Space Physics in Greece: Experience and Future Prospects

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Abstract. Space Physics was born with the launch of the first artificial satellite, Sputnik, in 1957. The ability to conduct *in situ* physical measurements in distant, previously inaccessible regions, has made Space Physics a distinct discipline. Space flight has led to important discoveries that clarified and revolutionized our knowledge about near-Earth space. Furthermore, scientific payloads of ever-increasing complexity have been developed for space missions, pushing technology to new frontiers. Here we are presenting a synoptic review of past and current space physics activities in Greece. Future prospects in our field are outlined, with reference to international trends and national possibilities. This review is not exhaustive, and it focuses on the activity of the space physics groups at the National Observatory of Athens and at the University of Thrace, which are the main space physics groups in Greece. Needless to say, the report does not include the activities of the numerous Greek space scientists living and working abroad.

1. Introduction

The Greek space physics community is relatively small in quantitative terms. Nevertheless, it has acquired a rich experience and has gained international recognition through early and productive involvement in a number of space missions (e.g., IMP, ISEE, AMPTE). The field of research has covered both solar/interplanetary and magnetospheric physics. Currently, there is active involvement of Greek space physicists as Co-Investigators in the missions Geotail, Interball, Ulysses and Polar. Instrumentation on all these missions are state-of-the-art and scientific data are of highest quality. They are highly suitable for studies on solar-terrestrial coupling, energy flow in the interplanetary medium and the terrestrial magnetosphere, magnetic storm dynamics, space weather predictions, and impulsive particle acceleration in the heliosphere. Measurements in space are complemented by computer modeling and simulations, which are essential components of space research. Future research prospects include the upcoming missions of Cassini to Saturn (already launched), of the multispacecraft Cluster II to the terrestrial magnetosphere (to be launched), as well as the participation in the planned Solar Probe mission. Ongoing data analysis and modeling studies in a variety of research topics and in the framework of both national and international collaborations, will keep the Greek space physics community on the front line of space research.

2. Past experience and current activity

Greek space research has spanned the whole range of space physics topics, from solar energetic particle events (e.g., Sarris et al. 1984), down to the role of the terrestrial ionosphere in the dynamics of space magnetic storms (e.g., Daglis 1997). The early era of Greek space research is connected to the collaboration between the Division of Telecommunications and Space Science at the University of Thrace and the Johns Hopkins University Applied Physics Laboratory in the framework of the IMP (Interplanetary Monitor Platform) missions during the 1970s and later. A number of important contributions to the international literature, mainly in the field of ion acceleration (e.g., Sarris et al. 1978) established the significance of Greek space research in the international community.

An increasing number of space programs have involved Greek space physicists as team members: Voyager, International Sun-Earth Explorer (ISEE), Active Magnetospheric Particle Tracer Explorers (AMPTE), Viking, Geotail, Combined Release and Radiation Effects Satellite (CRRES), Cassini, Advanced Composition Explorer (ACE). Moreover, Greek space physicists have participated as invited Co-Investigators in the preparation and realization of a number of space missions: Geotail, Ulysses, Interball, Mars-94, Cluster, Polar, Satelite de Aplicaciones Cientificas (SAC-B).

Following we give a brief indicative (and consequently incomplete) list of major research topics and corresponding groups in Greek Universities and Research Centers, which involve processing, analysis and interpretation of spacecraft measurements, theoretical studies, modeling and simulations: energy balance in the terrestrial magnetosphere and substorms (University of Athens, University of Thrace, National Observatory of Athens), modeling of particle motion and acceleration in the terrestrial magnetosphere and ionosphere (Univ. of Thrace, National Observatory of Athens), terrestrial magnetotail dynamics and acceleration processes (Univ. of Thrace, National Observatory of Athens), geomagnetic storm dynamics (National Observatory of Athens), particle propagation and acceleration in the interplanetary space (Univ. of Athens, Univ. of Thrace), particle acceleration at collisionless shock waves (Univ. of Thessaloniki, Univ. of Thrace, Univ. of Athens), energy release and particle acceleration in solar flares (Univ. of Thessaloniki, Univ. of Athens, National Observatory of Athens), dynamics of planetary atmospheres and ionospheres (Academy of Athens, Univ. of Patras).

Below, we synoptically present a few significant Greek contributions to space research during the last two decades. One of the most important research topics of space physics is the acceleration of charged particles to high energies. Sarris & Krimigis (1985) showed on the basis of Voyager 2 measurements that quasi-perpendicular interplanetary shocks provide most efficient acceleration of ions (up to $\sim$200 MeV) and electrons (up to $\sim$2 MeV). Their results confirmed the theoretical predictions of the concept of shock drift acceleration (e.g, Armstrong et al. 1977).

Anastasiadis & Vlahos (1991, 1994) studied the acceleration and transport of high energy particles (electrons and ions) for the case of solar flares. Their approach was based on the consideration that active regions are driven dissipative systems with a number of interacting elements. They considered that the acceleration of solar energetic particles is due to the presence of a number of shock waves distributed randomly inside an active region.

Closer to Earth, Daglis et al. (1990, 1991a) presented evidence for efficient outflow and acceleration of ionospheric ions during magnetospheric substorms, resulting in active participation of ionospheric-origin ions in substorm development. Significant enhancements of O^+ ions, observed during the substorm growth phase by the AMPTE/CCE spacecraft, were suggested to trigger substorm onset by favouring the occurrence of plasma instabilities (Daglis et al. 1990). Such O^+ enhancements can also contribute to the reconfiguration of the near-Earth magnetosphere from dipole-like to tail-like during the substorm growth phase by enhancing the near-Earth cross-tail current (Daglis et al. 1991a).

In a series of follow-up studies, a significant body of work on observations in the inner magnetosphere addressed the dynamic relationship between the energetic part of the magnetospheric plasma and the ionospheric activity and outflow, during substorms and storms. A number of studies with data from the AMPTE and CRRES missions (Daglis et al. 1991b, 1992, 1994, 1996), focused on the expansion phase of substorms. They revealed a strong correlation between O^+ energy density and auroral electrojet intensity during substorm expansion, on timescales of several minutes. This implies that enhanced magnetospheric activity drives an increased ionospheric participation in magnetospheric processes.

However, magnetospheric activity influences not only the magnetosphere-ionosphere coupling and the internal magnetospheric characteristics, but also the near-Earth "external" space. Measurements from several spacecraft (IMP 7 and 8, ISEE 1 and 2, AMPTE/CCE) repeatedly showed that magnetospheric activity results in "leakage" of energetic particles to regions of space outside of the magnetospheric domain (Sarris et al. 1987, Paschalidis et al. 1994).

Magnetic storms are most remarkable global-scale processes, and they are of particular interest because they often have severe impacts on technological systems. Daglis (1997) investigated CRRES observations of one moderate and four large magnetic storms, and showed that the ionospheric-origin O^+ ions are the dominant ion species around the maximum of the main phase of intense storms. Consequently, the intensification of the storm-time ring current is mainly due to the contribution of O^+ ions. Taking into account that a fraction of H^+ (about 30% in the storm-time outer ring current) is also of ionospheric origin, it is clear that the majority of the storm main phase ring current particles are of terrestrial origin. In other words, it is the terrestrial plasma that causes the strong disturbances during the main phase of intense storms (Daglis et al. 1999b). It is most remarkable that during the March 24, 1991, storm the contribution of O^+ alone to the total energy density of the ring current reached almost 80% (Daglis et al. 1999a).

A fundamental process in space physics is magnetic reconnection, which is the driver of energy transport during magnetic storms as well as solar flares. Anastasiadis et al. (1997) have examined the connection of the spatiotemporal evolution of the energy release process with the acceleration environment during solar flares. They used the concept of self-organized criticality on a cellular automaton model (see Georgoulis & Vlahos, 1996) to estimate the way and the ammount of the released energy, by means of magnetic reconnection processes. Their acceleration model was based on the interaction of electrons with a number of reconnecting current sheets (RCS), due to the convective electric filed inside the RCS.

3. Future prospects

The principal short-term objective of international space physics is the comprehensive exploration of solar-terrestrial coupling - the so-called Sun-Earth Connection. This task is to be met mainly through the availability of the large satellite armada of the International Solar-Terrestrial Physics (ISTP) Program (which will include the upcoming Cluster II mission) and through complementary ground-based measurements. The main goal is the advanced understanding of the transport of mass, momentum and energy throughout the solar wind, and the magnetosphere-ionosphere system.

An important innovative tool in this endeavor is the imaging of energetic neutral atoms. The importance of global magnetospheric imaging through energetic neutral atom imaging has been increasingly recognized (e.g., Williams et al. 1992). Imaging of charge-exchange neutral atoms, or shortly neutral atom imaging (NAI), is a relatively new technique that enables global imaging of magnetospheric plasmas, as well as plasma ion populations in general (e.g., McEntire & Mitchell 1989). The *in situ* observations of the terrestrial magnetosphere performed over the past decades of space research have provided a rather good understanding of many partial localized dynamic processes. However, the continuing lack of global observations inhibits the understanding of the magnetosphere in terms of global dynamics. NAI is a revolutionary way to monitor the magnetosphere. Measurements of energetic neutral atoms (ENAs) enable global observation of the magnetosphere, because ENAs are not bound to electromagnetic fields and therefore provide global information on distant magnetospheric regions - as opposed to local, *in situ* information provided by charged particles. We have been involved both in relevant modeling studies (Orsini et al. 1994, Milillo et al. 1996a,b, De Michelis et al. 1997) and studies of pioneering measurements (Wilken et al. 1997).

The arrival of solar disturbances and the development of geomagnetic storms pose a threat to advanced technological systems in near-Earth space and on the ground. A new term has been coined for such magnetic disturbances, the associated energetic charged particles, and their effects: Space Weather. The efforts to understand the mechanisms of energy and mass transport throughout the solar-terrestrial system will eventually enable us to understand space weather, which is already a priority for nations with extensive (and vulnerable to Space Weather) space activities, like the US.

Obviously, an important part of solar-terrestrial research, applying to space weather and magnetic storms, is the development of prediction techniques of geomagnetic activity. It is essential to develop techniques that will someday enable us to forecast space weather, much the way we can forecast weather on Earth. We have been involved in the development of non-linear filter methods (Vassiliadis & Daglis 1994) and of cellular automata models (Isliker et al. 1998, Vassiliadis et al. 1998), which will be valuable tools in our efforts to develop reliable prediction capabilities.

Space weather, however, is not the only effect of solar variability on Earth. Changes of one of the most fundamental quantities, the solar irradiance, on time scales ranging from seconds to millions of years and on all wavelengths, are now well established and are associated with Sun's surface magnetic activity. In addition, a correlation is found between the various indicators of solar activity (e.g. number of sunspots, solar cycle length, flux at 10.7 cm etc) and a number of meteorological parameters with good statistical significance (Labitzke & van Loon 1990, 1993, Reid 1991, Friis-Christensen & Lassen 1991). Apart from the total solar irradiance variations, there is now evidence that changes associated with solar cycle variations in the UV radiation have major implications on middle atmosphere ozone and temperature. On the other hand, large variations of energetic particles initiate significant changes in upper atmosphere odd-nitrogen, which can destroy ozone if transported down to the high lattitude middle atmosphere. The knowledge of the impact of the solar forcing is important if we want to improve our knowledge about the impact of human activities on climate changes. We believe that the strong evidence presently avalaible on the existence of a causal relationship between solar activity and meteorological phenomena is sufficient to warrant further investigations in the field.

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