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COMPARISON OF THE LIGHT FLASH PHENOMENA OBSERVED IN SPACE AND IN LABORATORY EXPERIMENTS*

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ABSTRACT

Astronauts on Apollo and Skylab missions have reported observing a variety of visual phenomena when their eyes were closed and adapted to darkness. These observations were studied under controlled conditions during a number of sessions on board Apollo and Skylab spacecraft and the data available to date on these so-called light flashes is in the form of descriptions of the phenomena and frequency of occurrence. Similar visual phenomena have been demonstrated in a number of laboratories by exposing the eyes of human subjects to beams of neutrons, alphas, pions, and protons. More than one physical mechanism is involved in the laboratory and space phenomena. No direct comparison of the laboratory and space observations has been made by observers who have experienced both. However, the range of visual phenomena observed in the laboratory is consistent with the Apollo and Skylab observations. Measured detection efficiencies can be used to estimate the frequencies with which various phenomena would be observed if that subject was exposed to cosmic rays in space.

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1. Introduction

It is now evident that the variety of particle-induced visual sensations (PIVS) observed in space cannot be explained in terms of a single physical mechanism. The role that Cerenkov radiation plays in the PIVS observed by Apollo astronauts was discussed by us at the 18th meeting of COSPAR. There has only recently been clear evidence for non-Cerenkov flashes in space when astronauts on Skylab 4 reported intense bursts of eye-flash activity as their spacecraft passed through the South Atlantic Anomaly (SAA) [1]. The number of charged particles in the SAA that could penetrate an astronaut's eye at speeds above the Cerenkov threshold and generate a flash bright enough to be visible is too small to explain the event rates. A mechanism for the SAA flashes has been suggested in the preceding paper.

The purpose of this paper is to compare the laboratory PIVS with the phenomena observed in space and to explore the extent to which the Apollo and Skylab observations can be explained in terms of the same physiological processes that function in normal vision. It is important to know whether the radiation-induced phenomena can be explained by interactions which initiate the same neurophysiological processes that form the basis for normal scotopic vision because this information would bring us a long way towards understanding the potential hazards the eye flashes may represent.

2. The Visual Process

The dark-adapted retina utilizes the scotopic visual system, the photoreceptors of which are the rod cells. Incoming light interacts with rhodopsin, the chromophore molecule in the rod cell's outer segment. The absorption of a single photon is sufficient to excite a rod cell and, thereby, generate a detectable graded potential at the rod cell's synapse with neighboring bipolar and horizontal cells. The reader is referred to Ref. [2] for details of what is known about how the retina functions in translating these graded potentials into the "all or nothing" action potentials by which the ganglion cells transmit visual information to the central nervous system.

One important characteristic of scotopic vision for our purposes is the enormous amount of convergence of information that occurs between the rod cells and the ganglion cells. During complete dark adaption a typical ganglion cell may integrate excitatory signals over a region of the retina that is about 300 μ in diameter. Psychophysical studies have shown that between 2 and 20 rod cells within this summation area must be excited for a flash to be detected by the observer with most measurements yielding values between 6 and 15 [5].

A second important characteristic of scotopic vision is the sudden rise in detection efficiency with increasing flash intensity [5]. One typically has zero detection efficiency at low intensities followed by a rather fast rise to 100%. This sharp rise makes the concept of threshold, defined as the intensity for 50% detection efficiency, a particularly useful parameter to characterize an individual's sensitivity to light. Two types of threshold measurement are relevant to the space observations. If the flash is confined to a single summation unit the measured thresholds range between 10 and 100 photons of an optimum wavelength of 510 nm incident at the retina, which corresponds to the excitation of between 2 and 20 rod cells. If the incident light covers a large area on the retina the total number of photons required for threshold is, of course, much larger but the average number of photons incident per summation unit (and, therefore, excitations per summation unit) exposed is smaller than the single unit value by a factor of 10 [3,4].

3.1 Cerenkov Flashes

Most of our experimental effort has focused on the role that Cerenkov radiation plays in PIVS in space because it was possible to make quantitative comparisons between theory [6] and experiments [7-11]. Knowledge of how an individual's visual system responds to flashes from an appropriate optical source can form the basis for predicting his response to the flashes of Cerenkov light generated by the passage of a charged particle through his eye. The Cerenkov model [6] is simple and free of adjustable parameters. It involves the identical physiological processes as the detection of optical flashes. Once the Cerenkov contribution to the flashes in space is understood, the role played by other mechanisms may be quantified.

Two types of Cerenkov experiments are underway. We are currently measuring the detection efficiencies of human observers exposed to HZE particles one at a time. The experimental procedures followed are described in Ref. [8]. By using psychophysical procedures that involve forced-choice responses and catch tests, one can obtain reliable detection efficiencies as a function of the Cerenkov flash intensity generated by the particle, i.e. in terms of the particle's charge, velocity and angle of incidence. The greatest number of Cerenkov photons enter the summation units closest to the particle's trajectory as it exits the eye. Because only one unit must be excited for a flash to be detected, threshold for the observer can be approximated by the threshold condition for the unit most likely to be excited [6].

If a HZE particle generates M photons that arrive at the retina within the closest summation until, the probability that at least some threshold number, R, will be absorbed at the rod outer segments and initiate a visual sensation is given in Ref. [6] in terms of a summed binomial distribution. A nitrogen nucleus (Z=7) that arrives at the retina with a kinetic energy of 503 MeV/AMU generates the equivalent of 47 photons of 510 nm wavelength. The detection efficiency of 10% measured for three subjects at the Princeton Particle Accelerator corresponds to a threshold value of 12. This value agrees with the 6-15 photon absorptions determined in optical studies [5].

The atomic number (Z) for which nuclei can be accelerated to relativistic velocities above the Cerenkov threshold are limited at present which limits the intensity of Cerenkov flashes that can be experienced. In order to study Cerenkov flashes of greater intensity we initiated a series of experiments with bursts of singly charged (Z=1) muons and pions. The Cerenkov pattern generated by N particles would simulate over much of the retina the pattern of a single particle of charge $Z=N^{1/2}$. Because the pion beams were only collimated to a few mm in diameter, there has not been any observation of thin streaks or point-like flashes in these experiments. The visual phenomena varied with the beam's intensity, cross-sectional area, location and orientation at the retina. The observed phenomena included large crescent-shaped flashes on the periphery, wide streaks or bands, flashes that filled the field of view, and large flashes with dark centers.

The intensity of Cerenkov light is distributed roughly uniformly over the region of the retina covered by the beam spot. Beyond the beam spot the intensity falls off in a manner similar to the pattern of a HZE particle. Of course the thresholds measured in these Z=1 experiments should be compared to the large area optical thresholds rather than the thresholds for individual summation units. The pion and muon Cerenkov flashes have recently been shown [10,11] to be in agreement with the large-area optical measurements [3,4]. The measured Cerenkov and optical thresholds correspond to 0.2-2.0 and 0.5-1.3 photon absorptions per summation unit, respectively. These values are about a factor of 10 lower than the single unit values given earlier. The Cerenkov and optical data agree, therefore, in this important ratio.

3.2 Non-Cerenkov Flashes

Visual phenomena have been induced by neutrons [12-14], stopping alphas [15] and stopping nitrogen nuclei [16], under experimental conditions such that Cerenkov radiation could be ruled out as a significant contribution. Little else is known regarding the mechanism or mechanisms behind these flashes which leads us to group them under the general heading, non-Cerenkov flashes. They include star-like flashes, streaks, and interrupted streaks. No larger area flashes, long streaks, or clouds have been reported. Careful measurements of detection efficiency using proper psychophysical procedures are needed for these non-Cerenkov flashes. It is important that the detection efficiency be measured as a function of the location on the retina being exposed, the beam particle's angle of incidence, and the degree of the subject's dark adaption.

Of particular interest would be an experiment to determine whether threshold is a valid concept for the non-Cerenkov as it is for optical and Cerenkov flashes. The available experimental data is unclear on this point. There is some evidence that the detection efficiency for each particle through the retina at grazing incidence (within an LET of 10 keV/μ) depends upon the beam rates, varying from 5% at one alpha per sec. to 40% for 10 per sec. [15]. The detection efficiencies of nitrogen nuclei that arrive at the retina near the end of their range with LET values a factor of 10 or more higher is also 40% [16].

If we assume that ionizing radiation can interact in some unspecified manner to excite the rod cells and that the excitation of a threshold number of rod cells leads to a visual sensation by the same neurophysiological pathways as for normal scotopic vision, then from analogy with normal scotopic vision one can expect the following relationships. First, the appropriate physical parameter that determines detection efficiency is the energy deposited per summation unit. Secondly, the energy deposited per unit in large area flashes should be a factor of 10 lower than that required of individual HZE particles. The threshold doses measured for large area X-ray flashes is 0.5-1.0 mrad which is equivalent to 0.063-0.126 MeV deposited within a 300μ diameter region on a 30 μ thick sensitive layer. Individual alphas with an LET value of 10 keV/μ deposit between 0.3 and 3.0 MeV within a similar unit, depending on whether it is incident normal to the retina or grazing, which is roughly a factor of 10 higher [15].

3.3 PIVS in Space

Like the laboratory flashes, the phenomena observed in space have been colorless with the exception of one flash that appeared "blue with a white cast, like a blue diamond" [17]. Pinsky, et al [17] catagorized the Apollo observations as stars, streaks, and clouds which occur 66%, 25% and 80% of the time, respectively. However, there is an impressive variety of phenomena within these catagories. The star-like flashes include point flashes, double stars, and larger phenomena referred to by astronauts as nova and supernova. The streaks vary in description from sharp lines to diffuse bands of light. Some of the streaks had gaps and there was often a sense of apparent motion.

The cloud-like flashes ranged from crescent-shaped flashes in the far periphery to events that fill a major portion of the field of view. Some clouds filled the peripherial field but left the central portion dark.

The average dark-adapting time before the first detected flash was 19.3 minutes on Apollo and the average post dark-adaption event rate was 0.34 flashes per minute [17]. However, the count rates for individuals often ranged as high as 1-2 per minute when dark adapted for 30 minutes or more. On Skylab 4 the flash rates were as high as 20 per minute inside the SAA and 1-2 per minute outside.

The flashes inside the SAA consistently appeared as "short streaks or tadpoles". Outside the SAA the flashes appeared as spot-like flashes, streaks, threshold flashes, and some cloud-like phenomena.

4. Comparison of Laboratory and Space PIVS

Unfortunately, there is no individual who has experienced the PIVS of space and either the Cerenkov or non-Cerenkov PIVS generated in the various laboratories. In fact, there has yet to be a direct comparison of Cerenkov and non-Cerenkov flashes by the same individual. Until such direct comparisons are made one is limited to comparisons of subjective descriptions by different observors.

If we accept these descriptions at face value, there is considerable agreement between the space and laboratory observations. In fact all of the phenomena reported by more than one astronaut have already been simulated in one laboratory or another. Table I summarizes the observations. The large area flashes have only been simulated with Cerenkov radiation. The descriptions of the shapes, including crescent shaped flashes in the peripheral field of view, wide streaks, and flashes that fill major portions of the field of view are common to both. The observation of large flashes with dark centers in our experiment led to their confirmation on Apollo and Skylab. Simple experiments can be designed to determine whether HZE particles with very high LET values moving at velocities that are too slow to generate Cerenkov light can also induce visual phenomena that occupy large visual angles. Within our present ability to compare, such a contribution would not be required.

It has not been possible to determine whether the thin streaks and point flashes can be induced by Cerenkov. The pion beams have not been collimated below a few mm. The thin streaks observed with relativistic nitrogen would appear to be due to Cerenkov but the possibility of a contribution from ionization effects has not been eliminated. Thin streaks and point flashes have certainly been observed in the non-Cerenkov exposures. However, it is not clear that non-Cerenkov mechanisms occurring along the particle's trajectory can explain the long streaks observed on Apollo.

The previous paper attempts to explain the high flash rates on Skylab in terms of nuclear interactions in and near the retina. Because more than one summation unit is likely to be excited by a detectable nuclear star the phenomena would typically be observed as randomly oriented short streaks.

5. Summary and Conclusions

The eye-flash investigations are at a critical state. All evidence suggest that the phenomena can be explained in terms of the same physiological processes that underlie normal scotopic vision; only the physical mechanism for exciting the rod cells need be different. This hypothesis is not proven, however. It is encouraging that count rates comparable to those of the Apollo and Skylab observations are calculated from the Cerenkov and nuclear-star models that are based upon this hypothesis. The ratios of single unit and large area threshold measurements of energy absorbed per unit are roughly 10 for optical, Cerenkov, and non-Cerenkov flashes. Similar dark adaption periods are required for all three types of flashes. Finally, and most exciting, we are now at a stage where a few simple experiments can test the hypothesis. Deviations from theory would then be significant in evaluating potential hazards.

TABLE I

VISUAL PHENOMENA OBSERVED BY DARK-ADAPTED SUBJECTS

	Space Flight		Non-Cerenkov			Cerenkov		
	Deep Space	SAA	Neutron	Stopping Alpha	Stopping Nitrogen	Nitrogen	Muon Bursts	Pion Bursts
Star	X	X	X	X	—	—	—	—
Streak	X	X	X	X	X	X	—	—
Cloud	X	—	—	—	—	—	X	X
Crescent	X	—	—	—	—	—	X	X
Band	X	—	—	—	—	—	—	X
Annulus	X	—	—	—	—	—	X	—

REFERENCES

[1] L.S. Pinsky, W. Z. Osborne, R.A. Hoffman, and J.V. Bailey, Science <u>188</u>, 928 (1975).

[2] R.W. Rodieck, <u>The Vertebrate Retina</u> (W.H. Freeman and Co., San Francisco, 1973).

[3] E.J. Denton and M.H. Pirenne, J. Physiol. <u>123</u>, 417 (1954).

[4] M.H. Pirenne and F.H. Marriott in <u>Psychology a Study of Science</u>, Vol. 1, S. Koch, ed. (McGraw-Hill, New York, 1959).

[5] N.R. Bartlett in <u>Vision and Visual Perception</u>, C.H. Graham, ed. (John Wiley and Sons, Inc., New York, 1965).

[6] R. Madey and P.J. McNulty, <u>Proc. Natl. Symp. Natural and Manmade Radiation in Space</u>, 1971, E.A. Warman, ed. (NASA-TMX-2440, 1972), p. 757.

[7] P.J. McNulty, Nature <u>234</u>, 110 (1971), Air Force Cambridge Research Laboratories Report No. 71-0377 (1971).

[8] P.J. McNulty, V.P. Pease, L.S. Pinsky, V.P. Bond, W. Schimmerling, and K.G. Vosburgh, Science <u>178</u>, 166 (1972).

[9] P.J. McNulty, V.P. Pease and V.P. Bond, Science <u>189</u>, 453 (1975).

[10] P.J. McNulty, V.P. Pease, and V.P. Bond, J. Opt. Soc. Am. <u>66</u>, 49 (1976).

[11] P.J. McNulty, V.P. Pease, and V.P. Bond, Radiation Research (in press).

[12] J.H. Fremlin, New Scientist <u>47</u>, 42 (1970).

[13] C.A. Tobias, T.F. Budinger, and J.T. Lyman, Nature <u>230</u>, 596 (1971).

[14] W.N. Charman, J.A. Dennis, G.G. Fazio, and J.V. Jelley, Nature <u>230</u>, 522 (1971).

[15] C.A. Tobias, T.F. Budinger, and J.T. Lyman, <u>Proc. Natl. Symp. on Natural and Manmade Radiation in Space</u>, 1971, E.A. Warman, ed. (NASA-TMX-2440, 1972) p. 1002.

[16] T.F. Budinger, H. Bischel, and C.A. Tobias, Science <u>172</u>, 868 (1971).

[17] L.S. Pinsky, W.F. Osborne, J.V. Bailey, R.E. Benson, and L.F. Thompson, Science <u>183</u>, 957 (1974).