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SPACE STATION INDUCED ELECTROMAGNETIC EFFECTS

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Abstract. We have identified several mechanisms which can cause electric (E) and magnetic (B) field contaminations of the Space Station environment. The level of E and B fields generated by some of them such as the motion of the vehicle across the ambient magnetic field B_0 and the 20–kHz leakage currents and charges can be controlled by proper design considerations. On the other hand, there are some mechanisms which are inherent to the interaction of large vehicles with the plasma and probably their contributions to E and B fields cannot be controlled; these include plasma waves in the wake and ram directions and the effects of the volume current generated by the ionization of the neutrals. The interaction of high–voltage, solar cell arrays with plasma is yet another rich source of E and B fields and it is probably uncontrollable. Wherever possible, quantitative estimates of E and B are given. A set of recommendations is included for further study in areas where we seriously lack an indepth knowledge.

1. Introduction

Space Station is likely to affect the electromagnetic environment in several ways, some of which are discussed here. A summary of various possible causes of generating electromagnetic fields in the immediate neighborhood of the Space Station is as follows.

(1) Radiation of EM waves by the currents induced in the structure by $V_S \times B_o \cdot L$, where V_S is the Space Station velocity, B_o is the geomagnetic field, and L is an appropriate dimension of the spacecraft.
(2) Currents and charges induced on the structure due to the 20 kHz power line leakage.
(3) Leakage of the 20–kHz power to the metallic interconnects in the solar cell arrays.
(4) Wake as a source of plasma waves; both the strong density gradients and the nonthermal charge particle velocity distributions are likely to induce enhanced levels of electric and magnetic fields.
(5) Interaction of the contaminant cloud with the ambient plasma in the ram direction.
(6) Ionization of the contaminant neutrals (such as H_20) produces a volume current (pick–up current) which can modify the ambient magnetic field and also can cause plasma instabilities.
(7) Solar cell arrays as a source of EM noise.

In the following discussion we describe our present state of the understanding of the above mechanisms for generating EM effects. Wherever it is possible, we attempt to provide quantitative estimates for the electric and magnetic fields generated by the mechanisms. At the very outset we emphasize that the estimates are not sacrosanct as they are based on physical arguments and not on rigorous mathematical treatments of the individual problems. The estimates on the electric and magnetic fields are compared with the available specifications for the Space Station.

We note that the EM fields generated by the mechanisms (1), (2), and (3) can be controlled to some extent by proper design considerations for the Space Station structure, power distribution system, and ac to dc conversion. On the other hand, the EM fields generated by mechanisms (4) to (6) are inherent to the plasma environment of the Space Station. Since very little is known about the noise generation by high–voltage, solar cell arrays, it is immature to comment about its controlability.

2. Radiation of EM Waves by Currents Induced in the Structure by the Motional EMF (Figure 1).

The motional EMF in a moving conductor at the altitudes of the Space Station can be as large as 0.3 V m^{-1}. Assuming a length of about 100 m (as that of the keel), an estimate of the maximum possible EMF is about 30 volts. The induced EMF can drive a current through the structure, but the current drawn is critically controlled by the ambient plasma and its contact with the structure. These are difficult unsolved problems. However, the current collection at the positive end involves the collection of electrons, while at the negative end the collection of ions. Since the ion thermal current density in the ambient plasma is considerably smaller than the electron current density, the ions are likely to dictate the current in the structure. If the ion current collecting area at the negative end is S_i, the current flow through the structure is approximated by

$$I = J_i S_i \, , \; N_o e \, V_{ti} < J_i < N_o e \, V_s \tag{1}$$

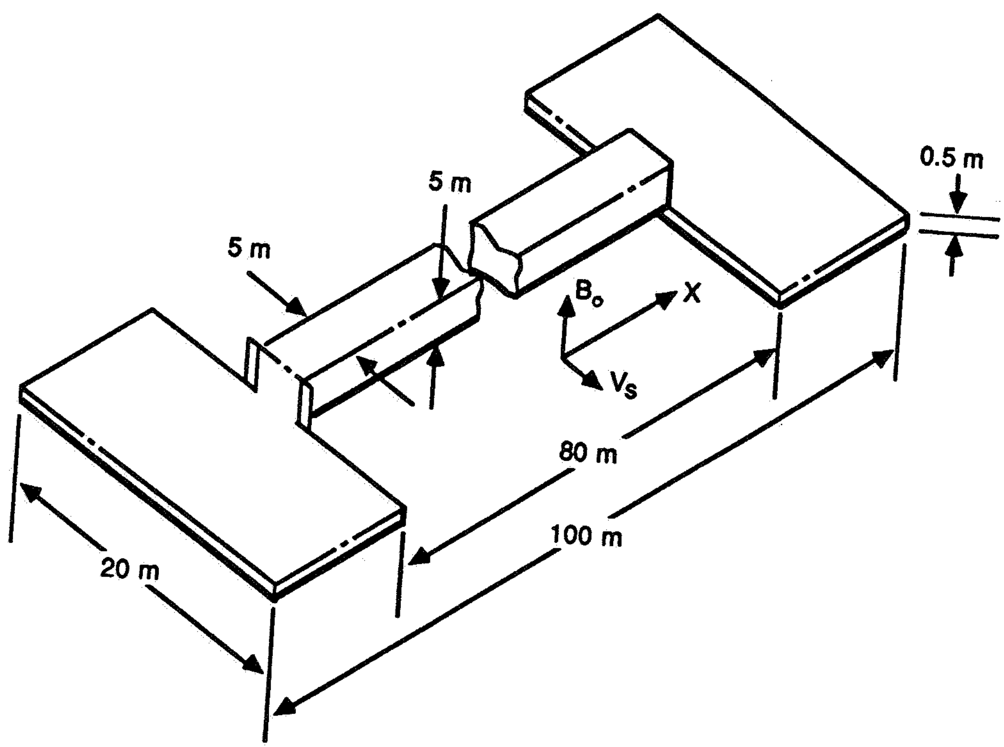

Fig. 1. Schematic diagram showing motion of a space station like structure across the geomagnetic field B_o.

where V_{ti} is the ion thermal velocity, N_o is the ambient plasma density, and e is the magnitude of the electronic charge. The upper limit on the ion current density J_i is determined by the ram current while the lower limit by the ion thermal motion. Thus, the maximum possible power available for radiation is given by

$$P = V_s B L J_i S_i \tag{2}$$

The ion current density with the ambient plasma density $N_o = 10^5$ cm^{-3} and ion temperature of 0.3 eV is found to be in the range 10^{-4} A m^{-2} > J_i > 3 × 10^{-5} A m^{-2}. Thus, the radiated power is found to be

$$9\times10^{-4} S_i < P < 3.3 \times 10^{-3} S_i \text{ watts} \tag{3}$$

Assuming S_i to be about 500 m^2, the radiated power lies in the range 0.45 watts < P < 1.65 watts. This estimate of power, based on intuitive arguments, is approximately the same as obtained by more rigorous calculations (Hastings et al., 1987; Chlouber, 1987).

Now let us consider the frequency range over which the power will be distributed. The radiation occurs at frequencies given by

$$f = \underline{k} \cdot V_s/2\pi \text{ Hz} \tag{4}$$

where $\underline{k}$ is the wave vector of the radiation. Since maximum possible value of k in a plasma is roughly λ_d^{-1}, the highest radiated frequency is given by

$$f \simeq \frac{1}{2\pi}\frac{V_s}{\lambda_d} \simeq f_{pe}\frac{V_s}{V_{te}} = f_{pi}\frac{V_s}{V_{ti}} \tag{5}$$

where f_{pi} and f_{pe} are the ion and electron plasma frequencies and V_{ti} and V_{te} are the ion and electron thermal velocities.

At the altitudes of Space Station $f_{pi} \simeq 23.4$ kHz and $f_{\ell h} \simeq 5.4$ kHz. Thus, a variety of wave modes are likely to be excited; these include Alfvén waves, electromagnetic ion–cyclotron mode, ion–acoustic mode, ion Bernstein waves, and lower hybrid waves.

Whether a given wave mode is radiated or not also depends on the wavelength spectrum of the current source in the structure. If some wavelengths are not in the source, they are not radiated even if the plasma allows such a radiation.

The component of $\underline{k}$ parallel to the velocity of the structure is relevant here. Thus, if the dimension of the structure in the direction of the motion is L_v, the typical radiated wave number spectrum is given by

$$k_v < L_v^{-1} \tag{6}$$

and the radiated frequency

$$f_o < \frac{1}{2\pi} V_s/L_v \tag{7}$$

Since $V_s \simeq 7.3$ km s^{-1} and $L_v \approx 5$ m, $f_o < 230$ Hz. Thus, the Space Station structure is likely to curtail the radiation in frequencies higher than about 230 Hz. This frequency is lower than H^+ cyclotron frequency, but several times larger than 0^+ and $(H_20)^+$ cyclotron frequencies. Thus, the possible wave modes are the Alfvén waves, electromagnetic ion–cyclotron waves, ion–acoustic waves, and 0^+ Bernstein modes. The latter two waves are warm plasma effects.

The warm plasma effects on the radiation from structures in space have not been investigated at all. Longitudinal plasma waves may have some important ramifications as they heat the plasma near the source. Heating involves Landau damping and/or ion–cyclotron damping.

Since the plasma waves are likely to be damped near the structure, the radiated power away from it will be primarily in the form of Alfvén waves. The electric field strength of the Alfvén waves is approximately

$$E \simeq \left(\mu_o V_a \frac{P_a}{S}\right)^{1/2} \quad V\,m^{-1} \tag{8}$$

where V_a is the Alfvén velocity, S is cross section of the Space Station perpendicular to the ambient magnetic field, $\mu_o = 4\pi \times 10^{-7}$ H m^{-1} and P_a is the power in Alfvén waves. Assuming, $P_a = 1$ watt and $S - 10^3$ m^2, $V_A = 200$ km s^{-1}

$$\boxed{E \simeq 16 \ \ mV\,m^{-1} \text{ and } B = 80 \ \ nT} \tag{9}$$

The electric field strength given above is roughly comparable to the requirement given in Figure 3.1–3 of JSC 30420. But the corresponding B field specifications are much lower than the estimate given above.

Recommendation: Very close to the structure, the electrostatic waves arising because of the warm plasma effects may play an important role in determining the electric field fluctuation level and also the extent of plasma heating which may have some ramifications for the chemical reactions near the Space Station surface. Thus, it is important to develop a quantitative understanding of these effects. A more unified theory including warm plasma effects and the calculations of the current patterns on complex structures in space is needed to fully understand the problem of radiation because of the motion of the Space Station

3. 20 kHz Power Line Radiation

It is decided that the power system on Space Station will operate at 20 kHz. This frequency falls in a frequency band, which is very important for natural plasmas; it is the band in which whistler and VLF waves propagate in the ionosphere. Assuming a plasma density $N_o = 10^5$ cm^{-3} and magnetic field $B_o = 0.31$ Gauss near the Space Station, the various characteristic frequencies are

$$f_{pe} = 2.8 \text{ MHz}, \quad f_{pi} = 16.3 \text{ kHz}, \quad f_{ce} = 0.87 \text{ MHz},$$
$$f_{ci} = 29.6 \text{ Hz}, \quad f_{\ell h} = 3.2 \text{ kHz}$$

Thus, the 20 kHz falls in the range $f_{\ell h} < f < f_{ce}$

The sources in this frequency band radiate EM and plasma waves within a cone aligned with the magnetic field with the cone apex at the source (Singh and Gould, 1971). The half cone angle for $f << f_{ce}$ is given by (Figure 2)

$$\theta_c = \sin^{-1}(f/f_{ce}) \simeq 1.3^{\circ}$$

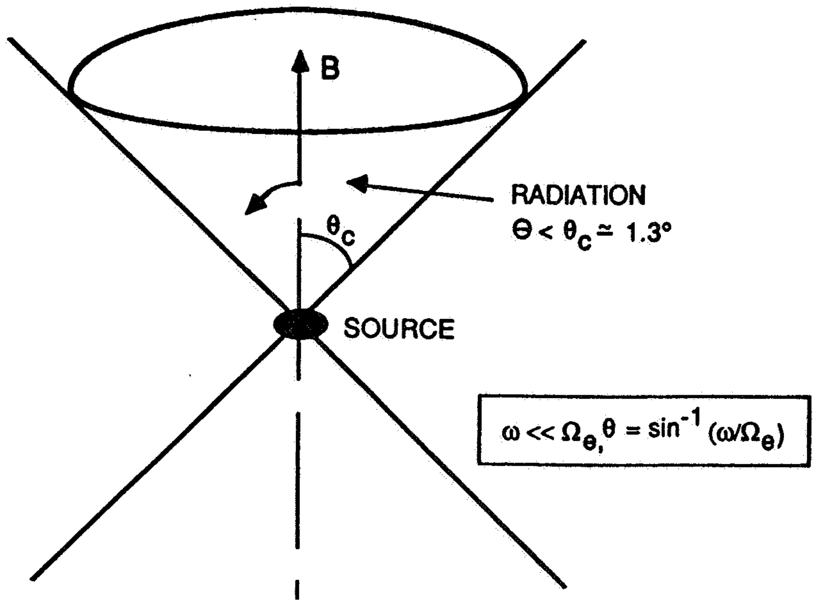

Fig. 2. Radiation cone of 20–kHz power from Space Station power systems. In the figure cone angle is exagerated; the half–cone angle is only about 1.3° implying highly magnetic field–aligned radiation.

Thus, the radiation of 20 kHz will be primarily focussed along the B field.

The estimation of the power and radiated fields requires some knowledge of the magnitude and distribution of the leakage currents and charges on the Space Station structure. Unfortunately, this exercise has not been carried out and without such an exercise, I feel that an estimation analysis is primarily academic.

Recommendations: A complete analysis of the power distribution system is needed to predict how much and where on the structure it is likely to have leakage currents and charges. Cable connectors, where fringing fields are likely to occur, can be a source of radiation. Surface currents at 20 kHz are additional sources of radiation.

Determination of the leakage of ac (20 kHz) currents and charges to the solar cell array interconnects after dc to ac conversion is worthwhile because the numerous tiny interconnects can radiate an appreciable amount of power in plasma waves

4. Wake as a Source of Plasma Waves

Wake can be a rich source of plasma waves because there are a number of non–equilibrium features present inside the wake. Some of these features are (Figure 3):

(1) Sharp density gradients, specially in the near wake region.
(2) Production of non–Maxwellian (non–thermal) distributions of the electrons and ions by means of plasma expansion into the wake.
(3) Collision of the counterstreaming plasma streams in the far wake region.

We briefly address these issues one by one.

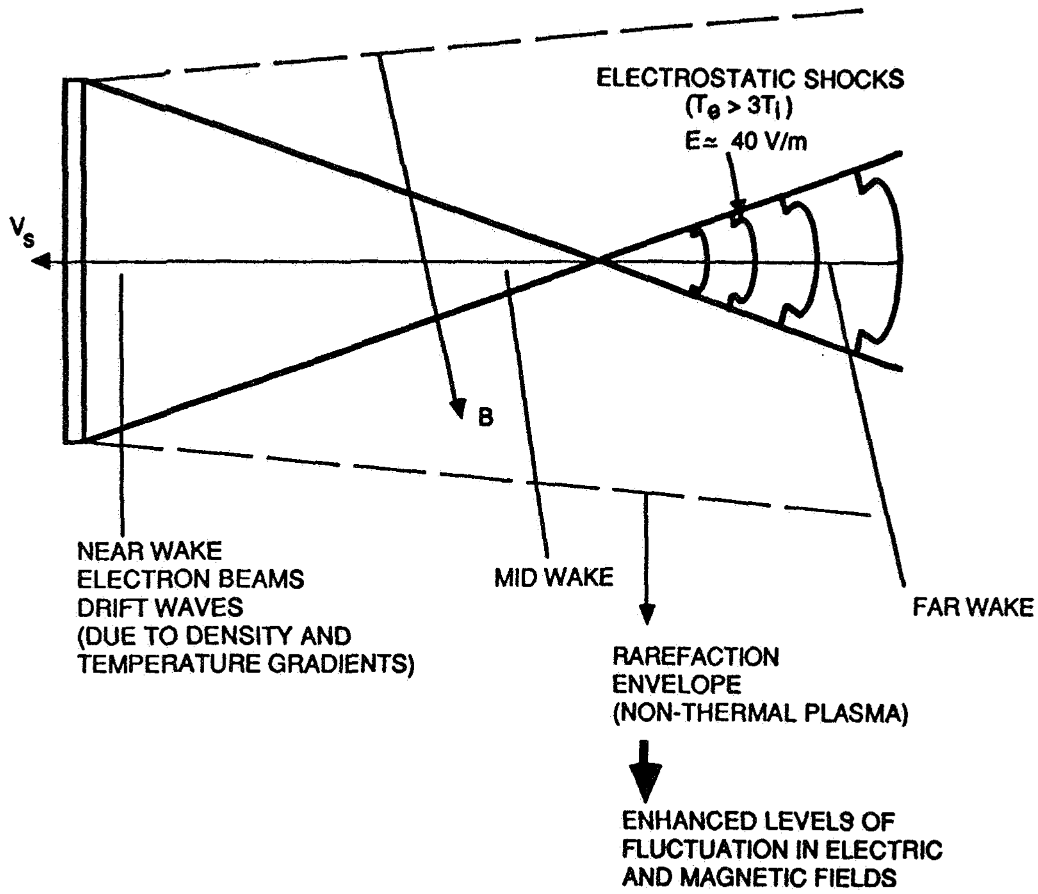

Fig. 3. Schematic diagram showing wake of a large body in a plasma. Different types of plasma processes contributing to the enhancements of E fields are indicated.

4.1 Sharp Density Gradients

Density gradients in the wake region are likely to drive a number of drift wave modes. Since the plasma in the vicinity of the Space Station is likely to have approximately equal electron and ion temperatures, possible drift modes are the ion–cyclotron ion density drift (ICID) mode and the lower hybrid drift (LHD) mode; these modes are driven by ion drifts given by

$$V_i \simeq \frac{a_i^2}{\Omega_i} \frac{1}{n} \frac{\partial n}{\partial x} \simeq a_i^2/(L_\perp \Omega_i) \approx a_i \rho_i / L_\perp$$

where a_i is the ion thermal velocity, L is the scalelength of the density gradients perpendicular to B, and ρ_i is the ion Larmor radius. When $L < 2\rho_i$ or ($V_i > 0.5\ a_i$), lower hybrid drift waves with following parameters are likely to occur:

Frequency: $\omega \simeq kV_e \simeq \frac{a_e}{L_\perp} = \frac{a_e}{\Omega_e} \frac{\Omega_e}{L_\perp} = \frac{\rho_e}{L_\perp} \Omega_e > 2\Omega_i$

Wavelength: $\lambda_\perp \simeq \rho_e$

Saturation level (Gary, 1980):

$$\frac{\varepsilon}{nT} \simeq 0.1\,(\Omega_i/\omega_{\rho i})^2\,(\rho_i/L_\perp)^2\ ,\ \varepsilon \simeq \frac{1}{2}\,\epsilon_0 |E|^2$$

When the density gradients have scalelengths in the range $2\,\rho_i < L < 10\,\rho_i$, ion cyclotron drift modes are driven with parameters as follows:

Frequency: $\omega \simeq \Omega_i$

Wavelength: $\lambda_\perp \simeq \rho_e$

The saturation level for these ICID waves are found to be similar to that for the LHD waves.

The rms electric fields for these waves are estimated to be

$$E_{rms} \simeq 4(n/10^5)^{1/2}\,(T/0.3)^{1/2}\,(\rho_i/L_\perp)^2\ \text{mV m}^{-1}$$

where n is in units of cm^{-3} and T in eV.

For LHD waves $L < 2\rho_i$, $E_{rms} > 1$ mV m^{-1} is likely to occur depending on the sharpness of the density gradient. On the other hand, for the ICID waves $E_{rms} < 1$ mV m^{-1}.

The above estimates show that it is likely that density gradients in the near wake create electrostatic waves with amplitudes of the order of 1 mV m^{-1} or greater in the range of ion–cyclotron frequencies. This estimate appears to be compatible with the broadband electric field specification in JSC 30420.

4.2. Non–Thermal Plasma in the Wake

The plasmas in the wake region are expected to have non–Maxwellian velocity distribution functions. This is particularly true for the velocity components along the B field threading the plasma void in the wake. This arises because of plasma expansion; the electrons in the near wake may have counterstreaming electron beams (Singh et al., 1987) and the ions appear as ion beams in the near and mid wake regions while in the far wake they also appear as counterstreaming ion beams (Singh et al., 1986).

In the near wake regions the beam electrons are likely to excite beam–plasma modes. Some preliminary calculations for the wake of small satellites show this to be a distinct possibility. However, for large structures such as the Space Station, it remains to be investigated.

When $T_e \simeq T_i$, the ion beams in the wake region are not likely to excite instabilities. However their non–thermal distributions are likely to enhance the fluctuation level of the electric field. A systematic investigation on the enhanced electric fluctuation level is required to complete the determination of EMI effects in the wake region.

Recommendation: Contributions to the fluctuation level of electric field by non–thermal features of the electron and ion velocity distributions need attention. It is recommended that the spectrum of the fluctuation be estimated using the theoretical formulations available (Akhiezer et al., 1975).

4.3. Electrostatic Shock Formation in the Far Wake (Figure 3)

If $T_e > 3\ T_i$, the ion beams are likely to excite ion–acoustic waves propagating primarily long the B field. In the far wake region the colliding ion beams are capable of creating an electrostatic shock pair; the shocks form by ion–ion instability and they move away from the wake axis (Singh et al., 1986). The electric fields in the shock fronts are typically

$$E \simeq \frac{2\ T_e/e}{10\ \lambda_d}$$

Assuming $T_e/e \simeq 1V$, $\lambda_d \approx 0.5$ cm, dc electric fields of the order of 40 V m^{-1} are likely to be found in the far wake region. This is a large electric field from the space plasma point of view.

5. Interaction of the Contaminant Cloud with the Ambient Plasma in the Ram Direction (Figure 4)

It has been suggested that the large space structures moving across the magnetic fields with their contaminant clouds simulate the same condition as a comet. Furthermore, the motion of the contaminant cloud simulates the same situation as in Alfvén critical ionization velocity (CIV) experiments (Newell, 1985). Laboratory and space experiments along with theories show that the interaction of a neutral cloud moving across a magnetic field in a background plasma creates a rich variety of electromagnetic effects, some of which are as follows.

5.1 Generation of dc Electric Fields Perpendicular to the Ambient Magnetic Field Near the Cloud Front (Figure 4)

The electric field arises because the electron and ion pairs, formed by some ionization processes, respond differently to the ambient magnetic field; the electrons, being highly magnetized, are guided along the B field while ions continue their journey across B, at time scales of Ω_i^{-1}. This charge separation supports an electric field approximately given by

$$E_\perp \simeq \frac{1}{2}\ m_c V_s^2/e\rho_i \approx 5\ V/10\ m.$$
$$\approx 0.5\ V\ m^{-1}$$

where m_c is the mass of the contaminant neutrals. Such electric fields may be the cause of creating oblique ion beams in the ram direction of the Space Shuttle (Stone et al., 1983).

The electric potential drop, $\Delta\phi$, across magnetic field is expected to be about the kinetic energy of the contaminant neutrals. If the neutrals are predominantly H_20, $\Delta\phi \simeq 6$ V.

5.2 Wave Generation

The ions produced by the ionization are likely to drive lower hybrid waves, which can heat the electron population. It is likely that conditions for the critical ionization may not occur, but the processes associated with it are likely to be present in the ram direction of the Space Station (Newell, 1985).

Recommendation: It is recommended that the electrostatic and electromagnetic noise level in the ram direction because of neutral cloud–plasma interaction be investigated, and quantitative estimates of E and B fields be obtained.

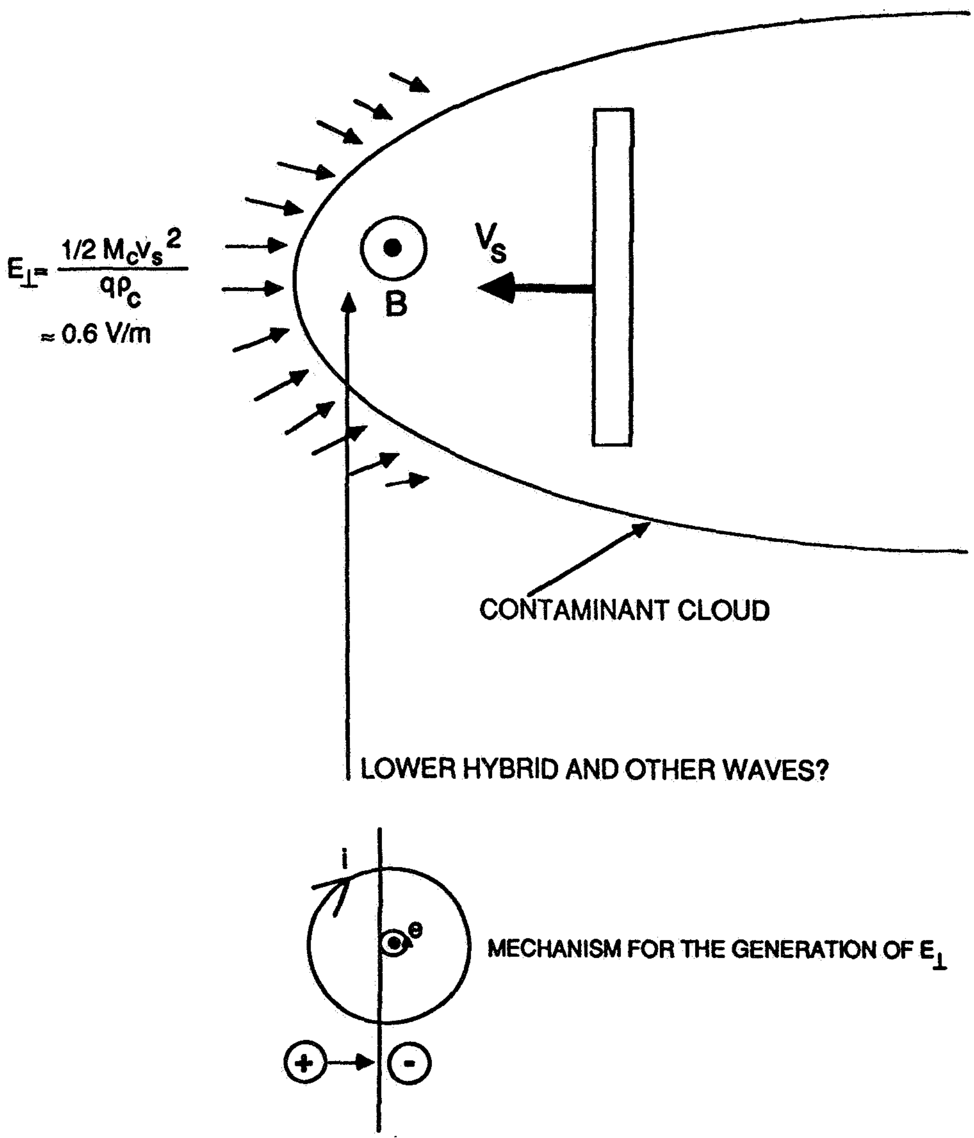

Fig. 4. Interaction of a contaminant cloud around a large vehicle in space; the processes occurring in the ram direction are highlighted.

6. EM Effects Associated with the Ionization of the Contaminants

A newly created ion of mass m_c moving with the vehicle sees an electric field $E = V_s \times B$ and as it gains a velocity in the direction of E, it is deflected by the $\underline{V} \times \underline{B}$ force. If the vehicle velocity is in x direction and B is along z, the equations of motion for a charge particle is given by

$$x = (V_s/\Omega_\alpha)\,(\Omega_\alpha t - \sin \Omega_\alpha t)$$
$$y = (V_s/\Omega_\alpha)\,(1 - \cos \Omega_\alpha t)$$

$$\dot{x} = V_s (1 - \cos \Omega_\alpha t)$$

$$\dot{y} = V_s \sin \Omega_\alpha t$$

where $$\Omega_\alpha = q_\alpha B/m_\alpha$$

Thus, the position and velocity of a charge particle averaged over one cyclotron period are given by

$$<x> = V_s t \quad , \quad <y> = \frac{m_\alpha V_s}{qB}$$

$$<v_x> = <\dot{x}> = V_s \quad , \quad <v_y> = <\dot{y}> = 0$$

Thus, as the charge particles are produced they are moved along ±y direction depending on the sign of the charge. This constitutes a (pick–up ion) current in the plasma. If the ionization rate is n, number of ions produced per second, the current is given by

$$J_y = \frac{V_s}{B} \dot{n} (m_c + m_e) \approx \frac{V_s}{B} m_c$$

This current perturbs the ambient B field;

$$\frac{\partial B}{\partial X} \simeq - \mu_0 \frac{V_s}{B} m_c \dot{n}$$

The magnitude of this perturbation depends on $\dot{n}$, which depends on the contaminants densities and the various types of ionization processes. An estimate of $\dot{n}$ is needed to quantify the effects of the pick–up ion current.
Recommendation: In order to establish the effect of pick–up ion current, the ionization rate of the contaminant ions needs to be determined.

7. Solar Cell Array as a Source of Electric and Magnetic Field Noises (Figure 5)

Depending on the location of the ground, the electric potentials on the solar cell interconnects may range from large positive potentials (>> T/e) to large negative ones. The interconnects (pin holes) with positive potentials collect electrons while those at negative potentials collect ions. The electron current collection in the presence of the geomagnetic field becomes a very difficult problem. However, it is certain that electrons and ions in the vicinity of the interconnects or pin holes will develop non–thermal features, which will be spatially structured.

There is no experimental or theoretical work to carry out educated estimates of the electric and magnetic fields in the vicinity of the solar–cell array.

Recommendation: The practical design consideration of a solar cell array and the determination of the electromagnetic noise level in its vicinity warrant serious investigations on interactions of the high–voltage solar cell array with the plasma. At negative voltages, arcing occurs in the close vicinity of arrays. The arcs are a rich source of electromagnetic radiation. Work is needed to estimate the level of such radiation and its frequency spectrum.

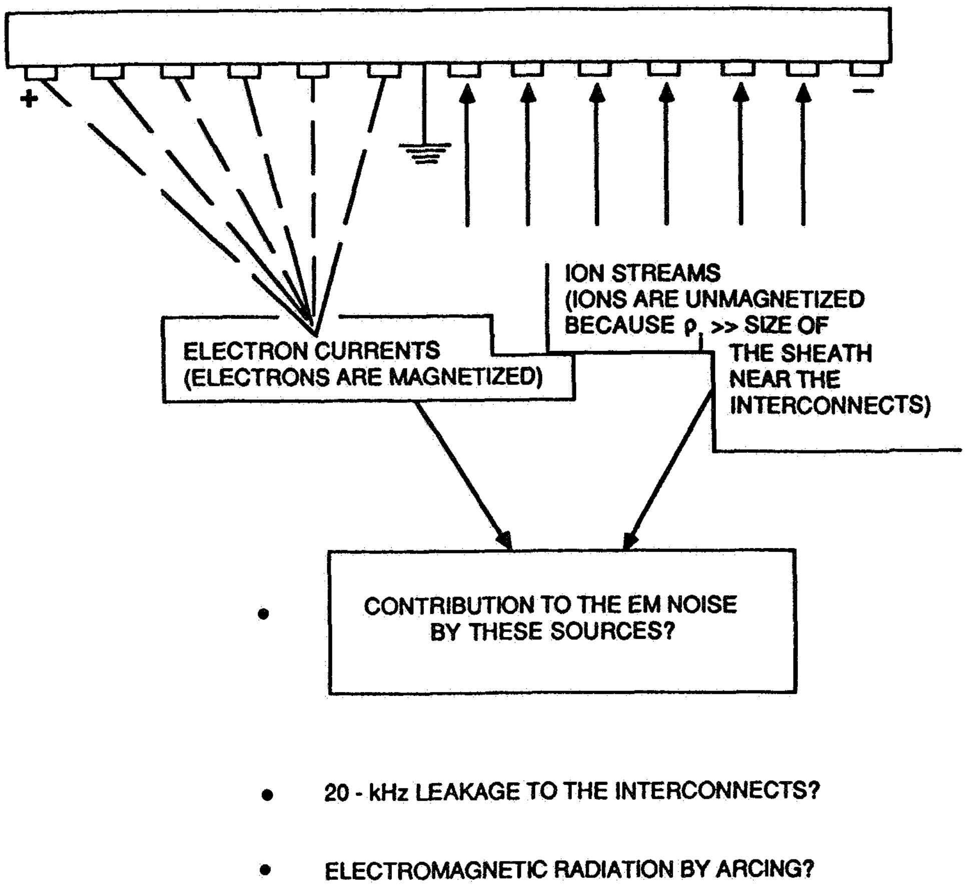

Fig. 5. The ion and electron streams due to the voltages on the interconnects in a solar cell array are shown. Processes leading to the generation of electromagnetic fluctuations are indicated.

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