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THE EFFECTS OF SPACECRAFT – PLASMA INTERACTION ON PLASMA AND ELECTROSTATIC PROBE MEASUREMENTS

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Introduction

Since the advent of space flights the effects of spacecraft interaction with the ambient plasma and with the solar UV radiation have motivated a very large number of studies which make this field an important domain of space physics. As a matter of fact, the consequences of these processes are of outmost importance on the reliability and significance of in situ plasma and electric fields measurements and may also, in extreme cases, represent a major concern for the reliable operation of spacecraft in orbit. In a first section the major charging mechanisms and their results on the spacecraft electrical equilibrium will be briefly presented. The two following sections will be devoted to a review of the perturbations induced on plasma measurements by means of particle analyzers and on electrostatic probe characteristics. In a conclusion we shall summarize the conditions which must be fulfilled to ensure reliable measurements.

Spacecraft charging processes and resulting electrical equilibrium

The basic physical processes governing the charging of spacecraft has been described by many authors and excellent reviews were given in particular by Garrett (1981) Whipple (1981) and more recently by Hastings (1995).

This paper will be mainly focused on the more common case of ionospheric and magnetospheric satellites or planetary probes, with no active experiments to emit beams of energetic electrons or ions. In this case, the equilibrium potential essentially results from the balance between on one side the collection of thermal and energetic electrons from the ambient thermal and hot plasmas and, on the other side, the collection of thermal and energetic ions and the emission of secondary electrons due either to photo emission by solar UV photons or to energetic charged particle impacts on the spacecraft external surfaces. Ions sputtered by high energy ions or neutrals (Olsen and Norwood, 1991) have, in most practical cases, a negligible influence in the global charge collection budget, but this may be not true in extreme conditions such as in the Jupiter radiation belts. Similarly, except for high velocity fly-by missions through planetary or cometary atmospheres, the secondary electron emission by neutral impacts remain negligible. The equilibrium electric potential is thus obtained as a solution of the general equation :

$$Ie_{th} + Ie_h + Ii_{th} + Ii_h + Is_e + Is_i + I_{ph} = 0 \quad (1)$$

The photoelectric current is subject to the variations of the intensity of solar UV fluxes, hence on solar cycle variations and also depends on the nature and history of the surface materials (Brace, 1988). Typical values at 1 AU are ~ 40µA/m^2 for oxidized aluminium and ~ 20µA/m^2 for stainless steel. These values have been deduced from measurements on high altitude satellites where surfaces have been cleaned by a long exposure to solar UV and to energetic particle bombardment. Current densities can be significantly lower for orbits which penetrate deeper in the atmosphere due to the adsorption of atmospheric gases by the surface materials, in particular atomic oxygen (Pedersen, 1995). Thermal electron and ion currents are subject to considerable variations as a function of the thermal plasma characteristics encountered along the orbit. Average values of plasma density and temperature in the Earth's ionosphere range from 10^2 to 10^6 el/cm^3 and 0.2 to 1 eV respectively; in the Earth's or Jupiter magnetosphere corresponding numbers range from 10^{-2} to 10 el/cm^3 and 1 eV to 10^2 eV. In LEO typical auroral electron fluxes at 1 to a few keV reach 10^8 el/cm^2.s.st.eV, at geostationary orbit and in the plasma sheet fluxes amount to 10^7 el/cm^2.s.st.keV at energies of 10 to 30 keV, in Jupiter magnetosphere fluxes of electrons are typically 10^2 to 10^3 el/cm^2.s.st.keV at about 1 MeV. Energetic ion fluxes are typically at least an order of magnitude smaller. In the Earth high latitude ionosphere and magnetosphere energetic electron fluxes are strongly modulated by the auroral activity and spatial and/or temporal increases of up to 2 orders of magnitude are not uncommon. For low altitude orbits (i.e. in Earth or planetary ionospheres) the effect of thermal plasma is generally dominant and, as shown in table 1, spacecraft potentials (referred to the local plasma potential) average at about less than a few volts, negative in the dense ionosphere or at night, positive at higher altitudes in daytime due to photo emission. However, even at moderate altitudes (~ 800 km), significant negative charging have been reported in the nighttime winter auroral regions and for periods of enhanced auroral activity (Gussenhoven et al.,1985 ; Frooninckx and Sojka, 1992 ; Anderson and Koons, 1996). This is due to the simultaneous occurrence in active auroral arcs of intense fluxes of energetic electrons with a rather low production of secondary electrons and of plasma depletions down to 10^2 el/cm^3 or less, not enough to neutralize the negative charging due to the collection of energetic electrons.

In the magnetosphere where the thermal plasma density is low, the two dominant terms in equation (1) are the photoelectric I_{ph} and the energetic electron Ie_h currents. In the magnetospheric lobes where the thermal plasma density is << 1 el/cm^3, satellite potential can reach high positive values of the order of ≥ 50 volts. In these regions, measurement of spacecraft potential from data of the electric field experiments on board ISEE-1 and POLAR have been used to infer the plasma density (Escoubet et al., 1997 ; Mozer, 1998). At geostationnary orbits or in the near plasma sheet and in eclipse conditions energetic auroral electron fluxes can drive the spacecraft potential to very negative potentials typical of the equivalent temperature of the particles. This effect, first described by De Forest (1972) has been since documented and studied by numerous authors (e.g. Garrett and Rubin, 1978 ; Mullen et al., 1986).

As far as planetary or cometary environments are concerned some observations are available for Mars (Phobos), Jupiter (Voyager 1 and 2) and P/Halley (Giotto). For Mars (Grard et al., 1991) and P/Halley (Lammerzhal et al., 1987), the floating potential of the spacecraft was, as anticipated , similar to the case of LEO, within a few volts of the plasma potential. The Jovian magnetosphere, on the contrary, is filled with very energetic electron and ion populations with, as a consequence, high levels of spacecraft charging. From particle measurements on Voyager 2, Khurana et al. (1987) have concluded that dropouts of the low energy particle fluxes could be explained by large, negative spacecraft potentials from several kV to several tens of kV, in accordance with the variations of the characteristic energy of the high energy electron fluxes.

Up to now we have implicitly assumed a uniform charging of spacecraft with an external conductive surface. In practice, the situation may be more complicated owing to the non equipotentiality of spacecraft surfaces and thus to the large potential difference between sections exposed to solar radiation and sections in shadow and also to their complicated shape and appendices such as solar cells. A wide variety of conditions involving various asymetries due to wake, insulating surfaces, etc…have been shown (e.g. Katz and Mandell, 1992; Prokopenko and Laframboise, 1980; Parker, 1978; Laframboise and Luo, 1989) to lead to differential charging where various external sections may acquire significantly different potentials. These potentials depend in a complex way of the characteristics of the local and adjacent materials, of the 3D structure of the potential in the spacecraft sheath and on the characteristics of the energetic ambient plasma.

Effects of charged spacecraft on plasma measurements

In the simplest case of a spacecraft which can be considered as uniformly charged, the first and straightforward consequence is that particles with electrical charges of the same polarity as the spacecraft potential are repelled by the electric field in the sheath. If their kinetic energy is lower than the potential they cannot overcome this potential and reach the spacecraft : the low energy part of the plasma remains thus undetected. Before the recent advent of devices to control the charging of magnetospheric spacecraft, this phenomenon effectively prevented to detect the thermal, low energy plasma of ionospheric origin which threads the distant regions of the Earth's magnetosphere. The existence of this “hidden” population was first inferred by Olsen (1982) from measurements performed on SCATHA when the spacecraft went into eclipse and consequently its potential decreased from significant (> 10 volts) positive values down to low enough levels. This can also explain the long term discrepancies between plasma density values deduced from particle analyzers and those inferred from plasma resonance sounders (Olsen et al., 1986). “Repelled” particles with high enough energy can reach the spacecraft and be detected by plasma analyzers. However, their energy and angular distributions suffer noticeable distortions before reaching the analyzer and due corrections must be performed to retrieve the undisturbed free space particle distribution function. The true energy of the repelled particles is given by the relation

$$E = E_m + q\,\Phi_{s/c}$$

where q is the particle electrical charge, $\Phi_{s/c}$ the spacecraft potential and E_m the measured energy in the spacecraft frame of reference. Determining the true energy spectrum requires a precise enough knowledge of $\Phi_{s/c.}$ When data on attracted particles of opposite electrical polarity are available, it can be inferred from the position of the peak in their observed energy spectrum (e.g. Gussenhoven et al. , 1985); in case of transient charging events one can also evaluate it from the shift in the energy spectrum from before to during the event (e.g. Wrenn and Johnstone, 1986). With regards to the angular distribution, which is often a parameter of prime importance to study transport and acceleration processes in space plasmas, the situation is even more critical since one needs to perform non local corrections involving the evaluation of perturbations imposed on particle trajectories by the electric field in the spacecraft sheath. For most cases with significant charging attempt to correct the observations are therefore rather imprecise, not to say speculative, and at the best only a qualitative estimate of particle characteristics can be obtained.

The situation is however more favorable on the recent magnetospheric spacecraft POLAR and GEOTAIL ; the spacecraft potential can be accurately obtained from the electric field probe potential and the satellite equipotentiality and simple shape should allow a reliable and precise enough modeling of the sheath, thus enabling corrections on particle measurements to be made.

Particles which are attracted by the spacecraft potential can evidently be detected but similar effects as those above mentioned make also difficult and moderately reliable the needed corrections. The energy spectrum displays in general a threshold or a peak corresponding to the spacecraft potential which can therefore be determined in principle . In case of a charging voltage significantly greater than the characteristic energy of the low energy particle population, the finite energy resolution of the analyzers precludes to make any valid determination of the energy spectrum of attracted low energy particle. The work of Scime et al. (1994) gives an interesting presentation of the complex and detailed corrections performed on the ULYSSE electron spectrometer data and show the remarkably successfull results which have been achieved, probably for the first time for solar wind electron measurements.

Differential charging makes particle measurements even more difficult to correct. The numerical modeling of the spacecraft sheath with the needed spatial resolution and taking into account the characteristics of all different materials is practically out of reach and thus determination of the particle trajectories is, in most cases, impossible. Also differential charging often leads to the existence of saddle point for the potential in the sheath or potential barriers. This can be a large scale effect, for example between the illuminated and shadowed sections of the spacecraft (Garret and Rubin, 1978) or this can happen locally if the entrance area of the plasma analyzer is neighboured by surfaces with different charging potentials. In such a case the observed threshold in energy on repelled particles do not correspond to the potential of the analyzer entrance but is controlled by the level of the barrier potential in front of it. Charging near the entrance of the analyzer may also be the cause of spurious effects.

In the case of attracted particles, differential charging can give rise to a peak in the energy spectrum corresponding to secondary particles emitted by a surface at a potential such that the entrance area of the detector can attract and even focus those particles. Examples exist (Grard et al., 1983) which show the energy of the peak evolving in time as a function of the corresponding variation of the charging voltage of the emitting surface or of the analyzer entrance. An interesting case of unstable spacecraft charging has been recently studied by Lai (1991). The instability results from the existence of triple roots in the solution of equation (1), one of the root being unstable. The existence of these roots and the corresponding potentials strongly depend on the characteristics of the incident primary particles and of the secondary emission properties of the emitting surfaces, this latter being controlled, among other parameters, by local potential barriers. The variations of the potentials which are solutions of (1) due to changes in the environment of the spacecraft may give rise to the disappearance of roots or coalescence of two of them, with resulting jumps in charging voltages and observed characteristics of particles fluxes.

To end this section it may be interesting to recall more subtle effects which can affect low energy particle measurements and be of concern when a precise evaluation of thermal plasma parameters is required . Following a pioneering work by Guernsey and Fu (1970), Zhao et al. (1996) have shown that potential barriers may exist even in the spherically symmetrical photoelectron sheath of a conductive spacecraft even when its charging potential is controlled by ion beam emission. Cragin and Hanson (1993) have shown that unusual spacecraft-plasma interaction occurs at times when the spacecraft velocity is nearly aligned with the local magnetic field leading to an artificial increase of ~ 15 % of the measured thermal ion current. Anderson et al. (1994) have shown that precise measurements of the thermal plasma velocity requires to take properly into account the side effects of the induced $\overline{V} \times \overline{B}$ electric field.

Electrostatic probe measurements on charged spacecraft

Electrostatic probes, often called Langmuir probes, are among the simplest instruments to determine basic plasma parameters such as the electron density and temperature. As such they have been widely used on rockets and satellites in the Earth's ionosphere and also on a number of planetary probes. They are also, and probably more importantly, the almost unique sensors to measure DC and AC electric fields by the double probe technique. To operate conveniently they must be located outside the spacecraft sheath – i.e. at some ~ 10 Debye lengths from the spacecraft body – and well away from the wake. Experience has shown that good measurements can be performed on moderately charged (~ a few volts positive or negative) vehicles by sweeping the voltage applied to the probes in order to retrieve the current-voltage characteristics and the plasma electron parameters. This is even true, at least in dense enough plasma, when the probes are located quite near the spacecraft surface and thus within the sheath ; this is likely to be due to the angular uniformity of current collection and good enough measurements can still be made if the spacecraft blocks part of the full space solid angle; the only condition is that no potential barrier prevents the low energy ambient plasma to be collected by the probe. One of the major drawbacks of these sensors is associated with the non uniformity of their surface potential and its variations due to adsorption of gases and contaminants. In spite of improved surface coatings using carbon or TiN, these effects generally preclude to perform reliable low (≤ 500° K) electron temperature measurements and limit the accuracy of electron density measurements at plasma potential to within ± 10 to 15 % owing to the rounding of the knee of I-V curves near space potential. When used as electric field sensors at ionospheric levels, probes can be polarized close to space potential which makes them less sensitive to the surface effects mentioned above, thus lessens their inaccuracy, and also lowers their sheath impedance.

Although most space missions – and in particular in Earth's orbit – are flown in magnetized environments, the problem of electrostatic probe operation in a magneto-plasma did not receive much attention in the past, except for the pioneering works of Parker and Murphy (1967) and Sanmartin (1970). It was felt that, for ordinary probe dimensions and at typical ionospheric altitudes, the electron gyroradii were too large to play a role. More recent works by Laframboise and Sonmor (1993), and references therein, and Singh et al. (1997) have revived the subject by showing that the effect of the magnetic fields, although difficult to include in a very general theory, should probably be significant. In particular Singh et al. (1997) have shown that the E x B drift in the potential structure near the probe may increase the collected currents, a conclusion which slightly differs from that of

Laframboise and Sonmor who show that other associated effects may counteract this process. It has also been established that introduction of even a small plasma drift prevent perturbations due to the probe to extend towards infinity along its magnetic shadow. The effect of turbulence on current collection has also been examined by Laframboise and Sonmor which concluded that, in space plasma conditions, it was not likely to have any significant influence. On the other hand the existence of trapped orbits could lead to an enhancement of the collected currents by collisional ionization at altitudes where neutral density is significant.

In the case of magnetospheric satellites electrostatic probes are mainly used in electric field experiments and to measure plasma waves and plasma density fluctuations. The most critical problem to be solved was that of the operation of double probe electric field detectors on highly charged spacecraft in plasma with large Debye lengths of the order of a few to tens of meters. Simplified but representative models worked out by Cauffman and Maynard (1974) and more recently by Pedersen et al. (1998) have shown that the use of long (~ 50 to 100 m) wire booms makes it feasible to measure the small (≤ 1 mv/m) magnetospheric electric fields in tenuous plasma. Also the extension of probe support rods enable an increase and a better control of the effective length of the double probe antenna (Pedersen et al. 1998). One of the most adverse problems stems from the presence of a photoelectron cloud on the sunward side of the spacecraft. Even a small (~ 1 %) fraction of these photoelectrons flowing through its highly resistive sheath to the sunward probe can result in a significant error on the DC electric fields by inducing a parasitic component along the Sun direction of magnitude similar to the natural field. The use of negatively biased guard rings located near the end of the wire booms at ~ 1m from the probe has solved this problem by preventing most photoelectrons emitted by the spacecraft and the wire boom itself to reach the probe (Mozer, 1998).

A rather similar problem was studied by Hilgers (1995) to derive the effect on the probe behaviour of a “magnetic short circuit” between the probe and an obstacle such as another probe or the spacecraft body. There are basically 2 perturbations : one is the screening of ambient plasma by depletion of the field tube and the other, the enhanced collection of photoelectrons emitted by the obstacle. The relative importance of these 2 effects depends on the size of the screening body and there is a threshold on either its potential or the electron temperature which governs the ratio between the photoelectron current and the plasma electron current..

To end this section we wish to mention the work by Eriksson and Bostrom (1998) who used simple models of the interaction between plasma, spacecraft and probes in order to improve the accuracy of AC electric fields and density fluctuations associated with plasma waves.

Conclusion

With the recognition of the importance of low energy plasma in processes which govern the dynamics of the Earth and planetary magnetospheres, there is presently an increasing need to perform reliable and precise measurements in this energy domain. As was shown in the first section, it is unlikely to succeed without properly designed spacecraft. This has been already recognized for the recent magnetospheric missions such as GGS POLAR and GEOTAIL and the coming ESA mission CLUSTER II ; due attention was paid to the following most important questions :

- the spacecraft must be externally conductive and polarized entrance areas of instruments must be avoided or at least minimized
- the spacecraft geometry must be as simple as possible and close to a convex shape
- the potential of the spacecraft must be controlled by an active device in order to stay close to plasma potential. For the above mentioned missions, with a specific scientific interest in distant regions of the magnetosphere, the most critical problem was to avoid a positive charge. This was achieved on POLAR by having a plasma source which is designed to clamp the satellite potential very near the local space potential. One of its drawback are the large perturbations induced on the local plasma and in the potential structure of the spacecraft sheath. On GEOTAIL, and on the future CLUSTER II, the elimination of positive charges from the satellite is achieved by using an indium-ion gun which has proved on GEOTAIL to work very satisfactorily without detrimental effects.
- even when all these rules have been applied a detailed modeling of the spacecraft sheath structure, taking into account the characteristics of surface materials for photo and secondary emission, is necessary.

As for electric fields, the present situation appears more satisfactory than for low energy plasma since measurements of DC and AC fields have been performed with a good enough accuracy to enable significant progress to be made in the physics of auroral plasmas. Certainly some improvements could be achieved by more precise numerical modeling of the interaction of plasma with spacecraft and probes. One of the difficulties is the multiscale nature of the problem with the corresponding demand on computer resources.

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