# Reports

## Tracks of Cosmic Rays in Plastics

Abstract. *Cosmic ray nuclei have been observed with the use of plastic track-detecting solids in satellites and high-altitude balloon flights. Nuclear emulsions in the stacks of plastic sheets allowed the positive identification of cosmic ray nuclei as light as nitrogen. The most striking new information was the failure to observe relativistic iron nuclei, a result which has led to an advance in the understanding of track registration criteria.*

Dielectric track detectors (*1*) have a number of characteristics that make them uniquely useful for the study of heavily ionizing particles in cosmic radiation. Recent studies of ancient stored tracks of heavy cosmic rays in silicate minerals found in meteorites have provided information on the relative abundance of cosmic rays heavier than iron (*2, 3*), on the amount of material ablated from meteorites during atmospheric entry (*2, 4*), and on the space erosion rate of meteorites (*4*). Although the dimensions of meteoritic mineral detectors are small (usually $< 1$ mm$^3$), collecting times are extremely long (usually $\gg 10^6$ years), so that rare particles can be studied, and information about cosmic radiation in the geological past can be obtained.

Dielectric track detectors are also useful for studying the present-day cosmic radiation, both solar and galactic. This report is a preliminary account of the first observations of cosmic ray tracks in plastic sheets flown in balloons and satellites (*5*). In contrast to studies of ancient radiation, these observations were made with short exposure times, of the order of hours or days, but with large collecting areas, up to about $10^3$ cm$^2$.

Tracks are normally developed by immersing the detector in a suitable etching bath. The reagent attacks the chemically altered material along the trajectory of the particle, thereby producing a hole, which, when sufficiently large, is easily visible under a low-power microscope. In addition to this magnification technique, various optical amplification schemes can be used, so that in principle a few tracks in several square meters of detector can quickly be located. In this study an Al-film amplification scheme (*6*) was used to locate tracks in some of the large plastic sheets. After etching in 6.25*N* NaOH solution until the cosmic ray tracks are etched through the entire thickness of a sheet, a thin Al-film is evaporated onto one side of the sheet. The other side is covered with NaOH solution, which runs quickly through the etched tracks and leaves large circular holes in the film, thus locating the events.

Results are summarized in Table 1, which describes the flights from which data have been analyzed. For each flight the detectors are listed in the sequence they appeared in the stacks,

Table 1. Tracks of cosmic rays in plastics. Detectors are: DCNc, Dai Nippon cellulose nitrate, clear, 2000 $\mu$ thick; DCNr, Dai Nippon cellulose nitrate, red 100 $\mu$ thick; NBCNc, Nixon-Baldwin cellulose nitrate, clear, 250 $\mu$ thick; Lexan, Lexan® polycarbonate resin, clear, 50 $\mu$ thick; emulsion, Ilford G-5, 600 $\mu$ thick; Makrofol, Makrofol® polycarbonate resin, clear, 12 $\mu$ thick.

| Location and date | Area × time (cm$^2$ day) | Energy* (Gev/nucleon) | Detector | Observed tracks | Observed flux (No. per cm$^2$ day) | Conclusions |
|---|---|---|---|---|---|---|
| | | | *Balloon flights* | | | |
| Hyderabad, India | 250 | $\geq 7.5$ | DCNc | 0 | $< 4 \times 10^{-3}$ | Relativistic nuclei |
| 7.6°N; 6 g/cm$^2$† | 500 | $\geq 7.5$ | DCNr | 0 | $< 2 \times 10^{-3}$ | with $Z \lesssim 28$ do not |
| 7 April 1966 | 250 | $\geq 7.5$ | Lexan | 0 | $< 1.3 \times 10^{-3}$ | show up in CN |
| | 250 | $\geq 7.5$ | Emulsion | | $< 2 \times 10^{-3}$ | or Lexan |
| Hollomon AFB, N.M. | 100 | $\geq 1.5$ | NBCNc | 0 | | Relativistic nuclei |
| 41°N; 11 g/cm$^2$† | 100 | $\geq 1.5$ | Lexan | 0 | | with $Z \lesssim 28$ do not |
| 5 April 1965 | 100 | $\geq 1.5$ | Emulsion | | | show up in CN |
| | | | | | | or Lexan |
| Palestine, Texas | 195 | $\geq 1.5$ | NBCNc | 0 | $< 5 \times 10^{-3}$ | Relativistic nuclei |
| 41°N; 3.7 g/cm$^2$† | 195 | $\geq 1.5$ | Lexan | 0 | $< 5 \times 10^{-3}$ | with $Z \lesssim 28$ do not |
| | 195 | $\geq 1.5$ | Emulsion | | | show up in CN |
| | | | | | | or Lexan |
| Fort Churchill, Canada | 232 | $\gtrsim 0.14$ (oxygen) to | NBCNc | 134 | 0.58 | Al-film location |
| 69°N; 3.7 g/cm$^2$† | 232 | $\gtrsim 0.27$ (iron) | Emulsion | | | scheme works; sub- |
| 3 August 1965 | 232 | | NBCNc | 267 | 1.15 | relativistic particles |
| | 232 | | Lexan | $\geq 1$ | $4.2 \times 10^{-3}$ | are recorded |
| | | | *Satellite 42A* | | | |
| Inclination 66° | 83 | Varying with latitude | NBCNc | 72 | 0.87 | Tracks in Lexan and |
| 2.7 g/cm$^2$† | 83 | from $\gtrsim 0.12$ (oxygen) | Lexan | 5 | .06 | Makrofol correspond |
| 23 May 1966 | 83 | and $\gtrsim 0.22$ (iron) | Makrofol | $\geq 5$ | $\geq .06$ | to tracks in NBCNc |
| | 83 | up to $\gtrsim 7.5$ | Emulsion | | | |
| | | | *Satellite 29A* | | | |
| Inclination 75° | 113 | Varying with latitude | NBCNc | 258 | 2.28 | Tracks in Lexan and |
| 2.7 g/cm$^2$† | 113 | from $\gtrsim 0.12$ (oxygen) | Lexan | 9 | 0.08 | Makrofol correspond |
| April 1966 | 113 | and $\gtrsim 0.22$ (iron) | Emulsion | | | to tracks in NBCNc |
| | | up to $\gtrsim 7.5$ | | | | |

* Cutoff energy is determined by magnetic cutoff, absorbing material above the detector, and detector thickness. † Thickness of overlying material.

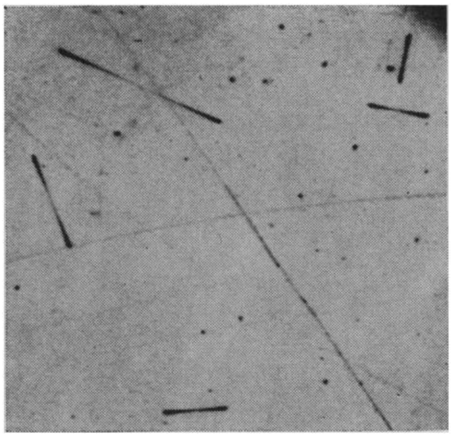

Fig. 1. Cosmic ray tracks etched in a 250-$\mu$ thick disc of cellulose nitrate exposed for 7 days in a polar-orbiting satellite. The longest track has a projected length of 600 $\mu$.

usually with G-5 emulsion on the bottom. Each etched track given in Table 1 extended completely through a plastic sheet or it extended from either surface so far into the sheet that it was obvious that the ends would meet if etching were continued. A photomicrograph of tracks is shown in Fig. 1.

All of the exposed cellulose nitrate sheets and also any unexposed cellulose nitrate control samples contained a background of short tracks (about $10^2$ per square centimeter) up to about 18 $\mu$ long; these tracks were caused by alpha particles from decay of $Rn^{222}$ in the air adjacent to the plastic sheets after their manufacture. An additional low density of short tracks in the exposed plastics is expected to result from cosmic-ray interactions in the plastics. This contribution probably does not exceed about 5 tracks per square centimeter per day. Tracks from alpha-decay and cosmic-ray interactions were immediately eliminated from consideration simply on the basis of length.

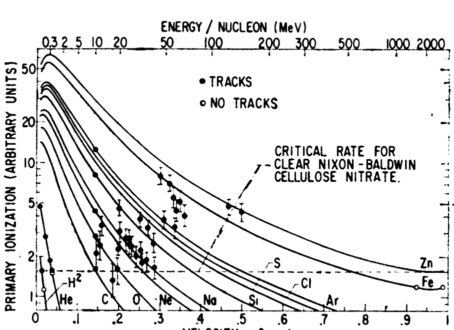


Fig. 2. Primary ionization rates of particles that form etchable tracks in cellulose nitrate. The points with error bars refer to tracks of cosmic rays identified by measurements in emulsion adjacent to a sheet flown at Fort Churchill. The other points, as well as the calculated primary ionization rate curves and the critical rate for registration (horizontal dashed line) were taken from Fleischer *et al.* (*8*).

In both the balloon flight at Fort Churchill and the high-inclination satellite flights, many tracks of subrelativistic cosmic rays, extending up to ~ 1 mm in length, were observed going through one or more plastic sheets and coinciding with tracks of heavy cosmic rays in the superimposed emulsions. Thus the experiments demonstrate that very long tracks of cosmic rays can be produced and studied with the track-etching techniques that heretofore have been applied only to low-energy particles with ranges of the order of $10^{-2}$ mm.

The Al-film amplification scheme (*6*) for finding rare, interesting events in a large area of detector was also successful. In a cellulose nitrate sheet (15 by 30 cm) flown over Fort Churchill, this technique successfully located about half of the tracks that penetrated the sheet. The remainder, found later after the Al was removed and the entire sheet was scanned microscopically, had gaps in their centers. These tracks, which entered the sheet at shallow angles, were so long that the etchant had not penetrated to their centers. With a longer etching time more of the tracks could have been located by use of the Al-film.

Perhaps the most important result of these experiments was the failure to see tracks that could be attributed to relativistic iron nuclei. The fluxes of iron nuclei, as determined from emulsion measurements, were as much as $10^3$ times higher than the maximum fluxes listed for the first three balloon flights in Table 1. It is thus clear that relativistic iron nuclei do not give rise to etchable tracks even in the clear Nixon-Baldwin cellulose nitrate, the most sensitive plastic we studied.

This result was unexpected because of our previous work on track registration (*7*), which suggested that such particles should form tracks. The negative finding reported here has led us to reexamine our previously proposed criterion for track formation—namely, that each solid is characterized by a critical rate of average energy loss that determines whether a track will or will not be formed—and to perform additional experiments and analysis. This new work, which will be reported elsewhere (*8*), shows that a better criterion for track formation is the existence of a critical value for the rate of primary ionization for each solid. The present failure to see relativistic iron nuclei is completely consistent with this new point of view.

Figure 2 summarizes the measurements made with the use of emulsions to identify the particles that left etchable tracks in the cellulose nitrate sheet flown at Fort Churchill. Curves of primary ionization rate, as well as the critical rate for cellulose nitrate, were taken from Fleischer *et al.* (*8*). Figure 2 shows that all tracks that have been identified were made by particles whose primary ionization rates are consistent with the critical rate determined for cellulose nitrate by Fleischer *et al.* (*8*).

At present the major advantages of plastic detectors for studies of cosmic rays appear to be their usefulness in locating tracks of heavily ionizing particles in emulsion and their ability to discriminate against an intense background of lightly ionizing radiation. Further developments may make it possible, with a stack of plastic detectors, to identify charges and energies of heavy particles up to relativistic energies.


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## Volcanic Sunset-Glow Stratum: Origin

Abstract. *Reexamination of the phenomenon of volcanic-dust sunsets, as typified by the Krakatoa event, supports a theory that the scattering layer is produced by the interaction of ozone and sulfur dioxide in much the same manner as is the normal "Junge" aerosol layer at 20 kilometers.*

The phenomenon of volcanic-dust sunsets, such as have been noted after major eruptions of volcanoes, is well known. The extensive observations included in Symon's report (*1*) on the Krakatoa eruption constitute a standard reference work concerning the heights of the glow stratum and ash layer from the most famous eruption of modern times. The eruption of Agung in 1963 has also drawn wide attention to the high-altitude dust that it distributed all over the world. We (*2*) have continued our observations of the height of the scattering layer by the twilight method, and believe that a new interpretation of the dust-layer hypothesis is required by all the evidence now available.

It is rather surprising that the dust layer, as evidenced by the sunset-glow stratum, persists for many years although the particle sizes responsible for the scattering of the sunlight (approximately 1 $\mu$) should have a settling time of the order of 1 year. The Krakatoa sunsets were still being observed after 5 years, when the Symons report went to press, and the Agung sunsets are still conspicuous after 3 years.

It is also surprising that the height of the glow stratum is constant with time after the event, and that separate eruptions produce layers at the same height. One would not expect different volcanoes to eject dust to the same altitude, well above the tropopause, since the violence of eruptions varies widely. The eruption of Agung, for instance, was clearly less violent than that of Krakatoa, yet our heights of 20 to 22 km agree within experimental error with those for the Krakatoa event. There have been several other eruptions in rapid sequence since Agung: in Costa Rica, Iceland, the Philippines, and Indonesia. We believe that our observations show that these minor eruptions have contributed reinforcement of the twilight glows, but we find no evidence of the multiple layers that would be expected if the height of injection of the scattering layer depended on the ballistic or convective mechanics of each event itself.

We suggest that the sources of worldwide effects of volcanic "dust" can be considered as: (i) an initial ash layer that is broadly distributed in height and that settles in the first few weeks or months, and (ii) a more-persistent aerosol layer of chemical rather than ash origin. We believe that the "dust" layer responsible for the persistent twilight-glow stratum results from continual precipitation of sulfates upon nonscattering condensation nuclei.

The sulfates responsible for the "dust" are produced by interaction of atmospheric ozone and the $SO_2$ that is temporarily augmented by the mass of volcanic gaseous effluent. According to this theory, the glow stratum is not ejected to high altitude by a violent event but results from diffusive mixing of a large injection of $SO_2$. The origin of the volcanic "dust" aerosol layer therefore appears to be identical with that of the natural sulfate aerosol layer, at 20-km altitude, described by Junge (*3*) and Mossop (*4*), except that the abundance of $SO_2$ in the case of the volcanic leads to more or larger particles (or to both). Persistence of the enhanced glow stratum after an eruption then depends on constant replenishment of the sulfate-coated particles by chemical means rather than on suspension of particles that were injected during a single event.

The association in our records of dates of stronger glows with polar air masses accords with this hypothesis of sulfate precipitation, since higher concentrations of ozone at the low side of the 25-km ozone maximum are associated with polar air masses. However, one must also remember that under these conditions the sky is very clear, and reddened sunlight of higher-than-normal intensity characterizes the grazing rays.

This hypothesis evokes many interesting questions: what is (i) the global production of $SO_2$ from volcanoes; (ii) the extent of annual fluctuations in this quantity; (iii) the entire aerochemical reaction chain if the end product is in the form of ammonium sulfate, as in the case of the normal 20-km aerosol layer (*4*); (iv) the global influence of a variable rain of highly hygroscopic particles? It is unfortunate that the U-2 experiments by Mossop were stopped on 15 March 1963 by the eruption of Agung; this event would have provided a wonderful opportunity to examine this hypothesis, even though Mossop's original object, study of extraterrestrial particles, was cut off by the eruption.

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## Marine Dolomite of Unusual Isotopic Composition

Abstract. *A piston core taken off of the coast of Oregon in 358 meters of water contained an indurated calcareous layer composed partly of dolomite with a composition $Ca_{58.7}Mg_{41.3}$. Dolomites of this chemical composition are typical of the supratidal environment. However, the dolomite has isotopic composition $\delta O^{18}$ = 5.8 per mille, $\delta C^{13}$ = −35.1 per mille relative to the Chicago PDB-I standard. The unusual carbon isotope ratio is similar to that of calcites produced as a byproduct of bacterial breakdown of hydrocarbons.*

This report on deep marine dolomites is the first to include a complete study of the samples (*1*). The dolomite that we used came from a piston core taken at 46°03.2′N, 124°45.7′W. This location is 30 nautical miles (56 km) west of the mouth of the Columbia River on the continental slope near the south edge of Astoria Canyon at a depth of 358 m (Fig. 1).