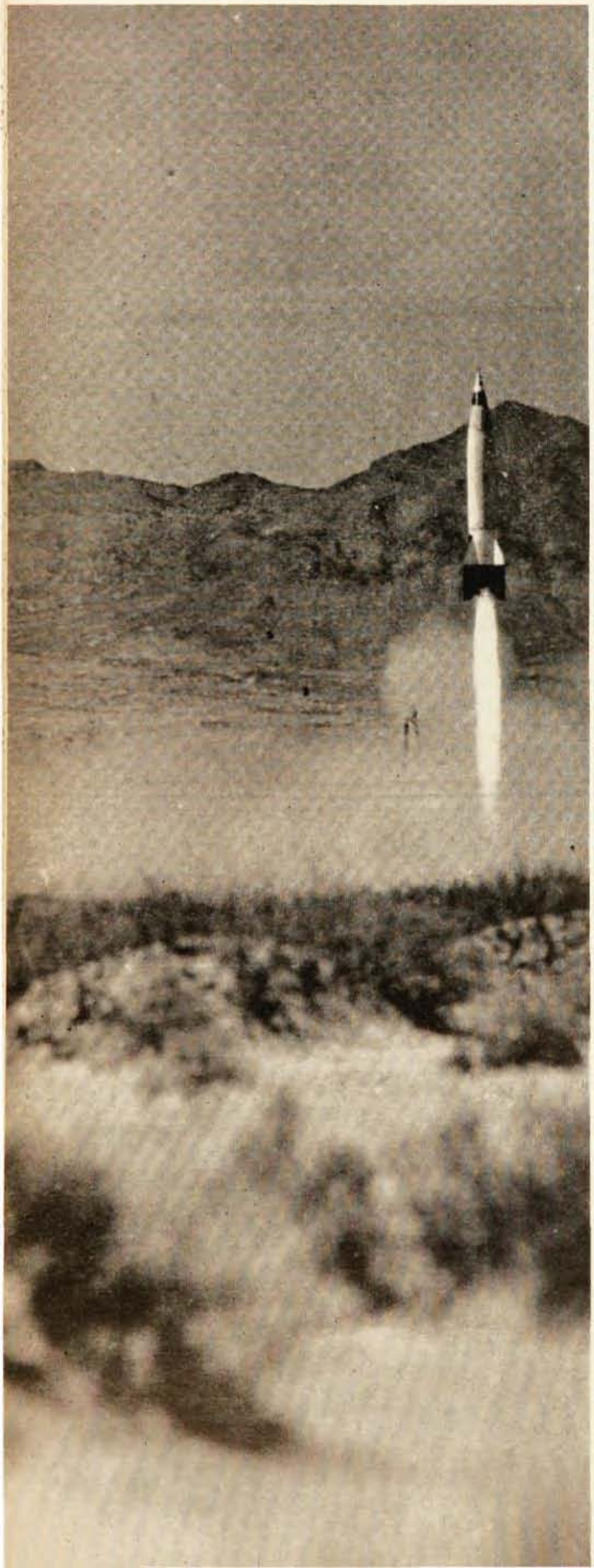
The RECOVERY of COSMIC-RAY EMULSIONS from ROCKET and SPACE PROBES

By Herman Yagoda



THE atmosphere presents a barrier between the cosmic-ray physicist and the object of his study. In its absorptive capacity for cosmic radiation the tenuous mantel of air adds up at sea level to 1040 grams per cm^2 equivalent to a shielding of about one meter of lead. To identify and to measure the relative proportions of the diverse components present in the primary cosmic-ray beam arriving from space the instrumentation must be sent above the atmosphere. Unlike the astronomer who can wait patiently for a night of "good seeing" in order to resolve planetary detail no such natural opportunity awaits those who are curious about the charge spectrum of the heavy primary component. Owing to the large collision cross sections of these massive charged particles an appreciable alteration of the beam takes place even at elevations readily accessible to high-altitude balloons, particularly for particles which arrive at large zenith angles.

An opportunity to transcend the atmosphere first became available at the end of World War II when a group of German V-2 rockets were brought to White Sands Proving Ground in New Mexico and scientists attempted to utilize the warhead compartment as a laboratory housing instruments for the study of atmospheric problems. These bulky war birds (Fig. 1) could reach peak altitudes of a little over 100 miles where the residual vertical air mass is of the order of 10^{-6} grams per cm^{-2} and the exponentially attenuating atmosphere may be said to be no longer in existence. It is one thing, however, to mount a package of nuclear emulsions inside a rocket to watch the vehicle take off, reach its apogee after a successful firing, and quite another matter to effect its physical recovery after its fleeting sampling of free space. The first V-2's that were launched had no provision for recovery, they reentered the atmosphere at high velocities and created craters from 15 to 30 feet in diameter when the wreckage was found in the desert sands. This was of little concern to "electronic-minded" physicists who tele-

Herman Yagoda is currently serving as a task scientist with the Ionospheric Physics Laboratory, Geophysics Research Directorate, Bedford, Massachusetts.

Fig. 1. Take-off of V-2 rocket No. 49 from White Sands Proving Grounds in New Mexico.

metered their observations to ground receiving stations, but presented a challenging problem to experimentalists who wished to recover evidence of micrometeorite cratering or blocks of nuclear emulsion exposed to cosmic radiation. This was solved in a gross way by severing the rocket on its way down by detonating explosive primacord at radio command. Because of their poor aerodynamic shape the severed portions are slowed down by air drag to an impact velocity of the order of 100 miles per hour. This is still quite a jolt, but properly encased instrumentation survives [1] and can with luck be located after arduous search by helicopter and jeep, abetted with footwork.

Our first sample of nuclear emulsion was recovered by this brute force technique on September 29, 1949, after exposure on V-2 No. 49 which reached a peak altitude of 151 km. The small unit of electron-sensitive plates exhibited a very much larger star population of 5420 ± 1300 cc^{-1} day^{-1} than shown in similar emulsions exposed by balloon (815 ± 104 cc^{-1} day^{-1}) in the stratosphere.[2] Because of the brevity of the flight, the statistics were poor and the observation served to increase one's desire for further transatmospheric exposures. It was a case of beginner's luck. For package after package failed to come back (Fig. 2) until a second successful recovery was effected on May 5, 1952, from an Aerobee rocket which reached 128 km. The new emulsion was cast in the form of a circular disk 7 cm in diameter and 2.05 mm thick, specially designed to withstand the rigors of impact. Study of the developed preparation again showed a high differential star population as compared with a similar disk which accompanied the flown emulsion as a ground control, indicative of a star production rate of 4800 ± 1000 cc^{-1} day^{-1}.

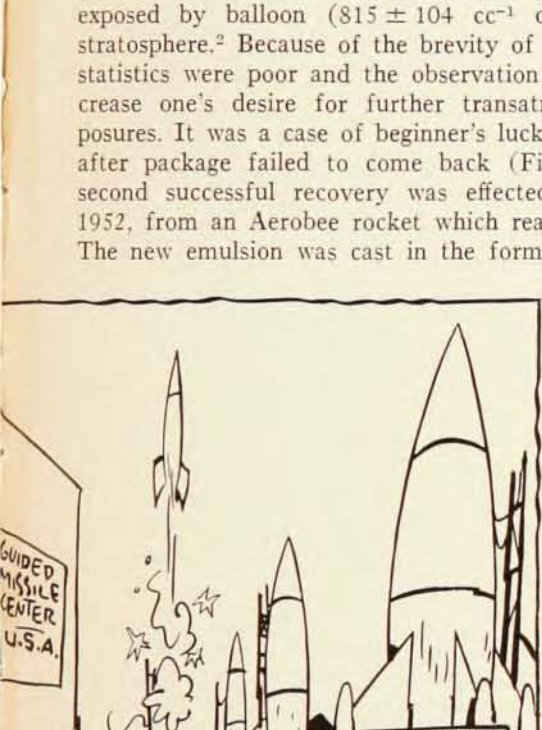


Fig. 2. Cartoon expressing sentiments on lack of recovery. (*Courtesy George Lichty*—Chicago Sun-Times *Syndicate*.)

The rocket probes spend about 400 sec above the atmosphere. The emulsions, being continuously sensitive, integrate all star production processes over a period of a month or more which may elapse between the manufacture of the detector and its eventual recovery. The star population which accrues during flight is obtained by subtracting two rather large numbers and the final result is therefore subject to large statistical uncertainty. It was decided to make an all out effort to reduce the magnitude of the control reading by manufacturing the emulsion at the launching ground, timing the final drying so as to coincide with the rocket launching.

Opportunity for this experiment was found in conjunction with the US Navy Viking No. 9 operation. When the equipment and I arrived at White Sands the laboratory space assigned to this operation proved unsuitable owing to its proximity to x-ray equipment and radioactive sources. White Sands itself is located at an elevation of 1230 meters, where star production is a fairly appreciable process, and I was on the lookout for a massive building with a basement so that the overhead construction material would serve as an attenuator for the flux. The only shelter which met these requirements was the Navy BOQ which was of all concrete construction and had a miniature subterranean storage room without windows, providing a natural darkroom. It also proved conveniently close to the bar which had an ice-making machine—an ingredient vital to the preparation and development of the thick castings.

We proceeded to pour and dry the noodles of Ilford G5 gel, initiating the operation so that the emulsions would become sensitive several hours before the anticipated time zero of the launching. Rockets are temperamental creatures and some trouble would usually develop during the static checkouts which would delay the firing. This episode repeated itself for about five weeks, so that when the bird (Fig. 3) finally took off

Fig. 3. Viking No. 9 on launching pad.

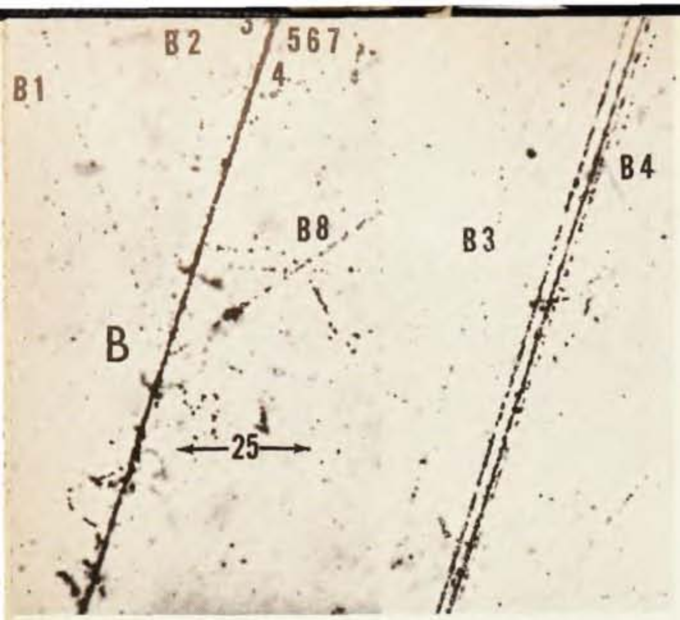
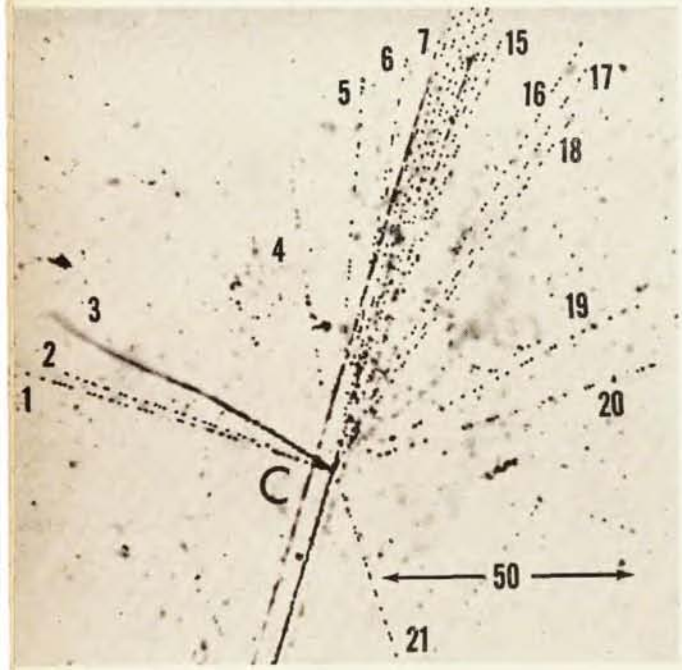


Fig. 4. Breakup of silicon nucleus into narrow-angle beam composed of a boron, a lithium, and an alpha particle (tracks 567) and four protons. Side insert shows the three heavy fragments separated a few hundred microns from point *B*.

Fig. 5. Wide-angle shower initiated by boron nucleus after traversing a path length of 1.03 mm emulsion.



on December 15, 1952, about five different batches of emulsion were available for exposure. The last batch to be prepared aged for only four days between drying and recovery and proved ideal for a star-intensity determination. This yielded a value of 1180 ± 280 stars cc^{-1} day^{-1} consistent with stratospheric measurements, if one took into consideration the opening up of the effective solid angle of the star producing radiation at great altitudes.[3]

It is difficult to understand why the earlier rocket exposures indicated a value some four times greater. In part this may have arisen from proximity of large masses of matter near the emulsions. Since the sampling time is brief, it is conceivable that the flux of low-energy protons, now known to vary with sunspot activity, may have been augmented as a result of some local change in the magnetic field during the particular few minutes of flight. Sampling the cosmic radiation by means of rocket vehicles is analogous to the momentary glimpse of the sky obtained by flying fish. If one imagines a species of intellectually minded fish aiming to explore the mysterious realm above the water-air interface they may also encounter series of contradictory observations. One daring aeronaut leaps into the air on a clear night, gets a glimpse of the moon and the stars, and on re-entry writes a report (with a ball-point pen) on the strange luminous objects hanging in the sky. The president of the icthyological academy of trans-aquatorial explorations wishes a confirmation and sends up a group of specially trained long-distance flyers so as to extend the period of observation. The attempt is made on a cloudy night and they return with a negative report.

THE emulsions were distributed all over Viking No. 9 in order to increase the probability of recovering some intact. This conservative approach, however, did not provide opportunity to follow individual tracks through large volumes of the detectors. On the average the individual castings recorded about one heavy primary track per cm^2, a not too unreasonable working population in view of the brevity of the exposure. In discussing future flights with Milton Rosen, in charge of the Viking program,[4] he mentioned that the nose cone of the next vehicle would be devoted to temperature measurements and would be flown empty so as not to perturb the readings. This provided an exceptional opportunity for a good geometry experiment as the flux would be attenuated uniformly in all directions of azimuth. I persuaded Rosen to allow a two-pound payload of emulsion in this ideal location. He reluctantly gave permission but doubted whether I would recover the emulsion block, explaining that on impact the empty thin-walled nose cone would fold up like an accordion.

Strange series of events sometimes happen in this random world which lead to situations that would be well-nigh impossible to plan. On the morning of May 7, 1954, when Viking No. 10 was to be fired, a group of people from Las Cruces decided to go out for a picnic. Ignoring all signs warning that the White Sands area was restricted they set up a table covered with a large sun umbrella and proceeded to relax. About a half hour after the rocket was launched and the recovery group were seated in jeeps awaiting sounding data on the probable area of impact, a telephone call came in to the blockhouse stating that a flying saucer had landed. This one was real as it destroyed an umbrella and wrecked a picnic table. The dimensions of the conical aluminum object which had arrived from outer space coincided with that of our nose cone. This proved to be the most efficient recovery in the history of rocketry. While sounding techniques "pinpoint" the impact area to a radius of about one mile, it is a great help to have a group of people waving at you as you enter the circle. Fortunately, no one was hurt as the group was playing baseball several yards away when our instrument section demolished their table. The emulsions were retrieved in perfect condition, thanks to the step deceleration afforded by the umbrella.

The abundance of lithium, beryllium, and boron nuclei in the primary cosmic-ray flux is an important number yielding information on the age of the cosmic radiation.[5] These light nuclei are absent in stellar spectra and those particles arriving at the top of the atmosphere presumably were formed as secondary fragmentation products as a result of collision with interstellar dust and gas. It is difficult to evaluate this parameter by flying emulsions in balloons as the residual air may contaminate the incident beam as a result of collision with nitrogen and oxygen nuclei. Owing to experimental difficulties and lack of precise knowledge of fragmentation probabilities the ratio of light to medium nuclei has been estimated between 1 and 0. Clearly the way to make this measurement is above the atmosphere and the emulsions recovered from Viking No. 10 offered such an opportunity as the rocket skin and the aluminum can housing the emulsion block presented a path of only 2 g per cm^2 of absorber. An analysis of the charge spectrum showed that the L/M ratio was 0.3. Subsequent flights on specially designed Aerobees [6] confirm this estimate, our composite value being 0.26 $\pm$ 0.09. More recent balloon measurements at elevations above 120 000 ft tend to confirm this value.

The Viking No. 10 emulsion block also recorded a very unusual chain of events designated as anomalous heavy primary cascades.[8] A particle with a charge of 14 ± 1 enters the detector and after traversing 0.31 mm of emulsion makes a collision in which it breaks up into a proton and a silicon nucleus. The residual heavy nucleus (Fig. 4) proceeds for 3.61 mm and fragments into a boron, a lithium, an alpha particle, and four protons. All three heavy splinters make additional collisions after traversing distances of emulsion very short compared with their mean free paths. Indeed, the boron nucleus moved only 1.03 mm before making the star (shown in Fig. 5), a distance 1/145 of its mean free path.

This strange chain of events having an apparent collision cross section 20 times greater than geometric may have originated as a chance series of fluctuations in the mean free path with a probability of 2×10^{-7}. On the other hand, if it is representative of a real phenomenon the fact that it was recorded under experimental conditions permitting its detection makes it worthwhile speculating as to its nature. This event was first described at the New York Meeting of the American Physical Society [8] coincident with the discovery that the collision cross section of the antiproton was twice geometric. This gave rise to rumors in the smoke-filled hotel vestibules that I had discovered an anti-silicon nucleus. If so, I have no evidence for it. My own pipe-dream guess is that a new type of matter may exist in which the nucleus contains several bound hyperons in a stable configuration, that this entity persists until it makes a primary glancing collision whereupon the residual fragment undergoes rapid mesonic decay, and that the short distance between certain stages of the cascade chain may represent the lifetime of the unstable secondary nuclei. The answer to this fascinating possibility resides in the detection of more events of this character, particularly ones initiated by nonrelativistic particles so that the decay products at rest can be identified by phenomenological considerations.

Having made two successful recoveries in a row we were swamped down by the laborious scanning operation. Indeed several months elapsed after the Viking No. 10 firing before the anomalous cascade was observed. To secure further information on this unusual phenomenon an experiment was designed whereby the block of emulsion would be extended outside the rocket skin, once the vehicle was above the atmosphere, using a rack and pinion-controlled paddle with an arm about one meter long. This would provide an essentially free-space exposure and reduce the shadow effect of the rocket. Owing to prior allocation of space, room for this experiment could not be found until Viking No. 13 was assembled. Meanwhile a third successful recovery was made on Viking No. 11 which reached a record-breaking altitude of 158 miles. This kept us further employed until the instrumentation for flight 13 became available. Viking No. 13, however, was not flown from White Sands. A week before the launching date the Viking program was discontinued so that the personnel could work on the newly established Vanguard satellite program. The vehicle was launched from Cape Canaveral, Florida, as part of a practice staging operation, and since the shot was over water no recovery could be planned.

My cosmic-ray rocket exposures were always made on a hitch-hike basis. Now that my last sponsor had departed I started looking around for another free ride. It came to my attention that at Cambridge Research Center, Maurice Dubin was planning to study the frequency of micrometeorite impacts utilizing a new

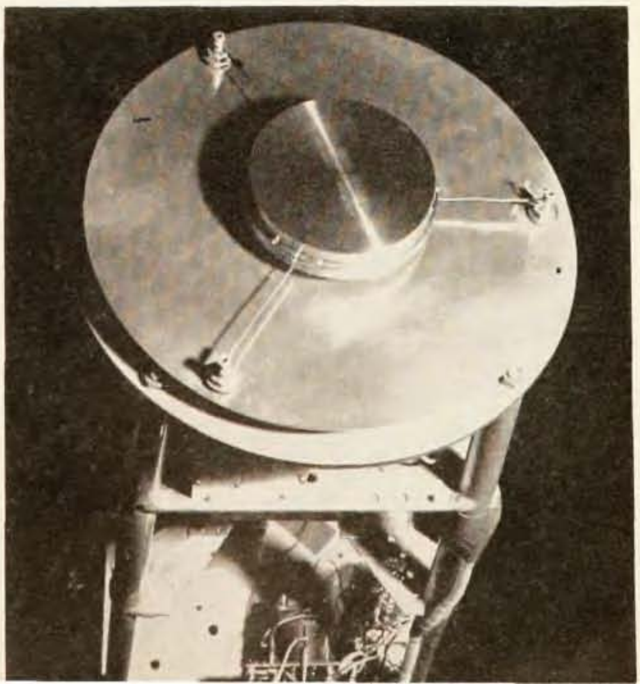


Fig. 6. View of instrument section of Aerobee rocket. When the nose cone is ejected it exposes the apparatus to free-space conditions.

type of Aerobee rocket fitted with a parachute recovery system. In his flights the nose cone was ejected after the vehicle pierced the atmosphere thereby exposing a sonic diaphragm (Fig. 6) to the stream of high-velocity cosmic debris. Ideally the emulsion unit should be placed above the sonic diaphragm. This Dubin was loath to permit as it would diminish his effective collecting area. I promised, however, to supplement this loss by imparting a high polish to my emulsion cassette which in turn would permit detection of pits and craters when the metal was subject to microchemical and microscopic examination. We thus made a compromise in which we shared the diameter equally, but since the emulsions were to be located centrally I ended up with one-fourth the area.

Starting in the spring of 1957 five of these specially instrumented rockets were launched. Only two of the attempts were successful in the recovery of the emulsion cassettes.[6] Since the vehicles were fitted with parachutes the impact velocity was greatly reduced and very thin-walled emulsion housings could be designed. Sometimes the parachute would fail to open and when the instrument section was located the cassette was missing, being torn out of its piano wire supports during re-entry into the atmosphere (Fig. 7). When everything functioned properly (Fig. 8) the entire instrument section would be in mint condition and a brief cosmic-ray exposure would be secured in the presence of only 140 mg per cm^2 of condensed matter. On one of these flights a cratering effect was noted (Fig. 9) which, because of the fused condition and flow of the surrounding metal, could be attributed to a high-velocity meteorite impact. The two new recoveries, abetted by our results from Viking No. 10, permitted us to evaluate the relative elementary abundance of heavy nuclei ($Z \geqslant 6$) in the cosmic-ray beam. These results are shown in Table I and compared with an analysis by Waddington[7] from emulsions flown in a balloon at about the same geomagnetic latitude. Our results indicate that carbon is the most abundant of the C-N-O group. The most conspicuous difference between the rocket and balloon observations is the greater abundance of $Z \geqslant 10$ nuclei. These particles have the largest collision cross sections and hence are the ones preferentially depleted in traversing the residual air above the balloon.

Table I. Comparison of Heavy Primary Charge Spectra at Balloon and Rocket Elevations.

Component	*Balloon*	*Rockets*
C	28.7%	24.7%
N	22.7	14.9
O	22.5	18.3
F	4.6	3.5
$Z \geqslant 10$	21.5 ± 3.2	38.5 ± 4.9

In July of 1957 a summary was presented of our efforts to expose and recover emulsions from rockets at the first International Conference on Corpuscular Photography.[1] Physical recovery was made in about two-thirds of the vehicles flown. The emulsions, however, survived impact in only one-third of all the attempted flights. In the intervening three years an additional seven flights in Aerobee rockets have been made of which only two yielded useful results. The reasons for this poor yield are manifold. The rocket booster will ignite and carry the vehicle only a mile or two owing to a failure in the ignition system of the main engine. The rocket may go off course and is then destroyed in flight by the range safety officer. The shot is mechanically good, but winds deviate the parachute into a mountainous area. Such equipment is difficult to locate and when found is usually mangled from rolling and tumbling down into the valley. The parachute may fail to open, or breaks away as a result of too great a re-entry velocity at the time of deployment.

These are the common difficulties. Sand storms and freak weather may give rise to additional predicaments. The small instrument section of the Aerobee is usually located by spotting the large orange-colored parachute. This canvas may get covered by wind-borne sands between the shot and the arrival of the recovery party. The White Sands area is normally arid. On one occasion the day before our rocket was scheduled to be fired a tornado hit the area and the desert became flooded with temporary lakes. After the firing a reconnaissance plane sighted the instrument section on a miniature island surrounded by about half a mile of water. The sudden tornado had wrecked the helicopter which would normally have picked up the equipment

Fig. 7. Poor recovery of instrument section (the parachute tore away).

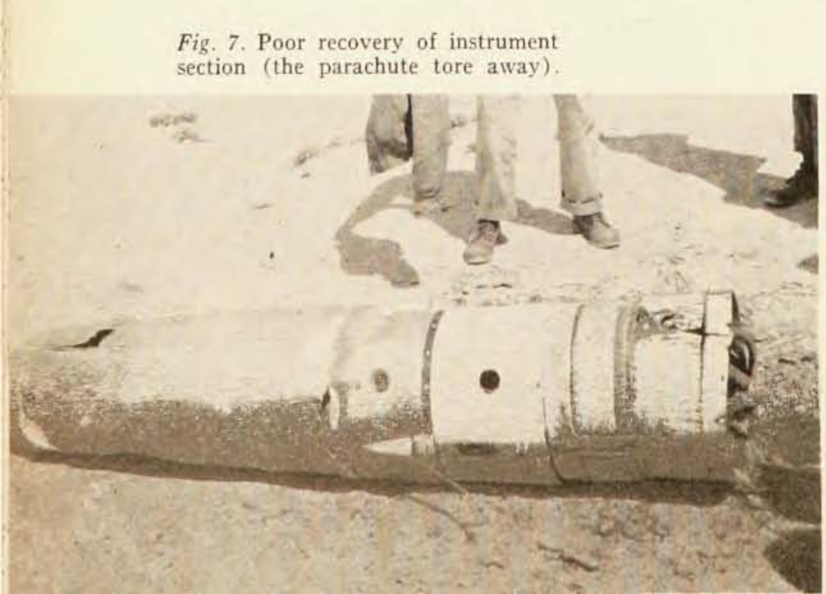
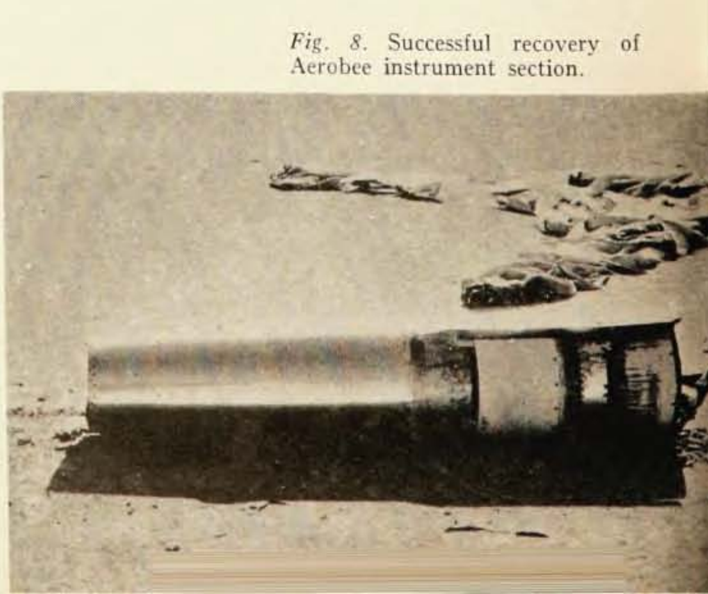


Fig. 8. Successful recovery of Aerobee instrument section.



with ease. Understandably neither the Army, who is in charge of recovery, nor the Navy had any row boats in the area. We solved the problem by purchasing fisherman's hip boots and waded to the impact site (Fig. 10). These heroic efforts were in vain as the emulsions had broken away and could not be found on the island. Examination of the internally charred instrument section indicated that an explosion had taken place as a result of hydrogen accumulation from the operation of the batteries.

WHILE the initiation of the satellite launching era diminished prospects for physical recovery, in the long run it had a beneficial effect by spurring the development of very large rocket engines which could reach altitudes undreamt of in the days of the Viking program. When the Thor and the Atlas became operational the US Air Force instituted a "piggy-back" program permitting payloads of scientific instrumentation to be carried to altitudes of the order of 700 miles. Some of these test shots were equipped with an elaborate recovery system so that the package (Fig. 11) could be fished out of the waters in the vicinity of Ascension Island. Freden and White [9] of the Lawrence Radiation Laboratory were among the first to take advantage of this program. On April 7, 1959, a Thor-Able ballistic missile carried a small stack of nuclear emulsions to an apogee of 1230 km, thereby exposing them to the particles of the lower Van Allen belt which could penetrate the 6 g/cm^2 wall thickness of the instrument section. They were able to demonstrate the presence of a large flux of protons with kinetic energies exceeding 75 Mev.

After a number of failures, our laboratory recovered a 4-lb package of emulsions on July 21, 1959, exposed in an Atlas re-entry nose cone which reached an elevation of 1176 km. One edge of the emulsion block faced a reduced absorber mass of only 1.65 g/cm^2, which permitted the entry of trapped protons with kinetic energies in excess of 40 Mev. Our preliminary observations [10] of the differential energy spectrum indicate an appreciable flux of protons at 43 ± 2 Mev with a magnitude 0.62 ± 0.17 that of the flux at 76 $\pm$ 1.5 Mev, suggesting the possible existence of a maximum in the energy distribution between 80 and 60 Mev. Emulsions have also been flown by Louis Rosen and co-

Fig. 10. The author in an unusual recovery garb.

Fig. 11. An Atlas re-entry nose cone is hauled aboard ship from water near Ascension Island.

Fig. 9. Crater 100 microns in diameter surrounded by irregular ridges of fused metal extending to a radius of about 300 microns.

workers of the Los Alamos Laboratory.[11] One stack was recovered from an Army Jupiter which spent about 10 minutes near an altitude of 500 km. The Los Alamos group also recovered emulsions from the Thor-Able and the Atlas shots described earlier.

While these high-altitude probes provide relatively long cosmic-ray exposures, the tracks produced by the primary particles are swamped by an enormous background of trapped Van Allen radiation. The more energetic of the trapped protons produce a large population of small stars (Fig. 12) estimated at 297 000 ± 15 000 per cc per day from our Atlas flight.[11] This new source of star-producing radiation offers another explanation for the variable star counts observed in our early V-2 and Viking rocket exposures. The Van Allen belts are known to shift to lower altitudes so that the effect can be noted on rare occasions even at balloon altitudes. The contamination of the cosmic-ray beam by shifting trapped radiation is probably more pronounced and frequent at 100 miles elevation.

The existence of the trapped radiation belts is a mixed blessing. While an interesting entity for study in itself, its presence greatly complicates one's ability to obtain a suitable transatmospheric cosmic-ray exposure. One answer to this situation is the recoverable satellite system which orbits at about 200 miles and is thus above the atmosphere and below the intense radiations of the Van Allen belts. Our laboratory has exposed blocks of emulsion in the US Air Force Discoverer satellite which carries an ejection capsule capable of re-entry. To date none of these capsules have been retrieved.

IN view of our present-day extensive knowledge of the cosmic radiation one might well ask why expend enormous effort in securing brief rocket exposure, when long duration flights in balloons which bypass 99 percent of the air mass are readily available. Also, what new information can one hope to find by transcending the residual one percent of the atmosphere. These questions can be answered in two ways. First, extrapolation of our existing knowledge indicates that higher altitudes are essential for the detection of very low-energy protons and alpha particles, and as we have seen are fundamental to the establishment of an accurate primary charge spectrum. It is entirely possible that stripped nuclei with charges exceeding iron exist in the cosmic-ray beam, particularly at low kinetic energies. Nuclei such as californium ejected from stellar explosions may be accelerated to cosmic-ray energies and become part of the flux if they avoid catastrophic destruction as a result of collision with interstellar matter. Such massive nuclei are more apt to be detected at low kinetic energies, as the long periods of time in-

Fig. 12. Small star initiated by proton from trapped radiation.

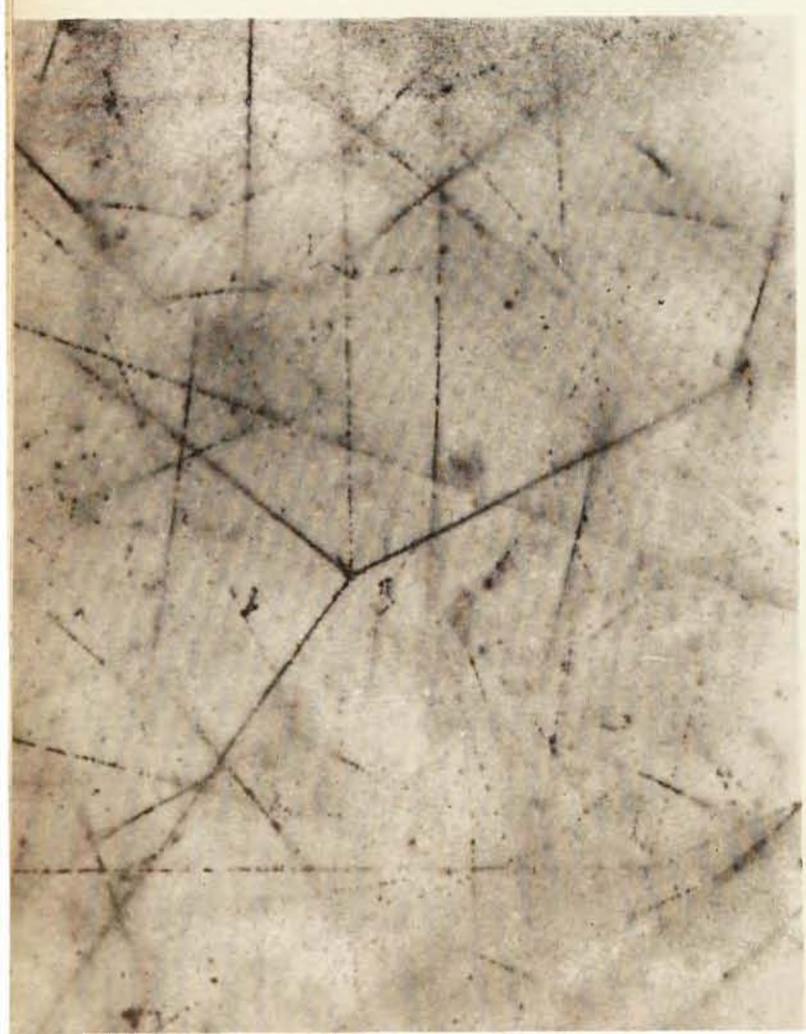


Fig. 13. Field of view of Ilford G5 emulsion exhibiting extremes of discriminating power. A relativistic beryllium nucleus (upper track) fragments into four singly charged protons near minimum of ionization. The lower broad swath was formed by a calcium nucleus near its maximum of delta-ray formation.

volved in the hydromagnetodynamic acceleration process to relativistic energies would also tend to destroy the species by collision processes.

The second argument for rocket and satellite exposures is less definitive than the first, but perhaps of greater importance because of one's inability to predict what is completely unknown. The recent discovery of the trapped radiation belts is an example of the case in mind. A sharp line of demarcation does not exist between serendipitous happenings and concepts that can be extrapolated. In this shadow area dwells the Dirac monopole which some physicists believe will produce a dense swath of ionization in an emulsion. It has also been hypothesized that giant molecules composed of some thousand atoms exist in nature and are accelerated to cosmic-ray energies.

The nuclear emulsion is an ideal tool for exploratory studies. As shown in Fig. 13 it has an enormous latitude for descriminating ionizing phenomena of varying rates of energy loss. Its constant sensitivity, however, will limit the use of emulsions to satellites of short orbiting time. Even on manned stratospheric balloon flights which often are longer than a day's duration a crowding effect of the cosmic-ray tracks becomes apparent (Fig. 14). Perhaps some useful information can be secured after several days' exposure in a 200–300 mile orbit by employing emulsions of reduced sensitivity as shown in Fig. 15. Similar techniques may also prove useful in high-altitude probes of even an hour's duration which penetrate into the center of the radiation belts. Probably the next step in the recovery of emulsions will be with the aid of manned rocket craft such as the X-15 or the Dynasoar. This should help to insure recovery.

References

1. For technical details of mountings see H. Yagoda, "Cassettes d'emulsions pour l'étude des rayons cosmiques dans les fusées a haute altitude", Proc. 1st Inter. Cong. Corpuscular Photography, Centre National de la Recherche Scientific, France, 1958.
2. H. Yagoda, H. G. de Carvalho, and N. Kaplan, "Stars and heavy primaries recorded during a V-2 rocket flight", Phys. Rev. **78**, 765 (1950).
3. H. Yagoda, "Observations on stars and heavy primaries recorded in emulsions flown in Viking Rocket No. 9", Canadian J. Phys. **34**, 122 (1956).
4. Milton Rosen, *The Viking Rocket Story* (Harper Bros., New York, 1955).
5. H. L. Bradt and B. Peters, "Abundance of light nuclei in the primary cosmic radiation", Phys. Rev. **80**, 943 (1950).
6. H. Yagoda, "Observations on heavy primary cosmic ray nuclei above the atmosphere", Geophysical Research Paper No. 60, July 1958, AFCRC, Bedford, Mass.
7. C. J. Waddington, Phil. Mag. **2**, 1059 (1957).
8. H. Yagoda, Bull. Amer. Phys. Soc. ser. II, **1**, 64 (1956); Nuovo cimento **10**, 559 (1957); Proc. 6th Rochester Conf. High Energy Nuclear Physics, IX-30 (Interscience Publishers, Inc., New York, April 1956).
9. S. C. Freden and R. S. White, "Protons in the Earth's magnetic field", Phys. Rev. Letters **3**, 9 (1959).
10. H. Yagoda, "Star production by trapped protons in the inner radiation belt", Bull. Amer. Phys. Soc., ser. II, **5**, 260 (1960); Phys. Rev. Letters **5**, 17 (1960).
11. A. H. Armstrong, F. B. Harrison, and L. Rosen, Bull. Amer. Phys. Soc., ser. II, **4**, 360 (1959).

Fig. 14. Photomicrograph from an emulsion exposed by Col. D. Simons on his Manhigh II flight of 32 hours duration.

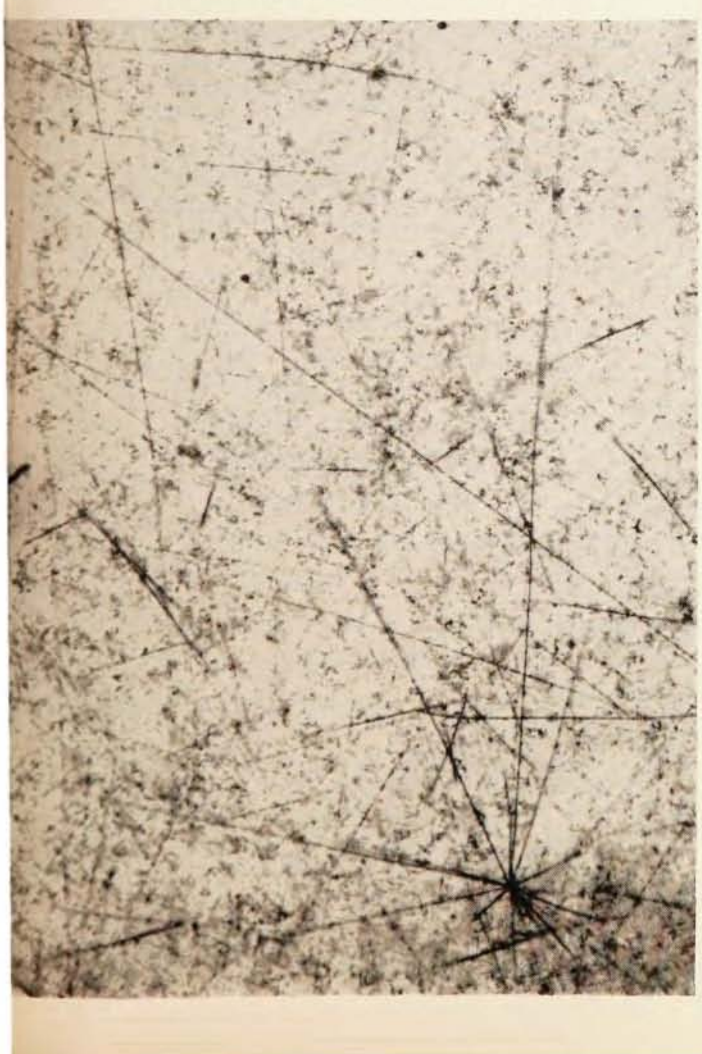


Fig. 15. Track produced by a magnesium nucleus in two adjoining layers of emulsion of different sensitivity. Portion at left is electron-sensitive G5 and exhibits the secondary delta rays. The portion at right is the Ilford G0 emulsion of identical stopping power, but devoid of sensitizer.