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REMOTE SENSING OF ASTROFUEL

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Remote Sensing of Astrofuel™

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Abstract

A direct, high-resolution measurement from lunar orbit of the location of high concentrations of ^3He in the lunar regolith is needed for the initiation of cost-effective mining operations on the moon. Gamma-ray spectroscopy has been successfully used to map the abundances and distributions of certain elements present in planetary regoliths. Helium-3 is unique among these elements since the gamma-rays produced in the $^3He(n, \gamma)^4He$ reaction are 20.6 MeV or above. Thus, detection of the gamma-ray flux from ^3He should be free of interference from the gamma-rays of any other neutron capture reaction. Since ^3He is present in the relatively small concentration of about 10 - 30 parts per billion by weight, the gamma-ray flux resulting from the $^3He(n, \gamma)^4He$ reaction using galactic cosmic-ray (GCR)-induced neutrons will be extremely small. We propose to map the 20.6 MeV gamma-ray from ^3He during very large solar proton flares (VLSPF) to take advantage of the increased flux of solar cosmic-ray (SCR)-induced neutrons. The neutron production spectrum in the lunar regolith has been calculated from GOES-7 satellite observations of the October 1989 VLSPF using the BRYNTRN charged-particle transport code. This spectrum is used as input for the ONEDANT neutron/gamma-ray transport code. The production of SCR-induced neutrons during a VLSPF is thus calculated to be several orders of magnitude greater than the production expected for GCR-induced neutrons. The production of 20.6 MeV gamma-rays is also calculated to be several orders of magnitude greater during a VLSPF. This method of mapping the 20.6 MeV gamma ray from the $^3He(n, \gamma)^4He$ reaction would also provide increased sensitivity for mapping other elements in the lunar regolith, and may allow the detection of previously unmapped elements in the lunar regolith as well as trace elements in the Earth's upper atmosphere.

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Introduction

A map of the spatial distribution of ^3He in the lunar regolith is needed to locate the first cost-effective mining operations on the moon. While the concentration of titanium has been shown to be a good guide to helium distribution, the amount of solar-wind deposited helium also depends upon the maturity of the regolith. Thus, a direct method of detecting ^3He from lunar orbit is desired. One such method involves the production and detection of prompt gamma-rays from the neutron capture reaction involving the $^3He(n, \gamma)^4He$ reaction. Due to the complicated nature of the problem, we will only discuss the production of these prompt gamma-rays in the current paper. The detection of these gamma-rays will be discussed in a future publication.

Production of Prompt Gamma-Rays From ^3He in the Lunar Regolith

Helium-3 - Neutron Capture Reaction

This detection scheme depends on the neutron capture reaction, $^3He(n, \gamma)^4He$. The flux of prompt gamma-rays yielded by this reaction depends on three quantities: the flux of neutrons present, $\phi_n(E)$; the neutron capture cross section of ^3He, $\sigma_{n,\gamma}(E)$; and the concentration of ^3He atoms in the regolith, $N_{^3He}$ (1).

$$\frac{\text{Gamma-rays}}{\text{cm}^2\text{-s}} = \sum \phi_n(E)\sigma_{n,\gamma}(E)N_{^3He} \tag{1}$$

The quantities in Equation (1) are quite small: ϕ_n = 10 - 20 neutrons/cm^2-s for galactic cosmic-ray (GCR) induced thermal neutrons [Heiken et al., 1991], $\sigma_{n,\gamma}$ = 0.03 mb at thermal energies [Heiken et al. 1991] and $N_{^3He} = 10^{16}$ atoms of ^3He per cm^3 in the lunar regolith. Since all of these values are relatively small, we are essentially "looking for a needle in a haystack." Fortunately, it is a different colored needle. The Q-value of this reaction is 20.6 MeV [National Nuclear Data Center 1993]. The only other neutron capture reactions capable of producing gamma-rays in this energy range are isotopes of the other low-Z elements which are more diffuse than ^3He in the lunar regolith. There should be very little competition from gamma-rays produced by other (n, γ) reactions at energies greater than about 20 MeV. The cross sections for the $^3He(n, \gamma)^4He$ reaction as well as two other possible neutron reactions involving ^3He and a neutron are shown in Figure 1. These data show that the probability of a prompt gamma-ray being produced is extremely small. Thus, the number of prompt gamma-rays available for remote detection is dependent only upon the flux of neutrons in the lunar regolith over a few attenuation lengths for the gamma-rays in the lunar regolith. The attenuation length of 20.6 MeV gamma-rays in the lunar regolith is 30.2 cm.

Possible Sources of Neutrons in the Lunar Regolith

The flux of prompt gamma-rays from ^3He in the lunar regolith is directly dependent on the number of neutrons available for capture. We have examined

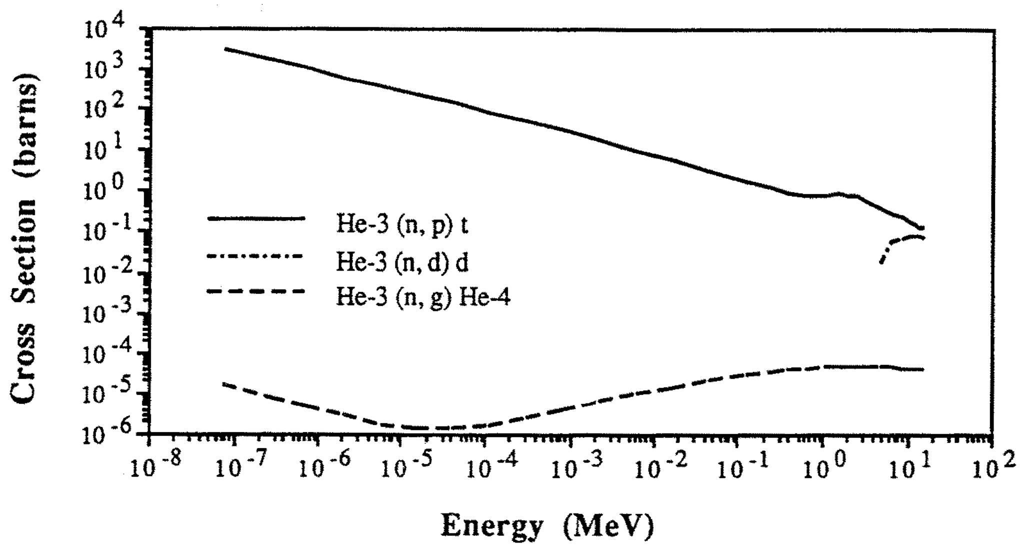

Figure 1. Possible ^{3}He - neutron interaction cross sections (National Nuclear Data Center, BROND-2 data base).

several possible sources of neutrons in the lunar regolith to determine if any might provide enough neutrons to make ^{3}He detectable. These sources include natural radioactivity from primordial and cosmogenic radioactive species, the solar wind, galactic cosmic-rays, solar flares and neutrons produced from neutral particle beams. Most of the neutrons in the regolith are the products of (p, n) reactions between incident protons and higher-Z nuclei with energies above about 30 MeV/amu and the major constituents of the regolith such as SiO_2.

The flux of neutrons in the regolith due to natural radioactivity and solar wind particles is negligible (<< 1 neutron/cm^2-s) while GCR's induce approximately 10-20 neutrons/cm^2-s [National Nuclear Data Center 1993]. Using this flux in Equation (1) results in a prompt gamma-ray flux of about 1.1×10^{-3} gamma-rays/m^2-hr. This flux is far too small to make remote detection feasible. Thus, very large solar proton flares (VLSPF's) were considered due to the large numbers of particles incident on the lunar surface during such events. A neutral particle beam (NPB) was also considered as a possible means of artificially inducing neutrons in the lunar regolith. Calculation of the neutron flux induced by a VLSPF and a NPB are discussed below.

Neutron Source Characteristics

Very Large Solar Proton Flares (VLSPF's)

The ideal means of remotely detecting ^{3}He from lunar orbit would use naturally present neutrons reacting with the ^{3}He as discussed above. Since the GCR-induced flux of neutrons is thought to be too small to make detection feasible, another naturally present source was sought. Solar flares present a danger to astronauts living and working on the moon due to the large doses of proton-induced radiation.

If the peak neutron flux created by flare protons -- via (p, n) reactions -- is large enough to overcome the background continuum, then a satellite could be placed in lunar orbit to wait for a large solar proton event.

Very large solar proton flares are relatively short and unpredictable. Only six VLSPF's have been recorded in the last three decades; three of these events occurred in 1989 alone. These events are predictable only in the sense that they tend to occur during the period leading to the maximum of the sun's 11-year sunspot cycle. These cycles vary greatly in amount of activity, and VLSPF's have also been known to occur after the maximum in the solar cycle. Very large solar proton flares are generally characterized by three bursts of high proton fluxes (Figure 3). These peaks vary greatly in duration, which is generally on the order of one day. The short duration of the peak flux would limit the surface coverage attainable by an orbiting detector.

The spectral properties of these flares are also highly unpredictable (Figure 4). The October 1989 solar flare was taken to be a typical VLSPF. The peak proton flux of this flare was about 10^5 protons/cm^2-s about 30 hours into the flare [Simonsen et al. 1991]. The omnidirectional integral fluence of protons with energies above 30 MeV contained in this event was 4.24×10^9 protons/cm^2 [Sauer 1993]. The flare of Feburary 1956 generated a proton spectrum much harder than any of the other VLSPF's on record and lasted for only about 2 hours [Simonsen et al. 1991]. Since this flare was expected to generate more neutrons than any of the other VLSPF's, it was included in the current study as an upper limit to the neutron spectrum that could be produced.

Characteristics of A Neutral Particle Beam

A neutral particle beam (NPB) device was considered as an artificial means of introducing protons or higher-Z particles into the lunar regolith for the purpose of inducing high neutron fluxes, and in turn, high fluxes of 20.6 MeV gamma-rays from the neutron capture reaction of these neutrons with ^{3}He. Neutral particle beam devices have been developed for use in space for the interrogation of nuclear warheads, and many of their properties remain classified. We have considered a 100 MeV, 30 mA beam of protons and assumed an beam area of 10 cm^2 in the calculations and results described below. The advantages of using a NPB for the remote detection of ^{3}He are the control of the device energies and beam direction. Instead of waiting for an unpredictable event on the Sun, the neutrons could be induced at any time. By rastering the beam over the lunar surface and detecting the resulting gamma-rays from a separate satellite, high-resolution maps of lunar ^{3}He could be obtained.

Particle Interaction and Transport Calculations

The objective of this research is to calculate the flux of prompt gamma-rays coming from ^{3}He in the lunar regolith during a VLSPF or due to a NPB. A

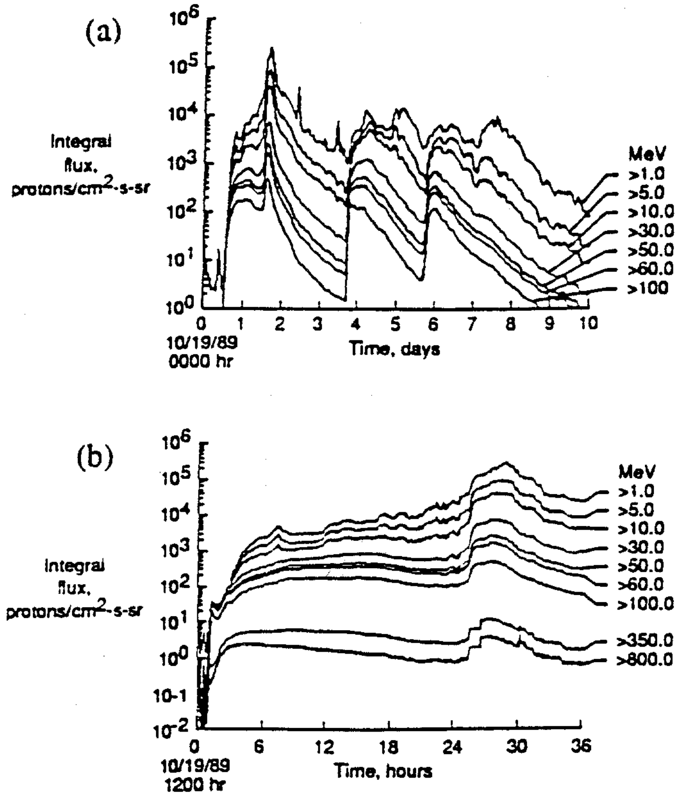

Figure 2. October 1989 VLSPF: (a) GOES-7 hourly average integral flux history and (b) GOES-7 five minute average integral flux history (GOES-7 data from NOAA Space Environment Laboratory) [Simonsen et al. 1991].

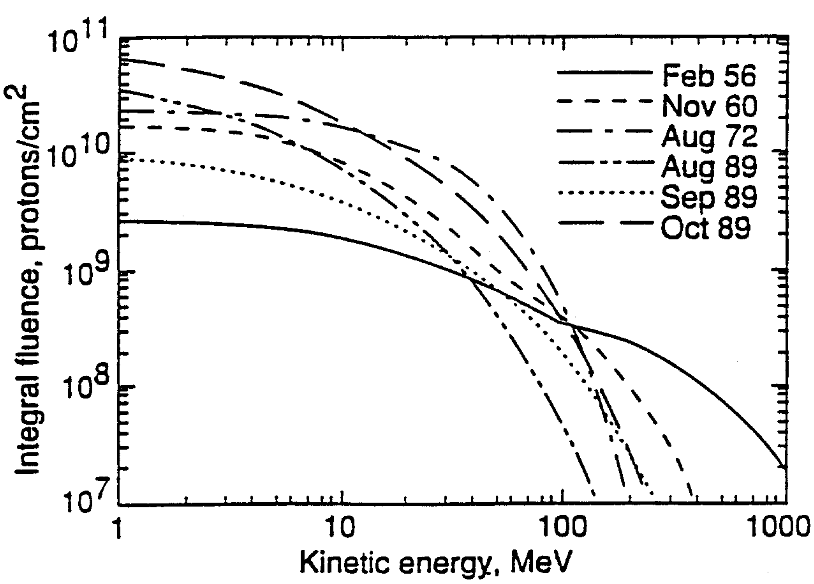

Figure 3. Integral fluence energy specta for six very large solar proton flares [Nealy et al. 1992].

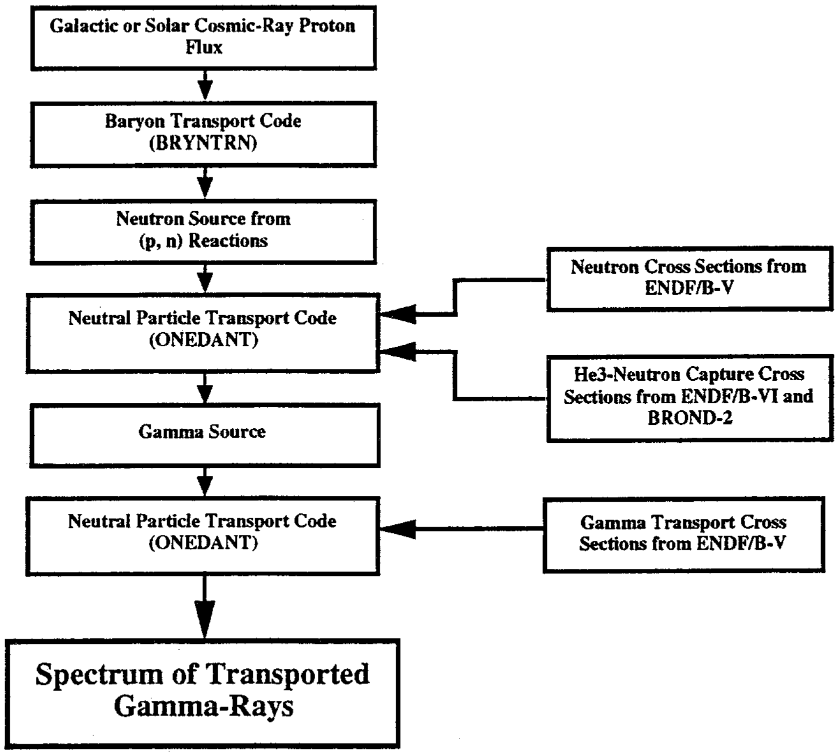

Figure 4. Flow chart of the computational method used in calculating the gamma-ray flux from ^{3}He due to an incident proton flux.

computational procedure that could model the production of neutrons via the interaction of incident protons with the regolith, transport the neutrons, model the (n,γ) reaction with ^{3}He and finally transport the resulting gamma-rays to the lunar surface was needed. Since a single computational model was unavailable, BRYNTRN was used to perform the charged particle interactions and generate the neutrons within the regolith ONEDANT was used to transport the resulting neutrons and generate the prompt gamma-ray flux (Figure 4). These codes are summarized in the following.

Charge Particle Interactions and Neutron Production: BRYNTRN

In order to utilize the neutron fluxes generated by the protons incident on the Moon during a solar flare, a numerical model capable of performing the interaction calculations is needed. Preferrably, this model would include a data base of VLSPF events. The NASA-Langley Research Center has been heavily involved in developing numerical tools for the transport of baryons through shield materials based on a straight ahead approximation of the time-independent Boltzmann equation [Wilson et al. 1989]. The BRYNTRN code is self-contained, computationally efficient and requires only a fraction of the computer resources needed by a typical Monte Carlo code. The code also contains an input data base consisting of GOES solar flare data from the National Oceanic and Atmospheric Administration (NOAA). In the current study, BRYNTRN is also used to calculate the neutron flux induced in the lunar regolith by the February 1956 and October 1989 VLSPF's and by a 100 MeV, 3 mA/cm^2 neutral proton beam.

Neutron and Gamma-Ray Transport: ONEDANT

Once a neutron production spectrum has been calculated for a particular event using BRYNTRN, the neutrons must be transported through the lunar regolith, the local gamma-ray yield calculated and the gamma-rays transported to the surface of the regolith. The neutron and gamma-ray transport calculations are performed using the one-dimensional discrete ordinates neutral-particle transport code ONEDANT together with the Los Alamos National Laboratory (LANL) MATXS5 cross section data library processed from the ENDF/B-V evaluated files. The standard LANL 30 neutron, 12 gamma-ray energy group structure are used and the calculations are performed using the P_3-S_8 approximation. Since cross section data does not exist for neutrons above 20 MeV, all neutrons with higher energies were included in the highest energy group available. This approximation will result in an underestimation of the gamma-ray flux since approximately 20% of the VLSPF-induced neutrons have energies higher than 20 MeV.

The gamma-ray flux was calculated for the top three meters of the lunar regolith using the neutron flux at 6.7 cm. This gamma-ray flux for VLSPF's can then be multiplied by the area of a detector in orbit around the moon to yield the number of counts per second that could be detected from a theoretical semi-infinte plane. Since the NPB is essentially a point source, the flux generated at the lunar surface must be divided by $4\pi r^2$ (where r is the detector's orbital distance from the lunar surface) before it is multiplied by the detector area.

Results

Neutrons Induced in the Lunar Regolith by Various Proton Sources

The total GCR-induced neutron production rate used was 16±5 neutrons/cm^2-s [Lingenfelter et al. 1972]. The neutron flux was calculated using BRYNTRN for each of the cases described above. This flux was then used as input for ONEDANT. At a depth of 6.7 cm (10 g/cm^2), the total neutron flux for the October 1989 flare was determined to be 2485 neutrons/cm^2-s. Figure 5 shows that the neutron flux as a function of depth below 10 MeV for the October 1989 flare is several orders of magnitude greater than the thermal neutron flux induced by galactic cosmic rays calculated by Lingenfelter et al., 1972. The local neutron flux induced by the NPB was calculated to be approximately 10^{16} neutrons/cm^2-s at a depth of 6.7 cm for a 100 MeV, 3 mA/cm^2 proton beam.

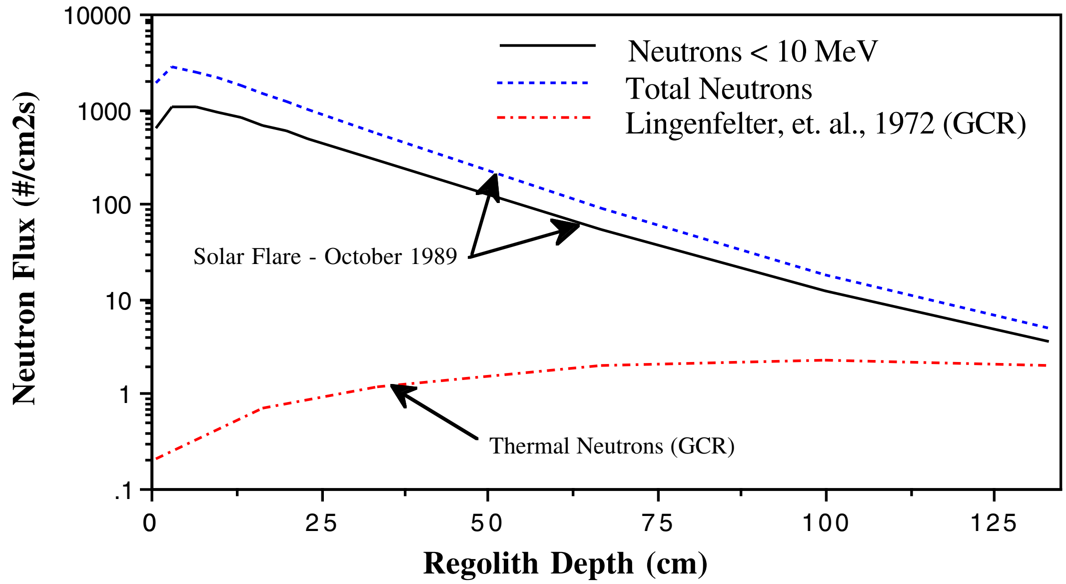

Figure 5. Neutron flux as a function of depth for the October 1989 VLSPF as calculated using BRYNTRN. The thermal neutron flux is that calculated by Lingenfelter et al. (1972) [7].

Gamma-Ray Fluxes from ^{3}He Resulting from Various Proton Sources

The GCR-induced gamma-ray flux was calculated using 16 neutrons/cm^2-s to be 4.2x10^{-3} gamma-rays/m^2-hr. The gamma-ray fluxes from ^{3}He were obtained by using the neutron fluxes calculated by BRYNTRN for the two VLSPF's and the NPB as input for ONEDANT. The VLSPF's of October 1989 and February 1956 yielded values of 0.85 and 8.8 gamma-rays/m^2-hr, respectively. The NPB yielded a flux of 5.5x10^9 gamma-rays/m^2-hr at the lunar surface. The increased gamma-ray flux due to VLSPF's and NPB's is seen to be significant compared to the background levels provided by GCR-induced reactions (Figure 6).

Conclusions

Very large solar flares can increase the ^{3}He(n, γ)^{4}He reaction rate by a factor of approximately 3000 over the background rate viewed from low lunar orbit generated by galactic cosmic-rays interacting with the lunar regolith via (p,n) reactions. This increased reaction rate will enhance the detectability of ^{3}He from low lunar orbit. A 100 MeV, 3 mA/cm^2 neutral particle beam has been shown to increase the local ^{3}He(n, γ)^{4}He reaction rate in the beam spot by a factor of approximately 10^{12} over the background rate due to incident GCR particles. The potential exists for high-resolution measurements of the spatial distribution of ^{3}He from lunar orbit using VLSPF's or optimized NPB's.

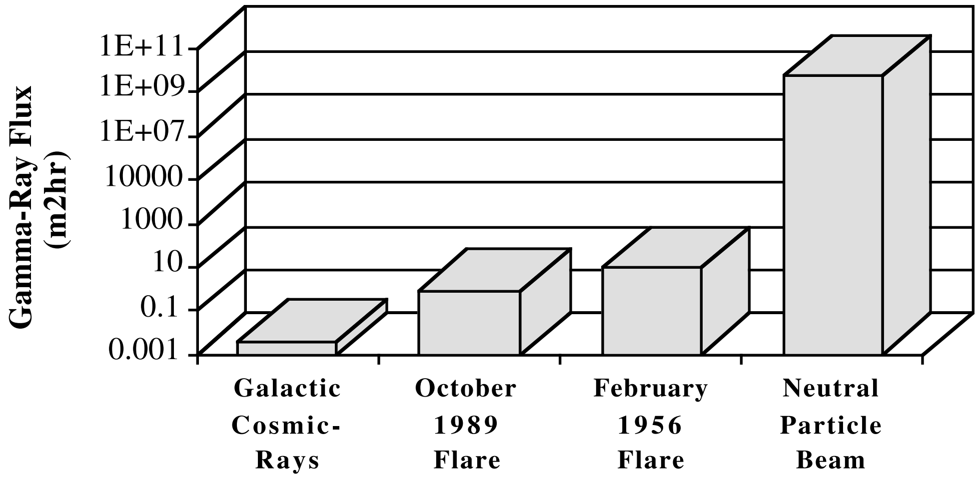

Figure 6. The 20.6 MeV gamma-ray flux from lunar ^{3}He calculated from various neutron sources. Note that the gamma-ray source from the NPB is a point source at the lunar surface.

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