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Evidence for Precipitation of Energetic Particles by Ionospheric 'Heating' Transmissions

J. W. WRIGHT

Space Environment Laboratory, Environmental Research Laboratories, NOAA, Boulder, Colorado 80302

On the infrequent occasions when the Platteville, Colorado, 10-MW transmitter radio frequency matched the F region peak plasma frequency, intense localized sporadic E layers occurred at low altitudes (<95 km). After exclusion of various alternatives it is concluded that energetic particle precipitation from the plasmasphere may occur under these circumstances.

INTRODUCTION

Evidence is given in this brief report that under certain circumstances of operation the Platteville, Colorado, HF radio transmitter [*Utlaut and Violette,* 1974] caused transient 'sporadic E' layers at low altitudes (<95 km); it is suggested that this occurs by precipitation of trapped energetic particles from within the plasmasphere. The effect was discovered during the viewing of a unique digital ionogram time lapse 'movie' sequence obtained for a different purpose by the 'dynasonde' [*Wright,* 1969]. This instrument was located at the Erie field site about 26 km west and 10 km south of the Platteville transmitter. Four frames of the movie including one low-height sporadic E event are shown in Figure 1. In the digital ionogram mode used, the dynasonde computes an exponentially increasing frequency step for each fourth pulse transmitted. A three-of-four echo coincidence in digitized echo 'height' (time of arrival) is the criterion applied by the dynasonde computer for echo recognition. Height is digitized with 0.1-km resolution. These ionograms were computer-plotted off line; a receiver delay calibration was applied, so that the apparent range values are correct as shown. However, spaced antenna, complex amplitude observations, although they are possible with this system, were not made, and so calculation of echolocation, vertical and lateral motions, and obliquity corrections [*Paul et al.,* 1974] is not possible here. For the 1.6- to 16-MHz frequency range employed, with 0.01 $\log_{10} f$ resolution, 400 pulses were transmitted at 100/s, 4 s being required for each ionogram; for the heating experiment and movie purposes, however, only three ionograms per minute were obtained.

The perturbing Platteville transmitter was tuned to 9.9 MHz (f_p, extraordinary mode) in continuous wave 15-min-on, 15-min-off cycles. The third 'off' occurred at 08h 45m 06s MST (mountain standard time), 5 min 42 s prior to the second ionogram shown. An intense sporadic E layer has suddenly (±10 s) appeared at 87.9-km range, which persists approximately in place and decays with an e folding time (for electron density, assuming total reflection) of about 160 s. From the absence of 'multiple-echo' reflections and 'blanketing' of the overlying ionosphere it is evident that the echo returns from a relatively isolated plasma cloud. From the absence of group retardation or blanketing of this echo at 1.6 MHz, the lowest radio frequency employed, we may confirm that the cloud lies beneath the likely D region altitude for this density and solar zenith angle (~93 km for $N_e = 3.2 \times 10^4$ cm^{-3}, see *Mechtly et al.* [1972]).

CIRCUMSTANCES OF OCCURRENCE

In Figure 2 the time variations of F region peak penetration frequencies in the ordinary and extraordinary modes ($f_oF_2 = 0$, $f_xF_2 = X$) measured at Erie are shown for this date. Horizontal bars at f_pX = 9.9 MHz identify on-off times at Platteville. Along the same time axis (top panel) are shown the altitudes (slant ranges) and times of occurrence of sporadic E echoes between 0600 and 1400 MST. The dynasonde at Erie was not operated outside 0735–1200 MST. For purposes of control, other local values of $f_{o,x}F_2$ and additional sporadic E observations have been obtained from routine analog ionosondes at Boulder (49 km west and 5 km south of Platteville) and White Sands, New Mexico (213 km west and 854 km south). These analog instruments permit neither echolocation nor obliquity corrections, but with care, sporadic E slant ranges within ±0.5 km (or for weak echoes, ±1.5 km) can be read from the recordings. These as well as the Erie dynasonde values are coded in Figure 2 by bars of different widths.

Low echoes ($\lesssim$90 km) occur during this experiment only near Erie. They are of approximately the duration and spacing (or less) of the f_P transmissions, but if a one-to-one correspondence is evident at all, time lags of 1–10 min must occur.

In this experiment and the other ones to be discussed, there is often abundant natural sporadic E. Whether the present echoes can be successfully distinguished from such natural events (and especially meteor echoes) is the most critical question at present. The Boulder and White Sands ionograms contribute substantially to confidence that the $\lesssim$90-km echoes are localized to the Erie-Platteville area, since at the other two stations the great majority of transient echoes are found at significantly greater ranges (>96 km); they are uniformly less abundant or absent altogether (96–100 km) at White Sands (which is expected to be far beyond any Platteville E region effects). Finally, in Figure 2 and other figures to be discussed below, there are often echoes observed at Boulder simultaneously with the $\lesssim$90-km echoes at Erie, at greater ranges consistent with the Boulder-Erie distance, this observation suggesting that they return from the same transient low-altitude structure. Such echoes at Boulder appear at 0805–0815, 0835–0855 (97 km), and at 1015–1044 (98 km), for example, in Figure 2, coincidently with 88- to 89-km echoes at Erie; and similar echoes do not appear at Boulder at other times throughout this day. On geometric grounds, meteors may be rejected as a likely cause of the low echoes at Erie, since only a very small number of meteors can be expected to produce nearly horizontal trails at the short ranges (and hence lower heights) in question.

Figures 3, 4, and 5, in the same format as that used for Figure 2, are additional examples of the same phenomenon. In

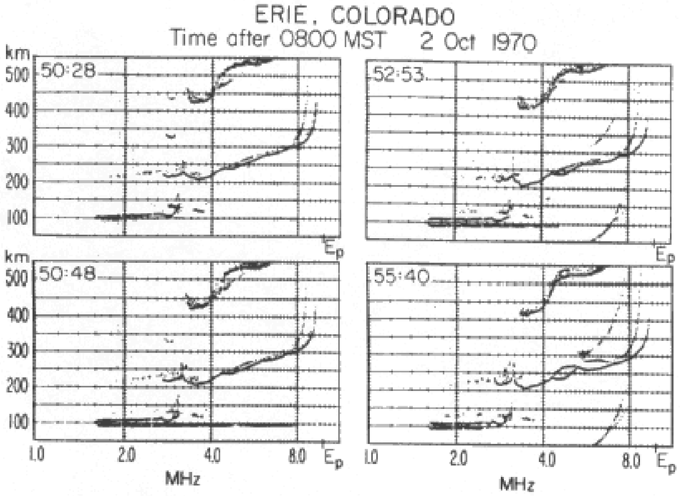

Fig. 1. Four frames from the digital ionogram sequence employed in Figure 2 (07h 35m 20s to 12h 54m 45s MST). The frame at 08h 50m 28s follows the 9.9-MHz f_P transmission (08h 29m 59s to 09h 45m 06s). An intense 88-km layer appears on next ionogram, 08h 50m 48s, and decays thereafter.

Figure 3, X mode f_P transmissions are accompanied by low-altitude sporadic E layers only after the 2005–2023 transmission. In Figure 4, only the 2000–2015 transmission (O mode) has this effect. In Figure 5, nearly continuous X mode transmissions were at frequencies which varied so as to follow (irregularly) the variations of f_xF_2. Throughout most of this period they are accompanied by low-height echoes at Erie which have no counterparts visible at Boulder.

Twenty-five heating experiment sequences were examined for this study. These were selected to include instances in which f_P approached or exceeded f_oF_2 or f_xF_2, as this clearly appears to be a necessary condition for generation of low-height sporadic E layers. Unfortunately, throughout all of the 1970–1973 extent of the Platteville program the conditions $f_P < f_oF_2$ or $f_P < f_xF_2$ were considered to be of most interest; experiments at fixed f_P rarely started long before f_oF_2 or f_xF_2 increased through f_P, nor were observations usually continued for useful periods after the F_2 peak frequencies had decreased through f_P. The 25 days examined therefore include many instances where $f_P < f_{o,x}F_2$, in addition to the much smaller number where $f_P \gtrsim f_{o,x}F_2$. The chosen polarizations (for O or X) of the Platteville transmitting antenna appear about equally in this sample; a variety of transmitter modulations were used (CW, pulsed, two-frequency, FM, etc.). The sample includes only moderately disturbed geomagnetic conditions, ranging from $Ap = 2$ to $Ap = 37$. Of the 25 days, 16 were decisively remote from known meteor showers, and on about half of the days the experiments were conducted within the 1200–0000 MST interval when random meteor activity is minimum.

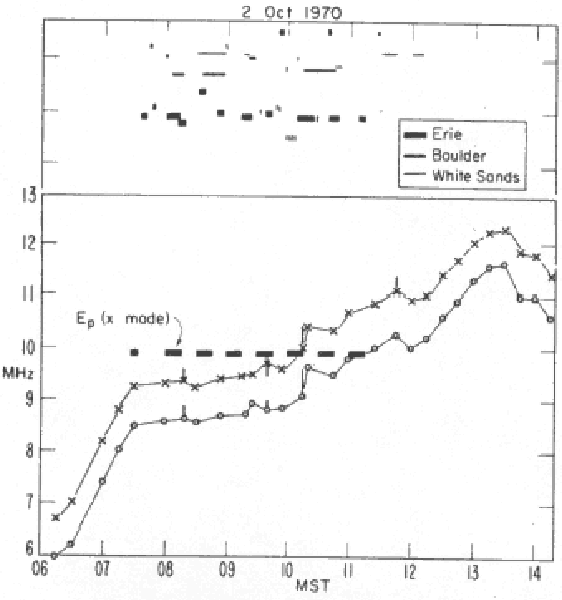

Fig. 2. (Bottom panel) Variation of f_o, f_xF_2, and f_P on-off intervals; this is the same event as that shown in Figure 1. Radio frequency intervals of spread F are shown at a few sample times. (Top panel) Heights and times of occurrence of sporadic E at Erie (digital ionosonde), Boulder, and White Sands (analog ionosondes). Sporadic $E > 105$ km is not shown.

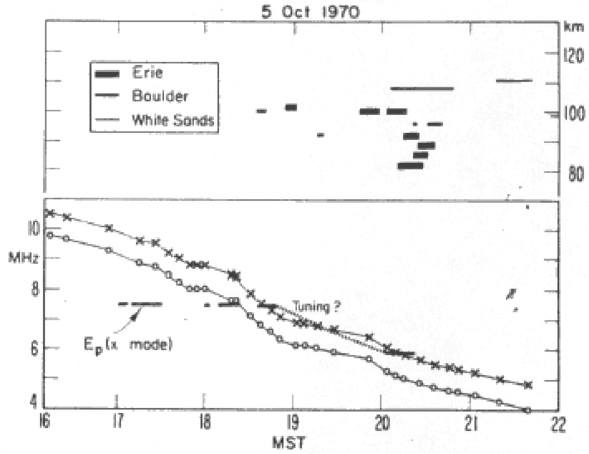

Fig. 3. Format similar to that used in Figure 2 for October 5, 1970, experiments. Tuning? signifies uncertain f_P transmissions and frequencies.

A total of 36 definite sporadic E events at low heights on 16 days were found in association with f_P transmissions near f_oF_2 or f_xF_2. The events never preceded f_P turnon, but delays between 'zero' (+20 s) and up to 10 min were found. No conclusions were possible on 11 turnon occasions for various reasons: prevalent sporadic E at unusually low heights; indefinite f_P on-off intervals (in early experiments, tuning of the Platteville system occurred at unreported times, frequencies, and power levels between scheduled transmissions); and short pulse modulated transmissions, which (at least) may be equivalent to reduced power. On three occasions, no low-

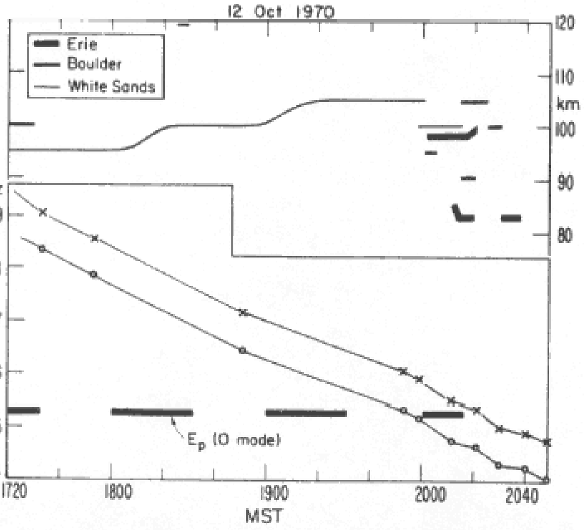

Fig. 4. Heating experiment of October 12, 1970. The format is similar to that used in Figure 2. Low echoes (82 and 98 km) occur only near 2000 MST turnon. Somewhat 'higher' echoes are also seen at Boulder.

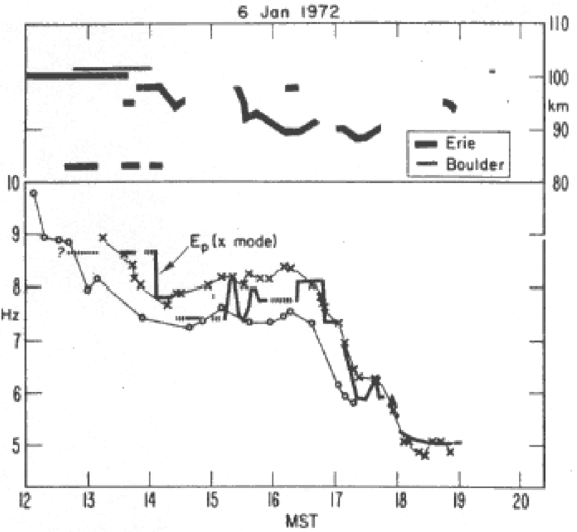

Fig. 5. Format similar to that used in Figure 2 for January 6, 1972, experiments. Here, f_P transmission frequency (X mode) is varied irregularly to remain near f_xF_2.

height echoes were observed under conditions where they might have been expected on the basis of the other experiments. Thus, although very few 'contrary' cases and a considerable number of uncertain cases have been found, a definite cause-effect relationship seems to be indicated.

INTERPRETATION

It seems unlikely that the f_P wave itself could act directly at 85–95 km to produce these effects. *Meltz et al.* [1974] have deduced small (10%) electron density enhancements near 70 km in the daytime after sustained (10 min) *Ep* transmissions, through reduction of the rate of dissociative recombination at the higher electron temperatures immediately produced. However, our phenomenon involves the sudden appearance of much higher electron densities ($\sim 10^5$ cm^{-3}) than those normally present at 85–90 km ($\sim 10^3$–10^4 cm^{-3}); moreover, we have cases (e.g., Figures 3 and 4) where the low layers appear at night, when the process discussed by Meltz et al. cannot occur. Any mechanical (acoustic-gravity wave) redistribution of ambient plasma is therefore also precluded. *Weinstock* [1974] has estimated the direct acceleration of F region electrons in the f_P field to suprathermal energies and finds it adequate ($\sim$6 eV) to explain the observations of airglow accompanying f_P reflection from the F region; these electrons cannot produce low-altitude effects, however.

Precipitation from the energetic particle population ordinarily stably trapped in the local L shell ($L = 2.35$ at Platteville) would appear to be the only remaining possibility, and it indeed possesses many of the features necessary to agree with the present observations. Analog ionogram movies made within the auroral oval by the Canadian Defense Research Telecommunications Establishment (now Communications Research Center) in 1951 at their Baker Lake station show very frequent natural events of the kind illustrated in Figure 1; there is little doubt that these are attributable to particle precipitation. Energetic electrons in stably trapped orbits within the radiation belts, if pitch angle scattered into the 'loss cone,' produce secondary ionization through Coulomb collisions; electrons with energies of 20–100 keV achieve maximum production rates at altitudes between 100 and 80 km, respectively [*Rees*, 1969]. Large fluxes at energies of <300 keV are permanent features of the inner radiation belt [*Vampola*, 1971].

With peak electron densities of $\sim 10^5$ cm^{-3} during these events, a steady state electron-ion pair production rate of 10^4 cm^{-3} s^{-1} may be inferred, implying a column production rate of 5×10^9 cm^{-2} s^{-1} if the layer peak is $\sim$5 km thick. If the characteristic energy of the precipitating particles were 35 keV, the required flux would be 5×10^6 cm^{-2} s^{-1}. A typical energetic electron spectrum from the Explorer 45 (S^3) satellite at $L = 2.35$ for moderately quiet conditions (D. J. Williams, private communication, 1975) provides about 10^5 el cm^{-2} s^{-1} sr^{-1} keV^{-1} in the range of 30–100 keV with an equatorial pitch angle of $\sim 90°$. A flux of about 3×10^7 cm^{-2} s^{-1} is consequently available outside the loss cone, and about 10% of these would be required to enter the loss cone by some process to explain the observed events. The same reasoning may be used to estimate the expected airglow intensities (L. R. Megill, private communication, 1975): about 300 R would be expected at the 3914- and 5577-Å lines. Unfortunately, no comparative airglow data are available from local instrumentation during the experiments discussed here (J. G. Haslett, private communication, 1975).

Opinion has been divided on the significance of natural precipitation at these relatively low latitudes; indirect evidence (summarized by *Potemra and Zmuda* [1970]) has been interpreted to imply significant contributions to the nighttime D region. In particular, VLF effects during magnetic storms have been attributed to precipitating energetic particles [*Belrose and Thomas*, 1968]. What is required, either for natural events or for the induced precipitation suspected here, is a suitable pitch angle scattering mechanism. It is now well established that the poststorm recovery of the plasmasphere involves precipitation of an augmented population of energetic electrons, with enhanced D region ionization production [*Spjeldvik and Thorne*, 1974]; ELF noise generated within the plasmasphere provides the pitch angle diffusion process [*Lyons et al.*, 1972].

It is surely significant that low-altitude sporadic E layers appear when—and in these experiments essentially only when—f_P matches f_oF_2 or f_xF_2. The observations are not sufficiently detailed to suggest whether matching f_o or f_x is more effective. In part, this uncertainty arises because of the relatively small difference $f_x - f_o$ ($\sim$0.7 MHz at Platteville) compared to that of natural and f_P induced F region plasma frequency fluctuations. The uncertainty is deepened because of the rather high intensity of the unwanted mode (−9 to −12 dB) when the Platteville antenna is configured for right-hand (O) or left-hand circular (X) polarization. For either mode, many special conditions apply when $f_P \simeq f_o$ or f_xF_2. The electric field amplitude 'swells' to a large value near the layer peak, and the vertical 'wavelength' expands to encompass a wide region (probably several tens of kilometers) there. Point source wave fields (for a constant gradient ionosphere, thus without a peak (M. Pitteway and J. W. Wright, unpublished manuscript, 1975)) suggest that the lateral width over which the wave field phase is substantially constant (i.e., the effective first Fresnel zone) is at least several times wider than it would be if refraction were absent. For the ordinary mode the polarization becomes linear, and the electric field becomes aligned with the geomagnetic field; the electromagnetic field decays into an ion acoustic and electrostatic wave pair [*Perkins et al.*, 1974]. Probably many other wave modes at the harmonics of the plasma, electron, and ion gyrofrequencies are generated as well. It has been observed [*Palmer and Barrington*, 1973] that high-frequency transmissions from the Isis 2 satellite excite VLF emissions in the vicinity of the spacecraft, which propagate at evidently low group velocity. It is thus possible that the Platteville transmissions might also excite VLF modes, which could propagate along the geomagnetic field. These, it is well known, can scatter energetic particles efficiently in pitch angle near the geomagnetic equator [*Helliwell*, 1974]. C. Park has mentioned (private communication, 1975) another, perhaps simpler, possibility: The F region perturbations caused by the Platteville transmitter may produce a geomagnetically field-aligned duct, within which natural VLF energy might become concentrated; enhanced wave-particle interactions would then be expected within the duct.

More carefully controlled f_P transmission experiments and more informative diagnostics are clearly required to establish the nature and circumstances of occurrence of these sporadic E events. If energetic electron precipitation is indeed the process, 'echolocation' by a digital ionosonde can establish the altitude and time variations of secondary electron production and loss, and thus the primary particle energy and flux can be deduced. Airglow observations would decisively indicate whether energetic particles are involved. VLF observations might confirm the relevance of pitch angle scattering by VLF waves to the present phenomenon. To what extent controlled experiments might be devised to probe the energetic particle spectra by these ground-based means also remains to be explored.

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