Extensive air showers rounded up by AIRES + SIBYLL/QGSJET

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Abstract

An analysis of the differences introduced by the hadronic interaction event generators during the development of the showers is presented. We have generated proton and nuclei induced air showers with energies up to $10^{20.5}$ eV, "herded up" by the code AIRES + SIBYLL/QGSJET. The most relevant observables are taken into account for the comparison.

It is well known that extensive air shower (EAS) event generators rely strongly on hadronic interaction models. Mainly, because the first generation processes have c.m. energies greatly exceeding those attained at man-made accelerators, and thus, theoretical guidelines need to be used to describe particle production. There are two codes with algorithms tailored for efficient operation to the highest cosmic ray energies. One of them was christened SIBYLL by Fletcher et al. (1994). Its details of nucleus-nucleus interaction were previously discussed by Engel et al. (1991, 1992). The other, QGSJET, was performed by Kaidalov (1982), Kaidalov & Ter-Martirosyan (1982, 1984) and Kalmykov, Ostapchenko & Pavlov (1997). See also, (Kaidalov, Ter-Martirosyan & Shabel'skii, 1986) for details of hadron-nucleus interaction, and (Kalmykov & Ostapchenko, 1993) for those of nucleus-nucleus interaction.

Recently, we have examined the sensitivity of free parameters of these programs (which have been derived from available collider data) when the algorithms are extrapolated several orders of magnitude (Anchordoqui et al., 1999); hereafter it will be referred as paper I. In particular, we have analyzed differences in the distribution of depths of shower maximum, and the evolution of lateral and energy distributions of showers induced by protons of $10^{20.5}$ eV. In this contribution we shall extend this analysis with results obtained from EAS initiated by heavy nuclei.

The nucleus-nucleus interaction is usually described using the wounded nucleon picture in a Glauber multiple scattering framework (see,e.g., Bialas, Bleszynski & Czyz, 1976; Pajares & Ramallo, 1985). We shall adopt here the so-called "semisuperposition" model which retains the original idea that a shower induced by a nucleus may be modeled by the superposition of A nucleon showers, but uses a realistic distribution of the positions of their first interaction. To put into evidence as much as possible the differences between the intrinsic mechanism of SIBYLL and QGSJET we have always used the same code to simulate the fragmentation of the projectile, namely, the Hillas Fragmentation algorithm (Hillas, 1979, updated in 1981). Differences introduced by primary fragmentation codes will be discussed elsewhere (work in progress).

Giant air showers induced by protons and nuclei with energies up to $10^{20.5}$ eV were generated with the code AIRES (Sciutto, 1999), a realistic air shower simulation system which includes electromagnetic interactions algorithms and links to the mentioned SIBYLL and QGSJET programs. Most of the electromagnetic algorithms are based on the well known MOCCA simulation program by Hillas (1997).

As in the paper I, in all the cases we have used the AIRES cross section, and all shower particles with energies above the following thresholds were tracked: 500 keV for gammas, 700 keV for electrons and positrons, 1 MeV for muons, 1.5 MeV for mesons and 80 MeV for nucleons and nuclei. The particles were injected at the top of the atmosphere (100 km.a.s.l) and the ground level was located at sea level. All hadronic collisions with projectile energies below 200 GeV are processed with the Hillas Splitting algorithm (Hillas, 1979, 1981), and the external collision package is invoked for all those collisions with energies above the mentioned threshold.

Although ^{56}Fe is certainly the best candidate for bottom up acceleration mechanisms, at extremely high energies (around 200 EeV) the cosmic background radiation makes the universe opaque to the propagation of

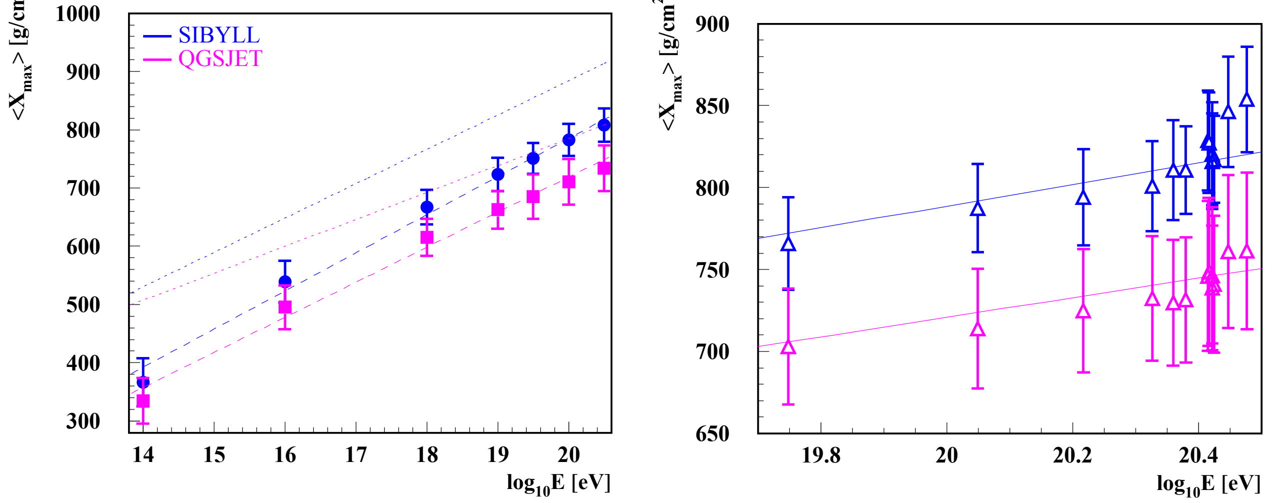

Figure 1: Average slant depth of maximum. Left hand side (a) – iron nuclei, right hand side (b) – heavy nuclei. (See the text).

iron nuclei, yielding severe constraints on the distance to the sources, as well as on the primary chemical composition. Based on our previous analysis (Anchordoqui et al., 1998) we have evaluated the photodisintegration of iron nuclei ($E \geq 5 \times 10^{19}$ eV) after a propagation distance of 3 Mpc. The results, listed in Table I, were be taken into account when computing the shower maximum energy dependence.

In Fig. 1a we present the simulation results for the average slant depth of maximum, $< X_{\rm max} >$, for iron nuclei induced showers. The error bars indicate the standard fluctuations (the rms fluctuations of the means are always smaller than the symbols). It is evident that AIRES+SIBYLL showers present higher values for the depth of maximum, the differences increasing with rising energy. This is consistent with the fact that in the first interaction SIBYLL produces less secondaries than QGSJET, yielding a delay in the electromagnetic shower development which is strongly correlated with decays of neutral pions. Besides, as it is expected, at the same total energy an air shower from a heavy nucleus develops faster than a shower initiated by a proton (the reader is referred to Fig. 7 of paper I). We have also computed estimations for the elongation rate, $d < X_{\rm max} > /d \log_{10} E$, by means of linear fits to the data presented in Fig. 1a. The slopes of the fitted lines are 65.47 g/cm^2 per decade and 60.23 per decade for AIRES+SIBYLL and AIRES+QGSJET respectively. Additionally, the dotted lines stand for the fits to $< X_{\rm max} >$ for proton induced showers. In this case the slopes are: 58.98 g/cm^2 for AIRES+SIBYLL and 46.28 g/cm^2 for AIRES+QGSJET. Around 10^{20} eV the primary chemical composition remains hidden by the hadronic interaction model. Notice that at such a huge energy, proton showers simulated with AIRES+QGSJET yield similar $< X_{\rm max} >$ that the corresponding simulation of iron showers with AIRES+SIBYLL. Figure 1b, shows the results obtained after simulating heavy nuclei (those listed in table I) showers, together with the fits for the elongation rate of ^{56}Fe induced showers. In this "quite realistic" scenario, the determination of the chemical composition is even more dramatic.

In Fig. 2 we repeat the comparisons already performed in paper I. The behavior of the evolution of electron-positron (first row of Fig. 2), muon, and gamma lateral distributions, do not show essential differences with respect to our previous analysis in paper I. As in the case of protons, despite the fact that the high altitude lateral distributions vary considerably with the hadronic interaction model, the differences seems to "thermalize" as long as the shower front gets closer to the ground level. The second row stands for the different particles energy distributions at sea level. Except for slight divergences in the muon case, again, the differences in energy distributions at sea level do not correspond with deviations at higher levels.

Putting all together, we found that the differences between AIRES+SIBYLL and AIRES +QGSJET at the

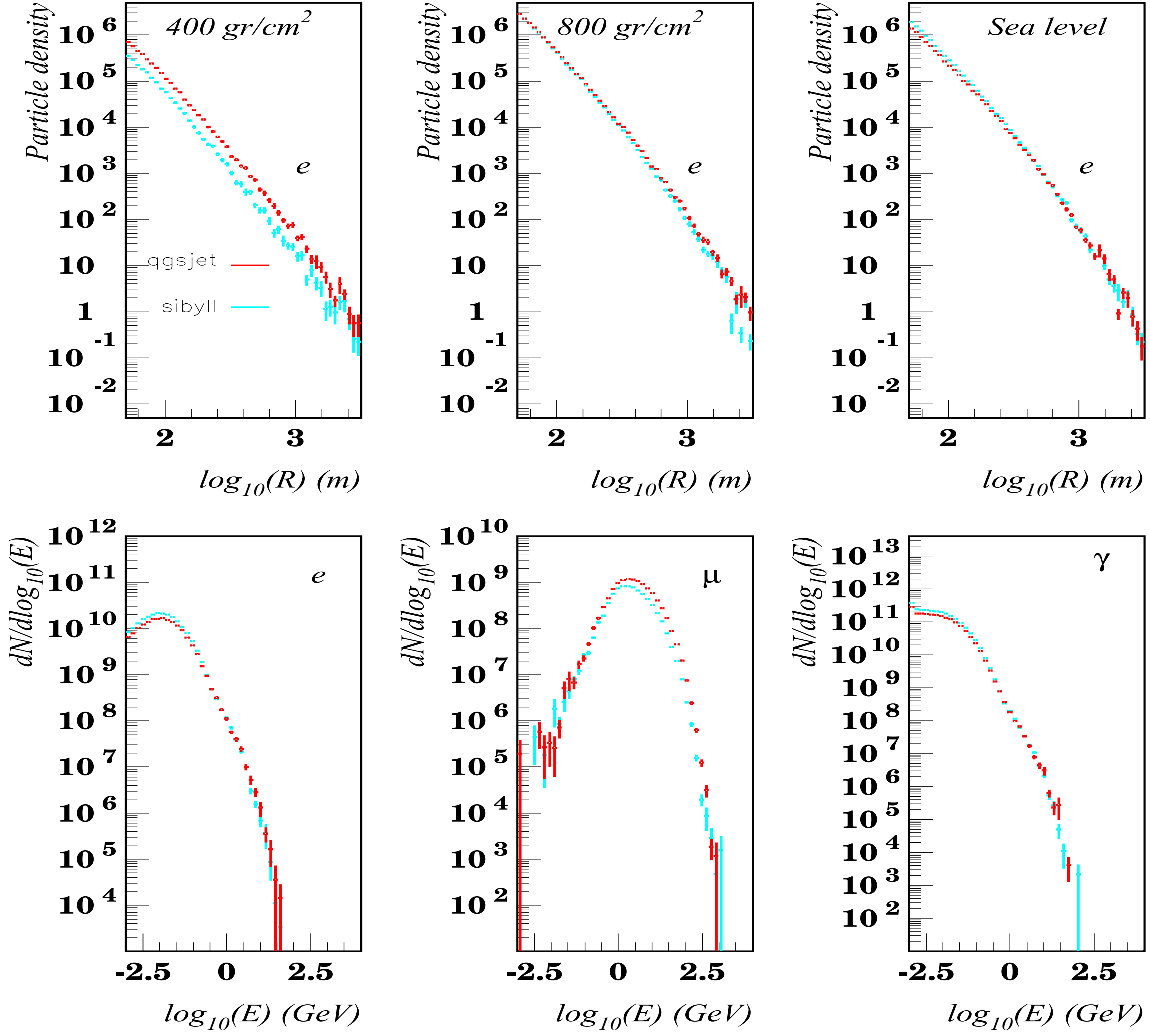

Figure 2: Main features of iron nuclei shower development

surface, cannot make realize the original differences present in the first generation of particles.

We turn now to the comparison of the recorded data between different primary nuclei. In Fig. 3 it is shown the muon lateral distributions for ^{12}C and ^{56}Fe (again black stands for QGSJET and grey for SIBYLL). Notice that there are no significant differences between the lateral distributions at sea level when changing the chemical composition. Nonetheless, the different predictions in the ground muon lateral distribution, induced by the hadronic interaction models are still present. Specifically, at 1000 m from the shower core the ratio between the number of muons produced by AIRES + SIBYLL/QGSJET is 0.60 in a ^{56}Fe induced shower and 0.62 in the case of ^{12}C. Concerning the number of electrons and positrons (at the same distance from the core), the ratio between AIRES+SIBYLL and AIRES+QGSJET predictions is 1.01 for iron nuclei, and 1.16 for carbon. Thus, comparing these results with the ones obtained in paper I we observe that the differences between the models diminish. This could be easily understood if we recall that the differences in single collision between the models increase with rising energy (see Sec. II of paper I). Now it is straightforward that the heavier the nuclei the lower the energy per nucleon in the first generation of particles.

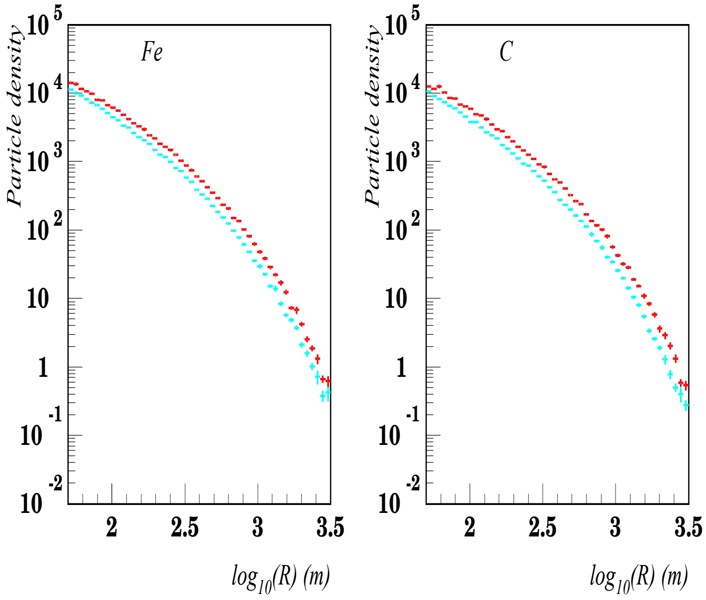

Figure 3: Muon lateral distributions at sea level

TABLE I. Photodisintegration of iron nucleus

Lorentz factor	Chemical composition	E [EeV]
1×10^9	^{56}Fe	56
2×10^9	^{56}Fe	112
3×10^9	^{55}Mn	165
4×10^9	^{53}Cr	212
4.5×10^9	^{51}V	229
5×10^9	^{48}Ti	240
6×10^9	^{44}Ca	264
7×10^9	^{38}Ar	266
8×10^9	^{33}S	264
9×10^9	^{29}Si	261
1×10^{10}	^{26}Mg	260
2×10^{10}	^{14}N	280
2.5×10^{10}	^{12}C	300

References

Anchordoqui L.A. et al., 1998, Phys. Rev. D57, 7103
Anchordoqui L.A. et al., 1999, Phys. Rev. D59, 094003
Bialas A., Bleszynski M. & Czyz W., 1976, Nucl. Phys. B111, 461
Engel J. et al., 1991, *Proc. of the 22nd International Cosmic Ray Conference*, Dublin, Ireland, Vol.4,p.1
Engel J. et al., 1992, Phys. Rev. D46, 5013
Fletcher R.S. et al., 1994, Phys. Rev. D 50, 5710
Hillas A.M., 1979, *Proc. of the 16th International Cosmic Ray Conference*, Tokyo, Japan, Vol.8,p.7
Hillas A.M., 1981, *Proc. of the 17th International Cosmic Ray Conference*, Paris, France, Vol.8,p.183
Hillas A.M., 1997, Nucl. Phys. B (Proc. Suppl.) 52, 29
Kaidalov A.B., 1982, Phys. Lett B116, 459
Kaidalov A.B. & Ter-Martirosyan K.A., 1982, Phys. Lett. B117, 247
Kaidalov A.B. & Ter-Martirosyan K.A., 1984, Yad. Fiz. 39, 1545 [Sov. J. Nucl. Phys. 39, 979]
Kaidalov A.B., Ter-Martirosyan K.A & Shabel'skii Y.M., 1986, Yad. Fiz. 43, 1282 [Sov. J. Nucl. Phys. 43, 822]
Kalmykov N.N., Ostapchenko S.S. & Pavlov A.I., 1997, Nucl. Phys. B (Proc. Supp.) B52, 17
Kalmykov N.N. & Ostapchenko S.S., 1993, Yad. Fiz. 56, 105 [Phys. At. Nucl. **56**, 346]
Pajares C. & Ramallo A.V., 1985, Phys. Rev. D31, 2800
Sciutto S.J., 1999, AIRES: *A System for Air Shower Simulations*, Auger technical note GAP-99-020

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