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GALACTIC COSMIC RAY EXPOSURE ESTIMATES FOR SAGE-III MISSION IN POLAR ORBIT

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ABSTRACT

An analysis of the effects of galactic cosmic ray (GCR) exposures on charge-coupled devices (CCDs) has been performed for the SAGE-III 5-year mission in sun-synchronous orbit between 1996 and 2001. A detailed environment model used in conjunction with a geomagnetic vertical cut-off code provides the predicted 5-year fluence of GCR ions. A computerized solid model of the spacecraft has been used to define the effective shield thickness distribution around the CCD detector.

The particle fluences at the detector location are calculated with the Langley heavy-ion transport code, and these fluences are used in conjunction with estimated nuclear stopping powers to evaluate dosimetric quantities related to the detector degradation. A previous study analyzing effects of trapped particle and solar flare protons indicated an approximate 20% reduction in detector sensitivity for the mission. The galactic cosmic ray contribution was thought to be relatively small and therefore was not previously analyzed. The present study provides quantification of the GCR effects, which are found to contribute less than 1% of the total environment degradation.

INTRODUCTION

The Stratospheric Aerosol and Gas Experiment (SAGE) III promises to provide accurate data about the temporal and spatial concentrations of a number of chemical species in the atmosphere[1]. For these measurements, however, an unprecedented degree of precision will be needed. This emphasis on precision in SAGE prompts analyses of instrument degradation due to radiation exposure.

The SAGE-III instrument design consists of a scanning Cassegrain telescope and grating spectrometer combination which examines spectral absorption of solar and lunar-reflected radiance in atmospheric occultation[1]. Fig. 1 shows a cross-sectional layout of the optical components in the platform. Of particular interest in the spacecraft is the 800x10 charge-coupled device (CCD) utilized by the spectrometer. The SAGE-III charge-couple device is a high-precision optical imager, consisting of arrays of silicon electrodes. CCDs are known to be very sensitive to interference and long-term degradation caused by the exposure to radiation[2].

The SAGE mission will last approximately five years. The plan for this mission involves an earth orbit that is relatively high (705 km), nearly circular and at a high inclination of approximately 98 degrees[1]. This orbit will subject the Sage-III platform to both trapped particles in the Van Allen belts at low and middle latitudes and to solar proton flare radiation near the polar regions. An analysis of the dose contributions due to both of these forms of radiation can be found in Ref. 3. In addition, SAGE-III will be exposed to galactic cosmic rays (GCR) throughout its orbit. Present work estimates dose contributions from galactic cosmic rays for the CCD, which were not included in the previous study.

GCR ENVIRONMENT FOR SAGE-III

The total fluence of GCR constituents in interplanetary space for a 5-year period beginning in 1996 has been calculated using the Langley Mission Radiation Calculation code (MIRACAL)[4]. This code incorporates the GCR environment model CREME (Cosmic Ray Effects on Micro-Electronics) developed at the Naval Research Laboratory[5], and provides a solar cycle modulation function for the variation of GCR fluxes between solar minimum and solar maximum conditions. The assumed time frame for the SAGE mission begins at approximately solar minimum conditions and ends near solar maximum; the corresponding GCR fluxes are thus decreasing during the mission.

The free space fluxes must also be modulated to include effects of the geomagnetic field, which deflects incident charged particles back into space. The Langley Dual-Dipole magnetic field model[6] has been used to provide orbit-averaged charged particle transmission factors as a function of particle rigidity. The magnetic rigidity R of a particle of charge Z is related to the kinetic energy T by

$$R = \frac{1}{Z}(T^2+2Tm_oc^2)^{1/2}$$

where m_oc^2 is the rest mass particle energy. The geomagnetic field model is used to calculate vertical cut-off rigidities as a function of geographic location, and particle transmission functions are obtained by averaging the cut-offs over the orbital period. The transmission functions for the 98.2-degree inclination orbit are shown as a function of kinetic energy in Fig. 2. Cosmic ray nuclei for Z=1 through 28 (H to Ni) are included in the calculations. Maximum transmission at high energies is restricted to a value of approximately 0.72, which accounts for the earth's shadow at the 705-km altitude.

Using the calculated transmission factors, the 5-year differential fluence energy spectra encountered in the SAGE-III for selected GCR species are shown in Fig. 3. Since the highest fluxes occur at energies in excess of several hundred MeV, these particles will be very penetrating. In passing through the components of the spacecraft, the particles undergo nuclear reactions which produce secondary charged particles and neutrons. In order to compute the delivered dose to the detector, the fluxes of particles at the detector location must be determined.

COMPUTATIONAL METHODS

In order to evaluate the radiation dose at the CCD, the transport characteristics of the GCR spectra through the spacecraft shielding need to be calculated. These calculations were performed by the use of Langley Research Center's HZETRN code[7], an efficient, deterministic, high-energy heavy ion transport program. A detailed description of the HZETRN code can be found in Reference 7. The HZETRN code was used to propagate the GCR spectra for the SAGE-III through aluminum shield thickness. The code then calculates the differential fluence of the various nuclei exiting the shielding as a function of energy.

A computer-aided-design(CAD) solid model of the instrument, available from the previous study[3], was used to provide material thicknesses as a function of angular direction around the detector. The CAD model includes components that significantly affect transport of GCR particles and secondaries. A cut-away view of the SAGE-III instrument is shown in Fig. 4. Another useful result from the previous study was that equivalent aluminum thicknesses can provide a reasonable estimate of the shielding provided by the various materials along a given direction. With this approximation, linear densities (g/cm^2) of the various materials is related to an equivalent aluminum value.

Using the CAD model, 1922 thicknesses evenly distributed in angle around the CCD location were calculated. These thicknesses were then used to define a thickness probability distribution function for use in the subsequent dosimetric calculations[3]. This function is shown in Fig. 5 and indicates that the most probable linear density value in a random direction is slightly greater than 5 g/cm^2 Al. This value of 5 g/cm^2 Al was then used as the representative shielding thickness in the transport calculation. The 5-year differential fluence results for the transport calculation of flux emergent from 5 g/cm^2 of aluminum is shown in Fig. 6. Comparison with Fig. 3 shows that substantial fluxes of lower energy protons and neutrons have been produced at the expense of high energy heavy particles.

An analysis of the CCD degradation also requires the determination of the nuclear component of silicon's stopping power. Nuclear stopping power, which is also called "non-ionizing energy loss" or NIEL, is a concern since long-term degradation of CCDs is believed to be caused mainly by displacements of silicon atoms within their crystal lattices. These displacements result from nuclear interactions with projectiles, and they cause a decreased charge transfer efficiency in the CCD[2].

The nuclear stopping power $S_{n,j}$ for particle type j in silicon can be calculated by using two independent methods. The first method involves a parametric formalism[8] where the nuclear component in reduced units is

$$S_{n,j} = \begin{cases} 1.59\varepsilon^{1/2} & (\varepsilon<.01) \\ \dfrac{1.7\sqrt{\varepsilon}\,\ln[\varepsilon + \exp(1)]}{1 + 6.8\varepsilon + 3.4\varepsilon^{3/2}} & (.01<\varepsilon<10) \\ \dfrac{\ln(0.47\varepsilon)}{2\varepsilon} & (10<\varepsilon) \end{cases}$$

and ε is the reduced energy given by

$$\varepsilon = \frac{32.53\, A_t A_j T}{Z_j Z_t\,(A_j+A_t)\,(Z_j^{2/3} + Z_t^{2/3})^{1/2}}$$

T is in units of kev/nucleon, A_j and A_t are the atomic masses of the projectile and the target, and Z_j and Z_t are the corresponding atomic numbers.

Non-ionizing stopping power is also found by using empirical stopping power values for neutrons and protons received from the Naval Research Laboratories[9]. Heavy-ion stopping power can be calculated from this data by using a scaling formula where

$$S_{n,j}(T) = \frac{A_p (Z_j^*)^2}{A_j Z_p^2} S_p(T)$$

In this formula, Z_p is the proton charge and $S_p(T)$ is the nuclear stopping power for protons in silicon at kinetic energy T.[7] The Z_j^* used in this calculation is the effective charge of the projectile[8] given by

$$Z_j^* = Z_j \left[1 - \exp\left(\frac{-125\beta}{Z_j^{2/3}} \right) \right]$$

where

$$\beta = \frac{(T^2 + 2Tm_0c^2)^{1/2}}{T + m_0c^2}$$

Fig. 7 shows the calculated nuclear stopping powers in silicon for neutrons, protons, and heavy nuclei using the latter method. This second method is believed to be more accurate, especially at high energies, since the parametric formalism was developed for lower energies.

RESULTS

An evaluation of radiation damage to CCDs may be related to direct energy deposition. In particular, energy depositions due to nuclear interactions in silicon are believed to be a good indicator of radiation dose. The quantity of dose for nuclear interactions is generally termed the nirad (non-ionizing radiation absorbed dose)[9], and may be evaluated according to

$$D_n = \sum_j \int_0^\infty \phi_j(T)\, S_{n,j}(T)\, dT$$

where $\phi_j(T)$ is GCR flux of particle type j at energy T, after transport through the most probable shielding thickness, 5 g/cm^2 Al. $S_{n,j}$ is the corresponding nuclear stopping power, as calculated above, and D_n is the nuclear interaction dose. The dose values for each ion type using the fluences of Fig. 6 and the stopping powers of Fig. 7 are shown in Fig. 8. Protons are responsible for most of the dose contribution (~.005 nirads), while significant contributions are also obtained for neutrons, alpha particles, and carbon, oxygen, magnesium, silicon, and iron ions. The total dose from all ion types amounts to 0.01 nirads. The evaluated dose using the parametric formalism was 0.0065 nirads. This lower value indicates that the stopping powers at high energies may be underestimated in the parametric formalism.

The nirad dose may be converted to reduction in charge transfer efficiency (CTE) using the coefficient reported in Ref. 9 of 0.00075 ΔCTE/nirad(Si). The previous study indicated a total mission dose due to solar flares and trapped protons of approximately .4 nirad with a corresponding reduction in CTE of 0.0002. The GCR dose of 0.01 nirad leaves the CTE essentially unaffected.

SUMMARY AND CONCLUSION

An analysis of the effects of galactic cosmic ray (GCR) exposures on the degradation of charge-coupled devices (CCDs) are performed for the SAGE-III 5-year mission in sun-synchronous orbit between 1996 and 2001. A detailed environment model used in conjunction with a geomagnetic vertical cut-off code provides the predicted 5-year fluence of incident GCR ions. A computerized solid model of the spacecraft is used to define the effective shield thickness distribution around the CCD detector.

The particle fluences at the detector location are calculated with the Langley heavy-ion transport code, and these fluences are used in conjunction with estimated nuclear stopping powers to evaluate dosimetric quantities related to the detector degradation. The GCR effects on SAGE-III CCD degradation were compared with a previous computation of degradatiion effects caused by trapped particles and solar flare protons. The GCR effects were found to contribute less than 1 percent of the total environment degradation.

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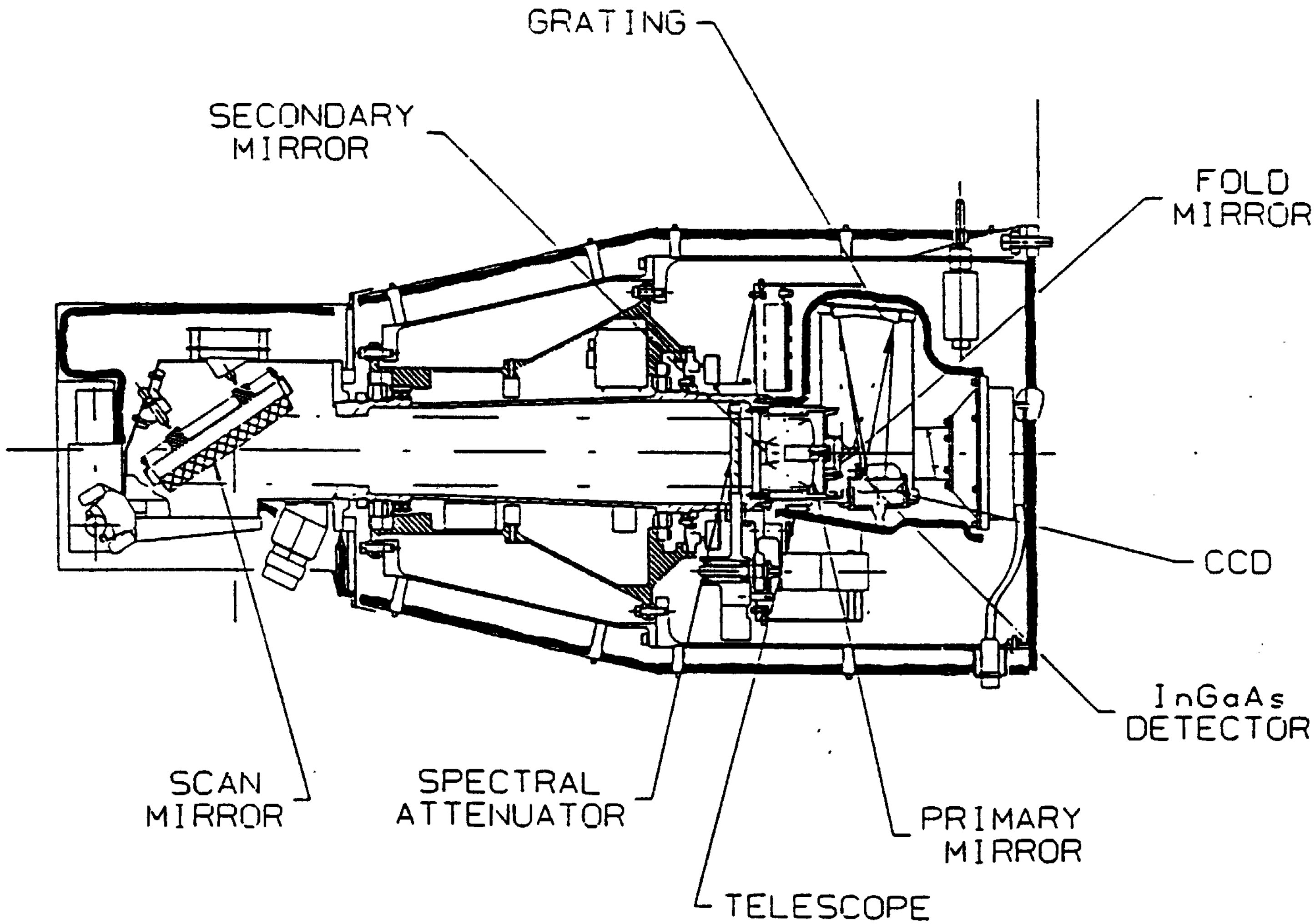

Fig. 1. Cross-sectional layout of SAGE-III instrument showing principal optical components.

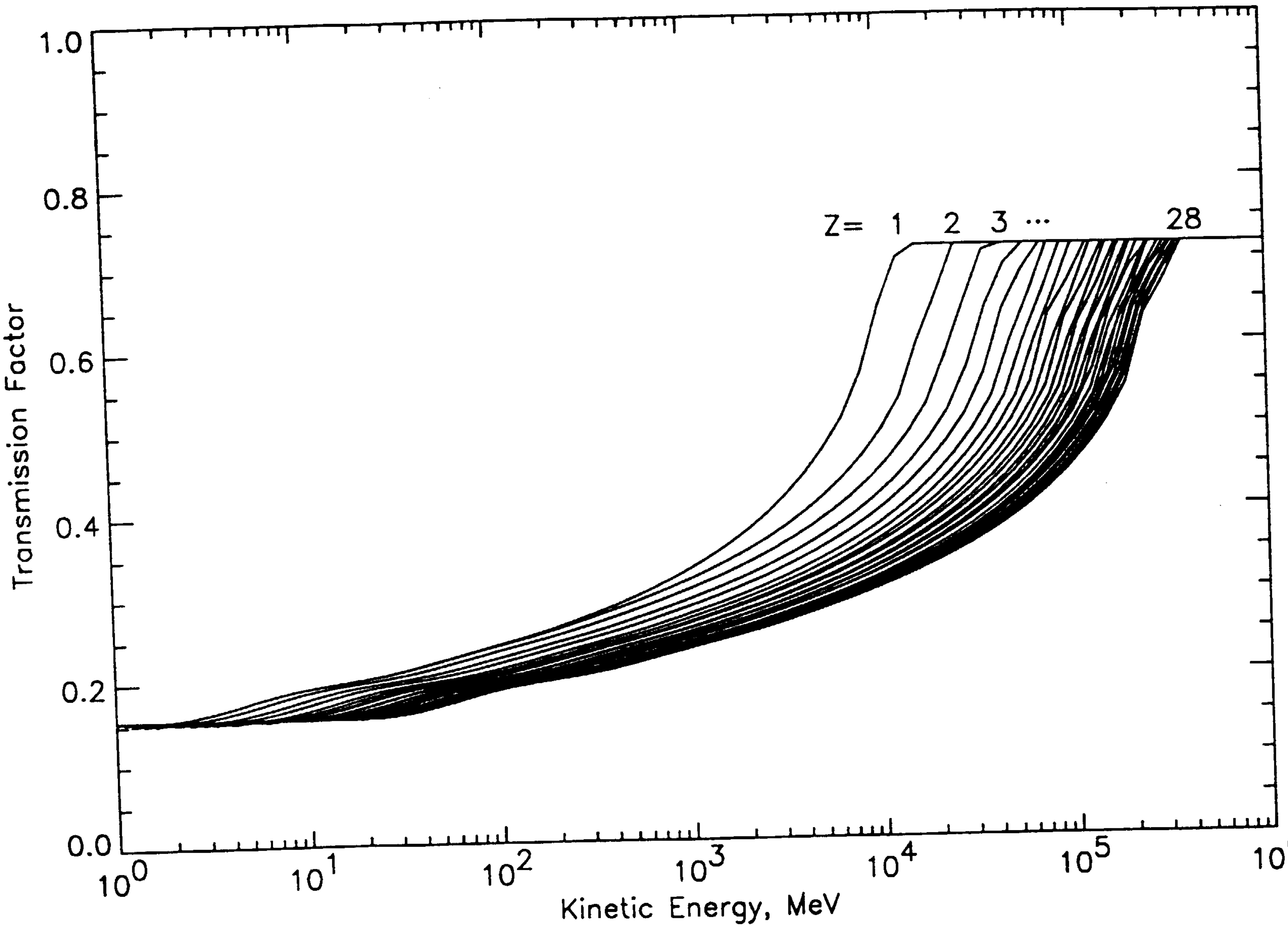

Fig. 2. Geomagnetic transmission factors as a function of kinetic energy for GCR ions at SAGE-III orbital conditions.

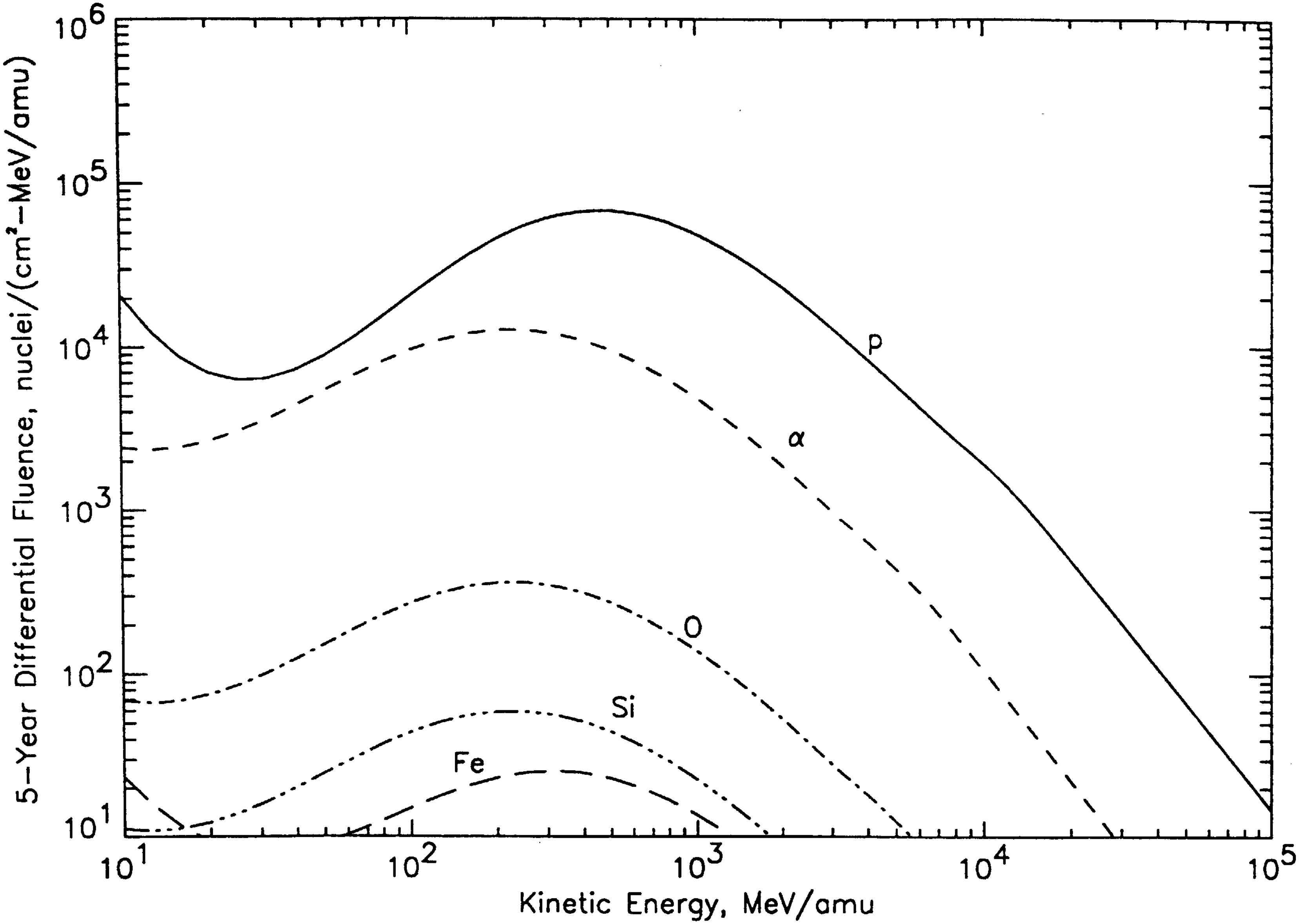

Fig. 3. **Five-year incident particle fluence for selected GCR ions for SAGE-III polar orbital conditions. Solar cycle and geomagnetic modulations have been included.**

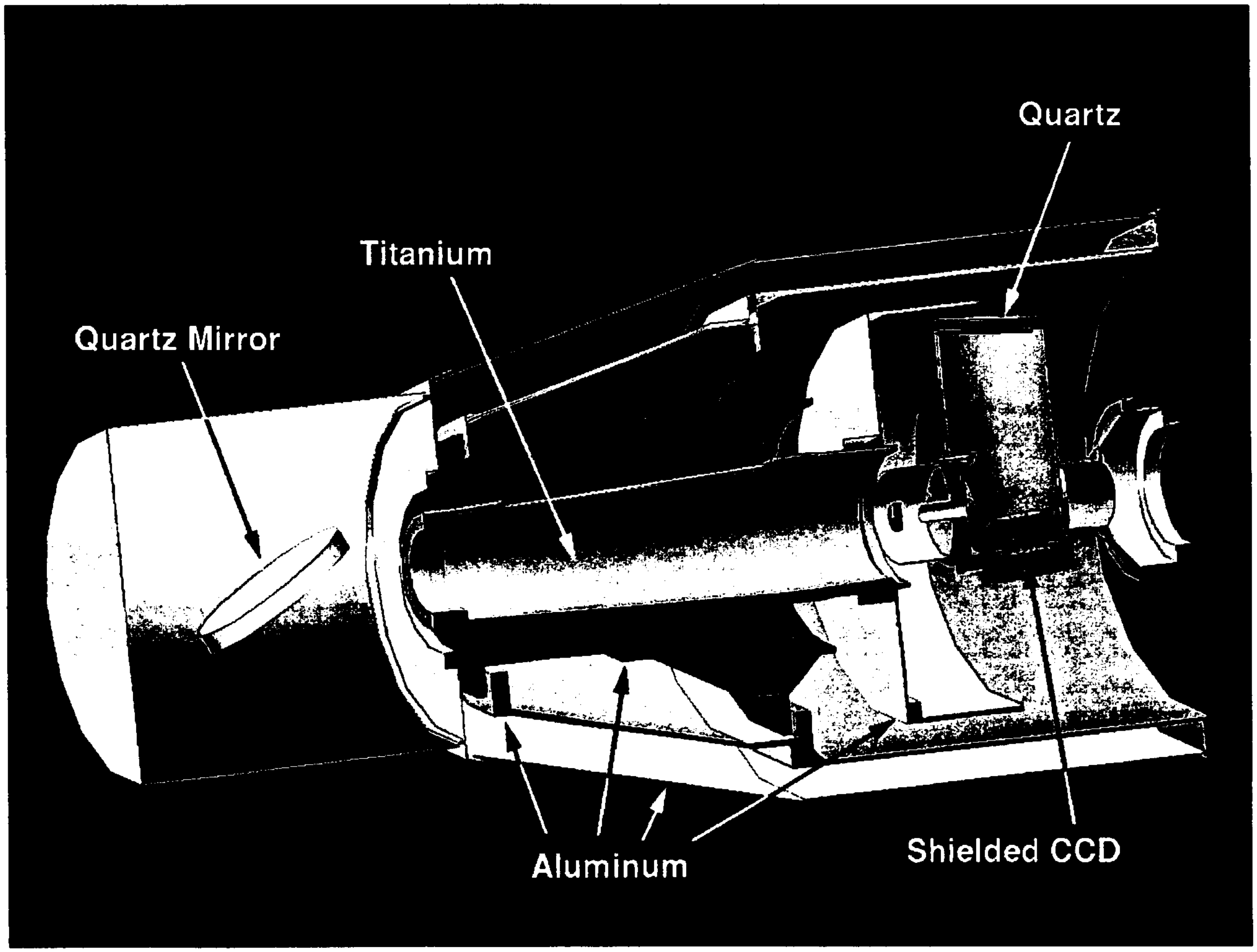

Fig. 4. CAD solid model cut-away view of the SAGE-III instrument.

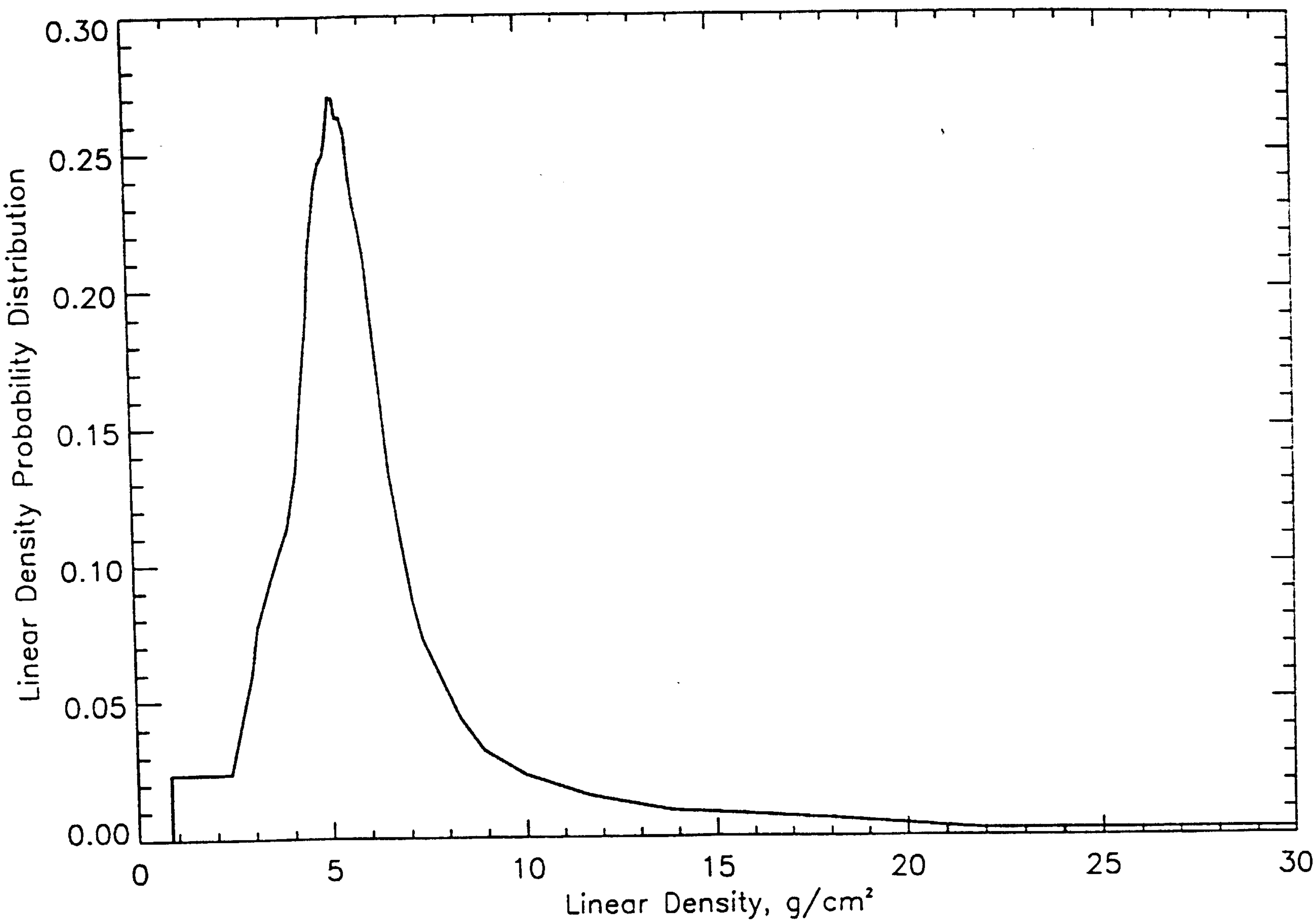

Fig. 5 Probability distribution of linear density at the SAGE-III CCD location.

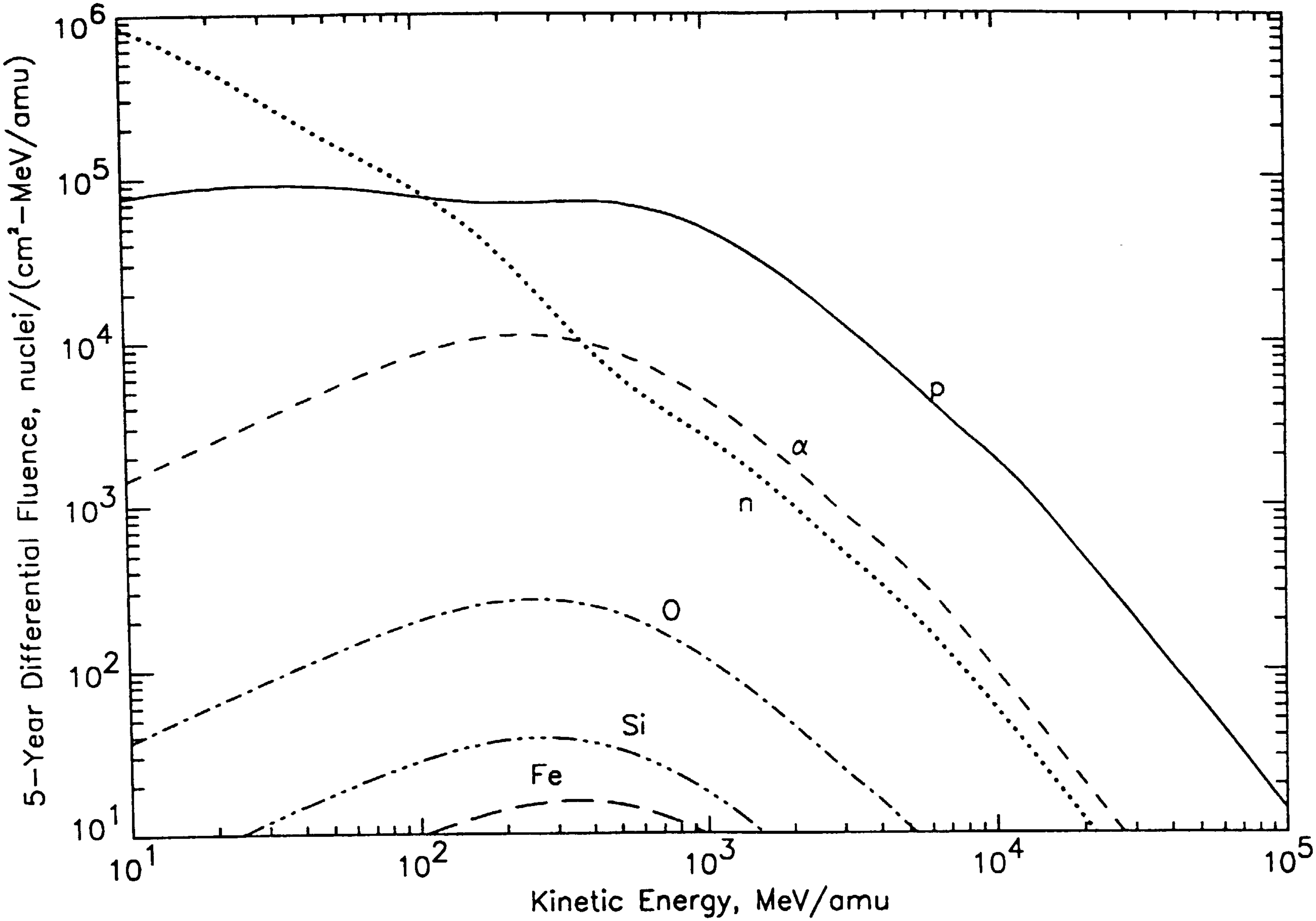

Fig. 6. Transmitted particle fluence for selected ions through 5 g/cm^2 Al for the SAGE-III GCR environment.

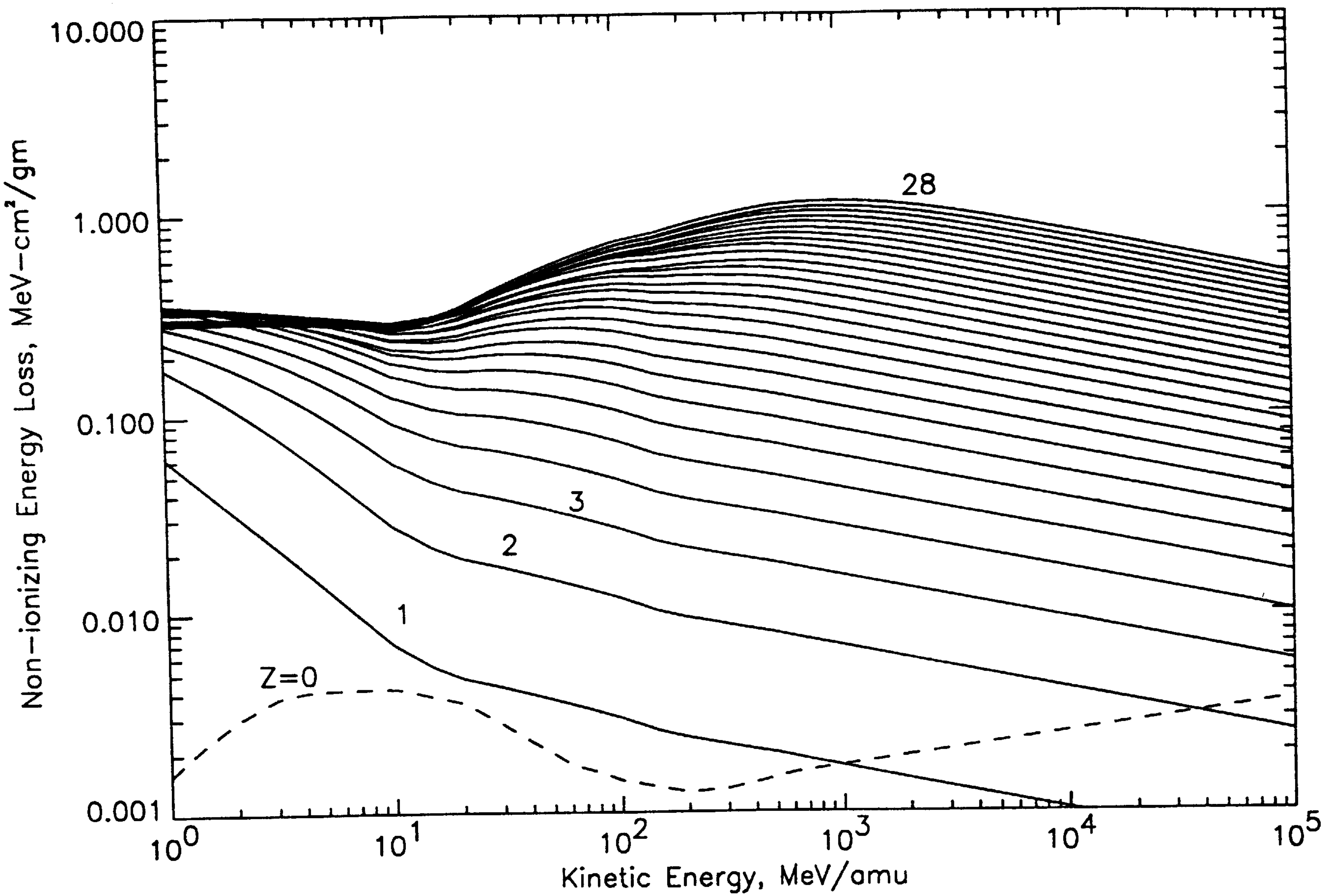

Fig. 7. Calculated nuclear stopping powers in Si for GCR ions. Neutron (Z=0) and proton (Z=1) values are from Ref. 8, and Z=2...28 values are scaled from the proton function.

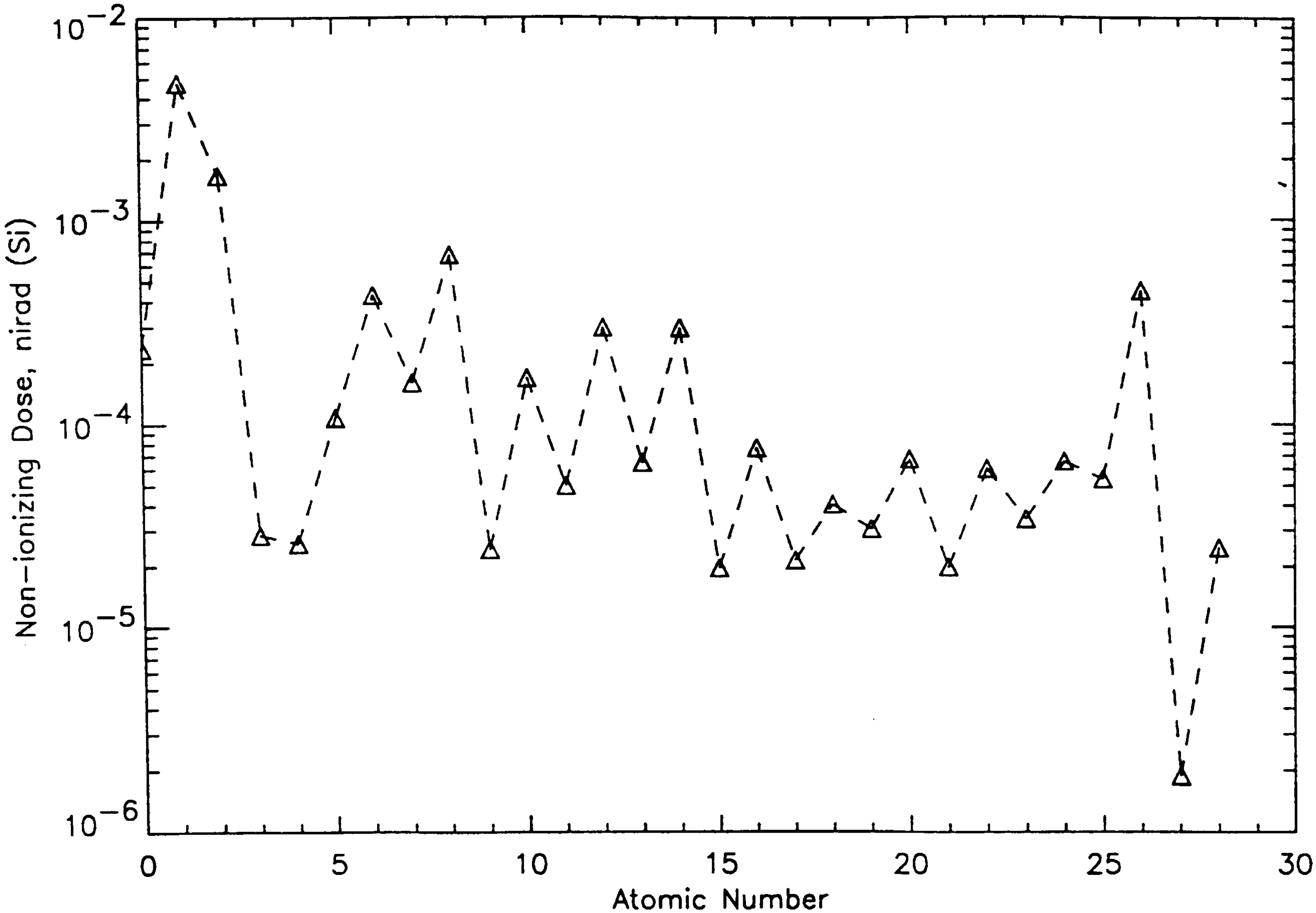

Fig. 8. Non-ionizing (nuclear interaction) total dose calculated for GCR constituents for the SAGE-III mission.

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