NOTICE

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ABSTRACT

Models of auroral processes have been advanced in which the ionosphere plays an active role in stimulating auroral particle precipitation. The validity of these suggestions can be investigated by releasing an artificial plasma cloud into the ionosphere and studying the effects. To this end, the sounding rocket experiment Trigger, comprising a diagnostic and a chemical release payload, was conducted.

As a consequence of the release, a drastic increase of the field aligned charged particle flux was observed over the approximate energy range 10 eV to more than 300 keV, starting about 150 ms after the release and lasting about one second. There is also evidence of a second particle burst, starting one second after the release and lasting for tens of seconds. In addition, there is evidence for a periodic train of particle bursts occurring with a 7.7 second period from 40 to 130 seconds after the release. A transient electric field pulse of 200 mv/m appeared just before the particle flux increase started. Electrostatic wave emissions around 2 kHz, as well as a delayed perturbation of the E-region below the plasma cloud were also observed.

Some of the particle observations are interpreted in terms of field aligned electrostatic acceleration a few hundred kilometers above the injected plasma cloud. It is suggested that the accelerating electric field was created by an instability driven by field aligned currents originating in the plasma cloud.

This paper gives an overview of the experiment design and the general results. Particular observations and their interpretation are discussed in more detail in companion papers.

INTRODUCTION

The classical view of the auroral ionosphere is that of a passive screen displaying the result of processes taking place and being controlled far out in the magnetosphere. However, present knowledge of the complex dynamical structure of magnetospheric substorms indicates that a substorm is the result of a complicated interplay between the ionosphere and the magnetosphere. Until now, the theoretical understanding of auroral phenomena has neglected either the influence of the ionosphere or the characteristic effects of the magnetotail. *Goldstein* and *Schindler* (1978) have among others recently pointed at the desirability of investigating the stability properties of the entire ionosphere-magnetosphere system, although a unified theory is not within the reach of present theoretical methods.

So far, no detailed treatment of the role of the ionospheric conductivity in relation to large scale substorms has been presented. However, a few authors have discussed the importance of conductivity irregularities in connection with quiet small scale auroral structures (auroral arcs). *Boström* (1964) discussed the electric polarization field within an arc and external field aligned current systems associated with the auroral arc conductivity. In a number of papers (*Atkinson*, 1970; *Coroniti* and *Kennel*, 1972; *Sato* and *Holzer*, 1973; *Sato*, 1978 and *Mallinckrodt* and *Carlson*, 1978) models are discussed in which the lower ionosphere actively participates in the formation of quiet auroral arcs. The essential features of such theories are as follows: Assume that there is an auroral arc consisting of a local plasma density enhancement with a large extent in the east-west direction and a small extent in the north-south direction. A westward component of a convection electric field drives a westward Pedersen current and a northward Hall current within the arc. Due to the variation of the conductivity in the north-south direction, there is a divergence of the Hall current. This divergence of Hall current will result in either magnetic field aligned currents or a polarization within the arc or both. The primary creation of one or the other of these phenomena depends on the ability of the magnetic flux tube to carry a sufficient amount of current (*Boström*, 1964).

The created field aligned currents are assumed to close in the magnetosphere via polarization currents across the magnetic flux tube. The currents can thus be maintained only if they are varying in time. Note, however, that the time variation need not occur in the reference frame of the auroral arc, but only in the reference frame of the plasma in the region of the polarization currents. If these field aligned currents exceed the threshold for creation of current driven plasma instabilities along the flux tube, charged particles might be accelerated towards the arc. Hence, one has a feedback mechanism capable of increasing the ionization of the original auroral arc and thus strengthening the field aligned currents.

The role of the E-region in the formation of auroral irregularities, such as auroral arcs, cannot be verified by means of traditional diagnostic sounding rocket or satellite experiments, since it would be difficult to distinguish between cause and effect. However, by releasing a plasma cloud, one can artificially introduce a horizontal current divergence, and study the perturbations caused by the plasma injection, knowing what the primary disturbance is.

Increased auroral particle precipitaion has been observed in connection with a few barium release experiments designed for electric field measurements. *Kelley et al.* (1974) have reported observations of different types of waves and increased fluxes of energetic particles in association with small ionospheric barium releases at high latitudes. *Wescott* (1976) and *Wilhelm* (1978) have reported indications that shaped charge barium releases may have triggered auroral particle precipitation. Indirect evidence of auroral modifications associated with barium releases are given by *Stoffregen* (1970) and *Deehr* and *Romick* (1977) who observed enhanced auroral optical emissions in connection with chemical releases in the ionosphere. Hence, it appears possible to modify the auroral particle precipitation by means of artificial plasma releases as proposed above. However, the above related observations were not foreseen by the experimenters. Therefore the collected information about the modifications is incomplete and in some cases uncertain. We will report here the results of an experiment, Trigger, fully dedicated to observations of perturbations associated with a cesium plasma release in the ionosphere.

EXPERIMENT DESIGN

In previous barium release experiments where unforeseen "trigger effects" were observed (*Kelley et al.*, 1974), the barium canisters were ejected in directions perpendicular to the rocket spin axis, in random spin phases, on the trajectory upleg. Hence, the relative positions of the canister and the payload at the time of the release, were not known. The fact that a "trigger effect" was observed on some occasions and not on others, was interpreted in terms of a magnetic field line connection between the barium cloud and the instrumented payload in the cases where perturbations were observed and an absence of connection in cases where no perturbations were seen.

In the Trigger experiment it was thus essential to establish a field line connection between the Cs-injection and the instrumented payload. That was achieved by taking advantage of the geometrical situation at Esrange (68.1°N, 21.0°E), the sounding rocket facility near Kiruna, Sweden. For a rocket launched in the magnetic meridian

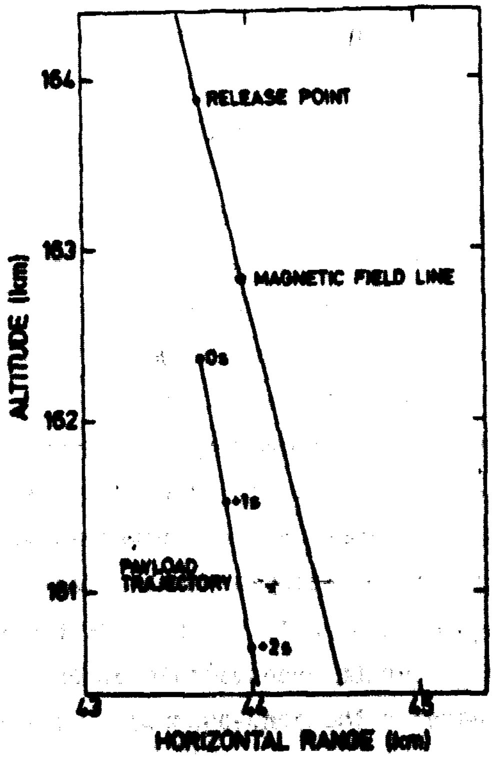


Figure 1. Positions of the release point, the intersecting magnetic field line and the payload shortly after the explosion, in the plane of the magnetic field.

with a 200 km apogee and 60 km range to impact, a considerable part of the downleg trajectory is closely parallel to the geomagnetic field lines. The chemical package was accomodated in a separable module mounted on the top of an instrumented payload. On the upleg, the upper module was separated forward by means of a spring mechanism at a relative velocity of 5.5 m/s.

The ejected payload was thus given a slightly higher trajectory than the mother payload. At the approximate altitude of 164 km on the downleg, the Cs^+-cloud was released. The instrumented payload was at that time situated below the Cs^+-cloud within the magnetic flux tube through the cloud as shown in Figure 1.

The chemical payload

Traditionally, chemical releases in the ionosphere have been used to measure neutral winds and electric fields. In the latter case barium is the most commonly used material. For electric field measurements, it is essential to introduce a disturbance as small as possible, that is the ratio of the height-integrated conductivities inside and outside the ion cloud, should be as close to unity as possible. In our experiment, however, the efforts should be the opposite. We were not primarily interested in tracing the ions, but desired to create as large conductivity gradients as possible. In order to meet the requirements of creating a large disturbance within a limited volume and avoiding a dependence on sunlight, thermal ionization of cesium by means of explosives was employed (*Rosenberg* and *Golomb*, 1963). In the Trigger (S21/3) experiment, described here, approximately 12 kg of a TNT-Al0-$CsNO_3$ mixture was explosively released at 164 km altitude, giving an estimated conductivity increase of more than two orders of magnitude above the undisturbed conductivity. In such an artificial ion cloud, the height integrated conductivity would be significantly enhanced compared to the undisturbed value, although typical auroral arc conditions would probably not be reached. Note, however, that the most relevant parameters are the horizontal conductivity gradients and the dynamics of the cloud expansion, not the conductivity itself. Since the volume of the Cs^+-cloud will be quite small (scale size of a few kilometers), large conductivity gradients will be achieved during the initial expansion phase and a while thereafter.

The height of the release, 164 km, was chosen well above the E-region, in order to make it possible to perform radio and optical observations of expected secondary effects in the E-region below the ion cloud, and in order to facilitate wave propagation upwards.

In addition, at 164 km altitude, the cesium ion gyro frequency approximately equals the ion-neutral collision frequency. As a consequence of that, the specific conductivity (conductivity per electron-ion pair) assumes its highest value, a fact which is favourable for the experiment.

The instrumented payload

The time of the detonation of the explosive cesium mixture was very accurately determined by detecting the flash with an optical sensor at the top of the payload. The time resolution was 4.88 μs as determined by the bit rate of the PCM telemetry system.

The charged particle experiment comprised two different types of detectors. Five low energy detectors consisting of curved plate electrostatic analyzers and channeltrons designed to measure electrons and positive ions with energies in the range 10 eV - 15 keV and four intermediate energy particle detectors consisting of solid-state detectors for detection of electrons and positive ions with energies greater than 40 keV. Viewing directions were 0°, 90° and 150° relative to the rocket spin axis. One of the channeltron detectors was semi-logarithmically swept up and down in energy with a sweep time of approximately 0.35 s. The basic sampling time for all detector channels was about 3.1 ms. The charged particle experiment is described in more detail in a companion paper (*Lundin* and *Holmgren*, 1979).

The quasi-static electric field was measured by means of a double probe experiment. Two pairs of booms, 3 m tip to tip, were used. The sampling time was 3.1 ms.

The wave experiment consisted of measurements of wave associated electric fields, using the same probes as in the quasi-static electric field experiment, and measurements of the relative plasma density fluctuations $\delta n_e/n_e$ made with a fixed-bias spherical probe mounted on a 50 cm radial boom. The simultaneous measurement of the wave associated electric field and the plasma density wave component made possible a distinction between electromagnetic and electrostatic waves. Together with electron temperature measurements the experiment also yields information on the real part of the dispersion relation for electrostatic waves (*Kelley* and *Mozer*, 1972).

The plasma density was measured by operating one of the E-field probes in Langmuir mode every 6.4 second during the flight, except during an interval of about 40 seconds around the time of the plasma injection. Between the Langmuir sweeps the plasma density was given by the DC-component of the fixed-bias $\delta n_e/n_e$-probe current. The relative ion density was given by a plane circular ion collecting surface at the top of the payload.

The electron temperature profile was deduced from the Langmuir sweeps. However, it was important to have at least a qualitative measure of the electron temperature associated with the expansion of the plasma cloud ([illegible] *al.*, 1979). In order to meet the requirement of high time resolution electron temperature measurements, an instrument specially devoted to temperature measurements was included in the payload. The instrument is based on the idea of continuously measuring the slope (di/dv) in the transition region of the Langmuir curve. Thus, the instrument was not capable of telling whether the plasma had really a single Maxwellian distribution, but it gave qualitative information about rapid changes in electron temperature.

Bremsstrahlung X-ray measurements

A companion rocket experiment was conducted as part of the Trigger experiment. A Super Arcas rocket carried an X-ray detector to an apogee of 80 km at which point the payload was ejected and descended by parachute. The trajectory of this vehicle placed the payload at a horizontal range of 16 km from the 100 km footpoint of the explosion field line and at an altitude of 62 km (~ 0.175 g cm^{-2}) when the explosion occurred. X-rays > 5 keV were measured with a NaI scintillation counter with a geometric factor of 10.4 cm^{2}sr. A complete account of the X-ray measurements appears in an accompanying paper (*Bering et al.*, 1979).

Ground based experiments

If high energy particles within an appropriate flux and energy range were precipitated, they should give rise to optical emissions from the E-region altitude. Therefore, a ten channel photometer, looking torwards the E-region footpoint, was set up at Esrange. The pointing direction for each of the different channels was slightly divergent. In each direction the 427.8 nm and 557.7 nm auroral emissions were recorded. The angle of view for each channel was 3^o giving a typical observed surface with 2.6 km radius at the 100 km level. Also the wavelengths 630.0 nm and 486.1 nm were monitored by single channels. Furthermore, a wavelength-sweeping spectrophotometer was employed. In order to obtain good time reference all photometer data were recorded on the same magnetic tape as the rocket data via a pulse code modulation system, with a time resolution of 30 ms.

Two low light TV-systems were employed to record the auroral situation. One was situated at the launch site and the other one near the magnetic footpoint through the ion cloud.

A Doppler-sounding system was set up for the Trigger experiments. The doppler sounding experiment consisted of three radio transmitters distributed along the Kiruna-Abisko railroad line west of the rocket range. They transmitted CW signals in the frequency range 1.5 - 2.0 MHz. The three signals were received at a single point east of the range, situated so that the reflexion points in the E-layer fell close to the magnetic footpoint through the released ion cloud. Both phase and amplitude of the three received signals were recorded (*Jones* and *Spracklen*, 1978).

In order to detect triggered VLF-emissions, VLF goniometer stations were operated in northern Norway and Finland (*Rycroft*, 1978).

EXPERIMENTAL RESULTS

Launch conditions

The S21/3 (Trigger) Nike Tomahawk vehicle was launched 11 February 1977 at 2049 UT from Esrange and the Super Arcas vehicle was launched at relative time + 100 s.

The geomagnetic situation was calm and had been so for more than three hours before launch as shown in the magnetogram of Figure 2. There was no visual aurora overhead, but there were stable arcs on the northern horizon, and some magnetic activity in the north. About one hour after the launch a magnetic substorm appeared at Esrange.

Cloud deployment

The mother-daughter separation occurred on the upleg, as planned, and the detonation took place on the downleg at the approximate altitude of 164 km, as shown in Figure 1. The time of the explosion, according to the flash indicator, was $t_{rel} = 314.15336$ s or 2054:19.15 UT.

From theoretical cloud models and the current measured by the positively biased electron probe, we can derive a simple model of the plasma cloud which was created. Immediately after the explosion, the internal pressure will cause the cloud to rapidly expand until its pressure has been reduced to the pressure of the ambient atmosphere. After the forced initial expansion, the cloud expansion will be dominated by ambipolar diffusion. [illegible] (1963) has estimated the radius of such

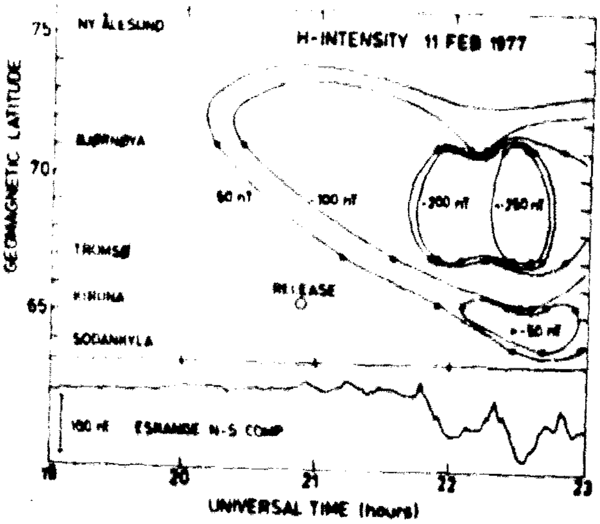


Figure 2. The magnetic disturbance situation at the time of the Trigger experiment.

a cloud after the initial expansion by calculating the work done against the atmosphere during the expansion. Following his calculation, we derive a radius of 1200 m for the 12 kg load at 165 km altitude. Furthermore, Groves analysis predicts, for our case, that the cloud reaches its maximum radius 0.6 seconds after the explosion. After that follows an oscillatory adjustment to equilibrium whereafter the ambipolar diffusion dominates the expansion.

According to *Rosenberg* and *Golomb* (1963), a total of 430 moles or $2.5 \cdot 10^{26}$ gaseous molecules are liberated from 18 kg of the kind of mixture used in this experiment. Accordingly it may be assumed that $1.7 \cdot 10^{26}$ molecules would be liberated from our 12 kg mixture. Radar reflexions from ion clouds have indicated that the degree of ionization is 10^{-4} when the initial expansion is completed (*Rosenberg* and *Golomb*, 1963). We therefore expected a total electron content in the cloud in the order of 10^{22} electrons.

After the initial expansion, when ambipolar diffusion is dominating, a Gaussian plasma density distribution probably gives an appropriate description of the cloud (*Rao et al.*, 1973). Since we will only consider the first few seconds after the explosion, we use a spherical model, whereas later an ellipsoidal model with its major axis along the field lines would give a better description. We thus assume a plasma density distribution

$$n(r) = n_0 \exp(-r^2/R_0^2) \qquad (1)$$

where n_0 is the plasma density in the cloud centre and R_0 is the scale size of the cloud.

At 164 km altitude, the ion-neutral collision frequency is on the order of 40 Hz. Therefore the centre of mass of the ion cloud should stop well within 0.1 s. We will assume that the cloud centre was situated at the estimated point of explosion. In the Trigger experiment, the electron probe current showed clearly that the ion cloud expanded past the payload, situated more than 1500 m away from the explosion point. Referring to the above discussion we consider the current variation after 2 s as basically a spatial variation of the plasma cloud density. Figure 3 shows an attempt to fit a spherical Gaussian plasma density distribution to the measured density. Such a procedure yields a peak plasma density of $3.1 \cdot 10^{12}$ m^{-3}, a total electron content of $1.4 \cdot 10^{23}$ and a scale size of 2000 m. The derived values are higher than expected. However,

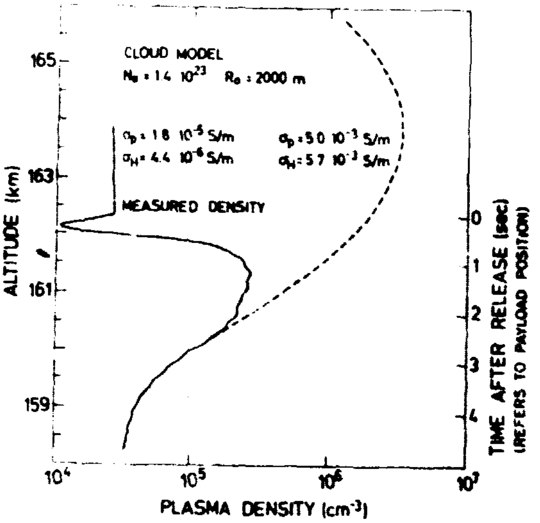


Figure 3. The measured plasma density perturbation (smoothed curve) associated with the plasma release. The broken line shows a Gaussian model of the cloud.

considering the uncertainties of the theoretical models, especially the rate of ionization, we adopt the above experimental values for the following discussion.

It is essential to estimate the conductivities inside the ion cloud. However, in order to calculate the Hall and Pedersen conductivities one needs the ion-neutral collision frequency. According to Banks, (1966), at low temperatures the most important ion-neutral interaction arises from an induced dipole attraction, which is independent of the chemical nature of a given ion and depends only upon the atomic polarizability of the neutral gas. For temperatures greater than 300 K the induced dipole force of attraction is countered by a short range quantum mechanical repusion. The repulsive force is linked directly to the details of the ion and neutral orbital electron structure. Thus, variations in cross section are to be expected for different ions in the same neutral gas at elevated temperatures. Banks further states that, since there exist virtually no data for either collision frequencies or cross sections at high temperatures, the study of ion-neutral collisions must be based on the assumption that the polarization force is the dominant process.

Considering the uncertainties involved in a theoretical estimate of the collision frequency and the lack of knowledge of the exact composition of the ion and the neutral atmosphere in the cloud, we cannot find any better approximation than using values representative for the ambient ionosphere. According to *Holway* (1965) the ion-neutral collision frequency $\nu_{in} \approx 40\ s^{-1}$ at 164 km height. (For Cs^+ in a N_2 background the polarization process yields $\nu_{in} \approx 19\ s^{-1}$).

For the peak plasma density $n = 3.1 \cdot 10^{12} m^{-3}$, we obtain the Pedersen conductivity, $\sigma_P = 5.0 \cdot 10^{-3}$ S/m and the Hall conductivity $\sigma_H = 5.7 \cdot 10^{-3}$ S/m. The conductivities inside the cloud were thus more than two orders of magnitudes higher than the background conductivities $\sigma_P = 1.3 \cdot 10^{-5}$ S/m and $\sigma_H = 4.4 \cdot 10^{-6}$ S/m. The height integrated conductivities through the cloud centre become $\Sigma_P = 18$ S and $\Sigma_H = 20$ S for the Pedersen and Hall conductivities respectively.

The first evidence of plasma density perturbations were seen at the mother payload at relative time, $t_{rel} = 314.212$ s, that is 58.6 ms after the explosion. 58.6 ms is an unreasonably short time to transport mass some 1500 m between the explosion point and the instrumented mother payload. However, the small time delay can be understood in terms of "frozen in field lines" during the cloud expansion, and a subsequent Alfvén wave travelling along the field lines from the cloud to the plasma density probe, as illustrated in Figure 4, and discussed in more detail by *Kelley et al.* (1979).

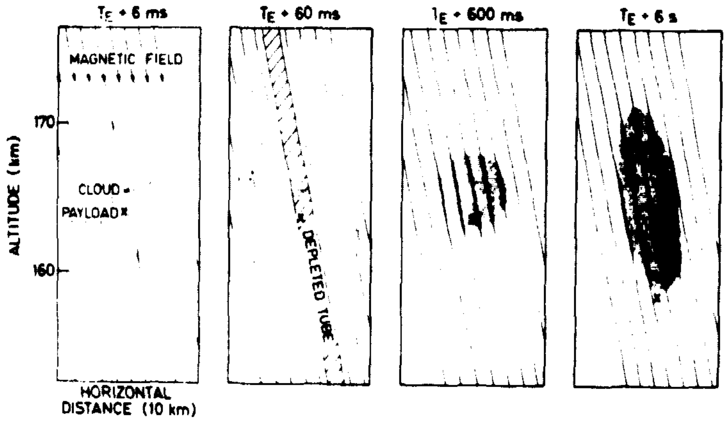
The initially observed plasma density perturbation could be associated with such a "field line displacement" with an associated displacement of the background ionospheric plasma. The relevance of such a mechanism can be tested by considering the time it would take for the ambient magnetic field to diffuse into the expanding overdense plasma cloud. A rough estimate of the time constant, τ, for such a diffusion is given by

$$\tau = \mu_0 \sigma_C L^2 \qquad (2)$$

where L is the scale length of the spatial variation of the magnetic field, μ_0 is the permeability of vacuum and σ_C is the Cowling conductivity.

$$\sigma_C = \sigma_P + \sigma_H^2/\sigma_P \qquad (3)$$

For our purpose we put L equal to the scale size of the cloud, $L = R_0 = 2000$ m and $\sigma_C = 1.1 \times 10^{-2}$ S/m. We thus derive a time constant $\tau = 58$ ms, which is not smaller than the observed delay and hence consistent with the proposed mechanism. The above time constant has been calculated for the situation ($t = 0.6$ s). However, assuming a constant electron content in the cloud, the time constant is inversely proportional to the cloud size. Hence, earlier in the expansion phase the time constant should be greater than 58 ms, and the "field line displacement" is even more efficient than our calculation indicates.



THE MAGNETIC PERTURBATION HAS NOT YET REACHED THE PAYLOAD

THE MAGNETIC AND IONOSPHERIC PLASMA PERTURBATION REACHES THE PAYLOAD

THE CESIUM PLASMA CLOUD HAS REACHED THE PAYLOAD AND THE FIELD HAS DIFFUSED BACK INTO THE CLOUD

THE PAYLOAD HAS DROPPED OUT OF THE CLOUD AMBIPOLAR DIFFUSION DOMINATES CLOUD EXPANSION

Figure 4. The cloud deployment sequence.

The distance between the mother payload and the field line through the cloud is about 350 m (Fig 1). Assuming that the cloud expands with the detonation velocity, about 7000 m/s, the perturbation should reach the field line through the mother payload after 50 ms. We thus have good agreement with the observed delay of 58 ms, since the vertical propagation time would be less than 2 ms.

Particle observations

Since the payload was launched under calm auroral conditions, the particle flux was very low and structureless during most of the flight. The fluxes in the 2 keV channels were generally less than 10^5 particles cm^{-2} sec^{-1} sr^{-1} keV^{-1}. However, in connection with the Cs^+-release a most remarkable increase in the charged particle fluxes occurred as shown in Figure 5. Figure 5 displays only the 2 keV particle countrates. However, we observed increased particle fluxes over the whole measured energy range 0.01 to 300 keV, although the increase was not as pronounced for all energies as for the 2 keV particles. A remarkable feature of the particle bursts at 314 s, associated with the cesium release, is that no increased fluxes were observed near 90^0 pitch angles, while both upward and downward field aligned particles showed several orders of magnitude increases. The slightly enhanced countrate on the 2 keV positive ion detector, shown in Figure 5, was probably due to an increased electron background caused by the very intense electron fluxes.

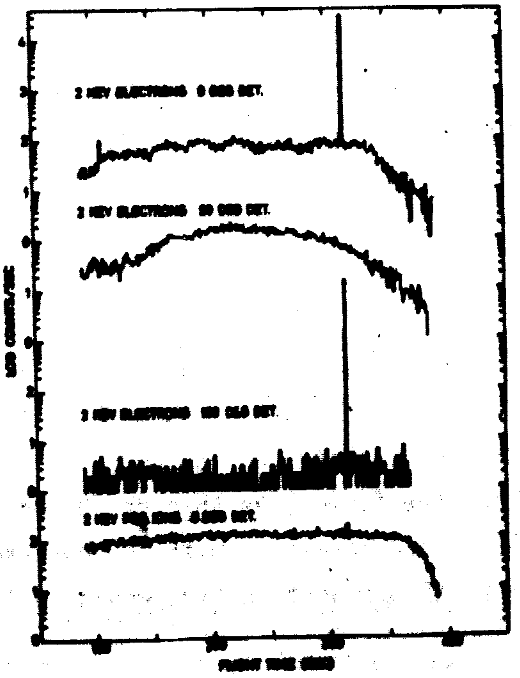


Figure 5. 2 keV particle measurements of the Trigger experiment.

Some details of the particle burst are shown in Figure 6 and can be summarized as follows: Approximately 150 ms after the explosion, the downward and upward directed field aligned 2 keV electron flux increased by more than two orders of magnitude for about half a second. It should be emphasized, however, that we did not see any increase of the perpendicular flux. The 2 keV particle burst thus can be described as two oppositely directed field aligned beams of electrons.

In comparing the upward and downward fluxes, we note that the backscattering ratio is very high compared to that prior to the burst. Actually, the very high backscattering ratio sometimes observed in the burst at 2 keV suggests that only about half of the downward energy flux at that energy was deposited in the lower ionosphere. As an example of the high energy particle bursts the > 40 keV countrates are shown in Figure 6 for the downcoming electrons. The initial peak is due to saturation related to the light flash of the cesium release and should be disregarded. The high energy (> 40 keV) particle

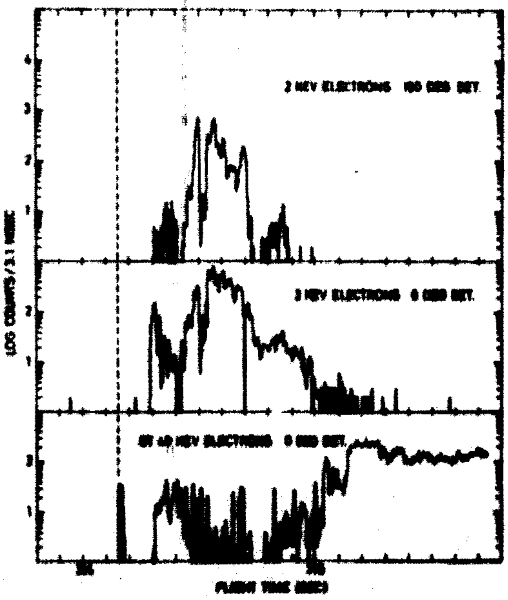


Figure 6. The particle burst immediately after the plasma injection of the Trigger experiment.

burst appeared at approximately the same time as the low energy burst, but decreased at the time when the 2 keV electrons reached maximum. About one second after the release, the high energy countrates increased again, and the increased flux prevailed for the rest of the flight. The solid state detectors (>40 keV particles) did not show any significant increase of the upward going particles, but a slight increase of the flux near 90 degrees pitch angle, thus indicating a more isotropic pitch angle distribution than the 2 keV particle fluxes.

The short duration and dynamic nature of the event makes it impossible to deduce any detailed pitch angle information and energy distribution. However, by assuming a flat pitch angle distribution in the range 0 to 45 degrees with negligible fluxes at higher angles, and using the measured energy spectrum during the burst, *Lundin* and *Holmgren* (1979) obtain 11 erg $cm^{-2}sec^{-1}$ as an upper limit of the downward energy flux during the burst. The corresponding current density would be about $1\mu A/m^2$.

In comparing the three curves of Figure 6, we note that there is a strong resemblence between the upward and downward 2 keV fluxes, while very little detailed correspondence can be seen between the low energy (2 keV) and high energy (>40 keV) electron fluxes. A noteworthy feature of the 2 keV flux is the quasiperiodic modulation with a frequency of about 25 Hz in the peak region, most apparent on the 0^o detector, a feature which is discussed more by *Lundin* and *Holmgren* (1979) and in the discussion section.

A widespread beam of high energy electrons with the observed energy flux would produce Bremsstrahlung X-rays observable by the payload located at 62 km altitude below the explosion. Since no such X-rays were observed at the time of the plasma release we conclude that the increased prompt particle flux was limited to a very narrow flux tube. As shown by *Bering et al.* (1979), the flux tube radius was limited to $\lesssim 3$ km, *i.e.* comparable to the cloud dimensions. Also, the absence of detectable optical or VLF emissions support the concept of a narrow flux tube.

In addition to the directly observed particle fluxes, shown in Figures 5 and 6, there is indirect evidence of particle precipitation in the time period 40 to 130 seconds after the release given by the Bremsstrahlung measurements. The X-ray payload observed a periodic train of X-ray pulses occurring every 7.7 seconds during that interval (*Bering et al.*, 1979).

Electric field observations

The electric field measured prior to the plasma injection never exceeded 10 mV/m, and was typically a few mV/m during most of the flight. However, following the cesium injection, a pronounced, temporary increase of the electric field appeared. Figure 7 shows a detailed plot of the amplitude variation during a short time after the explosion. Approximately 40 ms after the explosion the field amplitude suddenly increased, continued to increase in an oscillatory manner, and reached a pronounced peak of almost 200 mV/m about 140 ms after the explosion. Three more oscillations occurred during the decrease of the field after the large pulse at the same time that the first flux of energetic particles arrived. The oscillations before and after the large pulse seemed to be of different character. They all had approximately the same period, but the last three oscillations seemed to be circularly polarized, while the first seven oscillations were more linearly polarized. The rapid arrival of the electric field pulse precludes waves propagating at the acoustic speed. Thus the propagation mode must be electromagnetic or hydromagnetic. As discussed in a companion paper (*Kelley et al.*, 1979), the generation of the pulse was probably associated with the rapid initial expansion of the neutral cloud in the presence of the earth's magnetic field.

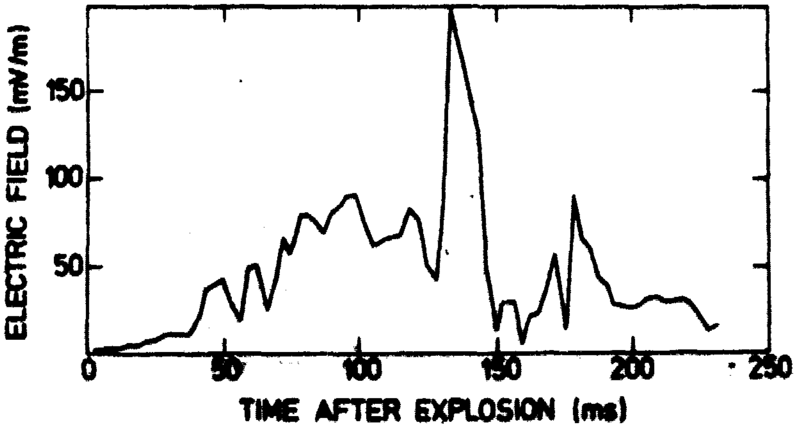


Figure 7. The electric field amplitude after the Trigger plasma injection.

Wave observations

A number of different wave phenomena were observed subsequent to the Trigger explosion. The electric-wave observations are summarized in the frequency-time sonogram presented in Figure 8. Black patches indicate high wave amplitudes in that particular frequency-time regime. Within twenty milliseconds after the release, a first burst of noise reached the payload. This noise burst lasted for about half a second.

About one second after the release a second burst of signal arrived which lasted for about two seconds. That emission was band limited between 1 kHz and 2 kHz and the electric field was spin modulated. The signal was also detected by the plasma density fluctuation experiment which showed a very similar spectral distribution as shown in Figure 9. Nulls in the E-field occurred when the antenna was perpendicular to the earth's magnetic field. Hence, it seems likely that the wave electric field was parallel to the ambient magnetic field. Thus the wave was electrostatic and, in this frequency regime, it must have propagated in

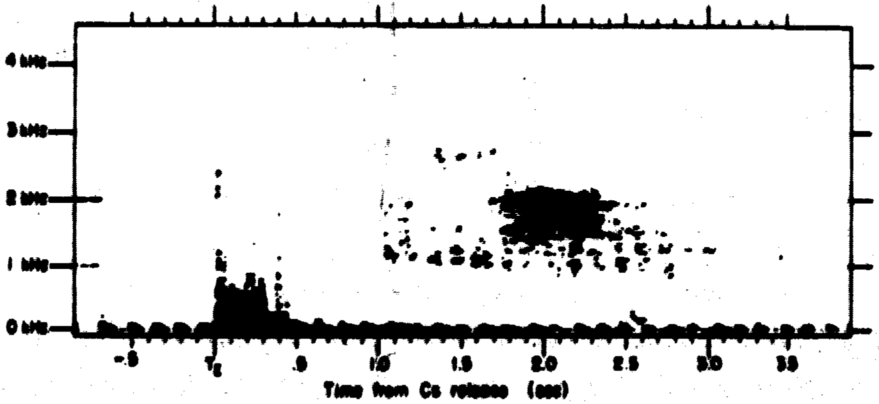


Figure 8. Electric wave observations after the Trigger plasma injection.

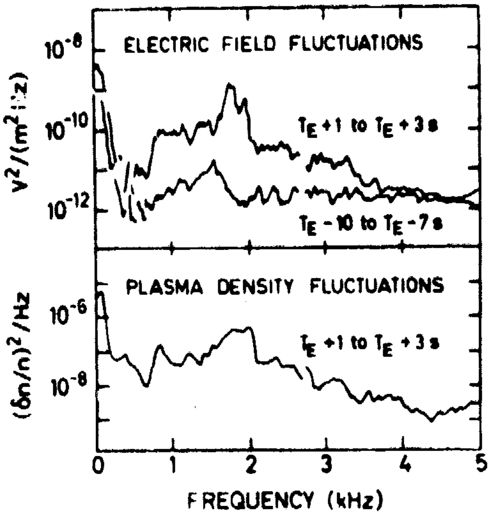


Figure 9. Wave spectra in association with the Trigger plasma injection.

an ion acoustic mode. The signal occurred while the cesium cloud was still surrounding the payload. Ion-ion streaming is suggested as a possible source for the waves, as discussed in more detail in a companion paper (*Kintner et al.*, 1979).

Ground based observations

A search for influence on the E-region below the released ion cloud was made by means of optical and radio methods as described in a previous paragraph.

No evidence of increased optical auroral emissions from the E-region footpoint was found with photometers or TV-systems. Nor were any VLF-signals detected, which could be related to the artificial plasma injection (*Rycroft*, 1978).

Theoretical estimates, based on the particle energy spectrum during the immediate particle burst (*Lundin* and *Holmgren*, 1979) yields an expected light emission between 0.1 and 1 kR at the wavelength 427.8 nm. The absence of such observations can be understood if the emission region did not subtend the whole solid angle of the photometer aperture. Hence, we take this as another indication that the event was limited to a flux tube smaller than 3 km in radius.

Some remarkable delayed effects in the E-region did show up on one of the Doppler sounding radio receivers however. Beginning 202 seconds after the release, the signal received from one of the three transmitters suddenly increased by 25 dB. The high signal level persisted for 95 seconds when there was a sudden return to the undisturbed level. A phase disturbance began some 20 seconds before the amplitude enhancement and there was a marked increase in the rate of phase advance of 6 wavelengths per second. No phase or amplitude disturbances were observed on the other two propagation paths further away from the footpoint of the cloud. This suggests that the disturbance was limited in extent and did not move a sufficient distance to produce effects on the other paths. An explanation of these observations in terms of an image cloud formed in the E-region below the released plasma cloud has been proposed by Jones and Spracklen (1978).

Event summary

Figure 10 summarizes, on a logarithmic time scale, the temporal relation between the events related to the plasma release. It shows that most of the observed effects started within 150 ms after the explosion and were of rather short duration. We also have indications of a long lasting (>10 s) high energy particle effect and a delayed (40-130 s) pulsed high energy electron precipitation effect. The 2 kHz electrostatic waves were observed inside the plasma cloud, after the initial rapid expansion of the cloud, when the ambient atmosphere was streaming back into the plasma cloud. The E-region disturbance detected by the Doppler sounding experiment, started well after the payload had returned to the ground.

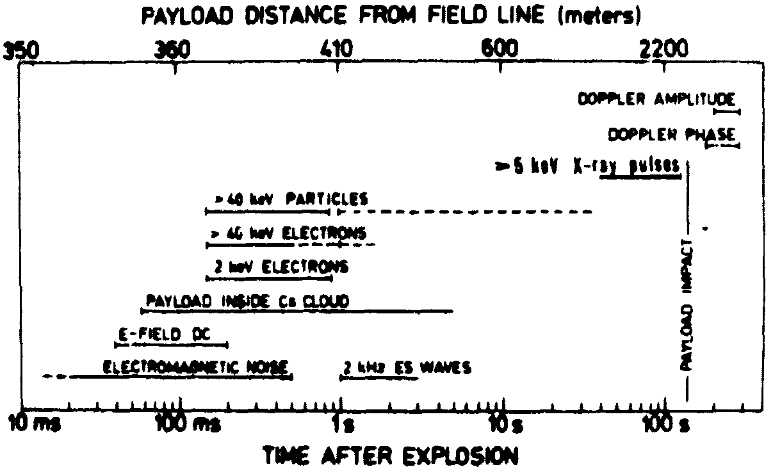


Figure 10. Trigger event summary.

DISCUSSION

A large number of phenomena appeared in association with the cesium release in the Trigger-experiment. Here we concentrate on phenomena pertinent to a possible artificial triggering of auroral particle precipitation or a local acceleration of particles. The observation of an electric field pulse is extensively discussed by *Kelley et al.* (1979). Wave phenomena with no obvious relation to the observed particle precipitation are discussed in a separate paper by *Kintner et al.* (1979). Delayed effects occurring in the E-region footpoint, observed by the Doppler sounding experiment are discussed by *Jones* and *Spracklen* (1978), and the X-ray Bremsstrahlung results are discussed by *Bering et al.*(1979).

Most of the immediate effects measured by the Trigger payload were made inside or close to the cesium cloud. In addition to normal experimental considerations, our measurements therefore have to be carefully examined with respect to instrumental malfunctions caused by the chemical release and it has to be considered whether our measured quantities were directly related only to the release as such or if they bear any information about the ionosphere-magnetosphere response to the release. Especially the particle measurements showed some peculiar behaviour. Since an understanding of them is essential, a separate paper (*Lundin* and *Holmgren*, 1979) is devoted to the interpretation of the particle measurements, and the conclusions are briefly related above.

Earlier related studies

A striking feature of the particle burst observed in the Trigger experiment is the high energies involved. However, this is not a unique feature of this particular experiment. *Köhn* and *Page* (1972) observed electron precipitation at energies above 15 keV in conjunction with a small isotropic barium release in the F-region above Esrange. About 200 ms after the ignition of a barium canister, the electron flux increased by a factor of about two and decreased to its former value with a time constant of approximately 5 s. These observations were made above the barium cloud. The pitch angle distribution changed from almost complete isotropy to anisotropy with higher intensities at greater pitch angles. That last feature appears to be contradictory to the Trigger results. However, *Köhn* and *Page* (1972) covered only the pitch angle range 45-90 degrees. The two results might therefore very well be consistent with each other, although we lack information about the field aligned flux in the experiment of Köhn and Page.

The only additional report of directly observed stimulated auroral particle flux in conjunction with chemical releases, that we know, comes from the Porcupine experiments (*Wilhelm*, 1978). Here the electron flux was field aligned during most of the flight except for 50 seconds after a barium shaped charge explosion. During that time the 1.7 keV electron flux shifted to a symmetric pitch angle distribution centered around 90 degrees.

Potential particle acceleration processes

First it should be established that the observed prompt high energy precipitation fluxes were the result of an acceleration process and not the result of pitch angle scattering. Two strong pieces of evidence point to this conclusion. The flux of precipitated ($\sim 0^0$ pitch angle) was much greater than the preexplosion $\sim 90^0$ pitch angle flux for all observed energies below 40 keV. There is no mechanism whereby scattering alone could account for this observation. Additional confirmation of the presence of an acceleration mechanism is provided by the fact that the flux of >40 keV electrons at $\sim 90^0$ pitch angle was enhanced after the explosion, as discussed above. This observation cannot be accounted for by pitch angle scattering. A third, weaker piece of evidence that the event was not a pitch angle scattering event is the absence of any explosion associated VLF-emissions.

Secondly it should be made clear that the observed prompt energetic particles were not directly accelerated by the explosion itself, but some secondary acceleration process had to be involved. From an energy point of view, the observed particle flux could have been energized by the released explosive energy. However, with the explosion temperature of 3500 K, only a negligible fraction of the electrons would have energies higher than 40 keV, assuming a Maxwellian electron velocity distribution. The ordered particle motion caused by the explosion is not expected to exceed 14000 m/s, which is twice the detonation velocity (*Michel*, 1974). A direct explosive energization of the charged particles should have resulted in, predominantly, radial or isotropic velocity distributions. Since, for example, 2 keV electrons have gyroradii of only 3 meters, they ought to have been detected on the perpendicular detectors, as well as on the parallel detectors. We thus conclude that some secondary nonisotropic acceleration process had to be involved in order to explain the appearance of the field-aligned high energy particles.

Events occurring in four different time regimes are of interest with regard to the particle acceleration mechanisms (c.f. Figure 10).
a) The immediate particle burst occurring in the time interval 150-900 ms, including energetic particles in the energy range of the instruments (0.01-300 keV).
b) A delayed particle precipitation, beginning one second after the explosion, consisting predominantly of high energy particles (>40 keV).
c) A delayed electron precipitation, beginning about 40 seconds after the explosion, consisting of periodic bursts of high energy electrons.
d) The much delayed effects that appeared in the E-region and were detected with the ground based Doppler sounding equipment (*Jones* and *Spracklen*, 1978). These effects were observed in the time interval 182-297 seconds after the explosion.

The most dramatic and indisputable effect of the plasma injection was the immediate particle burst (a). Let us, to begin with, focus on the <15 keV electrons, and especially on the 2 keV electrons. We have already concluded that the 2 keV particle burst consisted of two oppositely directed, field aligned beams of electrons, with fluxes more than two orders of magnitude higher than the background (see also *Lundin* and *Holmgren*, 1979). The two oppositely directed beams is a unique feature of this experiment, not observed in natural aurora. In fact, the very high "backscattering ratio", which increased towards higher pitch angles, appeared more like a reflexion than a normal atmospheric backscattering. This observation combined with the observation of the quasiperiodic modulation of the electron flux in the burst (Figure 6), has been used by *Lundin* and *Holmgren* (1979) to model the event in terms of a local trapping of the 2 keV electrons between two reflecting potential barriers in the ionosphere. The result using the 2 keV electron detectors for both 0^0 and 150^0 and also taking into account the accumulated time dispersion for several bounces versus pitch angle, gives an average altitude for the lower boundary of the upper potential drop of about 500 km. From the time dispersion for different pitch angles they estimate the altitude extent of the potential barriers to be on the average 32 km, corresponding to a uniform parallel electric field of approximately 60 mV/m. Thus, the particle measurements indicate potential barriers both below and above the plasma cloud, although we expect the critical current density to be exceeded only above the cloud. Note that if the model is relevant, it offers an alternative explanation why no optical emissions were observed, namely that the particles were reflected above the E-region.

The concept of a sudden parallel acceleration, within a few hundred km, above the plasma cloud is supported by the almost simultaneous increase of the flux detected by all the upward directed particle detectors, regardless of the energy passband. An estimate of the "source" altitude, using the 0^o, 2 keV and the 0^o, energy sweeping electron detectors has been made by [illegible] and *Holmgren* (1979). They derived a source altitude in the altitude region 350-850 km, with the higher value corresponding to a case with constant velocity from the height of acceleration, and the smaller value corresponding to a case with uniform acceleration from the source altitude.

In most cases when field aligned particle fluxes have been observed in natural aurora, the field alignment is explained in terms of acceleration by field aligned electrostatic fields, for example electrostatic double layers (*Block*, 1972) or anomalous resistivity (*Papadopoulos*, 1977), both of which can be created by field aligned electric currents. We will therefore consider the ability of the plasma cloud to create field aligned currents of densities high enough to exceed the threshold for current driven plasma instabilities. There are at least two different mechanisms that are capable of creating field aligned currents. We will call them "the expanding cloud mechanism" and "the conductivity gradient mechanism" respectively.

The expanding cloud mechanism can be understood as follows. As the TNT-Cs mixture detonates, an overpressure develops, which forces the vaporized cloud to expand. The expanding cloud thus constitutes a neutral wind, $\underline{v}_n$, with a component perpendicular to the geomagnetic field $\underline{B}$. Such a wind causes electric currents, $\underline{J}$, to flow as given by the expression

$$\underline{J} = \sigma_P \cdot (\underline{v}_n \times \underline{B}) + \sigma_H \underline{B} \times (\underline{v}_n \times \underline{B})/B \qquad (4)$$

Since the cesium plasma density and hence the conductivity inside the cloud is much higher than outside the cloud at the same height, the component of current in the radial direction cannot be carried in the background medium in the direction perpendicular to the magnetic field. The current is therefore reduced by the creation of a polarization field within the cloud, and a part of the current is closed in the magnetosphere or the lower ionosphere via field aligned currents. This model is treated in detail in one of the companion papers (*Kelley et al.*, 1979). They conclude that it is possible to reach many hundreds of microamperes per square meter in parallel current densities. Furthermore, the polarization field could very well explain the observed electric field pulse mentioned above. In some of the theories for acceleration of auroral electrons via field aligned electrostatic fields, a critical relationship between the current density and the ambient plasma density is found. A common critical value predicted for the differential, electron-ion, drift velocity is in the order of the electron thermal speed. With the parallel current density estimated by *Kelley et al.* (1979) the upward current density corresponds to 30% of the thermal velocity and the downward current is well above the thermal speed within several hundred kilometers above the explosion point. The typical altitude range is roughly 500-800 km altitude depending on the ambient electron temperature. That altitude range is much below the altitude, of more than 3000-5000 km, where natural auroral particle acceleration is thought to take place. However, one should keep in mind that we are here talking about current densities that are perhaps about two orders of magnitude greater than natural field aligned current densities in connection with auroral arcs, and the acceleration is activated by a current pulse from below. Then the instability starts as soon as the pulse reaches an altitude where the given high current density first exceeds the threshold for an instability.

For the other way of producing field aligned currents by releasing a plasma cloud, the conductivity gradient mechanism, the energy source of the parallel current is not the cloud itself, as in the expanding cloud mechanism, but a large scale external perpendicular electric field. In this case, the cloud deployment acts as the connection of a load impedance over the transmission line represented by the magnetic flux tube through the ion cloud. In other words, parallel currents are created above and below the cloud by discharging the magnetic flux tube. The magnitude of the parallel current density depends on the external large scale perpendicular electric field and the magnitude of the height integrated Hall and Pedersen conductivity gradients in the plasma cloud. A numerical estimate shows that even with the very weak external electric field of the Trigger experiment, it is not unreasonable to reach current densities of 10 $\mu A/m^2$ during the initial expansion of the plasma cloud. Of course, the associated polarization field cannot exceed the magnitude of the external field, that is a few millivolts per meter.

In both the expanding cloud mechanism and the conductivity gradient mechanism, the disturbance introduced will propagate with the Alfvén velocity as a current pulse along the magnetic flux tube. Both mechanisms are capable of producing current densities comparable to those observed in connection with natural auroral arcs, and that are expected to be able to drive instabilities in the topside ionosphere (*Kindel* and *Kennel*, 1971). However, due to the weakness of the external electric field, the expanding cloud mechanism is more powerful in this particular experiment. Kindel and Kennel showed that in an ionosphere consisting of pure O^+, current densities as strong as those of the expanding cloud model can drive the plasma unstable to ion cyclotron waves down to an altitude of a few hundred kilometers. For the comparatively weak currents of the conductivity gradient model, the corresponding unstable region would fall at a few thousand kilometers altitude. It is apparent that, with our atmosphere model, the current pulse could not have reached higher than a few hundred kilometers before the first high energy particles appeared. It is therefore unlikely that the first particle burst was associated with such an instability in the topside ionosphere due to the conductivity gradient mechanism. However, we also observed high energy (>40 keV) particles arriving later than a second after the explosion. They could, with respect to the time delay, be associated with an interaction between the current pulse and the plasma at an altitude of a few thousand kilometers. To the extent that the delayed precipitation event involved precipitation of electrons, the X-ray Bremsstrahlung results are consistent with the continued confinement of the precipitation to the cloud flux tube (*Bering et al.*, 1979). With present knowledge of auroral particle acceleration mechanisms, the extremely high energies of the particles cannot be understood, however, especially since the expected voltage across the plasma cloud was only on the order of 500 volts.

The long duration of the delayed particle effect is consistent with the conductivity gradient model, since, after the initial forced cloud expansion, the conductivity gradient decrease is determined by the slow ambipolar diffusion across the field lines. The expanding cloud mechanism, on the other hand, is effective only during the initial cloud expansion ($t \leq 0.6$ s).

In the third period of interest, 40 to 130 seconds, periodic X-ray pulses were observed. These pulses cannot be directly attributed to repeated bounces of initially injected particles because 7.7 seconds corresponds to the bounce period of 1.5 keV particles which are too low in energy to have produced the observed X-rays. The most likely source of the particles is a periodic pitch angle scattering of trapped electrons. This pitch angle scattering is produced by VLF whistler mode waves which have been generated by the 1.5 keV electron pulse from the release via a combination of electron cyclotron and bounce resonances. This relatively complex model is discussed in more detail in a companion paper (*Bering et al.*, 1979).

A fourth period of interest is 180-300 seconds after the explosion when the E-region effects were observed. *Jones* and *Spracklen* (1978) have proposed a possible explanation of the effect in terms of an image cloud below the plasma cloud, and a local transport of thermal particles between the F- and E-regions. However, it cannot be excluded that high energy particles originating in the magnetosphere were involved in that effect. Assuming that electrons or protons in the keV energy range were the active particles, and that they were accelerated as the result of an interaction between the current pulse and the magnetospheric plasma, then with regard to the Alfvén velocity the interaction might have taken place within 15000 km from the equatorial plane. In this context it should be noted that the X-ray Bremsstrahlung experiment observed an unexpectedly high level of 10-20 keV photon flux starting about 60 seconds after the explosion which continued for about 10 minutes thereafter.

SUMMARY AND CONCLUSIONS

By releasing a cesium plasma cloud at F-region height above Esrange, it has been confirmed that it is possible to artificially stimulate auroral particle precipitation. Contrary to previous similar experiments, the Trigger experiment was performed during calm auroral conditions, and with a different release technique, namely thermally ionized cesium, which gives a sudden ionization, instead of barium thermite or shaped charge releases, which result in a more gradual ionization.

The stimulated particles were measured within the flux tube of the ion cloud, and it was shown that the increased particle flux most likely was limited to this narrow flux tube.

Four independent observations indicate that the initially observed electrons, in the energy range 50 eV to more than 300 keV, were accelerated in the approximate altitude range 350-850 km.

a) It is consistent with the altitude an Alfvén wave would reach within the time between the explosion and the arrival of the particles.

b) It is consistent with the dispersion in time of arrival of the intermediate energy electrons (*Lundin* and *Holmgren*, 1979).

c) It is consistent with the concept of a local trapping of the 2 keV electrons (*Lundin* and *Holmgren*, 1979).

d) It is consistent with the altitude where critical current densities are reached using the estimated current densities deduced by *Kelley et al* (1979).

No definite theory for the event is presented, but it is suggested that the low energy acceleration was due to parallel electric fields, created by field aligned currents set up by the plasma injection. Pitch angle scattering in the deep magnetosphere may account for particle precipitation continuing for as long as 130 seconds after the release.

It remains to be explained how particles could be accelerated to the very high energies that were observed, a problem which has to be solved also with regard to natural auroral particle acceleration.

A very early plasma density perturbation observed about one kilometer away from the cloud center, has been interpreted in terms of magnetic field and associated ionospheric plasma perturbation caused by the forced expansion of the ion cloud.

Other effects of the plasma injection, not discussed in detail here, are generation of ion acoustic waves during the cloud expansion (*Kintner et al.*, 1979), and delayed disturbances in the E-region below the plasma cloud (*Jones* and *Spracklen*, 1978).

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REFERENCES

Atkinson, G., Auroral Arcs: Result of the Interaction of a Dynamic Magnetosphere with the Ionosphere, *J.Geophys.Res.*,*77*, 4746, 1970.

Banks, P., Collision Frequences and Energy Transfer, *Planet Space Sci.*, *14*, 1105, 1966.

Bering, E.A., E.G. Stansbery, W.R. Sheldon, J.L. Roeder and J.R. Benbrook, The Results from the X-ray Bremsstrahlung Experiment of Project Trigger, submitted for publication in *J. Geophys. Res.*, 1979.

Block, L.P., Potential double layers in the ionosphere, *Cosmic Electrodynamics*, *3*, 349, 1972.

Boström, R., A model of the auroral electrojets, *J.Geophys.Res.*, *69*, 4983, 1964.

Coroniti, F.V. and C.F. Kennel, Polarization of the Auroral Electrojet, *J.Geophys.Res.*, *77*, 2835, 1972.

Deehr, C. and G. Romick, Pulsating aurora induced by upper atmospheric barium releases, *Nature*, *267*, 135, 1977.

Goldstein, H. and K. Schindler, On the role of the Ionosphere in Substorms: Generation of Field-Aligned Currents, *J.Geophys.Res.*, *83*, 2574, 1978.

Groves, G.V., Initial Expansion to Ambient Pressure of Chemical Explosive Releases in the Upper Atmosphere, *J.Geophys.Res.*, *68*, 3033, 1963.

Holway, L.H., Ambipolar diffusion in the geomagnetic field, *J.Geophys.Res.*, *70*, 3635, 1965.

Jones, T.B. and C.T. Spracklen, A search for E-region disturbances induced by ion cloud releases at F-region heights, *J.Atm.Terr.Phys.*, *40*, 409, 1978.

Kelley, M.C. and F.S. Mozer, A technique for making dispersion relation measurements of electrostatic waves, *J.Geophys.Res.*, *77*, 6523, 1972.

Kelley, M.C., A. Pedersen, U. Fahleson, D. Jones and D. Köhn, Active experiments stimulating waves and particle precipitation with small ionospheric barium releases, *J.Geophys.Res.*, *79*, 2859, 1974.

Kelley, M.C., U.V. Fahleson, G. Holmgren, R. Boström, P.M. Kintner and E. Kudeki, Generation and propagation of an electromagnetic pulse in the Trigger experiment and its possible role, submitted for publication in *J. Geophys. Res.*, 1979.

Kindel, J.M. and C.F. Kennel, Topside current instabilities, *J.Geophys.Res.*, *76*, 3055, 1971.

Kintner, P.M., M.C. Kelley and G. Holmgren, The observation and production of ion acoustic waves during the Trigger experiment, submitted for publication in *J. Geophys. Res.*, 1979.

Köhn, D. and D.E. Page, A possible connection between a barium cloud and electron intensity fluctuations observed on a rocket flight at Kiruna, *J.Geophys.Res.*, *71*, 4888, 1972.

Lundin, R. and G. Holmgren, Rocket observations of particle precipitation triggered by an ionized cesium-cloud release, submitted for publication in *J. Geophys. Res.*, 1979.

Mallinckrodt, A.J. and C.W. Carlsson, Relations between transverse electric fields and field-aligned currents, *J.Geophys.Res.*, *83*, 1426, 1978.

Michel, K.W., Fluorescent ion jets for studying the ionosphere and magnetosphere, *Acta Astronautica, Vol. 1*, p.37, 1974.

Papadopoulos, K., A Review of Anomalous Resistivity for the Ionosphere, *Rev.Geophys. and Space Phys.*, *15*, 113, 1977.

Rao, P.B., E.M. Allen and G.D. Thome, Ray tracing synthesis of HF radar signatures from Gaussian plasma clouds, *Radio Sci.*, *8*, 857, 1973.

Rosenberg, N.W. and D. Golomb, Generation and properties of high altitude chemical plasma clouds, *Progress in Astronautics and Aeronautics*, *12*, 395-408, Academic, New York, 1963.

Rycroft, M., Private communication, 1978.

Sato, T., A Theory of Quiet Auroral Arcs, *J.Geophys.Res.*, *83*, 1042, 1978.

Sato, T. and T.E. Holtzer, Quiet Auroral Arcs and Electrodynamic Coupling between the Ionosphere and the Magnetosphere, 1. *J.Geophys.Res.*, *78*, 7314, 1973.

Stoffregen, W., Electron density variation observed in the E-layer below an artificial barium cloud, *J.Atm.Terr.Phys.*, *32*, 171, 1970.

Wescott, E.M., Review of Barium Shaped Charge Plasma Injection Experiments, paper presented at the Symposium on Active Experiments in Space Plasmas, Boulder, Colo. June 3-5, 1976.

Wilhelm, K., Low-energy auroral particle observations, paper presented at European sounding rocket, balloon and related research, with emphasis on experiments at high latitudes, Ajaccio, Corsica, 24-29 April, 1978.