original magma is estimated below from Fig. 2 on the assumption that its composition [in percentage (by weight)] lies near the middle of the two groups: SiO_2, 46.0; TiO_2, 3.0; Al_2O_3, 9.7; Cr_2O_3, 0.60; FeO, 20.0; MnO, 0.25; MgO, 10.2; CaO, 10.0; Na_2O, 0.27; and K_2O, 0.06 (*7*). The composition is considerably richer in FeO and poorer in alkalies than that of the terrestrial basalts with similar MgO contents. If the magma of this composition was formed by partial melting of the moon's interior at depths less than about 200 km, the source material was most likely plagioclase-bearing peridotite or ilmenite-bearing olivine gabbro. If the magma originated at depths where plagioclase is not stable, the source material may have been peridotite containing garnet or spinel plus pyroxene solid solution with considerable amounts of Al, Ti, and Na.

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5. The Apollo 11 and Apollo 12 rocks contain relatively small amounts of alkalies and this index is nearly the same as the percentage (by weight) of MgO relative to MgO plus FeO.
6. The most magnesian olivine in a relatively Mg-poor rock (sample 12065) has the composition $Fo_{71}Fa_{29}$, which is not much different from that of sample 12020 and plots close to OL in Fig. 2.
7. Plots for Cr_2O_3, MnO, and K_2O have also been made, although they are not shown in Fig. 2; values midway between those for the olivine-rich group and those for the olivine-depleted group have been obtained for these oxides.
8. We thank Dr. Y. Nakamura for helpful discussions.

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Solar Particle Tracks in Glass from the Surveyor 3 Spacecraft

Abstract. *A glass filter from Surveyor 3 has a surface density of* $\sim 1 \times 10^6$ *tracks per square centimeter from heavy solar flare particles. The variation with depth is best fitted with a solar particle spectrum* $dN/dE = 2.42 \times 10^6\ E^{-2}$ *[in particles per square centimeter per year per steradian per (million electron volts per nucleon)], where* E *is the energy and* N *is the number of particles, from 2 million electron volts per nucleon to* ~ 7 *million electron volts per nucleon and* $dN/dE = 1.17 \times 10^7\ E^{-3}$ *at higher energies. Not much difference is observed between 0.5 and 5 micrometers, an indication that there is a lack of track-registering particles below 0.5 million electron volts per nucleon. The Surveyor data are compatible with track results in lunar rocks, provided an erosion rate of* $\sim 10^{-7}$ *centimeter per year is assumed for the latter. The results also suggest a small-scale erosion process in lunar rocks.*

The Apollo 12 spacecraft has returned to earth Surveyor 3 samples that were exposed for 2.6 years on the moon. We present here preliminary results of studies of nuclear tracks in a piece of clear filter glass used to cover the lens of the TV camera from the Surveyor 3 spacecraft. The results give information about low-energy nuclear particles from the sun and provide a basic calibration for nuclear tracks in the surfaces of lunar rocks (*1, 2*).

The TV camera was mounted vertically inside a shroud open on one side (images were obtained from a mirror above the lens). The lens was covered by a horizontal filter wheel. After 2 weeks of operation the clear filter was left directly in front of the shroud opening until recovery.

We recently received a piece of this glass $\sim 0.35\ cm^2$ in area and 0.3 cm thick. A microprobe scan shows that the glass contains a large amount of Pb and smaller amount of K. From the density ($3.60\ g\ cm^{-3}$) and the index of refraction ($n = 1.61$), we infer that the Pb content must be close to 43 percent (by weight) (*3*). The microprobe also showed a small amount of Mg, presumably from a $\lambda/4$ coating of MgF_2.

The geometry of the glass with respect to the opening was specified as follows (*4*): (i) A reference line $\overline{AB}$ was drawn on the surface of the glass. This line ran from left to right for an observer standing in front of the camera. (ii) A wire was placed perpendicular to the line $\overline{AB}$ at the point where our sample was taken. The wire was then rotated in a vertical plane until it bisected the opening from top to bottom. (iii) A piece of clear plastic was then placed perpendicular to the wire, and the outline of the opening was traced out. Specification of the coordinates in the plane of the plastic (x,z), the elevation of the wire, and the distance from the sample to the x,z reference plane fix the geometry.

The sample was cut into three parts with the first cut made parallel to $\overline{AB}$ at an angle to the exposed surface of 60°. This was done to ensure that the tracks were incident at a steep angle. One piece (section 1) was put in epoxy, polished, and etched (1 percent HF solution) to study the depth dependence. The other pieces were used to study tracks on the exposed surface. Measurements were made with a scanning electron microscope at a depth of from 0 to 30 μm and with an optical microscope starting at a depth of 10 μm. As shown in Fig. 1, the density is $(1.14 \pm 0.06) \times 10^6$ track cm^{-2} at 3.8 ± 1 μm from the surface and drops off rapidly with depth.

The remaining samples of the top surface were given varying treatments in H_2SO_4 and HNO_3 solutions to etch the MgF_2 coating. There are two layers of material covering the glass surface: the MgF_2 coating, which is ~ 1400 Å thick, and a second layer, ~ 0.4 μm thick, with a composition somewhat enriched in Si with respect to the glass. Possibly the second layer is a silane coating used to enhance the adhesion of the MgF_2.

No tracks were found in the MgF_2, although the right etchant may not have been used. When the MgF_2 was removed by etching in HNO_3 at 75°C for 1 hour, the second film was left intact. Subsequent etching in dilute HF gave a high density of shallow pits ($\sim 3 \times 10^8$ cm^{-2}). Shallow pits could also be seen on the glass substrate in areas where the film was broken away. However, similar pits were seen on the bottom, unirradiated portions of the glass and in some areas of a control glass provided by the Jet Propulsion Laboratory of the California Institute of Technology; it is thus unlikely that they are tracks of nuclear particles.

Further etching in HF removed the thick film and gave deep, characteristic track etch pits in the exposed glass surface. These tracks are clearly oriented toward the camera opening (see Fig. 2). The density of these pits is $(8.3 \pm 0.5) \times 10^5$ track cm^{-2}. When corrected for the geometry, this corresponds to a

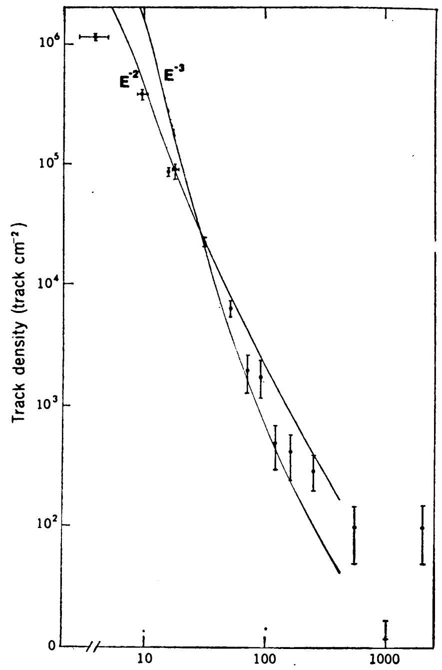

Fig. 1. Track density versus depth for section 1.

density of $(1.7 \pm 0.1) \times 10^6$ track cm^{-2} in the plane of section 1. As in other silicates, we assume that tracks are produced only by ions of the very heavy atoms (atomic number $Z \geqq 20$) (*5*). They could have been registered either on the moon or in passage through the radiation belts. Using the data on the ratio of alpha particles to protons (*6*) and the ratio of C, N, and O atoms to alpha particles (*7*), we estimate that $< 10^{-3}$ of the tracks come from the earth's radiation belts. It is most likely that the tracks were registered during energetic solar events, specifically the solar flare events of November 1968 and April and November 1969.

In Fig. 1 we compare the data with theoretical curves for different energy spectra of the type

$$(dN/dE) = CE^{-\gamma}$$

where N is the number of particles, E is the energy, C is a constant, and γ is the spectral index. The density ρ was calculated as follows (*8*):

$$\rho(d) = \sum_{x,z} \left(\frac{dN}{dE}\right)_{x,z} \left(\frac{dE}{dR}\right)_{x,z} \times \exp(-\psi R_{x,z}) \Delta R_c d\omega_{x,z} \quad (1)$$

where R_c is the etchable track length and ψ, the nuclear interaction probability per unit length, is equal to zero for $E < 10$ Mev per nucleon. Each set of x,z corresponds to a particular location on the previously defined reference plane; $R_{x,z}$ is the distance the particle traveled through the glass in going from the point x,z to a point located a distance d from the surface along the plane of section 1. The corresponding solid angle per unit area is given by $d\omega_{x,z}$. Equation 1 was summed over 136 sets of x and z. The range energy data were taken principally from the tables of Henke and Benton (*9*). The stopping power of Fe in Pb was estimated by the method of Barkas and Berger (*10*).

From 10 to 50 μm (~2 to 7 Mev per nucleon) our data are best fitted with a power law spectrum of the form $dN/dE = 2.42 \times 10^6\ E^{-2}$ particle cm^{-2} ster^{-1} yr^{-1} Mev^{-1} nucleon. At higher energies $dN/dE = 1.17 \times 10^7\ E^{-3}$ particle cm^{-2} ster^{-1} yr^{-1} Mev^{-1} nucleon seems a better fit although the E^{-2} spectrum is possible.

The spectra are in accord with what is known about solar flares (*11–14*). Although the spectral index of solar flare protons varies from one flare to the next and even changes with time for a given flare, values of γ of ~3 are typical. The spectral index tends to be lower for alpha particles than for protons (*13*). The differential flux generally shows a sharp break to a lower spectral index between 4 and 8 Mev. Arnold and his co-workers (*14*) also find that a spectral index of 2 gives the best fit to their radiochemical results on lunar rocks.

Now we shall consider the absolute values of the flux. Two measurements are available for comparison, one a satellite estimate of $\sim 3 \times 10^2$ particle cm^{-2} sec^{-1} for energies greater than 20 Mev for the solar maximum of 1956–1960 (*12*), and the other a long time average, determined radiochemically, of ~25 particle cm^{-2} sec^{-1} for energies greater than 10 Mev (*14*). Since the solar flare flux varies by a factor of 10^5 from solar minimum to maximum, it is difficult to know a priori which value to choose. However, the radiochemical comparison of different isotopes indicates that the flux for the period from 20 April 1967 to 19 November 1969 was no more than ~2 times the long-term average (*14*). Thus we might expect a value of ~50 particle cm^{-2} sec^{-1} for energies greater than 10 Mev.

Our data are not in good agreement with this estimate. Assuming a pure E^{-2} spectrum, we find values of 800 particle cm^{-2} sec^{-1} for energies greater than 10 Mev and 400 particle cm^{-2} sec^{-1} for energies greater than 20 Mev. If we take an E^{-3} spectrum starting at a depth of 30 μm, the corresponding numbers are 200 particle cm^{-2} sec^{-1} at energies greater than 10 Mev and 50 particle cm^{-2} sec^{-1} for energies greater than 20 Mev. On the basis of this comparison, the combination of an E^{-2} with an E^{-3} spectrum is preferred.

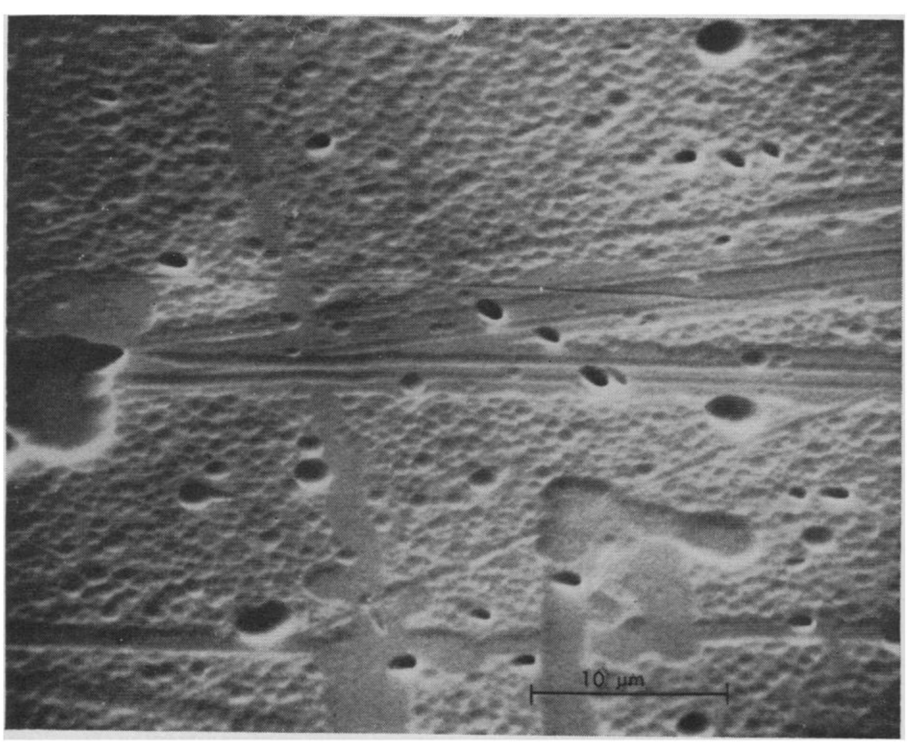

Fig. 2. Etched tracks on the top surface after removal of surface films. The tracks are the dark oval objects ~ 1 μm in size. They have a clear directionality pointing back to the camera opening. The backgrounds of very shallow pits are also found on the unirradiated portion of the glass and are not produced by nuclear particles.

Neither spectrum fits the data for a depth of 3.8 ± 1 μm (~1 Mev per nucleon), and it is likely that the differential flux falls off below this value (*15*). Essentially the same track density is found on the external surface as at a depth of 3.8 μm. To register in the glass surface the particles would have had to penetrate the two surface films encompassing ~0.5 μm of material. From this we conclude that there are relatively few particles in the interval between ~30 kev per nucleon and 1 Mev per nucleon. Recently Borg *et al.* (*16*) reported extremely high track densities ($\gtrsim 10^{11}$ track cm^{-2}) in small (< 1 μm) particles removed from the lunar soil. One explanation for the origin of these tracks is the 5- to 50-kev solar particle component observed in space probe experiments (*17*). However, no evidence for such particles is found here and the high track densities remain unexplained.

Previously we showed (*1*) that the track data in lunar rocks 10017 and 10058 could be fitted with either an E^{-2} or an E^{-3} spectrum, provided that an erosion rate of $\sim 10^{-7}$ cm yr^{-1} was taken. Unpublished data on other lunar rocks confirm this result. In these rocks the track density versus depth relation lies on a straight line on a log-log plot. However, the slope is gentler than that in the data for Surveyor glass. For example, in rock 10057 a tenfold change in depth produces only a sevenfold change in track density. The corresponding change in track density in Fig. 1 is a factor of 200 for a similar tenfold variation in depth. It is possible to show that this difference can be explained by an erosion rate of 10^{-7} cm yr^{-1} and a long-term spectral index of 2 (*18*).

If we take into account the solid angle and the stay time, and allow a factor of 2 for the increase in solar activity over a long time average, the track densities in Fig. 1 correspond roughly to those expected for a 2π irradiation in 1 year. Typical crystals from the rock surfaces have densities of $\sim 10^{9}$ track cm^{-2} at a distance of 20 μm from the edge. Because of the geometry, this corresponds to a depth of about 10 μm in Fig. 1. The level of 10^{9} track cm^{-2} would be achieved in an irradiation time of $\sim 2 \times 10^{3}$ years. Since this time is short as compared with the cosmic-ray exposure age of the rocks, it is likely that the 10^{9} track cm^{-2} is an equilibrium value reflecting a balance between erosion and irradiation. Although the rough estimate of ~ 20 μm removed in 2×10^{3} years is greater by a factor of 10 than the limit of 10^{-7} cm yr^{-1} set by us on the basis of other considerations (*1*), we do not consider this a serious disagreement in view of the various uncertainties. Our main point is that a considerable erosion rate is required.

The results also suggest that erosion occurs by a flaking off of small thicknesses of material, possibly caused by solar wind irradiation. If whole crystals ~100 to 300 μm in size had to be removed every 2×10^{3} years, the erosion rates would become unreasonably high.

One of the important points that needs to be examined in future work is the sensitivity of the Surveyor glass for the registration of particle tracks. If the glass were to register lighter particles of the C,N,O group, this would bring our absolute fluxes into better agreement with the radiochemical data and would modify somewhat (although not completely) our conclusions on lunar rock erosion.

Note added in proof: The discrepancy between the radiochemical data and the heavy ion track data has essentially disappeared for the following reasons: (i) Conversations with Fleischer and Price (*19*) have convinced us that we took a value for the maximum track length that was too low by a factor of 3. Our heavy particle flux values should be correspondingly lowered. (ii) Estimates of the proton flux by Arnold and his co-workers have also been raised by a factor of ~3 (*20*). Taking an E^{-3} spectrum at a depth of 30 μm, we would now estimate an average proton flux of 70 proton cm^{-2} sec^{-1} for energies greater than 10 Mev, in good agreement with the long-term value of 80 proton cm^{-2} sec^{-1} for energies greater than 10 Mev now estimated from radiochemical data. At this energy, therefore, there is no evidence that the ratio of iron nuclei to protons is higher in solar flares than the value 10^{-5} used here, as has been suggested by Barber *et al.* (*21*). Contrary to our statement in the text, it is also possible to construct a simple model in which the Surveyor results are used to obtain very high track densities in the lunar dust as observed by Borg *et al.* (*16*) and by Barber *et al.* (*21*). Finally, it has been called to our attention that the surface of the glass filter was partially covered with a fine layer of dust. Although this dust layer has the effect of artificially lowering the observed track density on the surface, our essential conclusion that there seem to be few additional particles at energies less than 0.5 mev per nucleon remains unchanged.

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