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Highlights in air shower studies, 1965

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Abstract. The present review of research on extensive air showers focuses its attention on new approaches in those problem areas which seem of major import to the author. First considered are new means of resolving the detailed structure and variability of the showers, properties which reveal indirectly the physics of high energy particle behaviour and the composition of primary cosmic rays. Secondly, brief note is made of the current state of the search for anisotropy in the primary flux. The third topic is the investigation of high-energy primary gamma radiation. Fourthly, attention is called to the recent success in detecting showers by radio methods. Finally, new attacks are described on the extension of knowledge of the primary spectrum to further extremes of energy. The article closes by mentioning some curious phenomena that may be expected at very high energies, and suggesting fundamental limitations that may either prevent the particle spectrum from extending much beyond 100 joules, or make the finding of such particles to be of impressive significance.

1. Introduction

It is not our present intention to summarize all that has been measured and concluded about air showers, even if that were within our capability. The subject is now 28 years of age, and while it has provided a fascinating sequence of surprising revelations about both the large scale universe and the tiniest particles, the details have meanwhile grown quite voluminous. Moreover, the surprises have been coming more slowly with advancing age of the subject, and enough systematic reviews have already been published in recent years.

Nor is it our wish to give a preview of the new papers on air showers that will be presented at this meeting, and thus to reduce the excitement of hearing the results at first hand from the originating authors. To any extent that we do this inadvertently, we hereby apologize. It is hard to avoid such encroachment completely, because major developments take a substantial time to reach full fruition. We wish to compromise by calling attention to those advances which are already in progress, have come to our attention within the last few years, and seem to hold particular interest for the future. Unavoidably we will slight some very significant work of which we do not have knowledge or adequate understanding, and for this we also offer our apology.

2. Structure and analysis: indirect high energy particle physics

At the 1963 meeting in Jaipur, India, and in the journals since then, there have been numerous papers on the important fine details of shower structure which are so crucial to the difficult task of deciphering what goes on in the early stage of each shower. It bears repetition that because of inaccessibility and inadequate frequency one cannot hope to see these high energy interactions nor detect the primaries directly; nor can one hope to duplicate them in the laboratory. The air showers conceal their secrets well, but not perfectly, and still offer the only means of studying phenomena involving extremely high particle energy. In seeking those features of showers that are most sensitively related to the nature of the primaries and the interactions occurring at the highest energies, particular attention has become attached to the following topics:

(1) the energy flow, its lateral distribution, and the change of these features with altitude;
(2) the high-energy N component spectrum, its lateral distribution and change with elevation; and similarly the spectrum of the most energetic photons;
(3) the bundles of parallel muons found in EAS;
(4) the core structure and multiplicity;
(5) fluctuations and correlations among the above properties;
(6) the increase in slope of the number spectrum of showers, and in that of the density spectrum; and
(7) analyses of the above phenomena in terms of models of the nuclear processes (inelasticity, transverse momentum distribution, isobar production, fluctuation probabilities, etc.) and in terms of the mass spectrum of primary cosmic rays.

In approaching these topics, numerous laboratories (notably in Tokyo, Osaka, Moscow and Bombay) have assembled elaborate arrays of equipment including scintillators, Cerenkov energy flow detectors, ionization calorimeters, spark and discharge chambers, cloud chambers and fast timing apparatus: these have been described in the proceedings of previous conferences held in Jaipur, Kyoto, La Paz and Moscow. We wish to call attention particularly, however, to some apparatus developments that offer new degrees of resolution and which are comparatively recent or still in process of construction. One of these is the large spark chamber of 20 m^2 area, which has replaced the 12 m^2 neon hodoscope of the INS Air Shower Project in Tokyo. It has often been questionable in the past, whether the reported frequency and dimensions of core structures were entirely representative of the showers, or were strongly affected by the resolution and dimensions of the detector. The new apparatus substantially reduces such distortions, in that it not only can resolve much finer detail, but will also record more examples and display a larger region surrounding the centre of each shower.

At the University of Sydney, this need for both finer detail and a broader field of view are being met by C.B.A. McCusker and H.D. Rathgeber in an even more ambitious way. They have under development a high-resolution image intensifier camera with which they propose to photograph the distribution of ionization in a large tank of liquid scintillator, 30 m^2 in area. The character of current strides forward in this type of investigation is revealed by contrasting the new imaging scheme with the previous Sydney equipment, which was already elaborate and quite effective in revealing the complexity and variability of core structure; this consisted of a close-packed array of 64 scintillators covering an area of ten square metres. Or one may consider the past effectiveness of the large multiplate cloud chambers which have been operated by the groups at Kobe, Osaka City and Michigan Universities at sea level and mountain elevations. It is the extremely revealing character of the data provided by such previous generations of apparatus which motivates the present drives to obtain a more complete and unbiased picture of the central part of the showers.

In probing the high-energy interactions which occur near the origin of EAS, it has been realized that the muon component has unique value, especially the muons of highest energy. The inertness of these particles permits them to retain their initial directions and spectrum despite passage through thick matter. The points of origin of high-energy muons are strongly biased towards the shower beginning, both by the degradation of N component energy as the shower progresses, and by the increase of atmospheric density, which diminishes the decay probability of high-energy pions and kaons. Motivated by these principles, the Tata Institute group announced at the Jaipur Conference an intention to displace their EAS array from Ootacamund to the Kolar Gold Fields and to supplement the sea level array with large spark chambers and Cerenkov detectors, installed at great depths underground.

Since muons are produced close to the shower axis and thereafter travel in nearly straight lines, the time (or direction) of arrival of a muon far from the axis permits one to find by triangulation the height at which it was created. This technique has been exploited to a limited extent by several groups in the past, but it is not immediately obvious how far its diagnostic capability can be extended. John Linsley of MIT has been carrying on an investigation of this problem, and the hope exists that a new device may result, which can distinguish between showers generated by proton primaries and those generated by heavy nuclei. It is true that this distinction may also be possible by observing the core structure, according to the analysis of the Sydney group, but that method is limited to comparatively small showers and it also needs independent confirmation.

3. Anisotropy of primary cosmic rays

The search for directional structure in the primary radiation continues to be of importance, but within our knowledge there has been no great break-through since the times of previous conferences, to resolve the experimental uncertainties in this area of investigation. At the Bolivia meeting, the Cornell group presented strong evidence for asymmetry among 166 showers having more than 10^8 particles at sea level, directions near the galactic equator being more populated than those at high galactic declination. However, this asymmetry has not been confirmed by MIT data recorded at Volcano Ranch (Linsley et al. 1962). At Jaipur, B. R. Dennis and J. G. Wilson reported no significant asymmetry among 6000 showers with size exceeding 3×10^7 particles at sea level. Japanese evidence based on about 200 selected 'mu-rich' showers continued to show a strong asymmetry (geometrically similar to that of the Cornell data), which has been interpreted by Sekido and Sakakibara (Jaipur Conference Proceedings) as indicating an excess flux inwards along the spiral arm.

At the Jaipur Conference, the Nagoya group (Sekido et al. 1962) described a new method of obtaining better statistics and improved angular resolution in recording the mu-rich showers, which are presumably generated mostly by heavy nuclei. This method utilizes two large-area gas-Cerenkov telescopes (10 m^2 each) oriented parallel to each other at a large zenith angle. Coincident pulses in the two detectors represent at least two parallel high-energy muons, and hence denote the core direction of air showers with a strong selectivity for those that are rich in muons.

If any of the indications of anisotropy is correct, one might reasonably expect that a doubling of the relevant data would remove all doubt of the reality of the effect. In the past this has not occurred, but it is possible that the present conference will contain surprises for us in this connection.

4. High energy photon primaries

There is widespread interest in the possibility of detecting primary gamma rays in all intervals of energy. The conceivable bandwidth, from 10^5 to 10^{19} eV, is 100 times greater than that which extends all the way from 10-metre radio waves to 100 kilovolt X rays; and much information must be carried by the gamma radiation which is not perceptible at the lower frequencies. The processes by which the radiation may be generated are numerous, and different ones must dominate in different kinds of sources and parts of the energy spectrum. The processes include thermal radiation, nuclear excitation, positron annihilation, bremsstrahlung by high-energy electrons, synchrotron radiation, Compton scattering of both thermal and synchrotron photons by high-energy electrons, and decay of neutral pions (and kaons). The pions, etc., may be produced via nucleon-antinucleon annihilation, by proton collisions with interstellar gas, or by photonuclear processes between thermal or synchrotron photons and high-energy protons. All but the first three processes in this list may be of significance in the high energy range, above 100 GeV, where the photons can be detected by the showers they generate in the atmosphere.

Possible source regions include interstellar and intergalactic space as well as unusual stars and nebulae. In general, the universe is transparent to this radiation, permitting it to be received from some areas, such as galactic nuclei, which may be obscured in other parts of the electromagnetic spectrum. Owing to resonant processes, however (such as $\gamma + \gamma \rightarrow e^+ + e^-$ between starlight and photons of about 10^{12} eV), particular bands of energy may suffer absorption over long distances; this phenomenon may be useful in assessing the density of matter and radiation in the universe. The strength of the various generating processes depends on field strengths and the densities of cosmic rays, gas and light throughout the universe, so that measurement of the gamma radiation may permit some of these parameters to be determined.

The particular feature of the gamma radiation which makes it so valuable is that it is not deviated or trapped by magnetic fields, as are the primary charged particles of cosmic rays, but travels in straight lines. What makes its detection difficult is that the primary gamma ray flux is very low compared with that of the charged particles (by at least a factor 1000 at corresponding energies), and is usually obscured by an abundant secondary gamma flux, created by interactions of the charged particles in the atmosphere. One way of avoiding this is by doing the experiments outside the atmosphere. Another way, however, is by observing a feature of the air showers (such as the presence or absence of associated muons) which can distinguish those caused by primary nuclei from those caused by primary photons. A further way is by looking for directional structure in the primary intensity, which would be preserved by a primary gamma flux but not in the particle flux. In searching for discrete sources by this method, the signal-to-background ratio is enhanced as the square of the angular resolving power of the detector, giving particular value to detection methods with high angular resolution.

Various approaches to the detection problem have been discussed in previous meetings, and further reports on such experiments may be expected in the present conference. The following paragraphs summarize the status of these methods as it is known to the writer.

4. 1. *Mu-less showers*

It has been definitely established by Firkowski, Gawin, Zawadski and Maze (1962) and by the Bolivian Air Shower Joint Experiment (Clark, Escobar, Murakami and Suga) that a distinct class of air showers occurs, in which the muon component is as absent as may be expected in a gamma-initiated shower: 20 to 30 times less abundant, relative to the electrons, than in ordinary air showers. The frequency of mu-less showers of 10^{14}-10^{16} eV was found at sea level to be about one per cent of the ordinary EAS having the same number of particles, while at 530 mb the relative frequency was one per thousand. These numbers are not significantly inconsistent because showers of nucleonic origin propagate differently from pure electromagnetic cascades in the atmosphere. At a given primary energy the relative frequency is probably about 4×10^{-4} but may vary with the energy.

Up to the time of this conference, there has been no proof of directional structure in the intensity of the mu-less showers, and hence no firm proof that they are indeed due to primary photons; but attempts to account for the showers in terms of known processes of energy transfer from the nuclear to the electromagnetic component have not yet provided a quantitative alternative explanation. We hope to hear more evidence during this conference.

4. 2. *Cerenkov telescopes*

The Cerenkov light of an air shower is strongly peaked in the forward direction, providing a natural angular resolution of about two degrees if the light is detected with an optical telescope. Although all air showers yield signals, one may search for an excess rate due to gamma-initiated showers from particular directions of suspected sources. An experiment of this sort was reported in the Kyoto and Bolivia cosmic ray conferences by Chudakov, V. I. Zatsepin, Nesterova and Dadikin. Except for the Cygnus A source the results were negative (less than 1% of the showers within the angular resolution of the telescope were due to gamma rays from the source under examination) and for the Cygnus source the significance of the result was marginal; nevertheless, the negative results, especially for Taurus A, were highly significant. More recently, a similar experiment with negative results (except for one marginally positive direction, in this case the direction of the quasar 3C147) has been reported by Fruin, Jelley, Long, Porter and Weekes (Fruin et al. 1964).

The energy required for efficient detectability of primary photons in these experiments was about 5×10^{12} eV, and the upper limits obtained for the primary flux were between 10^{-11} and 10^{-10} per cm^2 sec for the various sources. Such results would acquire more theoretical significance the lower the threshold for detection and the lower the value of the limiting detectable flux. Currently, G. Fazio of the Smithsonian Institute is attempting, by use of a much larger telescope, to extend the data into the energy range 10^{11}-10^{12} eV.

Hill, Overbeck and White of MIT, and Long and Porter of Dublin (Porter and Hill 1962), have reported in previous meetings (see especially the Bolivia Cosmic Ray Conference Proceedings) a capability of viewing the Cerenkov light directly with image intensifier systems. Such images make it possible greatly to increase the angular precision of shower locating, since boundaries of the cone of light are visible in the pictures. However, to our knowledge these methods have not yet been applied in surveying possible source directions with high statistical accuracy.

4. 3. *Radio methods*

The detection of coherent radio emissions, singled out for special note in the following section, seems to offer the possibility of large receptive area together with extraordinary angular resolution. By appropriate phasing circuits, it would appear that the antenna system could be arranged to follow a suspected source direction across the sky, and thus accumulate the excellent statistics which are needed to distinguish a small peak in the directional distribution.

5. Detection of EAS by radio methods

The reception of radio pulses from EAS was first demonstrated within the last year by a collaborative effort of scientists from Harwell, Dublin and Jodrell Bank (Jelley et al. 1965). The wavelength used was 7 metres and the bandwidth was 9%. The process chiefly responsible for the emission is not yet established; both Cerenkov radiation and synchrotron radiation yield estimates of radio power have the right order of magnitude. The received energy was only 10^{-12} to 10^{-11} erg from showers of total energy 1000 to 10 000 ergs. Transference of energy into the radio-frequency spectrum is certainly inefficient, but this is offset by the extreme sensitivity of radio receivers.

The technique is barely in its infancy, and too little is known about it to justify elaborate predictions. However, we feel confident that this achievement is a significant breakthrough, and that further study will reveal ways of obtaining types of information about the showers that were not available by other means. The signal will not, of course, be sensitive to fine details like the structure of the shower core; nor does the method seem adaptable to surveying at the same time all directions in which showers may arrive. However, it appears that the method may offer new orders of angular resolution, and it may complement particle detectors by being sensitive to the condition of the showers far above ground level. Also it will be able to detect showers in steeply inclined directions, in which the particles are absorbed before reaching the ground. Time will probably reveal many other possibilities that are not apparent at this early stage.

6. Further extension of the primary energy spectrum

6. 1. *Current knowledge of the spectrum*

Figure 1 represents a synthesis of information on the integral frequency of primary cosmic rays as a function of their total energy. From 10^{10} to 10^{15} eV the frequency is well represented by a power law with exponent −1. 6 and a value of 10^{-4} per m^2 sec sterad at 10^{14} eV. Between 10^{15} and 10^{16} eV the slope steepens and from 10^{16} to 10^{18} eV it is about −2. 2, with an absolute rate of 2×10^{-10} per m^2 sec sterad at 10^{17} eV (a convenient figure is one per m^2 sterad per year at 10^{16} eV). Beyond 10^{18} eV the slope appears to diminish, and above $10^{18.5}$ eV it seems to be again about −1. 6, or possibly even smaller, with an absolute rate of 4×10^{-16} per m^2 sec sterad at 10^{20} eV.

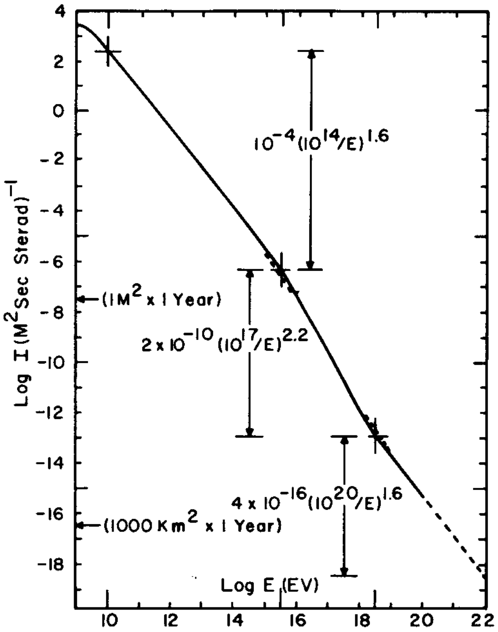

Fig. 1 Approximate representation of the integral primary energy spectrum of cosmic rays.

The representation in the latter region was made to conform with the data at highest energies recorded both by the Cornell group near sea level and by John Linsley of MIT at the Volcano Ranch station 1800 metres above sea level. The highest energy event was recorded at the MIT station and had an energy of about 10^{20} eV. There is considerable uncertainty in the quoted energies, of course, arising from the limited samplings of particle density and from lack of accurate information on the lateral distribution close to the axis of such large showers. Apart from this, however, the data between 10^{18} and 10^{20} eV are indeed sparse, and a remark is in order on the significance of the apparent change in slope of the spectrum in this region. An accurate value of the reduced exponent can certainly not be given, nor any assurance that the new value is a constant; but one is fairly sure that a substantial reduction has occurred, because an extrapolation of the lower-energy spectrum without change of slope predicts only two or three events in a part of the spectrum where eight or nine have been recorded.

Even this statement is open to challenge, however. At lower energies, accurate determination of the parameters in the spectrum is facilitated by the facts that (a) the exponent is nearly constant over a wide range of shower sizes, and (b) the shower size distribution is not strongly dependent on the zenith angle. For showers having more than 10^9 particles, however, the zenith angle distribution is no longer a simple function; it has a maximum in a non-vertical direction and its shape changes with the shower size. It is impossible to determine this shape and its variation empirically with the poor statistics that are available; but without knowledge of the dependence of frequency on atmospheric thickness, one cannot combine the events observed at different angles in a straightforward way to obtain the number spectrum (and thence the energy spectrum) of the showers. What happens is that the effective angular aperture for recording very large showers shifts and increases with shower size. The extent to which the apparent flattening of the spectrum may be due to incorrect evaluation of this widening of the field of view is not yet clear to the writer. What is needed is more data. The purpose is not a trivial one. Not only is the flattening of the spectrum in this region of astrophysical significance in itself, if real, but the implied extrapolation to still higher energies has remarkable consequences which are discussed in the last section of this paper.

Figure 1 makes it clear why the provision of more data will not be easy. Taking the effective aperture as three steradians, the counting rate above 10^{20} eV is only one per 25 km^2 per year, and the extrapolated rate above 10^{21} eV is one per 1000 km^2 per year.

6.2. *New experimental attacks*

Whether the technique of detecting showers by radio signals will help in extending the area of detectability of huge showers is not yet clear. However, one straightforward approach is simply to extend counter arrays over more ground. An extensive array, the details of which are not known to the writer, is in operation at Haverah Park, near Leeds. The most ambitious plans in this direction, to the writer's knowledge, are those of C. B. A. McCusker and collaborators at Sydney. They propose to build up an array covering 250 km^2, using large liquid scintillators spaced at wide intervals (about 500 m) and installed below ground, for several reasons of convenience. The shielding will not greatly reduce the rates, since muons are the most abundant particles far from the axes of EAS. According to the spectrum of figure 1, when this array is completed it may expect to detect ten showers per year exceeding 10^{20} eV in energy.

From his own experience, the writer sees the following difficulty in this method. At the energies in question, neither the lateral distributions of the electrons and muons in the showers are known, nor is the efficiency of muon production (which certainly diminishes with increasing primary energy). Calibration will be a serious problem. The detectors, being necessarily very far apart, will only sample the particle density far from the region near the axis that contains most of the particles—a region that probably shrinks as the energy rises. Hence the determination of total particle number and primary energy of the events will be open to question—unless the questions can be resolved by other techniques such as the next one to be described.

Detection of EAS by means of the fluorescent light of the atmosphere has long been considered by a number of scientists, and was discussed at the Bolivia conference by K. Suga and A. Chudakov. This method offers several important advantages: (i) instead of sampling a shower at a few scattered points in space, it uses the atmosphere as a calorimeter, and can indicate directly the total energy of the shower, without being influenced by fluctuations or depending on the intervention of any uncertain theory; (ii) it is capable of revealing the history of each shower, whereas particle detection at best reveals each shower in only one stage of development; and (iii) the radiation that is detected is emitted isotropically, and hence diminishes more slowly with distance from the axis than the other detectable effects of a shower.

There are also, of course, inconveniences and limitations to this method. One is that it can only be applied on clear, moonless nights. Even then, fluctuations in the background of starlight and light from the night sky obscure the fluorescent radiation except in the case of very large showers. Thirdly, the atmosphere, though cheap and abundant (our method would utilize 3×10^{10} tons of it), is neither a very efficient scintillator nor an ideal transmitter of the emitted radiation.

Alan Bunner of Cornell University has measured the spectrum of the light produced by fast particles in air (excluding the Cerenkov light), with the results shown in figures 2 and 3. The usable light is almost entirely in the 2P and 1N band systems of molecular nitrogen, about 80% in the 2P system and 20% in the 1N system. The yield as a function of density is proportional to $(\rho + \rho_0)^{-1}$ per unit of ionization energy loss, where ρ_0 corresponds to a pressure of 13 mb for the 2P system and 8 mb for the 1N system. Since showers do not multiply significantly until $\rho \gg \rho_0$ and the ionization loss per unit path length is proportional to ρ, the light yield per unit path length is essentially a constant, independent of altitude.

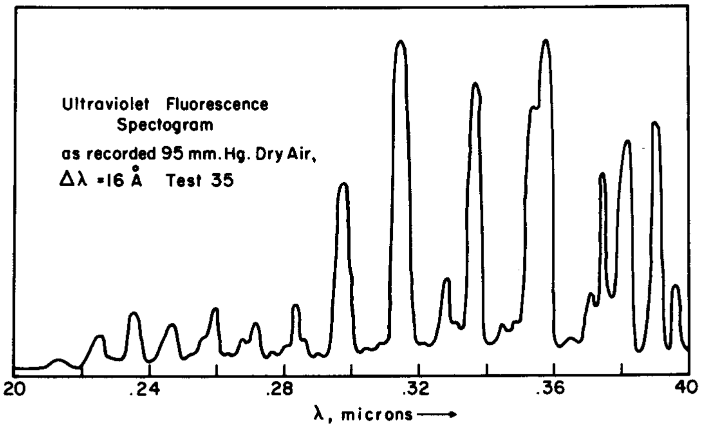

Fig. 2. Spectrum of the fluorescent light of air, produced by deuterons below the velocity threshold for Cerenkov radiation. The spectrometer resolution for this short wavelength part of the spectrum was 16 Å, and the present graph has not been corrected for variation in spectrometer resolution or photomultiplier response.

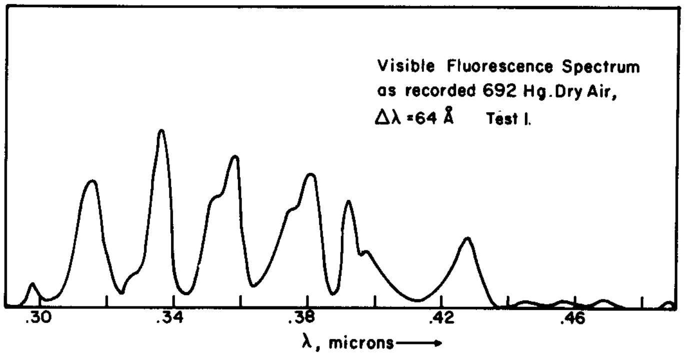

Fig. 3. Fluorescent light of air in the long wavelength region, recorded with a resolution of 64 Å.

The total measured yield per MeV of energy loss at one atmosphere is 11 photons, but 1/4 of this occurs at short wavelengths very poorly transmitted by the atmosphere. Hardly any of the light is found at wavelengths longer than 4280 angstroms; hence the signal-to-noise figure is improved by using a filter that transmits only in the deep blue and ultra-violet. Taking into account the transmission by a normal atmosphere and such a filter, as well as the energy loss of fast electrons in air, the effective yield is almost exactly one photon per metre of track length. (This applies at a distance of about 10 km; from very close sources the yield is almost doubled, and Rayleigh scattering reduces the light from great distances by a factor of about two for each additional 10 km.) The background light transmitted by the atmosphere and such a filter is about 10^5 photons per m^2 sterad per microsecond.

A consideration of the detectability and scheme of analysis of the light from the EAS depends on the registration system. S. Ozaki, of Osaka City University, is proceeding with the attempt to record the optical image with an image intensifier system. At Cornell we are developing a system that affords poorer image resolution but provides a continuous time scale (hence a third dimension in the image) as well as a much larger light collecting area. With the Osaka system the limiting factor (besides the need of an independent trigger) is the number of quanta needed to form the image, while with the Cornell system the limitation is signal-to-noise ratio. In what follows we shall consider only the latter system.

Let $\Delta\Omega = (\pi/4)\,(\Delta\phi)^2$ where $\Delta\phi$ is the full width of the angular resolution, and let Δt be the integrating time of the signal. Assume $\Delta\phi$ and the distance r of the receiver from the shower are large enough that the source of light can be treated as a point moving across the sky at speed c. Let θ be the angle between r and the shower axis, so that the 'impact parameter' of the shower with respect to the receiver is $r \sin\theta = R$. Let N be the number of electrons in the shower, Q the light yield per unit electron path length, A the optical collecting area, ϵ the photoelectric efficiency, and B the background light per unit area, solid angle and time. The light received in Δt comes from a length Δs of the shower, where $\Delta s = c\,\Delta t\,(1 + \cos\theta)/\sin^2\theta$; and the number of photoelectrons in the signal due to the light from the source in this time is

$$S = \frac{A(1 + \cos\theta)}{4\pi R^2}\,\epsilon\, NQc\,\Delta t.$$

It is notable that this depends on R rather than r, so the observability of a shower depends on the impact parameter rather than the instantaneous distance. The noise due to the background light received in this time is

$$\sigma = (\epsilon\, A\, B\, \Delta t\ \Delta\Omega)^{1/2}$$

hence the signal-to-noise ratio is

$$\frac{S}{\sigma} = \frac{N\,Q\,c\,(1 + \cos\theta)}{4\pi R^2}\left(\frac{A\epsilon\,\Delta t}{B\,\Delta\Omega}\right)^{1/2}.$$

If this ratio must exceed n for measurability of the event, the requirement is that

$$\frac{N(1 + \cos\theta)}{R^2} > \frac{4\pi n}{Qc}\left(\frac{B\,\Delta\Omega}{A\epsilon\,\Delta t}\right)^{1/2}.$$

Note that n need not be extremely large, because in selection of the event one may use the fact that numerous phototubes at neighbouring angles will display successive signals. With $n = 5, Q = 1, B = 10^5, \Delta\Omega = 10^{-2}, A = 10^{-1}\ \text{m}^2, \epsilon = 10^{-1}$ and $\Delta t = 1\ \mu\text{sec}$, one finds that N must exceed 1.3×10^8 at 2 km impact parameter and 1.3×10^{10} at 20 km. Even taking into account Rayleigh scattering, a shower of 10^{11} particles can be observed out to about 30 km, i.e. over a sensitive area of 1000 square miles. It is also possible to have several such detectors, enlarging the total area to nearly 10^4 km^2. Most of the showers will occur at large zenith angles, where the atmosphere is thick enough to contain almost the entire life history of each event.

An all-sky detector of this type would contain about 500 phototubes arranged in clusters behind a set of lenses. The orientation of the plane containing the shower axis and the radius vectors (r and R) would be fixed by the identity of the sequence of tubes which register the pulses. The angle θ of the axis in this plane, and the distance R, are determined by the pulse durations and the time intervals between them. Having these coordinates, the particle number N as a function of time is obtainable from the pulse heights and the relations given above.

This scheme has not yet been put into effect. A much simpler detecting arrangement has been tried at Cornell, with the assistance of S. Ozaki and G. Tanahashi from Osaka City and Tokyo Universities, but the smaller signal to noise ratio in this set-up has thus far prevented success in the analysis of the signals. Also, Ithaca is climatically an inefficient location for such work.

6. 3. *Curiosities and possible fundamental limitations at very high energies*

Several curious phenomena that are negligible at lower energies may produce observable effects as the primary energy approaches values which are within reach by means of experiments like those described above. Also it appears likely that at about 10^{21} eV the particle accelerating capability of the universe may become exhausted, unless nature has a scheme of organization on a larger scale than is now apparent. These speculations are summarized in the following paragraphs.

6. 3. 1. *Primary neutrons of* $E > 10^{16}$ *eV*. When the Lorentz factor of a primary cosmic-ray nucleus exceeds 10^7, ordinary starlight can excite the 'giant dipole resonance' and produce nuclear disintegrations. At higher Lorentz factors, infrared light and radio waves may cause the same effect. Hence if heavy nuclei are accelerated to this Lorentz factor or beyond, neutrons of $E > 10^{16}$ eV may arise, not only in intergalactic space but also in the galaxy and in strong discrete sources, without the need to invoke dissipative gas collisions. Approximate mean free paths for neutron decay are:

at 100 MeV : one astronomical unit (distance from Sun)
10^{16} eV : 100 parsec (radius of spiral arm)
10^{18} eV : 10^4 parsec (distance from galactic nucleus)
10^{20} eV : 10^6 parsec (metagalaxy).

Neutron showers would appear very similar to those initiated by protons. But neutrons are not deflected by magnetic fields, and hence may easier have an anisotropic directional distribution. Point sources may be superimposed on the general background by this mechanism, and the uneven distribution of cosmic rays and radiation in space may account for more gradual intensity variations.

This provides a conceivable explanation for the apparent anisotropy reported by Cornell among showers having more than 10^8 particles at sea level. The flux of sufficiently energetic cosmic ray nuclei diffusing in the spiral arms of the galaxy may still exceed the flux in the halo and in intergalactic space; and also the photon density and gas density are greater in the spiral arms. The mean time for photodisintegration is about 10 million years, short enough to produce neutrons from about 30% of the nuclei. Gas collisions would also occur preferentially in the galactic disk (as invoked at lower energy to account for the presence of the elements lithium, beryllium and boron), yielding neutrons from another large proportion (also about 30%) of the nuclei. Below 10^{16} eV there would be no strong asymmetry, because the mean path for neutron decay is small compared with the thickness of the spiral arms; but above 10^{17} eV one might expect an enhanced number of showers at low galactic latitudes, as was observed.

S. Hayakawa has pointed out (Bolivia Cosmic Ray Conference Proceedings) that when nuclei have Lorentz factors above 10^8, photopion production from visible light is possible, resulting in gamma rays of $E > 10^{16}$ eV. This is another possible mechanism for production of a radiation that travels in straight lines. However, the cross section (10^{-28} cm^2 per nucleon) is comparatively low, and the expected flux of gamma rays from this process is very small compared with that of protons and nuclei having the same energy. The major occurrence of this process is probably in intergalactic space, where it would not result in appreciable directional asymmetry of the radiation.

6. 3. 2. *Contraction of atmosphere and inhibition of* π^0 *decay*. At quite modest energies, the relativistic space-time relations prevent decay of charged pions and kaons; and at somewhat higher energies the decay of hyperons is suppressed. However, when pions are created in the high atmosphere with $E > 10^{19}$ eV, even the decay of neutral pions is inhibited—the main process of energy exchange to the electromagnetic component. This is certainly not a frequent occurrence below primary energies of 10^{20} eV, but when the primary energy is above 10^{21} eV it may delay the growth of the electromagnetic component for a couple of interaction lengths.

It is curious that to a proton of 10^{21} eV, the thickness of the Earth's atmosphere is only about 100 angstroms, and the density is 10^{21} g cm^{-3}: one factor of 10^{12} arises from the Lorentz contraction and the other from the relativistic increase of mass.

6. 3. 3. *Landau-Pomeranchuk density effect* (Landau and Pomeranchuk 1953, Migdal 1956). When the relativistic contraction of a medium is large, the superposition of amplitudes for reactions with successive atoms results in destructive interference, and both bremsstrahlung and pair production can be suppressed. An energy that characterizes this effect (in amorphous media) is $E_c = mc^2X_0/8\pi r_B$, where m is the electron mass, X_0 the radiation length and r_B the Bohr radius of hydrogen: in air at 1/10 atmosphere this energy is 10^{18} eV. Radiation of photons having energy less than E′ by an electron of energy E is reduced when $E^2/E'E_c > 1$, and pair production by a photon of energy E is reduced when $E/E_c > 1$. The suppression factor only varies as the square root of these ratios, however, so it is not great unless the inequalities are large. The influence which is felt at lowest values of E is the inhibition of the radiation of numerous comparatively low-energy photons by a high-energy electron: e.g. photons of $E' < 10^{12}$ eV by an electron of $E > 10^{15}$ eV. However, when the primary energy of a shower exceeds 10^{21} eV the rate of all the electromagnetic interactions may be reduced, thus slowing up the initial growth of the electromagnetic component. Lower in the atmosphere the reduction of E_c prolongs the effect.

6. 3. 4. *Straight travel of protons; expansion of sphere of origin.* At moderately high energies, charged particles are deflected by intergalactic fields, so that their average vector velocity, relative to the medium in which the fields are embeded, is small compared with c. The expansion of the universe therefore limits the radius from which such particles can be communicated: when the diffusion velocity is less than the speed of recession, the velocities of the particles are all directed away from us. (This was first pointed out to the writer by G. Cocconi.) At moderately high energies, therefore, only photons and neutrinos can convey information about cosmic-ray production in distant parts of the universe.

However, as the energy of charged particles increases, the diffusion velocity may be expected also to rise, and the sphere of communication to be enlarged. Ultimately the fields produce so little deflection that the sphere is limited only by the Hubble length, and the particle trajectories are closely correlated with the directions of the sources of origin.

Little is known about either the strength or the coherence length of intergalactic fields. For the sake of discussion we will assume a strength of 10^{-7} to 10^{-8} gauss, and that the fields are essentially uniform in direction over regions 10^6 light years or less in diameter, separated by distances several times their diameter. Then for protons of energy E (eV), the deflection by single regions is on the order of $10^{19}/E$ radians, and the total average deflection in 10^{10} years is less than $10^{20}/E$ radians.

As for the deflection by the galaxies encountered in this time, we take $B \simeq 3 \times 10^{-6}$ gauss and the length over which the field retains an essentially fixed direction as 10^4 parsec. Then the deflection in crossing a single galaxy is about $3 \times 10^{19}/E$, and too few galaxies are encountered in 10^{10} years to raise this number substantially.

Hence protons of 10^{21} eV are apt to retain, when they reach the Earth, the directions of their sources within about 5 degrees, no matter how far away the sources may be, unless the organization and strength of intergalactic fields are surprisingly great. More significantly, a discovery of structure in the directional distribution of primaries of 10^{20}-10^{21} eV can give significant information about these largely unknown quantities.

6. 3. 5. *Size and energy requirements of sources.* All plausible natural acceleration models have shared the requirement that R, the typical dimension of the source, be large compared with the cyclotron radius of the particles, ρ. This is true even for the collisionless shock mechanism, where ρ must be less than the thickness of the transition region, which in turn is small compared with the lateral dimensions. Indeed, experience in several instances (laboratory plasma experiments, and data on acceleration in the Earth's magnetosphere) indicates that the inequality must be very great, two or more orders of magnitude. Only with a perfectly orderly machine like a cyclotron can one have $R = \rho$. To be conservative in the following argument, we shall assume $R \geq 30\,\rho$.

We shall assume the accelerated particles to be protons. If heavy nuclei are accelerated, they are apt to undergo photodisintegration before reaching us; so the energy would have to be just as large per nucleon as if the protons which reach us were accelerated directly: the size and energy requirements of the sources would then be even greater. Thus we take $\rho = E\beta/Be$ making $R \geq 30E\beta/Be$.

If this were the only limitation, one could imagine a source of small dimensions, like the immediate surroundings of a neutron star, where the field may be very strong. However, there are two further requirements: (i) the particle density must not be too large, or the acceleration will be destroyed by collisions with gas atoms; and (ii) the field must not be too strong, or synchrotron radiation, even by protons, will drain the energy too fast. The latter condition gives the stronger restriction at very high energies, and we consider it first.

The path length of the particles before escaping from the source is large compared with R. Therefore we require

$$E > R\,\frac{dE}{ds} > 30\rho\,\frac{dE}{ds} = 30\left(\frac{E\beta}{Be}\right)\left[\frac{2}{3}\,B^2\beta\gamma^2\left(\frac{e^2}{Mc^2}\right)^2\,\right]$$

where γ is the Lorentz factor, and we have written B for the component of the field normal to the motion. This expression reduces to $B < 10^{21}/\gamma^2$ gauss: not a strong limitation at energies within past experience, but implying $B < 10^{-1}$ gauss for protons of 10^{20} eV, and $B < 10^{-3}$ gauss for protons of 10^{21} eV.

The corresponding restriction on R is $R > 10^{-13}\gamma^3$ cm, which is 0.1 light year at 10^{19} eV, 100 light years at 10^{20} eV, and 100 000 light years at 10^{21} eV. The rapid energy dependence of this lower limit on dimensions of the source leads to the conclusion that no observed structures in the universe are large enough to accelerate protons much beyond 10^{21} eV; and certainly not a compressed structure having a high energy per unit volume.

The total magnetic energy required in the source is

$$W = \frac{B^2}{4\pi}\left(\frac{4\pi R^3}{3}\right).$$

From the requirements on R and the product BR given above we conclude $W \gg 300\,\gamma^5$ ergs, which shows a very rapid dependence on the energy. Again, the limit is insignificant for energies corresponding to ordinary EAS, but $W \gg 3 \times 10^{57}$ ergs at $E = 10^{20}$ eV and $W \gg 3 \times 10^{62}$ ergs at 10^{21} eV. Thus it requires a quasar-like total energy to provide the fields which can accelerate protons to 10^{20}-10^{21} eV, and there is until now no indication of larger amounts of available energy in any single structures. The requirement increases so rapidly with γ that quibbling about the numerical factor will not permit a much larger particle energy than 10^{21} eV, unless new orders of magnitude are accepted in the energy content and scale of organization of field structures in the universe.

Of course, these arguments may well be proved wrong by experimental discovery of primary protons having 10^{22} eV. We have presented the arguments mainly to suggest that such a discovery will have far-reaching cosmological implications.

The previously mentioned limit on particle density amounts to $nR\sigma \ll 1$, or if N is Avogadro's number and M the total mass of the source, $R^2 \gg (3/4\pi)NM\sigma$. Taking $\sigma = 30$ millibarns, we find $R \gg 3 \times 10^{15}$ cm for one solar mass, 10^{16} cm for 10 solar masses, and 1000 light years if the mass is like that of our galaxy. If one remembers that the required total field energies are equal to the rest energy of a million suns, one may be sure that the sources of the most energetic particles involve masses like those of galaxies, and therefore large dimensions, though the lower limit of size obtained from consideration of the synchrotron radiation was a stronger one.

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Discussion

N. A. DOBROTIN. The intensity of the luminescent light from a shower depends upon atmospheric conditions. How do you check it?

K. GREISEN. Our experiment has not yet reached a state of satisfactory refinement in this respect, since we are still struggling merely to obtain signals which are identifiable with air showers and capable of even approximate analysis. At present the apparatus functions only on visually clear nights, when the atmospheric transmission does not vary seriously. Ultimately, we will certainly need a continuous monitor of the atmospheric transmission.

S. A. COLGATE. The angular width of the electromagnetic pulse is determined by the size and curvature of the soft component of the shower front, namely approximately 1/10 radian. Since the fluorescent radiation also originates where the energy is dissipated, namely the soft component, I would expect the rise time of the fluorescent light of the forward directed showers to be slower than that of the Cerenkov light which emphasizes the harder (less scattered) component of the shower. Have you seen rise time characteristics indicative of this difference?

K. GREISEN. When the 'impact parameter' of the shower axis with respect to the detector is small ($\ll 2$ km), the received light is primarily Cerenkov radiation and the observed pulses have not only short rise times but brief duration. Such records are not useful for our purpose, since we cannot extract enough data from the narrow pulses to establish the position and direction of the shower axis. When the impact parameter exceeds 2 km, the Cerenkov light not only is weaker than the fluorescent light, but is also due mainly to widely scattered electrons. At such large impact parameters the pulses are broad (characteristic width $R/c \simeq 30$ μsec at 10 km) and have a rather slow rise. For these reasons, and principally to optimize the signal-to-noise ratio, our amplifiers were designed not to respond to frequency components above 1 Mc/s in the pulse and in the background noise. Both the background noise and our amplifier characteristics prevent observation of the fine differences to which the question refers, between the parts of the light (at large distances from the axis) which are due to the Cerenkov and fluorescence processes.

F. ASHTON. Would you please describe your apparatus in terms of the number of photomultipliers used, photocathode area and geometrical arrangement.

K. GREISEN. A distinction must be made between the current form of our apparatus and a much more sophisticated form which we now have in mind and propose to construct. At present a single recording station has five large (15 inch diameter) photomultipliers pointing upwards and towards the four points of the compass. The relative pulse amplitudes in these tubes at each instant of time reveal the direction of the light source at that time, thus permitting the axis to be traced out in space. (The measured angular velocity of the light source, together with its known speed c, determines the distance.) In future, we propose to increase the signal-to-noise ratio by a large factor, by reducing the angular aperture of the light reception by each tube from 2π to 10^{-2} sterad. Each station will then contain 500 tubes placed in clusters behind 16 large lenses, such that the whole sky is under examination, but only a small portion of it by each tube. The records will then have the character of all-sky photographs taken with an angular resolution of about 3°, and with the third dimension supplied by the timing of the pulses. In this projected arrangement the lenses will be of 18 inch diameter but the numerous individual tubes will have diameters of 1.7 inches.

T. GOLD. Is there any proposal for using the information-theoretic advantage in the detection of scintillation light in the atmosphere to single out only line sources in the sky?

K. GREISEN. In selection of events for recording and analysis, we do propose to make use of the sequential character of the pulses in photomultiplier tubes directed at neighbouring portions of the sky. In principle this technique can be elaborated, as suggested in the question, by demanding an extended linear sequence of pulses. To do this in selection of the events would require storage of the signals for excessive periods before their display. It is simpler for us to impose this requirement, of a linear sequence in time and space, upon later examination of the oscilloscope records of the pulses. In this way we shall utilize the information-theoretic advantage to which the question refers, both in combating noise and in distinguishing air showers from other phenomena.