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ON THE ORIGIN AND COMPOSITION OF ULTRAHIGH ENERGY COSMIC RAYS

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In recent years, there has been much discussion of the problem of the origin of ultrahigh energy cosmic-rays which has centered around three characteristics of their energy spectrum: (1) an apparent steepening of the power-law integral spectrum, $E^{-\gamma}$ from $\gamma \simeq 1.7$ to $\gamma \simeq 2.2$ at an energy of $\sim 10^{15}$eV. (2) an apparent flattening of the spectrum at an energy above 3×10^{18} eV where $\gamma \simeq 1.6$ (3) the apparent absence of a cutoff in the energy spectrum of air-shower events at energies above 10^{19} eV. Recently, the validity of characteristic (2) has been questioned and a new analysis of both the Haverah Park and Volcano Ranch air-shower data has indicated that $\gamma \simeq 2.2$ for energies above 10^{17} eV [1,2]. We wish to suggest here that if such is the case, the absence of a flattening above 3×10^{18} eV may have implications on the debate concerning the origin of ultrahigh energy cosmic-rays (UECR).

The models suggested for the origin of cosmic-rays at ultrahigh energies will be designated here for the purpose of discussion as I (galactic), II (extragalactic, low redshift) and III (extragalactic, high redshift) and the models suggested for composition will be designated P (proton), H (heavy) and N (neutrino).

Model II suggests itself because of the apparent isotropy of UECR's,[3,4] because of the containment problem arising in galactic models and because, until the recent discovery of pulsars,[5] it seemed impossible to accelerate cosmic-rays to ultrahigh energies in galactic objects.

Model III obviously shares these advantages over galactic models with model II. In addition, it has been suggested by Hillas[6] that characteristics (1) and (2) could be explained by model III. This possibility was also explored by Blumenthal[7].

For all their advantages, models II and III appeared to present a problem not encountered with galactic models, a problem which was recognized by Greisen[8] and independently by Zatsepin and Kuz'min[9] and which was explored in further detail by various workers[10-13]. They pointed out that if the 2.7 K blackbody background radiation is a universal relict from the originial "big-bang" and pervades all of metagalactic space, then the UECR spectrum should suffer a cutoff at an energy of the order of 6×10^{19} eV due to photomeson production interactions between the UECR's and the blackbody photons. A large flux of far-infrared photons[13,14] existing in intergalactic space would greatly aggravate the problem and result in a cutoff at an energy between 10^{18} and 10^{19} eV[15]. The problem is, of course, much more severe at higher redshifts and becomes quite drastic for model III.

At this point, it becomes necessary to go into further detail by designating our models as I-P, II-H, III-N, etc., according to the notation defined above As has been shown previously[16], model II-H avoids the photomeson production cutoff but pair production interactions will cut off an iron spectrum at $\sim 6 \times 10^{19}$eV. Model III-N, which has been suggested by Beresinskii and Zatsepin also avoids the cutoff problem[17]. There is, however, another problem encountered by the form of Model III suggested in references 6,7 and 17. The problem arises in the production of too high a flux of gamma-rays originating at high redshifts to be compatible with the upper limits on the background gamma-ray flux determinded by various workers[18-20]. For example, if we take the revised upper limit on gamma-rays above 100 MeV reported by Clark, et al.[20] of 3×10^{-5} photons/cm^{2}sec·sr, and the parameters for model III of a maximum production redshift of $z_{max} \gtrsim 15$ and an evolutionary production model with source intensity $(1 + z)^m$ and $m \gtrsim 3$ as needed to explain the form of the UECR spectrum[6,7], then according to the calculations which we discussed previously relating to the gamma-ray production spectrum at high redshifts[21], the upper limit on the ratio of the extragalactic to galactic cosmic-ray intensity in the 1-10 GeV region is 6×10^{-4} if the present mean density of extragalactic gas is $\gtrsim 10^{-7}$ atoms per cm^3. If we assume extragalactic cosmic-rays to have a spectral index γ=1.5 for all energies up to 10^{15} eV and we assume that the galactic spectrum falls more steeply with an index γ=1.7 between 10^{10} and 10^{15} eV, we still find that at 10^{15} eV, the ratio of extragalactic to galactic cosmic-ray intensity should be $\lesssim 6 \times 10^{-3}$ and it therefore hardly seems likely that model III could explain the steepening of the cosmic-ray spectrum at 10^{15} eV.

We list below a table giving the various models, the characteristics explained by them((1), (2) or (3)) and whether they are compatible with the gamma-ray observations (column designated γ). Entries in the table marked (+) indicates that the characteristic is explained by the model; an 0 indicates that the characteristic is not a direct consequence of the model but does not contradict it either, and a (-) indicates that the characteristic is in direct contradiction to the model.

	(1)	(3)	(γ)	(2)
I-P&H	+	+	+	-
II-P	0	-	+	+
II-H	0	-	+	+
III-P&H	+	-	-	+
III-N	+	+	-	+

TABLE 1 - Characteristics explained by various models

As is noted in the table, model I accounts for the steepening of the cosmic-ray spectrum as due to a slow transition from protons plus heavies to pure heavies which the galaxy can contain up to higher energies. Model III explains this steepening as due to pair production from interactions with the blackbody photons. The absence of a cutoff is directly contradictory to models II-P and II-H and III-P&H ; the neutrino events of model III-N are not cut off by photomeson interactions. If we eliminate the reflattening characteristic from the table as unreal according to references 1 and 2, we are left with the galactic model (I-P&H) as the only presently satisfactory model for the origin of UECR's. The isotropy problem presented by the galactic model has recently been examined in detailed calculations by Karakula, et al[22]. They find that a galactic origin model is not ruled out by the present data provided the UECR's are heavies (Z>20). Thus, iron (Z=26) would seem the most likely candidate. Fluctuation studies of extensive air showers by Linsley[23] originally seemed to indicate that UECR's are pure protons, but a more recent study by Orford and Turner [24] has suggested that the mean mass of the primaries increases with primary energy (in accord with the galactic model) and has a value of $A \sim 20$ for $E \sim 2 \times 10^{17}$ eV, consistent with the heavy models discussed here. It may perhaps best be said at this point that the experimental situation is in doubt as to the composition of UECR's. However, it would seem, on the basis of the discussion presented here, that a heavy composition is indicated. We thus conclude that recent air-shower studies seem to indicate the resurrection of the galactic origin model. Should this model fail in future studies of isotropy, it would seem that either the energy of air-showers in the $\gtrsim 6 \times 10^{19}$ eV range has been overistimated, or a universal microwave blackbody radiation field cannot exist. (It should, however, be kept in mind that protons of energy $\sim 10^{20}$ eV can still reach us from ~ 300 Mpc without attenuation[12]).

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