UPPER LIMIT TO PARTICLE AND PHOTON ENERGIES IN PRE-GALACTIC PROCESSES

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Abstract

Pregalactic processes involving events like explosions or collapse of supermassive population III objects, as well as other violent events like fragmentation of primordial objects, would be expected to produce extremely energetic particles and photons. However, the cosmic background blackbody radiation at these earlier epochs with $z \sim 100$ or more, would have consisted of ambient photons of corresponding greater energy as compared to the present 3°k microwave background of photons (γ). As is known the presence of this radiation background, yields a threshold energy for nucleons (N) and photons to undergo particle interactions producing pions (π) (such as $\gamma + N \rightarrow N + \pi$, etc.), the threshold being $\sim 3 \times 10^{20}$ eV for protons (at the present epoch) thus suggesting a cutoff in the cosmic ray spectrum at this energy. Similarly, different threshold energies would exist at earlier epochs for the cutoff energies of photons and particles. The cutoff particle energies at these epochs would now be a function of the red shift z. The manner, in which the cutoff cosmic ray energy behaves with epochs, is studied and limits are put for a background of such particles.

1. Introduction. Fluctuations in the microwave background at intermediate scales due to initial density perturbations have not been detected creating difficulties for the usual models for the development of large scale structure in the expanding universe. On the contrary, there is much recent evidence /1/ that large scale perturbations in velocity and density do exist and presence of bubble like large scale structures are indicated interspersed with voids. An alternative viewpoint to the conventional theory where large scale structure grows from initial perturbations (for which evidence is meagre), has been proposed /2/, wherein gigantic cosmic explosions, i.e., seed explosions with energy of order $\sim 10^{61}$ ergs originating in young galaxy star burst events, supernovae explosions of supermassive Pop.III primordial stars forming at $z \approx 100$, quasar progenitor events, etc. can produce isolated bubbles with radii ~ 5 Mpc. With energy release $\sim 10^{62}$ ergs per event, these blast waves propagate out into surrounding intergalactic space and after the Sedov phase develop a thin shell structure which can cool becoming gravitationally unstable resulting in a generation of galaxies formed in groups having random velocities ~ 100 km/s located on shells of several hundred km/s radial velocities. Recent work /3/ shows these primordial explosions can produce a galaxy distribution on scales of tens of Mpc and with ~ 0.9 dark matter domination can provide natural biased galaxy formation to reconcile a flat universe with observations. Evidence for the formation of primordial supermassive stellar objects is also indicated by (1) even high-z quasars show lines of heavier elements (O, Mg, etc.) with solar abundances strongly suggesting that matter had already

undergone nuclear processing at even earlier epochs (2) even the oldest stars in our galaxy show evidence of metal content. This metal content could have been generated by pregalactic Pop.III stars with masses from 10^2-10^6 M_o which could have formed in clusters of a few hundred or thousand of these objects at $z \approx 100$. The eventual collapse of such clusters could have formed the massive central blackholes $\sim 10^9$ M_o which in turn triggered quasar activity /4/, by accreting the surrounding matter enriched in metals to solar abundances, by the nuclear reactions in these massive stars. It turns out such objects of mass ~ 300 M_o can explode and scatter the heavy elements, the star completely disrupting in the process. Anomalies like the O/Fe enrichment in metal poor stars and the G dwarf problem can be accounted for if $\sim 10^{-5}$ of the primordial material originating at $z \sim 1000$ (recombination era) is nuclear processed in Pop.III objects. Thus all these gigantic primordial explosions releasing energies $\sim 10^{62}$ ergs or less, would have been efficient in accelerating many of the charged nuclei of the various elements formed to very high energies.

2. Interaction of high energy particles produced in pregalactic processes with background radiation at $z > 100$. The cosmic microwave background at higher z, would have a temperature scaling as $T_o(1 + z)$, $T_o \approx 3°$k is the present temperature. The energy of the typical background photon would go as $E_\gamma \approx 3 \times 10^{-13}$ GeV (1 + z). A high energy nucleon N, produced in any of the pregalactic processes would have its energy E_N cut off at some upper limit owing to its interaction with the cosmic background of thermal photons with energy E_γ and number density $\sim 20\ T_o^3(1 + z)^3$. The energy degradation of the nucleon can occur by undergoing reactions with the background photons such as $\gamma + N \rightarrow N + \pi$, where π is the pion of rest mass ~ 140 MeV. Usual special relativistic kinematics involving four-momenta relations such as $P_\gamma + P_N = P_N^1 + P_\pi$ is the laboratory frame and $P_N^1 + P_\pi = (m_N + m_\pi, 0)$ in the CMS frame at pion production threshold then give: (for head-on collisions):

$$E_N + (E_N^2 - m_N^2)^{1/2} \quad \frac{2m_N m_\pi + m_\pi^2}{2\ E_\gamma}, \quad \text{or}$$

$$\text{for} \quad E_N \gg m_N \ ; \qquad E_N \simeq \frac{2\ m_N m_\pi + m_\pi^2}{4\ E_{\gamma_o}(1+z)} \ .$$

For $m_N \approx 1$ GeV, this gives for $z \approx 10^2$ and $z \approx 10^3$, cosmic ray particle cutoff energies of $\sim 3 \times 10^{12}$ MeV and $\sim 3 \times 10^{11}$ MeV respectively.

For an explosion energy of $W \sim 10^{61}$ ergs and a magnetic field of $B \sim 10^{-3}$ G at $z \approx 100$ (assuming flux conservation), the maximal energy E_m of the accelerated protons in the blast wave (which scales as $E_m \sim B\, W^{1/3}\, p^{-1/3}$) is $\sim 10^{14}$ MeV. However, because of interaction with the background, such protons would have their energies cutoff at $\sim 3\times10^{12}$ MeV. For Ca or Fe nuclei, the cutoff energy E_{Nc}, owing to interaction with the background photo-radiation is $\sim 10^{14}$ MeV, whereas the maximal energy by blast wave acceleration is $\sim 10^{15}$-10^{16} MeV. Of course, the cutoff energies of these primordially produced particles would be further redshifted by (1+z) at the present epoch, so that their present energy (for mass No. A) would be:

$E_{Nco} \approx 0.5\, m_N\, A\, m_\mu/2E_{\gamma_o}(1+z)^2$. Thus, the maximal energy for Fe nuclei produced in pregalactic processes at the present epoch is $\sim 10^{18}$ eV, and for protons $\sim 10^{16}$ eV. Thus, no cosmic rays presently observed above this energy range would have been produced in such processes. From the constraints on source energetics (i.e., the combined energy output of the pregalactic explosive processes should not distort the microwave background by $> 10^{-5}$), the total number of such particles (in the above energy range) produced is $\sim 10^{55}$, which would imply a background flux of such particles at the present epoch of $< 10^{-22}$ cm^{-2} s^{-1}.

3. Cutoff photon energies in pregalactic processes. Corresponding cutoffs to the energies of ultra high energetic photons produced in pregalactic explosive events (at large z) would also exist. Moving to a relativistic frame in which the background photons have the same energy as the ultraenergetic photons (frame Lorentz factor is γ), we have for the threshold photon energy for e^+e^- pair production, the relations:

$$E_{ph}/\gamma \approx 3 \times 10^{-13}\ \text{GeV}\ (1+z)\ \gamma \simeq 2\, m_e c^2 .$$

Eliminating γ, this gives the threshold photon energy: $(E_{ph})_{max} \simeq 4\, m_e^2 c^4/E_{\gamma_o}(1+z)$, which for $z = 100$, gives $(E_{ph})_{max} \approx 10^4$ GeV. Thus, the maximal γ-ray photon energy in such processes at $z \approx 100$ is $\sim 10^4$ GeV, and at the present epoch such photons would have been redshifted to energies $\sim 10^2$ GeV. This would be the maximal energy of the background photons produced in the earlier epochs.

References

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