SPACECRAFT-PLASMA INTERACTIONS: WELCOME AND THE ESA PERSPECTIVE

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Abstract

The scope of this conference is determined by the range of issues related to the ambient plasma and electrodynamic environment that have to be addressed in the preparation and operation phases of spacecraft missions. The ambient space plasma is a reservoir of charged particles (electrons and ions) with mean kinetic energy varying from less than one electron-volt to several tens of kilo electron-volts depending on the location of the spacecraft in space. These particles may directly interact with some spacecraft systems especially the ones involving a voltage source (e.g., solar array, photo-multiplicators, RF guides). Furthermore, the natural charged particle accumulation on spacecraft surfaces results in an electrostatic field distribution (sometimes with very high peak value of the electric field) on the spacecraft surface and in its vicinity (the sheath). Significant charge accumulation and associated field distribution may also take place inside material exposed to radiation in the keV to several MeV energy range. These two effects have impacts on the material surfaces and the electronic components (dielectric stress, arcing, sparks, accelerated ion impacts, change of electrical properties, charged contaminants), the plasma sensors (perturbation or screening of the electrodynamic environment to be measured), the radio-communication (refraction and diffraction by plasma structures). All these interactions are furthermore complicated by the presence of particles generated on spacecraft surfaces (e.g., photo-electrons, secondary electrons, thruster plumes). Models and data available to address the relevant processes involved in these effects are still very limited. This situation requires an ambitious research and development programme from space organisations. In this talk an overview of the status of the ESA programme in this field is presented together with future prospective including international collaborations.

Introduction

The European Space Agency is co-ordinating various scientific and application space programme in Europe and world-wide. The research and development programme of ESA includes several activities related to spacecraft plasma interactions in fields as diverse as electric propulsion, radio-frequency device, electromagnetic compatibility, space science instruments, material engineering.

Space systems are exposed to the plasma environment which is found above a few hundred kilometers altitude. Around the Earth the plasma is strongly organised according to the topology of the magnetic field and is therefore called a magnetosphere. Figure 1 shows a sketch of the magnetosphere with the overall distribution of the plasma regions. The whole magnetosphere is embedded in the so-called solar wind which is constituted of charged particles expanding from the solar corona and which transports its own magnetic field. At the lower altitudes, the plasma has a temperature around 0.1 eV (~1.6 10^3 K). It is mainly created by UV photo-ionisation of the atmosphere and is called the ionosphere. There is a peak density of about 10^6 cm^{-3} on the day side and at low altitude. It is conductive and therefore may short cut high power systems. The ionospheric plasma diffuses into a torus-shaped volume called the plasmasphere where the density is still relatively high (>100 cm^{-3}). The plasmasphere extends usually to about 4-5 Earth radii but occasionally reaches the geosynchronous altitudes (i.e. 5.6 Earth radii). Outside the plasmasphere, the plasma environment is somewhat different and it is not clear whether it is of terrestrial or solar origin or a mixture of both. The plasma density is getting much lower (varying from 0.1 to 10 cm^{-3}). The conductivity there is therefore negligible for most of the space devices. The plasma temperature, however, reaches values of the order of 100 eV to 1 keV (e.g. in the plasmasheet). There are also non-thermalized populations in various energy range from the order of 1 keV to 10 MeV. The 100keV to 10 MeV particles are found in the so-called Earth radiation belts. The others are produced sporadically like the so-called discrete auroral precipitations at the poleward edge of the plasmasheet (observed on polar orbiting satellites) and the storms and substorm associated particle injections at the Earthward edge of the plasma sheet (mainly observed at geostationary orbit). The electron in the range of 1 to 10 keV are the driver of high level surface charging while electrons in the range 100 keV to 10 MeV are responsible for deep-dielectric charging.

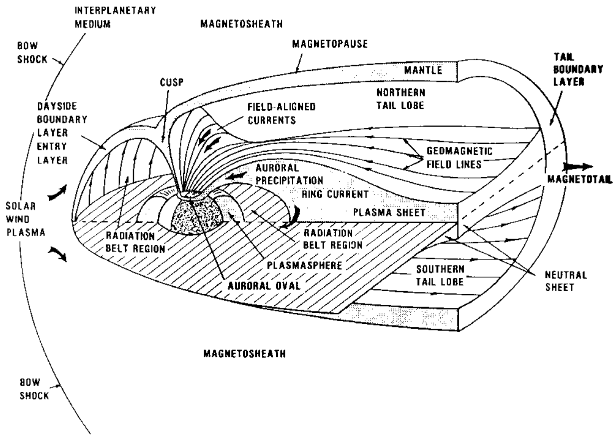

Figure 1: Cross section of the magnetosphere where various plasma regions are indicated.

Although recognised very early in the advent of space exploration, the importance of a detailed understanding and modelling of plasma interaction with spacecraft has in the last decade regularly gained more and more importance and presently appears as a major topic both for space applications and science. There are several reasons for this increase of interest. In the domain of space applications, the continuous evolution of technology calls for the development of more and more complex space systems that make use of new materials and instrumentation. While these systems are more sensitive to the effects of charging and of interaction with plasma and more energetic particles, the required level of reliability is continuously upgraded. In the area of space science, the exploration of unknown and often adverse planetary space environments goes presently along with the necessity of improved and more detailed measurements. Such new and refined measurements are always more susceptible to the effects of spacecraft-plasma interactions. They may also ask for the use of specially designed instruments such as electron or ion guns to maintain the satellite potential at low enough values and it is of great importance to be able to understand the operation of such instruments and be able to ascertain their influence on the ambient plasma. In addition, a spacecraft plasma interaction research programme must include the study of space systems which will or may be used in the coming years for orbit control or to accelerate interplanetary probes, such as tethers, ion thrusters and propulsion through the development of small scale artificial magnetospheres. These systems open a new field of phenomena, some of them being in fact only in the state of very early ideas.

Past activities

In the 70's the main concern related to spacecraft plasma interactions in the domain of space applications was the occurrence of electrostatic discharges induced by high level charging on large dielectric surfaces or floating metallic parts. To address this issue a major research and development activity has been undertaken mainly by USAF and NASA in the US which included an experimental spacecraft, SCATHA, and the development of a computer code, NASCAP. This numerical tool has been further used by the industry in US and also in Europe for charging analysis [Frezet et al., 1989; Daly 1987]. In parallel ESA has sponsored the development of simple engineering charging analysis codes, e.g., the LEOPOLD and EQUIPOT codes which have been made available world wide and free of charge via SPENVIS to assess the potential equilibrium of sample materials on spacecraft surfaces in typical space environments [SPENVIS]. For this kind of application a significant effort has been put in providing an interface that may assist the user to easily identify the required parameters and range to meet design requirements.

In the space science domain the main concerns have been related to the disturbances of the electrostatic environment due to surfacic and space charges and the contamination of the detectors by secondary particles. These effects, if not properly modelled, may prevent any accurate calibration of the instruments. Several modelling works have been undertaken to address these issues [cf e.g. Grard editor, 1973]. The quantitative models developed so far mainly relies on analytical formulas (Langmuir probe type) and on strong hypotheses on the symmetry of the instrument environment. These models are in general too simplistic to provide an accurate quantitative model of the measurements. Nevertheless, they helped to understand the various effects involved and how to reduce their influence.

Current situation

Nowadays, the level of understanding of surface charging processes has reached such a maturity that spacecraft designers are routinely addressing the issue of high level charging with the help of rather well established procedures [Purvis et al., 1984, ECSS]. Simple engineering tools are usually considered as sufficient when enough information on material properties are available. There are, however, new classes of phenomena that have become more and more critical issues for the European space community. These include secondary particle interactions with sensitive devices, electric thruster plasma plume interactions, solar array secondary discharges, and electrodynamic interaction of long conductors with magnetised plasma. The assessment of these effects may involve the dynamics of several particle species or space charge effects or small scale geometric details. As a result, much more sophisticated descriptions and algorithms than the ones used so far in any existing engineering charging code are now required.

Similarly, space scientists have rapidly learnt how to cope with the perturbations related to the spacecraft plasma interactions. It is sometimes possible to minimise the disturbances via e.g. the use of long booms or the use of redundant systems. For instance electrostatic probes are usually mounted at the end of several tens of meters booms and their geometry is made as symmetric as possible such that simple analytic formula may be used to analyse the measurements. All of such measures affect the spacecraft design and may have a non negligible impact in term of cost. In addition, absolute and accurate calibration of space plasma instruments is still an extremelly challenging task for space plasma physicist. Most detectors are still very close to spacecraft surfaces and their environment is therefore not symmetric. Furthermore, even on spacecraft with good electrostatic cleanliness there may be problems related to the absolute charging of the spacecraft structure which is in general very difficult to avoid unless active device are used [Torkar et al., 2001]. An example is given on Figure 2 where the time series of several plasma parameters as measured by the Swedish satellite, Freja, are shown around a period of electrostatic charging in the low altitude polar environment. The charging level in this case reached reached a value above -1000 V. For other spacecraft at much higher altitudes the scientific measurements usually suffer from the positive charging of the structure and the photo-electron contamination.

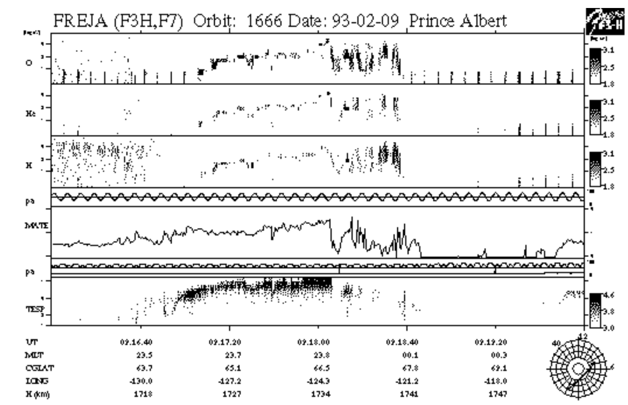

Figure 2: Time series plot of three type of ion measurements (3 top panels) and electron measurements (2 bottom panels) measured onboard Freja. The energy range is shown on the vertical axis and the grey level indicate the flux magnitude. The charging event is identified by a rise of the ion energy for all three ion species and all directions. This is because the ion are suddenly accelerated by toward the spacecraft and caught with such a high energy by the detector. One can see that such an event occur during a period where high energy electrons are observed. These electrons are typically observed during auroral arc crossings.

A promising approach to address the current remaining problems observed with plasma sensors may rely on the use of sophisticated plasma simulation tools. With such tools it would be possible to simulate the response of the instruments in a realistic environment. An example of such an investigation is found elsewhere in these proceedings [Roussel and Berthelier, 2001].

Perspectives

From the above summary of the current situation in the domain of spacecraft plasma interactions it is first of all clear that there are requirements for more sophisticated plasma simulation tools. Various academic research activities on this line have already been undertaken by several groups in Europe and in the US which have led to several computer based models which are just starting to provide results. The most promising models today appear to be based on the statistic simulation of a large number of particles e.g., via Particle In Cell technique (PIC) since they may potentially capture the whole spectrum of physical processes involved in spacecraft plasma interactions [cf e.g., Roussel, 1998; Forest et al. 2001, Tajmar et al. 2001 for the European groups].

Also, current engineering practices and the above described modelling activities require precise inputs in order to properly take into account the surface properties of the materials that are used to build space vehicles. Such information can only be gained from laboratory measurements where the properties of materials, such as photo emission and secondary electron yield, electrical conductivity and electrical break-down threshold are measured in conditions as close as possible to those encountered in space. The numerical models need also to be validated in laboratory plasma chambers and by comparison with other computational techniques.

As a result of these various requirements several national agencies, academic and industrial groups in Europe together with ESA are intending to strengthen the coordination in the development of models and data on spacecraft plasma interaction especially to reinforce the compatibility between the various approaches and the possibility to share resources. A first significant step has been taken when a network, SPINE (Spacecraft Plasma Interactions Network in Europe) of scientists and engineers has been set up at a Round Table held on 24-2-2000 at the European Space Technology and Research Centre (ESTEC). The main goal of this network is to share resources, co-ordinate efforts and provide to a large number of scientists and engineers in space related companies and organisations well accepted and recognised results and techniques in all domains related to the interaction of spacecraft with space plasmas. According to its term of reference, the primary area of collaboration in the SPINE network are:

- Numerical analysis methods and algorithms, software architecture and data interface (code implementation, validation techniques, testing and post-processing).
- Development of a database on material properties, environmental data and space flight observations.
- Preparation of in orbit investigations.
- Establishment of standard procedures and method for hardware design, including qualification, and testing [cf also ECSS].
- Training of young scientists and engineers.
- Establishment of international collaborations.

Several activities have already been initiated in the frame of, or in synergy with, this network including the development of a PIC spacecraft plasma simulation code, PicUp3D [Forest et al., 2001] and the preparation of a standard on Environment-Induced Effects on the Electrostatic Behaviour fo Space Systems [ECSS]. Many more activities are expected to be initiated in the coming few years. Furthermore, collaborations with interested international partners have also been initiated.

Conclusion

Various research and modelling activities have been undertaken over the last decades in the field of spacecraft plasma interactions. The success of these activities have lead to improved design and methodology for the well known and now old space technology. However, the continuous technological innovation in the space domain requires that new aspects of the spacecraft plasma interaction processes be investigated. In parallel, the evolution of computing resources makes now possible the development of very detailed numerical quantitative models using simulation techniques that have matured among the space plasma science community and that may be used now in a more operational context. The new types of collaborations that are currently being established among European partners and potentially world-wide are expected to create the conditions for new and rapid developments in this field.

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