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Contents

9. Nuclear Burst Plasma Injection into the Magnetosphere and Resulting Spacecraft Charging

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Abstract

The passage of debris from a high altitude (>400 km) nuclear burst over the ionospheric plasma is found to be capable of exciting large amplitude whistler waves which can act to structure a collisionless shock. This instability will occur in the loss cone exits of the nuclear debris bubble, and the accelerated ambient ions will free-stream along the magnetic field lines into the magnetosphere. Using Starfish-like parameters and accounting for plasma diffusion and thermalization of the propagating plasma mass, it is found that synchronous orbit plasma fluxes of high temperature electrons (near 10 keV) will be significantly greater than those encountered during magnetospheric substorms. These fluxes will last for sufficiently long periods of time so as to charge immersed bodies to high potentials and arc discharges to take place. Synchronous orbit satellites expecting to operate in a high latitude, high altitude nuclear burst environment should be designed against this effect as well as the radiation encountered.

I. INTRODUCTION

Turbulent coupling between the ejected debris plasma and background air plasma of a high-altitude nuclear burst appears capable of bringing about electron streaming to high altitudes. In the presence of the compressed magnetic field which can penetrate the debris bubble, plasma turbulence takes the form of large amplitude whistler waves. These waves can couple the background air plasma with the expanding debris plasma. Hot electrons are acquired and some have sufficiently large velocities to escape along the distended field lines. The nonlinear wave-resonant particle interactions produce anomalous resistivity whose scale length determines the extent of magnetic field penetration into the bubble which, in turn, determines the rate of escape of β and plasma electrons.

Superalfvénic debris plasma can escape directly through loss cone exits in the debris bubble since, in general, the cylindrical axis of the bomb casing is not initially aligned with the direction of the geomagnetic field. The more perpendicular the cylindrical axis is to the field lines, the greater the number of such escape particles. Their superalfvénic velocities suggest the formation of parallel collisionless shock waves ($\mathbf{V}_{shock} || \mathbf{B}$ = geomagnetic field). Studies[1, 2] reveal that such shock fronts are structured by turbulent whistler modes which couple the incoming background air plasma to the shocked debris plasma. Air plasma can therefore be picked up by the loss cone debris and accelerated to high altitudes.

The presence of a magnetic field has a significant effect on shock wave structure. Gradients in the magnetic field give rise to electron currents that can drive ion acoustic waves unstable and increase the effective collision frequency[(3, 4)] (this dictates the penetration depth of the compressed magnetic field into the debris bubble, so that the rate of escape of debris and air electrons is profoundly affected). When propagation is perpendicular to the magnetic field, the magnetic field can inhibit the electrons from shorting out ion plasma oscillations for wavelengths long compared with the electron gyroradius[5, 6, 7, 8, 9, 10] and wavelengths short compared with the electron gyroradius.[11, 12] Interactions between the ion beam mode and the electron Bernstein modes generate instabilities which are stabilized by electron heating, resonance broadening, or ion trapping. For oblique or parallel propagation, interactions of whistler waves with ion acoustic beam modes[13] or ion-cyclotron beam modes[1, 2] are likely to be important, and the existence of whistlers depends upon the presence of a magnetic field.

An instability found to be especially attractive as a collisionless mechanism for pickup and heating of air electrons is the ion cyclotron beam mode-whistler mode (current-free) instability that Golden[1, 2] found to be operative along the field lines and particle trajectories issuing directly from the loss cone exits.

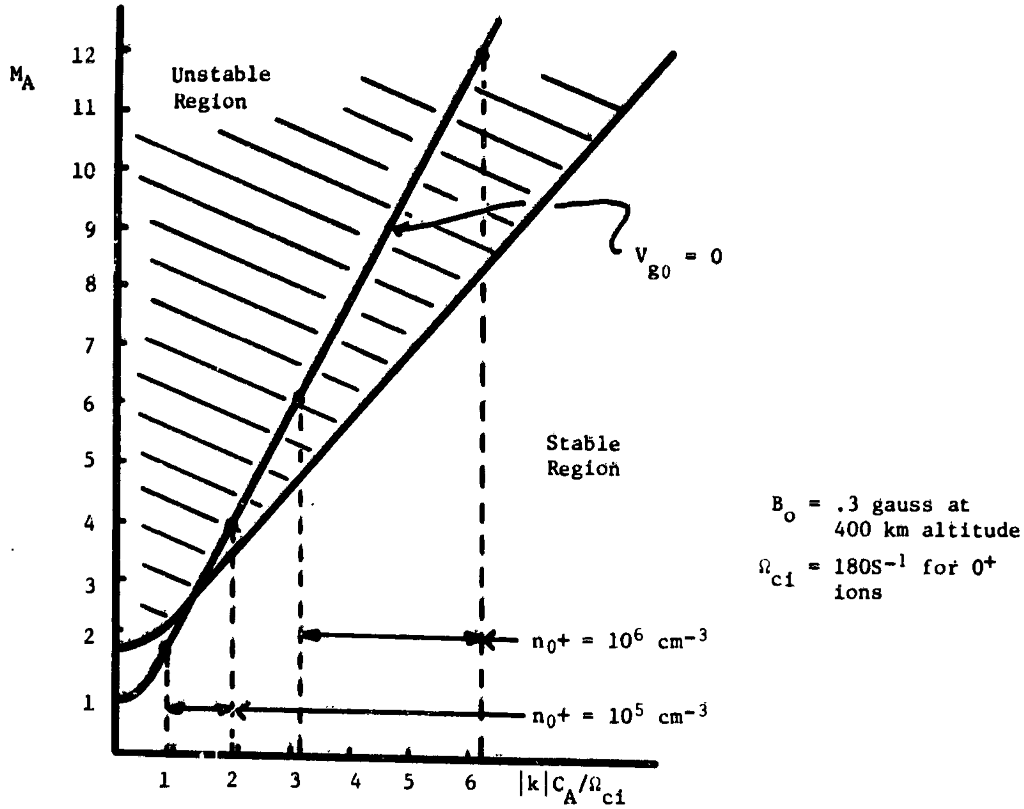
The collisionless shock waves can be modeled as Mott-Smith layers of interpenetrating unshocked (background air) and shocked (thermalized debris-air piston) flows, so that these layers are natural environments for streaming instabilities.

Recent linear dispersion investigations of parallel shock layers[2] which form ahead of the debris plasma issuing from the loss cone exits reveal that, for a given Mach number $M_A > M^* = 2.77$ ($M_A = V_u/C_A$, V_u = shock velocity, C_A = Alfvén speed in unshocked plasma), the shocked hot ion cyclotron beam mode can always drive unstable a particular whistler mode which, in the rest frame of the shock front, is stationary near the leading edge. An analysis of the shock interior reveals that the shock Mach number determines the portion of the shock thickness in which unstable whistlers are stationary in the shock rest frame. For $M_A = 2.77$, such modes may stand only at the leading edge, whereas for stronger shocks ($M_A > 2.77$), they may stand at all points between the leading edge and some interior point which is dependent on shock strength. For very strong shocks ($M_A \gg 1$), fully one-third of the shock thickness is filled with these modes, which can therefore grow to large amplitude and couple the quiescent background air plasma to the expanding debris-air piston.

2. INSTABILITY EXCITATION

The number of such debris particles which enter a loss cone exit depends critically on the mass and orientation of the bomb casing just prior to the burst. In the loss cone corridor, the debris plasma drives a shock wave. This shock is structured by unstable whistler waves which stand at its leading edge. To verify that these whistler modes can grow to sufficiently large amplitude to scatter incoming air ions (as viewed in the reference frame of the shock front) the following analysis is performed: During daylight burst conditions the density of oxygen ions is $n_o + \sim 10^5$-10^6, the larger value reflecting maximum sunspot activity. For an ambient field strength $B \sim 0.3$ gauss, this corresponds to an Alfven speed $C_A \sim 163$ - 516 km/sec in the ambient air plasma.

For typical initial casing velocities of from 500 km/sec to 2000 km/sec, the initial Alfven Mach numbers are from 1.96 to 12.22. A summary of the spectrum of stationary unstable leading edge whistlers, based on the whistler dispersion relation,[14] is given in Figure 1. It is seen there that a broad range of wave numbers can grow to large amplitude during daytime ($n \sim 10^6$ cm^{-3}) bursts. To investigate whether these modes can achieve these large amplitudes in the loss cone exit, we must calculate the growth rate of these unstable waves. For simplicity we choose $|k| C_A/\Omega_{ci} = 2$ for which $M_A = 4.12$, indicating a realistic initial debris velocity of $u = 674$ km/sec. In this case the calculated linear growth rate



	1,000 km/sec	2,000 km/sec
$n_o + = 10^6$ cm^{-3} C_A = 164 km/sec	M_A = 6.1 $\frac{k\, C_A}{\Omega_{ci}}$ = 3.05	M_A = 12.2 $\frac{k\, C_A}{\Omega_{ci}}$ = 6.1
$n_o+ = 10^5$ cm^{-3} C_A = 516 km/sec	M_A = 1.94 $\frac{k\, C_A}{\Omega_{ci}}$ = .9	M_A = 3.88 $\frac{k\, C_A}{\Omega_{ci}}$ = 1.94

Figure 1. Summary of Unstable Leading Edge Whistlers

for leading edge modes, from the whistler dispersion relation,[14] is $\gamma \quad 167\eta$ where η is shock strength expressed as the ratio of shocked to unshocked densities. For ℓ = 500 km and η = .2 at the shock leading edge, we find $\gamma \ell / u \approx 10$, indicating 10 e-folding times pass as the shock traverses 500 km of the loss cone corridor. This $|k| = 2\Omega_{ci}/C_A$ unstable whistler mode can grow to sufficiently large amplitude after traveling 500 km along the loss cone corridor to pick up background air plasma. The air electrons are rapidly accelerated by ensuing ion-electron electrostatic instabilities. Since the calculation is based on the lower bound of M_A, it is clear that 10 e-folding times in 500 km is a conservative estimate since stronger shocks will have larger growth rates.

3. COMPARISON OF BURST FLUXES WITH MAGNETOSPHERIC SUBSTORM FLUXES

In the past few years there has been considerable concern over the phenomena of synchronous orbit satellites charging to high potentials as a result of magnetospheric substorms.[15] These substorms consist of the injection of high energy plasma from the earth's magnetotail into the region of synchronous orbit. Those portions of a satellite subject to the high energy plasma will charge to a potential several times the electron energy, while other portions of the satellite will remain at ground potential. Potentials near ground are maintained by photoelectron emission from illuminated surfaces on the spacecraft or by contact with the ambient low energy plasma.

During eclipse photoelectron emission disappears, and during a substorm the ambient low energy plasma flux is strongly dominated by the injected high energy plasma. The most damaging discharges probably occur between shadowed spacecraft components influenced by substorm plasma and illuminated components at ground potential. When the discharge passes through electrical circuitry between the components, damage can result. Electromagnetic interference can also result from surface discharges and considerable surface deterioration can be caused by arcing.

The following discussion will be an assessment of the possible spacecraft charging effects which can result from the large scale transport of ionospheric plasma to synchronous orbit by a nuclear burst. The plasma instability just discussed demonstrates a mechanism for structuring a collisionless shock wave. This mechanism will operate during a high altitude nuclear burst as the expanding nuclear debris passes over the stationary ionospheric plasma. Through the interaction of large amplitude whistler mode waves, plasma will be picked up by the collisionless shock and accelerated into the magnetosphere.

Using nuclear burst parameters for a Starfish-like (nominally 1.5 megaton) burst,[16] calculations[14] have conservatively estimated that near 10^{27} 0^+ ions would be carried by the shock when 1 percent of the total debris exits the loss cone. Depending on orientation, mass, and shape of the bomb casing, this number could be considerably higher. This number is reasonably estimated by the mass of debris which exits the loss cone, for ion pickup slows the debris piston and eventually shuts off the pickup instability.

The total propagation time for the plasma mass from the burst point just above the earth's surface to synchronous orbit is tens of seconds and more than sufficient to have thermalization of the complete plasma mass at near the ion temperature as the mass slows and diffuses.[17]

The estimated pickup of 10^{27} 0^+ ions by the nuclear burst shock wave would have an energy of approximately 10 keV at reasonable shock velocities. The demands of plasma neutrality would quickly accelerate an equal number of electrons which would thermalize with energies equal to or greater than the ion energy.[17] At the loss cone exits these 10^{27} electrons with energies of 10 keV would be in a cylindrical volume of approximately 2×10^{21} cm^3, assuming 1 percent of the nuclear burst bubble as comprising the loss cone exit and the plasma pickup region being several hundred kilometers in extent. These numbers and energies translate to an omnidirectional flux at the loss cones of $J_o \approx 3 \times 10^{15}$ electrons/cm^2-sec.

The calculation of fluxes at higher altitudes than the burst altitude follows directly from the Liouville Theorem that a differential intensity along particle trajectory is constant ($j_o = j_f$). Conservation of magnetic flux ($B_o dA_o = B_f dA_f$) and solid angle area ($dA_o d\Omega_o = dA_f d\Omega_f$) yields the following relation between initial omnidirectional flux (J_o) and final omnidirectional flux (J_f); from $\left(J = \int_{4\pi} j \, d\Omega\right)$ and

$$\left(J_f = \int_{4\pi} j_f \, d\Omega_f = \int_{4\pi} j_o \frac{dA_o}{dA_f} d\Omega_o = \frac{B_f}{B_o} \int_{4\pi} j_o \, d\Omega_o\right) ,$$

the relationship $\left(J_f = \frac{B_f}{B_o} J_o\right)$ is obtained.

During a magnetosperic substcrm, many of the plasma injections observed are characterized by omnidirectional electron fluxes ner 10^9 electrons/cm^2-sec.[18, 19] The previous calculations would yield omnidirectional electron fluxes from high altitude nuclear bursts of approximately $J_f \approx 10^{13}$ electrons/cm^2-sec at synchronous orbit. It is clear that these fluxes are significantly greater than those encountered during a magnetospheric substorm and would poise a strong spacecraft charging environment.

While the duration of the nuclear burst and resulting injection will be on the order of seconds and therefore much shorter than a typical substorm, studies[20] indicate the charging process takes only fractions of a second.

4. CONCLUSIONS

The atmospheric nuclear burst environment appears to present the potential for spacecraft charging effects at synchronous orbits. The calculated fluxes, and energies of the injected electrons are greater than those encountered during substorms, and which have been observed to cause spacecraft charging.

These calculations contain many approximations, but preliminary results indicate that it may be expected that synchronous orbit satellites under certain nuclear burst conditions would find themselves subject to a short, but intense, period of spacecraft charging. Potentials in the tens of kilovolts are suggested. The resulting transient charging and arc discharging should be a part of the design criteria of any spacecraft expected to survive a situation where high altitude nuclear bursts are involved.

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