III-2. Primaries

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Sept. 7	15 : 30 – 17 : 30	from III-2-1 to III-2-5
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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-2-1. Spectrum and Isotropy of EAS

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The number spectrum of EAS has been found to extend to showers of more than 10^{10} particles without noticeable increase in steepness. The logarithmic slope has some uncertainty because of an unknown variation of lateral distribution near the axis with shower size; the corrected value of γ is about 1.7 for $6\times10^6<N<6\times10^9$ particles. Assuming a lateral distribution corresponding to an age parameter $s=1$, the largest shower recorded had 2.6×10^{10} particles.

Large showers ($N>10^7$) seem to exhibit substantial anisotropy, but the statistical significance of this observation is not very great. The persistent feature is a pronounced minimum around 15 hours l.s.t. In the showers of $6\times10^6<N<10^8$ such a minimum appeared associated with a large second harmonic (17%) in the fourier amplitudes, while in the showers of $N>10^8$ this minimum appeared to be associated with a large first harmonic (35%). A minimum in the third quadrant also appears in the MIT Agassiz data for showers of $N>10^8$, and in the MIT Volcano Ranch data, as well as in Japanese data on "μ-rich" showers, "μ-less" showers, and m. p. p. observed underground.

Fourier analysis of the frequencies of smaller showers reveals no second harmonics, but a possibly significant first harmonic of amplitude about 0.4% with maxima in the range 13 to 20 hours l.s.t., for EAS of $10^4<N<10^6$ particles. Because of the complexity of solar periodic atmospheric effects on EAS, this apparent anisotropy of the primaries may be spurious; but it is suspicious that many experimenters in different places on the earth have found maxima at approximately the same local sidereal time, both in the rates of small EAS and in the background cosmic-ray intensity.

§ 1. Apparatus

Showers were recorded at Ithaca, N. Y. (elevation 260 m above sea level) with 15 large scintillators in an array of diameter about 1000 m. Two types of registration were used. Small showers were recorded by simple coincidences between 3 or 4 scintillators at spacings varying from a few meters up to 600 m. Fig. 1 shows the computed re-

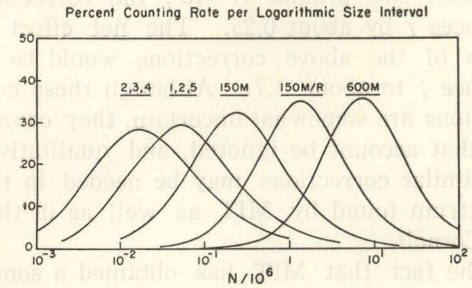


Fig. 1.

sponse of five different coincidence channels as functions of shower size. For the events registered in this way, only the collimating effect of the atmosphere gives knowledge of the directions of the primaries. Large showers were recorded and analyzed in more detail. For $N>6\times10^6$, showers were detected with practically 100% efficiency over a known area, which increased from 0.02 sq. km. at $N=6\times10^6$ particles to 1.5 sq. km. for $N>2\times10^8$. Directions of these showers were determined by the timing method. Shower cores were located and sizes determined by means of the pulse heights in the array of scintillators.

§ 2. Number Spectrum

The frequency of showers having more than N charged particles can be represented well, according to our data, by a single straight line on a log-log graph over the interval $N>6\times10^6$. By means of the measured zenith-angle distribution we have corrected the coefficient of the spectrum to represent the vertical intensity at sea level. Expressing the results as $K(N/10^6)^{-\gamma}$, we find $\gamma=1.84\pm0.06$ and $K=(3.58\pm0.28)\times10^{-8}$ (m² sec sterad)⁻¹. For comparison, the MIT group in the Agassiz experiment obtained $\gamma=1.90\pm0.10$ and $K=(3.48\pm0.53)\times10^{-8}$, while a summary of EAS data in the Annual Reviews of Nuclear Science (Greisen, 1960) gave $K=(3.0\pm0.6)\times10^{-8}$ and $\gamma=1.86\pm0.06$ in the neighborhood of $N=10^7$.

In obtaining the present results we have taken into account the following sources of systematic error:

(1) variation of *a priori* probability of shower occurrence with N,

(2) random errors in determining N,

(3) systematic errors in core location,

(4) imperfect detection efficiency,

(5) variation of scintillator efficiency with temperature.

However, there are two significant sources of error for which we have not yet made corrections, because we could not evaluate them accurately. The smaller one is the variation of zenith angle distribution with N. According to our data, the distribution grows flatter as N increases, at such a rate

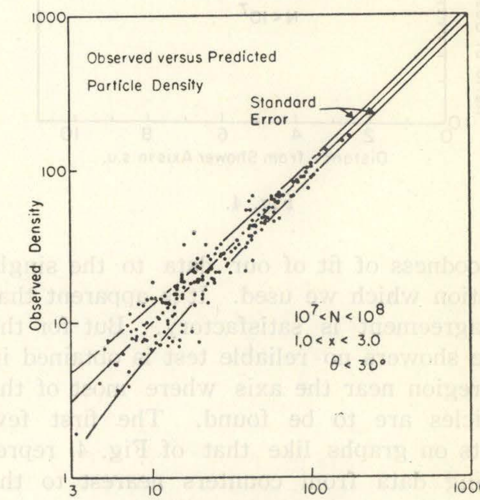


Fig. 2.

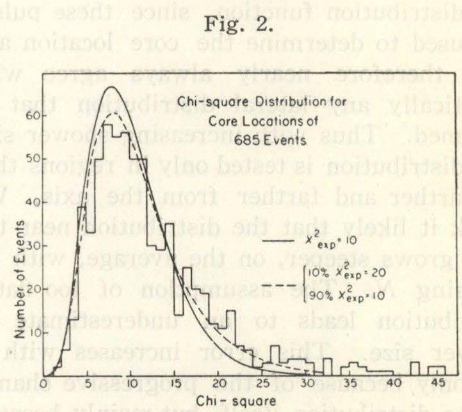


Fig. 3.

as to make our value of γ too small by about 0.085 ± 0.03. The more serious effect is due to a systematic variation of the lateral distribution of the particles with N. We were not able to determine this variation, and therefore we used the same lateral distribution in analyzing all of our showers regardless of their size. Figs. 2-4 show tests

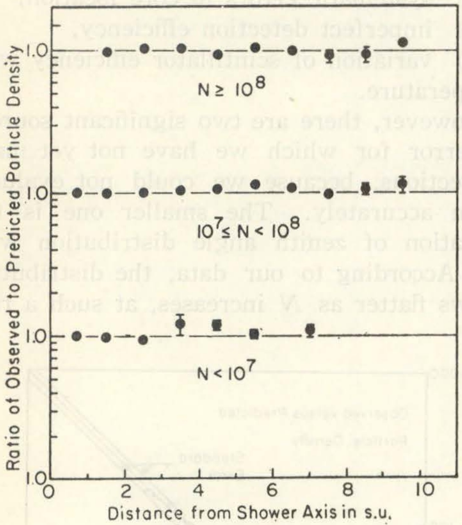


Fig. 4.

of goodness of fit of our data to the single function which we used. It is apparent that the agreement is satisfactory. But for the large showers no reliable test is obtained in the region near the axis where most of the particles are to be found. The first few points on graphs like that of Fig. 4, representing data from counters nearest to the core, do not constitute a significant test of the distribution function, since these pulses are used to determine the core location and will therefore nearly always agree with practically any lateral distribution that is assumed. Thus with increasing shower size the distribution is tested only in regions that lie farther and farther from the axis. We think it likely that the distribution near the core grows steeper, on the average, with increasing N. The assumption of too flat a distribution leads to an underestimate of shower size. This error increases with N not only because of the progressive change in the distribution itself, but mainly because the total number of particles is evaluated from density measurements at larger and larger distances from the axis. For our biggest shower, the discrepancy is a factor 5 between the size given by our normal analysis (5×10^9 particles) and that obtained (2.6×10^{10}) with the lateral distribution corresponding to an age parameter $s=1$, as is expected for showers near their maximum development.

If we assume that we have evaluated N correctly near 10^7, but underestimated N by a factor two around $N=10^9$, the correction reduces γ by about 0.25. The net effect of both of the above corrections would be to reduce γ to about 1.7. Although these corrections are somewhat uncertain, they cannot on that account be ignored, and qualitatively similar corrections may be needed in the spectrum found by MIT as well as in that of Cornell.

The fact that MIT has obtained a somewhat larger value of γ at their Volcano Ranch station than we have found at Cornell may be explained by the difference in elevations. Showers of $N=10^7$ are about four times more numerous at 820 g/cm^2 than at 1000 g/cm^2, while showers of $N=10^9$ (in the vertical direction) are about equally numerous at both stations; hence the change in elevation can account for a difference as large as 0.3 between the two values of γ.

§ 3. Largest Recorded Showers

As noted above, uncertainty in the lateral distribution introduces substantial possible error in the sizes of the biggest showers. Japanese reports have indicated that young showers have a distribution near the axis at least as steep as the computed function for $s=1.0$. The MIT group has found that large showers near maximum development fit the curve for $s=1.0$ well over a large range of radius. Our own data indicate that showers of $N\simeq10^{10}$ reach maximum development at sea level (see "Properties of EAS" by Bennett *et. al.*, presented in one of the sessions on EAS). If we therefore analyze our largest shower with the function for $s=1$, we find $N=2.6\times10^{10}$ particles. This may be compared with the largest size found by MIT, $N=3.2\times10^{10}$, using the same lateral distribution. Depending on the exact variation of s with N that is assumed, the total number of EAS with $N>10^{10}$, recorded at Cornell in two years of operation, is between 2 and 4. Two of these (including the largest event) were within the nominal acceptance area of 1.5 sq. km.

It is not implied by existing data that 3×10^{10} particles is a maximum size of EAS; quite the contrary. Within the poor statistics available on this question, the number spectrum near the upper end of the data is just as flat as in the interval $10^7 < N < 10^8$. Because of the steepness of the lateral distribution of charged particles, thorough investigation of the spectrum and isotropy of EAS with $N > 10^{10}$ will require new methods of detection and measurement. Several groups throughout the world are now studying new methods using radio waves and atmospheric scintillation light. We expect that the next IUPAP conference will hear of showers containing as many as 10^{11}-10^{12} particles.

For the present, one must accept the fact that the primary energy spectrum continues smoothly up to an energy of at least 6×10^{19} ev, or about 10 joules. Normal to a uniform field of 4 microgauss, a primary of charge Z with this energy would move in a circle of diameter $10^5/Z$ light years. If the field changes erratically in direction over distances of this order, the path is much closer to a straight line. It seems inconceivable that even iron nuclei of such energy can be effectively confined within the galaxy.

Incidentally, no sign was observed of multiple showers with cores far apart, such as might arise from photodisintegration of heavy nuclei outside the atmosphere.

§ 4. Possible Anisotropy of Large Showers

A. EAS of mean size 2×10^7 particles

Fig. 5 shows on an Aitoff equal-area projection the celestial coordinates of 913 analyzed showers having $N > 6\times 10^6$ particles. The variation of the density of points with declination is mainly due to the collimating effect of the atmosphere at latitude 42.5°; but the variation with right ascension is not an atmospheric effect. Showers with $N > 10^8$ are discussed separately below. If one makes a fourier analysis of the distribution in right ascension of the 853 EAS within $6\times 10^6 < N < 10^8$, one finds a large second harmonic with maxima at 9.7 and 21.7 hours local sidereal time, the minima falling at 3.7 and 15.7 hours. The apparent relative amplitude is 17% and the probability of getting an amplitude this large by random fluctuations is only 0.2%. The first harmonic is insignificant. The first and second harmonics in solar time are also insignificant. This is a consequence of our careful compensation for temperature effects in the apparatus: periodic atmospheric effects on the EAS themselves are small compared with the r.m.s. accidental amplitude, which was 6.8%.

Fig. 6 shows a test to see whether the apparent asymmetry is related to galactic declination. The smooth curves are the computed effect of atmospheric absorption on the distribution, calculated for a shower absorption length equal to 1/8 of the vertical

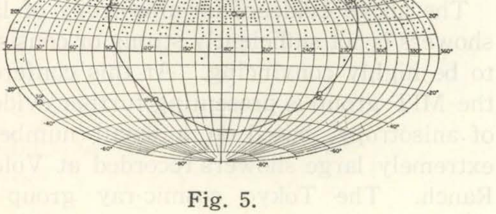


Fig. 5.

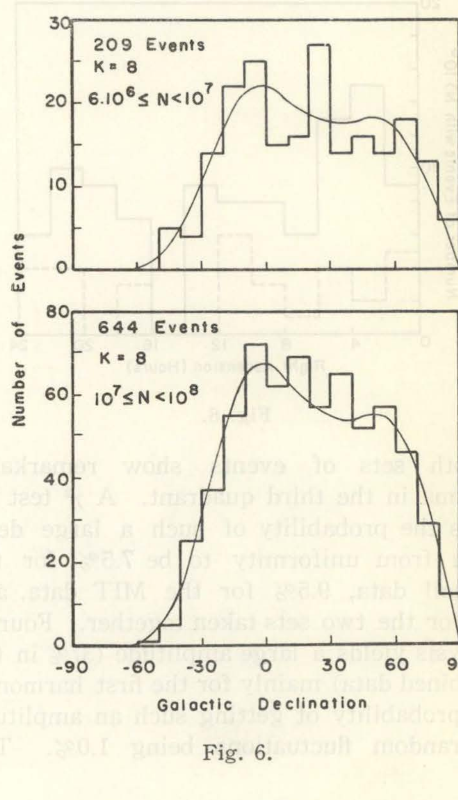


Fig. 6.

atmosphere above Ithaca. No association of asymmetry with galactic declination is apparent.

B. Showers of more than 10^8 particles

Fig. 7 is an Aitoff plot of the coordinates of 88 events (indicated by round points) having more than 10^8 particles at Ithaca (the sizes being inferred from our standard lateral distribution function, which probably underestimates N somewhat), together with 32 events (indicated by triangles) of "equivalent vertical size" exceeding 10^8 particles, as recorded by MIT at their sea-level (Agassiz) station[1]. Fig. 8 shows histograms of the distribution in right ascension of 100 showers of $N>10^8$ recorded at Cornell and the 32 above-mentioned MIT showers.

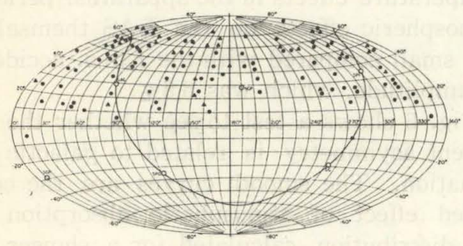


Fig. 7.

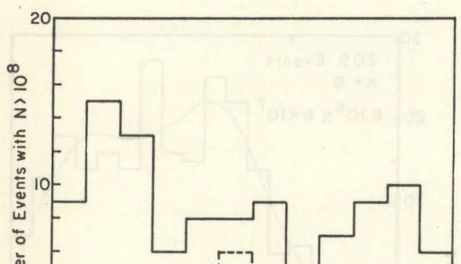


Fig. 8.

Both sets of events show remarkable minima in the third quadrant. A χ^2 test reveals the probability of such a large deviation from uniformity to be 7.5% for the Cornell data, 9.5% for the MIT data, and 2% for the two sets taken together. Fourier analysis yields a large amplitude (37% in the combined data) mainly for the first harmonic, the probability of getting such an amplitude by random fluctuations being 1.0%. The minimum is at 15 hours.

Fig. 9 shows the distribution of Cornell showers of size $10^8<N<10^9$ with respect to galactic declination. A clustering near the galactic equator suggests itself, but is not highly significant statistically.

In Fig. 10 the coordinates are shown for 11 Cornell events of nominal size exceeding 10^9 (actual size probably exceeding 2×10^9 particles). The largest shower is indicated by a cross. Any asymmetry that may be present is not sufficient to be revealed with such a small number of events.

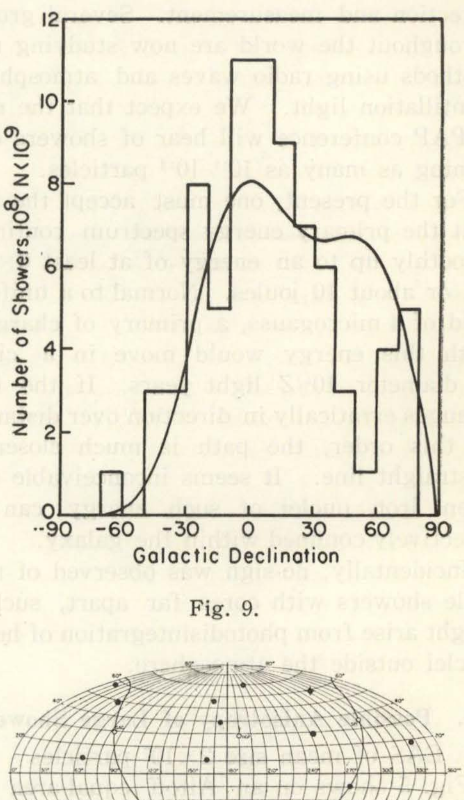


Fig. 9.

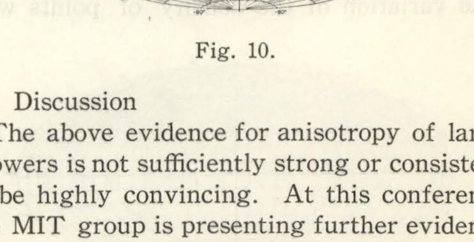


Fig. 10.

C. Discussion

The above evidence for anisotropy of large showers is not sufficiently strong or consistent to be highly convincing. At this conference the MIT group is presenting further evidence of anisotropy, based on a small number of extremely large showers recorded at Volcano Ranch. The Tokyo cosmic-ray group reports strong asymmetry among small numbers of comparatively small "μ-rich" showers and even smaller numbers of "μ-less" showers; and the Osaka group finds asymmetry in the distribution of a few dozen cases of showers with multiple penetrating particles underground. Each of these evidences is weak in itself. One must be cautious in interpreting the computed probabilities for these distributions to occur by chance, since the number of possible forms or configurations of asymmetry that one can search for in such data is very large, and *any* specific result could only be predicted to occur with low probability. The experience of many groups in the past has been that subsequent improvement of the statistics always diminishes the apparent effect; while at every stage of such research, one can select a new restricted class of events among the data, such that the number of cases is small and the departure from uniformity is large.

However, it is even more erroneous to interpret these data as proof of absence of anisotropy; and if one can find some common feature in all the diverse reports of asymmetry, and a plausible common cause of such an effect, the combined weight of evidence from the different experiments may be impressive. At the least it may be of use in directing future investigations. In sets of data having individually such weak statistics, one cannot expect the apparent asymmetries to agree in complete detail, even if there *is* a common cause of underlying real anisotropy. Only some general feature of the asymmetry should be approximately reproduced. Indeed, such a point of similarity has emerged. All of the sets of data show an excess of events in the first or second quadrant of right ascension, in directions approximately normal to the local spiral arm of the galaxy, and a pronounced minimum in the interval 200°-270°, where directions normal to the spiral arm occur only at large zenith angle for stations at northern latitude. It is conceivable that the asymmetry applies principally to the heavy nuclei among the primaries, and that two ways of selecting such events are (a) to select EAS unusually rich in muons, as done by the Tokyo and Osaka groups, and (b) to select showers of high total energy, as done by the groups at MIT and Cornell*. We must wait to see whether future data substantiate such an interpretation.

§ 5. Evidence Regarding Anisotropy of Smaller Showers

By simple coincidences as described in § 1, very large numbers of showers in the size range $10^4 < N < 10^7$ were recorded. It is clear that the anisotropy of these showers is very small, and therefore instrumental and atmospheric effects are important. The following precautions were taken to avoid periodic variations of instrumental origin.

(1) Use of amplifiers with strong feedback

(2) Design of discriminators to maximize stability, particularly against temperature changes

(3) Regulation of all AC power

(4) Thermister feedback from scintillators to compensate for variation of light efficiency with temperature

(5) Thermal insulation of scintillators to avoid rapid temperature changes, which would cause phase errors in the above compensation

(6) Thermister feedback from amplifiers to compensate for variation of gain with temperature

(7) Air conditioning of room containing the electronics

(8) Monitoring of background rate in all counters.

The data were analyzed simultaneously for pressure and temperature coefficients and for first and second harmonics in solar, sidereal and antisidereal time (365, 366 and 364 cycles per year). The data extend over two full years (1958 and 1959) so that the above fourier components are orthogonal. The purpose of the antisidereal time analysis is to detect the effect of seasonal modulation of solar atmospheric influences, which should induce equal spurious first harmonics in sidereal and antisidereal time. The apparent antisidereal amplitudes were used to correct the sidereal waves, on the assumption that the spurious harmonics are due purely to

* This synthesis of the observations is not original at Cornell, but was suggested to the speaker by Dr. M. Oda, and has apparently occurred to the MIT group as well.

Channel	Median Shower	Solar Wave (Pressure and Temperature Corrected)			Sidereal Wave (Corrected by Antisidereal Wave)		
	Size	Amplitude	Phase	Probability	Amplitude	Phase	Probability
Backg'nd	1	0.30	15.2	$4x10^{-7}$	0.02	14.6	97.3
2–3–4	$2x10^4$	0.41	13.6	0.025	0.41	13.8	1.6
1–2–5	$6x10^4$	0.25	19.5	18.4	0.46	19.8	6.0
150M	$2.7x10^5$	0.47	0.8	3.6	0.59	16.0	7.5
150M/R	$1.4x10^6$	0.89	0.2	8.3	0.70	13.0	46.0
600M	$7.5x10^6$	2.53	2.3	10.6	3.04	15.3	19.8

amplitude modulation (no phase modulation) of the solar harmonics. Proper account was taken of the consequent increase in the statistical error of the results.

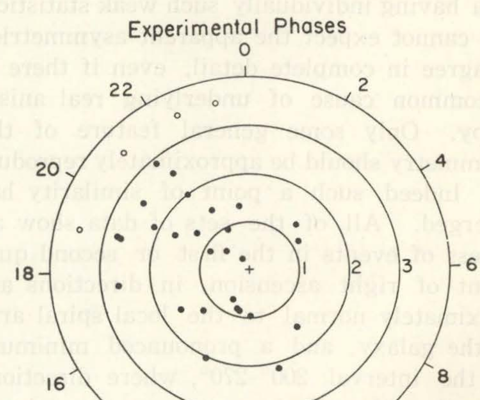
As for the results themselves, no consistent or highly significant second harmonics were found in either solar or sidereal time. The results for the first harmonics are given in the following table. "Phase" means time of the maximum; "probability" means the probability of an amplitude that large or larger arising from random deviations, of magnitude determined by the residual variance of the data. Amplitude and probability are given in percent, phase in hours of local time.

The solar effects are obviously real. Their variation in amplitude and phase with increasing separation of the counters indicates clearly that they are a residual temperature effect of the atmosphere on the EAS.

The sidereal first harmonics are remarkably consistent in phase, and the probability is rather small that they could be due to chance, especially the results for showers of $10^4 < N < 10^6$.

We have investigated the reality of the spurious harmonics arising from seasonal modulation of solar atmospheric effects. During 1958 and 1959, the average annual modulation of the sea-level diurnal temperature cycle was 64%, creating large spurious temperature cycles in both sidereal and antisidereal time. These waves were mostly but not entirely accounted for by an amplitude modulation; some phase modulation had to be introduced to account for them entirely. Moreover, the apparent temperature coefficient of EAS underwent substantial annual variation (perhaps associated with humidity, or with the varying relation of sea-level to upper air temperatures). If the EAS rates suffer phase modulation as well as amplitude modulation of a solar variation, the antisidereal wave bears an unknown phase relation to the spurious sidereal wave, and corrections such as we have applied are inaccurate. Error in the correction is also introduced by inaccuracy in the phase of the solar wave. We estimate that on these accounts, a residual spurious amplitude of a few tenths of a percent could arise in sidereal time. Therefore we regard our results in the above table as *not* constituting strong evidence of a real asymmetry in the primary cosmic rays.

One must still account for a remarkable consistency in phase among measurements of primary asymmetry by many different ex-



Radial Distance = Ratio of Amplitude to Random Walk.
Open Circles = Background Measurements at arbitrary Radial Distance.

Fig. 11.

perimenters at different places on the earth. Fig. 11 shows the distribution of phase and amplitude among various results that have been reported from EAS experiments at Naimi Tal, Yakutsk, Chacaltaya, Pic du Midi, Manchester, Auckland, Harwell, Leeds, Pisa, and Ithaca; as well as background measurements with ion chambers and counter telescope at Cheltenham, Christchurch, Hobart, Huancayo, and Tokyo. There is a clear tendency for maxima to occur around 20 hours l.s.t., not far from the right ascensions of the galactic center, the inwards-directed spiral arm, and the expected maximum of the Compton-Getting effect—also not far from the *minimum* reported for very large showers and showers of special types in § 4 above.

Since the majority of the EAS experiments have been conducted in the northern hemisphere, atmospheric effects such as those discussed above might account for some consistency in phase of spurious sidereal variations found by different observers. Therefore we regard the reality of these sidereal waves as not yet established, but in need of further investigation, especially by experiments widely distributed in latitude, or at the equator.

References

1) Clark, Earl, Kraushaar, Linsley, Rossi, Scherb, and Scott: Phys. Rev. **122** (1961) 637.

Discussion

Yamaguchi, Y.: Do you have an experimental test on the axial symmetry in the lateral distribution of EAS?

Greisen, K.: Statistical fluctuation in pulse heights conceals small asymmetries in individual showers. The *average* azimuthal asymmetry was used to study the absorption of particles in inclined showers. However, no *large* azimuthal asymmetries were apparent in individual cases, and the average asymmetry due to the particle absorption is very little.

Oda, M.: About the temperature effect. Would not the observations over cycles of seasons deduce the effect?

Greisen: The experiments on asymmetry of small showers have in general been carried out over complete years so that a *periodic* solar effect on the atmosphere would not generate any spurious counting rate variation synchronized with sidereal time. However, the solar effects are not exactly periodic in solar time. There is a seasonal variation in the *amplitude* if the diurnal atmospheric temperature changes, and apparently also in the *phase* of these effects. Besides, the temperature *coefficient* of the counting rates seems to vary seasonally. All of these effects can generate a small spurious variation of counting rate that seems to be synchronized in sidereal time. It is this that causes insecurity in those experiments of high statistical accuracy, which have yielded very small, but positive, amplitudes of sidereal time variations.

Millar, D. D.: Since fluctuation in pulse height from a scintillator for a given incident particle density to be asymmetric (due to nuclear interactions, μ-meson knock-on shower for example), what effect is this likely to have on the determination of shower size?

Greisen: Asymmetric fluctuations in pulse heights present a very real danger. However, both the Cornell and MIT groups have studied the fluctuations and found them to be in good agreement with a Poisson distribution. In rare cases, a larger pulse is seen than would be expected from the Poisson distribution of random particles; and events may represent nuclear interaction in the plastic. However, such events are not only rare, but always rather small in pulse height. The scintillators were too thin to cause large multiplication of a local nuclear cascade.