# Accelerated Dust Grains and the Highest Cosmic Ray Energies

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*Abstract*

The events following the impact of a fast ionised grain with the atmosphere are examined, and some similarity is found between the expected air shower and observations of the largest cosmic ray showers. It is concluded that the largest air showers are in any case initiated by primaries accelerated outside the solar system, whether the primaries are dust grains or single nuclei.

**Introduction**

Recent theories of the origin of cosmic radiation attribute the acceleration of the primary particles to electromagnetic processes either in the sun's environment or in the Galaxy.

If the primaries are generated in the sun's environment, it is unlikely that their magnetic rigidity $H\varrho$ can exceed $10^{11}$ gauss cm corresponding to, for instance, $H = 10^{-5}$ gauss inside the solar system and $\varrho = 10^{16}$ cm (ALFVÉN, 1954, p. 251). For a proton this upper limit of the rigidity would correspond to an energy of $3 \times 10^{13}$ eV. On the other hand, analyses of extensive air showers (COCCONI, COCCONI-TONGIORGI and GREISEN, 1949; CRANSHAW and GALBRAITH, 1954) indicate the existence of primary particles with energies exceeding $10^{17}$ eV, and evidence is forthcoming (CRANSHAW and GALBRAITH, private communication) for the occurrence of considerably higher primary energies.

It has been suggested (ALFVÉN, 1954, p. 252) that the primaries initiating the largest showers may be multiply-charged, and that extremely great energies may be reconciled with moderate magnetic rigidities in this way. A relativistic particle carrying $Z$ elementary charges has an energy

$$pc = 300\, H\varrho Z \text{ eV} \qquad (1)$$

For a given rigidity $H\varrho$, a heavy nucleus would bring the energy up by one or two powers of ten as compared with a proton, and an ionised dust grain of suitable dimensions might possibly admit even higher values of $Z$. These suggestions have direct bearing on the question whether at least some cosmic ray particles are generated outside the solar system.

It is the purpose of the present note to outline the events following the impact of a fast ionised grain with the atmosphere, and to indicate how such primary particles, if they exist, might be identified and their rigidities estimated by cosmic ray observations.

**The Maximum Charge on a Grain**

A cosmic dust grain can be expected to acquire a positive charge, in the first instance by photo-ionisation, and after acceleration, by collisions with atoms or ions. Any recombination process is unlikely to be important, but an upper limit for the positive charge is certainly reached when ions are beginning to leave the surface of the grain. This process would first tend to round off corners and edges, making the grain more spherical.

To estimate the upper limit for the number $Z$ of positive charges, we consider a spherical grain with radius $r$, containing $n$ atoms. As reasonable values we adopt for the lattice energy $W = 15$ eV/atom (= 690 kcal/mole for a diatomic substance; cf. LANDOLT-BÖRNSTEIN, 1955), and for the lattice constant $d = 2.2$ Ångström.

The grain will certainly dissociate completely when the electrostatic energy divided by the number of atoms exceeds the lattice energy, i.e., the maximum value of $Z$ is determined by

$$\frac{(Ze)^2}{8\pi\varepsilon_0 r}\frac{1}{n} = W \tag{2}$$

$\varepsilon_0 = 10^{-4}/36\pi$ is the dielectric constant of vacuum.

The radius $r$ is given by

$$4\pi r^3/3 = nd^3 \tag{3}$$

and we obtain from (2) and (3), together with the constants quoted above

$$Z = \beta n^{2/3} = 1.7\, n^{2/3} \tag{4}$$

It may be noted that if the number of charges given by eq. (4) is divided by the number of surface atoms, we find that a fraction 0.35 of all surface atoms are ionised. In a different way this illustrates that the chemical binding is just being destroyed by electrostatic disruption. In any case, the grain must be a perfect crystal without lattice defects in order to withstand electrostatic forces up to this magnitude.

The corresponding field strength is 13 volts/Ångström at the grain surface.

The grain is then charged to a potential of $13\, r$ volts, where the grain radius $r$ is measured in Ångström. Later it will appear that we are interested in grains with radii up to $10^2$ or $10^3$ Ångström, and hence the corresponding maximum potentials are of the order of 1 to 10 kV. It is outside the scope of the present paper to discuss whether grains moving at relativistic velocities may acquire potentials of this magnitude by cosmic processes, but it is quite clear that the value $\beta \approx 1$ given in eq. (4) is an upper limit, which may have to be reduced by one or two powers of ten.

### Impact of a Fast Grain into the Atmosphere

The size of grains of interest in the following discussion is limited to $10^{-4}$ cm or less, containing less than $10^{10}$ atoms, and the energy per nucleon will appear to lie in the range $10^{12} - 10^{14}$ eV.

A grain entering the ionosphere will be disrupted by collisions with air molecules, and already at heights somewhat below 100 kilometres the grain has received sufficient energy to split into a beam of relativistic ions and nuclei. It seems likely that when the beam has expanded to widths of the order of centimetres, each ion or nucleus will behave as a free particle, and the slight effect of multiple scattering by air molecules will from then onwards be the main dispersive force acting on this nuclear beam.

Nuclear interactions become important after traversal of air masses of the order of $10 - 30$ g/cm$^2$, i.e., at heights of $30 - 40$ kilometres, and the main effect at these heights is to break up the nuclei into a beam of protons and neutrons. The number of surviving nuclei will decrease exponentially downwards, and it is unlikely that even a single nucleus can reach sea level without disruption.

The nucleonic beam is being absorbed exponentially with a characteristic thickness of somewhat more than 100 g/cm$^2$, giving rise to $\pi$-mesons, whose decay products are observed as soft and penetrating particles at sea level. With primary nucleon energies in the range $10^{12} - 10^{14}$ eV, the $\pi$-mesons are mainly contained inside a forward cone with vertex angle between 5° and 0.5° as seen from the laboratory system of coordinates. This effect is by far the most important factor governing the density distribution observed at sea level, and only at the upper limit of the energy range considered will Coulomb scattering of electrons in the latest stages of the cascades become of comparable importance.

In a search for showers due to dust grains one should, therefore, analyse showers which are wider than expected by Molière's distribution (cf. HEISENBERG, 1953). Furthermore, it is to be expected that the penetrating particles at sea level are dispersed over a larger area than the soft secondaries, because the majority of $\mu$-mesons at sea level are due to charged $\pi$-mesons produced at heights exceeding $10 - 15$ kilometres, whereas the electrons and photons reaching down to the ground are mainly due to short cascades originating at heights of only a few kilometres. As the angular distribution of charged and neutral $\pi$-mesons are probably the same, the electrons are therefore spread over a smaller area.

**Structure of the Electron Shower at Sea Level**

The probability for a primary nucleon, after having traversed a thickness $m$ g/cm$^2$, to collide and give rise to $\pi$-mesons in a thickness interval $dm$ is

$$e^{-m/\mu}\, dm/\mu \tag{5}$$

The characteristic thickness $\mu$ is taken to be 100 g/cm$^2$, which is somewhat smaller than the absorption thickness for the nucleonic component in the atmosphere (cf. HEISENBERG, 1953, p. 385).

In the energy range $10^{12}$—$10^{14}$ eV per nucleon, the number of $\pi$-mesons produced in a collision is somewhat greater than 10 (HEISENBERG, 1953, p. 162). A precise value is not important for our purpose, and for numerical convenience each collision is assumed to produce 6 charged $\pi$-mesons and 3 neutral $\pi$-mesons, which decay into 6 $\gamma$-quanta initiating cascade showers.

Up to energies exceeding $10^{13}$ eV per nucleon, the angular distribution of the $\pi$-mesons in a system following the centre of gravity of the interacting nucleons is fairly isotropic (LORD, FAINBERG and SHEIN, 1950), but tends with increasing energy to become concentrated along the line of flight. In the present calculation an isotropic distribution has been adopted, and this may lead to some overestimate of the width of the resulting shower.

A transformation from the centre of gravity of the two nucleons to the laboratory system (BRADT, KAPLON and PETERS, 1950, eq. 11 a) shows that the number of relativistic $\pi$-mesons $N(\Theta)\,d\Theta$ emitted at angles between $\Theta$ and $\Theta + d\Theta$ with the primary particle track in the laboratory system is

$$N(\Theta)\,d\Theta = \frac{2N_0}{B}\frac{\alpha}{(\alpha^2+1)^2}\,d\Theta \tag{6}$$

$N_0$ is the number of mesons emitted isotropically in the centre of gravity system, $\alpha = \Theta/B$ where $B = (2M_0c^2/U)^{1/2}$, $2M_0c^2$ is the rest energy of the two interacting nucleons and $U$ is the energy of the primary nucleon. It is assumed that $\Theta$ is small, which is certainly the case in the present calculations.

Each $\gamma$-quantum, secondary to a neutral $\pi$-meson, initiates a cascade shower. The number of electrons $\Pi\ (M-m)$ at sea level ($M = 1{,}000$ g/cm$^2$ = 26.5 radiation lengths below the top of the atmosphere) is obtained from ROSSI (1952, p. 259). An inspection of Rossi's graphs shows that grains for which the energy per nucleon is $10^{11}$ eV or less, will only give rise to a multitude of short cascades in the upper atmosphere, but do not produce noticeable amounts of soft secondaries at sea level. On the other hand, if $U$ much exceeds $10^{14}$ eV, it is very hard to distinguish between the secondaries of a single energetic nucleon and a dust grain with the same total energy.

If the dust grain contains $N$ nucleons, each giving rise to 6 quanta initiating cascade showers of $\Pi\ (M-m)$ electrons at ground level, the total number of electrons observed on the ground is

$$N_e = 6\,N\int_0^M e^{-m/\mu}\,\Pi(M-m)\,dm/\mu \tag{7}$$

The number of electrons per unit area $D_e(R)$ at distance $R$ from the shower axis is

$$D_e(R) = \frac{6N}{B^2\pi}\int_0^M e^{-m/\mu}\,\Pi(M-m)\frac{1}{h^2(\alpha^2+1)^2}\frac{dm}{\mu} \tag{8}$$

where $h$ is the geometrical height at thickness $m$ below the top of the atmosphere (ROSSI, 1952, p. 545), and $\alpha = R/Bh$. It is readily seen that $N_e = \int_0^\infty D_e(R)\ 2\pi R dR$. The dependence of the $\pi$-meson energy on the angle $\Theta$ is ignored, and this may lead to some overestimate of the width of the resulting shower.

**Table 1. Radial density distribution of electrons $D_e(R)/D_e(0)$ for different values of distance $R$ and nucleon energy $U$**

| $R$ (metres) | $U=10^{12}$eV | $U=10^{13}$eV | $U=10^{14}$eV |
|---|---|---|---|
| 0 | 1.00 | 1.00 | 1.00 |
| 20 | — | — | .47 |
| 30 | — | .67 | — |
| 50 | .74 | .45 | .12 |
| 100 | .47 | .17 | .02 |
| 200 | .20 | .03 | — |
| 300 | .10 | — | — |
| 400 | .05 | — | — |
| 500 | .03 | — | — |

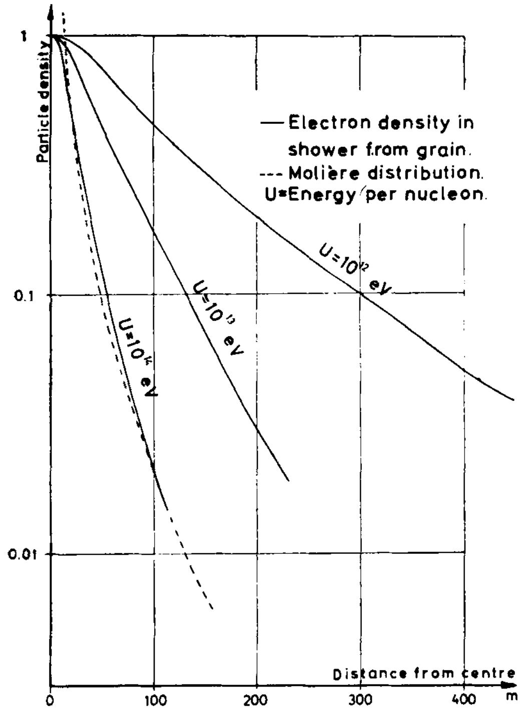


Fig. 1. Radial distribution of electrons in showers initiated by grains (———) compared with radial distribution in electron-photon cascade (- - - -). (HEISENBERG, 1953, p. 434.)

Table 1 and Fig. 1 show that the distance at which the electron density has been reduced to 1/10 of the central density, varies from 300 metres for $U=10^{12}$ eV to 60 metres for $U=10^{14}$ eV. In the outer parts of the Molière distribution the electron density goes down by a factor 10 over a distance of 50 metres. It is therefore apparent that for dust grains with energies per nucleon less than $10^{14}$ eV, the angular spread at production of the $\pi$-mesons will be more important than electron scattering, but for energies greater than $10^{14}$ eV it will be unimportant compared with electron

**Table 2. Number of electrons at sea level per incident nucleon, $G(U)=N_e/N$, for different values of nucleon energy $U$**

| $U$ | $10^{12}$eV | $10^{13}$eV | $10^{14}$eV |
|---|---|---|---|
| $G(U) = N_e/N$ . . . . | 6 | 150 | 4100 |
| log $[U/G(U)^{1/3}]$ . . . | 11.7 | 12.3 | 12.8 |



scattering, which will then mark any specific effects associated with dust grains as primary particles.

Table 2 shows that for energies below $10^{12}$ eV, the number of cascade electrons at ground level will be very small, as is also well known from studies of the ordinary soft component in the cosmic radiation.

**Table 3. $U=10^{12}$eV. Relative contributions to electron density at sea level from cascades initiated at different heights**

| $m$ g/cm² | $h$ (km) | $R=0$ | $R=$ 50 m | $R=$ 100 m | $R=$ 300 m |
|---|---|---|---|---|---|
| 0 | — | .00 | .00 | .00 | .000 |
| 100 | 16.3 | .03 | .03 | .03 | .027 |
| 200 | 11.9 | .08 | .08 | .07 | .045 |
| 300 | 9.3 | .14 | .14 | .12 | .058 |
| 400 | 7.4 | .30 | .29 | .25 | .086 |
| 500 | 5.7 | .52 | .48 | .38 | .083 |
| 600 | 4.4 | .72 | .63 | .44 | .059 |
| 700 | 3.2 | .89 | .70 | .39 | .027 |
| 800 | 2.2 | .87 | .54 | .20 | .007 |
| 900 | 1.2 | .42 | .11 | .02 | .000 |
| 1000 | 0 | — | — | — | — |

Table 3 illustrates that for $U=10^{12}$ eV, the bulk of the electrons near the shower axis belong to cascades initiated between 2 and 4 kilometres above the ground, whereas the much greater number of cascades initiated at heights exceeding 10 kilometres is absorbed well above the ground. In the fringe of the shower cascades initiated at low altitudes contribute less because they are only dispersed over a small area near the axis, and cascades starting at heights of 4 to 7 kilometres become more important.

## Structure of the Meson Shower at Ground Level

The general features of the $\mu$-meson component at ground level can be studied by assuming that every charged $\pi$-meson gives rise to a secondary $\mu$-meson on the ground. At the energies which we consider, absorption and $\mu$-meson decay are not serious, but the development of meson-nucleon cascades may be significant, and the estimates of meson densities given in the present discussion are probably lower limits.

The number $N_m$ of $\mu$-mesons and their density $D_m(R)$ follow from eqs. (7) and (8) by putting $\Pi(M-m)=1$, i.e.,

$$N_m = 6N\int_0^M e^{-m/\mu}dm/\mu \approx 6N \qquad (9)$$

$$D_m(R) = \frac{6N}{B^2\pi}\int_0^M e^{-m/\mu}\frac{1}{h^2(\alpha^2+1)^2}\frac{dm}{\mu} \qquad (10)$$

**Table 4.** $U = 10^{12}$**eV. Density of** $\mu$**-mesons relative to density at the shower axis and to the electron density**

| $R$ (metres) | $D_m(R)/D_m(0)$ | $D_m(R)/D_e(R)$ |
|---|---|---|
| 0 | 1.00 | .095 |
| 200 | .65 | .31 |
| 500 | .25 | .81 |
| 1000 | .05 | — |

A comparison between Tables 1 and 4 shows that the meson shower is less dense than the electron shower at all distances from the axis of any significance, but that the meson density tends to exceed the electron density at distances greater than 500 metres. It is unlikely, however, that this excess of mesons at great distances will be noticeable, because the meson shower is virtually extinct at distances greater than 700 metres when $U = 10^{12}$ eV.

For higher values of $U$ the relative meson content will be negligible, because the electron photon cascade develops so rapidly with increasing energy, as seen from Table 2.

### Possible Comparison with Experiments

It seems clear that the air showers studied by Cocconi, Cocconi-Tongiorgi and Greisen (1949) and many others, with well defined cores and an electron distribution closely following Molière's theory, must be due to a single primary particle. It may, however, be worth considering whether the very wide showers observed by Cranshaw and Galbraith (1954) are evidence of fast grains, and if so, what is then the influence on the calculated magnetic rigidity.

Counter experiments give information about the total number of particles and their radial distribution.

For a grain containing $N$ nucleons, and of material with average atomic weight $A$, eqs. (1) and (4) show that the total energy is

$$NU = 300H\varrho\beta(N/A)^{2/3} \qquad (11)$$

From Table 2 we can find

$$N_e/N = G(U) \qquad (12)$$

Eliminating the number of primary nucleons from eqs. (11) and (12) we obtain for the magnetic rigidity

$$\log(H\varrho) = \frac{1}{3}\log N_e + \log[U/G(U)^{1/3}] - \log\beta + \frac{2}{3}\log A - 2.5 \qquad (13)$$

The first term in eq. (13) is observable. The second term is given in Table 2 and its value lies between 11.7 and 12.8. A more precise value may be obtained by comparing the observed electron distribution with Table 1 or Fig. 1, and estimate $U$. The third term $(-\log\beta)$ is not smaller than 0, and may possibly be as great as 1 or 2. The fourth term is about 0.7 or greater, corresponding to an average atomic weight not less than 10.

From these estimates we conclude that

$$\log(H\varrho) > \frac{1}{3}\log N_e + 11.7 + 0 + 0.7 - 2.5 = $$
$$= \frac{1}{3}\log N_e + 10 \qquad (14)$$

and is probably as much as two units greater.

Even if we accept the hypothesis of fast dust grains as primaries for the very wide showers, a shower containing $10^8$ electrons at sea level is therefore evidence for particles of magnetic rigidity not less than $10^{13}$ gauss cm, and possible as great as $10^{14}$ or $10^{15}$ gauss cm. It seems unlikely at present that such particles can have been accelerated inside the solar system.

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