HIGH-ENERGY NEUTRINOS FROM A LUNAR OBSERVATORY

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The detection of high-energy (HE) cosmic and solar-flare neutrinos near the lunar surface would be feasible at energies much lower than for a terrestrial observatory. At these lower energies ($\gtrsim 10^9$ eV), the neutrino background is drastically reduced below that generated by cosmic rays in the earth's atmosphere. Because of the short mean free path (<1m) of the progenitor pi and K mesons against nuclear interactions in lunar rocks, the neutrino background would be quite low. At 1 GeV, less than 1% of the pions would decay; at 10 GeV, 0.1%. Thus, if the neutrino flux to be observed is intense enough, and its spectrum is steep enough, then the signal-to-noise ratio is very favorable. The observation of HE neutrinos from solar flares would be dramatically enhanced, especially at lower energies, since the flare spectra are very steep. Detection of these neutrinos on earth does not appear to be feasible. A remarkable feature of solar flares as viewed in HE neutrinos from a lunar base is that the entire surface of the sun would be "visible". Diffuse sources of HE neutrinos, such as the Galactic disc (especially from the Galactic center), would be detectable at energies between, say, 10^9 and 10^{11} eV. On earth, they are swamped by the overwhelming atmospheric background.

1. Introduction. The advantages of a lunar observatory for neutrino astronomy were discussed some years ago by F. Reines (1965). In the present paper we suggest that the investigation of neutrinos from astrophysical sites at energies between 1 and 10^3 GeV can be carried out better on the moon than on the earth. In the dense lunar materials, competition between nuclear interactions of pions and their decay suppresses the frequency of decay. In the tenuous upper atmosphere of the earth, on the other hand, the decay of pions (and their muon progeny) does generate neutrinos. Hence the flux of neutrinos near the surface of the moon is about 10^{-3} of that on the earth at energies between 1 and 10^2 GeV, and about 10^{-2} at 10^3 GeV. Only the background due to prompt neutrinos from the decay of charmed particles in the atmosphere is not suppressed.

At energies below 1 GeV, however, the path length of pions against decay diminishes as the Lorentz factor approaches unity, and pion decay

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is no longer suppressed, even on the moon. Furthermore, due to the absence of magnetic shielding on the moon, the flux of low-energy cosmic rays incident on the lunar surface is much higher than the average flux at the top of the earth's atmosphere. This further enhances the low-energy neutrino intensity (E>1 GeV) on the moon. (The suppression of neutrino background was quantitatively explored by Cherry and Lande (1985).

Accordingly, a lunar base is probably an unsuitable site for observing the low-energy neutrinos (~10 MeV) from stellar gravitational collapse. Moreover, it is not competitive for recording neutrinos at very high energies ($E>10^3$ GeV); this can be done more readily with Cerenkov light detectors in a large volume of sea water (some 10^8 m^3) near the bottom of the ocean. Such an array--DUMAND--a deep underwater muon and neutrino detector, will be emplaced in the waters near Hawaii in the near future (Peterson 1983).

2. Criteria for Candidate Neutrino Sources to be Explored on the Moon.

What types of neutrino sources are likely to be observable between 1 and 10^3 GeV? This is the energy interval for optimum detection by a neutrino observatory under the lunar surface (say, about 100 m below). The sources should emit neutrinos much more copiously above 1 GeV than above 1 TeV, so as to permit the construction of a neutrino observatory significantly smaller than DUMAND. An important constraint is imposed by the interaction cross section of neutrinos, which increases linearly with energy between 1 and 10^3 GeV. As a result, the observation of lower-energy neutrinos becomes more difficult. This cross section is given by

$$\sigma_{\nu N} = (0.7 \text{ or } 0.8) \times 10^{-38} E_\nu \text{ cm}^2,$$

and

$$\sigma_{\bar{\nu} N} = 0.3 \times 10^{-38} E_{\bar{\nu}} \text{ cm}^2$$

for neutrinos and anti-neutrinos, respectively. Let the energy spectrum of the neutrinos be

$$\frac{dJ}{dE_\nu} = KE_\nu^{-\alpha}.$$

Then the event rate is proportional to

$$\int_{E_o}^{E_{max}} \sigma(E_o)KE_\nu^{-\alpha}\, dE_\nu;$$

i.e., it is proportional to

$$E_o^{-(\alpha-2)} - E_{max}^{-(\alpha-2)}.$$

Thus, one criterion for significant source strength in the energy interval between 1 and 10^3 GeV is a steep neutrino spectrum, with the exponent α appreciably greater than 2.

3. Some Promising Candidate-Sources. Solar flares generate particles having steep energy spectra, with $\alpha = 4$ to 7 at proton energies above 1 GeV. Erofeeva, Lyutov, and Murzin (1983) explored the use of a deep underwater detector of 10^6 tons for observing neutrinos from solar flares. They did not investigate the neutrino background in their paper. We estimate that the background rate is about 10^3 per day. If the neutrinos are emitted in about 20 minutes, as are the gamma rays from a flare, then the background rate is down to 10 for the duration of the flare. If, moreover, an angular resolution of 1 steradian is obtained, then the background is down to ~1 event for the duration of the flare.

For observation of neutrinos from very large flares, such as occur about once per solar cycle, a terrestrial underwater observatory of 10^6 tons seems adequate. However, for larger observatories, $>10^6$ tons, the neutrino background on earth becomes prohibitive. Thus, for observing fine-time structure or neutrino energy spectra of very large flares, or for recording somewhat smaller flares, a lunar observatory of $>10^6$ tons provides an opportunity to carry out studies of flares that are not possible on the earth. Even flares on the remote side of the sun become observable, since neutrinos with energies $<10^{11}$ eV can traverse the solar diameter. In fact, for a given size of flare, neutrinos should reach the detector in greater numbers from the far side than from flares on the near side. This is due to the favorable rate of production of pions (hence of daughter neutrinos) that move toward the observer, when the progenitor protons or other energetic nuclei--on the far side--are directed toward the solar surface.

Another, more diffuse source of neutrinos with a fairly steep energy spectrum $\sigma = 2.7$, is that from the central annulus of the Galactic disk, $\pm 60^\circ$ in longitude and $\pm 5^\circ$ in latitude about the Galactic center. Stecker, Shapiro and Silberberg (1979) explored the detectability of these neutrinos at 10^3 GeV with a DUMAND array of 10^9 tons (having an effective detection volume of some 10^{10} tons). The estimated rate of neutrino events to be expected was 130 per year, swamped by 1.8×10^4 background events per year. At 1 GeV, the event rate is about 100 times higher, so that even in a smaller detector of $\sim 10^7$ tons, the event rate is about 10 per year, with the signal and background counts being nearly equal in a lunar observatory.

In addition, there are many interesting discrete candidate-sources of neutrinos: accreting neutron stars (including pulsars) in binary systems, active galactic nuclei with accretion disks from which matter drifts into ultra-massive black holes (Silberberg and Shapiro 1979), and the expanding shells around young pulsars (Berezinsky 1976, Shapiro and Silberberg 1979). However, the energy spectra of neutrinos from these sources are as yet unknown.

We present here the results of a sample calculation for SS433, which appears to be one of the most promising candidate sources in our Galaxy, at a distance of about 3 Kpc. This object is probably an accreting black hole in a binary system; it has two relativistic jets and other remarkable features. Its estimated power output is 3×10^{39} ergs/sec (Grindlay et al. 1984), but values that are higher by an order of magnitude have also been proposed (Eichler 1980). If we assume that a power input of 3×10^{39} ergs/sec yields protons of energy ≥ 10 GeV, and that these protons suffer nuclear collisions, a detector of 10^6 tons would permit the observation of about 30 neutrino events per year. With 10^7 tons, several different sources of neutrinos become detectable.

4. Conclusions. We conclude that a neutrino detector of $\geq 10^6$ tons on the moon--i.e., one considerably more compact than the proposed DUMAND array--would open up a new window of neutrino astronomy, making possible the study of neutrinos at 1 to 10^3 GeV.* The effort must probably await the establishment of a substantial lunar colony. Because of its large size, the detector would probably have to be locally constructed (perhaps of glass fabricated from lunar materials.)

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*Even a smaller detector of 10^4 tons could detect a giant solar flare like that of Feb. 23, 1956. The pulse is likely to be of such short duration (<20 min) that the atmospheric background would not degrade terrestrial observation.

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