OBSERVATIONS OF COSMIC-RAY INDUCED PHOSPHENES ON APOLLO 14

P.K. Chapman*, L.S. Pinsky*, R.E. Benson*
and T.F. Budinger+

INTRODUCTION

Phosphenes, which may be defined as visual sensations in the absence of light entering the eye, are readily observed by dark-adapted subjects. The flashes and streaks produced by transient pressure on the eyeball (for example, by rubbing the eyes in the dark) are a familiar experience. It has been known for more than seventy years that X-rays of the head can produce diffuse flashes. Small pulses of electric current through the head produce displays which have been described as "lightning behind clouds". Recently, the experiments of Tobias et al (which were reported at this symposium and which have now been confirmed by other investigators) have shown that discrete flashes can be produced by a variety of nuclear particles, of widely varying energy, if they pass through the eyeball.

During a study of radiation hazards associated with flight at high altitudes and in spacecraft, Tobias[1] suggested in 1952 that "a dark adapted person should be able to 'see' very heavily ionizing single tracks as a small light flash". In the early 'Sixties, D'Arcy and Porter[2] carried out experiments which demonstrated a statistical correlation between sea-level cosmic radiation, primarily μ-mesons, and phosphenes observed by dark-adapted subjects. Tobias' prediction was strikingly confirmed during the flight of Apollo 11 in July, 1969, when Aldrin and Armstrong reported seeing flashes in lunar orbit, with their eyes closed or the spacecraft cabin darkened. All lunar crews since then have observed these flashes, so consistently that there can be no doubt that they are due to external stimuli, the obvious source being cosmic rays, rather than to some form of physiological stress. Nearly all the phosphenes reported by astronauts in the vicinity of the moon have been star-like flashes and narrow streaks, similar to those generated by accelerated particles in terrestrial experiments. Typically, about one flash per minute is seen in space.

Phosphenes have never been reported by astronauts in Earth orbit. Conrad[3] has stated that the flashes he saw on Apollo 12 were so bright that he could not have missed them if they had been present during his Gemini missions, V and XI. A possible explanation is that the phenomenon is caused by particles of such low energy that the magnetosphere of the Earth forms an effective shield, but this is inconsistent with at least one proposed mechanism, Cerenkov radiation from high-energy particles traversing the vitreous humor. Furthermore, the effect was not observed by the two lunar crews prior to Apollo 11. In particular, Lovell saw flashes on Apollo 13, but not on Apollo 8. The consensus appears to be that the flashes are readily observable, but only if one is alerted to look for them. The question of their observability in Earth orbit will be resolved at the next opportunity, which probably will not occur during the remaining Apollo missions, as they spend too little time in the vicinity of the Earth.

Apart from the intrinsic interest of this phenomenon, it is important to find the cause in order to determine whether a hazard may be present during long-duration (e.g., interplanetary) missions. By conventional radiation measurement standards, the whole-body dose due to cosmic radiation is quite low during most space missions, unless a major solar flare is encountered, but the biological interactions of the high-energy, high Z (HZE) particles common in space are not well understood. Further investigation is required to determine realistic human tolerance levels for extended missions and to evaluate the need to provide special spacecraft shielding.

The Cerenkov Hypothesis

Soon after the Apollo 11 mission, Fazio and Jelley[4] suggested that the flashes observed might be due to Cerenkov radiation generated by primary cosmic-ray particles passing through the vitreous humor of the astronauts' eyes. Since the electric field of a charged particle cannot propagate faster than the speed of light in the vitreous humor, it emits a conical electromagnetic shock wave, quite analogous to the sonic boom of a supersonic aircarft, if it is moving at a velocity $\beta = v/c > 1/n$, where n is the refractive index of the medium, ~ 1.34 in the present case. The shock front forms an angle

$$\theta = \cos^{-1}(n\beta)^{-1} \qquad [1]$$

to the direction of motion of the particle. For the fastest particles, this amounts to $\sim 41°$ in the eye. If the particle has charge Ze, the number of photons produced per centimeter, within the visual range 0.35-0.55 μ, is given by[5]

$$N \simeq 470\ Z^2 \sin^2\theta \qquad [2]$$

* NASA Manned Spacecraft Center, Houston, Texas
+ Lawrence Radiation Laboratory, Berkeley, Calif.

As the particle passes through a surface (e.g., the retina), a contracting annulus of light is thus produced, which is seen as a single flash because the process lasts about 0.1 nanosecond. For normal incidence, the illumination in the observed spot is easily shown to be

$$L = \frac{N}{2\pi \tan\theta} \simeq 38 \frac{Z^2}{r} \sin 2\theta \quad \text{photons/cm}^2 \quad [3]$$

where r is radial distance away from the point where the particle impacts the surface. Away from the fovea, the human retina contains about 13 million rods/cm^2, so the illumination may also be written

$$L = x/r \qquad \text{photons/rod} \qquad [4]$$

where the characteristic distance

$$x \simeq 0.03\, Z^2 \sin 2\theta \quad \text{microns} \qquad [5]$$

may be taken as a rough estimate of the size of the perceived spot. For a relativistic stripped iron nucleus (Z=26), this gives a radius of about 20μ, corresponding to an apparent angular diameter of some 4 arc minutes. According to Ricco's Law[6], the threshold for vision should then be independent of the size of the spot depending only on the total number of photons contained in it. By integration of [3], out to a radius x, this is given by

$$M = Nx \cot\theta \simeq 7 \times 10^{-4} Z^4 \sin^2 2\theta \qquad [6]$$

The fraction of light reaching the retina which is absorbed in dark adapted rods is [7] $\sim$0.2. However, the Cerenkov light contained in a spot of radius x is generated while the particle traverses a distance x cot θ. Since this is much less than the thickness of the retina, any perceived small spot caused by Cerenkov radiation is produced while the particle is actually traversing retinal cells (the photosensitive segments of the rods being on the outer side of the retina, next to the choroid), not while it is in the vitreous humor. The efficiency factor, determined from optical measurements, is therefore somewhat doubtful. To an adequate approximation, the number of absorbed photons is taken as

$$M' = 1.5\times10^{-4} Z^4 \sin^2 2\theta \qquad [7]$$

For brief flashes subtending small angles, the measured visual threshold for thoroughly dark-adapted subjects corresponds[6] to about 10 photons absorbed by the rods. For relativistic particles, [7] then implies that point Cerenkov flashes will not be observed for $Z < 16$. If it is assumed that the uncertainties in the calculation produce an order of magnitude uncertainty in the coefficient of Z^4, the lower bound on Z becomes 9. In practice, this is not very important, since it is known that iron group nucleii (Z=24 to 28) predominate amongst the heavy (Z>10) cosmic rays[8]. According to [7] a relativistic stripped iron nucleus should produce a star-like flash which is of an intensity about one order of magnitude above the scotopic treshold.

Eq. [2] indicates that HZE particles produce about $200Z^2$ photons/cm while traversing the vitreous humor. If the average path length in the eye is taken as 15 mm, a fast iron nucleus can thus generate as many as 200,000 photons in the eyeball, but only a very small fraction of them are concentrated in the area of the retina around the point where the particle penetrates. The rest are scattered over much of the retinal surface, giving a very faint illumination which may produce a visual sensation, but not of the star-like type characteristic of observations in space. It is possible that particles of much lower charge can produce Cerenkov flashes, but it is expected that these would be of the diffuse, "summer lightning" type.

This analysis allows the following conclusions to be drawn concerning star-like Cerenkov phosphenes:

1) Since the photosensitive outer segments of the rods are considerably longer than the path length of the particle involved in generating the flash, it can produce a percentible sensation even if it is coming from behind the eye, after penetrating the pigmented epithelium forming the outer surface of the retina. Since shielding by the head is negligible for these high-energy particles, there should not be a marked difference in the frequency of these flashes, depending on the orientation of the observer's head with respect to the source of the particles. It is therefore doubtful whether the Cerenkov hypothesis can be tested by looking for an anisotrophy in the effect in lunar orbit, where the cosmic-ray flux is anisotropic because of shielding by the moon.

2) These flashes are produced only by heavy cosmic rays. At the top of the Earth's atmosphere, the flux of particles having $Z > 10$ and sufficient energy to produce Cerenkov radiation in tissue is $\sim 1/m^2$-sterad-sec.[9] In lunar orbit, where approximately 2π steradians are shielded by the moon, a heavy particle should pass through one eye or the other about once every four minutes. The rate may dobule during transit to or from the moon. In view of uncertainties in the actual flux, this is in reasonable agreement with the observed frequency.

3) Since the intensity of the spot is so small, the flash should be observed by scotopic vision only. The spot should therefore be colorless.

4) For the same reason, since the proportion of rods over cones increases away from the fovea, there should be a tendency for star-like flashes to concentrate in the peripheral field of vision. A particle passing through the fovea would not produce a percentible flash at all.

5) Since the intensity is not much more than an order of magnitude above the scotopic threshold, extensive dark-adaption is required in order to see these flashes. The light adapted eye would require at least 15 minutes of total darkness before they became visible. This is a sensitive test of whether Cerenkov radiation is responsible for the star-like phosphenes observed on lunar missions.

Observations on Apollo 14

On previous missions, observations of phosphenes had been entirely informal. Prior to Apollo 14, the crew was briefed on what their predecessors had seen, the phosphene phenomenon was discussed in general terms, and interest in the degree of dark adaption required to see the flashes are expressed. These discussions with the crew led to the development of a common language for describing different types of flash and to a single protocol for making the observations.

During trans-lunar coast, the crew looked for flashes before each sleep period, after the spacecraft cabin had been darkened. They reported their observations on awakening, and described three types of event: a) star-like flashes, b) streaks, and c) cloud-like flashes ("summer lightning"). This was the first lunar mission to report diffuse displays.

At the beginning of one sleep period the Command Module Pilot (Roosa) shone a flashlight in his eyes, to ruin his dark adaption. He reported seeing flashes "in less than a minute" after the flashlight was turned off.

These results prompted a dedicated, formal session of observations during trans-Earth coast, which began at 1343 CST, February 8, 1971, when the spacecraft was 115,000 nautical miles from Earth. The spacecraft cabin was configured for total darkness, although slight light leaks around the window shades were reported when the sun shone directly on them -- the spacecraft was in the Passive Thermal Control ("barbecue") mode at the time. However, each crew member tried to keep his eyes closed throughout the observations.

The Commander, Alan Shepard, was in the left couch, looking up; the Lunar Module Pilot, Edgar Mitchell, was in the right couch, looking up; and Roosa was below them in the Lower Equipment Bay, also looking up. The experiment was started by having each crew member stare directly into a flashlight until thoroughly light-adapted.

For the first 16 minutes, no events were reported. There were indications from the Aeromed sensors that at least two crew members were becoming drowsy. On query from the CapCom in Houston, the crew confirmed that they had seen no events and expressed their feeling that this was very unusual. Very shortly thereafter, Mitchell reported the first event. The session was continued for a further 30 minutes and a total of 48 flashes were reported.

Observations were reported via the downlink by saying "Mark" as soon as a flash was seen, followed by a short description including the type of event, which eye it was seen in, position in the visual field, and any other pertinent information. The 48 events in this session were all of the previously reported type, with the addition of some "double stars" (two stars in one eye).

Mitchell illuminated his eyes again at the 24-minute mark in the session, dark-adapted for 12 minutes, and then repeated this procedure. Care was taken to avoid exposing the other crew members eyes to the flashlight while Mitchell was light-adapting.

Figure 1 gives a breakdown of the events by observer, type, and eye in which the flash was seen. "Stars" and "flashes" are similar phenomena, "flash" denoting a spot of larger apparent size. If "streaks" are assumed to be caused by particles moving tangentially in the retina, they would be expected to be relatively infrequent, and in fact the ratio of spots to streaks observed was 3:1.

Figure 2 shows the number of events reported in each eye by each crew member. Note that all three are biassed towards the right eye, although Mitchell had the impression just after the session that he had seen more in the left than the right eye. All the crew members felt sure of their ability to distinguish which eye the flash occurred in.

		STREAK	STAR	FLASH	CLOUD	DOUBLE
LMP	RIGHT EYE	2	4	6		
	LEFT EYE	2	1	1	2	
	BOTH EYES				1	
	NOT REPORTED	1		1		1
	TOTAL 22	5	5	8	3	1
CDR	RIGHT EYE	1	1	5	1	2
	LEFT EYE	2		2		
	BOTH EYES					
	NOT REPORTED					
	TOTAL 14	3	1	7	1	2
CMP	RIGHT EYE	1		5		
	LEFT EYE	1				1
	BOTH EYES					
	NOT REPORTED			3	1	
	TOTAL 12	2	0	8	1	1
TOTAL	48	10	6	23	5	4

FIGURE 1

	TOTAL	RIGHT EYE	LEFT EYE	BOTH EYES	NOT REPORTED
LMP	22	12	6	1	3
CDR	14	10	4	0	0
CMP	12	6	2	0	4
TOTALS	48	28	12	1	7

FIGURE 2

Analysis of the times of occurrence of flashes reported by Mitchell after light-adapting yields what seems to be a random distribution. Figure 3 is a timeline plot of these events. It is clear that it is not necessary to be dark adapted to see these phosphenes. On event (a streak) occurred only 51 seconds after beginning dark adaption.

Figure 4 is a histogram showing the distribution of intervals between successive events (not broken down by observer), in ten-second bins. The theoretical (Poisson) distribution function having the same mean is shown for comparison. A χ^2 test yields a probability of fit of the data to the theoretical distribution of 19%, so it is concluded that the flashes do in fact occur at random times.

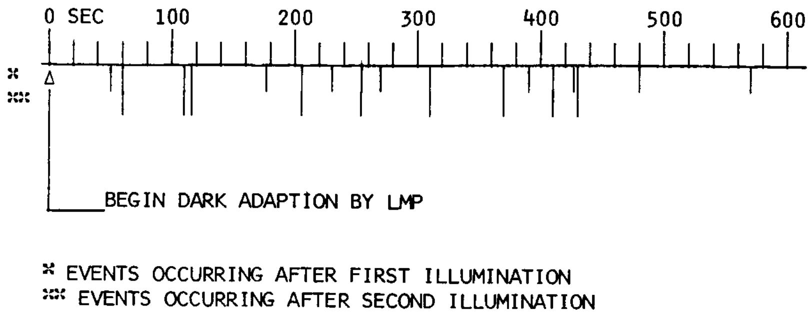

FIGURE 3

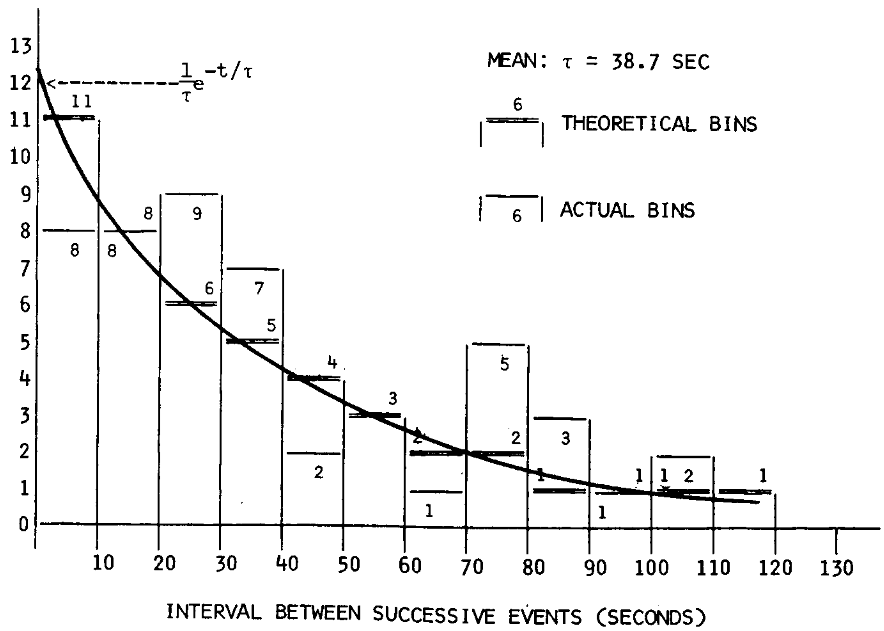

FIGURE 4

There was only one report of color in the flashes during the entire mission. This was a double star seen by Mitchell during the formal session, which he described as "white with a blue cast", like a blue diamond".

At the end of the observation session, Roosa commented that both the frequency and brightness of the events were much lower than he had experienced during informal observations. His position in the LEB may have contributed to this phenomenon. However, both Mitchell and Shepard felt that the flashes they had seen earlier in the mission were much brighter (especially when they woke up during a sleep period), although they could not say whether they had been more frequent.

During debriefing in the Lunar Receiving Laboratory, after the mission, all three crew members were positive that it was possible to tell which way a "streak" was moving. This was surprising, in view of the exceedingly brief time taken by a cosmic-ray particle to traverse the eyeball. However, recent experiments[10] have revealed similar sensations of movement in the streaks produced when accelerated particles are injected tangentially to the retina. It seems probable that the impression of movement is due to a characteristic variation in the width of a streak, along its length, due to variation in the rate of loss of energy of the particle. This may provide evidence that streaks, at least, are produced by relatively low energy particles, for which Cerenkov radiation is not a factor, but the observations are not definite enough as yet to allow firm conclusions on this point.

Conclusions

The observations of cosmic-ray phosphenes on Apollo 14 were very simple, required no equipment, and were carried out on a time-available basis. They provided the first quantitative data on the statistics of this phenomenon, but by far the most significant result was the discovery that it is not necessary to be dark-adapted to see flashes. This is strong evidence that some, and probably most, of the flashes are produced by mechanisms other than Cerenkov radiation.

It is probable that many of the flashes are due to direct ionizing interactions in the retina. This conclusion is supported by experiments of Tobias and his associates, in which flashes were observed by subjects exposed to low-energy neutron beams. Neutrons, being uncharged, of course cannot produce Cerenkov radiation directly, and the beams employed were energetically incapable of producing charged spallation products of sufficient velocity.

The sensitivity of the retina to light increases monotonically during dark adaption, with a break in the slope corresponding to the shift from photopic to scotopic vision. It is known[11] that sensitivity to electrical phosphenes does not follow this pattern -- in fact, there is a peak in sensitivity within a minute after dark adaption begins. The dark adaption curve for particle phosphenes is quite unknown at present, although terrestrial experiments with accelerators should be capable of providing this information. It would be useful to carry out such experiments using subjects with different degrees of dark adaption and beams of sufficiently low intensity to provide countable numbers of flashes. In general, the shape of the dark adaption curve may be diagnostic of the type of phosphene involved.

More detailed experiments are planned for upcoming Apollo missions. Because the frequency of flashes is relatively low compared to dark-adaption time-constants, many trials are required to obtain reliable information on the shape of the dark-adaption curve. Light-tight goggles will be carried on all future missions, to standardize the dark adaption process.

In lunar orbit, comparison of the observed frequency of flashes between the day and night sides of the moon should allow determination of the role, if any, of solar cosmic rays in producing these phosphenes. On later missions, the experiments may include equipment to determine the energy, charge, direction and position of the track relative to the head of a particle producing a visible flash. These experiments should produce definitive data, including confirmation that the flashes are produced in the eye, rather than in the visual ganglia or cortex. When the opportunity arises, observations in Earth orbit may provide additional data on the magnetic rigidity of the particles involved.

Acknowledgement

The authors wish to thank the crew of Apollo 14, Alan Shepard, Edgar Mitchell and Stuart Roosa, for their cooperation in investigating cosmic ray phosphenes in space.

References

1. Tobias, C.A., Journal of Aviation Medicine 23, 345 (1952)

2. D'Arcy, F.J., & Porter, N.A., Nature 196, 1013 (1962)

3. Conrad, C., Jr., private communication.

4. Fazio, G.G., & Jelley, J.V., internal report, Smithsonian Astrophysical Lab., Cambridge, Mass. (1970).

5. Jackson, J.D., Classical Electrodynamics, Wiley, N.Y. (1962), p. 495

6. Pirenne, M.H., loc cit, p.131.

8. Price, P.B., et al, Phys. Rev. Lett. 21, 630 (1968)

9. Ginzburg, V.L., & Syrovatskii, S.I., The Origin of Cosmic Rays, Pergamon, N.Y., (1964), p. 13

10. One of the authors (TFB) was a participant in these experiments.

11. Budinger, T.F., Lawrence Radiation Lab. Report UCRL 18347 (1968), unpublished.