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Evaluation of Some Geophysical Events on 22 September 1979

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Evaluation of Some Geophysical Events on 22 September 1979

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EVALUATION OF SOME GEOPHYSICAL EVENTS ON 22 SEPTEMBER 1979

by

E. W. Hones, Jr., D. N. Baker, and W. C. Feldman

ABSTRACT

TIROS-N plasma data and related geophysical data measured on 22 September 1979 were analyzed to determine whether the electron precipitation event detected by TIROS-N at 00:54:49 universal time could have been related to a surface nuclear burst (SNB). The occurrence of such a burst was inferred from light signals detected by two Vela bhangmeters ~2 min before the TIROS-N event. We found the precipitation to be unusually large but not unique. It probably resulted from passage of TIROS-N through the precipitating electrons above a pre-existing auroral arc that may have brightened to an unusually high intensity from natural causes ~3 min before the Vela signals. On the other hand, no data were found that were inconsistent with the SNB interpretation of the 22 September Vela observations. In fact, a patch of auroral light that suddenly appeared in the sky near Syowa Base, Antarctica a few seconds after the Vela event can be interpreted (though not uniquely) as a consequence of the electromagnetic pulse of an SNB.

I. INTRODUCTION

On 22 September 1979, a light flash bearing the distinctive signature of a low-yield (few kiloton) surface nuclear burst (SNB) was detected by two Vela bhangmeters. All past observations of light flashes with this signature have been subsequently verified, either through intelligence channels or by detection of radioactive debris, as signalling the occurrence of an SNB. This event has not been similarly verified. The absence of verification, coupled with an inconsistency between the two bhangmeter outputs, casts some doubt on the uniqueness of the SNB interpretation of the 22 September Vela light signals.

This uncertainty has led to a search for auxiliary information in the form of disturbances of the terrestrial environment that may have been SNB-induced. One such disturbance was measured by the total energy detector (TED), a plasma analyzer, on TIROS-N satellite, which sensed unusually intense precipitation of magnetospheric electrons into the auroral ionosphere near Halley Bay, Antarctica ~2 min after the Vela light flash. This report evaluates the 22 September TIROS-N plasma data with regard to a possible SNB association and places them in the context of other geophysical observations. It also discusses a notable sudden localized auroral brightening near Antarctica that occurred a few seconds after the Vela event.

The results of our TIROS-N data analysis are presented in Section II. We conclude that such an event, although rare, is not unique and, furthermore, that this particular event was associated with an auroral arc that probably existed before the Vela event. Although it may be argued that the segment of the arc sampled by TIROS-N was intensified by an SNB, we find no evidence to support this thesis or to suggest that the observed precipitation was anything but the result of natural magnetospheric processes. In Section III, we discuss the localized auroral brightening that occurred near Antarctica very near Vela event time, showing how it might have been caused by an SNB. But an SNB association is by no means unique.

II. THE TIROS-N EVENT

A. Background

At 00:54:49 universal time (UT) on 22 September 1979, ~2 min after the Vela flash at ~00:52:44 UT, the TED on TIROS-N, in a circular near-polar sun-synchronous orbit at 854 km alt, detected a brief (~1 s) very intense (~240 ergs/cm^2/s) flux of electrons (E_e ~ 3-10 keV) precipitating into the southern auroral ionosphere when the satellite was over Antarctica at 79° south latitude, 21° west longitude (Fig. 1). Figure 2, depicting the response of the TED during several consecutive passes over the northern and southern auroral zones on 21-22 September, shows that the peak electron energy flux reached on the southern auroral zone pass just before hour 25 (i.e., 01:00 UT, 22 September) was far greater than that for neighboring orbits.

Observed, as it was, two minutes after the Vela flash, the Tiros precipitation was encountered too early to have been caused by acoustic wave effects of the postulated near-ground-level nuclear detonation, effects of which would have taken ~4 min to reach the ionosphere and influence magnetospheric electron precipitation. Thus, if

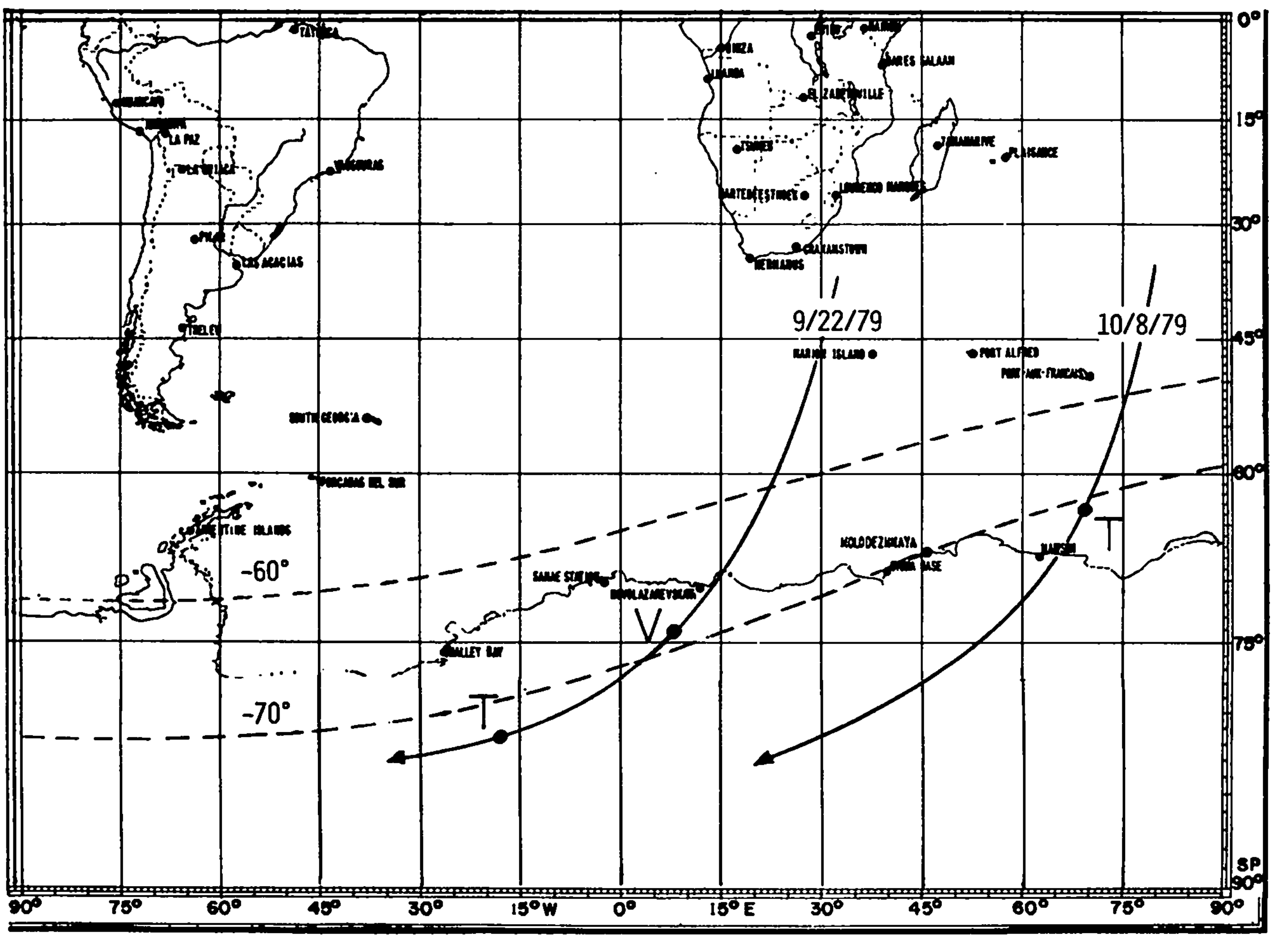

Fig. 1.
A map of a portion of the southern hemisphere showing the locations of geophysical observatories of importance in the present report. Also shown are trajectories of TIROS-N satellite on 9/22/79 and 10/8/79, projected along magnetic field lines to 100-km alt. On the 9/22/79 trajectory, V marks the TIROS-N position at the time of the Vela bhangmeter signal, and T marks its position at the time of the very intense auroral precipitation event described in the text (00:54:49 UT). On the 10/8/79 trace, T marks the location of TIROS-N at 21:44:55 UT when it detected another intense auroral precipitation event. Dashed lines mark 60° and 70° south geomagnetic latitude, the approximate equatorial and poleward boundaries of the southern auroral zone.

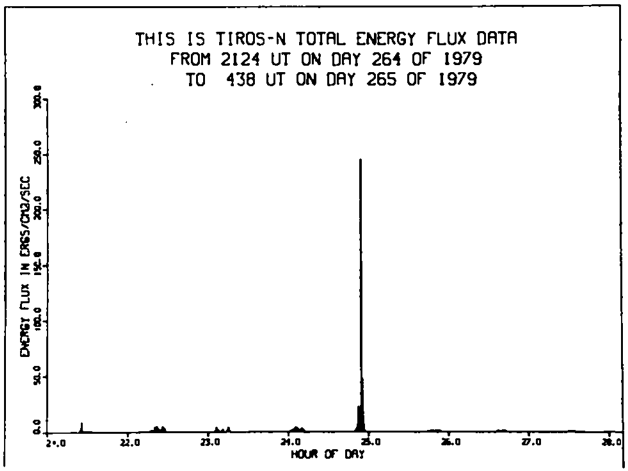

Fig. 2.
The calculated total precipitated energy flux measured by the TIROS-N plasma detectors as a function of time late on 21 September and early on 22 September 1979. The relatively small increases in deposited energy flux typically seen in sequential passes through the southern and northern auroral regions (as at ~21:30, ~22:20 and ~23:10 UT) are to be contrasted with the extremely intense precipitation spike seen at ~00:55 UT on 22 September.

the precipitation was SNB-induced, it had to result from some manner of interaction of the bomb's electromagnetic pulse (EMP) with the ionosphere and/or the magnetosphere. The effects of such an interaction would appear in seconds (Section III) after the detonation. So, determining whether the Tiros event was actually a time-dependent (as opposed to space-dependent) phenomenon and, if so, establishing the precise time of its onset are crucial in assessing whether it was a natural or an SNB-induced phenomenon. Ground-based instruments near the site of the event, capable of measuring explicitly the effects of precipitating auroral particles, such as an all-sky camera, a riometer, or an ionosonde, could have resolved this question immediately. The nearest station, Halley Bay, ~300 km away to the north (Fig. 1), is equipped with these instruments, but unfortunately none were operating on this occasion. The nearest station from which such data were available (Syowa Base) was too far (~2000 km) to observe particle precipitation effects in the ionosphere near the magnetic "footprint" of TIROS-N. In the absence of such important direct ground observations of the environment near TIROS-N, less direct lines of investigation had to be followed. These will now be described.

B. Test of Uniqueness of the TIROS-N Event

After discovering the TIROS-N event of 22 September 1979, D. S. Evans closely searched 11 months of data (November 1978—September 1979) from the TED for other such cases of brief intense electron precipitation. He found 512 cases with precipitated energy flux >60 ergs/cm^2/s. Figure 3 shows the distribution in energy flux of these events. The energy bin containing the 22 September event is indicated by an arrow. That event lies toward the high-energy end of what appears to be a single population of events. We therefore conclude that although such an intense precipitation is rare, it is not unique. Figure 4 shows the distribution of the 512 events in geomagnetic latitude and geomagnetic local time. Broad in both dimensions, the distribution peaks between 18 and 22 h local time and ~72° latitude, not unlike the

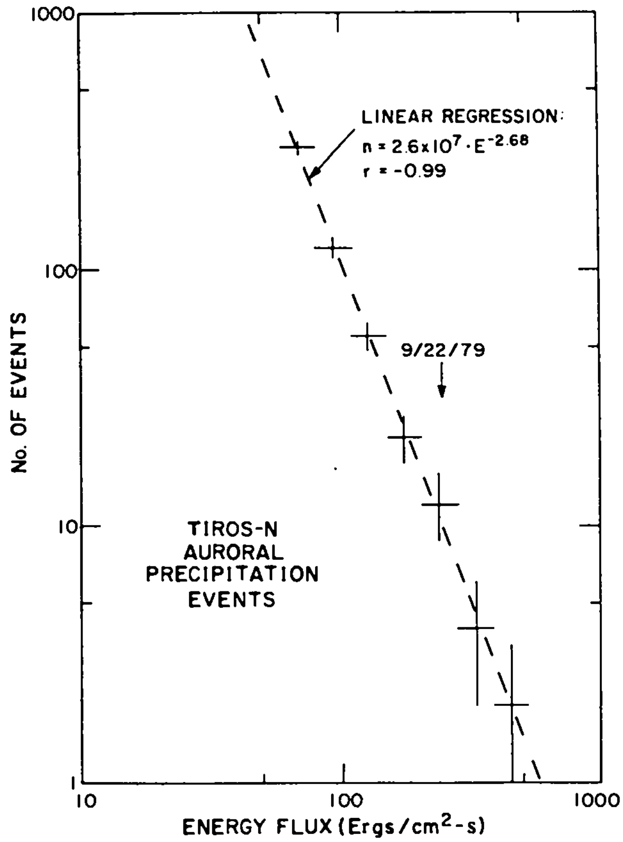

Fig. 3.
A plot of the number of intense auroral precipitation events observed by TIROS-N vs the energy flux of those events. Equal logarithmic intervals of energy flux are used and a smooth power law distribution of events is found. The result of a linear regression fit to the data is shown by the dashed line. The 22 September 1979 event is indicated by the arrow and is seen to be in the upper end of the population of precipitation events but is not uniquely large.

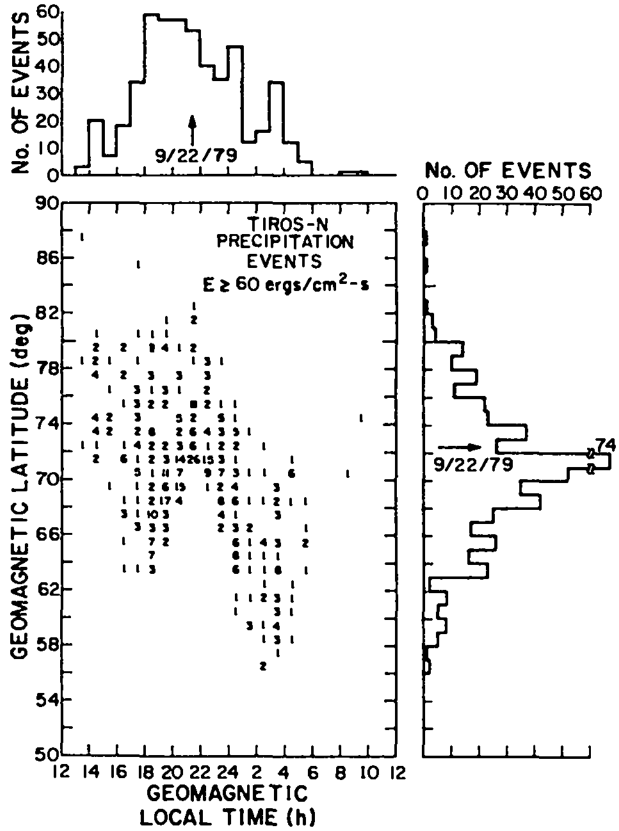

Fig. 4.
The distribution of TIROS-N intense precipitation events (E ≥ 60 ergs/cm²/s) in geomagnetic latitude and geomagnetic local time. The sums over rows and columns are given at right and top. The 22 September 1979 event is situated near the peaks of the latitudinal and local time distributions.

distribution of evening auroral arcs. The 22 September event was near the middle of the distribution. Taking the size distribution shown in Fig. 3, together with the characteristics of the satellite orbit, we estimate an ~1% probability that the satellite will encounter a precipitating energy flux ≥240 ergs/cm²/s during an individual pass over the night-side auroral oval.

C. Determination of Magnetospheric Conditions and Activity

The results just described suggested strongly that the TIROS-N event of 22 September resulted simply from the satellite's encounter of the precipitating electrons above a naturally occurring auroral arc. Geophysical and magnetospheric conditions surrounding the event were studied to determine whether unusual conditions may have prevailed at that time. Examination of magnetograms from southern and northern auroral zone stations revealed that TIROS-N encountered the precipitation late in the recovery of a moderate magnetospheric substorm that began at ~23:10 UT on 21 September (Fig. 5). Notable on several of the magnetograms (for example, Narssarssuaq) was a train of weak micropulsations of ~1 min period that began at ~00:50 UT on 22 September and lasted for ~6 min. These were recorded also on pulsation recorders at Halley Bay and at King Edward Point, South Georgia (Fig. 6). Such pulsation trains, called Pi2 pulsations, are associated with temporary brightenings of auroral arcs, that is, with enhanced precipitation of auroral electrons.[1,2] A further indication that electron precipitation may have been enhanced briefly in the neighborhood of TIROS-N about

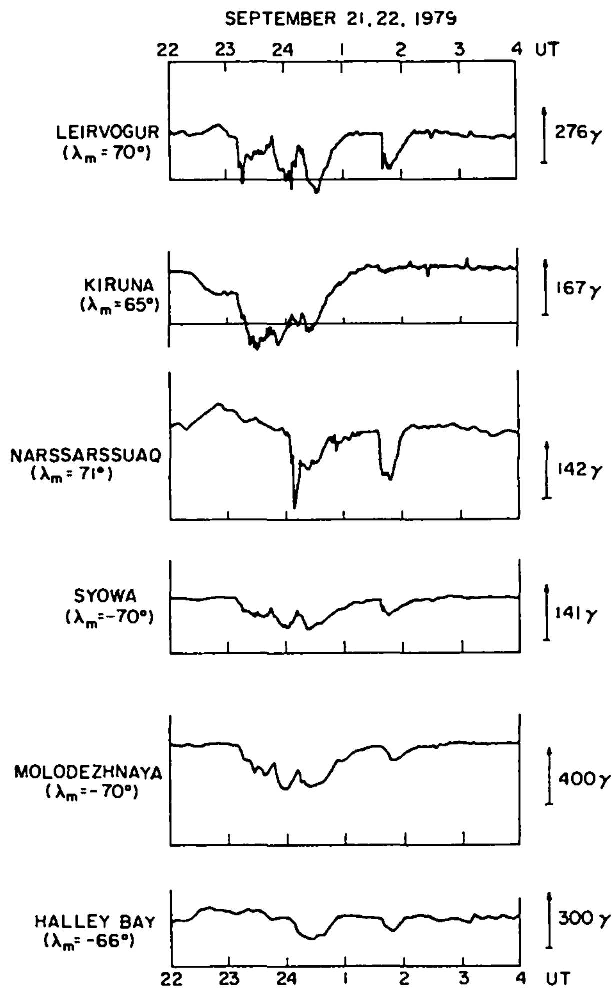

Fig. 5.
Traces of the horizontal component of the geomagnetic field at three northern and three southern auroral zone stations on 21-22 September 1979.

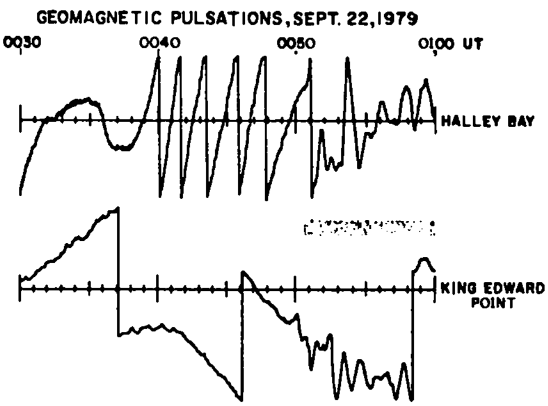

Fig. 6.
Pulsation magnetometer records from Halley Bay, Antarctica and King Edward Point, South Georgia (Fig. 1) for part of 22 September 1979. These highly sensitive magnetometers show several gain changes between 00:37 and ~00:50 UT. As indicated by the horizontal shaded bar, irregular geomagnetic pulsations (Pi2) of ~1 min period begin at ~00:50 UT and last until ~01:00 UT. As mentioned in the text, such Pi2 activity is normally associated with intensification of auroral arc structures.

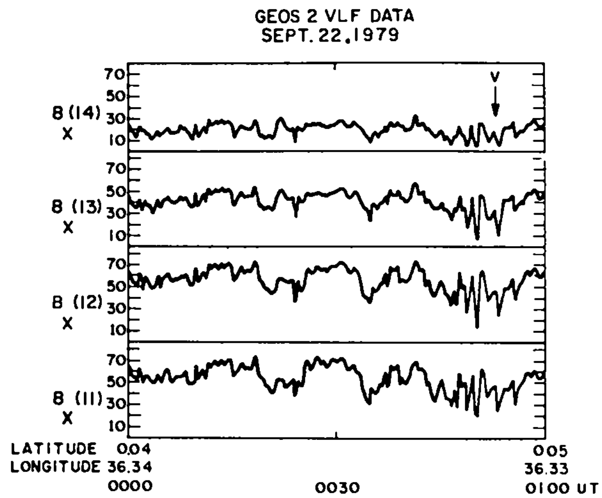

Fig. 8.
Traces showing the relative intensity of magnetic field fluctuations at frequencies of (from the top) ~0.5 kHz, ~1.0 kHz, ~2.0 kHz, and ~4.0 kHz, measured from 00:00 to 01:00 UT, 22 September 1979 by the GEOS 2 satellite in geosynchronous orbit. The time of the Vela bhangmeter event is indicated by the V.

this time is contained in riometer data from Narssarssuaq, Greenland, roughly conjugate, magnetically, to this neighborhood (Fig. 7). These data imply enhanced electron precipitation lasting from ~00:50 to ~01:00 UT. Very low frequency (vlf) plasma wave data from the GEOS 2 satellite in geosynchronous orbit at ~36° east longitude also indicated an enhancement of magnetohydrodynamic wave activity in the outer magnetosphere from ~00:48 to ~00:53 UT (Fig. 8). A Los Alamos National Laboratory electron detector on another geostationary satellite, S/C 1977-007, measured intensities of >30 and >45 keV electrons that were rather high, exceeding the Kennel-Petschek limit above which scattering of electrons into the loss cone becomes quite rapid (Fig. 9). These electrons were injected into the

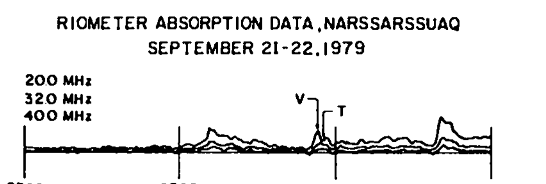

Fig. 7.
Relative ionospheric opacity meter (riometer) records from Narssarssuaq (61° N, 45° W) for the period 23:00 UT on 21 September to 02:00 UT on 22 September 1979. The V marks the time of the Vela bhangmeter flash, and the T marks the time of the intense precipitation event seen by TIROS-N.

synchronous orbit region of the magnetosphere by the ~23:10 UT substorm mentioned above and shown in the magnetograms of Fig. 5.

The foregoing data suggest that auroral electron precipitation may have been substantially enhanced in the premidnight sector of the auroral zone for a few minutes around the time of the TIROS-N event. But because the signatures of this presumed enhancement began ~3 and 5 min before the Vela and TIROS-N events, respectively, we conclude that TIROS-N passed through a narrow, spatially pre-existing region of auroral precipitation that may have been temporally enhanced, not by an SNB, but by natural magnetospheric processes.

D. Further Evidence Regarding the Physical Nature of the Tiros-N Event

We examined data from the ISIS II satellite to test further the above deduction that the TIROS-N event resulted simply from an encounter of the satellite with a narrow auroral arc, a phenomenon commonly seen in the evening sector of the auroral oval. ISIS II is in polar orbit at 1400-km alt and carries an auroral particle detector and a spin-scanning photometer that produces images of the auroras. Dr. J. D. Winningham and Dr. C.

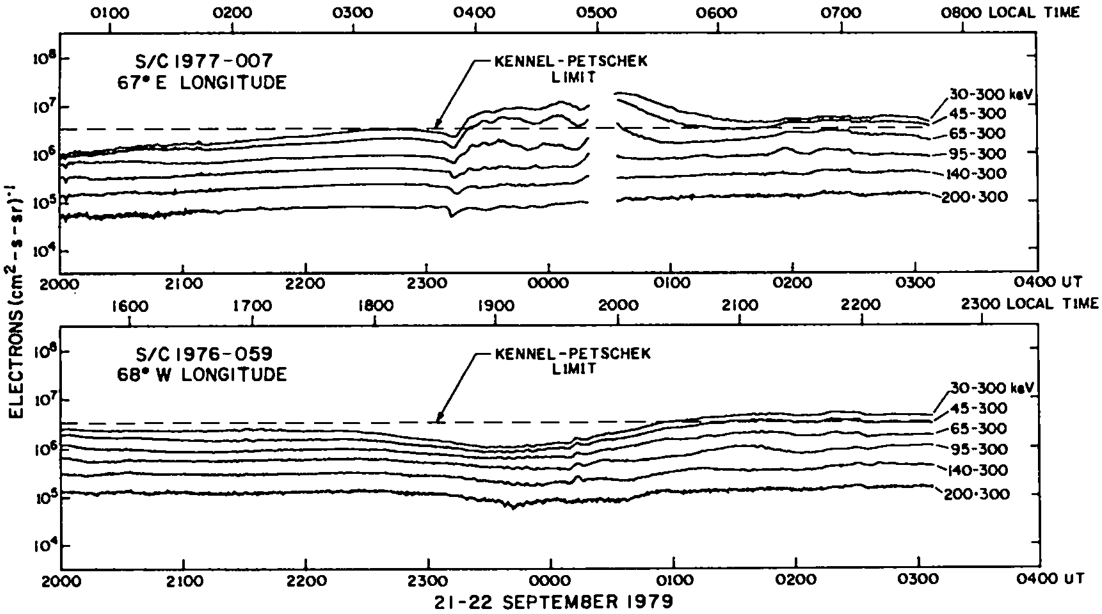

Fig. 9.

Directional fluxes of electrons measured on 21-22 September 1979 with Los Alamos detectors on satellites 1977-007 and 1976-059 in geosynchronous orbit at the geographic longitudes shown. Local times of the satellites are indicated at the top of the graphs. The Kennel-Petschek limit, i.e., the flux level above which intense scattering of the electrons by wave-particle interactions occurs, is designated by the dashed curve. Notice that fluxes of >30 keV and >45 keV electrons at S/C 1977-007 rose suddenly above this limit at ~23:10 UT, 21 September, in conjunction with the onset of a substorm (see text and Fig. 5) and remained high until the substorm's subsidence at ~01:00 UT, 22 September.

D. Anger provided data from these experiments together with helpful discussions. It was found that the ISIS II particle detector also occasionally experienced very brief electron precipitation events at least as intense as that recorded by TIROS-N on 22 September 1979. In the 3-month period of ISIS II data that we examined, 12 such events were seen. For five of these there were simultaneous imaging data. The intense electron precipitation occurred over a longitudinally extended bright auroral arc in all five cases. This is illustrated in Figs. 10 and 11. ISIS II measured precipitating electrons with a peak energy flux of ~70 ergs/cm²/sr/s ($\lesssim$400 ergs/cm²/s) in one 1-s sample taken at ~ 01:39:18 UT on 10 January 1972 when the satellite was at invariant latitude ~74° and magnetic local time (MLT) ~20.8 h (Fig. 10). Figure 11 shows that the satellite path (small triangles in the three pictures at left) crosses the poleward segment of a very bright evening arc shortly after 01:39 UT. The very intense electron precipitation evidently was associated with this arc. These data from ISIS II nicely demonstrate the type of natural phenomenon with which the TIROS-N event was most likely associated, and they further support our belief in such an association.

All-sky camera pictures (Fig. 12) taken at the time of the TIROS-N event of 22 September from Syowa Base, ~2000 km to the northeast of the satellite (Fig. 1), did not reveal any bright arcs within that camera's field of view (~400- to 500-km radius at ionospheric height). This, however, cannot be taken as serious evidence that an arc did not exist at the TIROS-N position, even though Syowa Base and TIROS-N were at similar magnetic latitudes ($\lambda_m \sim -71°$ and −70°, respectively). Figure 11 demonstrates that auroral arcs are not necessarily aligned strictly along constant magnetic latitudes and that they can terminate abruptly in longitude.

A quite different situation is illustrated in the Syowa all-sky camera picture (Fig. 13) taken at ~21:45 UT on 8 October 1979, coincident with the occurrence of another TIROS-N precipitation event when the satellite was at 61° south latitude, 65° east longitude, ~1400 km northeast of Syowa. In that case, the peak precipitating energy flux was 194 ergs/cm²/s and TIROS-N was at ~−69° geomagnetic latitude and ~00:00 MLT. A bright arc extends from above Syowa (at ~22:00 MLT) toward magnetic east, conceivably reaching TIROS-N.

The observations presented in this section demonstrate that (1) brief sensing of intense electron precipitation,

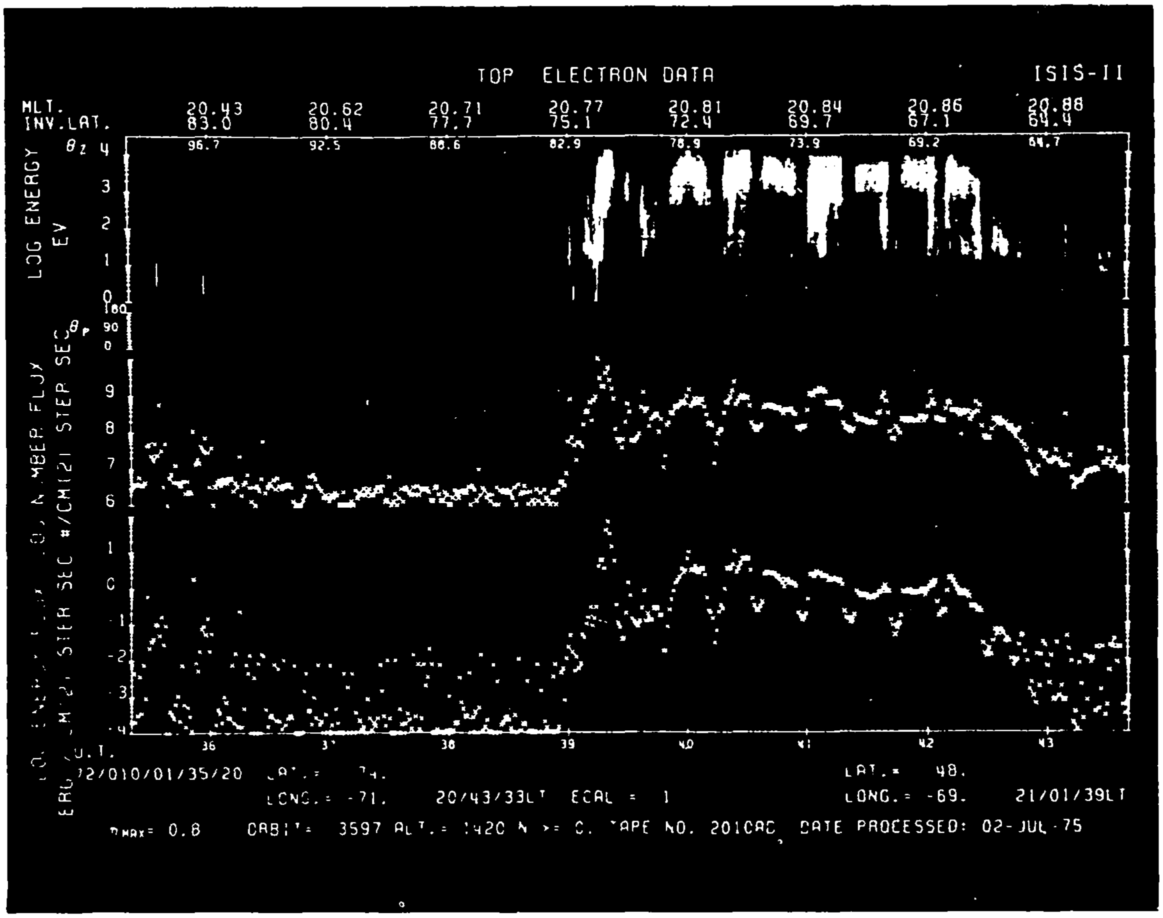

Fig. 10.

Records from the soft particle spectrometer on ISIS II for a pass over the evening sector of the northern auroral zone from 01:35:20 to 01:43:40 UT on 10 January 1972. The gray-scale (spectrogram) representation at top shows electron intensity (brightness) vs energy (vertical scale) and time (horizontal scale). The middle graph depicts the number flux of electrons and the bottom graph shows the energy flux carried by the electrons. The dotted sinusoidal curve below the spectrogram indicates the pitch angle of the electrons being sampled. Here 0° means downward moving electrons and 180° means upward moving electrons. The satellite's MLT and invariant latitude are shown at top. Note the very brief (~1 s) burst of downward moving electrons whose peak occurs at 01:39:18 UT. (Provided by J. D. Winningham.)

similar to the 22 September event (and others) seen by TIROS-N, can be specifically related to passage of a satellite over a bright auroral arc, and (2) one TIROS-N event (8 October 1979) could be associated believably with an intense auroral arc observed at a ground station 1400 km away along the auroral oval. They, along with the spatial distribution of events shown in Fig. 4, support the view that the TIROS-N events (including that on September 22) signified passages of the satellite over naturally occurring bright auroral arcs.

III. THE SUDDEN LOCALIZED AURORAL BRIGHTENING NEAR SYOWA BASE

A. Background

The all-sky camera at Syowa Base made a 7-s exposure of the sky every 10 s starting at integral 10-s points of UT. On the frame exposed from 00:52:50 to 00:52:57 UT (fourth frame from left, top row of Fig. 12), a roughly trapezoidal patch of light appears (top half, right of center) that did not occur in the frame before. It appears essentially unchanged in the next frame and then, during the next minute, changes shape and is gone.

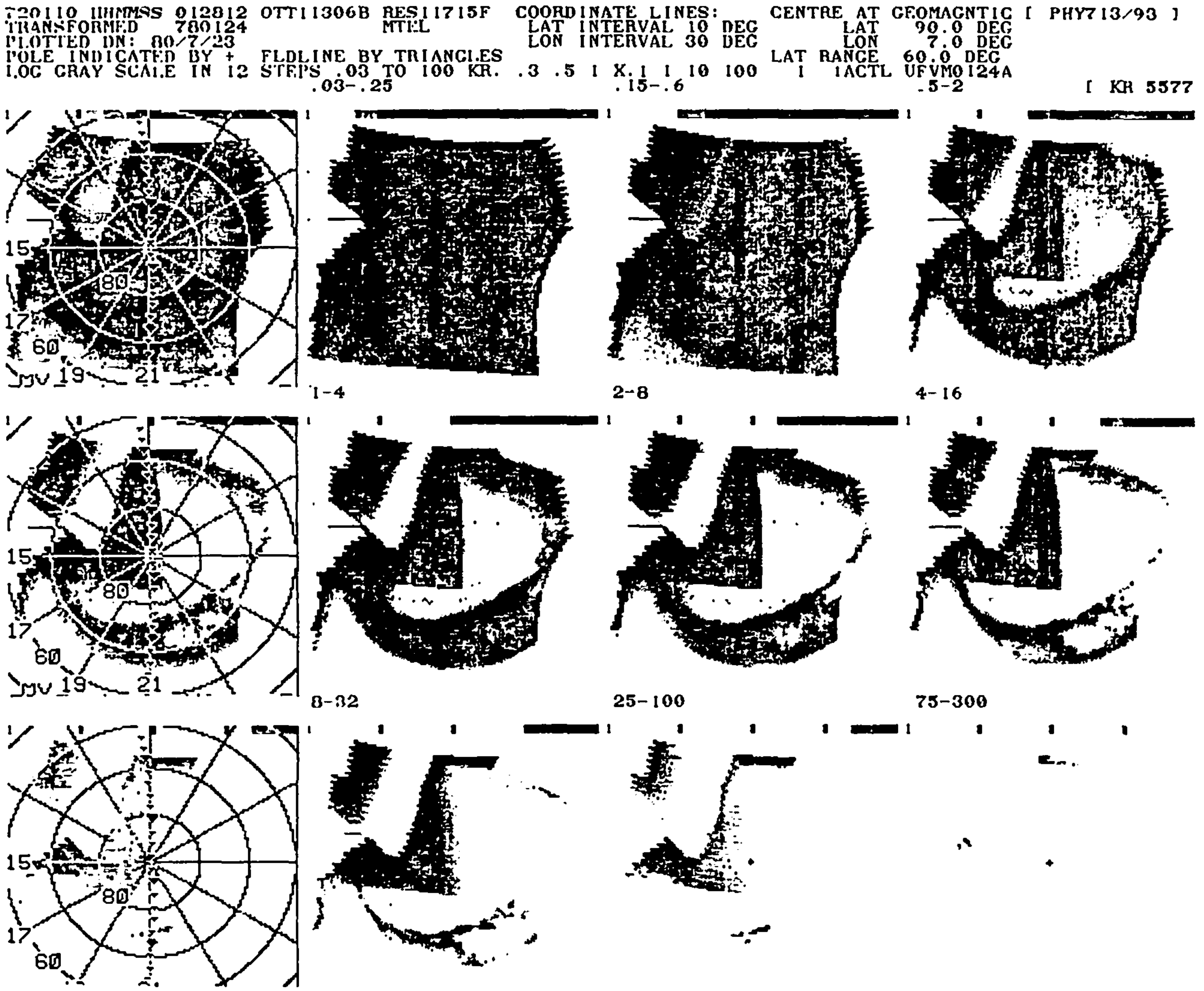

Fig. 11.
Records from the auroral imaging instrument on ISIS II, taken during the north polar pass starting at ~01:23 UT on 10 January 1972. The images are in negative, showing the most intense emission (at 5577 Å) as the darkest areas. The three images at left have been overlayed with grids showing geomagnetic latitude and local time. All 12 images have identical sizes and orientations so the same grid can be applied to all. The location of the satellite (projected along the magnetic field to 100 km alt) is indicated at integral 1-min intervals by the sequence of arrows that point in the direction of its motion. The time of the topmost arrow is 01:23:00 UT. The location at integral 5 min intervals is indicated by heavier arrows. Each of the 12 frames shows the distribution of auroral intensity within a specified intensity range. The intensity range of each of the non-gridded frames is given at its upper left in kilorayleighs. (One kilorayleigh is 10^9 photons/cm^2/column and results from the deposition in the upper atmosphere of roughly 1 erg/cm^2 of precipitating particle energy.) Note: the angular area of light occupying parts of the upper left quadrant of the pictures is light scattered from a baffle system. The auroras produce the roughly circular pattern that extends around the remaining ~270° of the pictures. At the time (~01:39:18 UT) of the energy flux peak shown in Fig. 10, ISIS II had just crossed the northern edge of a long auroral arc whose intensity extended into the 25 to 100 kilorayleigh range. (The computer-produced picture from which this figure was copied showed small sections of this arc extending into the 75 to 300 kilorayleigh range.) (Provided by C. D. Anger.)

(The sequence of pictures around this time is shown again in Fig. 14, an earlier print made before the microfilm became scratched by repeated use. Here the 00:52:50 UT frame is fifth from left on the bottom row. The trapezoidal patch is more easily seen in this print.) Although other changes in the auroral light occur among successive pictures in the series of Figs. 12 and 14, the appearance of the trapezoidal patch in the 00:52:50 UT frame is the most sudden and distinct change of the auroral pattern in the series of pictures shown, as well as

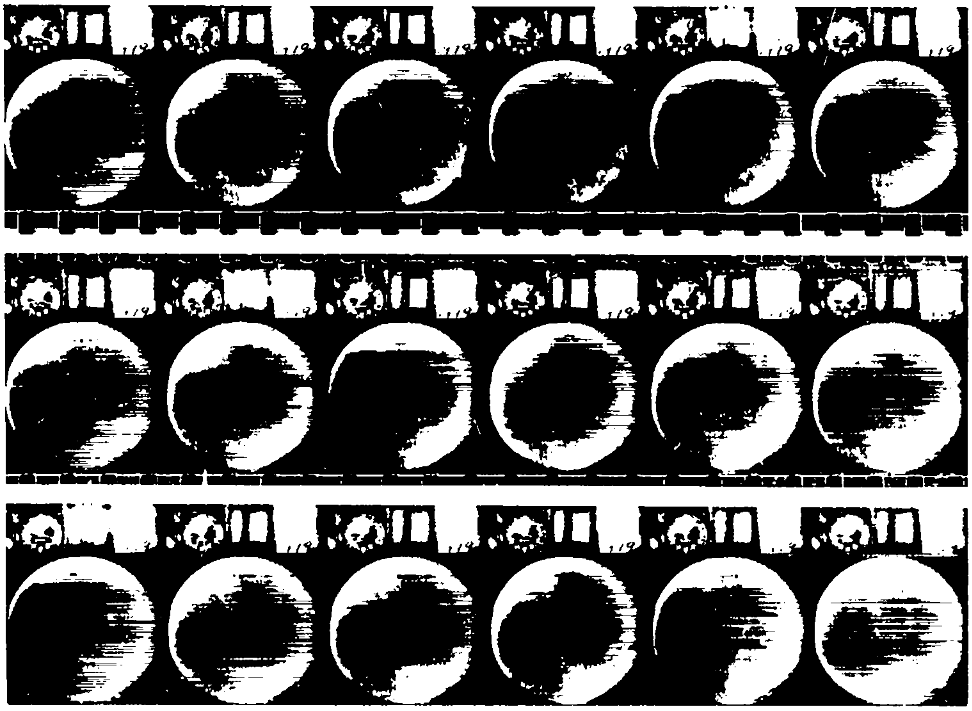

Fig. 12.
Pictures of the sky taken with the all-sky camera at Syowa Base. The exposure of each picture is 7 s. The exposure of the upper left picture started at 00:52:20 UT, 22 September 1979, and the exposures of the subsequent pictures started at 10-s intervals. Geomagnetic east is at the top of each picture and geomagnetic south is at the left. The auroral patch discussed in the text appears first in the frame for 00:52:50 UT. (Note: The times shown by the pictured clock are not precise. Its minute hand is ~20 s fast and its second hand is ~2 s slow.)

for many minutes before and after the interval presented there. Both because of the close time correlation of its appearance with the Vela light flash and because a chain of geophysical phenomena, verified in detail by past experiments, exists whereby it might have been causally related to the EMP of a nuclear burst, we carried out some further investigation of this auroral light patch. Although it could well have been an entirely natural phenomenon, we believe that the circumstances of its occurrence are remarkable enough to be reported and discussed in this document.

B. Results of Photo Enhancement

In an effort to learn more of the structure and time variability of the auroral patch, we used the sophisticated computerized densitometry techniques available at EG&G, Inc., Los Alamos. A 256 by 256 pixel densitometer map was made of each of 15 successive frames of the Syowa all-sky film starting with the third frame before the 00:52:50 UT frame. The range of light transmittance from fully opaque to fully transparent was divided into 256 linear steps in the densitometry measurement. Two different background subtraction techniques were then applied to enhance the auroral patch as well as other changes of the auroral pattern that occurred in the 150-s interval encompassed by these 15 successive pictures. (1) The first two pictures were averaged and that average was then subtracted from all succeeding pictures. The result of this process is shown in Fig. 15. (2) Each frame had the previous frame subtracted from it. The result of this process is shown in Fig. 16. In both techniques, 128 intensity units were added to each pixel after the subtraction, the result was displayed on a TV screen, and a positive photograph made of it. In this display, regions of relatively brighter auroras appear as dark areas.

In Fig. 15, the occurrence of the auroral patch at 00:52:50 UT (second picture from left, top row) shows up as a very significant change from the constant two-picture averaged background, whereas no such significant change is seen in the picture before it. Subsequent changes in the patch can be followed in

Fig. 13.
All-sky camera picture from Syowa Base taken at ~21:45 UT, 8 October 1979.

successive pictures. Later pictures show greater and greater spatial variability as the gradual changes of the aurora make the constant background less and less relevant.

In Fig. 16, the occurrence of the patch at 00:52:50 UT causes a significant change from the (subtracted) previous picture. But the next frame shows little further change, reflecting the fact that the patch had nearly the same appearance in the frames at 00:52:50 and 00:53:00 UT (Figs. 12 and 14).

C. Uniqueness of the Auroral Patch

We have not been able to address the question of uniqueness of the auroral patch in any more quantitative fashion than that just described, that is, showing that the patch seems to represent a remarkably sudden change of the auroral pattern when compared with the surrounding 15 camera frames that were computer-analyzed. We considered doing such an analysis of a much longer time sequence (~1 h) but decided that the quality of the pictures did not warrant this extended effort. Notice that the background intensity is not the same in all the pictures. This is most easily seen in the variation from picture to picture of the brightness of the twilight at the left edge. This possibly reflects a nonuniformity of exposure time in the developing of the original film or in copying the developed film.

Patchiness is a commonly reported feature of the natural auroras. An example is shown in the all-sky camera picture from College, Alaska shown in Fig. 17.[3] Patches tend to be a feature of the morning sector of the auroral oval as illustrated in the DMSP satellite auroral photograph of Fig. 18.[3] (Note that Syowa was at ~01:00 MLT at 00:52:50 UT on 22 September 1979, a local time region where natural auroral patches can be expected.) Patches often flicker on and off with periods of 10-30 s but tend to retain a pattern that is fixed or evolves only slowly over several flicker cycles.* This behavior of naturally occurring patches is rather unlike the 22 September patch that appeared suddenly, not seeming to evolve gradually from an earlier very similar pattern.

D. Physical Sequence Possibly Linking the Auroral Patch To An SNB

In this section, we discuss several physical processes and interactions, each verified by published observations, which taken together could provide a chain of logic linking the auroral patch over Syowa to an SNB.

It is well known that the EMP of an atmospheric nuclear burst can trigger whistlers. The EMP radiation, its intensity peaking in the ~10-kHz range, travels through the earth-ionosphere wave guide and can "leak" upward into the magnetosphere along previously existing magnetic field-aligned whistler ducts. The ducts are magnetic flux tubes, some tens of kilometers in diameter at the ionosphere, with plasma content slightly greater than that in the surrounding magnetospheric medium. The radiation is dispersed as it travels through the magnetosphere and can be detected as a descending tone when it leaks through the ionosphere into the opposite hemisphere where it can again travel some distance in the earth-ionosphere wave guide. Natural whistlers are triggered by EMPs generated by lightning strokes.

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*This information was furnished by D. W. Swift, University of Alaska.

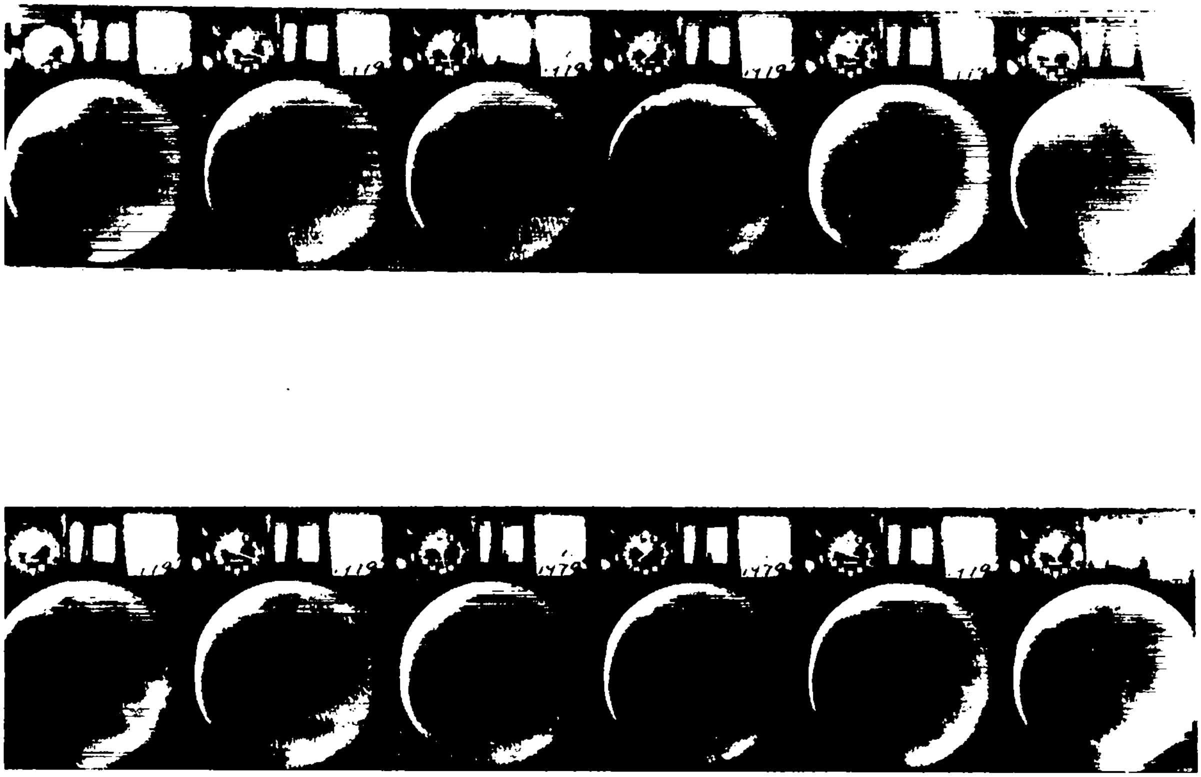

Fig. 14.
All-sky camera pictures from Syowa Base, Antarctica, 22 September 1979. Time runs from bottom left to bottom right, then from top left to top right. The exposure of the first picture started at 00:52:10 UT and each successive exposure started 10 s later. These pictures are included in Fig. 12. The auroral patch first appears in the 00:52:50 exposure.

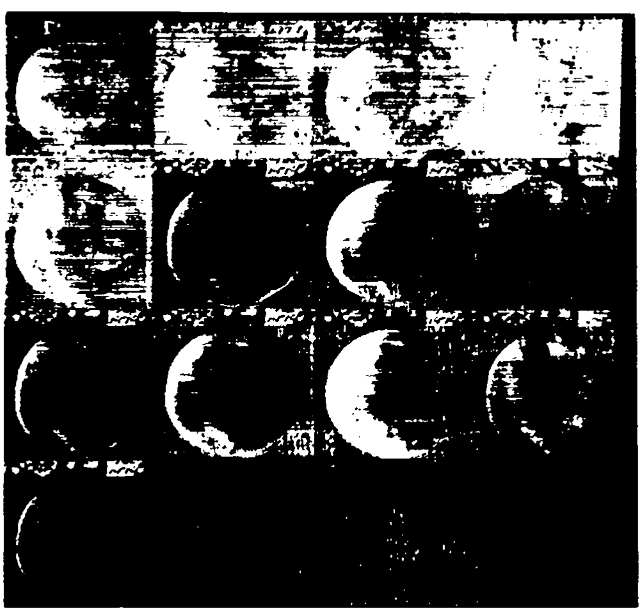

Fig. 15.
Background-subtracted pictures from the Syowa all-sky camera, 22 September 1979. For this figure, the 00:52:20 and 00:52:30 UT Syowa frames were averaged (see text) and subtracted from those for 00:52:40 onward, through 00:54:40 UT.

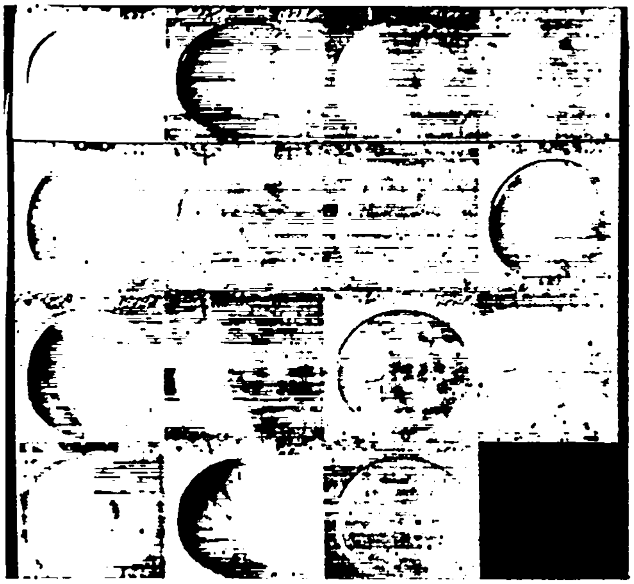

Fig. 16.
Background-subtracted pictures from the Syowa all-sky camera, 22 September 1979. In this figure the top left frame is the uncorrected exposure of 00:52:20 UT. To its right is the exposure of 00:52:30 UT minus the 00:52:20 UT exposure (see text); next is the 00:52:40 UT exposure minus the 00:52:30 UT exposure, etc.

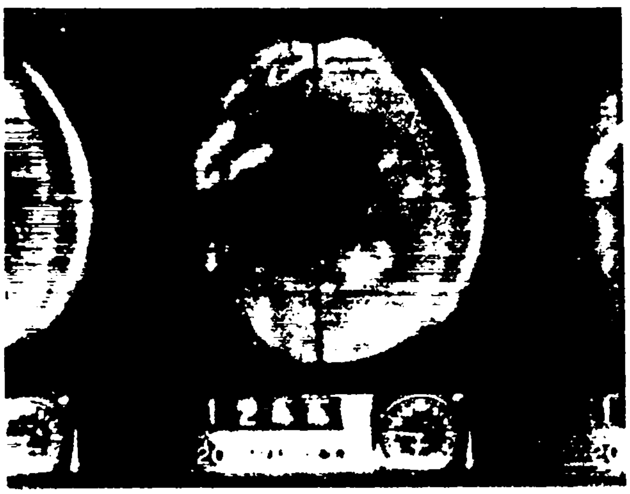

Fig. 17.
An all-sky camera picture from College, Alaska showing auroral patches in the early-morning sector (~01:00 MLT) of the auroral zone. (Provided by D. W. Swift. Reprinted from "Mechanisms for Auroral Precipitation: a Review," Reviews of Geophysics and Space Physics 19.)

With equipment at Stanford, Carpenter and Helliwell[4] recorded the EMPs and resulting whistlers from several US nuclear tests, including Lea, a 1.4-kT burst at 0.5 km alt over Nevada, 600 km away. The Lea whistler is barely visible in the bottom spectrogram of Fig. 19. The top two spectrograms show natural whistlers that were recorded near Lea shot time. They are two-hop whistlers that originated in the northern hemisphere and were observed at Stanford after propagating to the opposite hemisphere and back along magnetospheric paths. The similar dispersion characteristics of the Lea-triggered 13:20:00 UT whistler show that it, too, followed a similar path.

In addition to whistlers, there is another class of natural ducted radio phenomena known as vlf emissions. These are thought to originate in the magnetosphere and to derive their electromagnetic energy from the kinetic energy of charged particles spiraling along the magnetic lines of force. They can be "triggered" by whistlers or other emissions. Figures 20 and 21 from Helliwell[5] show several illustrations of a type of vlf emission, called "chorus" (sequential rising tones) being triggered by whistlers. The chorus can continue 10-20 s or more after triggering.

Recently Helliwell and Mende[6] have observed one-to-one correlations between bursts of ducted vlf noise and ionospheric optical emissions signifying local precipitation of 1-100 keV electrons. One example of this correlation is shown in Fig. 22, where the vlf noise is shown by the intensified portion of the spectrogram, and the intensity of optical emission, measured with a zenith pointing photometer, is indicated by the line labeled "photometer VCO." They explained these results as electron scattering by Doppler-shifted cyclotron resonance between energetic magnetospheric electrons and whistler-mode waves travelling in opposite directions.

The sequence of physical processes by which the Syowa auroral patch might have been caused by an SNB can now be traced as follows (Fig. 23).

(1) A few-kiloton SNB, detonated possibly at Prince Edward Island ~2200 km north of Syowa, generates an EMP.

(2) EMP energy travelling in the earth-ionosphere wave guide enters a pre-existing duct whose foot is in the ionosphere about 100 km northeast of Syowa.

(3) The northward-travelling whistler wave interacts in the equatorial region with southward-travelling magnetospheric electrons, growing in intensity, and triggering vlf emissions while scattering the electrons. The scattered electrons precipitate into the ionosphere at the southern

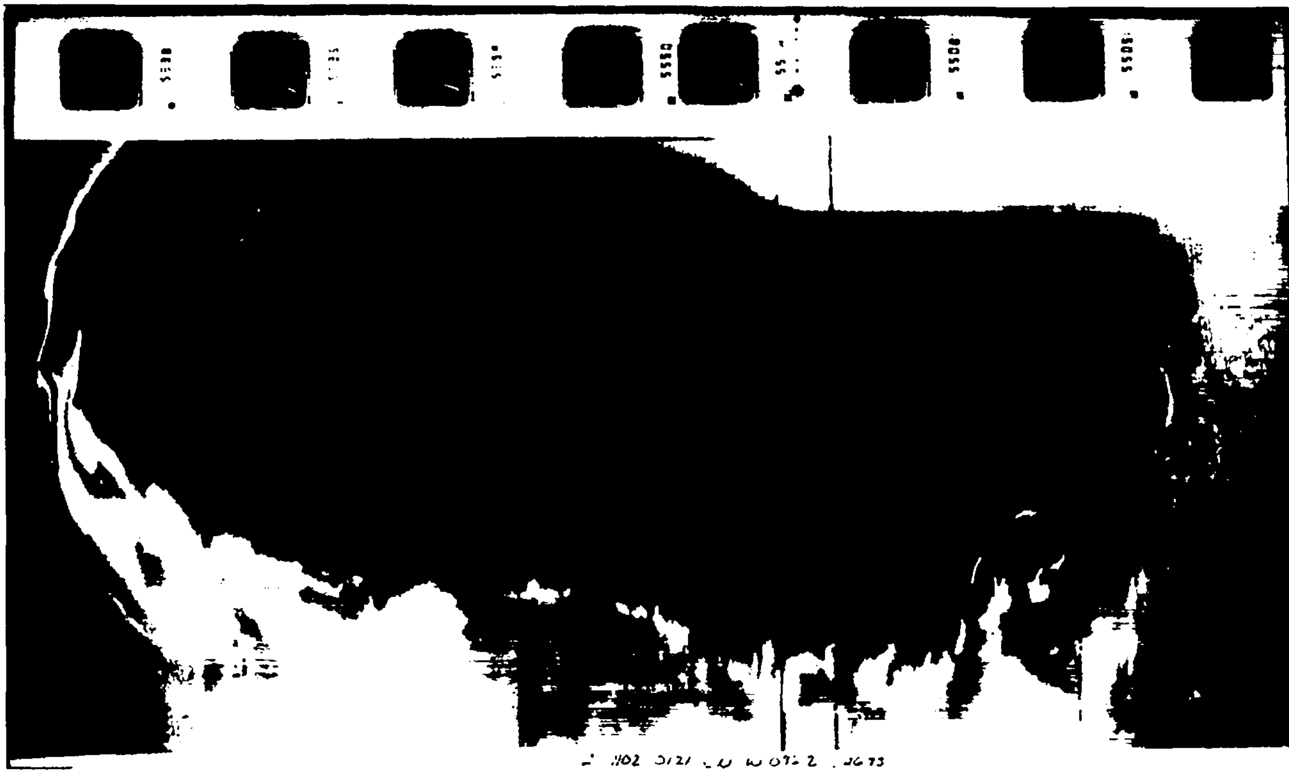

Fig. 18.
Picture of the auroral oval taken by a DMSP satellite during an interval of moderate to strong auroral activity. (Provided by D. W. Swift. Reprinted from "Mechanisms for Auroral Precipitation: a Review," Reviews of Geophysics and Space Physics 19.)

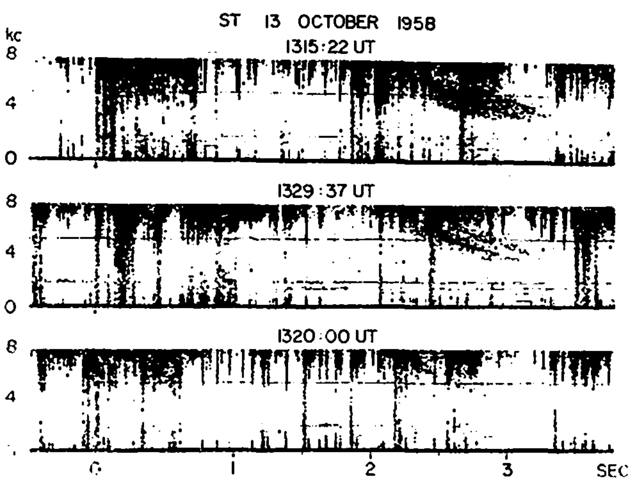

Fig. 19.
Broadband vlf receiver records from Stanford, California on 13 October 1958. Lightning-produced whistlers are seen in the top two frames and the whistler produced by the Lea test in Nevada is seen very faintly in the third frame. The causative "sferic" or EMP is indicated by an arrow in the top two frames and occurs at 0 s in the third frame. (Provided by R. A. Helliwell and D. L. Carpenter. Reprinted from "Whistlers Excited by Nuclear Explosions," Journal of Geophysical Research 68.)

end of the duct, causing photo emission from that area of the ionosphere. Because of the characteristic wave and electron travel times for auroral field lines, precipitation is expected to start ~1-2 s after the SNB. Triggered emissions (for example, chorus, illustrated in Figs. 20 and 21) may then cause the precipitation to continue for many seconds.

This hypothesis, although physically logical, is not a unique interpretation of the Syowa auroral patch. First, patchiness is a frequently observed feature of the post-midnight auroral oval as we have mentioned above. Second, if the patch *was* induced by an EMP, the EMP could have been that of a lightning stroke; a large storm was centered south of Africa at the time of these observations.

IV. DISCUSSION AND CONCLUSIONS

A. The TIROS-N Event

The TIROS-N satellite, at 854-km alt, geographic latitude 79° south, geographic longitude 51° west,

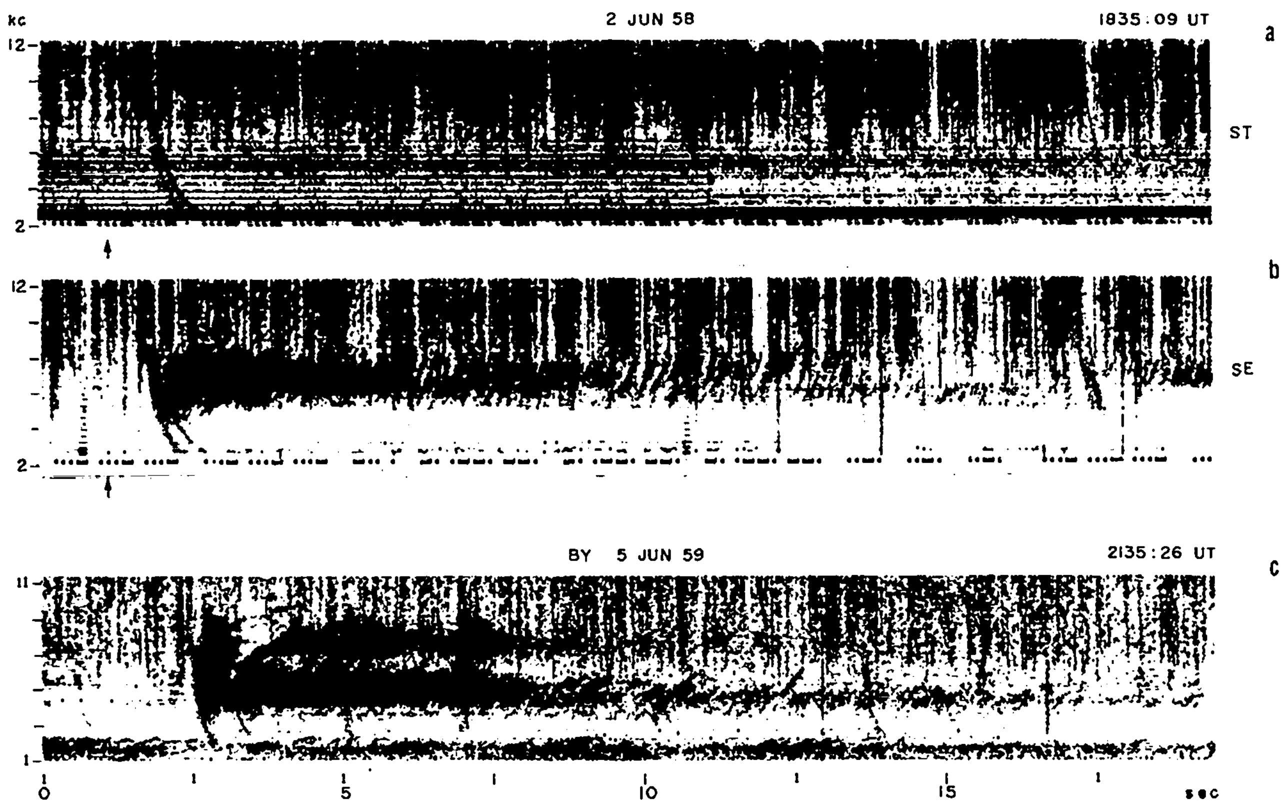

Fig. 20.
Examples of chorus triggered by a whistler. The top trace, from Stanford, shows a whistler with no accompanying chorus. The same whistler did trigger chorus (the multitude of upward-slanting traces) lasting more than 15 s on the flux tube at Seattle (middle trace). (Provided by R. A. Helliwell. Reprinted from *Whistlers and Related Ionospheric Phenomena*, Stanford University Press.)

encountered precipitating electrons ($E_e \sim 10$ keV) with energy flux ~246 ergs/cm^2/s, for ~1 s. For the following reasons, developed in foregoing sections, we conclude that this phenomenon very likely represented passage of TIROS-N above a very intense, naturally occurring auroral arc and was not related to a hypothetical SNB.

(1) This event fit well within the intensity, magnetic latitude, and MLT distributions of the more than 500 similar events found in a survey of 11 months of TIROS-N data.

(2) Comparably intense, brief precipitation events were found in data from the ISIS II satellite, whose complement of instruments was able to show, in addition, that each such event was encountered over a very intense auroral arc.

(3) What little evidence we have been able to find in ground and satellite data for a temporary intensification of auroral particle precipitation shows that such intensification started about 5 min before the TIROS-N event and about 3 min before the Vela light flash.

B. The Syowa Auroral Patch

The all-sky camera at Syowa Base, Antarctica (geographic latitude 69° south, geographic longitude 40° east) revealed a brightening of an area of the sky some tens of kilometers in diameter and about 100 km northeast of Syowa. This brightening occurred sometime between 00:52:40 and 00:52:50 UT, no more than 4 s before the Vela light flash and no more than 6 s after it. Although this phenomenon can plausibly be associated with an SNB through a chain of previously observed ionospheric and magnetospheric processes, our belief in such an association is weakened by the following facts.

(1) A certain degree of patchiness and flickering is a commonly observed feature of postmidnight auroras.

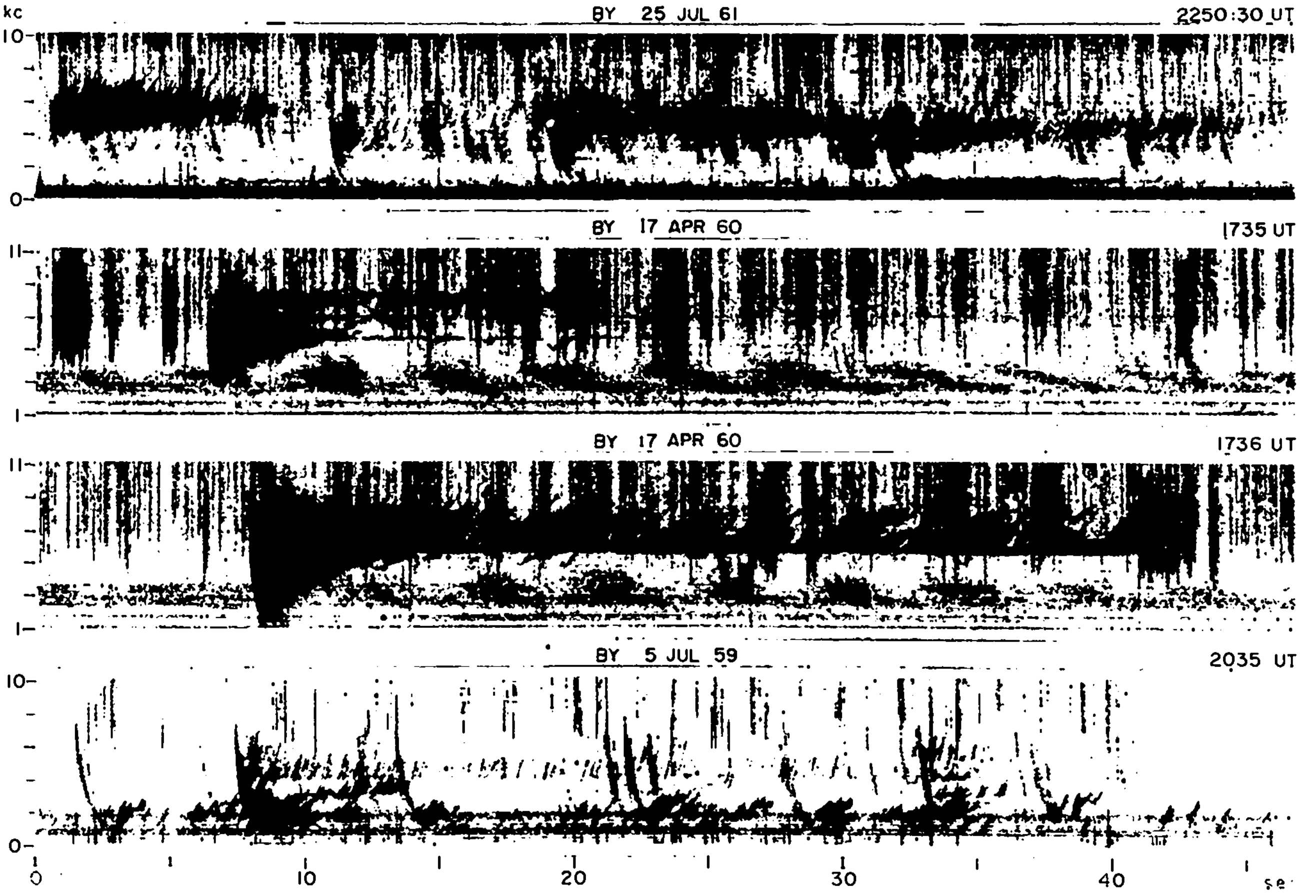

Fig. 21.
Further examples of whistler-triggered chorus. (Provided by R. A. Helliwell. Reprinted from *Whistlers and Related Ionospheric Phenomena*, Stanford University Press.)

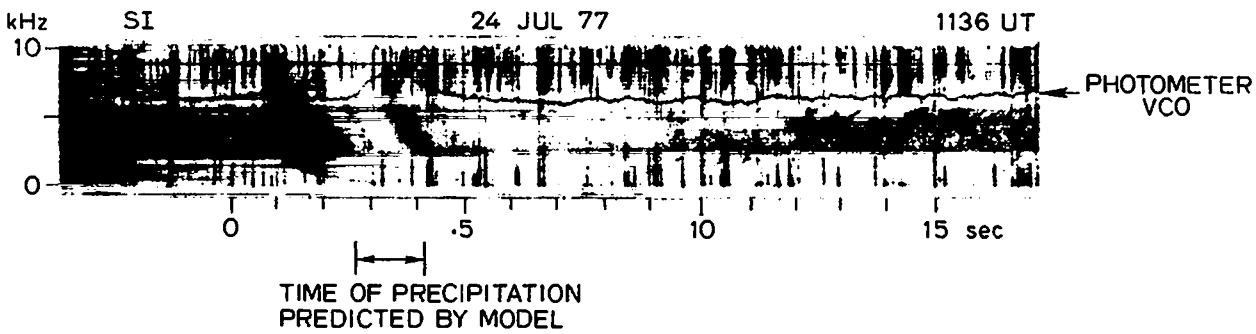

Fig. 22.
Broadband vlf receiver data from Siple, Antarctica showing a whistler that caused electron precipitation that produced an auroral enhancement recorded by a photometer at Siple. The photometer record is the line labeled photometer VCO. A model of vlf wave particle interactions predicted that electron precipitation would occur in the time interval indicated at bottom. (Provided by R. A. Helliwell and J. B. Mende. Reprinted from "Correlations between λ4278 Optical Emissions and vlf Wave Events Observed at L ~ 4 in the Antarctic," Journal of Geophysical Research 85.)

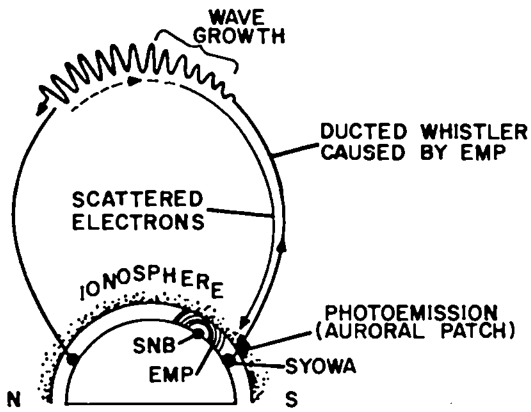

Fig. 23.
Model showing schematically how the auroral patch observed at Syowa in close time coincidence with Vela light flash on 22 September 1979 might have been caused by the postulated SNB. EMP radiation enters a duct, becomes a whistler, and grows through interaction with plasma near the equatorial plane. The enhanced wave scatters electrons that precipitate into the atmosphere causing auroral emissions at the foot of the duct near Syowa.

(2) The sequence of physical processes traced above, if it did occur, could have been set off by a lightning stroke in the major storm that was centered off the southern tip of Africa at the time.

C. Other Data Sets

For this study, we sought a wide variety of data, much of which we have not discussed above because (1) it was not available, (2) it has not yet been received, (3) it was received but not appropriately recorded, or (4) its examination yielded a null result, that is, showed no signature relevant to the question of occurrence or non-occurrence of an SNB. It is worthwhile here to give a brief account of these other data sets.

1. vlf Receiver Data. The EMP and the resulting whistler from even a very small SNB have been detected at distances of hundreds of kilometers, as we reported above (Fig. 19). But standard vlf receiving equipment must be operating in a broadband mode to record these signals (Fig. 19). Such operation, however, quickly fills large amounts of magnetic tape. Consequently, existing equipment is, except for brief planned intervals, typically run in a synoptic mode. The resulting data are not adequate to reveal either an EMP or a whistler. We sought vlf data from several stations and found that the vlf equipment in Syowa, Antarctica was in synoptic mode; that in Halley Bay, Antarctica was not operating; and that in Siple Station, Antarctica was in synoptic mode. Lanzerotti and Park[7] list 12 more Antarctic stations at which vlf receivers exist (or have existed). Our inquiries continue about the status of these.

2. Auroral Measurements

a. All-Sky Camera Data. Lanzerotti and Park[7] list all-sky cameras at two Antarctic stations, Halley Bay and General Belgrano, ~350 km and 450 km, respectively, from the location where TIROS-N recorded the intense electron precipitation (Fig. 1). From these sites, the bright arc that we believe TIROS-N passed over should have been at least marginally visible. However, the camera at Halley Bay was not operating nor was the one at General Belgrano.

The all-sky camera film for 21-22 September 1979 from Molodezhnaya (Fig. 1) was obtained from Russian sources through the services of NOAA's WDC-A for Solar Terrestrial Physics. Molodezhnaya is only ~250 km east-northeast from Syowa, and the auroral patch seen from Syowa occurred about half way between these two stations. Thus, good pictures from Molodezhnaya would help in triangulating on the patch or in further determining its characteristics. But, unfortunately, while the Molodezhnaya film was of high quality, the morning twilight at that more eastern location was intense enough that no auroras could be discerned by the time the Syowa auroral patch occurred.

b. Auroral TV Camera. A very sensitive, wide-field auroral TV camera is installed at Syowa Base. This camera records many pictures per second and might have determined the evolution of the auroral patch (and its time association with the Vela flash) to much higher resolution than the ~10 s resolution of the all-sky camera. However, this camera was not being operated during the night of the Vela event.

3. vlf Transmissions. vlf (~100 Hz to ~100 kHz) waves travel in the spherical wave guide formed by the solid earth and the D-region of the ionosphere. The phase of a received vlf signal is very sensitive to the thickness of the wave guide between the transmitter and receiver and thus to the height of the D-layer. This fact makes it possible to study natural[8,9] and weapon-related[10] perturbations of the ionosphere by monitoring long-path vlf transmissions. There are eight "Omega" vlf

transmitters (~10-13 kHz) around the world that constitute a navigational network. These are routinely monitored by each other and by individuals for various operational and scientific purposes. On the remote possibility that the postulated SNB of 22 September 1979 may have caused significant perturbation of the D-region near South Africa, we examined transmissions along two different paths that cross that region. Neither showed any abnormal variations near the time of the postulated SNB.

4. Geomagnetic Records. Geomagnetic perturbations result from variations of currents flowing in the ionosphere. Thus, one anticipates that a nuclear detonation of sufficient strength to significantly disturb the ionospheric structure might produce a recognizable signature in ground magnetic records. In fact, Unterberger and Byerly[11] recorded a prompt 5-gamma pulse in the magnetic field in California caused by the high-altitude shot Starfish Prime over Johnston Island, ~5000 km away. SNBs are likely to be much less effective in producing geomagnetic perturbations. We have examined magnetic records from Honolulu taken during >1 MT SNBs on Christmas Island and Johnston Island, ~2000 km and ~1200 km distant, respectively. No characteristic signals of these large detonations were recognizable in these records. We obtained the magnetogram for 22 September 1979 from Marion Island, a suggested site of the postulated SNB. No irregularity of that record is seen at or near the supposed event time that cannot be identified as response to a natural geomagnetic variation.

5. Ionosonde Records. Ionosondes transmit a beam of high-frequency radio waves upward to the ionosphere and measure the frequency dependence of the delay of the returned echo. A low-altitude nuclear explosion excites a neutral atmospheric gravity wave that propagates radially outward from the point of the explosion. The interaction between the gravity wave and the ionosphere can set up a travelling ionospheric disturbance (TID) that produces characteristic effects on ionosonde records. Albee and Kanellakos[12] reported that the TID from the megaton range burst, Housatonic, produced observable signals on ionosondes 6600 km away. But this method for detection of nuclear detonations has not been well calibrated for SNBs in the very low (few kiloton) yield range. We are conducting a program of calibration of ionosonde sensitivity to SNBs over a wide range of yields, using available ionosonde records obtained during US nuclear tests in Nevada and in the Pacific. The results of this program and an evaluation of ionosonde data recorded on 22 September 1979 will be presented in a later report.

D. Implications for Future Monitoring Systems

In this study, we have attempted to find evidence in available geophysical data records that would substantiate or refute the hypothesis that an SNB was the cause of the Vela light flash early on 22 September 1979. We have not succeeded in this attempt. We have shown only that the TIROS-N event was, with high probability, a consequence of natural auroral processes and that a localized auroral brightening near Antarctica, coinciding very closely with the Vela flash, could, with indeterminate probability, be either a natural phenomenon or the consequence of an SNB.

In this era of increasing probability of nuclear weapon proliferation, successful monitoring for unannounced tests that may be of any yield, at any altitude, any time, and anywhere on earth requires a detection system that is specifically designed for and dedicated to this mission and that is totally global in its scope.

Nondedicated scientific, commercial, or other systems, either ground- or space-based, are likely to lack sensitivity or to be turned off or in an incorrect mode at event time; and acquisition of data from them is likely to be slow, tedious, uncertain, and perhaps impossible (especially if important recording sites lie in the territory of disinterested or unfriendly countries or in countries that have a vested interest in concealing a test).

Even a dedicated system is not free of the problem of achieving high sensitivity in the presence of natural background signals. Rather, it is designed to maximize the signal-to-noise ratio. It is our impression, having conducted the study described here, that none of the geophysical phenomena that we investigated provide an adequate base for design of a dedicated system filling the detection needs listed at the beginning of this section. Geomagnetic records seem to be quite insensitive to SNBs. Ionosondes sense large SNBs at substantial ranges (thousands of kilometers), but their response to small SNBs is not established, and TIDs occur fairly frequently because of natural processes in the auroral zones. vlf receivers detect the EMP from even small SNBs at ranges approaching 1000 km, but lightning-induced EMPs, entirely similar in character to those of SNBs, occur very frequently and create a serious background. Satellite systems using observations of particles or waves have large natural backgrounds, and the signal of an SNB is likely to be quite localized in the magnetosphere.

In contrast to this assessment, a bhangmeter system, placed on only a few appropriately positioned satellites in Vela-like orbits, affords high sensitivity with good discrimination ability (by pulse shape measuring and interspacecraft comparison) and is completely global in scope.

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