VOL. 78, NO. 25 JOURNAL OF GEOPHYSICAL RESEARCH SEPTEMBER 1, 1973

Balloon and VLF Whistler Measurements of Electric Fields, Equatorial Electron Density, and Precipitating Particles during a Barium Cloud Release in the Magnetosphere

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Two electric field and X-ray measuring balloons have been flown from Great Whale River, Canada, near the foot of the magnetic field line on which a barium cloud was released in the magnetosphere. VLF whistler techniques were used at Great Whale, at Roberval, Canada ($L \sim 4$), and at Byrd, Antarctica, to obtain information on magnetospheric electron density near the plasmapause and on equatorial electric fields within the plasmasphere at $L \sim 2.7$. Electric fields obtained from the balloon data agreed with those deduced from ground magnetometer records, and these two sets of data disagreed with those obtained from observations of the barium cloud motion and VLF whistlers. Because the independent ionospheric and equatorial measurements were internally consistent but disagreed with each other, these discrepancies may be due to effects of parallel electric fields or of perpendicular fields induced by changing magnetic fields. Alternatively, they may be due to spatial variations between the different measurement locations. No electric field variations attributable to the cloud were found. Electron density was found from whistlers to be 38 ± 16 el/cc at $L = 4.5$, which is characteristic of the low-density region beyond the plasmapause during quieting conditions when the electron density is in the process of slow (several-day) recovery to plasmasphere levels. Extrapolation of the measurements from $L \sim 4.5$ to $L \sim 6$ provides an estimate of $n_e = 16 \pm 7$ el/cc at the position of barium release. The ground station appeared to overtake a region of larger plasmasphere radius near ~0600 UT, or local midnight. This is interpreted as evidence of quieting that is accompanied by continued low-level convection activity, a condition consistent with the reported electric field measurements. The intensity of X rays measured on the balloon was unaffected by the barium release. The implication of this result on the possible precipitation of energetic particles by the barium release depends on the area over which the precipitation occurred, such that an assumed large-scale precipitation would be consistent with the X-ray data only if the precipitated flux was less than ~1% of the trapped flux, whereas precipitated fluxes as large as the trapped flux would be possible if they occurred over confined spatial regions. In view of the constancy of the trapped energetic particle fluxes measured on ATS 5, this latter possibility seems unlikely. That the release did not affect electric fields or trapped particles is consistent with expectations because of the low level of magnetic activity and the trapped particle fluxes on the night of interest.

Two balloons were flown from Great Whale River, Canada, on September 21, 1971, to measure X rays and ionospheric electric fields near the foot of the magnetic field line on which a barium cloud was released into the magnetosphere near 0305 UT. The smaller of the two balloons carried only an electric field detector, had a volume of 1650 cubic meters, was launched at 0000 UT, reached ceiling near 0130 UT, and floated at an altitude of about 26 km during the experiment. The larger balloon had a volume of 7,000 cubic meters, carried both an X-ray and an electric field detector, was launched at 0105 UT, reached a float altitude of 34 km about 1 hour after the cloud was released, and produced useful electric field and X-ray data after about 20 min. following cloud release.

A cooperating experiment was the measurement of broadband VLF at Great Whale, at Roberval, Canada ($L \sim 4$, 73° W), and at Byrd, Antarctica, conjugate to Great Whale. This report presents a description of the results on electric fields obtained by the balloon and VLF whistler techniques and relates these results to the magnetospheric barium release. Results on electron density from whistlers are also described, and the details of balloon X-ray observations are discussed. (The balloon measurements were associated with the University of California at Berkeley, the VLF work with Stanford University.)

Electric Field Measurements

In Figure 1, 30-sec averages of the balloon-measured, perpendicular, ionospheric, electric field components in a rotating geomagnetic frame of reference are presented for the 2 hours following the cloud release. Because one of the two ground receiving stations malfunctioned during the experiment, data were collected alternately at 5-min intervals from each balloon. The spread in the data from either balloon in Figure 1 is real and is due to temporal and spatial variations of the ionospheric electric field. The difference between the fields measured by the two balloons is also real and is due to horizontal spatial variations of the ionospheric electric field with scale sizes of less than 100 km [*Mozer*, 1972].

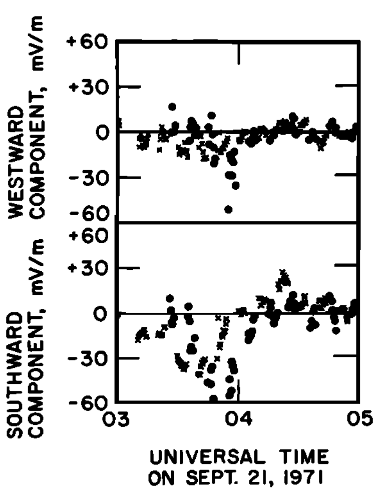

Fig. 1. Thirty-sec averages of the perpendicular components of the ionospheric electric field in a rotating, geomagnetic frame of reference, with the two different symbols representing data from the two balloons.

To compare the data of Figure 1 with electric field estimates from the barium cloud motion, ground magnetometer readings, and VLF whistler observations, the balloon measurements should be averaged over the ~30-min interval following the barium release, during which the average barium cloud motion was obtained. The average ionospheric field in a rotating system during this time interval was:

Eastward ionospheric component = 3.7 mv/m

Northward ionospheric component = 12.1 mv/m

These field components map to the equatorial plane, under the assumption that parallel electric fields are negligible, to give the following equatorial field strengths [*Mozer*, 1970]:

Eastward equatorial component = 0.28 mv/m

Radially outward equatorial component = 0.39 mv/m

The electric fields deduced from the barium cloud motion have somewhat larger magnitudes during the first 15 min following cloud release [*Rieger et al.*, 1972], have somewhat smaller magnitudes at later times [*Adamson et al.*, 1972], and point in the opposite direction to that deduced from the balloon data. Because of this discrepancy, it is important to consider other information on the electric field existing on the night of interest.

Ground magnetometer observations during the 30 min following cloud release showed positive H and negative Z deviations [*Boyd et al.*, 1972], which indicate that an eastward current was flowing to the south of Great Whale. Since a northward and/or eastward ionospheric electric field is required to drive eastward Hall and/or Pedersen currents, the magnetometer data are consistent with the direction of the electric field given by the balloon measurement.

The balloon electric field data may also be compared with equatorial electric field measurements near $L = 2.7$, obtained from VLF whistler measurements at Byrd, Antarctica. In Figure 2, 15-min averages of the balloon data are compared with whistler results that are filtered to remove fluctuations with $T < 20$ min [see *Carpenter et al.*, 1972]. The amplitude scales are adjusted such that the ionospheric field would map into the equatorial plane to give an equatorial field of the same amplitude in Figure 2 if $\nabla \times \mathbf{E}$ and the parallel electric field were zero [*Mozer*, 1972]. The two sets of data are in surprising agreement at all times other than during the hour following the barium release, at which times the direction and magnitude of the field at $L = 2.7$ was in good agreement with that deduced from the barium cloud motion.

The coverage in L of the VLF method depends on the prevailing distribution of whistler paths. In the present case, a single path near $L = 2.7$ and several paths near $L = 4$–4.5 exhibited whistler traces at various times. Only the activity at $L \sim 2.7$ appeared with sufficient frequency and definition for E-field measurements.

The percentage uncertainty in the balloon electric field data of Figure 2 is typically 10% to 20%. The VLF E-field results shown in Figure 2, particularly the detailed features, should be treated with some caution. An uncertainty of $\sim\pm 0.2$ mv/m is provisionally ascribed to the instantaneous values of the curve (error bar in Figure 2). The whistler data used in determining cross-L drift velocities were relatively faint, and there were certain problems in recognition of frequency-versus-time fine structure that could produce spurious effects of duration 10 to 15 min. In spite of these problems, the general trends of the data are believed to be real. The relatively good agreement following 0400 UT may reflect the deeper quieting that began near this time [*Boyd et al.*, 1972] and that may have involved an increase in the degree of homogeneity of magnetospheric electric fields.

In conclusion, the four estimates of electric fields on the night of the barium release show some consistencies and some discrepancies. This may be due to local spatial variations at the four different measurement locations because

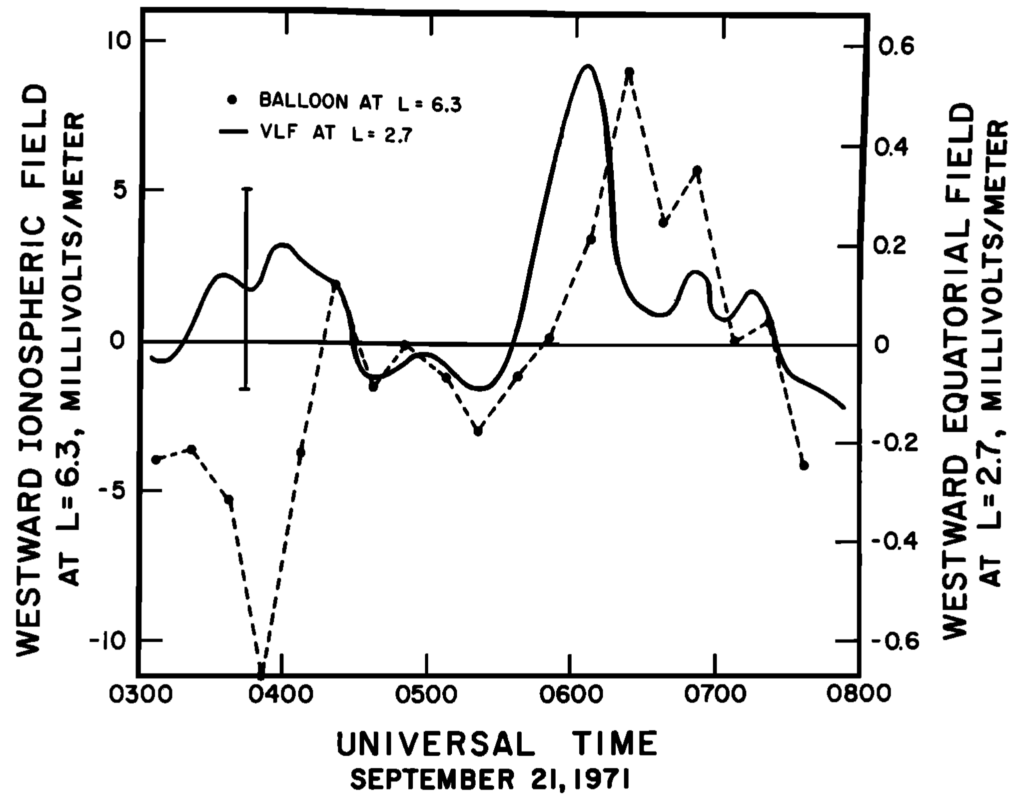

Fig. 2. Comparison of the 15-min averages of the balloon westward ionospheric field measurement with VLF whistler measurements representing the westward electric field at the equatorial plane at $L \sim 2.7$.

such small-scale turbulence is often present [*Mozer*, 1972]. It may also be significant that the two ionospheric measurements agreed with each other, as did the two equatorial measurements. The disagreements existing between the ionospheric and equatorial data could be due to the presence of parallel electric fields or to perpendicular electric fields induced near the equator by time-varying magnetic fields.

From experience gained through the flight of 58 electric field payloads on balloons, it is concluded that there is nothing unusual in the electric field data that might be related to the presence of the barium plasma. The most unusual aspect of the balloon data is the small size of the measured fields, the average values of which were the second smallest ever measured by balloons in the auroral zone. This fact attests to the low level of magnetic activity on the night of the release [*Boyd et al.*, 1972].

ELECTRON DENSITY MEASUREMENTS

During periods of relatively steady magnetic activity, the plasmasphere is roughly fixed in sun–earth coordinates, exhibiting an increase or bulge in radius on the duskside [*Carpenter*, 1966]. Under such conditions, the plasmapause radius in the 2200 LT sector is usually greater than in the 1600 LT sector, while at 2200 LT the electron concentrations beyond the plasmapause are smaller (at a given L value) than concentrations near 1600 LT. Both differences appear to reflect the role of magnetospheric convection (and other related processes) in determining the topology of the plasmasphere and in generally inhibiting rotation with the earth of plasma in the dusk sector [see *Axford*, 1969; *Carpenter*, 1970; *Chappell*, 1972; *Corcuff et al.*, 1972].

During periods of quieting, such as that beginning at ~2100 UT on September 20, 1971 [*Boyd et al.*, 1972], the plasma in the vicinity of the bulge is found to move in the direction of the earth's rotation [*Carpenter*, 1970]. A ground station, observing at ~1600 LT as quieting begins, may observe roughly the same plasmapause radius and concentration profile for the following several hours. The electron concentrations observed beyond the plasmapause at about 2200 LT will tend to be at afternoon-dayside levels, a factor of ~2 to 10 above those usually observed on the nightside under conditions of increasing or steady disturbance. This appears to have been the general situation on September 21, 1971, as determined from whistlers recorded at Byrd, Antarctica.

Figure 3 shows various sets of whistler results on equatorial electron density versus dipole L value. From these data, the electron density at the point of the barium release (or $L \sim 6$) is estimated to have been 16 ± 7 el/cc.

In Figure 3, reference data from a relatively quiet period, August 13 to 15, 1968, are shown (open circles) to indicate relatively high plasmasphere concentration levels [from *Carpenter and Chappell*, 1973]. Triangles show results from ~0340 to 0420 UT on September 21, about an hour following the barium release. Values for the filled symbols were obtained by assuming a diffusive-equilibrium model of the distribution of ionization along the earth's field lines. The open triangles are based on a 'collisionless' or $\sim R^{-4}$ model of the field line distribution [see *Angerami*, 1966; *Park*, 1970]. Since the actual field-line distribution was not known, the electron density is estimated to lie between the two levels; i.e., $n_e = 38 \pm 16$ el/cc at $L = 4.5$. The uncertainty range essentially reflects the uncertainty in the model. Such a 'hybrid' estimate may be partly justified by the combined presence of relatively high density levels, which would favor the diffusive-equilibrium condition, and continued low-level convection activity, which may help to establish a 'collisionless' regime. There is also limited evidence from the observed ratio of whistler upper cutoff frequency to whistler nose frequency (or frequency of minimum group delay) that a field-line distribution more rapidly varying than diffusive equilibrium was present (for a description of results on whistler upper cutoff frequency, see *Carpenter* [1968] and *Angerami* [1970]).

Since whistlers propagating beyond $L \sim 4.5$ were not detected, the electron concentration estimate of 16 ± 7 el/cc at $L = 6$ was obtained by drawing a curve with slope $n \propto R^{-4}$ through $n_e = 38$ at $L = 4.5$ (dashed curve in Figure 3). The slope R^{-4} has been found to be appropriate in a number of studies of the region beyond the plasmapause, and in particular in regions that are recovering to plasmasphere levels [*Chappell et al.*, 1971; *Angerami and Carpenter*, 1966].

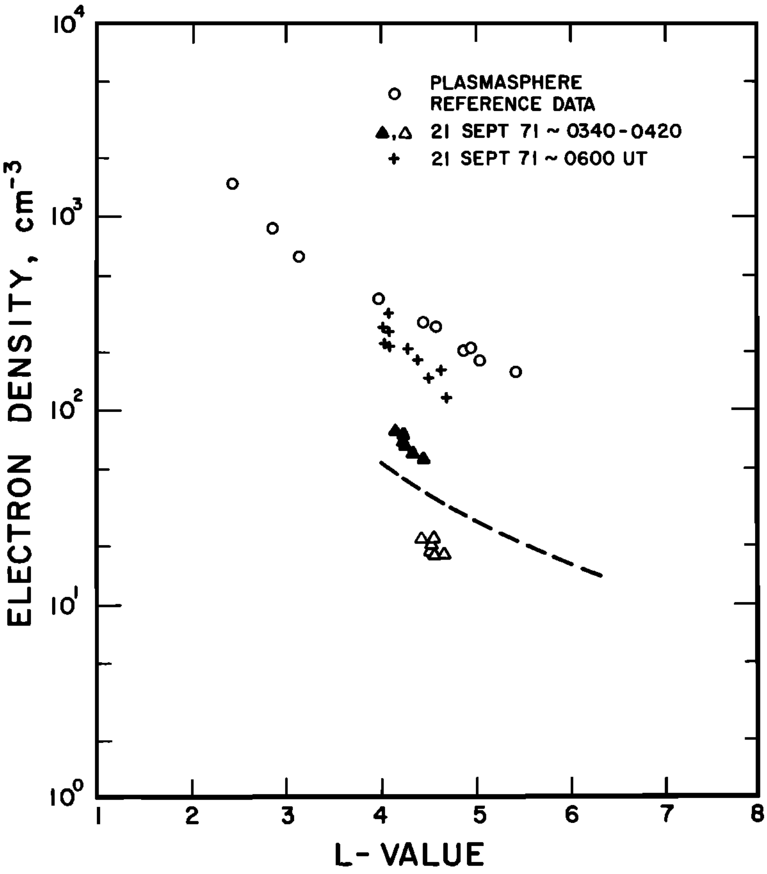

Fig. 3. Results from whistlers on equatorial electron density in the magnetosphere near the time of the barium release. The reference data represent a relatively quiet period August 13–15, 1968. The whistlers were recorded at Byrd, Antarctica.

The plasmapause was not precisely defined near 0400 UT, but it was clearly present somewhere between $L \sim 2.7$, where normal plasmasphere concentrations were observed (not shown in Figure 3), and $L = 4$–4.5, where the low, recovering concentrations of Figure 3 were found. A plasmapause radius $\lesssim 4\ R_E$ was also indicated by earlier data from the local afternoon sector.

Near local midnight at ~0600 UT on September 21, whistlers recorded at Byrd revealed a region of relatively high-density plasma near $L = 4.5$, as shown by crosses in Figure 3. This is tentatively identified as a region of larger plasmasphere radius that may have moved in the direction of the earth's rotation during the preceding period of quieting. The 'overtaken' region presumably did not move with the earth's angular velocity but was affected by the low-level convection activity that is implied by the E-field data of this paper. Thus the barium release took place within ~15° to 40° in longitude of some irregular plasmasphere structure, which may have extended to larger L values than are indicated by the limited whistler data.

X-Ray Measurements

The counting rate of X rays measured on the larger balloon is presented in Figure 4. The error bars of this figure represent statistical uncertainties only. The decrease of counting rate with time is due to the variation of the background atmospheric X-ray intensity with altitude. The balloon reached ceiling near 0410 UT, about 1 hour after the barium release, and

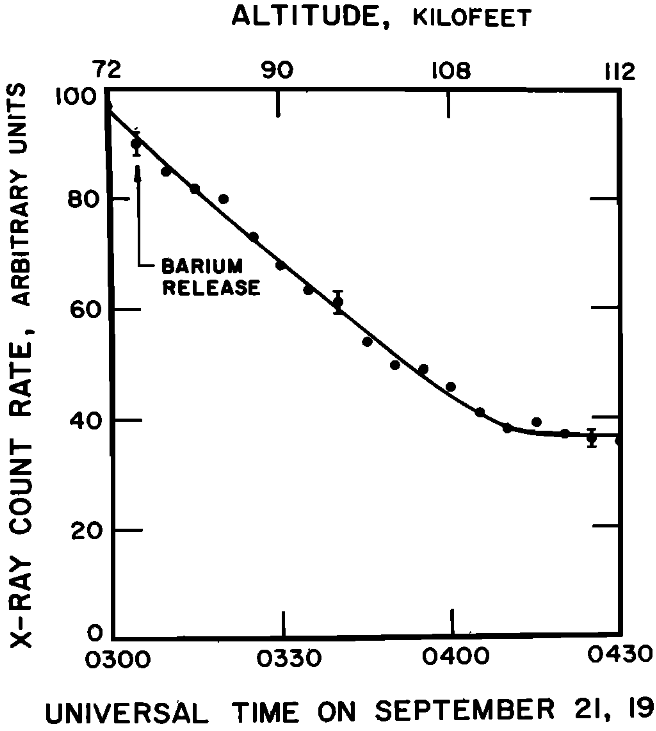

Fig. 4. Counting rate of the X-ray detector on an ascending balloon during the time interval following the barium release.

thereafter its altitude decreased slowly with time. Except for a slight increase in counting rate as the balloon altitude decreased, the counting rate remained constant within statistical errors during the 2 hours following the end of Figure 4. Thus, there is no evidence in the X-ray measurements of any natural or artificial precipitation of energetic electrons on the night of the release.

There are many theoretical [*Brice,* 1970; *Brice and Lucas,* 1971; *Young et al.,* 1971] and experimental [*Mozer and Bogott,* 1972] suggestions that artificial cold plasma deposition in the magnetosphere can trigger particle acceleration and precipitation. It is therefore necessary to interpret the negative results of the X-ray measurement in terms of limits on the flux of artificially precipitated particles. At the time of the barium release, the X-ray detector was near an altitude of 23 km. The atmospheric attenuation of X rays incident from above is given in Table 1, from which it is seen that the detector was insensitive to X rays from precipitating particles at the cloud release time. On the other hand, one might not expect artificial acceleration and precipitation of trapped electrons at the time of the release because the barium plasma interacts weakly with the trapped particles, as it is an expanding diamagnetic gas that excludes external magnetic fields and particles. After a few tens of minutes, portions of the cloud should have expanded sufficiently to allow entry of terrestrial magnetic field lines, and the triggered acceleration might then occur. At such times (for example, 0330, when the balloon was at 28 km, or 0410, when it was at 34 km; see Table 1), the balloon was

TABLE 1. Atmospheric Attenuation of X Rays at Various Altitudes

	Attenuation Factor at Various Altitudes, km		
Energy, kev	23	28	34
30	>100	~10	~3
40	~20	~3	~1.3
50	~3	~1.5	~1.2

sufficiently high to measure energetic X rays with nearly its full sensitivity. From such times until 0630 UT, there was no variation of the X-ray intensity within the statistical uncertainty of a few percent, except for that due to altitude variations of the sensor. Because of these altitude variations, one may only conclude that the X-ray counting rate associated with precipitating particles after about 0330 UT was less than about 20% of the background counting rate observed at float altitude. This limit allows deduction of the flux of precipitating particles under various assumptions on the size of the precipitation region. If the top of the atmosphere was uniformly illuminated by precipitating electrons over a spatial region greater than several hundred kilometers in extent, a 20% enhancement of the X-ray background would be produced by an ambient flux of ~2 · 10^5 electrons/cm^2 sec with energies above about 30 kev. If, on the other hand, the precipitation occurred over a confined spatial region, a larger incident electron flux would be required to produce a given response in the X-ray detector. For example, if particle acceleration and pitch angle diffusion were confined to a 100-km region near the cloud and if the precipitation occurred over the balloon, the flux of precipitating particles required to increase the X-ray background by 20% was ≈2 · 10^7 electrons/cm^2 sec. If the precipitation did not occur over the balloon, the atmospheric attenuation would have been larger and the required flux would have been even greater.

The above estimates may be compared with the fluxes of trapped equatorial particles by use of the energetic particle data obtained on ATS 5 [*Bogott and Mozer,* 1971] and presented in Figure 5. The observed equatorial flux of 40-kev electrons at the time of the barium release was 3 · 10^4 electrons/cm^2 sec ster kev. If we assume an isotropic angular distribution and an exponential energy spectrum with an *e*-folding energy of 20 kev, the trapped flux of electrons with energies above ~30 kev was ~10^7 electrons/cm^2 sec. Thus, the ratio of precipitated to trapped particles was measured by the X-ray detector to be less than ~1%, if

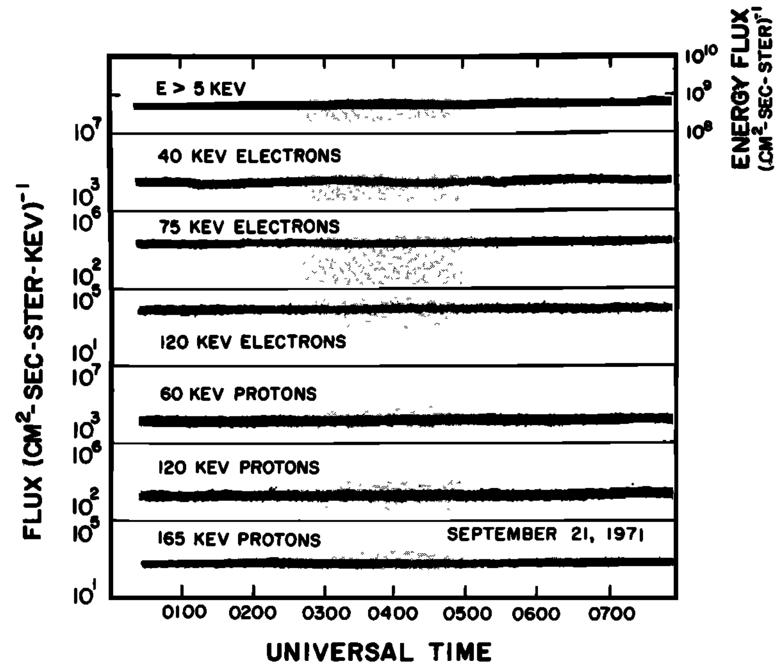

Fig. 5. Energetic particle fluxes measured on the synchronous orbiting satellite ATS 5 on the night of a magnetospheric barium cloud release on approximately the same *L* shell and 25° east of the satellite position.

the precipitation occurred uniformly over the upper hemisphere. If acceleration or pitch angle diffusion was confined to an ~100-km spatial region near the cloud, the precipitated flux could have been equal to or larger than the trapped flux.

This latter possibility seems unlikely in view of the fact that the ATS-5 fluxes of Figure 5 were essentially constant through the night of interest. ATS 5 was located on approximately the same L shell as the explosion and was about 25° east of the release position. The longitudinal drift of the energetic electrons or protons of Figure 5 from the explosion region to the satellite took less than a few hours. Because no flux changes were observed on this time scale, it is probable that the explosion did not substantially alter the trapped particle intensities. Likewise, the X-ray data indicate that no major, large-scale enhancement of precipitation occurred.

The effect of these negative results on concepts of artificial stimulation of the magnetospheric plasma is not great because it is likely that such stimulation best occurs during active nights or when the trapped fluxes are large. The constancy and relatively low intensity of the fluxes of Figure 5 attest to the low level of magnetic activity on the night of interest and to the unlikelihood that a barium release would stimulate instabilities in the plasma.

Acknowledgments. We are indebted to Professor R. R. Brown, who provided the X-ray detector and assisted in the interpretation of its data, to the several balloon launch crews, who sat through launch windows at Great Whale, and to the Project Skyhook Office of the Office of Naval Research for logistics support. We are also indebted to John Katsufrakis and to Jon Stables and John Billey for their efforts in the VLF program. We thank the commanding officer and personnel of the U.S. Naval Communication Station at Stockton, California, for their valuable assistance, and the National Research Council of Canada for its support of activity at Great Whale.

The work at the University of California at Berkeley was performed under NASA contract NAS-6-1922, and the authors wish to acknowledge the cooperation provided by the Langley field group of NASA during the course of the experiment. The work at Stanford was supported in part by the Section on Atmospheric Sciences of the National Science Foundation under grants GA-32590X and GA-18128, in part by the Office of Polar Programs of the National Science Foundation under grants GV-28840X and GA-12317, and in part by the National Aeronautics and Space Administration under grant NGL-05-020-008.

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(Received October 13, 1972;
accepted January 18, 1973.)