Cosmic Rays: Detection with the Eye

During the translunar flight of Apollo 11, astronaut Edwin (Buzz) Aldrin saw intense flashes of light that appeared as often as once a minute. Although he was at first hesitant to tell his crew mates, Aldrin asked them to confirm his observations on their way back to the earth. When they safely landed, Neil Armstrong and Michael Collins agreed that they had also seen "points of light," "streaks," and a few "double points." The crews of all of the later Apollo flights reported similar flashes—even with their eyes closed. They were not victims of space hysteria, but were "seeing" cosmic rays which penetrated their spacecraft and interacted with their eyeballs. For the past 2 years, earthbound experimenters have attempted to explain the mechanism behind the flashes and to assess the hazards due to radiation damage in the astronauts' eyes.

Seventeen years before the historic Apollo 11 flight Professor Cornelius Tobias, of the University of California, Berkeley, anticipated this phenomenon. During studies of radiation hazards associated with manned space flight and high-flying airplanes, Tobias conjectured that "a dark-adapted person should be able to 'see' very heavily ionizing single tracks as small light flashes." Thus the subject is not completely new, although the astronauts have focused interest on it.

That cosmic rays do transverse the astronauts' heads was dramatically demonstrated by Dr. Robert Fleischer and his colleagues at the General Electric Research and Development Center, Schenectady, New York, together with Dr. P. Buford Price, University of California, Berkeley. They reported (*Science*, 9 April 1971, p. 154) observations of cosmic ray tracks in the plastic helmets worn by the Apollo astronauts. By analyzing the damage in the plastic helmets caused by the cosmic rays, the GE-Berkeley researchers calculated that an astronaut on a 2-year mission, such as a trip to Mars, would suffer the destruction of a potentially worrisome number of irreplacable body cells unless extra shielding were added to the craft. Their estimates of the tissue damage range to as much as 0.12 percent of the nonregenerative cells in the cerebral cortex area of the brain, 0.05 percent in the retina of the eye, and over 1 percent in portions of the central nervous system. Since tracks seen in plastic helmets do not represent all heavy ion particles that passed through an astronaut's head, the actual damage may be even higher.

Flashes similar to the ones seen by the astronauts have been observed in experiments conducted on the earth. The most exciting results were obtained very recently by Tobias and his colleagues at Berkeley. They took advantage of the "man-made cosmic rays" now available from the bevatron at the Lawrence Berkeley Laboratory. Accelerator physicists at LBL have modified the bevatron, a proton synchrotron, so that it accelerates nitrogen ions to energies as high as 36 billion electron volts (36 Gev). These high-energy ions are similar to those encountered by the astronauts in outer space.

Human Experiments

Three scientifically trained observers —LBL director and Nobel laureate E. M. McMillan, scientist-astronaut Philip Chapman, and Tobias—placed their heads in the beam of nitrogen ions and saw bright streaks when the ions penetrated the posterior part of their retinas. No flashes were seen when the beam passed through the occipital lobes of the brain (where vision is processed) or through the anterior portions of the retina and the vitreous humor. They concluded that the accelerated ions produce bright streaks and flashes if they directly interact with the retina and if they are near the end of their range where the ionization is greatest.

Prior to the nitrogen-ion work, several experimenters, both in the United States and in Great Britain, had put their heads in the paths of beams of energetic neutrons and had seen "points of light" and "streaks." These flashes were apparently caused by direct excitations of the retina. It has been suggested that either protons or alpha particles, resulting from the neutron-initiated reactions in the eye, trigger the flashes.

However, the situation in space may be different. The cosmic rays are not composed of neutrons—they are predominantly atomic nuclei—and the energies of the particles encountered in space are higher than the energies of these laboratory particles. In space, it may be possible that at least some of the flashes are caused by Cerenkov radiation produced in the vitreous humor of the eye.

Cerenkov radiation is produced whenever a charged particle moves through a transparent medium faster than the velocity of light in the same medium. This faint light arises from a shock-wave phenomenon and can be thought of as the optical analog of the sonic boom. Detection of Cerenkov radiation requires very sensitive receptors, such as photoelectric tubes. The dark-adapted eye under ideal conditions can match the performance of the best electronic devices.

The idea that the astronauts might be seeing the Cerenkov radiation from cosmic rays passing through their eyes was first proposed by John Jelley, of the Atomic Energy Research Establishment, Harwell, England, together with Giovanni Fazio, of the Smithsonian Institution Astrophysical Observatory, Cambridge, Massachusetts, and W. Neil Charman, formerly of AERE, Harwell, and now at the University of Manchester Institute of Science and Technology, England. According to their calculations, high energy nuclei with a charge greater than or equal to six (for example, carbon nuclei) can produce Cerenkov light, which is compatible with the light flashes seen by the astronauts.

The intensity of the light flash is proportional to the square of the nuclear charge. This may explain why ground-based observers usually do not see such flashes from "sea-level" cosmic rays. The cosmic radiation observed outside of our atmosphere consists of a wide range of particles and atomic nuclei, including protons, alpha particles, and nuclei of carbon, oxygen, and iron. These particles never penetrate to ground level because of absorption and disintegration in the atmosphere. Most of the particles that do strike the surface of the earth are singly charged particles such as electrons, muons, and a few protons. These particles do not carry sufficient charge to produce Cerenkov light of intensity above the visual threshold.

The effects of sea-level cosmic rays in human eyes were the subject of a study in the early 1960's. Neil Porter, a physicist, and D. J. d'Arcy, a psycologist, at University College, Dublin, investigated correlations between sea-level cosmic rays and light flashes seen by fully dark-adapted persons. The cosmic rays, mostly muons, were detected with scintillators placed above and below the subjects who had been in the dark for at least 30 minutes and were kept quiet and ostensibly were relaxed. Porter and d'Arcy concluded that the subjects could see flashes in direct response to the cosmic rays, but did not make any conclusions about the nature of the mechanism causing the flashes.

An improved version of the Porter-d'Arcy experiment is now being conducted by Neil Charman and Christina Rowlands at Manchester. They define the geometry of the cosmic-ray muons with a telescope composed of one or two small disks of plastic scintillator placed directly on the subject's head and a much larger tank of liquid scintillator placed below the subject. Coincident counts in the detectors signal a cosmic-ray event that is accompanied by an audible click. Another cosmic ray telescope, identical to the first, except that no human subject is sandwiched in it, produces similar clicks that the subject can hear. The dark-adapted observer said "yes" whenever he heard a click and simultaneously saw a flash. Charman and Rowland performed a statistical analysis which indicated a positive correlation between the cosmic rays and the light flashes when the cosmic rays went through the observer's eye.

The data taken from the observers in the prone position—whether the face was up or down—and with small detectors placed directly over their eyes, were averaged and showed a positive correlation. When the observers were lying on their sides, they saw a statistically significant number of flashes when the small detector was positioned so that the muons passed laterally through both eyes. However, there was no correlation between the clicks and the flashes when the small detectors were placed over the visual cortex of the brain. From these results it appears as if the flashes result from a direct stimulation of the retina rather than from interactions in the part of the brain which processes visual information.

If Cerenkov radiation were causing the flashes the subjects, while lying face down, should have seen fewer of them. Since the Cerenkov light is radiated in a cone along the forward direction of the moving charged particle, much more of the retina could receive the light originating in the vitreous humor when the subject is facing upward. There seems to be no difference between the detection efficiency in the two positions, strengthening the case for direct interaction on the retina. In any case, Fazio, Jelley, and Charman had already shown that singly charged particles, such as the muon, are unlikely to create a detectable amount of visible Cerenkov radiation. Contrary to this Manchester experiment and that of Porter and d'Arcy, Tobias and his Berkeley colleagues—Thomas Budinger, a research physician, and John Lyman, a biophysicist—have not been able to see flashes, either at ground level or in aircraft at 10,000 meters, which they could attribute to cosmic ray muons. The Berkeley team also noted that subjects exposed to positive pi mesons of low intensity (with a momentum of 1.5 Gev/c) observed nothing.

Flashes definitely have been seen in Earth-based experiments performed with neutron beams at Berkeley, at AERE, Harwell, and by John Fremlin at the University of Birmingham, England. After dark adaption, Tobias and Budinger placed their heads in the path of a neutron beam produced on Berkeley's 184-inch (467 cm) cyclotron. They saw primarily small, starlike light flashes which appeared when the beam was switched on. Jelley and his coworkers observed both points and streaks. When the beam entered both eyes laterally, the observers saw more streaks than were present in frontal exposure. The Berkeley group reported similar phenomena. The streaks were along the beam direction. When the beam entered the rear of the head, fewer flashes appeared. This result indicates that the flashes are probably not produced by direct stimulation of the visual cortex, a finding in agreement with the other experiments. The reduction in signal may be due to absorption of the neutrons by the skull and the brain tissue when the beam is directed at the back of the subject's head.

Most likely these flashes are produced by direct excitation effects in the retina, by charged particles created from nuclear reactions involving the neutrons, and by atomic nuclei. The flash rate and the length of the streaks, as estimated by the observers, agree well with the properties expected for hydrogen nuclei knocked forward by the neutrons. Direct neutron events are ruled out because the flash rate would have been far in excess of that observed.

Cerenkov radiation is not a contender for the flash-producing mechanism in these neutron experiments. The energy threshold for Cerenkov light produced by protons in the vitrous humor is about 500 Mev. It is impossible for the protons to attain this energy in some of the experiments. Thus for low energies, at least, the flashes are produced by ionization in close proximity to or actually in the retina.

Despite the adverse evidence, Cerenkov radiation has not yet been ruled out as a contributer to translunar light flashes. However, the high-energy nitrogen experiment shows that Cerenkov radiation is not necessary to explain the flashes, but may contribute when cosmic rays of very high velocity penetrate the eye. Simple experiments performed by the crews of Apollo 14 and 15 support these results.

It is interesting that astronauts on flights launched earlier than the Apollo 11 flight did not report these flashes. Because Earth-orbiting flights in the Mercury, Gemini, and Apollo series were above the Earth's atmosphere, the cosmic rays should not have been attenuated. However, the effect may be due to the earth's magnetic field, which is strong enough to deflect all but the most energetic cosmic rays. Another possibility is that the astronauts on these flights usually had their cabin lights on and were in constant contact with the earth. Under these conditions they did not have the enforced rest periods needed to see the flashes.

What is an interesting phenomenon to the physicists and the physiologists unfortunately poses health problems for space travelers. At Berkeley, Joshua Zeevi, Ted Lewis, and Tobias have detected definite signs of degeneration in the retina of a mud puppy (*Necturus maculosus*) exposed to their nitrogen beam. During the relatively short flights to the moon, astronauts have suffered no apparent injury. But if longer flights are to be made, additional shielding might well be necessary in order to avoid irreversible damage to brain cells, eye cells, and nerves.—GERALD L. WICK