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Bounds on relic neutrino masses in the Z-burst model

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Neutrinos from far-away sources annihilating at the Z-resonance on relic neutrinos may give origin to the extreme-energy cosmic rays (EECR). If "Z-bursts" are responsible for the EECR events, then we show that the nonobservation of cosmic ray events at energies above 2×10^{20} eV by the AGASA Collaboration implies a lower bound ~0.3 eV on the relic neutrino mass. Since this mass exceeds the mass-squared differences inferred from oscillation physics, the bound in fact applies to all three neutrino masses. Together with the upper bound provided by comparisons of the CMB anisotropy with large-scale structure, this bound leaves only a small interval for neutrino masses around 0.3 eV, if Z-bursts are to explain the existing EECR events.

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I. INTRODUCTION

The existence of extreme-energy cosmic rays (EECR) with energies above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1] of about 5×10^{19} eV, presents an outstanding problem [2]. Nucleons and photons with those energies have short attenuation lengths and could only come from distances of 100 Mpc or less [3,4], while plausible astrophysical sources for those energetic particles are much farther away.

Data from the HiRes experiment [5] brought the violation of the GZK cutoff into question. Yet the EE events in even the HiRes data set remain unexplained since the local Universe (~100 Mpc) is devoid of strong candidate sources. This controversy will be solved conclusively by the Pierre Auger hybrid observatory [6], perhaps as soon as summer of 2005. Here we assume that the published AGASA spectrum is correct. Interestingly, it is the absence of events above 2×10^{20} eV in these data, rather than the presence of events above $E_{\rm GZK} \sim 5 \times 10^{19}$ eV, that motivates this work.

Among the solutions proposed for the origin of the highest energy events observed by AGASA, an elegant and economical solution to this problem is the "Z-burst" mechanism: annihilation at the Z-resonance of extreme-energy neutrinos ($\nu_{\rm EE}$) coming from remote sources, and relic background neutrinos within ~50 Mpc of Earth, produces the nucleon and photon EECRs [7]. The observed EECRs from the Z-bursts are the emission analogues of the absorption features (Z-dips) predicted long ago [8]. One of the most appealing features of the Z-burst mechanism is that the energy scale of $\gtrsim 10^{20}$ eV at which the unexpected events have been detected, is generated naturally. The Z-resonance occurs when the energy of the incoming $\nu_{\rm EE}$ is

$$E_{\rm res} = \frac{M_Z^2}{2m_\nu} = 4 \times 10^{21}\ {\rm eV}\left(\frac{\rm eV}{m_\nu}\right), \tag{1}$$

where m_ν is any of the three masses of the relic neutrinos. Given the lower limit ~0.04 eV deduced from atmospheric oscillations for the heaviest neutrino mass, at least one $E_{\rm res}$ is below 10^{23} eV.

Since the individual energies of the nucleons and photons emerging from the Z-burst cannot exceed the total energy of the burst, $E_{\rm res}$ is the new end-point of the EECR energy-spectrum in this mechanism. Partitioning this burst energy among the $\langle N\rangle \sim 40$ final state particles, one arrives at precisely the primary energies needed to produce events observed above the GZK energy.

Combining their recent measurements of the anisotropies of the Cosmic Microwave Background (CMB) radiation with data on the large-scale structure of the Universe, Wilkinson Microwave Anisotropy Probe (WMAP) [9] produced a strong limit on neutrino masses, $\Sigma_i m_{\nu_i} <$ 0.69 eV. Since a single neutrino mass above ~0.04 eV implies near mass-degeneracy for all three active neutrinos (given the mass-squared splittings from neutrino oscillation data, described below) one has $m_\nu < 0.23$ eV at the 95% C.L. However, objections [10] to the priors assumed, or to the data sets included, have led to a relaxed bound $\Sigma_i m_{\nu_i} < 1$ eV, or $m_\nu < 0.33$ eV. A subsequent analysis [11] which includes WMAP, 2dF, and SDSS data, and another which includes these and galaxy cluster data [12], have arrived at the bound, $\Sigma_i m_{\nu_i} \lesssim 0.7$ eV. Still another analysis [13] with CMB and Large Scale Structure (LSS) data finds $\Sigma_i m_{\nu_i} \lesssim 1$ eV, but finds $\Sigma_i m_{\nu_i} \lesssim 0.6$ eV when priors from supernova data and the Hubble Key Project are included. These newer bounds are very similar to the original WMAP bound.

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In this work we focus on a particular feature of the AGASA spectrum, namely, the end-point energy. Requiring that the Z-burst mechanism not overproduce events beyond this AGASA end-point, we derive a lower bound on the neutrino mass. The significance of an end-point energy for constraining model fluxes has been noted much earlier in the context of topological defect decay [14]. A more ambitious project would be to actually fit the neutrino mass to the full AGASA spectrum. This has been done, by Fodor, Katz and Ringwald (FKR) [15]. However, the allowed range of the neutrino mass that results is not tight. Rather, it depends sensitively on how one parametrizes the transition from nonburst spectrum to burst spectrum near and above the ankle. FKR find $\pm 2\sigma$ fitted mass ranges of 0.1 eV to 1.3 eV if all EE events are assumed to originate with Z-bursts, 0.02 eV to 0.8 eV if an additional extra-galactic source of EE protons is allowed, and 1 eV to 7 eV if an additional Galactic-halo source of EE protons is allowed.

Super-Kamiokande has provided a strong evidence for the oscillation in atmospheric showers of two neutrino species with mass-squared splitting $\delta m^2 = m_3^2 - m_2^2 = (1-3) \times 10^{-3}$ eV, consisting of nearly equal amounts of ν_μ and ν_τ, and little or no ν_e [16]. If neutrino masses are hierarchical, like the other leptons and quarks, then $\sqrt{\delta m^2} \simeq 0.04$ eV $\equiv m_{\rm SK}$ *is* the mass of the heavier of the two oscillating neutrinos (call it $\nu_{\rm SK}$). Some previous works [17,18] on Z-burst production of the EECRs have made this assumption. However we will show in this work that $m_\nu \sim 0.04$ eV is not compatible with the AGASA end-point spectrum if Z-bursts produce the EECR. The reason is that with $m_\nu = 0.04$ eV, the new EECR cutoff $E_{\rm res} \simeq 10^{23}$ eV predicts too many super GZK EECR events beyond the AGASA end-point.

As the relic neutrino mass increases, $E_{\rm res} \propto 1/m_\nu$ decreases, and the features in the EE spectrum move progressively to lower energies. In particular, the number of events predicted at high energy decreases, and the number beyond the AGASA end-point becomes compatible with zero for $m_\nu \gtrsim 0.3$ eV. Note that our result is much sharper than, but compatible with, the allowed mass ranges of the FKR models with no additional EE proton source, or with an additional extra-galactic source of EE protons.

In the next section we present our simulations and the resulting spectrum of EECR in detail.

II. SPECTRUM OF EECR FROM Z-BURSTS

We have performed simulations of the photon, nucleon and neutrino fluxes coming from a uniform distribution of "Z-bursts", namely $\nu\bar{\nu}$ annihilations at the Z pole ($\nu\bar{\nu} \rightarrow Z \rightarrow p\gamma \ldots$). The burst energy is given in Eq. (1). Our simulations cover the range $m_{\rm SK} \leq m_\nu < 1$ eV for relic neutrino mass. The Z-bursts were simulated using PYTHIA 6.125 [19], and the absorption of photons and nucleons was modeled using energy-attenuation lengths provided by Bhattacharjee and Sigl [20], supplemented by radio-background models by Protheroe and Biermann [21].

We simulated a uniform distribution of about 10^7 Z-particles up to a maximum $z_{\rm max} = 2$. If other Z-burst spatial distributions are used, the main features of the spectrum of the ultra-high energy nucleons, photons and neutrinos remain the same as given below.

The decay of the Z bosons through all possible channels was done automatically by the PYTHIA routines [19], using the default options of this program. For comparison with our later figures, we show in Fig. 1 the spectra given by PYTHIA, normalized per Z boson, for $m_\nu = 0.3$ eV; redshifts and energy absorption are not included in PYTHIA. The multiplicities that PYTHIA gives per Z-decay are 1.6 nucleons, 17 photons, 15 ν_e, 30 ν_μ and 0.23 ν_τ (in each case counting particles and antiparticles).

In our simulation, each Z boson generated by PYTHIA was placed on the "event list" of the cascade generator at a randomly selected distance. The cascade of decay products was then boosted. The γ factor corresponding to an energy $E_\nu = E_{\rm res}$ in Eq. (1) is

$$\gamma \equiv \frac{E_\nu + m_\nu}{M_z} \simeq \frac{M_z}{2m_\nu} \simeq 0.46\left(\frac{0.1 \text{ eV}}{m_\nu}\right) \times 10^{12}. \qquad (2)$$

We then followed the propagation of the nucleons, pho-

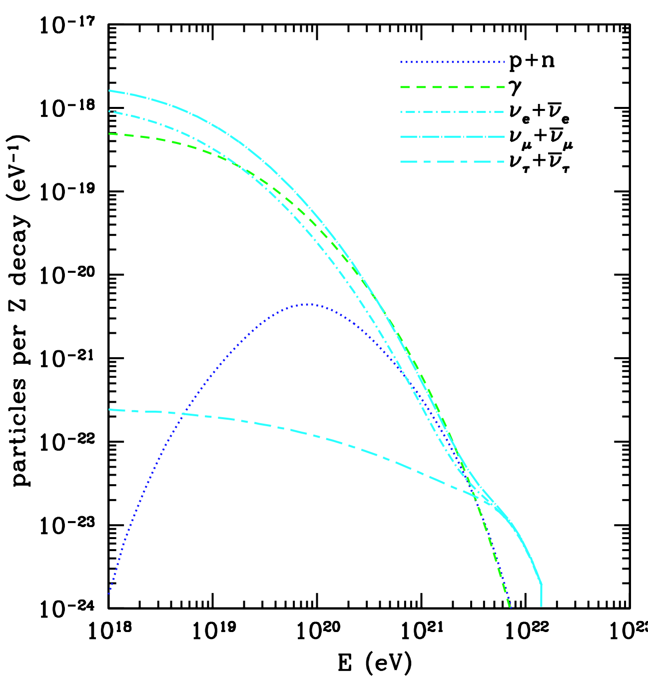

FIG. 1 (color online). Spectra of stable particles produced per Z-decay by PYTHIA (no absorption or redshift included). The resonant-energy in this example is $E_{\rm res} = 1.3 \times 10^{22}$ eV, coming from the choice $m_\nu = 0.3$ eV.

tons and neutrinos resulting from the boosted Z-decays. The gamma factor of the secondary particles was corrected to include their red-shifting subsequent to the Z-decay.

Each neutrino, nucleon or photon was created by PYTHIA in the initial cascade at a fixed position, with fixed energy and direction of motion with respect to the Earth frame of reference. The distance each particle had to travel before reaching Earth was compared with the appropriate attenuation length in space for the particle energy. If the distance was smaller than the attenuation length, the particle was assumed to reach Earth unchanged. In the opposite case, the energy and momentum of the particle were degraded by a factor $\frac{1}{e}$ after traveling a distance equal to the attenuation length (and the particle was placed again in the list constituting the cascade at the new position, with the degraded energy and momentum).

Neutrinos do not interact in their propagation. Thus, the energy spectra of the three kinds of neutrinos were simply generated by summing the number of particles over energy bins and normalizing to neutrino multiplicities per Z times the total number of Z-particles used. On the other hand, nucleons and photons do suffer energy-absorption interactions, and here we included energy absorption. The propagation process for nucleons and photons was continued until particles reached Earth and were counted in the final spectra, or until particle energies became too small to be significant. In the latter case, the particles were simply discarded from the cascade. At this point, the final nucleon and photon spectra were appropriately normalized to the total number of Z-particles used, as was done with the neutrinos. The results are given in Fig. 2 for $m_\nu = 0.3$, with a fit to the six most energetic occupied bins in the AGASA data [22]. These bins consist of 24 events spanning the energy range from $10^{19.8}$ eV to $10^{20.3}$ eV.

The energy-attenuation of the nucleons and especially photons requires more discussion. For nucleon attenuation, uncertainties are small, and so the predicted GZK suppression is highly credible. For the nucleon energy-attenuation, we used the length given by Bhattacharjee and Sigl in the Fig. 9 of Ref. [20], based on results from Ref. [23,24]. However, for photon energy-attenuation, the length is quite uncertain, due to the uncertain spectrum of the absorbing radio-background. The photon flux shown in Fig. 2 as curve (1) results from using the attenuation length shown in Fig. 11 of Ref. [20], based on observations of Clark *et al.* [25]. Protheroe and Biermann [21] produced two models for the radio background which lead to shorter interaction lengths (and therefore more absorption) than those based on Clark *et al.*. From the interaction lengths they provided, we constructed approximate attenuation lengths for the models of Protheroe and Biermann. We did so by reducing the

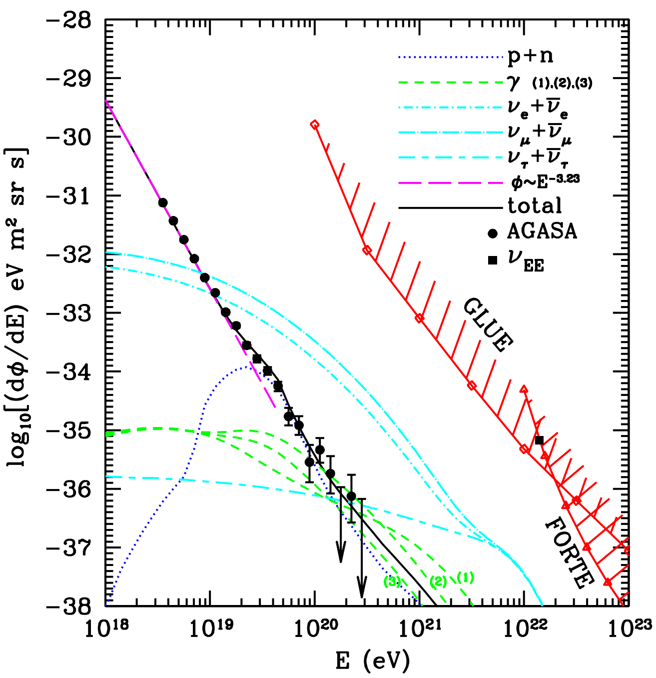

FIG. 2 (color online). Predicted spectra for $m_\nu = 0.3$ eV from Z-bursts with a uniform distribution up to $z = 2$, added to a power law spectrum which fits the data below the ankle $\sim 10^{19}$ eV, and terminates at 4×10^{19} eV. It is seen that EECR primaries above the ankle are nearly 100% nucleons up to 10^{20} eV, and photons plus nucleons at higher energies. Also shown is the EE neutrino flux at the unique resonance energy which produces the required Z-burst rate.

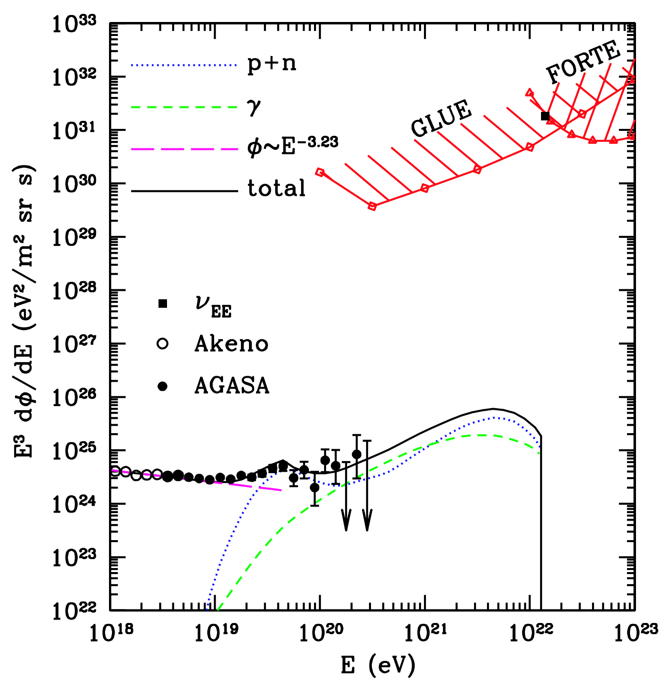

FIG. 3 (color online). As in Fig. 2 but with the flux multiplied by E^3. The photon flux shown is the lowest of the three of Fig. 2 (labeled as (3)).

attenuation length based on Clark *et al.* by the ratio of the respective interaction lengths, and obtained the curves (2) and (3) in Fig. 2. Since mean interaction lengths and mean energy-attenuation lengths do not have exactly the same energy dependence, our construction is an approximation. However, we believe the three curves which we display give a good representation of the possible range of predicted photon fluxes.

In this work, we seek a bound on the *excess* of events predicted. Therefore, we adopt the lowest observable photon flux, curve number (3), associated with the maximum photon absorption, when computing the total event number. This is the photon flux shown in Fig. 3. Notice that with this choice, the photon flux does not become comparable to the nucleon flux until $E \sim 2 \times 10^{20}$ eV. We add to the Z-burst proton and photon fluxes a power law spectrum with slope -3.23, terminated somewhat arbitrarily (as it is not known where this component actually dies out) at 4×10^{19} eV. Such a power law was found by AGASA to fit the data below the ankle, from 4×10^{17} eV to 10^{19} eV (see Table V of [26]).

III. LOWER BOUND ON THE RELIC NEUTRINO MASS

In Fig. 4 the observed and predicted integrated number of EECR event rates above 7×10^{19} eV are shown for different values of the relic neutrino mass. The Z-burst fluxes have been normalized to reproduce the 24 highest-energy events observed by AGASA [22] in the energy range from $10^{19.8}$ eV to $10^{20.4}$ eV. These events are spread among the first six bins of Fig. 4.

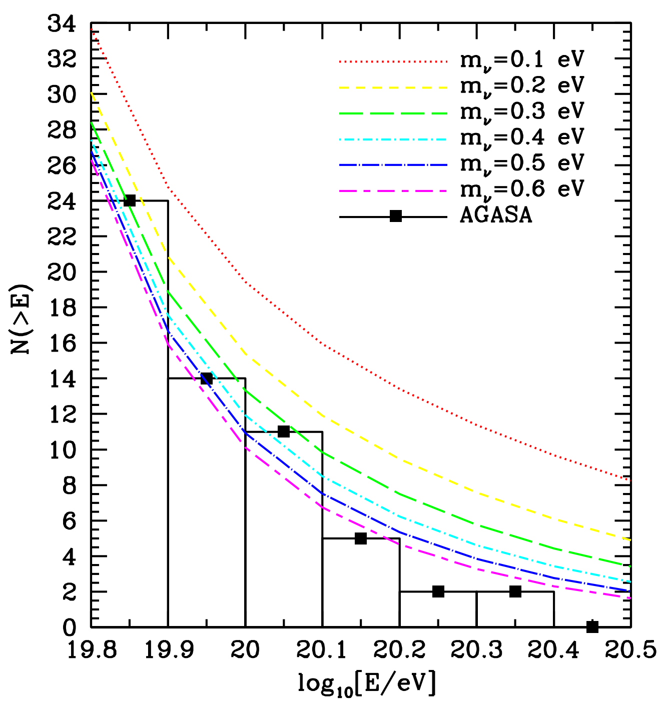

FIG. 4 (color online). Integrated Z-burst fluxes for different relic neutrino masses, normalized to reproduce the 24 highest-energy AGASA events in the energy range $10^{19.8}$ eV to $10^{20.4}$ eV (corresponding to the first six of seven bins shown here). The neutrino mass parametrizes the curves, with lighter mass at top and heavier mass at bottom.

The value of each curve at the beginning of the last bin shows the integrated number of events from 2.5×10^{20} eV to infinity predicted by that so-normalized Z-burst flux. This number of excess events can also be read off from the value of the curve at $E = 10^{19.8}$ eV less the 24 normalizing events. Since AGASA has observed no events above 2.5×10^{20} eV although their aperture remains constant with increasing energy [22], it is justified to call the events predicted beyond 2.5×10^{20} eV an excess; we label the predicted number of excess events as $N_{\rm ex}$. In Table I the predicted event excess above 2.5×10^{20} eV is shown as a function of the neutrino mass. Also shown is the Poisson probability that a fluctuation downward from the predicted value gives zero events, as observed. This latter quantity is just $e^{-N_{\rm ex}}$.

The probabilities show that masses lighter than $\sim$0.3 eV have a probability less than a percent. Expressed as Gaussian variances, one infers from the percentages in the table that $m_\nu \gtrsim 0.2$ eV is disfavored at $\sim 3\sigma$ while $m_\nu > 0.4$ eV is disfavored at only $\sim 2\sigma$. Together with the cosmological limit on the neutrino mass discussed earlier, the value $m_\nu \sim 0.3$ eV emerges as less than robust, but viable.

We remark that our definition of "excess" as events above 2.5×10^{20} eV is somewhat conservative in that the two highest energy AGASA events occur at $E \sim 2 \times 10^{20}$ eV ($\pm 25\%$ experimental energy-resolution), nearer to the beginning of the highest-energy occupied bin than to its end. On the other hand, we have not considered in our analysis the very-highest energy event, at 3×10^{20} eV, from the Fly's Eye experiment. This is in the spirit of neglecting fluorescent data, e.g. HiRes, as we have chosen to focus in a self-consistent way on just the ground-scintillator data set from AGASA.

There are three immediate inferences to be drawn from the preferred neutrino mass value. The first is that since the energy of no secondary from the Z-burst may exceed

TABLE I. Poisson probabilities that no events are observed above the AGASA end-point, given the excess predicted by the Z-burst mechanism as a function of neutrino mass.

Neutrino mass	Predicted event excess $N_{\rm ex}$	Poisson probability $e^{-N_{\rm ex}}$
0.6 eV	2.29	10.1%
0.5 eV	2.76	6.3%
0.4 eV	3.43	3.2%
0.3 eV	4.43	1.2%
0.2 eV	6.09	0.23%
0.1 eV	9.67	0.0063%

the burst energy, the model predicts a new cutoff for EECRs. With 0.3 eV relic neutrinos, the cutoff energy is $E_{\rm res} \simeq 1.3 \times 10^{22}$ eV. Given the large mean-multiplicity in Z-decay, $\langle N \rangle \sim 40$, a more realistic cutoff in the model is $\sim 10^{21}$ eV. Future experiments such as Auger, ANITA, RICE, EUSO, and SALSA may be able to test this prediction. The second inference is that with $m_\nu \sim 0.3$ eV, a significant clustering of relic neutrinos around very large galactic superclusters is expected [27]. This clustering could be evidenced as an enhancement of the EECR flux coming from the direction of M87, just 16 Mpc away, near the Virgo center. And the third inference is that given the smallness of mass-squared differences inferred from neutrino oscillation experiments, $m_\nu \sim 0.3$ eV implies near mass-degeneracy for the three active neutrinos. Mass-degeneracy enhances the possibility of directly observing absorptive "Z-dips" in the EE neutrino spectrum [8].

IV. DISCUSSION

We note that our analysis of the spectral shape of the AGASA data does not depend on the issue of rate. In particular, it does not depend on the EECR neutrino flux, and it does not depend on the value of the relic neutrino target density. The latter could, in principle, be enhanced by either gravitational clustering or by a lepton asymmetry. In practice, simulations argue against gravitational clustering for light ($\lesssim 1$ eV) neutrinos on all but the very largest super-Galactic mass-scales [27] (which comprise a small solid angle of sky), and BBN physics argues against a lepton asymmetry enhancement above $\sim$20% [28]. (Strictly speaking, the BBN limit is strongest for ν_e's, but the large lepton mixing angles inferred from oscillation studies extend the limit equally to ν_μ's and ν_τ's.) Regardless of these kinds of rate arguments, our bound on the neutrino mass holds.

Farrar and Piran [29] have argued that any mechanism accounting for the events beyond the GZK cutoff should also account for the events down to the ankle, including the observed isotropy and spectral smoothness. It is seen in our Fig. 2 that the Z-burst mechanism can accommodate the position of the ankle and all the events above it, if the position of the ankle is close to that measured by AGASA, at $E_{\rm ankle} = 10^{19.0}$ eV (see [26], in particular, Table V, and references therein). Fly's Eye claims a value for $E_{\rm ankle} \sim 10^{18.5}$ eV, a factor of three smaller than the AGASA value (see Table V of [26]). This value is difficult to accommodate with the Z-burst mechanism, although one could perhaps gain agreement by increasing $z_{\rm max}$ of the astrophysical neutrino sources. This would allow for more red-shifting of the nucleons, thereby lowering the soft end of the Z-burst spectrum. A higher $z_{\rm max}$ may be expected, for example, if the source is decaying massive particles or topological defects.

The fit of the AGASA data with our total flux provides the normalization of the photon and nucleon differential fluxes F, denoted as $d\phi/dE$ in Figs. 2 and 3, assuming a standard relic neutrino density of 100 cm^{-3} (in this case $F_{\rm AGASA} = 6.6 \times 10^{-15}({\rm m^2 srs})^{-1} F_{\rm PYTHIA}$). This allows us to determine the (assumed homogeneous and isotropic) flux of extreme-energy neutrinos close to the Z-resonance energy (more precisely, within the energy interval from $E_{\rm res}/(1 + z_{\rm max}) = E_{\rm res}/3$ to $E_{\rm res}$) to be

$$F_{\nu_{\rm EE}} \simeq 6.6 \times 10^{-36} \frac{1}{\rm eV\ m^2\ sr\ s}. \qquad (3)$$

This flux is shown in Figs. 2 and 3, with the label "$\nu_{\rm EE}$". Within the level of accuracy of our simulation, we only determine the order of magnitude of this flux. Nevertheless, the flux requirement is formidable. This very-high energy flux is at present marginally ruled-out by present GLUE [30] and FORTE [31] bounds, as can be seen in Figs. 2 and 3 (see also [32]) The large required flux in the Z-burst hypothesis is also a challenge to theory. It appears that new physics is required to produce such a large neutrino flux at such extreme energy [33].

In this work, we have not included any effects of extragalactic magnetic fields. For the analysis of this paper to hold as is, these fields should be sufficiently small, $< 10^{-9}$ G. A way to weaken the bound derived here would be to assume the existence of large enough extragalactic magnetic fields, say 10^{-8} G or larger, so that through electron pair-production and subsequent synchrotron radiation, photons would be eliminated as EECR primaries. This would reduce the event count above the AGASA end-point, and so allow a smaller neutrino mass. However in this case the flux of EE neutrinos at the Z-resonance energy, $F_{\nu_{\rm EE}}$, required to produce the observed EECR's would be larger. Moreover, the resonant-energy, $E_{\rm res} \propto 1/m_\nu$, would be larger. Both the increased flux and the increased energy bring this possibility into conflict with the GLUE and FORTE bounds, on EE neutrino fluxes, shown in Figs. 2 and 3. Specifically, we find that without the photon contribution to the Z-burst flux, we would require $F_{\nu_{\rm EE}} = 7.23 \times 10^{-36}({\rm eV\ m^2\ sr\ s})^{-1}$ at $E_{\rm res} = 2.08 \times 10^{22}$ eV for $m_\nu = 0.2$ eV, or $F_{\nu_{\rm EE}} = 4.26 \times 10^{-36}({\rm eV\ m^2\ sr\ s})^{-1}$ at $E_{\rm res} = 4.16 \times 10^{22}$ eV for $m_\nu = 0.1$ eV. Such possibilities are rejected by the GLUE and FORTE bounds.

Another prediction of the Z-burst mechanism is the enhancement of the event rate at the GZK cutoff energy, $E_{\rm GZK} \sim 5 \times 10^{19}$ eV, due to the accumulation of nucleons after energy-attenuation. Such an enhancement (or "GZK bump") is expected from any model which provides a nucleon spectrum flatter than E^{-2} above $E_{\rm GZK}$ (spectra falling faster than E^{-2} do not provide sufficient flux above $E_{\rm GZK}$ to make an observable pile-up.). A hint for such a bump is seen in the AGASA data, Fig. 2 and 3. However, one must be careful in interpreting the shape as an enhancement. An alternative explanation of the shape feature has been provided in [34], namely, that another energy-loss mechanism, $p + \gamma \rightarrow p + e^+ + e^-$, depletes the flux at energies just below E_{GZK}.

Finally, a reliable prediction of the model is that most primaries above the ankle should be nucleons up to $10^{20.0}$ eV or more, and photons and protons at higher energies. A much larger event sample is needed to test this prediction.

V. CONCLUSIONS

The nonobservation of cosmic ray events at energies higher than $\sim 2 \times 10^{20}$ eV by AGASA provides a lower bound of about 0.3 eV on relic neutrino masses, if Z-bursts are responsible for the EECRs. This bound together with comparisons of the microwave background anisotropy to today's large-scale structure, leave a small interval for the relic neutrino mass, centered around 0.3 eV, if Z-bursts explain the EECRs. The $\sim$0.3 eV mass provides a very accessible signal for neutrinoless double beta-decay experiments (assuming neutrinos are Majorana particles), and is in fact compatible with a reported positive signal [35]. This $\sim$0.3 eV mass interval may also be probed by the future KATRIN tritium end-point experiment [36], and by expected improvements to the astrophysical bound from weak lensing of distant galaxies by intervening matter distributions [37], and from mining future Planck measurements of the CMB [38]. We note that our small allowed range for m_ν is incompatible with an upper bound of 0.15 eV that arises from invoking the see-saw mass spectrum as a source of successful early-Universe baryogenesis [39].

We have not included in this work any possible effects of extragalactic magnetic fields. For the analysis of this paper to hold as is, these fields should be sufficiently small, $\lesssim 10^{-9}$ G. A survey of the literature shows that extragalactic fields much larger than 10^{-9} G are not expected, except in regions around galaxy clusters. In any event, large extragalactic magnetic fields which would reduce or eliminate the EE photon component of the Z-bursts (thus lowering the neutrino mass we obtain) would also lead to larger required EE neutrino fluxes at the Z-resonance energy. This possibility is rejected by the GLUE and FORTE bound.

We have shown that Z-bursts may account not only for the super GZK events, but for the "ankle" and all EECR events above it. In doing so, the Z-burst mechanism meets the "naturalness" requirements of isotropy and spectral smoothness. In our simulation we found the ankle close to $E_{ankle} = 10^{19.0}$ eV as measured by AGASA. We found that most EECR primaries above the ankle should be nucleons up to about $10^{20.0}$ eV and nucleons and photons at higher energies. We also found that primary nucleons do accumulate at the GZK cutoff energy, which could account for the slight accumulation seen in the data (see, however, [34]).

With $m_\nu \sim 0.3$ eV needed to accommodate the AGASA end-point, the Z-burst hypothesis predicts a new absolute energy cutoff for EECRs, at $E_{res} \simeq 1.3 \times 10^{22}$ eV. However, due to the large multiplicity in Z-decay, the vast majority of incident primaries are expected to carry only a few percent of this cutoff energy.

In summary, we believe that the Z-burst mechanism provides a plausible explanation to the puzzle of extreme-energy cosmic rays, not only for the super GZK events, but for the ankle and all events above it. But the hypothesis will stand or fall on the required nearness of m_ν to 0.3 eV, and/or on the proximity of the required neutrino flux at $E_{res} = 1.3 \times 10^{22}$ eV to existing flux limits.

If Z-bursts are invalidated as the source of the observed EECRs, then we would encourage future, larger experiments (e.g., Auger, EUSO) to continue the search for Z-burst signatures, for they provide the only known window to discovery of the relic neutrino background. The Z-burst mechanism is entirely Standard Model particle physics coupled with Standard Hot Big-Bang Cosmology. Consequently, the mechanism itself cannot be ruled out. However, the Z-burst rate depends linearly on the resonant-energy neutrino flux which Nature provides. Nature may not be generous.

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[1] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G.T. Zatsepin and V.A. Kuzmin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 114 (1966).

[2] M. Takeda *et al.*, Phys. Rev. Lett. **81**, 1163 (1998); M. A. Lawrence, R. J. Reid and A. A. Watson, J. Phys. G **17**, 733 (1991); D. J. Bird *et al.*, Phys. Rev. Lett. **71**, 3401 (1993); Astrophys. J. **424**, 491 (1994).

[3] S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833

(1993); F. A. Aharonian and J.W. Cronin, Phys. Rev. D **50**, 1892 (1994); J.W. Elbert and P. Sommers, Astrophys. J. **441**, 151 (1995).

[4] F. Halzen, R. A. Vazquez, T. Stanev and V. P. Vankov, Astropart. Phys. **3**, 151 (1995).

[5] T. Abu-Zayyad *et al.*, astro-ph/0208301.

[6] See for example J. Swain, astro-ph/0309515.

[7] T. Weiler, Astropart. Phys. **11**, 303 (1999); D. Fargion, B. Mele, and A. Salis, Astrophys. J. **517**, 725 (1999).

[8] T. J. Weiler, Phys. Rev. Lett. **49**, 234 (1982); Astrophys. J. **285**, 495 (1984); E. Roulet, Phys. Rev. D **47**, 5247 (1993); Updated recently in B. Eberle, A. Ringwald, L. Song, and T. J. Weiler, Phys. Rev. D **70**, 023007 (2004).

[9] D. N. Spergel *et al.*, Astrophys. J. Suppl. Ser. **148**, 175 (2003).

[10] S. Hannestad, J. Cosmol. Astropart. Phys. 05 (2003) 004; S. Hannestad and G. Raffelt, J. Cosmol. Astropart. Phys. 04 (2004) 008; Ø. Elgarøy and O. Lahav, J. Cosmol. Astropart. Phys. 04 (2003) 004.

[11] V. Barger, D. Marfatia, and A. Tregre, Phys. Lett. B **595**, 55 (2004).

[12] S.W. Allen, R.W. Schmidt, and S. L. Bridle, Mon. Not. R. Astron. Soc. **346**, 593 (2003).

[13] P. Crotty, J. Lesgourgues, and S. Pastor, Phys. Rev. D **69**, 123007 (2004).

[14] R. Protheroe and P. Johnson, Nucl. Phys. B, Proc. Suppl. **48**, 485 (1996); R. Protheroe and T. Stanev, Phys. Rev. Lett. **77**, 3708 (1996).

[15] Z. Fodor, S. Katz, and A. Ringwald, J. High Energy Phys. 06 (2002) 046.

[16] Super-Kamiokande Collaboration, K. Scholberg, hep-ex/9905016.

[17] G. Gelmini and A. Kusenko, Phys. Rev. Lett. **82**, 5202 (1999)

[18] G. Gelmini and G. Varieschi, hep-ph/0201273.

[19] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[20] P. Bhattacharjee and G. Sigl, Phys. Rep. **327**, 109 (2000).

[21] R. J. Protheroe and P. L. Biermann, Astropart. Phys. **6**, 45 (1996); **7**, 181(E) (1997).

[22] M. Takeda *et al.*, Astropart. Phys. **19**, 447 (2003); Interesting discussions of apertures, AGASA and otherwise, can be found in L. Anchordoqui, J. Feng, H. Goldberg, and A. Shapere, Phys. Rev. D **65**, 124027 (2002); Phys. Rev. D **66**, 103002 (2002).

[23] F.W. Stecker, Phys. Rev. Lett. **21**, 1016 (1968).

[24] F. Halzen *et al.*, Astropart. Phys. **3**, 151 (1995).

[25] T. A. Clark, L.W. Brown, and J. K. Alexander, Nature (London) **228**, 847 (1970).

[26] M. Nagano and A. A. Watson, Rev. Mod. Phys. **72**, 689 (2000), and references therein.

[27] S. Singh and C. P. Ma, Phys. Rev. D **67**, 023506 (2003).

[28] A. Dolgov, S. Hansen, S. Pastor, S. Petcov, G. Raffelt, and D. Semikoz, Nucl. Phys. B **632**, 363(2002); K. Abazajian, J. Beacom, and N. Bell, Phys. Rev. D **66**, 013008(2002); Y. Y. Wong, Phys. Rev. D **66**, 025015 (2002); V. Barger, J. Kneller, P. Langacker, D. Marfatia, G. Steigman, Phys. Lett. B **569**, 123 (2003).

[29] G. Farrar and T. Piran, astro-ph/0010370.

[30] P.W. Gorham, K. M. Liewer, C. J. Naudet, D. P. Saltzberg, and D. R. Williams, astro-ph/0102435;P. Gorham, C. Hebert, K. Liewer, C. Naudet, D. Saltzberg, and D. Williams, Phys. Rev. Lett. **93**, 041101 (2004).

[31] N. Lehtinen, P. Gorham, A. Jacobson, and R. Roussel-Dupre, Phys. Rev. D **69**, 013008 (2004).

[32] D. Semikoz and G. Sigl, J. Cosmol. Astropart. Phys. 04 (2004) 003.

[33] O. Kalashev, V. Kuzmin, D. Semikoz, and G. Sigl, Phys. Rev. D **65**, 103003 (2002); Phys. Rev. D **66**, 063004 (2002); D. Gorbunov, P. Tinyakov, and S. Troitsky, Astropart. Phys. **18**, 463 (2003); V. Berezinsky, hep-ph/0303091;V. Berezinsky, M. Narayan, and F. Vissani, Nucl. Phys. B **658**, 254 (2003).

[34] V. Berezinsky, A. Gazizov, and S. Grigorieva, hep-ph/0204357.

[35] H. Klapdor-Kleingrothaus *et al.*, hep-ph/0404062.

[36] Karlsruhe Tritium Neutrino Experiment (KATRIN), with homepage http://www-ik1.fzk.de/tritium/

[37] K. N. Abazajian and S. Dodelson, Phys. Rev. Lett. **91**, 041301 (2003).

[38] S. Hannestad, Phys. Rev. D **67**, 085017 (2003); M. Kaplinghat, L. Knox, and Y. S. Song, Phys. Rev. Lett. **91**, 241301 (2003)].

[39] W. Buchmuller, P. Di Bari, and M. Plümacher, Phys. Lett. B **547**, 128 (2002); Nucl. Phys. B **665**, 445 (2003); hep-ph/0401240; G. F. Giudice, A. Notari, M. Raidal, A. Riotto, and A. Strumia, Nucl. Phys. B **685**, 89 (2004).