9. The samples of the Allende meteorite were provided from the Smithsonian Institution by B. H. Mason.
10. It is suggested that the alkalies potassium, rubidium, and cesium were fractionated into the earth's core, producing marked deficiencies of these elements in the crust. See, for example, J. S. Lewis, *Earth Planet. Sci. Lett.* **15**, 286 (1972). In experiments with carbon crucibles no potassium was detected in the sulfide phase (detectability limit 0.01 percent) compared with 0.1 percent found in the silicate melt at 20 kbar. To provide a reducing environment more conducive to a potassium-metal association we experimented with Allende bulk meteorite plus silicon metal in carbon crucibles at 20 kbar. Similarly, no potassium was detected in the sulfide-silicon melt (detectability limit 0.01 percent) compared with 0.1 percent in the silicate melt, indicating that potassium would not separate with the sulfide phase, at least in the upper 65 km of the earth's surface.
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20. We thank E. Anders for discussions and P. M. Bell, S. R. Hart, T. Irvine, Y. Nakamura, and H. S. Yoder, Jr., for critical reviews. Supported by NASA grant NGR 09-140-017.

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Light Flashes Observed by Astronauts on Apollo 11 through Apollo 17

Abstract. *The crew members on the last seven Apollo flights observed light flashes that are tentatively attributed to cosmic ray nuclei (atomic number ≥ 6) penetrating the head and eyes of the observers. Analyses of the event rates for all missions has revealed an anomalously low rate for transearth coast observations with respect to translunar coast observations.*

The observation of visual phenomena described generically as light flashes was reported by Apollo 11 Lunar Module pilot Edwin Aldrin during one of his postmission debriefings. Subsequently, the crews of Apollo 12 and Apollo 13 were briefed on the phenomena and asked to report their observations. All of them reported the ability to "see" the flashes with relative ease when the spacecraft was dark, and with their eyes either open or shut. Apollo 12 commander Charles Conrad stated that "there were big bright ones all over," and added that he had not noticed anything like it on his two previous Gemini missions orbiting the earth (*1*). Apollo 13 commander James Lovell observed the flashes during Apollo 13, but did not remember seeing them during his Apollo 8 lunar mission.

Because of these reports, a 1-hour session on Apollo 14 was dedicated to observe light flashes (*2*). Subsequently, there were three separate 1-hour sessions on Apollo 15 and two 1-hour sessions on Apollo 16 (*3*) and Apollo 17 (*4*). Simple blindfolds (designed to avoid pressure on the eyeballs) were used on the last three missions. The crew's comments and descriptions of each event were radioed to the earth and simultaneously recorded on tape in the spacecraft. To explore the most widely accepted hypothesis of the origin of the flashes (*5*)—that they are caused by cosmic ray nuclei traversing the head or eyes—a device known as the Apollo Light Flash Moving Emulsion Detector (ALFMED) was used on Apollo 16 and Apollo 17. The ALFMED is a masklike apparatus containing two sets of nuclear emulsion plates. One set of plates is fixed with respect to the head, and the second set can be translated parallel to the fixed set at a uniform rate during a 1-hour observing session. When the ALFMED data have been analyzed they should tell whether there are coincidences between reported flashes and cosmic rays (atomic number $Z \geq 6$) passing through the head or eyes. This report is concerned with the subjective data obtained during the dedicated sessions described above.

The flashes are generally described as white or colorless (the only exception is the report by Apollo 14 Lunar Module pilot Edgar Mitchell of a flash that appeared "blue with a white cast, like a blue diamond"). Three basic types of flashes have been reported. The most prevalent type (occurring about 66 percent of the time) is the "spot" or "starlike" flash, which has also been referred to as a "supernova." David Scott, the Apollo 15 commander, described it as resembling a photographic flashbulb that has been flashed across a dark arena, several hundred feet from the observer. Mitchell stated that the phenomenon was not as clear as he thought it would be. "There still seemed to be at least two flashes, maybe a bright flash followed an instant later by a more subdued flash, or perhaps a halolike effect—there does not seem to be a set pattern in each case. Sometimes it is a very clear single flash; at times it seems followed by a halo. Sometimes it seems followed by an adjacent flash." On several occasions stars have been reported in pairs, either both in the same eye or one star in each eye.

The second most abundant type of flash (occurring about 25 percent of the time) is described as a "streak." Some observers reported that the streaks were sharp lines, and to others they appeared more (laterally) diffuse. Some of the streaks were like dashed lines, the most common version consisting of two principal segments with a gap in the middle. The most interesting characteristic of the streaks is that they all appeared to have a definite sense of propagation (typical descriptions were "going from left to right" or "coming straight at me"). Most observers agreed that the "motion" was exceedingly fast, and may in fact have been due to shape cues rather than actual motion. Light flash experiments with accelerators have apparently duplicated this sense of propagation feature of the streaks (*6*). The streaks are probably caused by particles with trajectories approximately tangent to the retina.

The third type of flash (occurring in the remaining 8 percent of the cases) is referred to as a "cloud." Clouds were always seen in the periphery, and do not seem to have any distinct shape. Apollo 14 Command Module pilot Stuart Roosa described the clouds as resembling a lightning discharge when viewed from behind terrestrial clouds in the distance. Some of these cloud-like events have appeared to fill the entire periphery, while leaving the central visual field dark.

Analyses of the elapsed time between events for a particular observer, and between events for any observer, both indicate that the events seen during each 1-hour session fit an interval distribution (that is, the events were randomly distributed in time). Further, there does not appear to be a significant preference for one eye over the other, either for a single type of event or for all the events taken together.

Table 1. Summary of light flash events observed during Apollo dedicated sessions. The time to the first event is defined as the dark adaptation time (see text). The tapes containing detailed descriptions of events observed on the Apollo 15 translunar coast (TLC) were lost during playback to the ground. On the Apollo 17 transearth coast (TEC) no events were reported. Abbreviations: LO, lunar orbit; CMP, Command Module pilot; LMP, Lunar Module pilot; and CDR, commander.

Phase of flight	Crewman	Length of session (min)	Time to first event (min)	Number of events: Total	Streak	Star	Cloud	Mixture
			Apollo 14					
TEC	CMP	47	29	12	2	8	1	1
	LMP	47	17	22	5	13	3	1
	CDR	47	18	14	3	8	1	2
			Apollo 15					
TLC	CMP	60	10	22				
	LMP	60	9	12				
	CDR	60	10	25				
LO	LMP	60	10	12	6	5	0	1
TEC	CMP	60	30	8	2	5	0	1
	LMP	60	26	9	3	5	0	1
	CDR	60	17	6	0	6	0	0
			Apollo 16					
TLC	LMP	60	†	47	7	36	2	2
	CDR	60	†	22	6	14	1	1
TEC	CMP	60		0	0	0	0	0
	LMP	60	‡	21§	1‖	4‖	2‖	1‖
	CDR	60	21	8	1‖	0	0	0
			Apollo 17					
TLC	CMP	60	15	17	5	10	1	1
	CDR	60*	39*	11	6	4	1	0
TEC	CMP	60						
	LMP	60						
	CDR	60						

* A high phosphene level was reported during the first half of the session. † The crew were already dark-adapted and seeing flashes when the timed session began. ‡ The first seven flashes were not reported in real time; the elapsed time to the first event is not available but is probably about 15 minutes. § The total includes those not reported in real time. ‖ Complete event descriptions were not available.

Table 2. Mean time between events after dark adaptation and average dark adaptation times. No observing session was scheduled for the Apollo 14 translunar coast. No events were reported in the Apollo 17 transearth coast session. See legend to Table 1 for abbreviations.

Flight	Crewman	Translunar coast sessions: Mean time between events (min)	Translunar coast sessions: Dark adaptation time (min)	Transearth coast sessions: Mean time between events (min)	Transearth coast sessions: Dark adaptation time (min)
Apollo 14	CMP			$2.82^{+1.19}_{-0.81}$	29
	LMP			$2.05^{+0.56}_{-0.43}$	17
	CDR			$3.23^{+1.22}_{-0.86}$	18
	Average			$2.68^{+0.58}_{-0.41}$	21.3
Apollo 15	CMP	$2.38^{+0.66}_{-0.50}$	10	$4.29^{+2.50}_{-1.50}$	30
	LMP	$4.64^{+1.96}_{-1.33}$	9	$4.25^{+2.25}_{-1.40}$	26
	CDR	$2.08^{+0.53}_{-0.41}$	10	$8.60^{+6.63}_{-3.73}$	17
	Average	$3.05^{+0.72}_{-0.50}$	9.7	$6.01^{+2.85}_{-1.62}$	24.3
Apollo 16	LMP	$1.28^{+0.22}_{-0.16}$		$2.50^{+0.71}_{-0.54}$	
	CDR	$2.73^{+0.73}_{-0.57}$		$5.57^{+3.25}_{-1.95}$	21
	Average	$2.00^{+0.38}_{-0.29}$		$3.85^{+1.48}_{-0.91}$	21.0
Apollo 17	CMP	$2.81^{+0.93}_{-0.68}$	15.0*		
	CDR	$2.10^{+0.94}_{-0.63}$			
	Average	$2.59^{+0.70}_{-0.51}$	15.0		
All sessions combined		$2.58^{+0.38}_{-0.27}$	11.0†	$4.16^{+1.09}_{-0.63}$‡	22.6§

* Dark adaptation time available for the CMP only. † Averaged over four observers. ‡ Average excluding Apollo 17 observing time. § Averaged over seven observers.

Table 1 shows the number of events of each type seen by each observer in individual 1-hour sessions. Also shown is the elapsed time in minutes from the start of dark adaptation to the observation of the first event for sessions where that time is known. This elapsed time is defined as the dark adaptation time, and the average for all sessions is 19.3 minutes, compared with an average event rate after dark adaptation of one event every 2.9 minutes for each observer. This event rate is compatible with the hypothesis that cosmic ray nuclei of $Z \geqq 6$ cause the light flashes.

Thomas K. Mattingly, the Apollo 16 Command Module pilot, reported that he was never able to observe the phenomenon. He is the only Apollo crew member briefed to look for the phenomenon who failed to see it. He volunteered the information that he has very poor night vision. Measurements of the vision thresholds after dark adaptation for all of the participating Apollo crewmen are planned, but have not yet been accomplished.

During the Apollo 14 transearth coast (TEC) (*7*) session, an attempt was made to further examine the dark adaptation requirement. Mitchell began the session thoroughly light adapted (after several hours in the fully illuminated Command Module), and reported seeing his first event after 17 minutes of adapting to the dark. During the next 8 minutes he reported four additional events. He then attempted to destroy his dark adaptation by slowly waving a penlight from one eye to the other [the penlight has a maximum apparent brightness of about 240 foot-lamberts (822 candles per square meter) over the range from 2 to 15 cm in front of the penlight cover glass, and it was shone in each eye for about 1 second on each pass]. This penlight procedure lasted some 60 seconds. Mitchell reported an event 51 seconds after the penlight was switched off. Including that event, he saw a total of eight events over the 12-minute period immediately following the penlight illumination. At this point he repeated the penlight procedure and observed for an additional 10 minutes. During this final 10-minute period, he reported seeing nine events. After this session, some doubt was expressed about the validity of Mitchell's light-adapting procedure. Since the characteristic dark adaptation period that has been apparent for all observers at the beginning of each session indicates that dark adaptation is required, we believe it is likely that Mitchell's penlight procedure was insufficient to completely destroy his dark adaptation, and that one must be reasonably well adapted to the dark to observe the phenomena. Evidently, the flashes are subtle and usually near threshold. This explains the need to concentrate to notice the events.

Table 2 lists the mean time between events after dark adaptation for each observer, and the average value for all observers for each session. The errors given were computed by using the 68 percent confidence limits from the summed Poisson distribution for the number of events seen by each observer after dark adaptation. The session averages were computed by weighting the individual values according to the corresponding dark adapted observing times. Table 2 also includes the dark adaptation times.

A close examination of Table 2 reveals an interesting anomaly. The TEC sessions have a considerably greater mean time between events than the translunar coast (TLC) sessions, and the average dark adaptation times for the TEC sessions is twice that for the TLC sessions. Also, most of the crew members commented that the flashes seemed not only less frequent during the TEC sessions but also much less brilliant. The most dramatic example of this anomaly occurred on Apollo 17, when all three crewmen reported that no events were seen during the entire 1-hour TEC session (*8*). During the similar TLC session the two observing crewmen reported a total of 28 events. We believe that the data and the subjective comments are evidence for a real effect.

In an attempt to understand this anomaly, we examined the following possible mechanisms that would decrease the flux of cosmic rays of $Z \geqq 6$ during the TEC sessions relative to the TLC sessions: geomagnetic shielding effects from the earth's magnetosheath tail, the relative difference in spacecraft shielding, and possible flux modulation due to solar activity. None of these mechanisms was capable of explaining the anomaly. We conclude the cosmic ray flux was the same inside the spacecraft during the TEC and TLC sessions on each flight, and thus have no physical explanation for the anomaly. However, we still believe that the light flash phenomena are caused by some portion of the ($Z \geqq 6$) cosmic ray flux.

Finally, even though all the crew members reported feeling well rested and alert for the TEC sessions, and no fatigue or vision impairments were reported, it is still conceivable that the TEC light flash suppression was due to some physiological effect.

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References and Notes

1. These Gemini flights had orbital inclinations of about 35°, which implies that the entire trajectory was confined to regions of high (> 4 Gv) geomagnetic cutoff. Thus, the flux of cosmic ray nuclei was lower by an order of magnitude during the Gemini flights compared to the Apollo flights.
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7. The translunar coast is the part of the mission from the earth to the moon, and the transearth coast is the return to the earth.
8. The crew did report seeing some flashes during sleep periods before and after the TEC observing session. However, no objective rate measurements are available.
9. We acknowledge the contribution to this investigation by scientist astronauts P. K. Chapman and J. P. Allen. C. Goodman provided essential support, and many helpful comments and suggestions were made by P. J. McNulty, V. P. Pease, and T. F. Budinger. Finally, we acknowledge the unfailing assistance of the flight controllers and personnel at the Johnson Space Center, Houston, Texas, and the enthusiasm, competence, and cooperation of all Apollo crew members with whom we worked.
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Eustatic Sea Level 120,000 Years Ago on Oahu, Hawaii

Abstract. *Extensive dating of the fossil corals associated with the Waimanalo shoreline on Oahu has shown that 120,000 years ago the ocean was approximately 7.6 meters above its present level. Corals grown during that time constitute a major portion of the subaerial reef-derived material on the island, with exposures ranging from about 10 meters to near sea level. This evidence corroborates the notion that 120,000 years before the present was the last time during which the sea stood significantly higher than it does today. The reported benches at 3.7, 1.5, and 0.6 meters, if not of Recent origin, could be features created by brief halts of the sea during rapid regression shortly after the Waimanalo high stand.*

The eustatic rise and fall of sea level resulting from Pleistocene glaciation and deglaciation are recorded along shorelines in the form of marine erosional benches and depositional terraces. The times of interglacial periods can be determined by age-dating of the coralline material associated with the terraces. However, the absolute positions of sea stands during these times are relatively difficult to ascertain. One major complication is the difficulty of identifying tectonically stable coasts.

The island of Oahu (Fig. 1) in the Hawaiian Archipelago provides good opportunities for studying past fluctuations in sea level, since reef limestones fringe about 30 percent of its shoreline (*1*) and the island is considered to have been tectonically undisturbed at least since its so-called Waimanalo shoreline was formed. This ancient strandline occurs extensively in the archipelago (notably on Oahu but also on Maui, Molokai, and Lanai) at about 7.6 m (25 feet) (*2, 3*). Its type locality is defined by wave-cut features, thus making it possible to obtain more precise information on the elevation of the former sea level than that deduced from littoral deposits (*4*).

We report here the results of our age measurements on fossil corals collected from Oahu (Fig. 1). The ages were determined from the ratios of ^{230}Th to ^{234}U (*5, 6*), and in many cases the results were checked with the measurements of $^{231}Pa/^{235}U$ (*7, 8*) and $^{234}U/^{238}U$ (*9*) ratios. We analyzed the uranium and thorium isotopes by