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Investigation of Electron Dynamics in the Magnetosphere with Electron Beams Injected from Sounding Rockets*

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Abstract. The Electron Echo experiments are based on early measurements of auroral X-rays discovered with balloon experiments in 1957. These X-rays were caused by strong pitch angle scattering and subsequent precipitation, and frequently accompanied the injection of electrons into the earth's radiation belts as shown by a combination of balloon and satellite measurements in 1967. Echo I, launched in 1970, injected 40 keV, 0.1 amp electron pulses at low latitude ($L = 2.6$) and successfully measured the returning pulses from the conjugate region. Electric fields and multiple Coulomb scattering were studied. Echo II, launched in 1972 from high latitude ($L = 8$) studied the interaction of the beams with background radiation and the detailed motion of the beams near the rocket. Evidence for a beam plasma instability was obtained. Echo III launched in April 1974, ($L = 5.5$) detected a series of conjugate echoes during the presence of a strong convective field in the magnetosphere. It was shown that the electric field measurement in the ionosphere using the incoherent backscatter radar and detectors on the rocket was transferred to the equatorial plane as though field lines were equipotentials. On Echo III, a search for beam bunching at the local plasma frequency gave a null result.

Key words: Electron Beams — Beam-Plasma Interactions — Precipitation — Scattering — X-Rays — Aurora — Electric Fields.

I. Introduction

This paper describes an empirical study of the basic mechanisms by which electrons precipitate from the geomagnetic field to produce "auroral X-rays" during periods of geomagnetic activity. These mechanism are complex and very difficult to understand in detail. Despite the many hundreds of measurements of auroral X-rays by balloons, and more recently by rockets and earth satellites, there exists only a handful of observations of wave-particle interactions in which cause and effect are convincingly documented (Rosenberg *et al.*, 1971; Koons *et al.*, 1972).

The "Electron Echo" experiments were devised to help solve these problems by the controlled injection and subsequent detection of artificial

* To Prof. G. Pfotzer in honor of his 65th birthday.

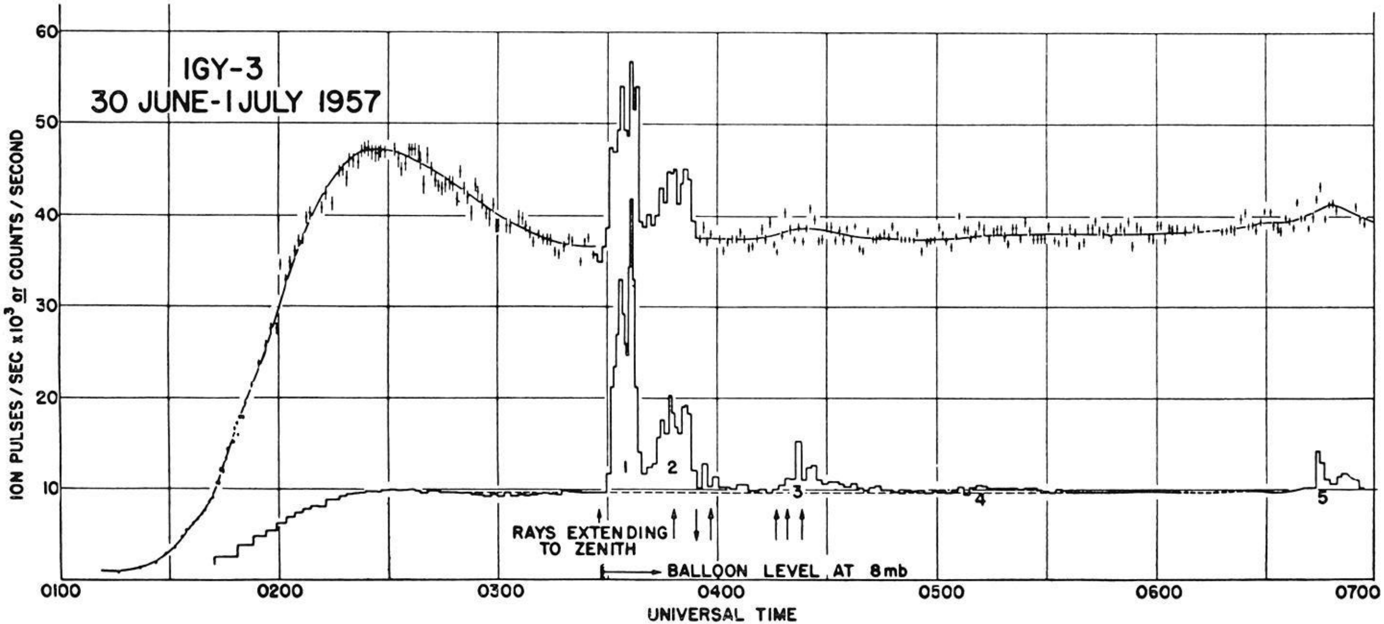

Fig. 1. The first measurement of X-rays associated with visual aurora, made by a constant-level balloon floating at 8 gm cm^{-2} depth on the first day of the International Geophysical Year at Minneapolis. The 2″ diameter brass-walled geiger counter (upper curve) and the 10″ diameter steel-walled integrating ionization chamber (lower curve) show a similar response, increasing when visually observed ready structures in the aurora intensified. Five such events were identified (numbered on figure). From Winckler and Peterson (1957)

electron beams moving in the magnetosphere like the natural electrons. Three rocket experiments have now been conducted in 1970 (Echo I), 1972 (Echo II) and 1974 (Echo III). These experiments mark a step-by-step development of the experimental technique with an attack on the simpler dynamical problems affecting the electrons such as coulomb scattering, motion in static electric and magnetic fields, rocket charge neutralization, electron scattering around the rocket, beam instabilities, plasma wave emission, etc. Considerable detail has already been published on the Echo I and Echo II experiments (Hendrickson *et al.*, 1971; Cartwright and Kellogg, 1974; McEntire *et al.*, 1974, Winckler, 1974; Arnoldy *et al.*, 1974; Winckler *et al.*, 1974). A further discussion of these results and possible future experiments will consistute the main part of this paper. But since the motivation for the Echo program has come from the results of earlier work with balloons and satellites, a brief historical resume of some features of precipitation seems useful.

X-rays associated with visual aurora were discovered by balloons in 1957 on the first day of the IGY period. (Winckler and Peterson, 1957). Fig. 1 is the record obtained on that occasion by an ionization chamber (lower) and a geiger counter (upper) flown at 10 gm cm^{-2} depth and intended to study cosmic ray variations. A detectable effect associated with an aurora at such a low altitude came as a great surprise. It was soon determined that the X-ray increases were very intense during negative excursions of the horizontal magnetic component which lasted up to several hours and were accompanied by active auroral displays. Strong current systems in the ionospheric *E*-layer called "electrojets", now interpreted as Hall currents flowing under the action of a transverse electric field and simultaneous ionization due to the precipitating particles (see, e. g., Boström, 1964), caused the magnetic perturbation easily measured at sea level associated with the precipitation.

It must be remembered that these early measurements were made at geomagnetic latitude 55° (*L*-value 3.5), so that the electrons were precipitating from the heart of the outer Van Allen radiation region. With hindsight, one can say that it should have been possible to predict the presence of the trapped radiation (electrons at least) from these measurements. In actuality a convincing association between the X-ray producing precipitation and truly trapped particles came only in 1967 when the time profiles of balloon-measured X-rays in the auroral zone were shown to closely follow trapped radiation increases mesaured simultaneously at the synchronous orbit (Parks and Winckler, 1968). An example is shown in Fig. 2. In this figure the electron increase at 6.6 R_e and the X-ray profile are remarkably similar, and occur together during the increase and decrease of the electrojet magnetic disturbance shown also in the figure from an auroral zone station (Cape Chelyuskin, USSR). The top panel of this figure shows the

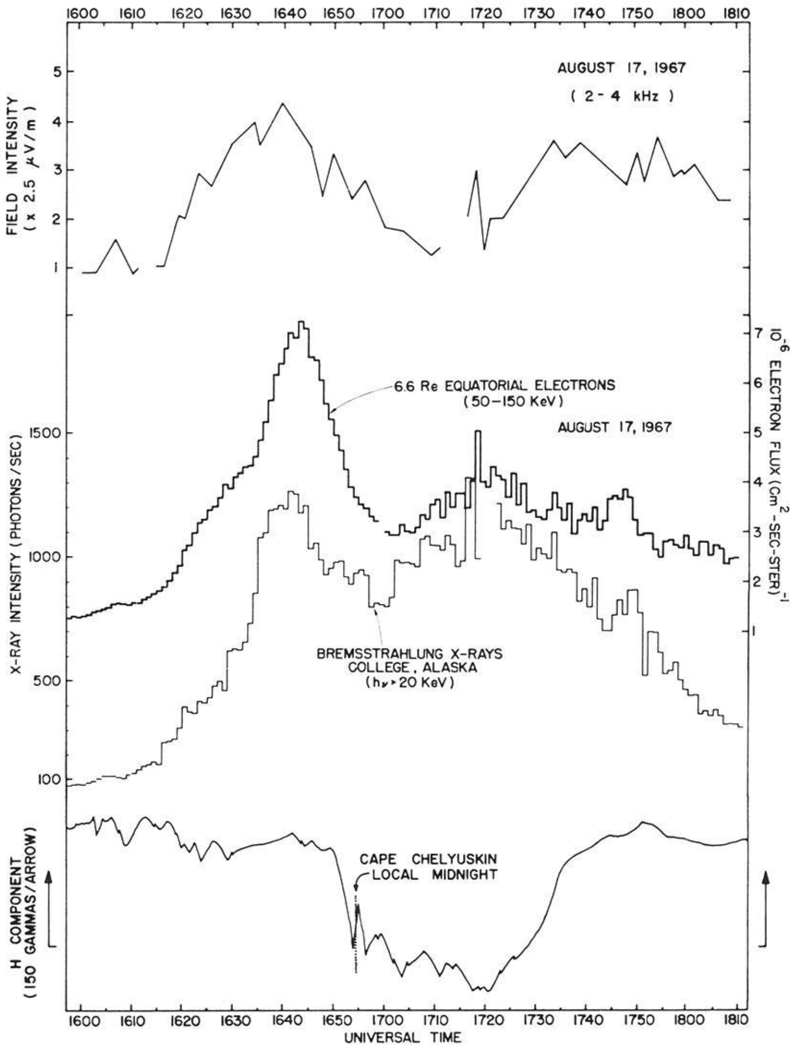

Fig. 2. The result of an experiment showing that the injection of trapped electrons (6 · 6 Re Equatorial at Synchronous Orbit) is accompanied by precipitation (Bremsstrahlung X-rays). The X-rays were measured by a balloon located near the point magnetically conjugate to the satellite (ATS-1). The trapped and precipitated directional intensity of electrons is similar. Also shown (lower panel) is the accompanying electrojet and (upper panel) VLF emission in the form of "hiss". This has been attributed to Cerenkov emission from the precipitating electrons. (From Parks and Winckler, 1968, modified)

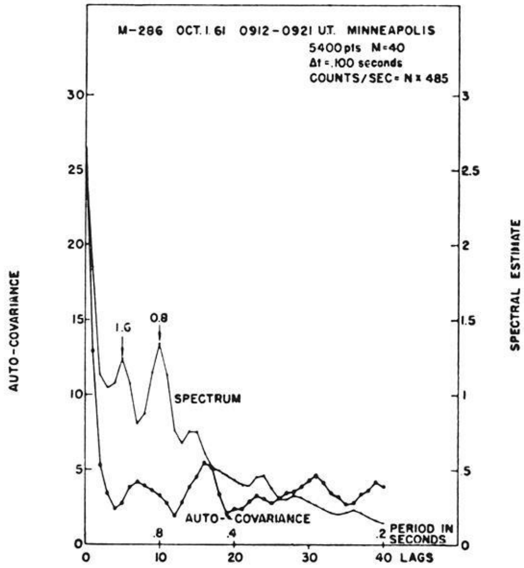

Fig. 3. Power spectrum analysis of the time-intensity series of an intense X-ray event measured at Minneapolis by balloons in 1961. The Fourier spectrum shows a significant peak at the bounce period (0.8 secs) and multiplies of this corresponding to 60 keV electrons at $L = 3.5$. (From Winckler *et al.*, 1962)

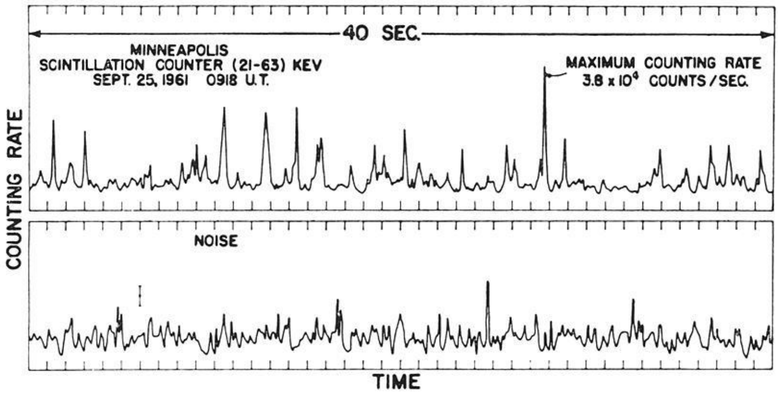

Fig. 4. A sample time-intensity series (upper) of the type used for the Fourier analysis. The bouncing or "ringing" shown in Fig. 3 generally followed the large injection spikes. Such "microbursts" are also correlated with flashes of the visible aurora in the midnight-morning local time region. The lower panel is a white noise spectrum for visual comparison. (From Winckler *et al.*, 1962)

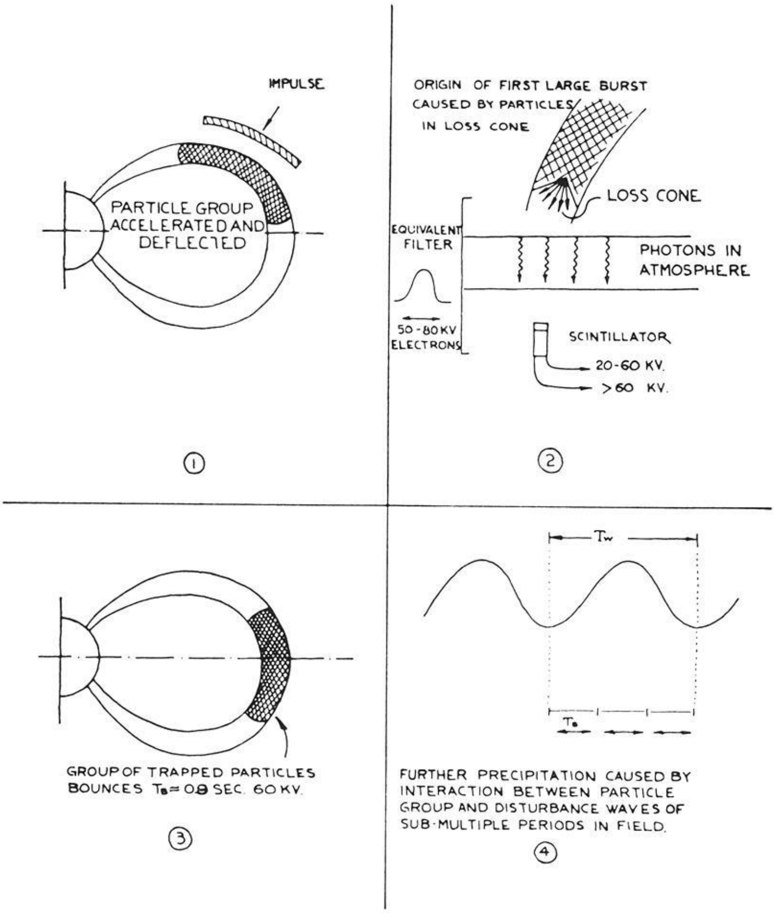

Fig. 5. A schematic idea of how the experimental situation used for figures 3 and 4 localizes the effective detected electron energy near 60–70 keV, thus providing a discreet bounce period (0.8 secs). Some mechanism for grouping the electrons must be present, as shown

intensity of VLF hiss recorded for the event. The precipitation is accompanied in a similar time pattern by the E-M radiation presumed generated by the precipitating particles through the Cerenkov process. This VLF energy is not enough in such cases to *cause* the particle pitch angle scattering and precipitation, but is a secondary effect attributable to the particles.

The X-ray variations show a large variety of time scales, some highly periodic accompanying auroral luminosity fluctuations and magnetic pulsations, and some very short, in the "micro burst" region (see, e.g., Parks *et al.*, 1968). Noteworthy among these was the discovery in 1961 (Winckler *et al.*, 1962) of a significant variation or modulation of X-rays occurring at the "bounce" period for electron groups moving along the dipole field lines between the northern and southern hemisphere mirror points. The Fourier analysis spectrum of such a process is shown in Fig. 3, where we see a peak at 0.8 and 1.6 seconds corresponding to groups of 60—70 keV electrons bouncing at $L=3.5$. (A sample of the time series yielding such a spectrum is given in Fig. 4). A qualitative explanation of the bouncing groups is given in Fig. 5. The bounce motion is a well known part of the general motion of trapped electrons, and corresponds to the second adiabatic invariant. However, the coherent bouncing of electron groups during precipitation is the natural analog of the artificially injected "Echo" electrons whose bounce motion between the two hemispheres has been successfully observed on two of the three Echo rocket flights (Echo I and Echo III) and which has permitted the analysis of electron and magnetic field influences as well as particle scattering. The periodic variations of precipitation have been only partially explained. (Coroniti and Kennel, 1970). We know that the strong pitch-angle scattering resulting in electron precipitation usually accompanies the "injection" or "acceleration" of plasma into the trapping region (Parks and Winckler, 1968), and that this "replenishment" of the radiation regions preferentially occurs when the auroral zone electrojet increases. The more energetic processes to which we have in effect referred here (electron energy E $10>$ keV) most frequently accompany the *visual* aurora (electron energy E $10<$keV) in the midnight to morning local time sector. Evening auroras are frequently entirely due to electrons $E<10$ keV and have no high energy counterpart. (Arnoldy, private communication).

II. Some Technical Details of the Echo Program

The Echo technique consists of injecting a short, intense burst of electrons (typically a 0.1 amp, 20—40 keV, 32 msec duration pulse) from a large sounding rocket at altitudes between 150 and 350 Km, i.e., in the ionospheric *F*-region. The rocket trajectory is aimed at magnetic east with the horizontal speed adjusted so that particle detectors on board can intercept the beam (or "echoes") after one or more round trips to the opposite hemisphere mirror altitude. A return current of *F*-region electrons to the rocket body or to a collector disc maintains rocket neutrality during injection.

It is useful to view the motion of both the rocket and the injected electrons as projected (along the magnetic field) onto a plane perpendicular to the magnetic field vector, and passing through the injection point (i.e., the electron gun on the rocket). This plane is called the injection plane.

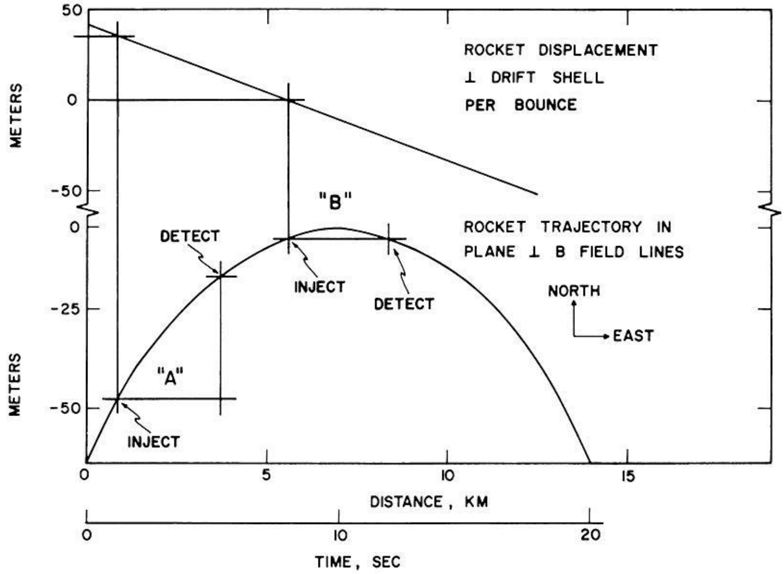

Fig. 6. The vertical parabolic motion of a rocket projected on the "injection plane" as a parabola. The apex of the projected parabola does *not* correspond to geographical apogee, but is called "drift apogee" or "L-apogee". Echoes may be detected with the least lateral diffusion (i.e., $\perp$ drift shells) near drift apogee. See text for details

The motion of the rocket in this plane is a parabola as shown in figure 6 and represents the projection into that plane of the parabolic profile of the rocket moving under gravity in the vertical plane. One notes that although the vertical parabola always maps into another parabola in the injection plane, that the vertical apex (geographic apogee) does not map into the apex in the injection plane. The magnetic or "drift shell apogee" (as shown in Fig. 6) may occur anywhere on the geographical rocket trajectory, depending on the inclination and direction of the magnetic field and the rocket azimuth. In the case of Echo I drift apogee occurred about one minute ahead of geographic apogee, as the rocket azimuth was *south* of drift shell east. Echoes were received on Echo III very close to geographic apogee as the rocket direction was very close to drift east. The straight line in the top panel in Fig. 6 gives the displacement of the rocket perpendicular to the drift shell in the injection plane during one bounce period and is proportional to the differential of the parabola below. This particular figure was drawn for the Echo II experiment at Fort Churchill with a bounce time of about 3.6 seconds. In example A, Fig. 6, if an injection is made prior to drift shell apogee, the rocket will displace about 35 meters away from the injection drift shell in one bounce period. Thus unless the echo

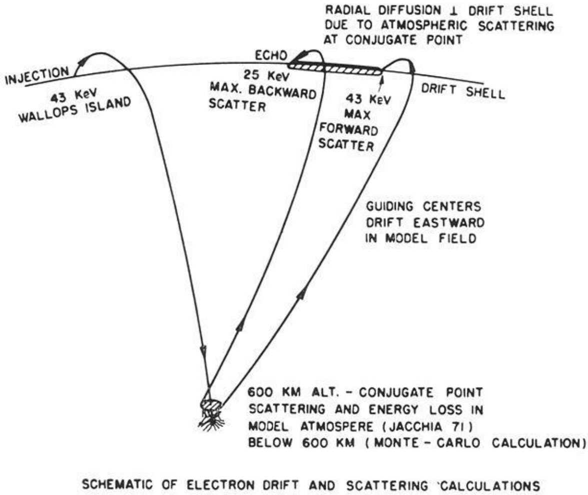

Fig. 7. Schematic of the echo process where the conjugate region mirror height is in or below the atmosphere as in the Echo I experiment

has spread by diffusion or the drift shell happens to be distorted, the echo will miss the rocket. However, in case B, near "drift shell apogee", both the injection and detection points lie in the drift shell and the echo can be detected. An additional requirement is that the X-component of rocket speed in this figure be equal to the bounce averaged particle drift vellocity so that the timing will be correct as well as the position. If the particles are injected with a certain energy spread giving a range of drift velocities resulting from magnetic curvature and gradient forces then the detection of conjugate echoes becomes feasible. This is shown by the experimental success in both the Echo I and Echo III experiments of detecting conjugate region echoes.

The construction of the electron injector and detector systems, plasma diagnostics and other relevant details are given in the publications referenced above and will not be repeated here.

III. Conjugate Echoes from the Echo I and Echo III Experiments

The first experiment, Echo I, was conducted at a low geomagnetic latitude (L = 2.6, Wallops Island, Virginia), where the magnetic field geometry is very well known and stable and the magnetic and electric fields are small. At this latitude the conjugate mirror points were 300 kilometers lower than those over Wallops Island so that the echoes were returned by multiple coulomb scattering in the atmosphere combined with the mirror effect. This process is shown schematically in Fig. 7. The multiple

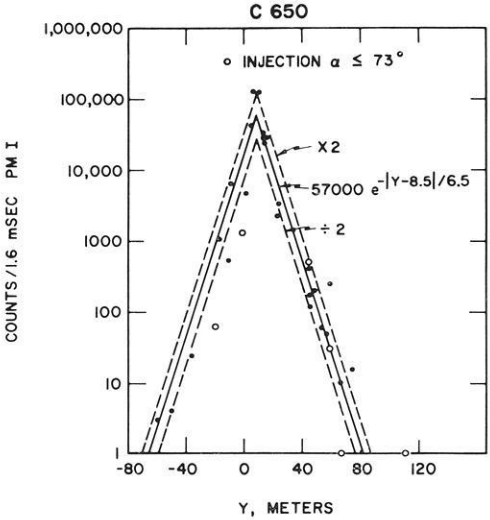

Fig. 8. Hendrickson's evaluation of the echo intensity (Echo I experiment) at an echo time of 650 msec as a function of lateral coordinate Y, ⊥ the drift shell. Note the exponential form for five orders of magnitude

coulomb scattering spreads the particles in a radially symmetric manner at the conjugate point. The energy straggling then spreads the particles along the drift shell because of the energy dependence of the magnetic curvature drift velocity. At the detection point this effect is very large compared to the transverse spread caused by the spatial diffusion. McEntire (McEntire *et al.*, 1974) has developed a Monte-Carlo scattering program for Echo I which evaluated the transverse diffusion, and found an approximate exponential dependence of particle intensity so that

$$I = I_0 \exp\left(-\frac{Y}{5.2}\right)$$

with Y in meters. A careful evaluation by Hendrickson (1972) of the echo intensity perpendicular to the drift shell for Echo I is summarized in Fig. 8. The exponential is a reasonable fit over many orders of magnitude and the observed exponential constant of 6.5 m is in reasonable agreement with the 5.2 m theoretical value. The observed bounce times (0.62 secs) and echo displacements along the drift shell (500 meters) are in close agreement with expected values for Wallops (see Hendrickson, 1972; McEntire *et al.*, 1974).

In the Echo II experiment no conjugate echoes have been identified although it is certain that Churchill ($L = 8$) was on closed field lines at the time of the experiment (Arnoldy *et al.*, 1974).

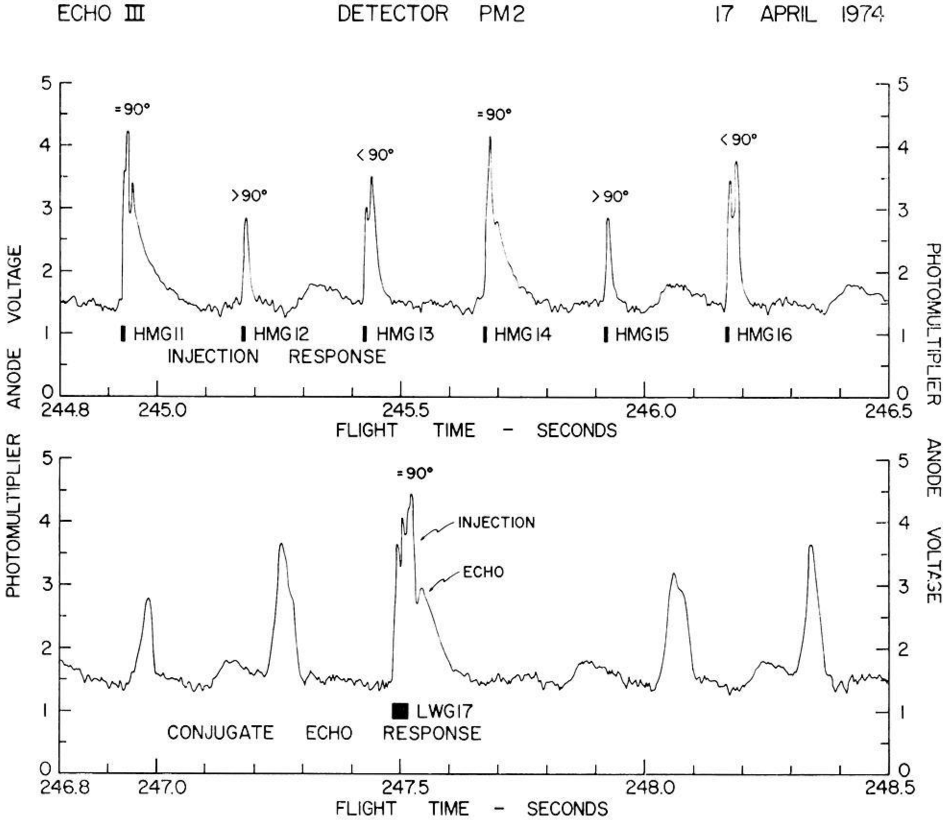

Fig. 9. A sample record from the Echo III experiment. Upper panel-six injections showing the response of a scintillation counter on the rocket during electron injection (injection period shown by the black bars). This response is due to scattering near the rocket, "quick echoes" from below the rocket, and some scintillator "afterglow", with a residual background of trapped or auroral electrons at $L = 5.4$ (Fairbanks, Alaska). Lower panel-the conjugate echo response of the same scintillator to the six injections. The echo time is about 2.05 secs. The intensity scale (photomultiplier anode voltage) is highly compressed

The Echo III experiment was launched from the Poker Flats range near Fairbanks, Alaska on 17 April 1974 near the end of a very quiet geomagnetically 5 day period. At this latitude (64.85°) ($L = 5.4$) and longitude (—147.83) the conjugate mirror points are about 300 Km *higher* than at Fairbanks so little diffusion is to be expected and the Echo pattern should be confined to a few Larmor radii distance from the injection drift shell. A group of echoes was received from six rather closely spaced (236 msec) injected pulses each of msec duration, with no further echoes detectable at plus or minus 1 second (or longer) from this group. The electron intensities measured by a scintillation counter during injection and during the echoes are shown in Fig. 9. The echoes gave a relatively large signal, except for the fourth in the sequence, whose guiding center evidently was further from the rocket (due to tocket spin) and was missed. In this experiment the ionospheric electric field was evaluated continuously at the launch site by using the Chatanika incoherent scatter radar (Blanks *et al.*, 1973). A steady northward electric field of about 40 volts per kilometer was observed on the night of 17 April. The resultant ExB drift was thus westward and compensated a large part of the eastward magnetic curvature drift so the net drift velocity approximately matched the eastward horizontal velocity obtainable with the rocket. The relevant parameters are given in Table 1. To first order at least, the experiment demonstrates that the F-region ionospheric electric fields measured by the Chatanika radar may be extended out along the magnetic field lines through the equatorial plane to the opposite hemisphere as if field lines were equipotentials. The measured ionospheric electric field thus acts over the full bounce motion of the electrons. The data given in Table 1 are model dependent and must be regarded as preliminary. One should expect (curvature drift — ExB drift = rocket velocity) but one obtains 1.53—0.8 = 0.7 vs 0.85 Km sec^{-1} rocket speed. Other field models are under study at present. The Olson-Pfitzer model (Olson and Pfitzer, 1973) predicts a bounce time very close to that oberserved, however. (See Table 1).

IV. Beam Stability and Beam-Plasma Effects

The fact that the echo beams can be detected after travelling large distances in the geomagnetic field to the conjugate point and return implies that no catastrophic beam instability has occurred under the echo conditions. However, it is very difficult to make a quantitative estimate of the loss of electrons from the beam in one bounce period. A careful study by Hendrickson (1972), showed that the total observed number of electrons in the Echo I experiment returning from the conjugate point was about a factor of 10 lower than the number expected from the known number injected and the theoretical backscattering process. Such an estimate has not yet been made for the echoes observed in the Echo III experiment. These echoes appear to be as strong as "quick echoes" observed from mirror point reflections just below the rocket. One can say that a sizable fraction of the injected electrons keep their original energy and have been observed over as many as three bounce periods.

Despite the above we have obtained evidence of strong beam plasma effects on several occasions. A study has been made for the Echo II experiment of the motion of the injected electrons near the rocket and for times

Table 1. Conditions Realized During Reception of Echoes for the Echo III Experiment

Injected pulse energy spread	32—36.5 keV
Predicted bounce time (Olson-Pfitzer field model)	2.175—2.050 secs
Predicted gradient-curvature Drift velocity (Olson-Pfitzer-field model)	1.53—1.75 Km sec^{-1}
Observed bounce time	2.19—2.05 secs
ExB drift from radar	0.8 Km sec^{-1} west (approx)
Rocket horizontal velocity	0.85 Km sec^{-1} east

during the injection or within a short time thereafter. Phase map 1 shown in Fig. 10 summarizes this type of result. The response of an electrostatic analyzer type detector with energy response centered at 29,8 keV was sampled during the injection time. On Echo II injected pulses were 64 msec in duration so that the electron intensity near the rocket could reach equilibrium, even for the "quick echoes" from below the rocket as the "quick echo" time was less than 20 msec. For each data sample the magnetic pitch angle of the injected electrons and of the detected electrons was evaluated. These are designated α_I and α_D. The "inject" and "detect" pitch angles were of course not independent as the injector and detector were aimed 90° with respect to each other around the rocket spin axis. Nevertheless, during each rocket coning cycle a considerable range of relative values was covered resulting in the square field displayed in Fig. 10. The density of points in this phase map is not relevant but rather the intensity of the electron signal has been coded with dots as described in the figure caption. The pattern shows certain marked effects: quadrant 1 (inject up, detect moving up) shows mostly weak responses; the center (90°, 90°) region shows a cluster of strong responses often saturating the detectors; quadrant 2 (inject down, detect moving up) shows many strong responses for $\alpha_I < 75°$; quadrants 3 and 4 show weak or moderate responses except for a group of strong responses in quadrant 4 around $30 < \alpha_D < 60$, (inject up, detect moving down).

We associate strong responses in the central region of the phase maps with a halo of scattered electrons produced when the gun beam impacts the rocket after a very few Larmor turns. The detectors are usually saturated in this region. We associate the strong responses in quadrant 2 with a scattering halo produced by the atmosphere below the rocket, when α_I falls below 90°, and the beam may impact the atmosphere and backscatter into the detectors. The detectors will respond provided $\alpha_D > 90°$. The strong responses in quadrant 4 occur for *upward* injection ($\alpha_I > 90°$) by both the

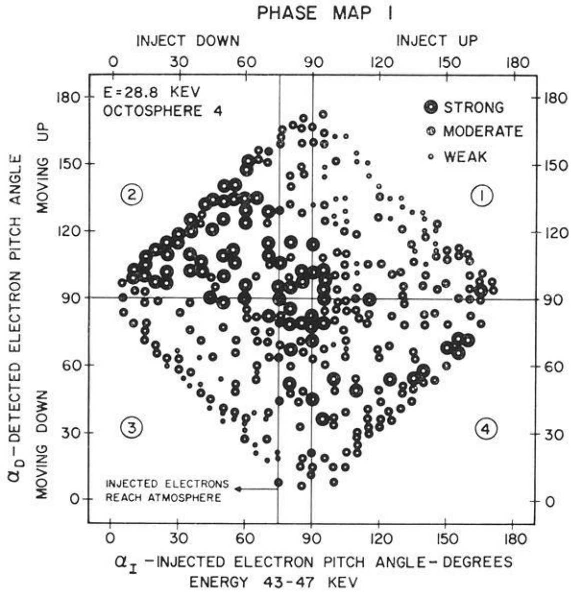

Fig. 10. Phase map in which detected pitch angle is plotted as a function of injection pitch angle for the artificial pulses of the Echo II experiment. The vertical line at $\alpha_I = 75°$ represents the loss cone boundary at a rocket altitude of 250 Km. See text for further details

octospheres and another type (a solid state detector) and may be very intense. We know of no physical explanation for such strong scattering *above* the rocket other than some form of strong beam instability accompanied by *E*-fields in the beam.

The detector responses for all these classes of events have the common property of showing a degradation of the original injection energy. This is consistent with an analysis which shows that without some form of scattering it is impossible to map the injection guiding centers onto that of the detector. An energy spectrum typical of both the unusual responses from upward injections as well as for the better understood responses from downward injections is shown in Fig. 11. The spectrum has the appearance of arising from a narrow energy width beam injection at the known energy of 40 keV followed by degraded collision straggling to produce a broad spectrum with maximum near 30 keV. No evidence is found for electrons with energy higher than the original injected energy and the spectrum falls to background close to the known beam energy. A more detailed discussion of these results is given in Winckler *et al.* (1974).

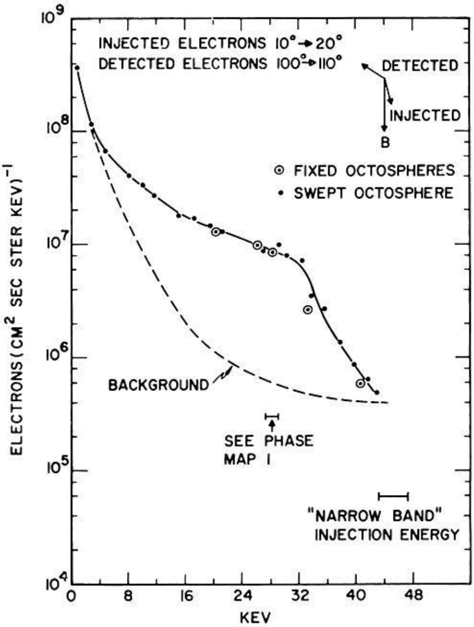

Fig. 11. The energy spectrum of the scattered electrons shown in Fig. 10. The intensity relative to background has a broad maximum at about 25 keV, and negligible intensity above injection energy shown by the horizontal bar (lower right). This spectrum also applied to the unusual pulses scattered from above in Quadrant 4 of Phase map 1 (Fig. 10)

Cartwright and Kellogg (1974) by utilizing a sweep frequency electric wave receiver in the detached rocket nose cone have measured a variety of emissions during injection pulses. Strong emission occurs at the local plasma frequency as shown in Fig. 12 by the series of intensifications tracing out a double maximum near 6 mHz. This trace accurately follows the independently measured plasma frequency at the rocket during its ascent and descent. The double peak represents 2 passes through the F-region maximum. A similar emission but more intense was observed during The Echo II experiment again on the detached rocket nose cone in the ionosphere. These emissions were not observed at ground level. A curious time dependence of the plasma wave emission occurs during injection as shown in the next Fig. 13, also from Cartwright and Kellogg (1974). There is a large intensification of emission near the beginning of the pulse followed by a low level for the last two-thirds of the pulse. (The Echo I pulses had a total duration of 16 msec). Winckler (1974) has discussed the relevance of these observations to the explanation of type III fast drift solar radio bursts. The mechanism producing the short leading edge

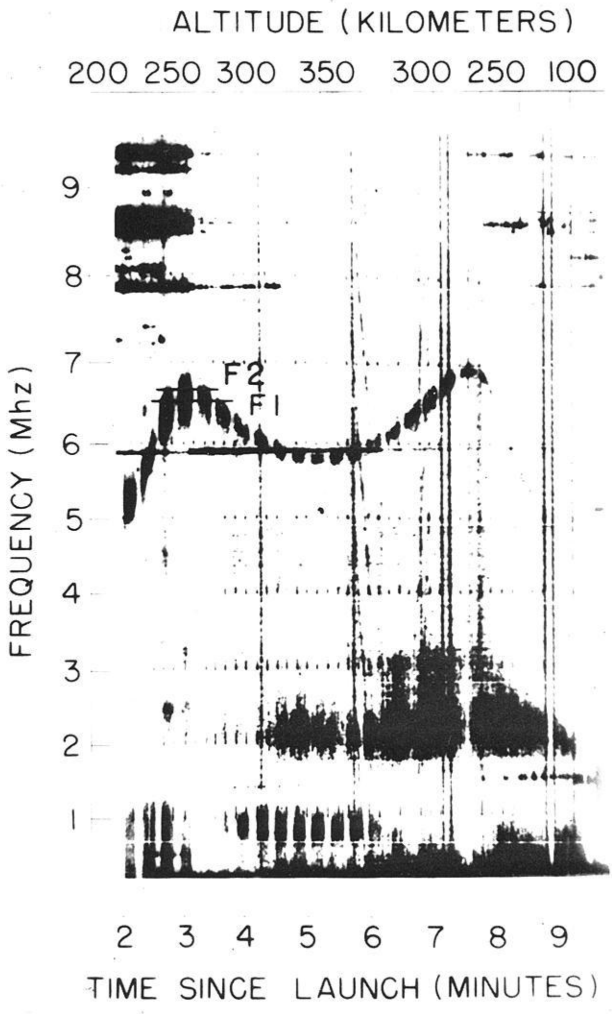

Fig. 12. Frequency spectrum of electric wave emission by the Echo I injections, measured in space about 1 Km above the injector rocket (from Cartwright and Kellogg, 1974)

intensification of the Echo I emission might also account for the short time duration of the type III bursts observed by Wild (see Wild and Smerd, 1972). Solar electron streams are known to be of long duration and thus the short type III radio bursts have been a puzzle. It is relevant to the present discussion that hard solar X-ray bursts are sometimes associated with type III radio emission, implying that the solar electron streams create

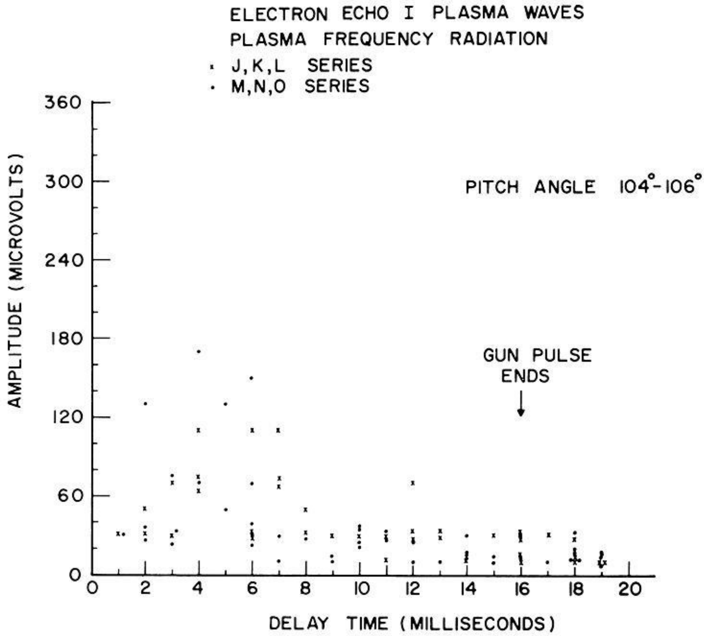

Fig. 13. Time-intensity profile of electric wave plasma frequency emission during the 16 msec duration pulse injected by Echo I. Measured as in Fig. 12

Bremsstrahlung in the solar atmosphere in a manner analogous to terrestrial auroral X-ray production. The electric wave plasma frequency emission observed during beam injection implies that the beam has to a certain degree striated longitudinally under the action of a beam plasma instability which creates periodic electric fields and density variations. On the Echo III experiment we have carried out an experiment to search for such density fluctuations during beam injection. A scintillation counter-photo-multiplier detector system designated PM-4 was equipped with a fast plastic scintillation crystal and was aimed downward at a 45° angle to detect injected electrons moving upward past the rocket after mirroring below ("quick echoes"). The photomultiplier output was equipped with 3 filter channels spanning the plasma frequency range expected for the auroral zone *F*-region. These filters could detect as little as a few per cent component. of periodic count rate variation in the otherwise white noise background of the photomultiplier output. A schematic is shown in Fig. 14 and a sample result for a quick echo as well as one of the Echo III conjugate echoes in Fig. 15. The result of the experiment is so far negative. No significant density variations in the detected electrons from the echo beam have been

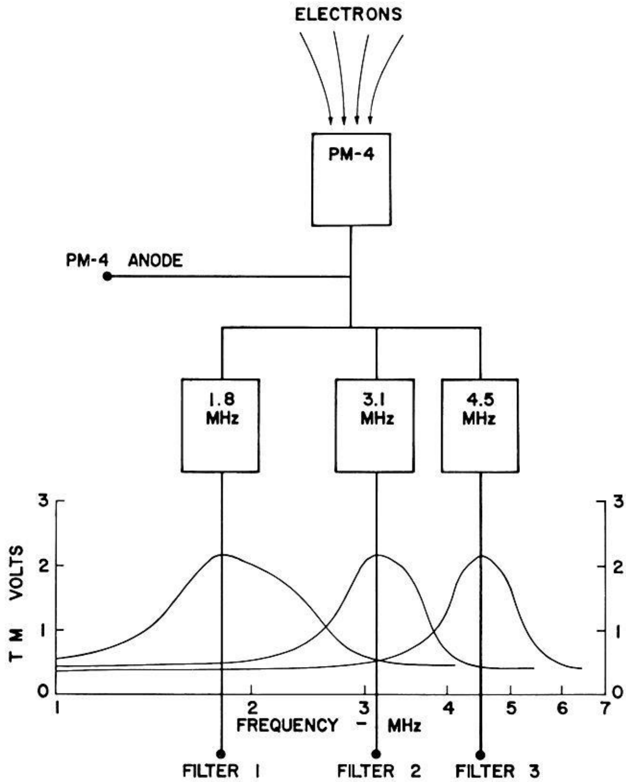

Fig. 14. Schematic of an experiment to search for plasma-frequency components in the count rate of a fast scintillation counter on the Echo III experiment. The frequency response of the three filters is correctly shown in the lower section, with the vertical index lines at filter maximum response. The TM volt scale is very compressed

found as the three filters show essentially the same amplitude for all the injections and echoes studied. However, the measurement was rather crude primarily because quick echoes may only be detected through some scattering process, such as impact on the rocket body. Such scattering may reduce the amplitude of the expected signal. In future experiments, it will be necessary to place the detector directly in the injected beam to study the longitudinal beam-plasma instabilities.

The Echo II experiment carried a large-area proportional counter directed downwards to search for X-ray emission caused by the Echo beams striking the atmosphere. So far no such effect has been identified, although the measurements were hampered by noise. During the rocket

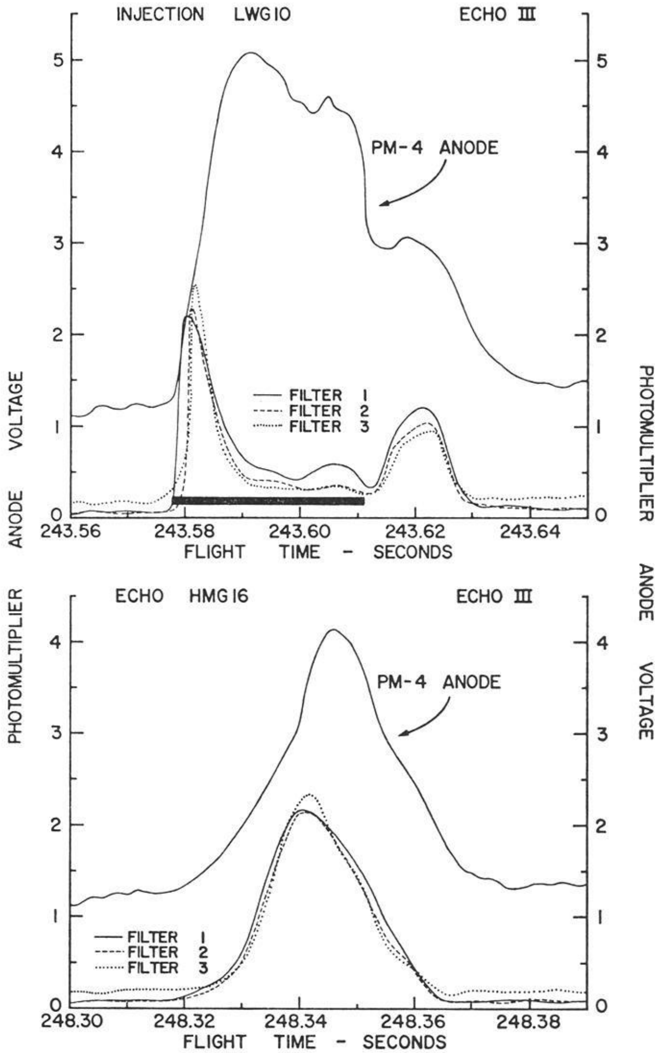

Fig. 15. Plasma-frequency filter response during a 32. msec long injection (upper) and during one of the conjugate echoes (lower). Within rather small fluctuations the three filters respond equally. This response is attributable to white noise, with no evidence for selective response. The ionospheric plasma frequency at the rocket position at this time was about 3.5 mHz

flight (at Churchill) a weak x-ray "glow" was detected coming from the southern horizon, possibly from weak electron precipitation. This is described in Arnoldy *et al.* (1974).

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