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A Common Origin of the Highest Energy Cosmic Rays and Baryon Asymmetry of the Universe?

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It is suggested that the origins of the observed small neutrino mass, the baryon asymmetry of the Universe and the UHECR events above 10^{11} GeV may be linked to a $U(1)_{B-L}$ symmetry-breaking phase transition in the early Universe at a energy scale $\eta_{B-L} \sim 10^{14}$ GeV.

1. Introduction

One of the most attractive scenarios of origin of the observed baryon (B) asymmetry of the Universe (BAU) is that it arose from an initial lepton (L) asymmetry created by the L- and CP-violating out-of-equilibrium decay of heavy ($\gg$ TeV scale) right-handed Majorana neutrinos [1]. The L-asymmetry is partially converted to a B-asymmetry by the electroweak B+L violating [but (B-L) conserving] sphaleron transition process [2]. This scenario has received strong support from the experimental fact (inferred from neutrino oscillation experiments [3]) that the usual Standard Model (SM) neutrinos have small (sub-eV) masses. Such small masses can be explained naturally through the see-saw mechanism [4] that involves the heavy right-handed Majorana neutrinos. According to this mechanism, for every generation, the light neutrino mass m is related to the heavy neutrino mass M through the generic relation $m \sim m_D^2/M$, where m_D is the Dirac mass that connects the SM left-handed neutrino ν to the heavy right-handed neutrino N_R. The Dirac mass m_D may be expected to be on the order of the electroweak scale $\sim O(100)$ GeV. Thus m can be as small as desired if the right-handed neutrino is sufficiently heavy.

The most natural and anomaly-free way to incorporate the heavy right-handed Majorana neutrino N_R is to extend the SM by an extra $U(1)_{B-L}$ gauge symmetry which is spontaneously broken at a sufficiently high energy scale η_{B-L} thereby giving large mass to the N_R. Alternatively, one can consider a Grand Unified Theory (GUT) based on a gauge group such as $SO(10)$ which contains $U(1)_{B-L}$ as a sub-group. Because $B-L$ is a gauge charge in such models, no primordial $B-L$ can exist as long as the $U(1)_{B-L}$ gauge symmetry remains unbroken. The spontaneous breaking of the $U(1)_{B-L}$ gauge symmetry gives heavy Majorana mass to N_R and a net $B-L$ can be dynamically generated through out-of-equilibrium decay of these heavy N_R's. Rapid violation of $B+L$ by the high temperature sphaleron transitions erases any $B+L$ generated earlier. These sphaleron transitions, however, conserve $B-L$. Thus, the final BAU is related to the $B-L$ produced after the $U(1)_{B-L}$ symmetry breaking phase transition.

An important aspect of any $U(1)$ gauge symmetry breaking phase transition in the early universe is the formation of cosmic strings [5]. In this paper we suggest that the decay of the massive gauge bosons, higgs bosons as well as the heavy N_R's (collectively called X particles hereafter) released from rapidly collapsing closed loops of the "$B-L$" cosmic strings (that arise from the $U(1)_{B-L}$ symmetry-breaking phase transition) can provide, for X particle masses $\geq 10^{11}$ GeV, a "top-down" mechanism (see, e.g., [6] for a review) of production of the observed extremely high energy cosmic ray particles with energies above 10^{11} GeV [7] which are otherwise difficult to produce by means of the standard acceleration mechanisms operating in known astrophysical objects. At the same time the decay of the N_R's released from the $B-L$ cosmic string loops can give a non-thermal contribution to the observed BAU through the leptogenesis route [8] ameliorating some of the problems of the purely thermal leptogenesis scenario[1]. Thus, the observed baryon asymmetry of the Universe, the extremely high energy cosmic rays (EHECR) above 10^{11} GeV and small neutrino masses inferred from neutrino oscillation experiments — all may have a common origin in a $U(1)_{B-L}$ symmetry-breaking phase transition in the early Universe.

Although cosmic strings formed at symmetry-breaking energy scales $\eta \gtrsim 10^{16}$ GeV are currently disfavored[9] due to absence of the predicted cosmic string signature in the cosmic microwave background (CMB) anisotropy pattern, lighter cosmic strings arising from symmetry breaking at lower energy scales such as the $B-L$ cosmic strings in the SO(10) GUT model, which can be formed at an intermediate scale of $\eta \lesssim 10^{14}$ GeV, for example, are not excluded by the CMB anisotropy data, and may well exist in the Universe.

Below, we use natural units with $\hbar = c = 1$. The dimensionless cosmic string parameter is then $G\mu \equiv (\eta/M_{\rm Pl})^2$, where $\mu \sim \eta^2$ is the energy per unit length of the string and $M_{\rm Pl} \sim 10^{19}$ GeV is the Planck energy.

2. Evolution of cosmic strings: Formation and evolution of closed loops and production of massive particles

After the formation of the cosmic strings at a phase transition, the string configuration quickly reaches a "scaling regime"[5] in which the energy density in the form of strings scales as, and remains a constant fraction of, the energy density of radiation in the radiation dominated epoch or the energy density of matter in the matter dominated epoch both of which scale as t^{-2} (t is the cosmic time). The fundamental physical process that maintains the string network in the scaling configuration is the formation of *closed loops* which are pinched off from the network whenever a string segment curves over into a loop and intersects itself. In the "standard" picture [5], the closed loops so formed have average length at birth

$$L_b = K\Gamma G\mu t\,, \tag{1}$$

and they are formed at a rate (per unit volume per unit time) which, in the radiation dominated epoch, is given by

$$\frac{dn_b}{dt} = \frac{1}{x^2}\left(\Gamma G\mu\right)^{-1} K^{-1} t^{-4}\,, \tag{2}$$

where $\Gamma \sim 100$ is a geometrical factor that determines the average loop length, and K is a numerical factor of order unity, and the number x lies approximately in the range 0.3–0.7. In the matter-dominated epoch the above formula is modified by a prefactor of $2/3$.

The behavior of closed loops of string after their formation may be broadly categorized into following two classes:

(a) *Slow death*: In this case, closed loops in non-selfintersecting configurations oscillate freely, lose energy by emitting gravitational radiation, and thereby shrink in size. When the radius of a loop becomes of the order of its width $w \sim \eta^{-1} \sim \mu^{-1/2}$, the loop decays into massive X particles. Among these particles will be the massive gauge bosons, higgs bosons, and in the case of the $B-L$ strings, massive right-handed neutrinos (N_R). The lifetime of a loop of length L due to energy loss through gravitational wave radiation is $\tau_{\rm GW} \sim \left(\Gamma G\mu\right)^{-1} L$. Equation (1) then implies that loops born at time t have a lifetime $\sim Kt \gtrsim H^{-1}(t)$, where $H^{-1}(t) \sim t$ is the Hubble expansion time scale. It is thus a "slow death" (SD) process. Numerical simulations [5] generally show that most loops disappear through this process. It was shown in [8] that the N_R's resulting from this process can make a significant non-thermal contribution to the BAU. However, since for this process the rate of X particle production varies as t^{-4}, this process makes negligible contribution to the UHECR flux in the present day Universe.

(b) *Quick death*: Some small fraction of the loops may be born in configurations represented by high harmonic numbers. Such string loops have been shown [10] to have a high probability of self-intersecting. A self-intersecting loop would break up into two or more smaller loops which can further break up into even smaller loops, and so on. This process can lead to a single initially large loop of length L breaking up into a debris of tiny loops of size η^{-1} (at which point they turn into the constituent massive particles) on a time-scale $\sim L$. Equation (1) then implies that a loop born at the time t in a high harmonic configuration decays, due to repeated self-intersection, into massive particles on a time scale $\tau_{QD} \sim K\Gamma G\mu t \ll H^{-1}(t)$. It is thus a "quick death" (QD) process — the loops die essentially instantaneously (compared to cosmological time scale), with almost the entire original energy of these loops eventually coming out in the form of massive X particles.

The rate of release of the X particles due to this QD process can be written as

$$\dot{n}_X^{\rm QD} = f_{\rm QD}(2/3x^2)(\mu/m_X)t^{-3}\,, \tag{3}$$

where $f_{\rm QD} < 1$ is the fraction of all loops that undergo QD. The t^{-3} dependence implies that this process dominates over the slow death process at late times, and can contribute to the observed UHECR flux.

3. Quick death of $B - L$ cosmic string loops: Production of UHECR particles above 10^{11} GeV

The Top-Down mechanism of production of UHECR particles from the decay of massive X particles released from topological defects such as cosmic strings has been discussed in detail in [6]. Typically, the X particles released from cosmic string loops ultimately decay to quarks and leptons. The quarks then hadronize producing mainly pions and a small number of baryons (nucleons). The decay of the pions then gives rise to a neutrino and photon rich spectrum of particles with energy up to m_X, the mass of the X particles which can easily exceed 10^{11} GeV, thereby explaining the observed UHECR particles above 10^{11} GeV which are otherwise difficult to produce by means of the standard diffusive shock acceleration mechanism. The energy spectrum of the particles is determined primarily by the Fragmentation Function (FF) of quarks and gluons (see, e.g., [11] for a recent discussion). The resulting spectra of particles in the energy region of interest can be approximated by a power-law, $\sim E^{-\alpha}$, with typically $\alpha < 2$, thus predicting a relatively hard spectrum of UHECR particles compared with that predicted in standard diffusive shock acceleration mechanism which generally yields a power-law spectrum with $\alpha \geq 2$.

The contribution to the UHECR flux can come from only those X particles that are released in the Universe due to the QD process in the present epoch. The size distribution of the loops present at any time t is, however, determined primarily by the SD process. For currently popular values of the relevant cosmological parameters, the most abundant loops today can be shown to have typical lengths $\sim 0.3(G\mu/10^{-12})$ pc, number density $\sim 1.6(G\mu/10^{-12})^{-1}\,{\rm Mpc}^{-3}$, and average separation between loops $\sim 8.6\times10^2(G\mu/10^{-12})^{1/3}$ kpc. (Note: $G\mu \simeq 10^{-12}$ for $\eta \sim 10^{13}$ GeV.) Only a small fraction $f_{\rm QD} \ll 1$ of these loops can be expected to undergo QD and contribute to the UHECR flux.

The injection rate of the X particles in the present epoch required to produce the observed flux of UHECR above 10^{11} GeV can be roughly estimated as

$$(\dot{n}_{X,0})_{\rm EHECR} \sim 1.1\times10^{35}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}\left(\frac{m_X}{10^{13}\,{\rm GeV}}\right)^{-1/2}\,, \tag{4}$$

with corresponding energy injection rate in the form of X particles in the present epoch

$$(Q_{X,0})_{\rm EHECR} \sim 1.7\times10^{45}\,{\rm erg}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}\left(\frac{m_X}{10^{13}\,{\rm GeV}}\right)^{1/2}\,. \tag{5}$$

In obtaining the above estimates we assumed the UHECR particles above 10^{20} eV to be photons, a power-law injection spectrum with $\alpha = 1.5$, a fiducial value of observed energy flux $E^2 j(E) \simeq 0.1\,\mathrm{eV\,cm^{-2}\,sec^{-1}\,sr^{-1}}$ at $E = 10^{20}$ eV, a UHE photon attenuation length of $\sim 10\,\mathrm{Mpc}$, and a pion fraction of ~ 0.9 in the total hadronic yield from the a single quark or gluon coming from the decay of the X particles. The above estimates may be uncertain by as much as an order of magnitude due to uncertainties in the measured flux of EHECR ($E > 10^{11}$ GeV particle) flux and other parameters.

Using eq. (3) we see that the above requirements can be met with $f_{\rm QD}(\eta_{B-L}/10^{14}\,\mathrm{GeV})^2(10^{13}\,\mathrm{GeV}/m_X) \sim 10^{-2}$.

There is an independent upper limit on $f_{\rm QD}$ which comes from the fact that a significant fraction of the total electromagnetic (EM) energy injected above $\sim 10^{15}\,\mathrm{eV}/(1+z)$ at any epoch of redshift z cascades down to below 100 GeV in the present epoch due to repeated cycles of the two processes $\gamma\gamma_b \to e^+e^-$ and $e\gamma_b \to e\gamma$ on the cosmological background photon field (γ_b). The measured Extragalactic Gamma Ray Background (EGRB) in the (10 MeV – 100 GeV) region [12] puts constraints on the allowed amount of EM energy injection at UHE above the pair production threshold on CMB/Radio background target photons. This gives the constraint $f_{\rm QD}(\eta_{B-L}/10^{14}\,\mathrm{GeV})^2 < 0.1$, which can be consistent with the requirement for explaining the UHECR flux above 10^{11} GeV for $\eta_{B-L} \gtrsim 10^{14}$ GeV, $m_X \sim 10^{13}$ GeV, and $f_{\rm QD} \lesssim 10^{-2}$.

4. Conclusions

To summarize, then, we suggest that the origins of the observed small neutrino mass, the baryon asymmetry of the Universe and the UHECR events above 10^{11} GeV — apparently unrelated to one another — may actually be linked to a $U(1)_{B-L}$ symmetry-breaking phase transition in the early Universe at a energy scale $\eta_{B-L} \sim 10^{14}$ GeV.

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