Radio-astronomy method for detecting neutrinos and other elementary particles of superhigh energy

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The possibility of using radio telescopes to detect the radiation of electron-photon and hadron cascades generated in the interactions of neutrinos and other particles of superhigh energy ($\gtrsim 10^{20}$ eV) with the moon and other celestial objects is discussed.

1. Existing theories of elementary particles predict the existence of massive new entities both in the microworld and in macroscopic space (e.g., magnetic monopoles or superconducting cosmic strings). One possibility for experimentally searching for such entities is to study the interactions of cosmic particles of ultrahigh and superhigh energy, their fluxes and energy spectra, and the upper boundaries on their spectra. Such studies will require large-scale hadron and lepton detectors.[1] For example, a design for an installation for detecting extensive air showers with an area up to 1000 km^2 has recently been proposed[2] for studying particles with energies $E \approx 10^{19}$–10^{20} eV. A complex of underground detectors with a sensitive volume up to 10^4 m^3 is being developed in order to detect the interactions of neutrinos and other cosmic particles.[3] It has been suggested that deep-water optical detectors of the DUMAND type be constructed to "look at" volumes of water $> 10^7$ m^3 (Ref. 4).

More than 25 years ago, Askar'yan[5] pointed out the possibility of detecting cascades in a dense medium (in particular, ice) on the basis of the coherent Cerenkov radio emission of the excess of negative charges in the cascade. He discussed the detection of cascades in various types of underground rock and also in the lunar soil, by means of apparatus on the moon.

In 1981 it was suggested that neutrinos from the lower hemisphere be detected on the basis of the radio emission of cascades which arose in the earth's mantle and then continued into the atmosphere.[6] Antarctic ice (a target with a volume $\lesssim 10^{10}$ m^3) has also been discussed[7] as a target for neutrinos with $E_\nu \gtrsim 10^{15}$ eV. Research is being carried out on the Vostok station to learn about the background conditions for radio detectors of muons and neutrinos (RAMAND).[8] It appears that the time has come to examine the prospects for developing an apparatus complex in the Antarctic, which would also include scintillation detectors for the electron component and for the low-energy muons of extensive air showers, telescopes to detect the Cerenkov radiation of cascades in the atmosphere, and possibly detectors of the Cerenkov radiation of muons[9] at those depths in ice at which the latter becomes transparent. According to Ref. 10, only sporadic inclusions of air bubbles are found in the "perfectly transparent ice" at depths of 1300–1400 m.

2. The energy of the coherent Cerenkov radio emission of a cascade is

$W \approx 10^{-10}(E[\text{eV}]/10^{14})^2$ erg (Refs. 1 and 7), so the distance at which this radiation can be detected is proportional to E. Neutrinos with energies of 10^{20}–10^{22} are predicted in several models with superconducting strings.[11] If such massive particles as monopoles and maximons exist, the upper limit on the neutrino spectrum might reach 10^{25}–10^{28} eV (Ref. 12). Advanced radio telescopes can detect cascades which arise in the interaction of such neutrinos even with the matter of the surface layer of the moon facing us.[13]

The radiation spectrum at frequencies $f \lessdot f_{\max} \approx 1$ GHz is proportional to f. The energy is radiated in a pulse ($\Delta t \approx 10^{-8}$ s) at some angle with respect to the velocity vector of the cascade, in a "thick cone," whose solid angle we will take to be 0.5 sr for estimates. An observer inside this cone on the earth will receive a radiation flux density

$$S_{\text{pulse}} = 2fW(f_{max}^2\,\Omega D^2\,\Delta t)^{-1} = 3\times 10^{-23} f_9 E_{20}\ \text{W}/(\text{m}^2\cdot\text{Hz}), \qquad (1)$$

where D is the distance to the moon, $f_9 = f[\text{Hz}]/10^9$, and $E_{20} = E[\text{eV}]/10^{20}$.

The sensitivity of a radio telescope is $\Delta S = 2kT(A_{\text{eff}}\sqrt{\Delta f'\tau})^{-1}$; where T is the noise temperature, A_{eff} is the effective area of the telescope, k is the Boltzmann constant, Δf is the bandwidth of the receiver, and τ is the signal accumulation time ($\tau \geqslant 1/\Delta f$). Taking into account the limitations on τ and Δf (the latter stems from dispersion in the ionosphere: $\Delta f \leqslant \Delta f_{\text{disp}} = 1.2\times 10^{-19} f^3$) and also the possibility of using multichannel reception with a synthetic bandwidth $\Delta f_{\text{eff}} = n\Delta f \approx 0.3f$, we find

$$\Delta S_{\text{eff}} = 2kT(A_{\text{eff}}\ \Delta t\sqrt{\Delta f_{\text{disp}}\Delta f_{\text{eff}}})^{-1} = 1.5\times 10^{-13}\, T(A_{\text{eff}}\ \Delta t f^2)^{-1}\,\text{W}/(\text{m}^2\cdot\text{Hz}). \quad (2)$$

It can be seen from this figure that it would be possible in principle even today to detect cascades which arise in the interaction of particles with energies $E \gtrsim 10^{20}$ eV with lunar matter.

3. Estimates of the fluxes of superhigh-energy neutrinos made by Hill *et al.*[11] can

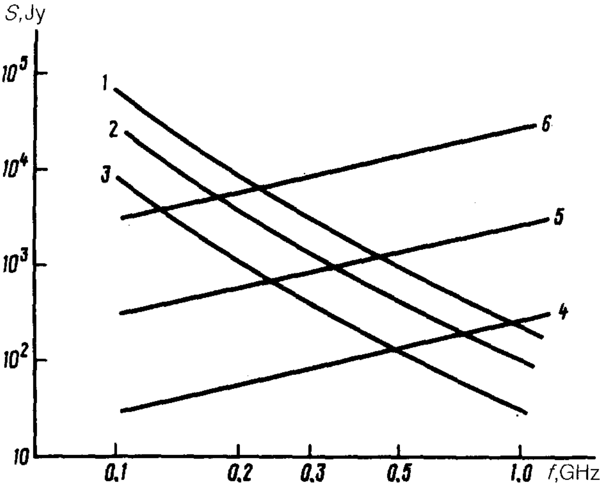

FIG. 1. Frequency dependence of the sensitivity ΔS_{eff} of radio telescopes (1) 70 m in diameter and (2) 100 m in diameter and of (3) the Arecibo radio telescope. Also shown here is the incident flux density S_{pulse} for cascades for (4) $E = 3\times 10^{19}$ eV, (5) 10^{20} eV, and (6) 3×10^{20} eV.

also be used to estimate the number of corresponding neutrino events. At $E \gtrsim 10^{20}$ eV, for example, up to 10^5 observable events per year should occur in a surface layer ~ 5 m thick on the side of the moon facing us (here we are assuming[14] $\sigma_{\nu N} = 10^{-31}$ cm^2). In other words, it might be possible to test several superconducting-string models of the universe.[11] The radio emission of cascades caused by protons (or nuclei) could escape from the lunar soil through scattering processes. Of particular interest might be the interaction of cosmic hadrons (γ rays) with energies $\gtrsim 10^{20}$ eV with the moon. In contrast with neutrino processes, the bursts due to protons would be observed only at the rim of the lunar disk.

The threshold detection energy might be reduced by putting antennas on lunar satellites or on certain planets. From special geostationary satellites it would be possible in principle to detect the radio emission of cascades generated by neutrinos in the ice masses of the Antarctic continent.

By making use of the characteristic "coloring" of a signal, which results from its passage through the ionosphere (the dispersive retardation of a pulse at lower frequencies), and also simultaneous observations by means of several instruments, one might substantially improve the reliability with which the radio bursts of interest are detected. Although existing radio telescopes are not yet equipped with suitable hardware, there is the hope that this project can be accomplished in the fairly near future.

4. In summary, the lunar surface might prove to be an extremely good target for the radio emission of neutrinos and hadrons with energies of 10^{20} eV and up. The effective area and the detection volume of this detector might be $\approx 10^7$ km^2 and $\approx 10^5$ km^3, respectively.

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