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COSMIC-RAY DETECTORS ON THE MOON

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The Place of Cosmic-Ray Studies in Astronomy

In the context of astronomy, cosmic rays are charged particles – usually protons or electrons – that have been accelerated through the action of naturally occurring electric fields, or they are neutral secondaries of such particles. Presumably, the electric fields are a consequence of changing magnetic fields. The high energy of the particles shows that these fields are remarkably strong and extensive. Cosmic rays provide direct and conclusive evidence that particle acceleration is a ubiquitous and energetically very important feature of the astronomical landscape, which increases in importance as one leaves the familiar territory inhabited by ordinary stars to explore the extreme conditions present in supernova explosions, near collapsed stars, and near active galactic nuclei.

Although the cosmic rays studied directly near the Earth are almost all protons or other nuclei until recently, the indirect evidence for cosmic rays in distant parts of the universe has shown only that high-energy electrons are present. This evidence comes from synchrotron radiation. Analogous evidence for the presence of high-energy nuclei, hence for the fields that have accelerated them, is given by gamma rays and neutrinos arising from the decay of pions produced in hadronic interactions.

Cosmic rays also provide the only directly accessible sample of matter from outside the solar system. Since they can travel very great distances, they may reveal the existence of mirror-image galaxies consisting entirely of antimatter. Carbon-14 and other "cosmogenic" nuclides provide information about the activity of the Sun in prehistoric times, whereas, on shorter time scales, cosmic-ray modulation is an important source of information about conditions in the heliosphere far from the ecliptic plane.

The Scale and Character of Cosmic-Ray Research

The current scale and character of worldwide cosmic-ray research is shown in table I in the form of a program summary of the Nineteenth International Cosmic Ray Conference, which took place in La Jolla, California, in the summer of 1985. These conferences have been held every 2 years since the first one in Kracow, Poland, in 1947. Like most conferences, they have grown, so that the attendance has been about 500 in recent years. The number of contributed papers has been about 1000; thus, even with a limit of 4 pages each, one is faced every 2 years with 10 or more thick volumes of conference proceedings. The number of professional scientists engaged in this work is about 1000. This number may be compared to Virginia Trimble's estimate that, currently, there are about 7000 professional astronomers worldwide.

In 1985, about one-fourth of the sessions (those listed under "High-energy interactions") concerned the application of cosmic rays to the study of particle physics rather than astronomy. Some of this activity, but not all, will dry up in the next few decades because of competition from manmade accelerators (colliding beam machines). A large percentage of the papers (almost 80%) concerned observations (called "experiments" in this context) and the manner of performing them.

Advantages and Disadvantages of the Moon as a Base for Cosmic-Ray Observations

Advantages

Some advantages of the lunar surface as a location for performing cosmic-ray observations follow.

1. Absence of atmosphere

2. Weak magnetic field

3. Low radiation background

4. Vast extent

5. Enormous mass, for use as shielding, as target material, in construction, and as raw material for manufacturing

6. Stability

7. Low gravity

8. High vacuum

9. Variety of environments (within a small range) by choice of latitude

The absence of an atmosphere has overwhelming importance. As humans, we tend to take for granted the atmosphere on planet Earth. We overlook the fact that its transparency to very-low-energy electromagnetic quanta is exceptional, a consequence of the capability of these quanta to propagate through the atmosphere in the form of waves. However, to higher energy electromagnetic quanta and to fast particles, our atmosphere is a formidable barrier; at sea level, it is equivalent to 33 feet of water. All the cosmic rays one observes at the Earth's surface consist of secondary particles, a greatly altered remnant of those striking its atmosphere from above.

Another form of shielding is provided by the Earth's magnetic field. Except near the geomagnetic poles, this field prevents charged particles from reaching the Earth's surface unless their energy is higher than 1 to 10 GeV, three orders of magnitude above the energy of charged particles produced by radioactivity.

It follows that, with a few notable exceptions, observations of primary cosmic rays must be performed currently using balloons, rockets, or space vehicles. Thus, for the majority of observations listed in table I, the Moon is an excellent site. The exceptions include, of course, some of the solar and heliospheric observations requiring special locations in the solar system. The other exceptions are observations of nuclei, gamma rays, neutrinos, and interactions of these particles, in the highest energy range, for which the Earth's atmosphere is used as an amplifying device in the production of extensive air showers.

In a number of cases, the Moon is not just an alternative to artificial satellites. Its other advantages – of vast extent, enormous mass, and low level of background radiation – will enable performing cosmic-ray observations on the Moon that otherwise would be physically impossible or economically impractical. One of these cases, neutrino astronomy, has been described in another paper; others are described in the final portion of this paper, following some comments about scientific style and its possible implications with respect to cosmic-ray detectors on the Moon.

Disadvantages

Some disadvantages of the lunar surface as a base for performing cosmic-ray observations are the high cost of transport from Earth and the absence of an atmosphere and of oceans.

The Scientific Backdrop

Since they first began, cosmic-ray studies have manifested a special style which may still influence the manner in which cosmic-ray physicists react to opportunities afforded by the establishment of permanent bases on the Moon. Cosmic rays were discovered not in the laboratory but at great heights by placing ionization chambers in manned balloons (Hess 1912). The extraordinary penetrating power that distinguishes cosmic rays from other forms of natural radiation was demonstrated not in the laboratory but by lowering ionization chambers to suitable depths in mountain lakes at different altitudes in the California Sierras (Millikan 1923-26). Proof that primary cosmic rays are mostly charged particles (Clay 1928-33, A. H. Compton 1930-36) and that their charge is positive (T. H. Johnson, L. Alvarez, Rossi and DeBenedetti 1933) was obtained not in the laboratory but by using the Earth's magnetic field, observing first the latitude effect and then the east-west effect. Proof that cosmic-ray energies can measure at least 10^{15} eV (Auger et al. 1938) depended on the fact that particles with this much energy generate enormous atmospheric cascades, called extensive air showers. Considering just the solid angle, any air shower experiment at sea level makes essential use of a cone-shaped chunk of atmosphere weighing some 10^{10} kg. This mass explains why the lack of an atmosphere can be a disadvantage for locating cosmic-ray detectors on the Moon.

The greatest contribution of cosmic-ray studies to science came from discoveries leading to a new branch of physics, particle physics, now performed almost entirely using giant particle accelerating machines. Some of these discoveries, of the positron, of μ-mesons or muons, of charged π-mesons or pions, of kaons, and of hyperons, were made in a conventional laboratory setting. Others involved going out of conventional laboratories and setting up unique new bases on the highest accessible mountains: on Mt. Evans in the United States, on the Jungfraujoch, Aiguille du Midi, and Testa Grigia in the Alps, on Chacaltaya in Bolivia, and in the Pamirs of central Asia. Going to the other extreme, the discovery of cosmic neutrinos was made using the deepest accessible mines, at Kolar Gold Field in India and in South Africa.

These accomplishments illustrate a certain scientific style. The physicists who performed these feats were equipped with an especially broad range of knowledge and skills. But they also were marvelously opportunistic, using whatever was available in the environment, and later on, using whatever new vehicles were introduced to gain access to new environments. The discovery of the Van Allen radiation belts was the first discovery using a space vehicle. There are important cosmic-ray detectors still functioning on the Explorer spacecraft, which are now reaching the boundary of interplanetary space.

The important advantages offered by the Moon no doubt will be exploited for the study of cosmic rays. However, this opportunistic style makes it hard to predict the form of cosmic-ray detectors on the Moon. Most of the earliest detectors will be similar to instruments already in use. Others will take advantage of unrelated activities in progress on the Moon at later times. Planners should be warned, perhaps, that cosmic-ray scientists are used to not paying for some essential parts of their equipment such as mountains, mines, or the overlying atmosphere. Planners must guess first what other investigators will be doing and then make guesses about how cosmic-ray scientists might avail themselves of the new research environment. Some of these guesses follow.

Cosmic-Ray Detectors on the Moon

Most studies of solar and heliospheric cosmic rays and of cosmic-ray phenomena require long-term observations using relatively small, lightweight detectors. Studies of gamma-ray bursts are similar in this regard. The lunar surface is an attractive location for work in these fields, but there is no obvious way to enhance the value of this work through the application of lunar resources.

The kind of cosmic-ray research that is likely to be performed on the Moon in the early stages of lunar base development is research in the low-energy range on constituents such as ultraheavy nuclei, positrons and electrons, gamma rays, antiprotons and antinuclei, and certain secondary isotopes useful as cosmic-ray clocks. These constituents share the property of being very sparse; therefore, detectors need to be very large, although they can be lightweight in relation to size. The detectors are well suited to modular design and for incremental assembly. By basing detectors of this kind on the Moon rather than on a space station, money may be saved in the areas of deployment, mechanical support, and some aspects of maintenance.

At higher energies, the intensity decreases; thus, the need for large detectors becomes even greater. It also becomes difficult to measure the energy of the particles and to differentiate between particles. As a rule, a target of some kind in which the particles undergo collisions with stationary nuclei must be provided. The detector must be very heavy and very large. Since unprocessed lunar soil is entirely adequate for use as a target and an absorber, the Moon has an overwhelming advantage over space stations as a base for detectors of every sort of very-high-energy (VHE) cosmic rays.

Illustrative Examples

Figure 1 shows the manner in which a detector of high-energy (greater than 1 TeV) gamma rays, electrons, and charge-resolved nuclei might be incorporated in the protective shield of a structure intended primarily for manufacturing or research of some kind unrelated to cosmic rays. The structure is imagined to be roughly cylindrical, 20 m in diameter and 50 m long. For the protection of personnel from the intense low-energy cosmic rays, it has been shielded with a 5-m-thick layer of lunar soil. I have imagined that during construction of the shield, several layers of lightweight gas-filled counters were deployed at intermediate depths. A similar layer of counters lies on top of the shield, and a final layer is attached on the inside to the ceiling of the tank.

The uppermost layer of counters measures the charge of individual incoming particles. The first layer of soil beneath it acts as a target in which the particles initiate cascades. The higher the incident energy, the larger the cascades will be and the further they will penetrate. The number of particles reaching successive layers of counters provides a measure of the primary energy and also serves to discriminate between incident hadrons (nuclei) and leptons (electrons) or gamma rays.

The product of detection area and solid angle is several thousand m^2-steradians; thus, the cosmic-ray counting rate will be several thousand per year for particles with an energy greater than 10^{16} eV. Useful results on cosmic-ray composition will be obtained to a maximum energy of 10^{17} eV per particle, the energy spectrum of electrons will be measured up to about 10^{14} eV, and gamma rays from point sources will be observed up to at least 10^{14} eV.

Lightweight counters can be constructed from metallized plastic foil as indicated in figure 2, and the cylindrical shape of the individual cells is maintained by the pressure of the filling gas. The tendency for distortion produced by the pressure of the overlying soil is reduced by the low gravity of the Moon, so the filling pressure does not have to be excessively great. Perhaps the filling gas, typically consisting mainly of argon, can be obtained as a byproduct of the gas extraction plants some authors have envisioned for generating hydrogen on the Moon.

Another interesting possibility is to measure the intensity of ultra-high-energy (UHE) antiprotons, using the Earth's magnetic field to separate them from the much more abundant protons. Antinuclei accelerated in antigalaxies, if they exist, can enter the Milky Way galaxy more easily if their energy is ultrahigh. To accomplish the separation, one would use a horizontal cosmic-ray telescope located near the Moon's limb so as to point at all times in the direction of the Earth.

In general, highly relativistic particles with a charge Z times the charge of an electron, and energy E (electronvolts), will be deflected by a transverse magnetic field $B_{\perp}$ (gauss) through an angle θ given by

$$\theta = \frac{300Z}{E} \int B_{\perp}\, ds$$

where the integration is over the path of the particle. For particles grazing the Earth's limb in the equatorial plane, the magnetic field integral equals 4×10^8 G-cm, some 400 times greater than the field integral of a superconducting magnet facility proposed for the U.S. Space Station. The energy coverage would therefore extend to energies that are higher by about the same factor.

A consequence of this deflection is that the Earth's cosmic-ray shadow, due to particles being intercepted by the Earth, will be displaced through an angle given by the equation. For a given particle energy, the shadows produced by protons and antiprotons will fall symmetrically on opposite sides of the geometrical shadow.

The telescope I envision, shown schematically in figure 3, would consist of a large ionization calorimeter for measuring E and of widely spaced drift chambers for finding particle trajectories. The ionization chamber would consist of gas-filled counters interleaved with bins of lunar soil. Electrons and antiprotons of the same energy would be distinguishable by virtue of their different cascade profiles; electron-initiated cascades are purely electromagnetic, whereas cascades initiated by antiprotons are hadronic. The calorimeter would be used concurrently, in combination with other counters not shown here, for other purposes, such as gamma-ray astronomy in the VHE-UHE bands.

TABLE I.- PROGRAM OF THE 19TH INTERNATIONAL COSMIC RAY CONFERENCE, LA JOLLA, CALIFORNIA, AUGUST 11-23, 1985

[Numbers of sessions devoted to the various topics]

GALACTIC AND EXTRAGALACTIC COSMIC RAYS			37
<u>Observations</u>		24	
Gamma rays	11		
Nuclei	9		
Electrons, positrons, antiprotons	2		
Neutrinos	1		
Searches for monopoles, quarks, etc.	1		
<u>Theory</u>		7	
<u>Techniques and Instrumentation</u>		6	
SOLAR AND HELIOSPHERIC COSMIC RAYS AND COSMIC-RAY PHENOMENA			21
<u>Observations</u>		16	
Solar flare particles and gamma rays	4		
Solar neutrinos	1		
Interplanetary acceleration, Jovian electrons	1		
Modulation	7		
Intensity gradients in the heliosphere	2		
Cosmogenic nuclides	1		
<u>Theory</u>		4	
<u>Techniques and Instrumentation</u>		1	
HIGH-ENERGY INTERACTIONS			18
<u>Observations</u>		10	
Hadronic interactions	5		
Cascades	3		
Secondary leptons (muons) and leptonic interactions	2		
<u>Theory and Simulations</u>		5	
<u>Techniques and Instrumentation</u>		3	

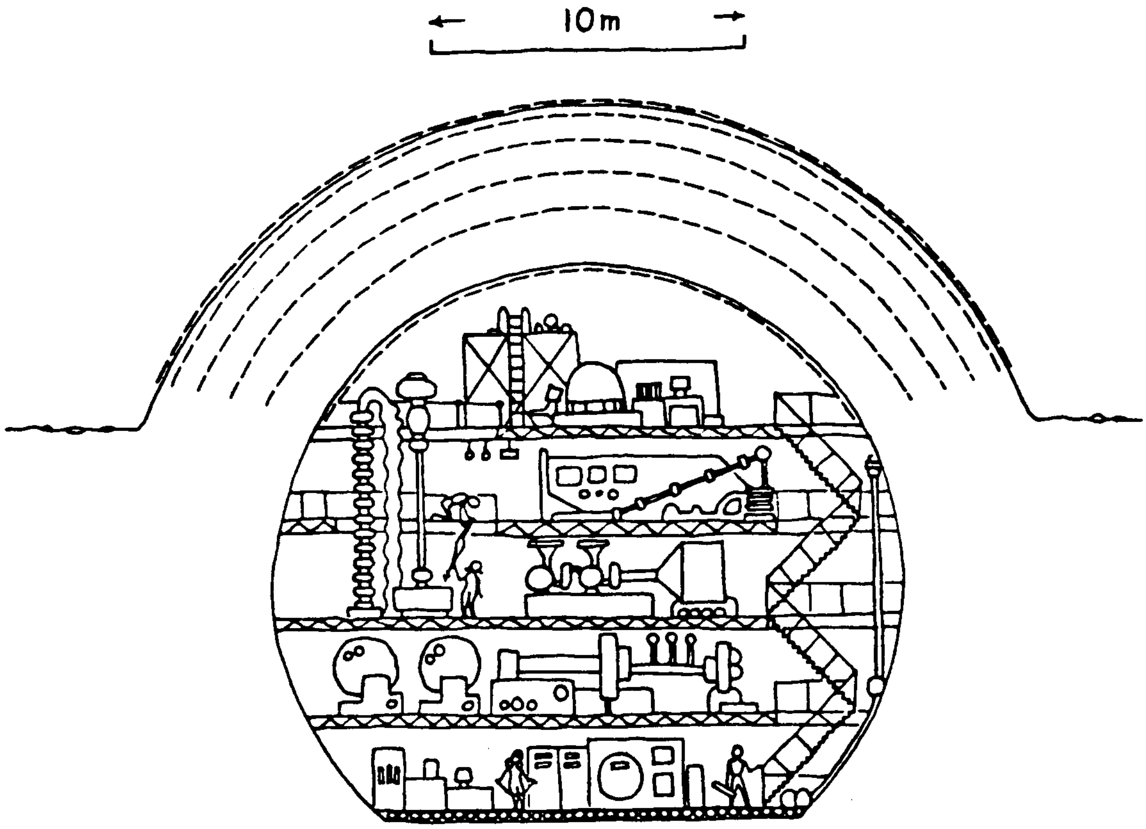

Figure 1.- A large ionization calorimeter built into the shielding of a manufacturing facility or a laboratory on the Moon. The dashed lines represent layers of gas-filled ionization counters.

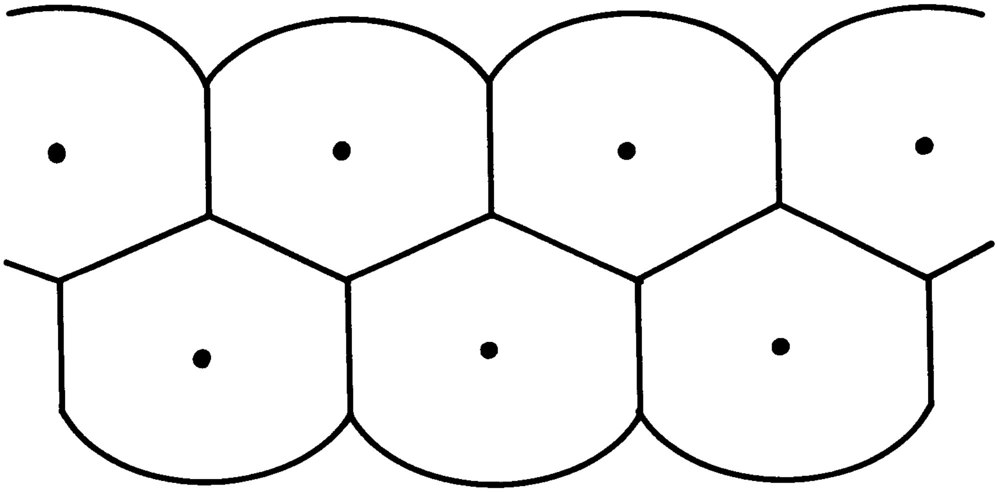

Figure 2.- Cross section of a lightweight gas counter panel made of metallized plastic foil (with the usual anode wires). To save cargo space, the panels would be deflated and pressed flat during shipment.

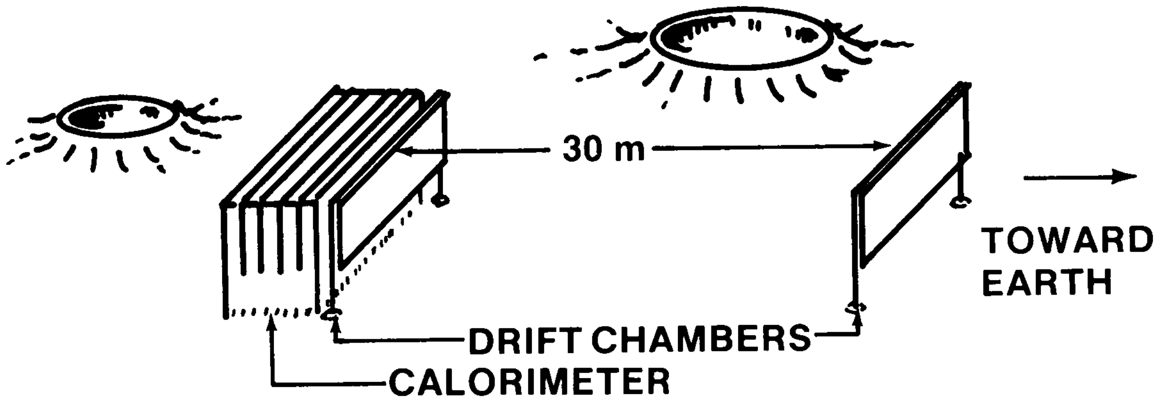

Figure 3.- A cosmic-ray charge analyzer designed to be located on the Moon and to use the Earth's dipole as a magnet.