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Neutrino clustering and the Z-burst model

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Abstract

The possibility that the observed Ultra High Energy Cosmic Rays are generated by high energy neutrinos creating "Z-bursts" in resonant interactions with the background neutrinos has been proposed, but there are difficulties in generating enough events with reasonable incident neutrino fluxes.

We point out that this difficulty is overcome if the background neutrinos have coalesced into "neutrino clouds" — a possibility previously suggested by some of us in another context. The limitations that this mechanism for the generation of UHECRs places on the high energy neutrino flux, on the masses of the background neutrinos and the characteristics of the neutrino clouds are spelled out.

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1 Introduction

The continuation of the cosmic ray spectrum beyond the GZK (Greisen, Zatsepen and Kuzmin) cutoff is a puzzle which has inspired many attempts at explanation. Neutrino-anti-neutrino annihilation into a Z-boson which subsequently decays to hadrons and leptons is one promising solution of the problem. Should relic neutrinos possess a mass in the eV/c^2 range the center of momentum energy required for resonant annihilation can be produced by cosmic ray neutrinos of energy $\sim 10^{21}$ eV. This proposal was first examined in detail by Weiler [1] [2] and Fargion [3] , who assumed that the relic neutrinos cluster in galaxies up to two or three times the mean relic density, and found that the required flux of cosmic ray neutrinos is larger than had previously been suggested. It has been suggested that the clustering may extend to densities of 100 to 10000 times the normal relic density on galactic scales, to moderate the required incident flux [4].

Independently, it has been shown that the relic neutrinos may have a local density, on scales of the solar system to a few parsecs, which may be many orders of magnitude higher than standard cosmology predicts without conflicting with any known experimental results [5]. Furthermore, the formation mechanism provides a strong argument for a natural association between the so called neutrino clouds of Ref. ([5]) with small celestial objects such as stars and solar systems.

In this note we investigate the consequences of this latter scenario for the measured Z-burst rate and for the bounds on the neutrino cloud. Specifically, we find the neutrino cloud radius and density range required to reproduce the observed flux of UHECRs and use the non-observation of coincident UHECR events to strengthen further these constraints.

We note that recent studies [6, 7] of the Z-burst explanation for UHECRs have derived information about the masses of the relic neutrinos. In the light of the present study of a dense local cloud of neutrinos as the target, we note that the Fermi motion of the neutrinos in the local cloud would complicate attempts to determine the neutrino mass spectrum from the observations of UHECRs.

2 Numbers and formalism

2.1 Z-burst flux

To evaluate the Z-burst flux at earth we will follow closely the formalism used by Weiler [2]. The change in the differential neutrino flux density $F_\nu(E_\nu, x)$

at a given energy E_ν and a distance x from its source is given by

$$dF_\nu(E_\nu, x) = -F_\nu(E_\nu, x)\sigma_\nu(E_\nu)n_\nu(x)dx, \tag{1}$$

where $\sigma_\nu(E_\nu)$ is the annihilation cross section, and $n_\nu(x)$ is the local neutrino density. The reduction in neutrino flux found at a distance D from the source is therefore found to be

$$\delta F_\nu(D) \;=\; \int dE_\nu F_\nu(E_\nu, 0)\Big(1 - \exp\{-\sigma(E_\nu)S(D)\}\Big), \tag{2}$$

where $S(D) = \int_0^D n_\nu(x)dx$ is the column density, and $\delta F_\nu(D) = F_\nu(0) - F_\nu(D)$.

In the narrow resonance approximation, where the variation in $F_\nu(E_\nu, 0)$ over the resonant energy is small, we can write

$$\delta F_\nu(D) \;=\; E_R F_\nu(E_R, 0)\int \frac{ds}{M_Z^2}\Big(1 - \exp\{-\sigma(s)S(D)\}\Big), \tag{3}$$

where the resonance energy E_R corresponds to a neutrino energy such that the center of momentum energy is $s = M_Z^2$. From this point on references to the neutrino flux should be taken to mean the quantity $E_R F_\nu(E_R, 0)$ with units $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The main contribution to $\sigma(s)$ is given by the s-channel Z-resonance, $\nu\bar{\nu} \to f\bar{f}$, with a branching ratio of 70% to hadrons, 20% to neutrinos and 10% to charged leptons[8],

$$\sigma_Z(s) \;=\; \sum_f \frac{2G_F^2}{3\pi} n_f s M_Z^4 \left[\frac{t_3^2(f) - 2t_3(f)Q_f s_W^2 + 2Q_f^2 s_W^4}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}\right] \tag{4}$$

where the quantities in the square brackets are the standard model weak isospin numbers, charge and sine of the Weak angle. In our calculation we set $\sigma(s) = \sigma_Z(s)$.

The only quantity entering these considerations which has been measured directly are the post GZK events, with fluxes quoted as $F_{p/\gamma} = 10^{-19}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ above 5×10^{19} eV and $F_{p/\gamma} \sim 2 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ above 5×10^{20} eV [2][9]. Assuming the Z-burst flux equals $\delta F_\nu(D)$, and that the Z's are then converted to nucleons and photons, we can write

$$F_{p/\gamma} = M \times \delta F_\nu(D), \tag{5}$$

where M is the photon and nucleon multiplicity per Z-burst, estimated to be ~ 30. The aim of any calculation must be to reproduce the measured value of $F_{p/\gamma}$.

2.2 Neutrino flux

The Z-burst model, be it in the presence of a non-clustered relic neutrino background or a neutrino cloud, requires a flux of UHE neutrinos. It is no surprise that the neutrino flux has not been directly measured at UHE energies; however there are theoretical as well as experimental upper bounds.

The experimental upper bounds are derived in Ref. ([2]) from the non-observation of deeply penetrating particles with energy $> 10^{17}$ eV at the Fly's Eye detector in Utah [10]. The upper bounds on the flux are: 2×10^{-13}, 3×10^{-14} and 5×10^{-16} cm^{-2}s^{-1}sr^{-1} for $E_\nu = 10^{17}$, 10^{18} and 10^{20} eV respectively. This is unfortunately not able to constrain the Z-burst model. In the absence of experimental data one needs to turn to models of astrophysical particle acceleration.

The mechanism by which primaries with energies above 10^{19} eV are produced is as much a puzzle as their propagation to the earth. Neutrino production resulting from the interaction of nucleons produced in AGN jets or gamma-ray bursts interacting with the cosmic microwave background is one explanation; other explanations involve more exotic physics such as decaying super heavy particles, or topological defects. For a review of such theories and a discussion of the expected neutrino flux see Ref. ([11]) and references therein. The former explanation is the only theoretical description which is non-speculative in that it uses only standard model physics. There is however an ongoing debate as to the magnitude of the neutrino flux which may be derived from conventional sources [12]. Depending on the assumptions made the upper-bound to the neutrino flux from astrophysical sources ranges from $E_R F_\nu(E_R, 0) \leq 3 \times 10^{-20}$ to 1×10^{-19}cm^{-2}s^{-1}sr^{-1}.

2.3 Cloud density and radius

While the neutrino cloud can be formed with a complex density profile, e.g. with more massive species at the center [5], we parameterise the cloud as a sphere with no diffuse boundary such that the density of the relic neutrinos is

$$n_\nu(x) = n_c(x)\theta(R - x) + n_0(x)\theta(x - R), \tag{6}$$

where $n_c(x)$ is the density inside the cloud and $n_0(x)$ is the density outside. In the standard theory the density of relic neutrinos is $n_0(x) = 54\text{cm}^{-3}$, the formation of neutrino clouds would deplete this number to a negligible quantity, such that in our calculations it can be safely ignored. A more complex model of the cloud structure would include a sum over the different mass eigenstates of the neutrino species, as well as a diffuse boundary, and perhaps some directional and temporal dependence taking into account cloud dynamics. However these additions will not result in large changes to the calculated flux. We consider relic and cosmic ray neutrinos with a mass of $1\mathrm{eV/c}^2$, and clouds with radii in the range of $10^{14} - 10^{20}$ cm [1] and density in the range of $10^{10} - 10^{16}$ cm^{-3}. These parameters are not in conflict with the requirement that the total mass of dark matter within the orbit of Uranus be $\leq 3 \times 10^{-6} M_\odot$ [13].

3 Results for neutrino clouds

Clouds of neutrinos with density ranging from 10^{10} cm^{-3} to 10^{16} cm^{-3} have a correspondingly large range in Fermi energy. In fact 1 eV/c^2 mass neutrinos in a 10^{10} cm^{-3} cloud are non-relativistic, while in a 10^{16} cm^{-3} cloud they are very much relativistic. In the following analysis we temporarily neglect the effects of the Fermi motion for clarity in the exposition, returning to it at a later point.

The crucial element in our analysis is the column density $S(D)$. In Fig. 1 the column density needed to produce $F_{p/\gamma}$ for various values of neutrino flux is shown. The upper curve corresponds to a flux of $F_{p/\gamma} = 10^{-19}$ cm^{-2}s^{-1}sr^{-1} while the lower curve corresponds to $F_{p/\gamma} = 10^{-20}$ cm^{-2}s^{-1}sr^{-1}. We would expect the actual value lies between these two values. The minimum column density for a source of neutrinos traveling 50 Mpc to earth, assuming a flat distribution of relic neutrinos with a density of 54 cm^{-3}, is approximately 10^{28}cm^{-2}, hence the column density is not evaluated below the point where the cosmic rays produced on the most dilute reasonable background exceeds the observed flux above the GZK cut off. With the clustering of relic neutrinos on scales described in Ref. ([2]) the column density is increased to $S(D) \sim 10^{29}$ cm^{-2}, while for a neutrino cloud with radius $R = 50$ pc and density $n(x) = 10^{14}$ cm^{-3} we have $S(D) \sim 10^{34}$ cm^{-2}. This makes the demands on the incident neutrino flux much more modest.

Using the fact that the flux of UHECRs is $10^{-20} \leq F_{p/\gamma} \leq 10^{-19}$ we can establish an allowed neutrino cloud parameter range, depending of course on the incident neutrino flux. In Sect. 2.2. we saw that the magnitude of the cosmic neutrino flux is open to question. Most models place an upper bound of $E_R F(E_R, 0) \leq 10^{-19}$cm^{-2}s^{-1}sr^{-1}, while the lowest expected flux is not at all known. However in the context of the Z-burst model we can define a minimum required flux, that is, the smallest neutrino flux able to produce

[1] In more familiar units $\sim 7 - 7 \times 10^6$ au or $\sim 3 \times 10^{-5} - 30$ pc

$F_{p/\gamma}$ assuming the incident neutrinos are absorbed in their entirety.

$$E_R F_{\nu\ min}(E_R, x) = \frac{M_Z F_{p/\gamma}}{M\Gamma_Z} . \tag{7}$$

This situation would occur if the average interaction length of the neutrino becomes significantly less than the cloud radius. Depending on the value of $F_{p/\gamma}$, $10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ or $10^{-19}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ the corresponding minimum neutrino flux is 5.6×10^{-21} or $5.6 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ respectively. The minimum neutrino flux is approached for high column density and small neutrino flux in Fig. 1.

The neutrino cloud radius and density permitted by the observed UHE CR data are plotted in Figs. 2 and 3. The neutrino flux in Fig. 2. is that of the upper bound $E_R F_\nu(E_R, 0) = 10^{-19}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$, and for Fig. 3, just above the minimum required, $E_R F_\nu(E_R, 0) = 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. In the first case the observed UHECRs can be fully accounted for, while in the second a maximum flux of $F_{p/\gamma} \sim 1.7 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ is produced.

We now return to the question of the Fermi motion of the neutrinos in the cloud. This motion will alter the value of the resonant energy E_R. For a cosmic neutrino interacting with a relic neutrino $s = 2(E_\nu E_c - \vec{p}_\nu \cdot \vec{p}_c)$ where E_c and $\vec{p}_c$ are the energy and momentum of the relic neutrino, at resonance and for a relic neutrino at rest $2m_\nu E_\nu = M_Z^2$, hence $E_R = \frac{M_Z^2}{2m_\nu}$. In a neutrino cloud of high density E_R will take on a range of values from $E_R = \frac{M_Z^2}{2m_\nu}$ to $E_R = \frac{M_Z^2}{2}(E_f - p_f \cos\theta)^{-1}$, where E_f and p_f are the Fermi energy and momentum of the cloud. To account for the smearing of resonant energy we define an average resonant energy $\bar{E}_R$,

$$\begin{aligned} \bar{E}_R &= \frac{1}{2N}\int_0^{p_f} \mathrm{d}^3 p_c \frac{M_Z^2}{(E_c - p_c\cos\theta)} \\ &= 4\pi\frac{M_Z^2}{2N}\int_0^{p_f} \mathrm{d}p_c p_c \sinh^{-1}\left(\frac{p_c}{m_\nu}\right) , \end{aligned} \tag{8}$$

where we have normalized to the Fermi momentum of the clouds, $N = \frac{4\pi}{3}p_f^3$. The resulting average energy is

$$\bar{E}_R = 4\pi\frac{M_Z^2}{8N}\left[\left(2p_f^2 + m_\nu^2\right)\sinh^{-1}\left(\frac{p_f}{m_\nu}\right) - p_f\sqrt{p_f^2 + m_\nu^2}\right], \tag{9}$$

which in the non-relativistic limit, as expected, reduces to

$$\bar{E}_R = 4\pi\frac{M_Z^2 p_f^3}{6N} = \frac{M_Z^2}{2m_\nu} . \tag{10}$$

In the case of a dense cloud, say $n_\nu = 10^{16}$ cm^{-3} the Fermi momentum for 1eV/c^2 mass neutrinos is $p_f \simeq 13$ eV. This results in an average resonant energy of $\bar{E}_R = 5.96 \times 10^{20}$ eV. Since our calculations have been performed in the center of momentum frame the reduction in resonant energy will not significantly alter any of our conclusions regarding the results discussed so far, in as much as the narrow resonance approximation holds over the width of the average energy distribution.

As an aside we note that the lowering of the resonant energy also allows the Z-burst mechanism to remain viable should neutrinos possess very small masses. In a non-clustered background the resonant energy for a 0.1 eV/c^2 mass neutrino, (rather than a 1 eV/c^2 neutrino) is $E_R = 4 \times 10^{22}$ eV, while in a dense neutrino cloud the average resonant energy can be as low as $\bar{E}_R = 1.6 \times 10^{21}$ eV making the Z-burst mechanism viable even if the differential neutrino flux drops off very rapidly with energy.

The standard deviation of the resonant energy, both in absolute terms and relative to the mean energy, increases with increasing Fermi energy.

$$(\Delta E)^2 = (E_R)_0^2 - (\bar{E}_R)^2. \tag{11}$$

However, for our present estimates we simply work with the mean resonant energy, and ignore the variation in flux over the width of the distribution.

A stronger constraint on the parameter range of the neutrino cloud comes from the non-observation of coincident CR events at ultra-high energies. The decay products of the Z-resonance are boosted into a cone of angle 10^{-11}, thus occupying an opening area of $A_p = \pi(\tan[10^{-11}]R_c)^2$, where R_c is the radius at which the neutrino annihilation took place. If the detection area of an experiment ($A_{\rm det}$) is larger than $A_{\rm p}/M$ then, on average a coincident event would be observed. The multiplicity in this context should count all particles produced at resonance not just those with an energy above the GZK cutoff.

With a multiplicity of ~ 60 and a detection area of $A_{\rm det} \sim 500{\rm km}^2$ a sphere of radius $R_c \sim 10^{18}$cm can be defined within which neutrino annihilations will on average result in the observation of a coincident event. The flux of coincident events ($F_{\rm c}$) will depend on the neutrino flux incident upon this sphere, and can be evaluated in the formalism of Sect. 2.1.

$$\begin{aligned} F_{\rm c} &= \delta F(E_\nu, x \geq (D - R_c)) \\ &= \Big(\delta F(E_\nu, D) - \delta F(E_\nu, D - R_c)\Big) \\ &= M \times E_R F(E_R, 0) \int \frac{ds}{M_Z^2}\Big(-\exp[-\sigma(s)S(D)] \\ &+ \exp[-\sigma(s)S(D - R_c)]\Big). \end{aligned} \tag{12}$$

If in addition we make the simplifying assumption that the relic neutrino column density outside the cloud is much less than the column density inside we are able to set $n(x) = n_c(x)$. Now the expression for the flux of coincident events becomes

$$\begin{aligned} F_{\rm c} &= E_R F(E_R, 0) \int \frac{ds}{M_Z^2} \exp[-\sigma(s) n_c R] \\ &\times \Big(\exp[\sigma(s) n_c R_c] - 1 \Big). \end{aligned} \tag{13}$$

The non-observation of a coincident flux implies the following bound on the total number (N_t) of such events observed by a particular experiment

$$N_t = \mathcal{A}\ t_r F_{\rm c} < 1, \tag{14}$$

where $\mathcal{A}$ is the experimental aperture at $E_0 > 10^{19.6}$eV and t_r is the experimental running time. In order for the neutrino cloud hypothesis to hold true, values of cloud density and radius must be found so that for each experiment,

$$\begin{aligned} F_{\rm c} &\geq E_R F(E_R, 0) \int \frac{ds}{M_Z^2} \exp[-\sigma(s) n_\nu R] \\ &\times \Big(1 - \exp[-\sigma(s) n_\nu R_c] \Big). \end{aligned} \tag{15}$$

The AGASA experiment currently has the largest exposure at

$$\mathcal{A} t_r = 670 \ \mathrm{km}^2 \ \mathrm{sr\ year} \simeq 2 \times 10^{21} \mathrm{cm}^2 \ \mathrm{sr\ s}\ . \tag{16}$$

This allows a coincident flux of $F_{\rm c} \simeq 5 \times 10^{-22} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$. The values of R and n_ν which solve Eq. 15 are shown in Figs. 2 and 3. The coincidence constraint allows a minimum cloud radius of $R_{\rm min} = 10^{18}$cm to be specified, and in some sense a maximum relic neutrino density, depending on the incident neutrino flux. The results of this calculation, and the bounds from the UHECR data serve to define an allowed parameter region for the neutrino cloud, see the shaded area in Figs. 2 and 3. We emphasize that, while the general principle that the non-observation of coincident events will eliminate a range of cloud radii less that a some "minimum" radius, the particular value of this minimum radius is determined only after a model for the cloud, is chosen, and the number density is calculated. The uniform cloud considered here is but the simplest of the cloud models introduced in Ref. ([5]), and even in that paper only a few simple cases were considered. These other models, with considerations similar to the above, will lead to different values for the minimum radius of the cloud. We do not pursue this discussion into limitations into the variety of possible clouds in the present paper.

The constraints on the parameter range of neutrino clouds as a result of the arguments based on coincident events have not taken into account the spatial resolution of the various CR experiments. While this is not an issue for medium to large clouds, it does become important for clouds with smaller radii. For example, if a neutrino cloud had a radius of 50au decay products would be confined to a cone of radius less than 10m at earth. This radius would be too small for most CR experiments to resolve, in which case the decay products will be measured as a single event with an energy of E_R. In the minimal Z-burst model E_R is a significantly higher energy than the highest energy CR event. However as we have shown in this note, for high density clouds the effect of the Fermi motion is to reduce the average value of E_R so that the possibility of small radii clouds is not excluded. We leave a full quantitative analysis to future work, and for the time being acknowledge that there is a region of allowed parameter space for small radii neutrino clouds.

4 Conclusion

We have shown it is possible that neutrino clouds, interacting with UHE neutrinos, are capable of producing the measured flux of UHECR's, and that this result is within both theoretical and experimental bounds imposed on the incident neutrino flux. The dimensions of the neutrino clouds required to produce the measured UHE CR flux assuming the Z-burst mechanism is responsible were investigated, and need no new theoretical treatment beyond that given in Ref. ([5]). The requirement that no coincident events are observed requires that uniform clouds, larger than some small radius still to be determined, are at least 0.3pc in radius — rather larger than originally envisaged in Ref. ([5]), but without disturbing the viability of the concept of neutrino clouds. Clouds with different density profiles will have different limitations placed on their radii.

Acknowledgments

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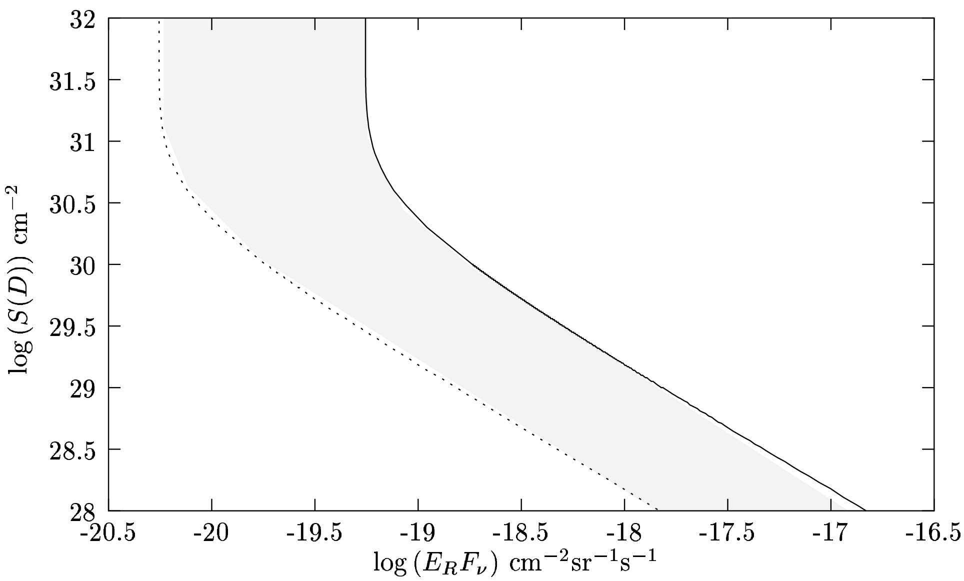

Figure 1: The dashed line corresponds to the required column density needed to produce a photon/hadron flux of 10^{-20}cm^{-2}s^{-1}sr^{-1}, while the solid line is the column density need for a photon/hadron flux of 10^{-19}cm^{-2}s^{-1}sr^{-1}. The shaded region corresponds to the experimentally allowed column density.

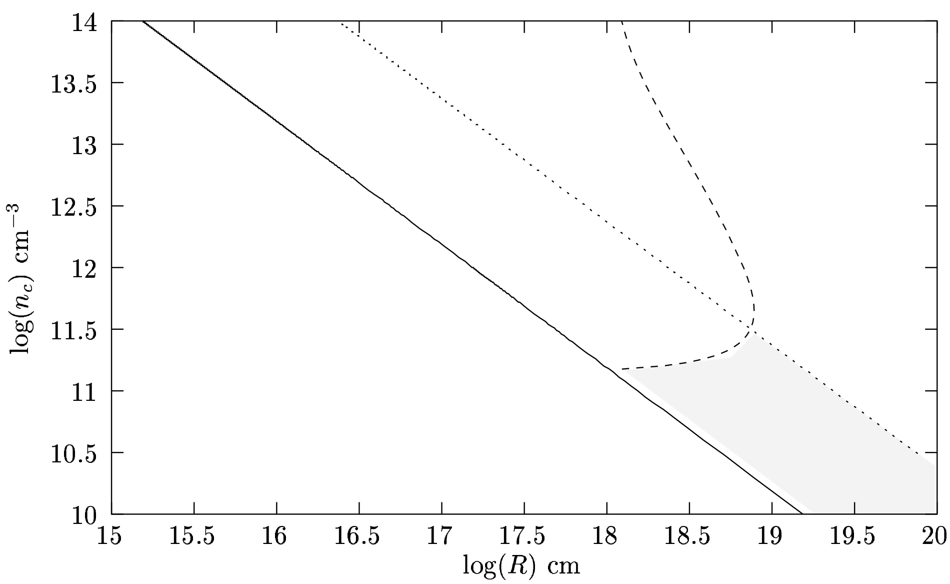

Figure 2: The solid line represents the cloud parameters required to produce a GZK flux of $F_{p/\gamma} = 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, with an incident neutrino flux of $E_R F_\nu(E_R, 0) = 10^{-19}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The dashed line represents a GZK flux of $F_{p/\gamma} = 10^{-19}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The short dashed line is the bound on R resulting from the non-observation of coincident events with an incident neutrino flux of $E_R F_\nu(E_R, 0) = 10^{-19}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The shaded region is the allowed parameter space.

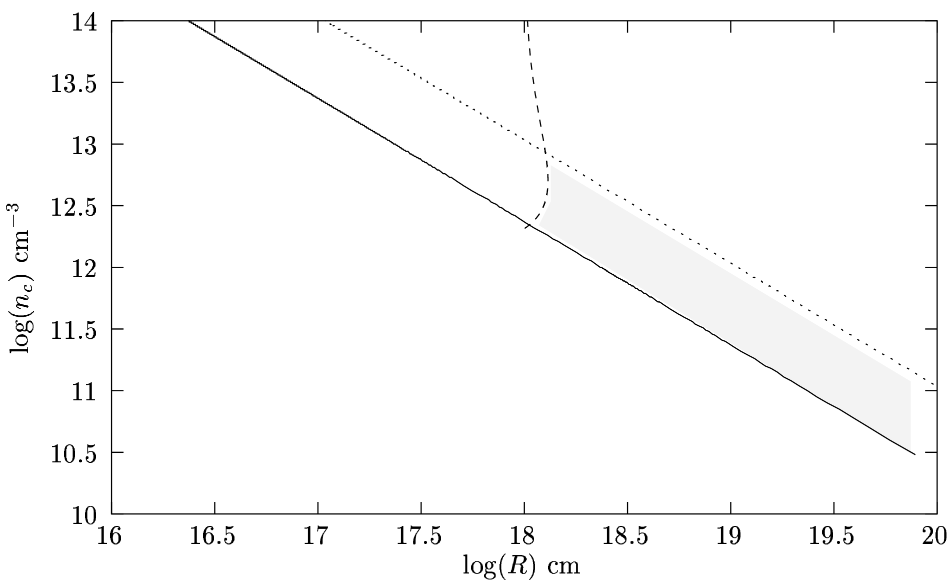

Figure 3: The solid line represents the cloud parameters required to produce a GZK flux of $F_{p/\gamma} = 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, with an incident neutrino flux of $E_R F_\nu(E_R, 0) = 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The dashed line represents a GZK flux of $F_{p/\gamma} = 1.7 \times 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, the maximum flux for this small incident neutrino flux. The short dashed line is the bound on R resulting from the non-observation of coincident events with an incident neutrino flux of $E_R F_\nu(E_R, 0) = 10^{-20}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The shaded region is the allowed parameter space.