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Grand Challenge for Space Physics

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INTRODUCTION

The new Specialty Chief Editor traditionally writes a Grand Challenge article laying out a vision of the field: cf. the previous Grand Challenge for space physics (von Steiger, 2013). This present Grand Challenge addresses a subset of the major outstanding issues of space physics. The issues chosen are a prominent and diverse selection from across the subfields of space physics. The selections, or course, reflect the bias and limited awareness of the author. A few of the important topics that are not discussed here are the physics of particle acceleration, particle transport, ionospheric physics, and space weather.

Some other recent papers collecting outstanding questions in space physics are Denton et al., 2016, Borovsky et al., 2020a, and Denton (2020) for the magnetosphere, a recent paper is Viall and Borovsky (2020) for the solar wind, and a recent paper is Heelis and Maute (2020) for the ionosphere. Some earlier collections of interest are Goldstein (2001) and Akasofu (2005).

The Origin and Acceleration of the Solar Wind

Several major outstanding issues exist concerning the origin and acceleration of the solar wind plasma and the origins of the heliospheric magnetic structure. The fast Alfvenic solar wind clearly originates from coronal holes on the Sun, but the details of the plasma release onto open magnetic field lines are as yet unknown, the heating and acceleration of the plasma are as yet not understood, and the origins of the ubiquitous outward-propagating Alfvenic fluctuations are not known. For the slower Alfvenic and non-Alfvenic types of solar wind, even the locations on the solar surface where the wind originates from are controversial, in addition to the release and acceleration being unknown. Recent reviews are by Cranmer et al., 2017 and Marsch (2018).

Solar-Wind/Magnetosphere Coupling

Understanding the driving of the Earth's magnetosphere-ionosphere system by the solar wind is fundamental to understanding magnetospheric dynamics and to predicting space weather. Surprisingly, there are many unknowns and gaining an understanding of the coupling has been impeded by the facts that 1) multiple mechanism are simultaneously operating and 2) solar-wind measurements at L1 do not provide adequate monitoring of the solar wind's small-scale magnetic structure that hits the Earth. Outstanding issues are the mechanisms underlying mass entry from the solar wind into the magnetosphere (and the controlling solar-wind factors), the mechanisms of the viscous interaction (and the controlling solar-wind factors), the full details of global dayside reconnection (and the controlling solar-wind factors), how polar-cap-potential saturation works, and the physics of upstream transients and their impact on the Earth system. Finally, the effect of the state of the magnetosphere on the magnitude of the coupling is an outstanding unknown; in particular the feedback of ionospheric outflows acting with time lags to mass load the dayside reconnection and reduce the coupling during storms. Recent reviews can be found in D'Amicis et al., 2020, Borovsky (2021a), and Walsh and Zou (2021).

The Aurora and the Nightside Magnetosphere

After decades of study, the physical mechanisms operating in the nightside magnetosphere to drive the various types of optical aurora are poorly understood. The prominent example is the quiescent

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(growth-phase) auroral arc: controversy exists as to whether these arcs in the atmosphere are magnetically connected into the dipolar magnetosphere, into the near-Earth magnetotail, or into the transition region between the two. Not only are the magnetospheric physical mechanisms that supply current and voltage to the arcs unknown, but the form of energy converted from the magnetosphere to power the arcs is unknown. There has been a long-held desire to use ground-based auroral observations as a "television screen" to monitor the dynamic processes ongoing in the nightside magnetosphere (Akasofu, 1965; Mende, 2016a,b), but as yet a Rosetta Stone to interpret these observations has not been uncovered. The root of the problem is that uncertainties in the magnetic mapping between the ionosphere and the equatorial magnetosphere preclude the ability to connect magnetospheric spacecraft measurements with specific atmospheric auroral observations. Recent reviews can be found in Lanchester (2017) and in Borovsky et al., 2020b.

The Atmospheric Impact of Energetic Particles

Energetic particles precipitating into the atmosphere connect with the atmospheric chemistry and atmospheric electricity. Of specific importance are relativistic electrons from the magnetosphere's radiation belt and energetic protons from solar proton events: both populations deposit their energies in the middle atmosphere well below the ionosphere. Energetic particles can alter the atmospheric chemistry of NO_x (nitrogen oxides), HO_x (odd hydrogen), and O_3 (ozone), altering the radiative cooling of the Earth's atmosphere. The precipitation of energetic particles also produces electrical conductivity in the atmosphere at altitudes where conductivity is normally weak. In the vertical fair-weather electric field within the Earth-ionosphere conductivity gap, this enhanced conductivity can allow charge to be vertically transported. Of particular interest here are intense, localized relativistic-electron microbursts from the radiation belt, which can create localized conductivity channels electrically connecting the conducting ionosphere to the middle atmosphere. The influence that energetic particles have on the atmosphere is one link between space physics and Earth system science. Recent reviews can be found in Sinnhuber and Funke (2020) and in Marshall and Cully (2020).

The Global Heliosphere

Of fundamental interest are the size and shape of the global heliosphere, its interaction with the local interstellar medium, and the solar-cycle dependence of the heliosphere on the types of solar wind emitted from the Sun. There have been a decade or so of observations of the outer heliosphere, the termination shock, the heliosheath, and the local interstellar medium, via both *in situ* instrumentation and remotely using neutral-atom imaging. For the global heliosphere, not fully known are the roles of cosmic rays, neutral atoms, particle energization at the termination shock, charge-exchange processes, turbulence, and magnetic reconnection. A recent informative article can be found in Kornbleuth et al., 2021.

Turbulence

In the solar wind throughout the heliosphere velocity and magnetic-field fluctuations are seen at all spatial scales: owing to the very high Reynolds numbers of the fluctuations it is natural to assume that an active MHD turbulence is ongoing in the solar wind. Fourier spectra of the solar-wind fluctuations point to an analogy with Navier-Stokes turbulence where there is an active inertial range of turbulence, which is driven by larger-scale energy-containing fluctuations, and which is dissipated at smaller scales. Two very different scenarios appear to be ongoing in the solar wind depending on whether the observed fluctuations are very Alfvenic or whether they are non-Alfvenic. Longstanding solar-wind-turbulence issues deal with how non-turbulent large-scale fluctuations are tapped to drive the turbulent energy cascade at inertial scales, how the turbulent cascade operates for Alfvenic versus non-Alfvenic fluctuations, how the turbulence fluctuations are dissipated into ion and electron heating, and how turbulence impacts the long-distance transport of energetic particles through the heliosphere. The question of how plasma inhomogeneity alters the operation of the turbulence is also present. Recent investigations by the author (Borovsky, 2021b) raise questions about whether or not turbulent mixing is ongoing in the solar wind, about why some structures in the solar wind are not destroyed by the turbulence, and about just how active (or fossil) the observed turbulence in the wind is. Recent reviews can be found in Bruno and Carbone (2016), in Matthaeus (2021), and in Smith and Vasquez (2021).

Magnetic Reconnection

Magnetic-field-line reconnection across current sheets is a very important plasma-physics process for the evolution of magnetic systems and for the transfer of magnetic energy into plasma heating and particle energization. Longstanding issues deal with the questions of how does reconnection initiate, at what rate does reconnection operate, and how does reconnection cease. More recent issues focus on the kinetic effects acting on reconnection that can alter the way in which it operates. After decades of focus on reconnection in a two-dimensional geometry, the new-found complexities of three-dimensional reconnection are being explored and new questions are being raised. A recent review is Hesse and Cassak (2019).

Future Directions: System Science

The space-physics research community is gaining appreciation for system science methodologies. There are two aspects to system science: applying system thinking (i.e. accounting for all of the relevant interconnected parts of a system) and applying system-analysis tools. As an example, the system-thinking methodology has been very successful at advancing our understanding of the evolution of the Earth's radiation belts (Li and Hudson, 2019). System thinking is also bringing about a new appreciation for the importance of the largely unobserved cold-ion and cold-electron populations in the magnetosphere (Delzanno et al., 2021). In space physics, system-analysis tools have mostly been applied to the solar-wind-driven magnetosphere-ionosphere system: for examples, examinations have been performed of the dimensionality of various measures of the magnetosphere, classifications have been made of the system's dynamical behavior (e.g. chaotic, periodic, …), and data searches have been made for evidence of self-organization. Global numerical simulation (e.g. of the solar-wind-driven magnetosphere) is itself an artificial system that aims to imitate the real system: applying system-analysis tools to simulations is another method for gauging the quality of a simulation numerical scheme (Delzanno and Borovsky, 2022). A recent review of magnetospheric system science can be found in Borovsky and Valdivia (2018) and a recent review of ionosphere-thermosphere system science can be found in Heelis and Maute, 2020.

Future Directions: Data Science and Machine Learning

With rapidly growing amounts of data and steadily improving computational capabilities, data science and machine learning are of increasing importance to space-physics research, particularly when there is a need to co-analyze diverse types of data sets. Neural networks and deep-learning methods have proven successful for pattern recognition, data mining, and turning data into models. Space weather prediction often relies on machine-learning methods. For scientific analysis, advanced statistical methods such as information transfer are going beyond the decades of standard correlation methods. A recent review of data science can be found in McGranaghan et al., 2017 and a recent review of machine learning can be found in Camporeale et al., 2018.

FRONTIERS AND THE FUTURE OF SPACE PHYSICS

The future of space physics looks excellent. In this last decade exciting spacecraft measurements have been returned from Solar Probe near the Sun (Versharen, 2019; Parker, 2019) to the Voyager spacecraft exiting the heliosphere into the interstellar medium (Richardson et al., 2019; Fraternale et al., 2019). The science questions of space physics are compelling and the questions evolve with our increasing knowledge. We look forward to new and innovative missions, to multispacecraft measurements in the ionosphere, magnetosphere, and solar wind, and to new global-imaging concepts. The scientists entering the field are first-rate and are bringing new tools and new thinking. Space physics is a fully international enterprise.

The Space Physics section of Frontiers will publish cutting-edge original research at the forefronts of the various branches of space physics. Frontiers journals will take a leadership role with Research Topics proposed from and edited by the international space-physics community to collect and communicate our wisdom and to drive the directions of space-physics research. This Specialty Chief Editor and all of the Associate Editors are at the service of the space-research community.

AUTHOR CONTRIBUTIONS

The author JEB initiated this project and wrote the manuscript.

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