmosphere close to the planetary surface. Like the ionopause this boundary is fuzzy and implies mixing between plasma in the magnetosphere and the neutral atmospheric gas. However, there are a number of important differences. Firstly, the plasma flow in the magnetosphere is not supersonic, hence no ram-pressure equilibrium occurs. Secondly, at low magnetic latitudes the magnetic field is essentially tangential to the atmosphere while at high magnetic latitudes it is essentially normal, which leads to completely different phenomena. Thirdly, depending on distance to the Sun (or the central star) the upper layers of the atmosphere may or may not become ionized by ultraviolet radiation. Further the ionization may vary depending on the rotation period of the planet relative to recombination time as well as on the season.

On Earth the upper atmosphere is ionized. Its upper ionized layer, the ionosphere, is collision-dominated in its lower part and governed by the atmospheric winds and tides that drag the dilute plasma component. During magnetic storms the main coupling between the magnetosphere and ionosphere—and also down to the neutral atmosphere—is along the magnetospheric field that connects the tail current sheet to the ionosphere. The optical—though energetically unimportant—signature of this coupling is the aurora, which can be seen at mid latitudes during strong storms, occasionally even at low latitudes. Its cause are collisions between energetic charged particles that flow along the magnetic field from the tailward magnetosphere and discharge in the ionosphere. The important coupling effects are caused by the currents carried by these particles, which are closing across the magnetic field in the ionosphere. Though the generation of electrical conductivity is collisional here and the structure of the ionospheric current system has been explored for a long time, the distribution of the field-aligned current and, in the first place, its origin in the magnetosphere and its physical nature are still badly understood. During magnetic storms, reconnection in the magnetospheric tail current sheet is commonly assigned responsibility for the generation of these currents. However, the reconnection process itself lies still in the dark and must be highly variable as indicated by the enormous variability of the aurora and the related ionospheric and magnetospheric effects.

The ionosphere itself poses many other problems in this coupling (see, e.g., Bösinger et al., 2012). The mixture of atmosphere, height dependence of conductivity, wind system, dependence on the magnetic field are factors which are very difficult to consider in their full importance. On the other hand, their investigation is badly needed in order to understand the heating of the upper atmospheric layers, the variability of the current system, and the dependence of the storm effects on the interplanetary driver. Without a deep understanding of these phenomena space weather will be very difficult to manage, i.e. space meteorology will remain largely unpredictable.

MAGNETIC RECONNECTION

In the previous sections the phenomenon of magnetic reconnection has been identified to be central to almost all of the listed unresolved space physics problems. Physically, magnetic reconnection implies the local merging of oppositely-directed magnetic fields across a thin current layer which locally separates the two fields. This process in the collisionless space plasma happens on a microscopic scale which is smaller than the ion gyroradius and probably corresponds to the electron inertial scale inside the essentially field-free transition region across the current layer. There are claims, in particular from astrophysical applications, that reconnection in turbulent plasmas depends on turbulent quasi-homogeneous resistivity. It is, however, not well known whether such claims bear any reality, because only in very dense plasmas the electrons are not frozen to the magnetic field. Such dense plasmas do barely exist in the regions where reconnection should be important. In plasmas of the necessary density, on the other hand, any magnetic reconnection will proceed extremely slowly and dissipate very little magnetic field. In dilute collisionless plasmas, at the contrary, the release of magnetic energy stored in the sheet current that separates the fields can become substantial. It causes strong heating of the plasma (e.g., Drake et al., 2013), emitting jets to both sides of the merging region, the so-called X-point of reconnection (derived from the geometrical X-shaped form the magnetic field assumes after merging has taken place). This has been observed *in situ* for instance in the magnetotail (e.g., Angelopoulos et al., 2008) and even in the solar wind (Gosling, 2005). Clearly, merging of magnetic flux and reordering of magnetic fields locally induces an electric field that necessarily accelerates charged particles (electrons) along the magnetic field into magnetic-field aligned currents. In magnetospheres these are the currents coupling to the ionospheres. However, though this picture is intuitively appealing, there is still no known mechanism that is capable of explaining the spontaneous or driven onset of reconnection (for reviews including laboratory measurements see, e.g., Yamada et al., 2010; Yamada, 2011). Various numerical simulations have been put forward in two and even three dimensions, but the physics is by no means understood. It requires freeing of the electrons from magnetic slavery or, vice versa, freeing the magnetic field from electron slavery (e.g., Mozer and Pritchett, 2010, 2011). Which process allows it, is unknown. Numerical simulations have been performed in multitude, but all of them are imposing the onset of reconnection artificially. They have produced a wealth of different effects in reconnection once it is ongoing, thus contributing to understand its phenomenology, but they have been unable to answer the most urgent questions which may, possibly, not have a single answer at all. Since reconnection as a physical process lies at the center of many other phenomena, the urgency of resolving its puzzle cannot be overstated, making reconnection one of the central observational and theoretical challenges in space physics.

COLLISIONLESS SHOCKS

Similar to the unresolved problem of the physical mechanism of reconnection, collisionless shocks pose another problem (for a recent review see Balogh and Treumann, 2013). Formally, it is not difficult to derive the jump conditions that a collisionless flow must satisfy when crossing a shock. Sufficiently far upstream of the shock transition the flow is undisturbed and has velocity relative to the shock faster than the magnetosonic Mach number, $M > 1$. Sufficiently far downstream the flow cannot be faster than the local Mach number, $M = 1$. The difficulty lies in the terms “sufficiently far,” which in principle mean at infinity. Only for subcritical shocks, i.e., shocks with very low Mach number just above $M = 1$, the velocity in question can be taken upstream outside the shock transition. For such shocks the anomalous collisionless dissipation manages to maintain the shock by converting the slight excess in upstream momentum and energy into heat inside the shock transition in order to retard the flow inside the shock. Bow shocks and most of the shocks in a collisionless flow are, however, highly supercritical, and any anomalous dissipation is incapable of maintaining the shock. Such shocks help themselves by reflecting a substantial fraction of inflowing particles back upstream. Depending on the angle between shock normal direction and upstream magnetic field these particles propagate far upstream as gyrating beams. They interact with the inflow and retard it, possibly at a large distance from the shock. This causes a so-called foreshock but effectively broadens the shock transition to the upstream region by a large factor such that all this foreshock region must be excluded when determining the jump conditions. Even worse is the situation on the downstream side. Here in many cases the entire space between the shock transition and the obstacle causing the shock must be included into the shock transition, in which case there is no downstream boundary of the shocked region that can be used for the jump. The problem is complicated further because one must distinguish between quasi-perpendicular and quasi-parallel shocks, depending on whether the upstream magnetic field is closer to being perpendicular or parallel to the shock normal. In the latter case the foreshock will be substantially larger and the shock transition broader.

The interaction between the upstream flow and the reflected particles causes a wealth of modes, which are excited upstream making this region highly turbulent. There will be no quiet (laminar) flow anymore. Downstream, on the other hand, the flow is not just heated but becomes highly turbulent as well. One immediately recognizes that these effects cause hardly surmountable difficulties for any complete theory of collisionless shocks. The only way of treating them is via numerical simulations, including all the technical difficulties and deficiencies introduced by simulation techniques; actually, all insight into shock physics has been achieved gradually and stepwise via numerical simulations in one and more dimensions. The challenge to space physics becomes obvious. The presence of Earth’s bow shock (and the bow shocks of other planets), which is curved and therefore simultaneously exhibits quasi-perpendicular and quasi-parallel properties at different locations, strongly demands the understanding of collisionless shock physics. Since this shock is the only permanently available collisionless shock, it provides the paradigm for all relativistic shocks in space and the Universe (for a review see Bykov and Treumann, 2011), even though it is just nonrelativistic and thus lacks several properties attributed to supernova shocks, jet shocks, and others. Extrapolation to such shocks must be guided by taking the nonrelativistic limits and comparing with observation.

TURBULENCE

Collisionless shocks relate to two other problems: generation of turbulence and acceleration, which we will briefly discuss in the two final sections. They generate upstream turbulence via providing the unstable conditions for excitation of low frequency plasma waves, which subsequently grow to large amplitudes and scatter the upstream flow, thus causing vortices and cascades down to other modes. Downstream the turbulence is due to both upstream modes that are convected by the flow toward the shock, contribute to shock formation, and subsequently are ejected downstream when the next vortex arrives. Thus most of the downstream turbulence is basically old shocks which make the downstream medium highly inhomogeneous, providing conditions for excitation of other wave modes and further cascading. In relativistic shocks these processes may become even stronger because of the higher Mach numbers and the higher flow energy available upstream that can be converted into wave cascading. In addition, the number of high-energy particles surrounding the shock is large and contributes to further cascading or instability.

However, shocks are not the only way to generate turbulence. Another source of turbulence is reconnection. It destroys the laminar structure of a current sheet transforming it into chains of X-points and closed magnetic vortices, heats the plasma, generates Alfvén waves which subsequently cascade, produces field-aligned currents which cause other wave types, and ejects plasma from the X-points into slow jets that collide and mix. Shear flows around the reconnection side in the current sheet contribute to Kelvin-Helmholtz instability and transform the small-scale vortices into larger scales.

Finally, low-frequency plasma waves such as Alfvénic and magnetosonic modes can be generated in the wind flow or inside the magnetosphere. Since the medium is collisionless these wave modes grow nonlinearly to large amplitudes until breaking with turbulent crests of shorter scales. Otherwise, when dispersion sets on, these waves may evolve into subcritical shocks, which are short scale along the shock fronts and resemble vortices. Such flows have the character of turbulence for all different scales that are generated in these processes: very short scales populating the so-called dissipation scale regime of turbulence if the waves break, and larger scales when the waves disperse or produce shocks. So far no complete turbulence theory exists except for a few old ingenious theories by Kolmogorov (1941) and by Kraichnan (1965). The latter has been highly debated and other proposals have been put forward mainly on simulational bases. Turbulence remains to be one of the grand challenges for the future.

ACCELERATION AND RADIATION

The origin of very high energy particles in cosmic rays produced in the Galaxy has puzzled physics and astrophysics for a century (for reviews see Fisk et al., 1998b; Bieber et al., 2000; Diehl et al., 2002; Heber et al., 2013). Accumulative acceleration of charged particles to high energies has, since Fermi's (1949) proposal, been attributed to shocks, assuming scattering of the particles back and forth across the shock and in each crossing picking up the kinetic energy difference between the upstream and downstream flows. This idea has been made more precise in the past half century by assuming wave spectra and calculating their self-consistent generation by resonant and nonresonant wave particle interactions (Lee, 1982). In spite of its deficiencies and the weak agreement with observation, it is basically this diffusive acceleration model, which the cosmic ray particle acceleration community is still pursuing by constructing ever more complicated models (for reviews see Drury, 1983; Blandford and Eichler, 1987; Balogh et al., 2012; Schure et al., 2012). Among the problems are that this model poorly reproduces the power law spectrum and, even more importantly, cannot explain the acceleration of particles out of the background flow; it requires the presence of an energetic seed particle population which can subsequently be further accelerated by the diffusive acceleration process. This is the so-called injection problem. A number of other molds have been suggested for producing this seed population. For relativistic parallel shocks a model has been proposed which uses a nonresonant flow cosmic ray instability (Bell, 1978, 2004) for pre-acceleration. Sophistications of this model have been discussed. Other proposals assume that some particles become trapped at the shock front by some mechanism for sufficiently long time to become accelerated. Numerical simulations seem to support such a model (for a review see Bykov and Treumann, 2011). Other proposals use acceleration inside the shock front by highly nonlinear structures like electron or ion holes.

The simplest way of obtaining high-energy particles would be putting charged particles into strong electric potentials. This would lead to prompt acceleration of the particles letting them pick up the full potential difference. However, the problem relies on the hypothetical mechanism that could generate such potentials. Space physics provides an example for this process in the auroral magnetosphere (for review see Paschmann et al., 2003) during storms and substorms, which so far has not found an application in astrophysics. This process is, however, known to be responsible for the extremely intense radiation in radio waves, so-called auroral kilometric radiation, emitted during substorms by electron-cyclotron maser-resonance interaction (for review see, e.g., Treumann, 2006). Similar radiation has been detected from Jupiter and Saturn as well and is believed to be a mechanism for emitting solar radio bursts. We mentioned already that reconnection in the magnetospheric tail produces strong field-aligned currents. In a mirror geometry these currents become amplified near mirror points and may become unstable with respect to micro-instabilities, which causes localized electric fields. Many such localized fields form chains along the field line adding up to large potentials of the order of the magnetic energy converted in reconnection. Any charged particle can pick up this energy, and the mechanism would be very efficient. In addition, in strong fields this would generates observable radiation. So far it has not yet been applied to shock acceleration and, in nonrelativistic shocks, is probably of little importance. However, in relativistic shocks one may easily imagine that sufficient mirror structure is produced in the vicinity of the shock or shock transition for a similar mechanism to take over and accelerate particles out of the flow to large enough energies for entering into the Fermi chain. In any case, particle acceleration within sufficiently short time, and the production of the associated power-law spectrum for explaining the cosmic ray spectra is one of the most urgent challenges to which space physics can contribute.

CONCLUSIONS

The present list of challenges for space physics in the twenty-first century discusses only a few of the most urgent problems; naturally, it remains incomplete. We picked just a few of the most interesting processes that we identified as challenges for future research in space physics. Our emphasis was on the physics. From a different point of view one may list possible improvements and challenges in instrumentation, spacecraft and launcher technology, storage systems, data transmission, multi-spacecraft missions, mass data analysis (see, e.g., Baker, 2008b), and the development of much faster and much greater computer systems possibly based on quantum technology. Progress in simulation techniques allowing huge three- or even higher-dimensional simulations with the number of particles many orders of magnitude higher than at present could allow the modeling of real systems. So far the technology stays behind by approximately ten orders of magnitude what concerns the number of particles in real systems. Also, embedding microscopic simulations into macroscopic fluid simulations would be an alternative. This however requires the evolution of some computational renormalization group technique, which is just a dream at present. In any case, such a list of challenges would complement our list of physical problems. But even without it, the present number of problems represents a strong challenge to space physics, yet promises that resolving at least some of them will be fruitful not merely for space physics but also for astronomy and astrophysics, if not for physics as a whole.

ACKNOWLEDGMENTS

I thank Rudolf Treumann for valuable input and discussions.

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Received: 23 May 2013; accepted: 30 July 2013;

Citation: von Steiger R (2013) Space physics—grand challenges for the 21st century. Front. Physics ***1****:6. doi: 10.3389/fphy.2013.00006*

This article was submitted to Space Physics, a section of the journal Frontiers in Physics.