Reports

Light Flashes Observed by Astronauts on Skylab 4

Abstract. *Two dedicated light flash observing sessions were conducted by one of the crewmen during the Skylab 4 mission. Analyses of his observations reveal a strong correlation between flash frequency and primary cosmic-ray flux, and an even stronger correlation between flash frequency and the South Atlantic Anomaly (SAA) region of the inner belt trapped radiation. Calculations indicate that an all-proton inner belt probably cannot produce the observed SAA flash rate, and they suggest that there may exist a previously unobserved inner belt flux of multiply charged nuclei.*

During the first 3 weeks of Skylab 4, the third and final manned Skylab mission, Dr. Edward Gibson, the science pilot (SPT), and Lt. Col. William Pogue, the pilot (PLT), reported observing occasional 5- to 10-minute bursts of intense visual light flash activity. These phenomena were seen only during crew sleep periods at times when the crewmen were awake in their darkened sleep compartments. On one occasion the SPT was able to associate the occurrence of this phenomenon with the passage of the spacecraft through the portion of the earth's inner trapped radiation belt known as the South Atlantic Anomaly (SAA) (*1*). These reports prompted two separate dedicated light flash observing sessions which were conducted by the PLT. His observations are the subject of this report.

The first session started at 14:56 G.M.T. on the 74th day of the mission (28 January 1974) and lasted 70 minutes. The second session started at 14:27 G.M.T. on the 81st day of the mission (4 February 1974) and lasted 55 minutes. For both sessions the PLT wore a pair of light-tight goggles and was located in his sleep compartment. This location afforded a minimum shielding of $\sim$ 1.5 to 2 g per square centimeter of aluminum over a solid angle of about 1.5π steradians. The remainder of the total solid angle was increasingly more heavily shielded. The PLT's observations were recorded with one of the on-board tape recorders and transmitted to the ground immediately after each session. The observer indicated an event by saying "mark," and then indicating in which eye the event was seen and its classification (that is, spot, streak, cloud, or whatever).

It is generally believed that the flashes are caused by charged particles passing through the eyes of the observer (*2, 3*), and that the eye must be dark-adapted in order that the phenomenon be perceived. The charged particle flux at Skylab orbital altitudes ($\sim$ 443 km) consists of primary cosmic rays and (during parts of some orbits) much less energetic geomagnetically trapped particles from the inner radiation belt.

The primary cosmic-ray flux, which includes energetic heavy nuclei as well as protons and electrons, is modulated by the geomagnetic field in such a way that only particles with rigidities (the momentum divided by the charge) above a certain threshold value can reach orbital altitudes. This value, referred to as the geomagnetic rigidity cutoff, increases monotonically as one moves from either geomagnetic pole toward the geomagnetic equator. Thus the total primary cosmic-ray flux near the earth decreases with decreasing geomagnetic latitude.

The only significant contribution to the charged particle flux from the inner trapped radiation belt at the Skylab orbital inclination of $\sim 50.5°$ occurred in the SAA. It is known that the inner radiation belt

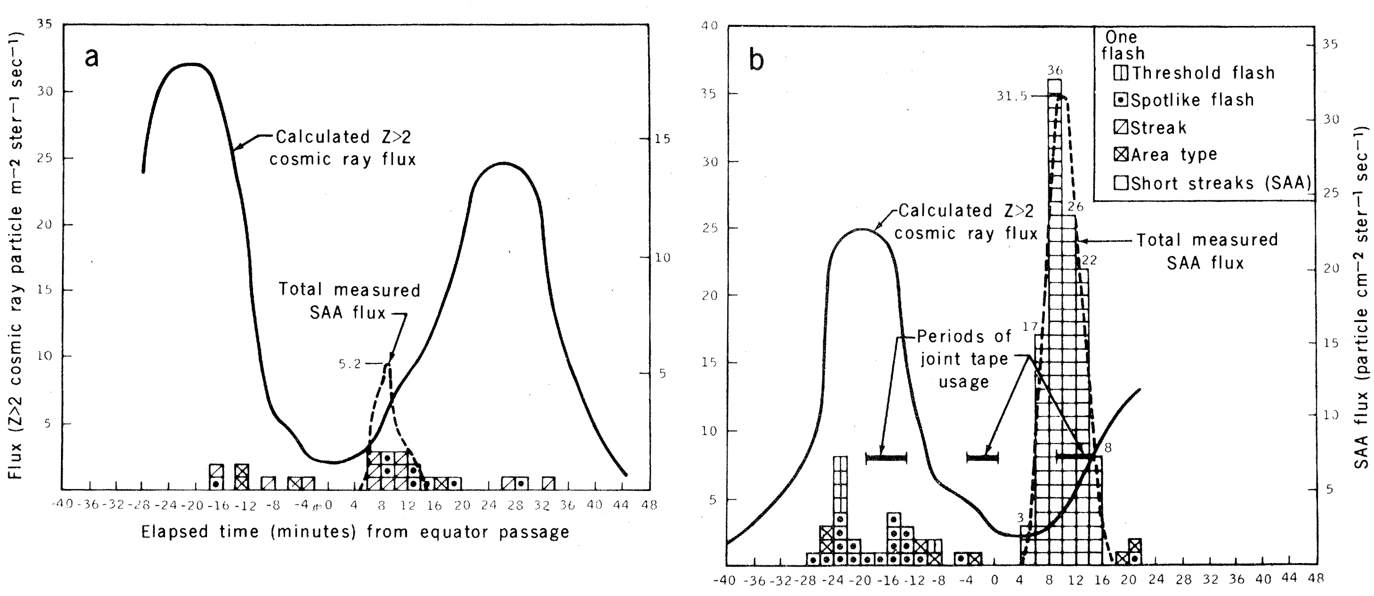

Fig. 1. Results of the first light flash observing session (a) and the second light flash observing session (b). Individual flashes are represented in histogram fashion versus time and compared with the calculated $Z > 2$ primary cosmic-ray flux (left scale). Also shown (dotted line referring to the right scale) is the measured $Z \geq 1$ SAA flux for each session. The types of events are indicated schematically.

contains protons and electrons, but no multiply charged particles have yet been reported. The current upper limit for multiply charged particles, that is, Z (atomic number) ≥ 2, trapped in the inner radiation belt is < 1 particle per 1000 trapped protons (*4*).

Since the rigidity spectrum of the cosmic-ray flux is very well known, one can accurately calculate the ambient cosmic-ray flux as a function of time during each of the two sessions. Figure 1 shows plots of the results from such calculations, as well as a histogram representation (2-minute time bins) of the 24 flashes reported during the first session and the 144 flashes reported during the second session. The flash classifications are indicated on the histogram. During the second session the PLT reported five separate "threshold flashes" that he was unable to characterize as being different from his normal phosphene background. These flashes are indicated in Fig. 1, but are not included in subsequent calculations, an exclusion that has no significant effects. Also indicated in Fig. 1 are the measurements of the > 75-Mev SAA flux made during the light flash observing session by the on-board active dosimetry system which included the ionization chamber Van Allen Belt Dosimeter (VABD) (*5*) located about 2 m from the observer in a similarly shielded area and the externally mounted Si(Li) Electron Proton Spectrometer (EPS) (*6*). Neither of these detectors determines particle charge. Both detectors are nondirectional, and the VABD had a more or less isotropic response. The responses of the two detectors are in good agreement with each other, and with earlier SAA flux measurements.

All of the flashes reported in the SAA during the second session were described as "short streaks" or "tadpoles." The PLT used the two terms interchangeably to describe sharp, straight, well-defined streaks that appeared "about 3/8 of an inch [0.95 cm] long at arm's length." He further commented that some appeared to have a spotlike head on one end, and that there did not seem to be any preferential orientation or location in the visual field. The flashes reported during the peripheral pass through the SAA in the first session included, in addition to short streaks, some spots and cloudlike flashes similar to some of those reported outside of the SAA and during the Apollo observations (*7*).

At times during the second session, Col. Gerald Carr, the commander, was using the same tape to make comments concerning another experiment. These times are indicated in Fig. 1. It is probable that the PLT was inhibited from making responses in periods of joint tape usage, and this affected the data during periods of high flash rates in the SAA much more so than it did in periods of the lower flash rates outside the SAA. Both crewmen concur with this observation. Thus, in our investigation of the correlation of the observed flash rates in the SAA with particle flux, we considered only the data obtained while the PLT had sole use of the tape.

If one assembles the data from the SAA pass during the second session into 1-minute time bins, then a correlation coefficient between the measured fluxes and the reported flashes can be calculated (*8*). Such a calculation yields a value of 0.95, which implies an excellent correlation. One can also calculate the ratio of the flash rate to the flux with the maximum likelihood method. If it is assumed that the flash rate is a linear function of the flux, then the ratio is $0.42 \pm ^{0.07}_{0.06}$, where the flash rate is in flashes per minute, and the flux ($Z > 1$, kinetic energy $\gtrsim$ 75 Mev/nucleon) is in particles per square centimeter per steradian per second as measured by the EPS. A similar calculation for the peripheral pass through the SAA during the first session yields a value of $0.49 \pm ^{0.16}_{0.13}$. The number of flashes reported during the first session is too small to allow the calculation of a meaningful correlation coefficient.

These techniques can also be applied to the flashes observed outside the SAA, where the measured fluxes are replaced by the calculated fluxes shown in Fig. 1. In this case the calculated fluxes are for the Z > 2 primary cosmic rays. The $Z \leq 2$ primary cosmic rays were not included because it is probable that the energy deposited by these relatively fast particles is not sufficient to cause the observed flashes.

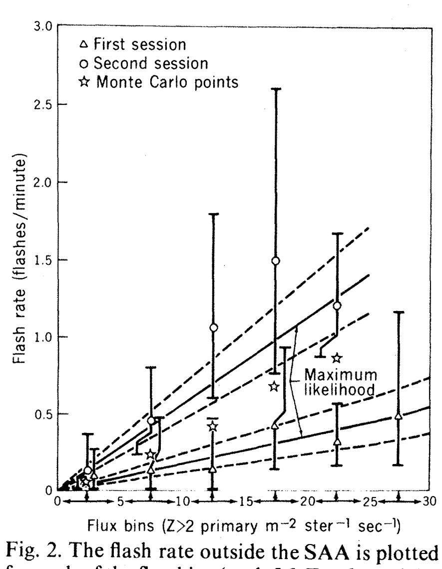

Fig. 2. The flash rate outside the SAA is plotted for each of the flux bins (each 5.0 $Z > 2$ particles per square meter per steradian per second wide) indicated. The total observing time and the number of flashes seen while in each flux region were compiled for each session, and the errors reflect the differing amount of time spent in each flux region. The maximum likelihood errors are indicated by the dotted lines which represent one standard deviation from a two-parameter linear function.

For the first session there were 53 1-minute time bins, excluding the SAA pass and the initial 10-minute dark-adapting period prior to the first flash. The flash rate/flux ratio for this time was $0.017 \pm ^{0.006}_{0.006}$ flashes per $Z > 2$ primary cosmic-ray particles per square meter per steradian per second. The same calculation for the 38 1-minute time bins after dark adaptation and excluding the SAA during the second session yields a ratio of $0.056 \pm ^{0.012}_{0.010}$. We grouped the observing time from each session into flux bins, each of them 5.0 $Z > 2$ primary cosmic-ray particles per square meter per steradian per second wide. If we consider each flux bin to be a distinct observing session with an approximately constant flux, we can calculate the flash rate/flux ratio for each flux bin and obtain the results shown in Fig. 2. The errors shown in Fig. 2 account for the statistical deviations as well as the differing lengths of time spent in sampling each flux bin.

It is convenient to separate these results into two groups—those from within the SAA and those from outside the SAA. There are several conclusions that can be drawn from the non-SAA data. First, both sessions began with about 10 minutes during which there was an absence of flashes while the observer was dark-adapting. This finding reinforces the already generally accepted view that one must be reasonably well dark-adapted to observe the flashes. Second, on the basis of the results shown in Fig. 2, we believe that there is a strong correlation between the flash rate and the calculated primary cosmic-ray flux. This is the first direct evidence that the light flashes seen in space are in fact correlated with charged particles in general and cosmic rays in particular. Finally, the non-SAA flash rate/flux ratios for the two sessions are not in good agreement. This difference might have been caused by physiological or psychological factors—experience has shown that individual sensitivity may vary considerably. However, any proposed explanation must take into account the fact that the flash rate/flux ratio in the SAA was comparable for the two sessions. Even so, we believe that this is not of fundamental significance, and we do not wish to enter into speculation about possible differences.

It is apparent that very high flash rates (relative to those outside the SAA) occur in the SAA, and that these flashes are strongly correlated with the measured $Z \geq 1$ flux. This is surprising because available evidence indicates that protons cannot directly produce such effects. Rather, large fluxes of slow protons have been thought to be capable of producing only a "haze or graying of the visual field" (*3*). Such an effect, "like snow on a TV screen," was reported in addition to the distinct flashes in the SAA during the second session, but the PLT could not distinguish this phenomenon from normal background visual phosphenes or "noise." He did remark, however, that this "noise" was gone and that he was seeing "just darkness" immediately after exiting the SAA. If the protons do not cause the flashes directly, then we are left with two immediate alternatives. Either the flashes were caused by heavier ($Z \geq 2$) secondaries from proton interactions in the surrounding matter, or they were caused by an as yet unobserved heavy ($Z \geq 2$) component of the inner belt trapped radiation, whose flux one would a priori expect to be approximately proportional to that of the trapped protons.

To explore these two possibilities further, a very detailed Monte Carlo program was devised to examine the charged particle flux in the vicinity of the retina (*9*). This program included the specific geometric properties of the actual incident charged particle flux, the spacecraft shielding, and the head and eyes of the crewman for each of the cases simulated. The incident particles were propagated with allowance for both energy loss and spallation. Three physiological parameters were used to determine if a particle would produce a flash. These are: (i) a minimum required linear energy transfer (threshold LET) of the particle in the sensitive region of the retina, (ii) a minimum required length of the track in the sensitive region projected onto a plane tangent to the surface of the retina, and (iii) the thickness of the sensitive retinal region which can respond to this stimulus. No attempt was made to include observer efficiencies. It was assumed that a 100 percent flash-producing efficiency existed for particles above the threshold determined by the three parameters and 0 percent for those below that threshold. In order to best fit the Skylab non-SAA data from both sessions and all of the Apollo light flash data with the same physiological parameters, the calculation shows, for example, that for a threshold LET of ~ 37 kev/μm (which is consistent with heavy ion accelerator light flash experience), a sensitive layer thickness of the retina of 50 μm and a minimum projected path length of 40 μm result. Since the parameters are coupled to each other, a range of reasonable values of the parameters was explored. The results for the various non-SAA flux environments have been indicated in Fig. 2. Finally, when an all-proton SAA flux equal to the maximum intensity known to exist at Skylab altitudes is employed with the Skylab non-SAA/Apollo parameter values in an attempt to simulate the SAA observations during the second session, the secondary alpha (*10*) flux fails to produce the maximum observed flash rate by a factor of 5 to 10 (*11*). A further calculation was carried out to determine the flux of multiply charged trapped particles required to produce the observed flash rate. This proved to be about one effective particle per 6000 trapped protons, a number consistent with the upper limits currently available from direct measurements.

We do not claim to have demonstrated the existence of trapped $Z \geq 2$ particles in the inner radiation belts. Rather we suggest that, on the basis of these light flash observations, it is one possible solution.

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References and Notes

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8. For example, see L. G. Parratt, *Probability and Experimental Errors in Science* (Wiley, New York, 1961), p. 140.
9. A detailed article describing the Monte Carlo calculations will be published elsewhere (W. Z. Osborne and L. S. Pinsky, in preparation).
10. Measured secondary production cross sections were used, and all approximations were conservative to produce a maximum secondary flash rate.
11. The maximum flash rate one would expect from secondary alphas is $\lesssim 3$ flashes per minute, whereas the maximum observed rate is > 20 flashes per minute.

12. We thank all of the flight controllers, flight planners, and support personnel at the Johnson Space Center who aided us during the experiment, and the Skylab flight crews whose competence and cooperation in this effort were outstanding.

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Binary Pulsar PSR 1913 + 16: Model for Its Origin

Abstract. *The existing observational data for the binary pulsar PSR 1913 + 16 are sufficient to give a rather well-defined model for the system. On the basis of evolutionary considerations, the pulsar must be a neutron star near the upper mass limit of 1.2 solar masses* ($M_\odot$). *The orbital inclination is probably high,* $i \gtrsim 70°$, *and the mass of the unseen companion probably lies close to the upper limit of the range 0.25* $M_\odot$ *to 1.0* $M_\odot$. *The secondary cannot be a main sequence star and is probably a degenerate helium dwarf. At the 5.6-kiloparsec distance indicated by the dispersion measure, the magnetic dipole model gives an age of* $\sim 4 \times 10^4$ *years, a rate of change of the pulsar period of* $\dot{P} \sim 2$ *nanoseconds per day, and a surface magnetic field strength* $\sim 1/3$ *that of the Crab pulsar. The pulsar is fainter than an apparent magnitude* $V \sim +26.5$ *and is at least* ~ 80 *times fainter than the Crab pulsar in the x-ray band. The companion star should be fainter than* $V \sim +30$, *and a radio supernova remnant may be detectable near the position of the pulsar at a flux level of* $\lesssim 10$ *janskys. Important tests of this model will be provided by more accurate measurement of* $\dot{P}$ *and by a careful search for a faint supernova remnant.*

Taylor and Hulse (*1*) have recently reported the detection of a new pulsar, with period $P \approx 59$ msec, at the position: right ascension $\alpha_{1950} = 19^h13^m13^s \pm 4$ seconds, declination $\delta_{1950} = +16°00'24'' \pm 60''$. The dispersion measure is 167 ± 5 cm^{-3} parsec, implying a distance of ~ 5.6 kiloparsecs, for an electron density of 0.03 cm^{-3}. The source is correspondingly weak, with an average flux density of 0.006 jansky (1 Jy = 10^{-26} watt m^{-2} hertz^{-1}).

This remarkable object is the first pulsar to show reliable evidence of binary motion. The orbital parameters (*1*) are as follows: orbital period $P_{orb} = 27{,}908 \pm 7$ seconds ≈ 7.5 hours; radial velocity semiamplitude = 199 km sec^{-1}; orbital eccentricity $e = 0.615$; projected semimajor axis of pulsar orbit = $a_n \sin i = 1.0\ R_\odot$, where i is the orbital inclination and $R_\odot$ is the solar radius; and mass function $f(m) = 0.13 \pm 0.01\ M_\odot$, where $M_\odot$ is the solar