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Active Magnetic Experiment: a magnetic bubble in the ionospheric stream

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Abstract

A space plasma experiment is discussed which consists of a magnetized plasma bubble interacting with the ambient (ionospheric) plasma. The magnetized plasma inside the magnetized bubble is tied to the dipole magnetic field generated inside the satellite. The parameters of the bubble are discussed in relation to the parameters of the ambient plasma and the plasma regimes and phenomena that can be investigated are indicated.

Plasma measurements from earth orbiting satellites are a basic feature of space physics and plasma physics research. Active experiments can either consist in the injection of particles and/or radiation beams into the ambient space plasma or can exploit the velocity difference between the Keplerian (orbital) velocity of the satellite and the streaming (corotation) velocity of the plasma in order to study the propagation of a plasma around a conducting obstacle. In the latter case, the obstacle (the satellite) acts as a forced electric circuit that generates a current which closes inside the surrounding plasma. In this configuration the novel phenomena to be investigated are those of the plasma nonlinear dynamics under the action of the time-dependent, localized potential difference created by the satellite motion (see Ref. [1] and references therein). This time-dependent potential leads e.g., to the excitation of different types of electric and magnetic waves through the plasma that reacts self-consistently on the potential difference at the satellite. The interest of such wave excitation has led to dedicated laboratory experiments which are however constrained by the presence of close boundaries. From a plasma physics point of view, it is even more interesting if the moving obstacle itself consists of a plasma tied to a moving conductor. This would open up the possibility of studying experimentally the physics of two counterstreaming plasmas in an open and boundary free environment that cannot be realized in the laboratory where boundary conditions strongly constrain the dynamics of the plasma. By controlling the physical and geometrical parameters of the plasma tied to the moving conductor we can study the spatial structure of the configurations that the two plasmas can attain, the onset of the instabilities that their relative motion can cause, and the plasma turbulence that can result from the development of these instabilities [2].

The miniaturization of the obstacle from a planet magnetosphere to a satellite magnetosphere leads to plasma regimes that are characterized by very different dimensionless numbers. Although a physically significant scaling of the magnetosphere solar-wind interaction may not be possible important information about the nonlinear dynamics of collisionless plasmas can be obtained by a relatively simple, satellite-based experiment involving a magnetized plasma bubble tied by a dipole magnetic field generated inside the satellite.

Plasmas confined by dipole magnetic fields have good stability properties that have been investigated in laboratory experiments and that have been considered for long term proposals of using thermonuclear fusion for space propulsion In all these schemes the characteristic size of the bubble, defined as the distance at which the strength of the bubble magnetic field equals that of the ambient field, is essentially determined by the strength of the dipole magnetic field generated inside the satellite. As a consequence, since the dipole field decreases with the third power of the distance from the satellite, it is difficult to confine plasma bubbles with a size more than one order of magnitude larger than the size of the satellite.

A different scheme has been recently proposed where the plasma is not confined in a static configuration (in the satellite frame), but a plasma flow is generated by a large neutral particle or plasma outflow from the satellite [3]. In this case if the currents stop closing through the satellite and the magnetic freezing condition is violated, part of the inflated bubble will become separated from the satellite. However, even in the presence of this disconnection process, the inflated bubble scheme would open up a new type of scenario for active experiments where particle injection and magnetic interactions are combined.

We examine which requirements on the plasma and the (earth orbiting) satellite parameters must be satisfied in order to enhance the plasma satellite interaction and, most importantly, which interaction regimes can be realized under realistic conditions. We are interested in determining the conditions that are needed for the interaction between the satellite and the ionospheric-magnetospheric plasma to be "collective" .

The requirement that the electrostatic interaction between the plasma and the satellite be collective implies that the size S of the satellite must be considerably larger than the characteristic plasma Debye length λ_D, $S > \lambda_D$. If the plasma density and temperature are not modified *ad hoc*, taking $S \sim 1\,m$ or marginally bigger, this restricts us to heights smaller than 2000 Km: 200 $Km < h < 2000\ Km$. The value of λ_D in the ambient plasma has large day-night variations, but in this height range is of the order of $10\,cm$ and increases with height. In this perspective we will focus our interest on the feasibility of active experiments from low earth orbit (LEO) satellites aiming at modifying and controlling the magnetic configuration around the satellite. The ionospheric-magnetospheric plasma must be magnetized on the scale of the satellite and of the magnetic bubble. This condition poses frequency and size restrictions. The electron and ion gyro-frequencies Ω_{cj}, $j = e, i$, should be larger than their collision frequencies (including collisions with the population of neutral atoms). For $h < 2000\ Km$ the electron gyro-frequency Ω_{ce} is in the few megahertz range i.e., it is much larger than the electron-ion collision frequency. In the same height range the ion gyro-frequency Ω_{ci} is in the few hundred hertz range while the ion-ion collision frequency is at least two orders of magnitude smaller for $h > 500\ Km$. Collisions with neutrals become unimportant as we approach heights of the order of 500 Km or higher. Both electrons and ions are magnetized (perform tens of gyro orbits "before colliding") for $h > 500\ Km$. In these estimate we take the electron to mean ion mass ratio to vary with height. For the region of interest the mean ion mass decreases from 15 to two proton masses. Ions are taken to be singly ionized. For $h < 2000\ Km$ the mean electron gyro-radius $\rho_e \sim 10\,cm$ is of the order of the Debye length λ_D, increases with height but remains smaller than the size of the satellite, $S > \rho_e \sim \lambda_D$. For the mean ion gyro-radius we have ρ_i of the order of a few meters, $S \sim \rho_i \quad \text{or} \quad S < \rho_i$, so that ions appear to be barely magnetized on the satellite size.

If we take the dipole magnetic field at the satellite two and three orders of magnitude bigger than the ambient magnetic field ($\sim 0.2 - 0.1\,G$, decreasing with height) then the size of the magnetic bubble L turns out to be an order of magnitude bigger than the size of the satellite $L \sim 10\ S$. This satellite magnetic field corresponds to a magnetic moment of $\mu \sim 3 \times 10^5 A\,m^2$ and can be produced by a solenoid made of a high-temperature superconductor with a transition temperature high enough to be maintained with a passive thermal control system (see Ref.[4]). The larger magnetic field inside the bubble closer to the satellite implies a relatively large increase of the particle gyrofrequencies and a reduction of their gyroradii. This increase can be sufficient to make the ions magnetized inside the magnetic bubble. In the ambient plasma, the ratio Ω_{ce}/ω_{pe} does not change much with height, but has strong time variations of one order of magnitude, $\Omega_{ce}/\omega_{pe} \sim 1 \ - \ 10^{-1}$. Inside the bubble the magnetic field is higher but the plasma density may be higher in the presence of a plasma source. Thus we have a relatively dense plasma where charge separation effects imply frequencies higher than the electron cyclotron frequency. The collisionless electron skin depth $d_e = c/\omega_{pe}$ is of the order of a few meters to a few tens of meters. This implies that electron inertia effects are rather important on the scale of the plasma bubble. In addition, electron inertia becomes an important term in the electron momentum balance equation and the magnetic field cannot be considered to be effectively frozen in the plasma, or even in the electron component as of interest in the whistler wave frequency range. This large value of the the ratio between the electron skin depth and the satellite size could represent a drawback of the envisaged configuration in the sense that collective electromagnetic effects would turn out to be inhibited. This limitation can be avoided by increasing the density around the satellite with a plasma outflow from the electric thrusters of the satellite[4]. The relative velocity between the satellite and the ambient (corotating) plasma is around $7Km/sec$ which is larger (by a factor of 3 to 10) than the ion thermal velocity, and smaller by a factor of up to ten of the electron velocity. This "infrathermal" regime is experimentally rather interesting, as it can give rise to Cherenkov emission of whistler waves close to the electron-cyclotron resonance, of (damped) ion acoustic waves and, in a magnetized inhomogeneous plasma of drift-type waves and instabilities. The bubble transit time is of the order of $10^{-3}sec$. The satellite transit time is a factor ten shorter. The bubble transit time is one order shorter than the ion gyro period. The transit time determines an effective range for the frequency of the perturbations that can be excited: a direct consequence is that it is not easy to excite MHD phenomena directly, as the frequency of the disturbances excited by the bubble turns out to be larger than the ion cyclotron frequency in the ambient plasma.

Phenomena that can be marginally described within the MHD framework can be excited within the bubble (in the portion close to the satellite where the ion gyroradii tend to become small). However as the bubble boundaries are approached, a transition must occur towards regimes of the EMHD type where the Hall term in Ohm's law becomes relevant. This is a very interesting transition to explore experimentally. The generation of whistler waves by the bubble will be of interest together with the generation of EMHD vortices and vortex streets. It will be possible to produce in a controlled way and to investigate EMHD effects, Hall-dominated, magnetic reconnection events, and the development of EMHD turbulence. Since the electron skin depth in the ambient plasma is larger than the bubble scale, one can explore the fine structure of current layers up to the electron gyro-radius scale. This is a range of scales that cannot be explored in laboratory experiments. The study of Kelvin-Helmholtz type instabilities on the electron inertia scale are of great interest in magnetospheric studies. Such instabilities will be naturally excited in the bubble configuration because of the relative velocity between the magnetic bubble plasma and the ambient plasma.

References

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