Dr. Vinograd
This includes a fair summary of our knowledge
Tom B.

13. QUANTITATIVE OBSERVATION OF LIGHT FLASH SENSATIONS

EXPERIMENT MA-106

T. F. Budinger,[a†] C. A. Tobias,[a] E. Schopper,[b] J. U. Schott,[b] R. H. Huesman,[a] F. T. Upham,[a] T. F. Wieskamp,[c] J. M. Kucala,[c] F. S. Goulding,[a] D. A. Landis,[a] J. T. Walton,[a] and R. E. Walton[a]

ABSTRACT

Light flashes caused by the interaction of cosmic particles with the visual apparatus have been observed by astronauts on all space missions since Apollo 11. The character of these flashes and the mechanism whereby they are elicited have been investigated both in flight and in ground laboratories for the past several years.

This Apollo-Soyuz Test Project experiment compared measurements of the observer's visual sensitivity with measurements of the ambient radiation environment and with the frequency and character of the flashes observed. The data obtained reveal a latitude dependence of the frequency of observed flashes. This distribution of flashes is correlated with the distribution of cosmic particles with stopping power >15 keV/μm in the eye. The interaction of dark adaptation, specific ionization, and range of particles in the retina as factors in the visualization of particle passage is discussed.

INTRODUCTION

This preliminary report records the quantitative observations of the light flash phenomenon seen by astronauts during the Apollo-Soyuz Test Project (ASTP). The experiment was conducted during two revolutions and consisted of the correlation of precisely reported visual phenomena noted by two astronauts with the measured and calculated cosmic particle environment near the astronauts' heads. This was the sixth mission during which planned observations of the light flash phenomenon were made.

---

[a]Lawrence Berkeley Laboratory, University of California at Berkeley.
[b]University of Frankfurt.
[c]Lawrence Livermore Laboratory.
[†]Principal Investigator.

BACKGROUND

Astronauts on Apollo 11 and subsequent missions (including Skylab) have observed randomly occurring visual phenomena that consist of the perception of tiny, brief, starlike flashes of white light or pencil-thin streaks of light. These observations were made when the interior of the spacecraft was darkened. Examples of the types of phenomena seen are shown in figure 13-1, which is based on descriptions by Apollo and Skylab crews as well as descriptions from Earth-based experiments with accelerated charged particles. Not all of these visual effects were seen during the ASTP mission. During the last six Apollo missions, and on a few occasions during Skylab, crews made both scheduled and unscheduled observations of the frequency and character of these events (refs. 13-1 to 13-6). These observations can be summarized as follows. After approximately 17 minutes of dark adaptation, tiny dots and thin streaks of white light were seen at frequencies of about 3 events/min by astronauts during the translunar or transearth coast phases of the Apollo missions or the polar part of Skylab orbits. Near the South Atlantic Anomaly (SAA), where the proton flux is 1000 times or more greater than in other parts of the orbit, the frequency increased to about 15 events/min (ref. 13-6) for Skylab altitudes of 443 kilometers.

The Apollo 11 lunar module pilot first reported these visual phenomena, which were predicted in 1952 by C. A. Tobias (ref. 13-7) who hypothesized that astronauts were likely to see flashes of light from cosmic particles when they were outside the shielding provided by the magnetic field of the Earth. The site of action of these cosmic particles, and whether cosmic particles actually caused the light flash phenomenon, were subjects of conjecture in 1970 when this phenomenon was first reported. Many known causes for luminous phosphenes exist, including ionizing radiation, mechanical pressure, electrical currents, magnetic fields, stimulation of the cerebral cortex, and central nervous system pathological conditions. For example, flashes can be seen during stages of retinal detachment, and the retina is sensitive to externally applied currents as small as 0.3 milliampere. In 1970, these phenomena were believed to be caused by carbon, nitrogen, and oxygen nuclei which traverse the spacecraft and the body at frequencies of 1 to 2 nuclei/min/cm^2 when outside the magnetic shielding of the Earth. Of continuing controversy is the conjecture that the major mechanism for these visual phenomena is Cerenkov radiation (refs. 13-8 to 13-11).

In 1970, a series of experiments was undertaken to determine whether carbon, nitrogen, and oxygen of approximately 300 MeV/amu and other ions with equivalent ionizing characteristics could cause qualitatively the same phenomena seen by astronauts. In a series of experiments using neutrons of 630 megaelectronvolt energy (ref. 13-12), neutrons of approximately 8 megaelectronvolt energy (ref. 13-13), helium ions from the 467-centimeter (184 inch) cyclotron at 230 MeV/nucleon (ref. 13-14), and nitrogen ions accelerated to approximately 260 MeV/nucleon at the bevatron (ref. 13-15), ionizing particles with a stopping power of approximately 10 keV/μm or greater caused similar phenomena. These experiments demonstrated that ionization or electronic excitation from cosmic particles could adequately account for the light flash phenomenon. Cerenkov light is produced by particles with velocities greater than those used in the experiments just described; therefore, it was concluded that whereas Cerenkov radiation might cause similar phenomena, it was not the predominant mechanism. The exact mechanism whereby the retina is stimulated by ionizing particles at velocities below those necessary for emission of Cerenkov light is still unclear. Experiments in which nitrogen ions were stopped in nine positions in the cerebral cortex have shown that the brain and the optic nerve are not stimulated by ions (ref. 13-15). Possibilities are electronic excitation resulting in near-ultraviolet (uv) radiation in the vicinity of the retina, ionization in a confined region associated with delta rays around the ion track, or a shock wave phenomenon from energetic charged particles passing through the tissue matrix.

The purpose of this experiment was to ascertain quantitatively the frequency, character, latitudinal dependence, and identity of cosmic particles that cause the light flash phenomenon. The ultimate objective was the assessment of radiation hazards for long-term Earth-orbiting and interplanetary missions. The special features of this experiment included measurement of dark adaptation, measurement of the characteristics of the cosmic particle environment in the vicinity of the eye, and continuous onboard accumulation of the light flash observations from astronauts and particle detectors throughout one continuous revolution.

EXPERIMENT PROTOCOL

Two revolutions were devoted to this experiment. During revolution 110, the silicon telescope-spectrometer was deployed for the measurement of the trajectory, atomic charge Z, and velocity of cosmic particles with a stopping power of 10 keV/µm or greater. During revolution 111, the Apollo commander and the command module pilot made continuous observations of visual sensations while dark adapted. The docking module pilot (DMP) operated the experiment control unit, which received data from the silicon detectors as well as from silver chloride cadmium-doped (AgCl(Cd)) crystals that were used to register particle tracks in four sectors of the orbit corresponding to northern latitudes, equatorial latitudes, the SAA, and southern latitudes.

The experiment commenced with the detector-alone orbit according to the Flight Plan at approximately 13:40 GMT on July 22, 1975. The manned orbit, revolution 111, began according to the Flight Plan at approximately 14:45 GMT, at which time the spacecraft was maneuvering to proper attitude because the attitude for revolution 110 was not optimum. Approximately 10 minutes later, the observing crewmembers had reached dark adaption. The first light flash was reported at 15:00 GMT at latitude 49° N when the spacecraft was approaching the northernmost point of the orbit. At each event, a pushbutton signal from the observing astronaut was recorded on the digital tape and the verbal description was recorded on the onboard tape recorder. The DMP switched the lighting for the AgCl(Cd) crystal compartments according to the Flight Plan at 17, 39, and 54 minutes after commencement of revolution 111. The experiment was terminated at 16:50 GMT. In accordance with the Flight Plan, the digital tapes, voice tapes, detector boxes, and masks were returned to the experimenters. The digital tapes were transported to the Lawrence Berkeley Laboratory (LBL) for analysis, and the AgCl(Cd) crystals were transported to Frankfurt, Germany, where they had been produced and calibrated.

EQUIPMENT

The hardware for the experiment consisted of two dark adaption masks, two pushbuttons, two cosmic-particle detector boxes, and a control and power unit that housed a data tape. The masks and pushbuttons were manned by two astronauts and the control and power unit was controlled by the third astronaut, who monitored the experiment (figs. 13-2 to 13-4).

Dark Adaption Masks

Each dark adaption mask was made of Lexan plastic approximately 2 millimeters thick and was fitted with a light-emitting diode (LED) behind a pinhole aperture approximately 2 centimeters from one eye. The masks, held to the head by straps, were fabricated from molds of each astronaut's head. The head molds were made by the LBL group using techniques adapted from fabrication of similar molds used for head positioning in radiotherapy of the pituitary gland. Plaster of paris head casts were made from the molds. The Lexan masks were then made by pressing near-molten Lexan over these head casts. A foam rubber insert was used to ensure a perfect light-tight fit, and each mask was then custom fitted to each crewmember.

The effective brightness of the LED was controlled by the duration of a constant voltage. The duration ranged from 5 microseconds to 1.7 milliseconds in six different levels and produced the expected response on normal subjects in terms of the rapidity with which each level of dark adaption was reached. Level 5 was reached approximately 15 minutes after commencement of dark adaption.

Pushbuttons

Events noted by astronauts were recorded on digital tape by means of a handheld pushbutton switch.

Detector Boxes

Each of the two detector units contained AgCl(Cd) crystals and a silicon solid-state telescope-spectrometer. Each detector box was composed of two units. The first unit (4.1 by 5.5 by 12.7 centimeters) was an aluminum housing in which there were four compartments (each 1.84 by 3.5 by 2.75 centimeters) for AgCl(Cd) crystals and small lights. The AgCl(Cd) crystals were 1- by 2-centimeter wafers 0.03 centimeter thick. Two crystals were placed in each compartment on either side of two white 6-volt lights, which were filtered to give predominantly yellow light by using 0.06-centimeter-thick Kapton plastic sheets between the lights and crystals.

The AgCl(Cd) crystals are nuclear particle detectors developed in Germany (ref. 13-16). They are similar to nuclear emulsions but have a unique property that allows evaluation of the time at which a particle traverses the detector. A nuclear particle passing through the crystal leaves a latent track of dislocated electrons and displaced silver or cadmium atoms. Within a few minutes, the migration of electrons and atoms will return the crystal to its original condition. However, if the crystal is exposed to visual spectrum photons, the latent track is fixed or stabilized. Hours or weeks later, if the crystal is exposed to ultraviolet light, the stabilized but still invisible tracks are developed, thus giving a permanent record of the nuclear particle track. The distribution of residual silver around the track is related to the charge and velocity of the ion as well as to the intensity and spectrum of the near-ultraviolet light used to develop the stabilized tracks. The time period between implantation of a latent track and fading is a few minutes, but the period between the time a stabilized track is made and fading is more than 1 week. Crystals were loaded into each of four compartments so that the particle environment could be measured in the four sectors of the orbit corresponding to the northern latitudes, the equatorial latitudes, the SAA, and the remaining minutes of the orbit over the Pacific Ocean.

The second unit (4.3 by 9.6 by 12.7 centimeters) of each detector box housed the electronic detector, which consisted of two sets of silicon solid-state wafers. Each set consisted of two individual wafers 1.7 centimeters in diameter and 0.03 centimeter thick. On each wafer were four active strips each 3 millimeters wide separated by 0.5 millimeter. The telescope was made by rotating one wafer 90° from the other. This set of two wafers gave 16 possible combinations (4 by 4) for particle position. The second set of two wafers was placed 1.5 centimeters from the first set, and a 0.5-centimeter-thick copper energy degrader was placed between the sets. This arrangement allowed measurement of the trajectory and energy loss of particles passing through the telescope.

The accuracy of energy and trajectory measurements is 5 percent. From these measurements, the most likely charge and velocity of the detected particle can be deduced, using the curves of figure 13-5. The threshold for the device is 10 keV/μm.

Control and Power Unit

The control and power unit consisted of power distribution, logic circuits, and a digital cassette tape recorder that received 16-bit word groups from the observer pushbuttons and the silicon detectors. The word groups from the silicon detectors contained information on the trajectory and energy loss of particles that passed through the silicon detector. Elapsed time and detector selector switch position information were also recorded.

PROCEDURES FOR DATA REDUCTION

Descriptions of the events observed by the crewmembers were recorded on the onboard voice recorder. The tapes were transcribed, and each event was related to the orbital position of the spacecraft. Events from the silicon detectors and pushbuttons and the status of the control unit were read from the digital tape by a specially constructed microprocessor. The pushbutton events and time marks were related to the verbal reports. The energy and trajectory information is being reduced in terms of particle velocity and most likely charge Z (fig. 13-5).

The AgCl(Cd) crystals were transported to Frankfurt, Germany, where they had been produced and calibrated. These crystals are being analyzed for the abundance of tracks that are related to protons, alpha particles, or heavier ions. The data are further separated into categories of stopping power and direction.

The characteristics of the cosmic particle environment inside the spacecraft were determined by converting the spectrum and abundance of particles outside the spacecraft to the number of particles with various stopping powers and residual ranges, using shielding data for 512 sectors of solid angle around the spacecraft. The shielding data were supplied by the NASA Lyndon B. Johnson Space Center.

The input abundances from free space for $Z > 3$ were obtained from Webber et al. (ref. 13-17), and the abundances for hydrogen and helium were obtained from Smith et al. (ref. 13-18). The spectra were assumed to be the same as those for carbon and oxygen, which were obtained from Juliusson (ref. 13-19). These free-space abundances were converted to the abundance outside the spacecraft at a 225-kilometer altitude using the spacecraft orbital parameters and B[1] and L[2] data obtained from the 99-term field of Hendricks and Cain (ref. 13-20) extrapolated to 1975. Vertical rigidity cutoffs were estimated by the empirical formula $P_c = 15.96\ L^{-2.005}$ from Smart and Shea (ref. 13-21). The present spacecraft orbit routine is based on the Flight Plan and assumed circular orbit because the ephemeris data are not yet available.

The energy-range relationship was derived from an empirical formula that gives range R as a function of kinetic energy:

$$R = \frac{\alpha A}{Z^2}\left(\frac{E}{A}\right)^{\beta} \qquad (13\text{-}1)$$

where A is the atomic number, Z is the charge, and E is the kinetic energy in MeV/amu.

For passage of ions through the spacecraft, aluminum shielding is assumed. Thus, the constants are $\alpha = 2.811 \times 10^{-3}$ and $\beta = 1.775$. The stopping power S is given as

$$S = \frac{Z^2}{\alpha\beta}\left(\frac{E}{A}\right)^{1-\beta} \qquad (13\text{-}2)$$

---

[1]Geomagnetic field strength.

[2]Distance from the center of the Earth in Earth radii.

Energy transfer in the eye is calculated using equation (13-2) and $\alpha = 1.88 \times 10^{-3}$ and $\beta = 1.802$.

RESULTS

The distribution of visual events reported by astronauts is shown along the track line in figure 13-6. Histograms depicting the frequency of events in time and with respect to latitude are shown in figures 13-7(a) and 13-7(b). Because the spacecraft transited latitudes for varying time intervals, normalization to equal time intervals is shown in figure 13-7(c).

A total of 82 events was reported by the two astronauts (table 13-I). No increased activity in the SAA and no graying of the darkened visual fields occurred. The relative expected distribution of cosmic particles with stopping power of greater than 15 keV/μm in the eye is superposed on the histogram of reported events in figure 13-8.

DISCUSSION

The results of the light flash experiment indicate that the abundance of ions that cause the light flash phenomena is minimal between latitudes 30° N and 30° S. The frequency of light flash events between latitudes 30° N and 50° N and 30° S and 50° S is 25 times that noted in equatorial latitudes. There were no reports of increased flash phenomena through the SAA, as might be expected from a Skylab 4 report of increased activity through the SAA (ref. 13-15). However, at the 225-kilometer altitude of the ASTP spacecraft, the proton flux is much less than at the Skylab altitudes, which were approximately 440 kilometers. Also, the shielding of the Apollo spacecraft is greater than that of Skylab.

Through the SAA, the number of protons with a stopping power of 15 keV/μm that would intersect the astronaut's eye was approximately 2 protons/min for each eye under the shielding conditions of the Apollo spacecraft. The range of these particles in the retina is approximately 100 micrometers. Based on the assumption that protons with a stopping power of this energy will produce visual phenomena and on the fact that two observers reported events at less than 1 event/min through the SAA, the efficiency is concluded to be approximately 10 percent. If the threshold is 10 keV/μm, then the efficiency is reduced to 5 percent. The efficiency should be a function of stopping power. Ground-based experiments with stopping protons are being conducted to corroborate these observations.

The expected flux of heavy particles in the northernmost and southernmost points of the orbits is 1 to 2 particles/min for each eye. Thus, the efficiency for seeing high charge energy (HZE) particles is approximately 50 percent for the dark-adapted eye. The abundance of heavy ions with various stopping powers is being calculated as previously described. The efficiency and character of light flashes should be a function of the stopping power and the velocity of the particle, because the range of the effective radiation around the particle track will increase as the velocity increases. Thus, a slow helium ion with a stopping power of 20 keV/μm might give a thinner and less efficiently seen streak than an iron particle at the same stopping power, because the distribution of delta rays is much greater in the latter situation.

REFERENCES

13-1. Chapman, P. K.; Pinsky, L. S.; Benson, R. E.; and Budinger, T. F.: Observations of Cosmic Ray Induced Phosphenes. Proceedings of the National Symposium on Natural and Manmade Radiation in Space (E. A. Warren, ed.). NASA TM X-2440, 1972, pp. 1002-1006.

13-2. Budinger, T. F.; Tobias, C. A.; Lyman, J. T.; Chapman, P. K.; et al.: Light Flash Phenomenon Seen by Astronauts. Proceedings of the Colloquium on Space Biology Related to Post-Apollo Program. ESRO, Paris, France, 1971, p. 209.

13-3. Benson, R. E.; and Pinsky, L. S.: Visual Light Flash Phenomenon. Sec. 27, Part C, of the Apollo 16 Preliminary Science Report. NASA SP-315, 1972.

13-4. Pinsky, L. S.; Osborne, W. Z.; and Bailey, J. V.: Visual Light Flash Phenomenon. Sec. 27 of the Apollo 17 Preliminary Science Report. NASA SP-330, 1973.

13-5. Pinsky, L. S.; Osborne, W. Z.; Bailey, J. V.; Benson, R. E.; and Thompson, L. F.: Light Flashes Observed by Astronauts on Apollo 11 Through Apollo 17. Science, vol. 183, no. 4120, Mar. 8, 1974, pp. 957-959.

13-6. Pinsky, L. S.; Osborne, W. Z.; Bailey, J. V.; and Hoffman, R. A.: Light Flashes Observed by Astronauts on Skylab 4. Science, vol. 188, no. 4191, May 30, 1975, pp. 928-930.

13-7. Tobias, C. A.: Radiation Hazards in High Altitude Aviation. J. Aviation Med., vol. 23, 1952, p. 345.

13-8. Fazio, G. G.; Jelley, J. V.; and Charman, W. N.: Generation of Cerenkov Light Flashes by Cosmic Radiation Within the Eyes of the Apollo Astronauts. Nature, vol. 228, no. 5268, Oct. 17, 1970, pp. 260-264.

13-9. McNulty, P. J.: Light Flashes Produced in the Human Eye by Extremely Relativistic Means. Nature, vol. 234, no. 5323, Nov. 12, 1971, p. 110.

13-10. McNulty, P. J.; Pease, V. P.; Pinsky, L. S.; Bond, V. P.; et al.: Visual Sensations Induced by Relativistic Nitrogen Nuclei. Science, vol. 178, no. 4056, Oct. 13, 1972, p. 160.

13-11. McNulty, P. J.; Pease, V. P.; and Bond, V. P.: Visual Sensations Induced by Cerenkov Radiation. Science, vol. 189, no. 4201, Aug. 8, 1975, pp. 453-454.

13-12. Tobias, C. A.; Budinger, T. F.; and Lyman, J. T.: Radiation-Induced Light Flashes Observed by Human Subjects in Fast Neutron, X-ray, and Positive Pion Beams. Nature, vol. 230, Apr. 30, 1971, pp. 596-597.

13-13. Budinger, T. F.; Bichsel, H.; and Tobias, C. A.: Visual Phenomena Noted by Human Subjects on Exposure to Neutrons of Energies Less Than 25 Million Electron Volts. Science, vol. 172, no. 3978, May 21, 1971, pp. 868-870.

13-14. Tobias, C. A.; Budinger, T. F.; and Lyman, J. T.: Biological Effects Due to Single Accelerated Heavy Particles - Problems of Nervous System Exposure in Space. In Life Sciences and Space Research XI (P. H. A. Sneath, ed.). Academie-Verlag (Berlin), 1973, p. 233.

13-15. Budinger, T. F.; Lyman, J. T.; and Tobias, C. A.: Visual Perception of Accelerated Nitrogen Nuclei Interacting With the Human Retina. Nature, vol. 239, no. 5369, Sept. 22, 1972, pp. 209-211.

13-16. Schott, J.-U.: Eigenshaften von AgCl(Cd)-Kristallen als Teilchenspur-Detektoren. Ph. D. Thesis, Institut für Kernphysik der Johann Wolfgang Goethe-Universität Frankfurt Am Main, 1974.

13-17. Webber, W. R.; Damle, S. V.; and Kish, J.: Studies of the Chemical Composition of Cosmic Rays with Z = 3-30 at High and Low Energies. Astrophys. Space Sci., vol. 15, Feb. 1972, pp. 245-271.

13-18. Smith, L. H.; Buffington, A.; Smoot, G. F.; Alvarez, L. W.; and Wahlig, M. A.: A Measurement of Cosmic-Ray Rigidity Spectra Above 5 GV/c of Elements From Hydrogen to Iron. Astrophys. J., vol. 180, no. 3, Mar. 1973, pp. 987-1010.

13-19. Juliusson, E.: Cosmic Rays at Very High Energies. Vol. I, Proceedings of the 13th International Cosmic Ray Conference 1974, pp. 373-377.

13-20. Hendricks, S. J.; and Cain, J. C.: Magnetic Field Data for Trapped-Particle Evaluations. J. Geophys. Res., vol. 71, no. 1, Jan. 1, 1966, pp. 346-349.

13-21. Smart, D. F.; and Shea, M. A.: A Study of the Effectiveness of the McIlwain Coordinates in Estimating Cosmic-Ray Vertical Cutoff Rigidities. J. Geophys. Res., vol. 72, no. 13, July 1, 1967, pp. 3447-3454.

TABLE 13-I.- SUMMARY OF EVENTS

Track sector	Stars	Streaks	Commas	Total
Northernmost point of orbit to Florida	[a]12	[b]6	2	20
Florida to Brazil	2	3	0	5
SAA	2	1	0	3
SAA to completion of orbit	27	16	11	54

[a]Includes events expressed as supernova in figure 13-6.

[b]Includes events expressed as hotdogs in figure 13-6.

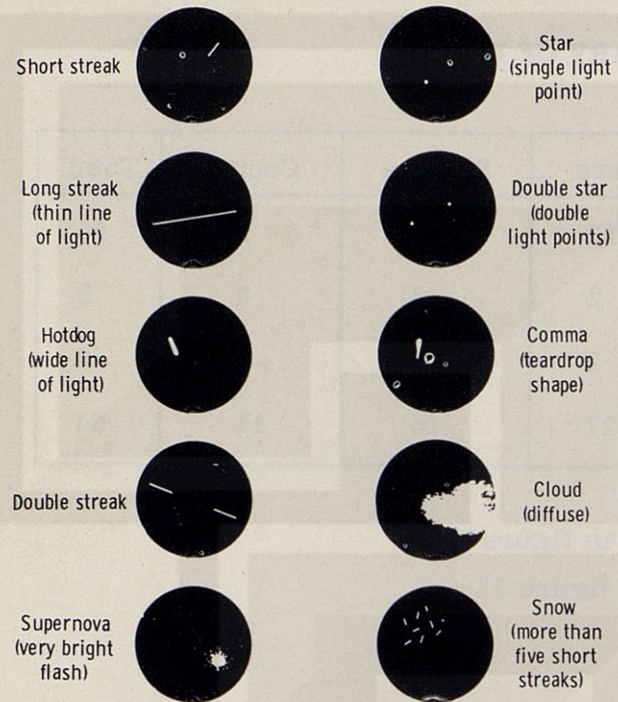


Figure 13-1.- Reproduction of visual events noted in space and in cyclotron experiments.

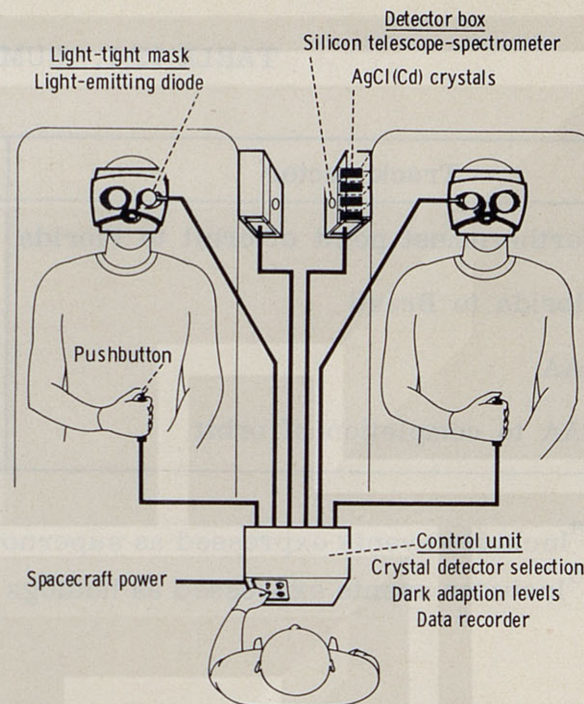


Figure 13-2.- Experiment layout.

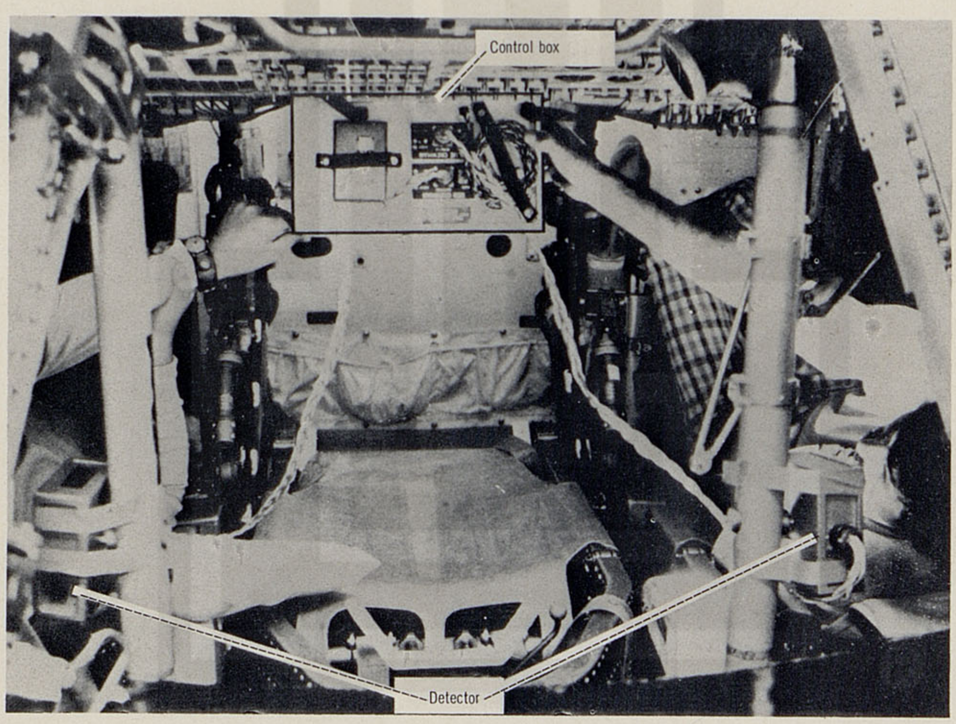


Figure 13-3.- Position of equipment in spacecraft.

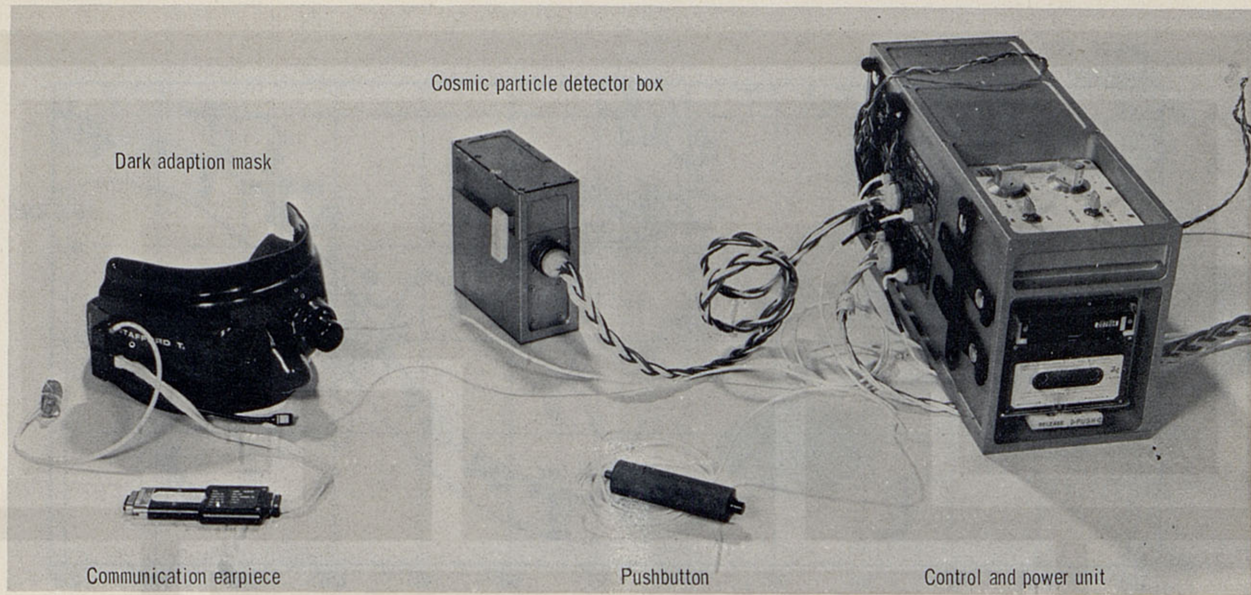


Figure 13-4.- Experiment hardware.

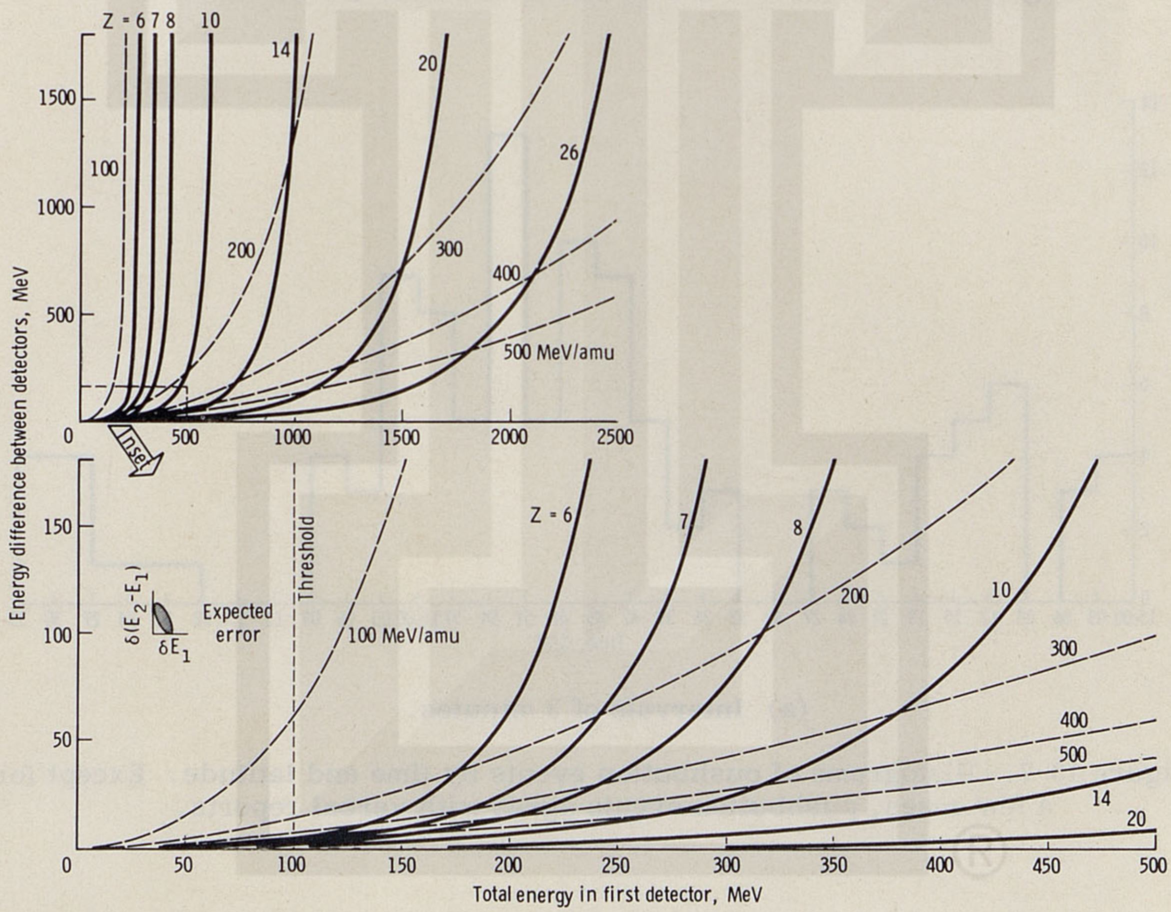


Figure 13-5.- Relationship between silicon detector response, particle charge, and velocity.

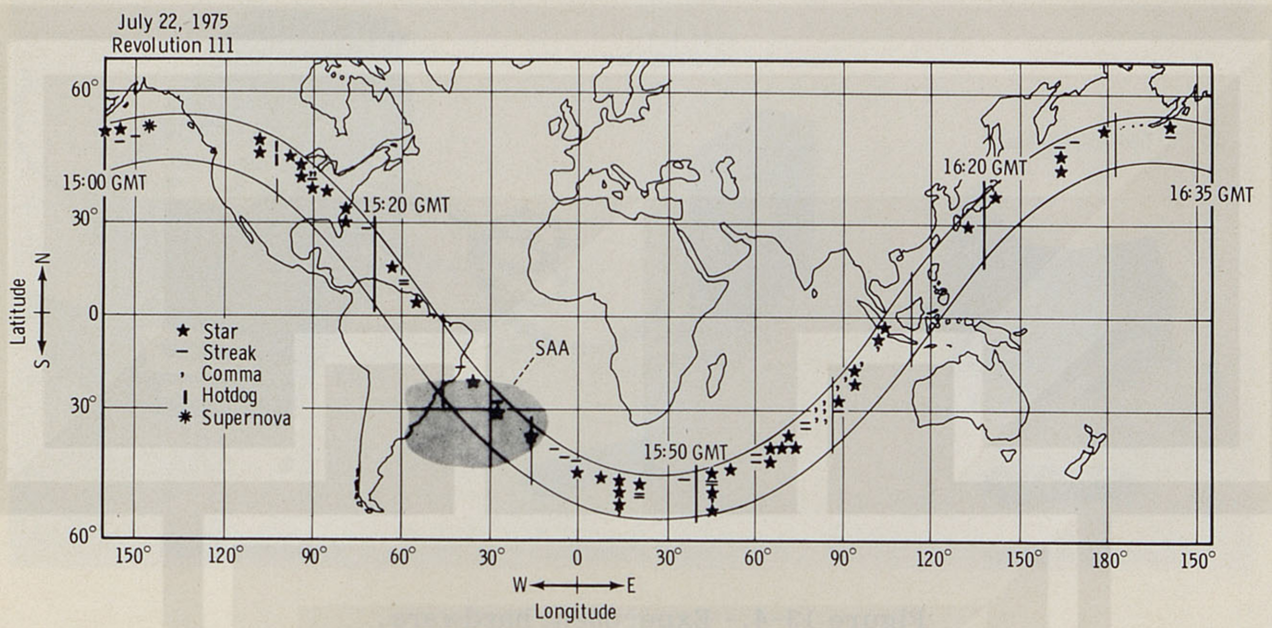
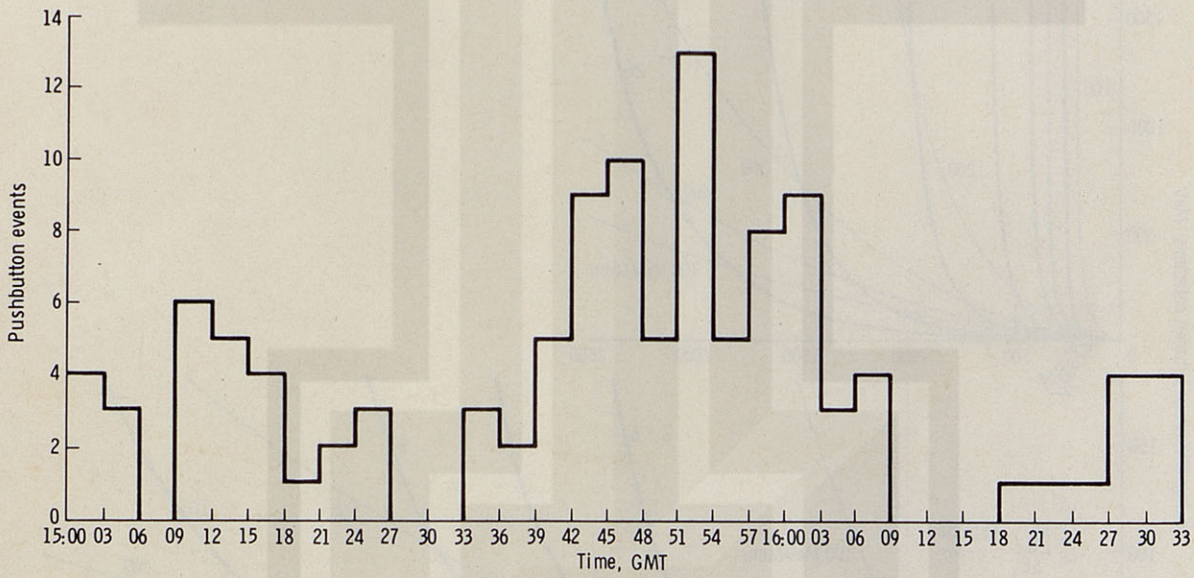
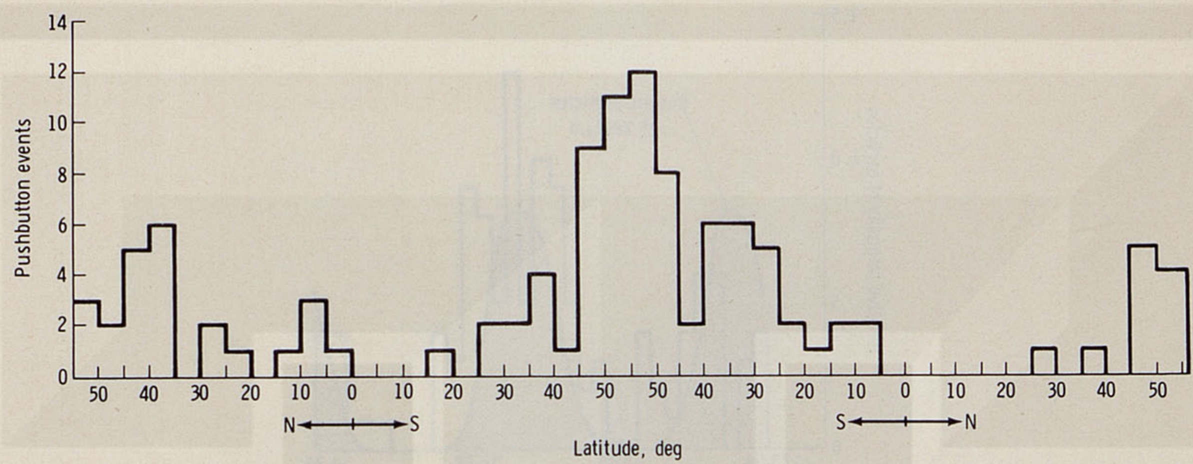


Figure 13-6.- Orbit track and distribution of reported events.

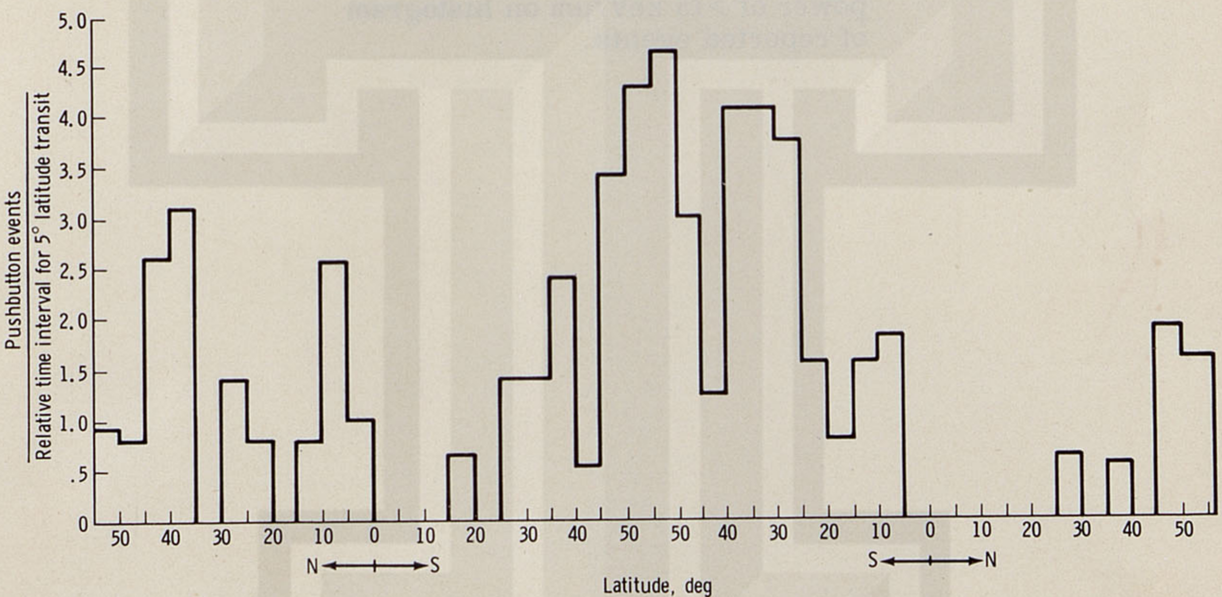


(a) Intervals of 3 minutes.

Figure 13-7.- Histograms of pushbutton events by time and latitude. Except for a few cases, pushbutton events agree with verbal reports.



(b) Intervals of 5° latitude.



(c) Intervals of 5° latitude normalized by time intervals.

Figure 13-7.- Concluded.

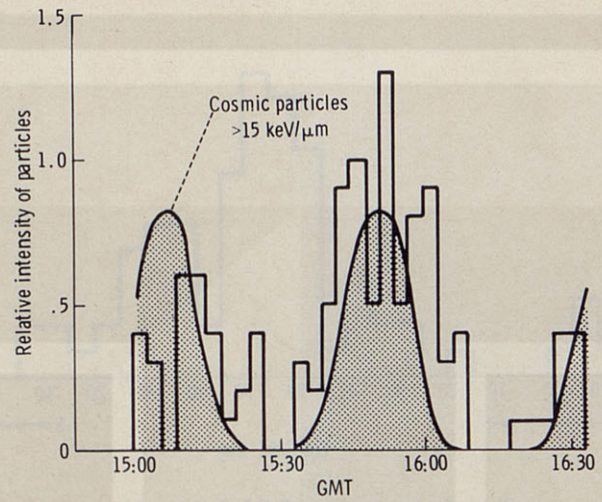


Figure 13-8.- Superposition of relative number of events with a stopping power of >15 keV/μm on histogram of reported events.