Cosmic dust grains strike again

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Abstract

A detailed simulation of air showers produced by dust grains has been performed by means of the AIRES Monte Carlo code with the aim of comparing with experimental data. Our analysis indicates that extensive dust grain air showers must yet be regarded as highly speculative but they cannot be completely ruled out.

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It has long been known that small solid particles (or dust grains) may be accelerated effectively at strong collisionless shock waves – popularly in supernovae – \[1\]. In addition, it was suggested years later that, even upon destruction, a substantial fraction of the super-thermal debris (those created in the pre-shock region) might re-enter the shock waves to undergo additional acceleration \[2\]. These ideas have been recently strengthened by astronomical observations \[3\] and by the analysis of primitive meteorites \[4\].

Despite some still open questions concerning the timescale for grain destruction in the source environment and, later on, during the trip to Earth, from time to time dust grains have been considered as possible progenitors of giant air showers. The earliest significant contribution we are aware of is due to Herlofson \[5\]. He argued that relativistic dust grains could indeed produce extensive air showers, provided that in the first interaction each constituent nucleon contributes with an energy above $10^{14} \text{eV}$. The field then lay fallow for eighteen years until Hayakawa \[6\] tried to explain the exceptional event reported by Suga et al. \[7\]. Prompted by this proposal several plausible suggestions came out in the 1970s \[8\].

Unfortunately, the values of the depth of shower maximum registered by Haverah Park and Volcano Ranch experiments do not provide an exact picture of showers initiated by dust grains \[9\]. Nonetheless, in view of the low statistics at the end of the spectrum and the wide variety of uncertainties in these experiments, one may be excused for reserving the judgment. In order to increase the statistics significantly, the Southern Auger Observatory is currently under construction: A surface array (that will record the lateral and temporal distribution of shower particles) + an optical air fluorescence detector (which will observe the air shower development in the atmosphere) \[10\]. A major advantage of the optical device is precisely its capability of measuring the depth for the maximum shower development.

Whatever the source(s) of the highest energy cosmic rays, the end of the spectrum remains unexplained by a unique consistent model \[11\]. This may be due to the present lack of precision of our knowledge of these rare events, or perhaps, may imply that the origin and nature of ultrahigh energy cosmic rays have more than one explanation. If one assumes the latter hypothesis, relativistic specks of dust are likely to generate some of the events.
The above considerations have motivated us to re-examine the effects of giant dust grain air showers. Before proceeding to discuss in detail how these extensive showers evolve, it is useful to review some key characteristics of the mechanisms that could lead to the destruction of dust grains. Notice that the opacity of the interstellar medium will impose lower and upper limits on the value of the Lorentz factor $\gamma$ for the primaries impacting on the Earth atmosphere.

An early investigation by Berezinsky and Prilutsky indicates that the grains turn out to be unstable with respect to the development of a fracture [12]. On the one hand, subrelativistic dust grains disintegrate in collisions with heavy nuclei of the interstellar gas. On the other hand, electrical stress induced by the photoelectric effect in the light field of the Sun results in the mechanical disruption and subdivision of relativistic grains. Doubts have also been expressed about the prospects of surviving against heating arising from photoionization within the solar radiation field [13]. The evaporation of the surface atoms [14] and even the capture of electrons from the interstellar medium have been suggested as possible ways to reduce the accumulation of charges.

All in all, the path length up to the first break-up in favor of these figures, ($\log \gamma \approx 2$ and initial radii between 300 - 600 Å) turns out to be of a few parsecs [15], i.e., much less than the characteristic size of the Milky Way. This entails that only RX J0852.0-4622, the closest young supernova remnant to Earth (distance $\approx 200$ pc) [16], could be considered scarcely far away.

Let us now turn to the discussion of dust grain air showers (DGASs). Relativistic dust grains encountering the atmosphere will produce a composite nuclear cascade. Strictly speaking, each grain evaporates at an altitude of about 100 km and forms a shower of nuclei which in turn produces many small showers spreading over a radius of several tens of meters, whose superposition is observed as an extensive air shower. For $\gamma \gg 1$, the internal forces between the atoms will be negligible. What is more, the nucleons in each incident nucleus will interact almost independently. Consequently, a shower produced by a dust grain containing $n$ nucleons may be modelled by the collection of $n$ nucleon showers,
each with $1/n\text{th}$ of the grain energy. Thus, recalling that muon production in proton showers increases with energy as $E^{0.85}$ \cite{17}, the total number of muons produced by the superposition of $n$ individual nucleons showers is, $N_{\mu}^{DG} \propto n (E/n)^{0.85}$, or, comparing to proton showers, $N_{\mu}^{DG} = n^{0.15} N_{\mu}^p$. Of course, these estimates are approximations, but without cumbersome numerical calculation one could naively select the event recorded at the Yakutsk array (May 7, 1989) as the best giant DGAS candidate in the whole cosmic ray data sample \cite{18,19}.

In order to go a step further and test these qualitative considerations, we have performed several atmospheric cascade development simulations by means of the \textsc{aires} Monte Carlo code \cite{20}. Several sets of showers were generated, each one for different specks of metallic nature, i.e. with different Loretz factors. The sample was distributed in the energy range of $10^{18}$ eV up to $10^{20}$ eV and was equally spread in the interval of $0^\circ$ to $60^\circ$ zenith angle at the top of the atmosphere. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons and nuclei. The particles were injected at the top of the atmosphere (100 km.a.s.l), and the surface detector array was put beneath different atmospheric densities selected from the altitude of cosmic ray observatories (see Table I). \textsc{sibyll} routines \cite{21} were used to generate hadronic interactions above 200 GeV. Notice that while around 14 TeV c.m. energies the kinematics and particle production of minijets might need further attention, for DGASs the energy of the first interaction is reduced to levels where the algorithms of \textsc{sibyll} accurately match experimental data \cite{22}. Results of these simulations were processed with the help of \textsc{aires} analysis program. Secondary particles of different types and all charged particles in individual showers were sorted according to their distance $R$ from the shower axis.

In an attempt to examine our qualitative considerations we first restrict the attention to the highest event reported by the group at Yakutsk. Next, details of the most relevant observables of the showers are given from the analysis of both the particles at ground and those generated during the evolution of the cascade.

The Yakutsk experiment determines the shower energy by interpolating and/or extrap-
olating the measurements of $\rho_{600}$ (charged particle density at 600 m from the shower core), a single quantity which is known from the shower simulations to correlate well with the total energy for all primary particle types. In the case of the event detected on May 1989, the trigger of 50 ground-based scintillation detectors at 200 - 2000 m from the shower core allowed to estimate a reliable value of $\rho_{600} = 54 \text{ m}^{-2}$ and a declination axis given by $\cos \theta = 0.52$ [19]. Examining the lateral distribution of our simulation sample, we note that showers initiated by relativistic particles ($\log \gamma = 4 - 3.8$) of energies in the range 36 - 38 EeV and with orientation $\theta = 59^\circ$ are compatible with such a value of $\rho_{600}$ [23]. It is important to stress that the lower and upper energy bounds are compatible with the event of interest within $2 \sigma$; however, for these high Lorentz factors the interstellar medium is extremely opaque to dust grains (again the reader is referred to Ref. [15]). In Fig. 1 we show the lateral distributions of muons and charged particles. It is easily seen that the predicted fluxes at ground level are partially consistent with those detected at the giant array (see Fig. 2).

In what follows we shall discuss the main properties of DGASs. The atmospheric depth $X_{\text{max}}$ at which the shower reaches its maximum number of secondary particles is the standard observable to describe the speed of the shower development. In view of the superposition principle this quantity is practically independent of $n$, depending only upon $\gamma$. For this reason the altitude of the $X_{\text{max}}$ is generally used to find the most likely mass for each primary. The behavior of the $X_{\text{max}}$ with increasing $\gamma$ in vertical showers has been already discussed in detail elsewhere [9]. Here we shall extend Linsley’s analyses studying the dependence of the shower evolution with the incident angle. In the last panel of Fig. 3 we show the numerical results from $10^{19}$ eV cascades initiated by nucleons with $\log \gamma = 3$ and different primary zenith angles. It can be observed that, at the same total energy, an air shower induced by particles with an oblique incidence develops faster than a vertical shower. Since muons are typically leading particles in the cascade, the position of $X_{\text{max}}$ is also related to the relative portion of muons in the shower. To illustrate this last point, the resulting fluxes at ground level from the same events are shown in first two panels of Fig. 3. As
it is expected, the radial distribution of the shower particles of inclined primaries (mainly dominated by muons) is flatter than the distribution of a vertical shower. The opposite behavior points onto the supremacy of electrons and positrons near the core. The density of these charged particles, however, falls off rapidly with increasing core distance, dimming the electromagnetic cascade.

To analyse the sensitivity of ground arrays to the shower parameters, the radial variation of different groups of secondary particles (we have considered separately $\gamma, e^+e^-$, and $\mu^+\mu^-$) was studied at two observation levels. In Fig. 4 we show the last steps of the evolution of the lateral distribution along the longitudinal shower path. It can be seen that there is practically no change in the radial variation. Thus, we conclude that the flux of particles does not have intrinsic sensitivity to the observation altitude until 1400 m.

Coming back to the general features of the longitudinal development, the last exercise is to analyse the dependence of the atmospheric shower profile with $\gamma$. To this end we carry out numerical simulations of vertical showers induced by primaries with the same mass and different Lorentz factors, namely $\log \gamma = 2.5$ to 3.2. The results are shown in the last panel of Fig. 4. As expected, for the same primary mass the number of secondary particles increases with rising $\gamma$, but it is interesting to note that both cosmic ray cascades present similar shapes and peak around the same atmospheric depth, i.e., $X_{\text{max}} \sim 350 \pm 47 \text{ g/cm}^2$ (consistent with the analysis of [9]).

Putting all this together one can draw the following tentative conclusions:

(i) The Fly’s Eye collaboration has presented evidence indicating that typical extensive air showers above $\sim 1 \text{ EeV}$ develop at a rate which is consistent with a steep power law spectrum of heavy nuclei that is overtaken at higher energies by a flatter spectrum of protons [24]. The group of the Akeno Giant Air Shower Array has reported 7 events above $10^{20}$ eV until August 1998 [25]. In general, the muon component agrees with the expectation extrapolated from lower energies [20]. However, the highest energy event recorded at Yakutsk ($E = 1.1 \pm 0.4 \text{ eV}$) seems to be a rare exception. It can be readily noticed from Fig. 1 that the almost completely muonic nature of particles detected may be explained by a 36 - 38 EeV DGAS.
Besides, if this speculation is true the lack of obvious candidate sources at close distances leaves the origin of this event still as a mystery.

(ii) The dependence of the DGAS longitudinal profile on $\gamma$ in the studied range is rather weak. The shower disc becomes slightly flatter and thicker with decreasing primary energy and/or increasing zenith angle. This is mainly due to the rising content of muons among all charged particles in the inclined shower.

Dust is a very widespread component of diffuse matter in the Galaxy with apparently active participation in charge particle acceleration. If such acceleration is possible, dust grains may play an important role in determining the composition of galactic cosmic rays. The question of whether the opacity of the interstellar medium could prevent relativistic dust grains from reaching the Earth is as yet undecided. Observation of giant DGASs would give an experimental and definitive answer to this question. We recommend that Auger search data be analysed for evidence of DGASs.

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### TABLE I. Sites of giant air shower arrays

| Experiment     | longitude      | latitude       | altitude   |
|----------------|----------------|----------------|------------|
| Volcano Ranch  | 35°09'N        | 106°47'W       | 834 g/cm²  |
| SUGAR          | 30°32'S        | 149°43'E       | 1020 g/cm² |
| Haverah Park   | 53°58'N        | 1°38'W         | 1020 g/cm² |
| Yakutsk        | 61°42'N        | 129°24'E       | 1020 g/cm² |
| Fly’s Eye      | 40°N           | 113°W          | 860 g/cm²  |
| AGASA          | 38°47'N        | 138°30'E       | 920 g/cm²  |
| Auger          | 35°12'S        | 69°12'W        | 875 g/cm²  |
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FIG. 1. From left to right, (a) Lateral distributions of charged particles and muons from AIRES simulations of a 36 EeV, $\log \gamma = 4$ DGAS. The error bars indicate the RMS fluctuation of the means. (b) Id. with $E = 38$ EeV and $\log \gamma = 3.8$. 
FIG. 2. Density of muons recorded at Yakutsk by ground and underground detectors on May 7, 1989 at 13 h 23 min Greenwich time. There is a remarkable contradiction with an extrapolation from results of the low energy region (dashed line). This figure was originally published in Ref. [18].
FIG. 3. From left to right: (a) Lateral distribution of charged particles of DGASs of 10 EeV. The primaries with log $\gamma = 3$ were injected vertically and with 60 degree zenith angle. The figure also shows the fluctuations measured in terms of RMS. (b) Idem for the case of muons. (c) Longitudinal evolution of the shower profiles. The error bars indicate the standard fluctuations.
FIG. 4. Lateral distributions of electrons, muons and gammas (at ground level) from AIRES simulations of $10^{18}$ eV vertical showers ($\gamma = 300$). The figure also shows the longitudinal cascade development profile of $10^{18} - 10^{19}$ eV showers as would be seen by the Auger fluorescence detector. The logarithm of the Lorentz factors are 2.5 and 3.2 respectively. The error bars indicate the standard fluctuations (the RMS fluctuations of the means are always smaller than the symbols).