some reaction between Ca (or Mg) and the alkali-depleted aluminosilicate framework forming perhaps alkaline earth silicates. It has been suggested that a silicate layer of this kind can act as a diffusion barrier (*10*) and as such may disrupt the regular growth of the hydration layer which is the basis of the obsidian dating technique.

The Si and Al depth profiles (Fig. 2, g and h) show very little variation of concentration with depth, indicating no replacement of Si or Al by H as expected. The depletion of the major alkalis and part of the alkaline earths means that there is an increase in the mole fraction of SiO_2 and Al_2O_3 at the surface. The essentially constant signal from these elements suggests that the densities of Si and Al remain constant. This result supports the idea that the aluminosilicate framework remains intact during leaching under near-neutral conditions. Hench (*8*) has reasoned from his glass-leaching studies that the formation of a silica-rich and alumina-rich surface layer acts as a protective film to further leaching. Hench and Clark (*9*) have reported that the thickness of the silica-rich or alkali-depleted layer is controlled by a $t^{1/2}$ dependence, which changes to a t dependence as the leaching time, t, increases. Despite the different hydration conditions, it is possible that obsidian may hydrate in a similar manner, as has been suggested by the results of Ericson *et al.* (*7*).

The results of this investigation demonstrate that the thickness of the hydration layer on obsidian artifacts can be established by the technique of sputter-induced optical emission. The depth profiles of the different elements suggest that the kinetics of diffusion in obsidian are highly complex and that chemical composition plays an important role in the hydration process (*1, 16*). This technique not only provides a new method for obsidian dating but can also be applied to the study of other pertinent problems such as the hydration of container glass surfaces by aqueous solutions and the leaching of proposed glasses for the encapsulation of radioactive wastes.

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Visual Phenomena Induced by Relativistic Carbon Ions With and Without Cerenkov Radiation

Abstract. *Exposing the human eye to individual carbon ions ($^6C^+$) moving at relativistic speeds results in visual phenomena that include point flashes, streaks, and larger diffuse flashes. The diffuse flashes have previously been observed by astronauts in space but not in laboratory experiments with particles of high atomic number and energy. They are observed only when the nucleus moves fast enough to generate Cerenkov radiation.*

There have been a number of investigations designed to determine the physical mechanism behind the visual phenomena observed by astronauts when exposed to the radiation environment in space (*1–5*). Our earlier experiments with muons, pions, and individual nitrogen nuclei (*3*) showed that Cerenkov radiation generated within the eye can induce visual phenomena similar in description to those reported by astronauts in deep space (*1*). However, the muon and pion data were obtained in experiments designed to simulate the passage of an ion of high atomic number, Z, and energy, E, with a pulse containing $N = Z^2$ singly charged particles. This raised the question of the extent to which the phenomena observed resembled those induced by the HZE (high Z and E) particles encountered in space (*6*). Moreover, experiments with neutrons, alpha particles, and nitrogen nuclei (*5*) showed that star- and streak-like phenomena similar to some of those observed in space can be induced in the absence of Cerenkov radiation, presumably as the result of ionizations and excitations along the trajectory of the incident particle or its secondaries. This raised the possibility that the HZE particles that generated visible pulses of Cerenkov light in the eyes of astronauts on Apollo missions would have been detected anyway because of ionization effects, and that while Cerenkov radiation may have influenced the visual phenomena experienced, it would not have significantly affected the rate at which the flashes were observed.

To directly compare the visual phenomena induced by HZE particles with and without Cerenkov radiation and to determine the effect of Cerenkov radiation on a subject's ability to detect the particles, we initiated a series of exposures of human subjects to HZE particles at the Bevalac accelerator at Lawrence Berkeley Laboratory. The details of the facility devised to deliver HZE particles one at a time are given elsewhere (*7*). This report describes the results of the preliminary trials, which involved comparing carbon nuclei at speeds above and below the Cerenkov threshold. The nuclei had kinetic energies of 595 MeV per nucleon and a stopping power in water of 94 MeV-cm^2/g at the higher speed, and values of 470 MeV per nucleon and 103 MeV-cm^2/g at the lower speed. The carbon nuclei do not stop in the eye, nor do they lose a significant amount of energy in traversing it. The patterns of ionizations and excitations along the trajectories are quite similar for the two cases, and a significant increase in a subject's ability to detect the passage of a higher-velocity nucleus through his eye would be attributable to Cerenkov radiation.

After dark-adapting for 40 minutes, the subject aligned himself to the beam line by using a personalized bite plate and fixated on a red light–emitting diode mounted on the far wall of the darkened room. This aligned the head and eye

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such that the beam particles entered at an angle of about 60° with the optic axis as defined by fixation. An initial alignment procedure was completed before the experimental sessions. A laser beam was passed through the beam collimator to the subject's head. When the laser spot fell on the proper region of the eye, the bite plate was locked in position. The particle beam pathway was directed away from the lens of the eye. After a foreperiod that was varied randomly from 2 to 4 seconds, a pulse of carbon nuclei or a catch test pulse (one containing no particles) was delivered. The subject signaled readiness by depressing a switch. He signaled detection (a hit) by depressing the same switch. The subject was also in communication with the experimenters in the control room by intercom. After each hit or miss, the subject was asked to confirm his response and describe the visual phenomena for all hits. The cross-sectional area of the beam was determined by a 2-mm-diameter collimator placed in the beam line about 30 cm upstream from the subjects. Particles entering the eye were counted in coincidence by a scintillator downstream from the collimator just before the eye and a scintillator upstream from the collimator.

In procedure 1 the subject did not know whether a pulse would contain one, two, or no nuclei or whether the carbon nuclei were at speeds above or below threshold. Catch tests were randomly distributed among the experimental trials at a rate of approximately 40 percent. Only one catch test in 81 resulted in a positive response (false alarm) and that visual sensation was described as similar to the phosphenes that subjects observed when dark-adapted in the radiation-free environment.

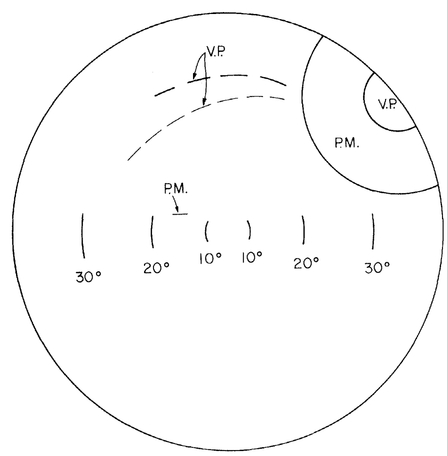

Fig. 1. Schematic drawing of visual sensations described by subjects P.M. and V.P. The scale represents visual angle.

In procedure 2 the subject did not know whether the carbon ions were incident at speeds above or below threshold. Catch tests were not employed. In procedure 3 the subject knew whether the particles in a particular series would arrive at speeds above or below threshold, but catch tests were included. There were no obvious differences between the data obtained by the three procedures.

Table 1 summarizes the data for the three subjects under the procedures followed. The visual phenomena were often complex combinations of diffuse flashes and streaks. One subject did not report any observations of particles either above or below the threshold speed for Cerenkov radiation. The ability of the other two subjects to detect carbon ions was considerably greater for speeds above threshold. The detection efficiency for pulses containing one or two particles at speeds below threshold generally agrees with the detection efficiency observed previously for stopping alphas and nitrogen nuclei (*5*). Diffuse flashes were observed only when the carbon nuclei moved through the eye at speeds above threshold. They consistently appeared in the region of the field of view that corresponded to the location on the retina where the beam particles exited the eye, which would be expected if the visible components of the Cerenkov optical shock wave (which propagates toward the nasal region of the retina) initiated the visual process. The diffuse flashes were similar in appearance to the flashes induced by muons and pions (*3*). This evidence indicates that the diffuse flashes observed in this experiment were the result of Cerenkov radiation. The more localized phenomena—streaks and pointlike flashes—were observed for particle speeds both above and below the Cerenkov threshold, which demonstrates that Cerenkov radiation is not the sole mechanism for these phenomena.

Figure 1 is a schematic drawing of typical visual sensations described by subjects P.M. and V.P. For both subjects the diffuse flash occurred in the right-hand field of view in the area shown. Both subjects reported that streaks often accompanied the diffuse flashes. When they did, a definite temporal sequence was observed. The diffuse flash appeared first, followed by the streak phenomena. This is the opposite of the physical sequence of events, in which the particle enters the region of the eye where the streaks are observed and exits in the area of the diffuse flash. This sequence takes less than 10×10^{-11} second from entrance to exit. The streaks appeared to be moving from right to left in the visual field. The streak phenomena for subject P.M. were at a location corresponding to beam entrance; for subject V.P. they were not always at such a location. For both subjects a single carbon ion often resulted in the observation of more than one streak. Subject V.P. reported the observation of curved broken streaks of the type shown in Fig. 1.

The length of the long broken trajectories is far greater than could be explained by path lengths in the retina.

Table 1. Summary of procedures and results for three subjects.

Subject	Procedure	Particle speed*	Pulses	Particles	Hits	Diffuse flashes	Streaks or points
V.P.	1	Above	19	35	8	5	6
		Below	19	23	5	0	5
	3	Above	25	33	20	13	14
		Below	22	33	2	0	2
P.M.	1	Above	35	58	14	10	8
		Below	31	44	3	0	3
	2	Above	16	21	7	5	3
		Below	14	18	1	0	1
V.B.	1	Above	38	56	0	0	0
		Below	9	13	0	0	0

*Above or below the Cerenkov threshold.

Table 2. Combined data for subjects P.M. and V.P. for single- versus multiple-particle pulses.

Type of pulse	Particle speed*	Particles	Pulses	Detections	Diffuse flashes	Points and streaks
Single particle	Above	53	53	27	18	18
	Below	55	55	8	0	8
Multiple particle	Above	95	42	23	15	13
	Below	63	31	3	0	3

*Above or below the Cerenkov threshold.

This is consistent with the observations of three subjects exposed to individual nitorgen ions at the Princeton Particle Accelerator (*3*). Broken streaks have been observed in space and in laboratory experiments (*5*). It is possible that fragmentation of the carbon nucleus and interactions that lead to the formation of nuclear stars play a role in these effects, but further study is needed.

Table 2 shows the data for subjects P.M. and V.P. and for pulses containing one or more particles. Their ability to detect pulses containing one particle was not significantly different from their ability to detect pulses containing more than one particle—that is, the detection efficiency per particle was far less for multiple-particle pulses. Tobias and coworkers (*5*) also reported a dependence of the subject's ability to detect HZE particles that did not produce Cerenkov radiation on the number of particles in the pulse. Table 2 shows that the effect holds true for the diffuse flashes, which were shown above to be due to Cerenkov radiation and hence optical phenomena.

In summary, carbon nuclei entering the eye are detected more often at speeds above the Cerenkov threshold than below. This finding lends strong support to the hypothesis that Cerenkov radiation plays a major role in the visual phenomena observed by astronauts in deep space. Large diffuse flashes are observed only at speeds above threshold and occur only at the location in the field of view corresponding to beam exit. They are similar in appearance to the large-area flashes previously observed with muons and pions. These data suggest that an important mechanism for these large flashes and possibly for those observed in space is Cerenkov radiation. Furthermore, the large flashes observed in space can be generated by nuclei with atomic numbers as low as 6 and not only by nuclei of higher atomic number.

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Deuterated Methane Observed on Saturn

Abstract. *Absorptions for the ν_2 band of deuterated methane (CH_3D) have been observed in the 5-micron spectrum of Saturn, obtained with a Fourier transform spectrometer. Analysis of the band yields a CH_3D abundance of 2.6 ± 0.8 centimeter-amagat and a temperature of 175 ± 30 K for the mean level of spectroscopic line formation. This temperature indicates that a substantial portion of Saturn's flux at 5 microns is due to thermal radiation, and that we are therefore looking fairly deep into its atmosphere, as is the case for the Jupiter 5-micron window. This CH_3D abundance leads to a deuterium/hydrogen ratio of about 2×10^{-5} in Saturn's atmosphere. This ratio is much lower than the terrestrial value but comparable to that determined for Jupiter and may be taken as representative of the deuterium/hydrogen ratio in the solar system at the time of its formation.*

Observations of the deuterium content in the atmospheres of the major planets is important for a determination of its abundance at the time of formation of our solar system. Present theories (*1, 2*) indicate that deuterium can only be produced during "big bang" nucleosynthesis. A determination of the primordial D/H ratio, therefore, poses important experimental constraints such as the mass density, the rate of expansion, and the neutron-proton density for theories of nucleosynthesis and the formation of the universe. Stellar processing of matter has the effect of destroying deuterium, and the sun and stars have thus burned most of their deuterium into ^3He. The value of the D/H ratio obtained from the massive hydrogen atmospheres of the major planets may be taken as most representative of a "primordial" D/H ratio since their deuterium has probably undergone very little reprocessing (*2*) and is not affected by fractionation in the interior (*3*).

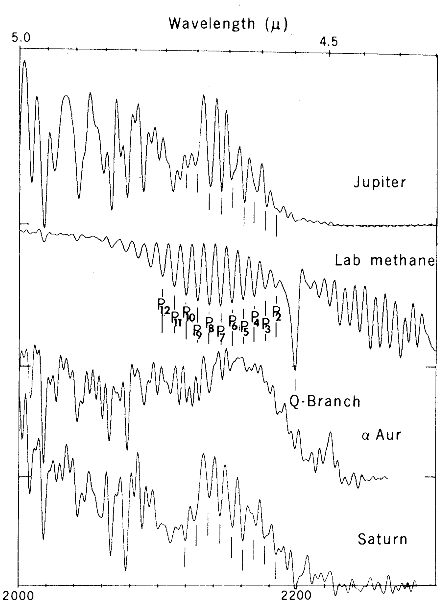

Fig. 1. A portion of the 5-μ spectrum of Saturn at a resolution of 2.8 cm^{-1}. A comparison star (α Aur), a laboratory CH_4 spectrum, and a spectrum of Jupiter in the same region are also shown. The Q-branch and P-branch lines of the ν_2 band of CH_3D are marked. Zero levels are displaced as indicated on the side.

Several years ago deuterium in the form of CH_3D was detected in the atmosphere of Jupiter by Beer *et al.* (*4, 5*). Their estimates of the jovian D/H ratio ranged between 2.8×10^{-5} and 7.5×10^{-5}. Sometime thereafter, the very weak 4-0 P(1) line of HD, observed in the jovian spectrum by Trauger *et al.* (*6*), allowed a direct comparison between the HD and H_2 abundances and gave a D/H ratio of 2×10^{-5}. The actual value for the D/H ratio in Jupiter's atmosphere is, at present, still uncertain because of correction effects introduced by the scattering nature of its atmosphere (*7*) and because of the recent revisions (*8*) of both the HD and H_2 line strengths used in the determination of the D/H ratio. Presently accepted jovian D/H values center around 5×10^{-5} (*9*).

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