Neutrinos from the Annihilation or Decay of Superheavy Relic Dark Matter Particles

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In light of the mounting evidence that the highest energy cosmic rays are dominated by protons and not gamma-rays, we discuss the prospect that these cosmic rays are generated in the decay or annihilation of superheavy relic particles. We calculate the high energy neutrino spectrum which results and normalize our results to the ultra-high energy cosmic ray spectrum. We show that most scenarios are already constrained by present limits placed by the AMANDA experiment.

1. Introduction

The discovery of cosmic rays with energy exceeding the GZK cutoff presents an interesting challenge to astrophysics, particle physics, or both. Numerous scenarios have been proposed to solve the problem. These include exotic particles, neutrinos with QCD scale cross sections, semi-local astrophysical sources and top-down models.

Recent measurements confirm that our universe contains a large fraction of cold dark matter. A top-down model in which annihilating or decaying superheavy particles produce the highest energy cosmic rays could potentially solve both of these problems.

Conventional particle physics implies that ultra high-energy jets fragment predominantly into photons with a small admixture of protons. This seems to be in disagreement with mounting evidence that the highest energy cosmic rays are not photons. This does not necessarily rule out superheavy particles as the source of the highest energy cosmic rays. The uncertainties associated with the cascading of the jets in the universal radio background and with the strength of intergalactic magnetic fields leave open the possibility that ultra high-energy photons may be depleted from the cosmic ray spectrum near $10^{20}$ eV, leaving a dominant proton component at GZK energies. With this in mind, we will choose to normalize the proton spectrum from top-down scenarios with the observed ultra high-energy cosmic ray flux.

Neutrinos are produced more numerously than protons and travel much greater distances. The main point of this note is to point out that this “renormalization” of the observed cosmic ray flux to protons generically predicts observable neutrino signals in operating high-energy neutrino telescopes such as AMANDA.

2. Nucleons from Ultra High-Energy Jets

To normalize the production rate of ultra high-energy jets, it is necessary to calculate the spectrum of nucleons resulting from their fragmentation. Each jet will fragment into a large number of hadrons approximated by a fragmentation function rooted in accelerator data. All hadrons produced eventually decay into pions and nucleons. For a detailed discussion of ultra high-energy fragmentation, see Ref.

To solve the ultra high-energy cosmic ray problem, this nucleon flux must accommodate the events above the GZK cutoff. Observations indicate on the order of $10^{-27}$ events $m^{-2} s^{-1} sr^{-1} GeV^{-1}$ in the energy range above the GZK cutoff ($5 \times 10^{19}$ eV to $2 \times 10^{20}$ eV). The formalism of a generic top-down scenario is sufficiently flexible to explain the data from either the HIRES or AGASA experiments. For an example, see Figure 1.
Figure 1. The ultra high-energy cosmic ray flux predicted from the decay or annihilation of superheavy dark matter particles producing $10^{21}$ eV hadronic jets is compared to the AGASA cosmic ray data. The distribution of dark matter used is isotropic with an overdensity factor of $10^5$ within 20 kpc. Note that all observed super GZK events can be explained by this mechanism.

3. Cross Sections and Lifetimes for Superheavy Particles as Dark Matter

If the superheavy relics responsible for the highest energy cosmic rays are also the solution to the dark matter problem, then

$$\rho_X \sim 0.3 \times \rho_{\text{critical}} \simeq 0.3 \times 8.45 \times 10^{-27} \text{kg/m}^3,$$

and may be much larger locally. Therefore, the lifetime of such a decaying particle must be:

$$\tau_X \sim \frac{\rho_X}{m_X \frac{dn_X}{dt}} \sim 10^{17}\text{years}.$$ (2)

Such a long lifetime may be disfavored by fine-tuning arguments, but can be possible. If, however, the superheavy relics in question were not the major dark matter component, this lifetime could be much shorter.

If instead we consider stable particles which can annihilate with each other, we can calculate their annihilation cross section as a function of velocity. For an isotropic distribution of particles,

$$\frac{\rho_X^2}{m_X^2} \sigma_{XX} v_{\text{rms}} \sim \frac{dn_X}{dt}.$$ (3)

For a extragalactic distribution,

$$\sigma_{XX} \sim \frac{2 \times 10^{-15} m^3 s^{-1}}{v_{\text{rms}}}.$$ (4)

or, for a galactic halo distribution,

$$\sigma_{XX} \sim \frac{10^{-19} m^3 s^{-1}}{v_{\text{rms}}}.$$ (5)

A characteristic velocity of 500 km/s, for example, would correspond to a annihilation cross section of $\sim 10^7$ bn for extragalactic dark matter or $\sim 10^3$ bn for a galactic halo distribution. If the dark matter were not uniformly distributed, however, but were distributed in clumps with characteristic densities of $\rho_{\text{clump}} \sim C \rho_{\text{mean}}$, then the annihilation cross sections could be in the mb range. It is interesting to note that if superheavy dark matter is distributed locally with mb elastic scattering cross sections, they would become gravitationally trapped in the sun and annihilate as described in Ref. [17].

4. Neutrinos from Ultra High-Energy Jets

Neutrinos are produced in several ways in the fragmentation of ultra high-energy jets: in semileptonic bottom and charm decays, in W producing top decays and most importantly, in the decay of charged pions. For a detailed discussion, see Ref. [16].

To obtain the neutrino flux, we multiply the injection spectrum by the average distance traveled by a neutrino and by the rate per volume for hadronic jets which we calculated earlier. Neutrinos, not being limited by scattering, travel up to the age of the universe at the speed of light ($\sim 3000$ Mpc in an Euclidean approximation). The predicted neutrino flux is shown in Figure 2. Note that this flux is significantly higher than the present limits placed by the AMANDA experiment [7] for the case of an isotropic distribution of ultra high-energy jets. For the galactic scenario, however, the flux predicted is comparable with present AMANDA-B10 limits. Also shown are the limits anticipated from AMANDA-II data and the IceCube experiment.
Figure 2. The muon neutrino flux from $10^{21}$ eV jets normalized to the highest energy cosmic rays. Shown are the fluxes calculated for an isotropic and for a galactic distribution of jets. The dotted lines shown are the experimental diffuse flux limits from present AMANDA-B10 data, projected AMANDA-II data and projected IceCube data. These limits are $E^2 \frac{dN}{dE} \leq 9 \times 10^{-7}$, $9 \times 10^{-8}$ and $5 \times 10^{-9}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$ respectively. Note that operating experiments can effectively test this range of models.

5. Event Rates in High-energy Neutrino Telescopes

The diffuse flux of high-energy neutrinos can be observed by operating and planned neutrino telescopes. AMANDA-B10, with an effective area of ~5,000 square meters has placed the strongest limits on the diffuse neutrino flux. Figure 2 shows that for a galactic distribution of superheavy dark matter particles, the predicted high-energy neutrino flux is on the order of the present diffuse flux limit. The neutrino flux for an isotropic distribution of ultra high-energy jets is well above the present limits. If superheavy particles are indeed the source of the highest energy cosmic rays, observations by high-energy neutrino telescopes should reveal the corresponding neutrino flux. For a review of cerenkov neutrino telescopes see Ref. [17,18].

Note that gamma ray astronomy can also provide an interesting test of these scenarios [19].

6. Conclusions

If the decay or annihilation of superheavy relics is the source of the highest energy cosmic rays, then a high-energy neutrino flux should accompany the observed cosmic ray flux. This neutrino flux will be much higher than the flux of nucleons due to the much greater mean free path of neutrinos and greater multiplicity of neutrinos produced in high-energy hadronic jets.

The high-energy neutrino flux generated in such a scenario can be calculated by normalizing the flux of appropriate particles to the ultra high-energy cosmic ray flux. With mounting evidence that the highest energy cosmic rays are protons or nuclei and not photons, we must require that the ultra high-energy photons are degraded by the universal radio background, leaving protons to dominate the highest energy cosmic ray flux. The neutrino flux must be normalized to the proton flux resulting in significantly improved prospects for its detection.

This paper shows that the neutrino flux accompanying the highest energy cosmic rays in these models is on the order of the limits placed by operating high-energy neutrino telescopes such as AMANDA. Further data from AMANDA II, or next generation neutrino telescope IceCube, can test the viability of models in which superheavy particles generate the highest energy cosmic rays.

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