Redundant failures of the dip model of the extragalactic cosmic radiation

Antonio Codino

aINFN and Dipartimento di Fisica dell’Università di Perugia, Italy.

The proton flux and the chemical composition of the cosmic radiation measured, respectively, by the Kascade and Auger experiments entail radical changes in Cosmic Ray Physics. A large discrepancy emerges by comparing the proton flux predicted by the dip model and that measured by Kascade in the critical energy interval $5 \times 10^{16}$  
$10^{17}$ eV. It is mentioned and substantiated that the proton flux measurements of the Kascade experiment are consistent with other pertinent empirical observations. It is shown that the chemical composition measured by Auger by two independent procedures, using the mean depth reached by cosmic nuclei in giant air cascades, is incompatible with that predicted by the dip model.

A notable consequence suggested here based on the failures of the dip model is that the spectral index softening of the primary cosmic radiation above $6 \times 10^{19}$ eV observed by HiRes and Auger experiments, is not due to the extragalactic cosmological protons suffering energy losses in the intergalactic space via the reactions,

$$ p \gamma \rightarrow \pi^0 p,$$

$$ \pi^+ n, $$

but to some physical phenomena occurring in the cosmic vicinity.

1. Introduction

An abrupt progress has been recently occurred in Cosmic Ray Physics, which in many respects is a revolutionary change of the current notions of the discipline, due to some measurements of the Auger and Kascade Collaborations.

The Auger experiment has determined the chemical composition of the cosmic radiation by measuring the mean depth reached by cosmic nuclei in giant terrestrial cascades in air [1,2] or the equivalent variable, $X_{\text{max}}$. By two independent methods it has been established that in the energy interval $4 \times 10^{17}$-$5 \times 10^{19}$ eV the cosmic radiation attaining the solar cavity consists predominantly of intermediate nuclei, and not of pure protons.

Figure 1 reports the $X_{\text{max}}$ versus energy measured by the Auger experiment (red dots) [1].

The Auger apparatus determines $X_{\text{max}}$ by fluorescent light released by nuclei penetrating the air. The longitudinal light profile recorded by the instrument is interpolated by an appropriate function, $f_{LP}$, which has a characteristic width denoted $\sigma(X_{\text{max}})$. The measurement of $\sigma(X_{\text{max}})$ at a given energy for a number of atmospheric cascades determines the average value of the chemical composition of the cosmic radiation, which is a second method, besides $X_{\text{max}}$. Figure 2 shows $\sigma(X_{\text{max}})$ versus energy (black dots) measured by Auger [2] along with its theoretical estimates of $\sigma(X_{\text{max}})$ for iron nuclei (turquoise lower band) and for protons (turquoise upper band).

In a series of measurements the Kascade experiment has determined that the proton flux in the energy interval $5 \times 10^{16}$-$10^{17}$ eV is $(1-2) \times 10^{15}$ particles/(m$^2$ sr s eV$^{-1}$) [3]. The proton flux has been measured by two methods hereafter referred to as QGSjet and Sibyll algorithms. Figure 3 reports the proton energy spectrum measured by Kascade using the QGSjet algorithm [3]. Data from the Sibyll algorithm [4] are equivalent for the purpose of this study and omitted for brevity.

It is the aim of this Letter to show that the three independent quoted measurements are incompatible with the corresponding predictions of the dip model [5].

This Letter benefits of a critical examination of the HiRes data on $X_{\text{max}}$ made in another study [7]. Figure 4 shows that above $10^{17}$ eV the HiRes data [8] on $X_{\text{max}}$ converted into $<\ln(A)>$ differ systematically from those of the Volcano Ranch, Yakutsk, Akeno, Agasa, Haverah Park, Fly’s Eye and Auger experiment [7]. Figure 5 shows that the $\sigma(X_{\text{max}})$ profile measured by HiRes [9] also differs from that measured by Auger [2].
2. Measurements of $X_{\text{max}}$ and $\sigma(X_{\text{max}})$ and related predictions of the dip model.

The dip model proposed in 1988 states that extragalactic protons originated at cosmological distances can reach copiously the solar cavity. They interact with cosmic fossil photons $\gamma$ with energies centered around $6 \times 10^{-4}$ eV and density of 420 particles/cm$^3$, via the reaction: $p \gamma \rightarrow e^- e^+ p$, where $p$ denotes extragalactic proton and $e^-, e^+$ electron pairs. The kinematical threshold of this reaction is at $4 \times 10^{17}$ eV, a basilar reference energy of the dip model. Extragalactic protons would suffer energy losses in the intergalactic space via the quoted reaction generating a depression in the original unperturbed spectrum released by the extragalactic accelerator which has constant proton index $\gamma_s$ in the range 2.0-2.7.

The dip model does not specify a precise acceleration mechanism, the exact sites where the accelerators operate, the spectral indices of the cosmic ions at the cosmic-ray sources (they are free parameters condensed in a single one $\gamma_s$), the ion filtering at the injection to the accelerators at the low energy and other parameters. It preassumes that in the intergalactic proton displacement, besides the expansion of the universe, no major processes other than the reaction, $p \gamma \rightarrow e^- e^+ p$, intervene. While most of the unknowns of the dip model enumerated above are not surprising in the present status of the discipline, the intergalactic proton displacement affected only by the reaction, $p \gamma \rightarrow e^- e^+ p$ (for instance, de-acceleration or re-acceleration processes with uneven magnitudes may take place) and a constant instead of a variable $\gamma_s$ are rather fragile hypotheses.

The chemical composition of the dip model has been calculated and converted by others [10] into the corresponding $X_{\text{max}}^{th}$ versus energy using three different hadronic codes denoted QGSjet, QGSjet-2 and Sibyll [10]. The minimum and the maximum values of the $X_{\text{max}}^{th}$ of the dip model at a given energy are shown in figure 1 defining the lower and upper theoretical values of $X_{\text{max}}$ of the dip model at a given energy correspond to different theoretical models of hadronic interactions in air.

Figure 1. Measurements of $X_{\text{max}}$ by Auger (red dots) compared with the corresponding $X_{\text{max}}$ derived from the dip model (turquoise band). The lower and upper theoretical values of $X_{\text{max}}$ of the dip model at a given energy correspond to different theoretical models of hadronic interactions in air.

Figure 2. Measurements of $\sigma(X_{\text{max}})$ by Auger (black dots) and the related theoretical estimates [2] for a cosmic radiation consisting of protons only (upper colored band) and Fe nuclei only (lower colored band).
Figure 3. Extragalactic proton flux at $10^{18}$ eV according to the dip model [10] (black square) with the standard index $\gamma_s=2$ and its extrapolation (black curve) down to $10^{17}$ eV calculated in this study. The proton spectrum of the same model with $\gamma_s=2.7$ (blue curve) normalized ad hoc to some experimental data [3], and that predicted by the Theory of Constant Spectral Index (red curve) are also displayed for comparison [11].

Taking into account the dependence of $\sigma(X^A_{max})$ on the mass $A$ of the cosmic nucleus [2], any ion abundances at a given energy can be converted into $\sigma(X_{max})$. It results that the Auger data in Figure 2 above $10^{19}$ eV exclude a proton dominance in the cosmic radiation as foreseen by the dip model (some 80-90% as stated in ref. [10]).

3. Proton flux measurements in Kascade and the related dip model predictions

The proton flux at $10^{18}$ eV derived from the dip model in its standard form and normalization with $\gamma_s=2.0$ [10] is $1.58 \times 10^{14}$ particles/(m$^2$ s eV$^{1.5}$) (black square in fig. 3). It results that the discrepancy between measured and theoretical flux (black square and extrapolated black
σ(X_{\text{max}}) \text{ g/cm}^2

Energy (eV)

Hires (2009)

QGSjet1 QGSjet2

proton Iron Auger Hires

Figure 5. Measurements of σ(X_{\text{max}}) of the Auger [2] and HiRes experiments [9] compared with the corresponding Monte Carlo simulations of nuclear interactions, by the QGSjet-01 and QGSjet-02 codes, assuming that all cosmic rays are protons (upper blue curves) or Fe nuclei (lower red curves) according to HiRes [9].

4. Data and cascade simulation codes in HiRes

Figure 5 shows the estimated theoretical profiles of σ(X^{H}_{\text{max}}) and σ(X^{Fe}_{\text{max}}) according to the HiRes experiment which adopts the hadronic codes QGSjet-1 and QGSjet-2 [9]. The first seven data points from Auger (black dots) in the interval 10^{18}-5 \times 10^{18} \text{ eV} would fall above the theoretical σ(X^{H}_{\text{max}}) profile obtained by the QGSjet-2 code. Therefore, eight Auger data points out of 13 would become unphysical (e.g. cosmic particles lighter than protons). Similarly, the last data point (Auger) is positioned below the theoretical profile σ(X^{Fe}_{\text{max}}) suggesting that hyperheavy cosmic nuclei (A > 56) dominate the cosmic radiation above 3 \times 10^{19} \text{ eV}, or more plausibly, again, an unphysical condition develops. It may not be surprising that, in two independent areas of comparison (on X_{\text{max}} and σ(X_{\text{max}})), the outcomes of the HiRes Collaboration might disagree with all other experiments. What is both surprising and embarrassing is that the hadronic codes to simulate nuclear interactions in air, in HiRes, over many years, generate more protons and less heavy nuclei than hadronic codes adopted in all other experiments. Figure 5 vividly demonstrates it in a recent example [9].

5. Conclusions

The fundamental tenet of the dip model is that protons observed in the solar cavity above 4 \times 10^{17} \text{ eV} have a cosmological origin and outnumber any other ion fractions. Since the dip model predicts unreal properties of the cosmic radiation, the Logic dictates, out of a few alternatives, that spatial sources of the cosmic-ray protons are in the cosmic vicinity (Galaxy or Local Group or Local Supercluster of Galaxies). In this circumstance: how could a softening of the spectral index from 2.6 to about 3.5 take place in the interval 5 \times 10^{19}-3 \times 10^{20} \text{ eV}, if the extragalactic cosmological protons below 5 \times 10^{19} \text{ eV} do not reach the solar cavity?

As the reaction p \gamma \rightarrow e^- e^+ p does not alter any cosmic-ray spectrum in the solar cavity (first alternative), the companion reactions p \gamma \rightarrow \pi^0
The ad hoc hypothesis that a cosmological extragalactic component would reach the solar cavity in the interval $6 \times 10^{19} - 3 \times 10^{20}$ eV but not below this energy band (second alternative) confront with three barriers: (1) protons suffering the energy losses via $p \gamma \rightarrow \pi^0 p$ do not disappear but they accumulate below $6 \times 10^{19}$ eV corrugating the spectrum; the dip model, as an example, attempts to calculate this effect with a simplified calculation scheme. (2) Any extragalactic accelerators, operating in the specific interval $6 \times 10^{19} - 3 \times 10^{20}$, and eventually above this maximum energy, would intrinsically generate enough spill-over particles in the low energy edge, below $6 \times 10^{19}$, which plausibly corrugate the galactic spectrum. (3) The rising dominance of heavy ions with energy discovered by the Auger Collaboration (see figures 1 and 2) in the band $10^{19} - 4.12 \times 10^{19}$ eV does not harmonize, for a number of reasons, with the aforementioned index softening.

The common value of 2.6-2.8 of the spectral index of the cosmic radiation close and below $6 \times 10^{19}$ eV observed in all experiments (HiRes, Auger, Agasa, Yakutsk), disfavors and belittles the second alternative.

According to the present investigation, the softening of the spectral index of the cosmic radiation above $6 \times 10^{19}$ eV is not due to any extragalactic cosmological protons. This conclusion might represent the most notable result rooted to the reaction $p \gamma \rightarrow e^- e^+ p$ as conceived and framed in the dip model.

REFERENCES

1. M. Unger et al., (Auger Coll.) 30th ICRC Merida Mexico 594; also astro-ph/0706.1495 (2007).
2. M. Unger et al., (Auger Coll.) Study of the Cosmic Ray Composition with the Pierre Auger Observatory, (Auger Coll.) Conf. SOCoR 15-18 June 2009, Trondheim, Norway.
3. R. Engel et al., (Kascade Coll.) astro-ph/0504358 (2005).
4. K. H. Kampert et al., (Kascade Coll.) astro-ph/0405608 (2004).
5. V.S. Berezinsky and S.I. Grigorieva, Astron. and Astrophys, 199 (1988) 1.
6. V.S. Berezinsky, A. Z. Gazizov and S.I. Grigorieva, Phys. Letters B 612 (2005) 147.
7. A. Codino and F. Plouin, Chemical composition of the cosmic radiation around the ankle and the related spectral indices, to appear this week on astro-ph.
8. J. W. Belz, (HiRes Coll.) CRIS 2008, Nucl. Phys. B (Proc. Sup.) 165 (2009) 5-11.
9. P. Sokolsky, (HiRes Coll.) Final HiRes Results and Telescope Array Experiment, Conf. SOCoR 15-18 June 2009, Trondheim, Norway.
10. R. Aloisio et al., Astro-ph/0706.2834v2, 19th November 2007.
11. A. Codino, Flussi misurati di protoni ed elio e l’origine del ginocchio nello spettro della radiazione cosmica, INFN Report/TC-09/06, (2009) Lab. Naz. di Frascati dell’ INFN, Frascati, Italy.