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Electromagnetic Signals from Nuclear Explosions in Outer Space

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The thermal x-rays produced by a nuclear burst in outer space cause polarization currents in the medium which, if distributed anisotropically, will emit electromagnetic radiation. Roughly, a burst of thermal x rays, equivalent in energy to 1 ton of high explosive, produces a detectable 10-Mc/sec signal at a range of 1 km. Since only the ratio of x-ray energy to range enters into the strength of the radiated signal, other ranges follow by adjusting the x-ray energy proportionately. This works up to $\sim 3\times10^3$ km; beyond this range, dispersive effects begin to reduce the signal received.

The power in the electromagnetic signal varies as the square of the electron density, so this effect may provide a sensitive measure of the density of electrons in outer space.

IT is well known that a nuclear burst in the atmosphere produces electromagnetic signals of substantial magnitude.[1] Such signals are attributed to the asymmetrical propagation of gamma and x rays in the atmosphere: at low altitudes, the presence of the earth supplies the necessary asymmetry; at high altitudes, it is furnished by the rapid variation in atmospheric density. The question now arises: What can one expect in outer space, where the medium is essentially spherically symmetric and uniform? Here, the x rays have a practically unlimited mean free path. They sweep out to very great distances from the burst, transmitting an impulsive momentum to the electrons in the medium. Under proper circumstances, the ensuing polarization current may emit electromagnetic radiation. The purpose of the following is to clarify the conditions under which this may occur and to estimate the strength of the signal that may be expected.

Consider the thermal x rays emitted by a nuclear explosion in outer space.[2] We suppose the x rays are produced as a square-wave pulse of width $\sim10^{-7}$ sec and we assume 10^3 ionized hydrogen atoms/cm^3 as a model of the medium surrounding the explosion.

Since the medium around the explosion is spherically symmetric,[3] two cases arise: (a) if the x rays are emitted isotropically, no electromagnetic radiation results[4]; and (b) if the x rays are emitted nonisotropically, electromagnetic radiation *can* be produced. Since we are interested in the generation of electromagnetic signals, we assume that the bomb—either by reason of its intrinsic design or because it has been modified—emits x rays nonisotropically. In particular, to simplify the calculation we assume that the x rays are emitted uniformly in angle into a hemisphere.

Although an impulse is given to the electrons by the x-ray pulse, their mean drift velocity is so small that there is no effective charge separation while the pulse is moving over them. To see this, let W be the energy carried by the pulse. Then the momentum in the pulse is W/c, and the total momentum that passes through a unit area at a distance R from the burst is $W/(2\pi R^2c)$.

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[1] J. C. Mark, Nucleonics **17**, 64 (1959); A. S. Kompaneets, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1538 (1958) [translation: Soviet Phys.-JEPT **35**(8), 1076 (1959)].

[2] The considerations that follow also apply to the γ rays produced by the explosion, but we limit the explicit treatment to the thermal x rays because they carry many times the energy of the γ rays.

[3] Inhomogeneities due to solar flares or other disturbances would require a trivial modification of what follows.

[4] The Maxwell field, as a vector field, carries a definite polarization with it; if the source and the medium are spherically symmetric, a unique polarization cannot be defined, and the field must be zero.

On the average, each electron acquires a fraction of this momentum given by the Thomson cross section, $\sigma(=0.6\times10^{-24}\ \mathrm{cm}^2)$. Thus, if W equals 1 megaton (4×10^{22} ergs), the mean drift velocity imparted to an electron 1 km away from the explosion is $\sim10^4$ cm/sec. Clearly, at this point, the mean charge distribution is essentially unchanged while the pulse is present. Farther away, the electrons move even more slowly on the average, since the impulse falls off as $1/R^2$.

The mean velocity of the electrons is not zero, however, and shortly after the x-ray pulse has gone by, charge separation begins. This produces a plasma oscillation, which ultimately damps out, leaving the medium neutral again.

Thus, we encounter two possible sources of electromagnetic radiation: first, the polarization current that exists just after the pulse has passed and before the plasma oscillation has begun; and second, the currents that are present later due to the plasma oscillations. Since the pulse lasts $\sim10^{-7}$ sec, frequencies up to ~10 Mc/sec will be present in the initial (polarization) current. With 10^3 electrons/cm^3 in the ionized medium, the frequency of the plasma oscillations is ~0.3 Mc/sec. The initial signals originating from the polarization current will therefore be able to penetrate the ionosphere and be detectable on the earth's surface, while the signals originating from the plasma oscillations will only be detectable in space. For this reason, we shall ignore the signals generated by the plasma oscillations from now on (though we may expect their strength to be about the same as the signals computed from the first current source). Incidentally, we can assure ourselves that collective effects are really negligible while the pulse is present, for the collective effects produce an acceleration[5] $\sim\omega_p^2$, while the x-ray pulse produces an effective acceleration ω^2, and $\omega_p^2/\omega^2\sim10^{-3}$.

With this description of the basic physics in mind, we turn to the calculation of the field generated by the initial distribution of polarization currents. If we calculate the magnetic field, only the curl of the current distribution contributes. For our assumed current distribution, only the currents on the base of the hemisphere have nonzero curl, so the remaining currents may be ignored.

To simplify the calculation further, we fix the point of observation on the plane passing through the base of the hemisphere, and we consider only those signals that arrive from the first reception of radiation until one x-ray pulse width later. Because of retardation, the currents that contribute to these signals are contained in an ellipse having the burst point and the point of observation as foci.

An approximate evaluation of the signal received from the currents in this ellipse shows that, if n is the electron density and r is the distance from the burst point to the point of observation, then

$$H\sim E\sim(ne\sigma/2\pi r)(W/mc^2).$$

At 10^6 km, using $n=10^3$, this yields $E\sim6\times10^{-10}$ volt/meter; since a half wavelength at 10 Mc/sec is 15 meters, we find that the expected signal is roughly $\sim10^{-8}$ volt. This is a very small signal; however, continuing in the spirit of approximation employed so far, we shall regard it as detectable, although we note that it is an overestimate, if only because it assumes that all the electromagnetic energy appears at the signal frequency. A more reliable judgement of detectability would require more detailed information concerning the pulse shape, etc., of the signal.

Thus, as a rough rule of thumb, 1 megaton of x-ray energy gives a detectable signal at 1 megakilometer. Or, since only the ratio of energy to distance appears in the expression giving the signal strength, 1 ton is detectable at 1 km. Moreover, the power in the electromagnetic signal varies as the square of the electron density, thereby suggesting that this effect may provide a sensitive measure of the density of electrons in outer space.

Most of the approximations involved in this calculation have been mentioned, except for one, namely, we have completely ignored the dispersive nature of the medium through which the signal must propagate. An exact evaluation of this effect is very difficult, but a rough estimate suggests that it lowers the value of E at 10^6 km by a factor of ~17. This reduction can be countered by moving closer to the burst point. For example, we recover the required factor by detecting the signal at 6×10^4 km from the burst point.

Moving closer to the explosion also reduces the influence of dispersion. In fact, for distances less than $\sim3\times10^3$ km dispersive effects are negligible, so within this range the estimate—1 ton, 1 km—should be approximately valid.

Finally, we remark that if the electron density is 10^5–10^6, the plasma frequency is close to the signal frequency we have been considering and collective effects then intrude. A nuclear burst in such a medium, with or without magnetic field effects present, would be a useful way to explore collective interactions in detail.

[5] $\omega_p=2\pi\times$(plasma frequency); $\omega=2\pi\times$(signal frequency).