# Monte Carlo Simulation of Proton-induced Cosmic-ray Cascades in the Atmosphere

Chris Hagmann, David Lange, Doug Wright*
Lawrence Livermore National Laboratory

February 12, 2012

**Abstract**

We have developed a Monte Carlo model of the Earth's atmosphere and implemented it in three different codes (Geant4, MCNPX, and FLUKA). Primary protons in the energy range of 1 GeV - 100 TeV are injected at the top of the atmosphere. The codes follow the tracks of all relevant secondary particles (neutrons, muons, gammas, electrons, and pions) and tally their fluxes at selectable altitudes. Comparisons with cosmic ray data at sea level show good agreement.

## 1 Model of the Atmosphere

We modeled the atmosphere as a series of 42 constant-density flat layers, each composed of 78% $N_2$, 21% $O_2$, and 1% Ar by volume. We set the density change between adjacent layers to 10%, and derived the densities from the 1976 US Atmosphere Model. We located the top of our model's atmosphere at an altitude of $\sim 31$ km, and had an integrated column density of $\sim 1000$ g/cm$^2$. We placed a void cell at both the top and bottom.

## 2 Cosmic Primaries

The flux of cosmic-ray particles in the atmosphere is mostly due to galactic protons, with minor contributions from alpha's and heavier nuclei. At present, we restrict ourselves to simulating the effects from primary protons only. For the flux of galactic protons hitting the top of the Earth's atmosphere, shown in Fig. 1, we use the parameterization from Papini [1]:[1]

$$J(E) = A(E+B)^{\alpha}E^{\beta} \quad \mathrm{protons/m^2/steradian/second/GeV},$$

with parameters defined in Table 1, where $E$ is the kinetic energy per nucleon. This parameterization was

Table 1: Parameters from Papini [1] for primary cosmic-ray proton flux.

| | A | B (GeV) | $\alpha$ | $\beta$ |
|---|---|---|---|---|
| Solar minimum | 18,000 | 0.92 | -4.00 | 1.25 |
| Solar maximum | 18,000 | 1.61 | -3.83 | 1.08 |

*Contact info: wright20@llnl.gov, 925-423-2347

[1] We have corrected here the sign error that appears in Papini Equation 8.

UCRL-TM-229452

derived from fits to data from balloon-born experiments. Note that the flux at low energy ($< 10$ GeV) is anti-correlated with the solar wind. As more magnetized solar plasma fills the interplanetary system, the more low-energy galactic protons are deflected away from Earth. The proton flux for a specific date, $J_{\mathrm{date}}(E)$, is

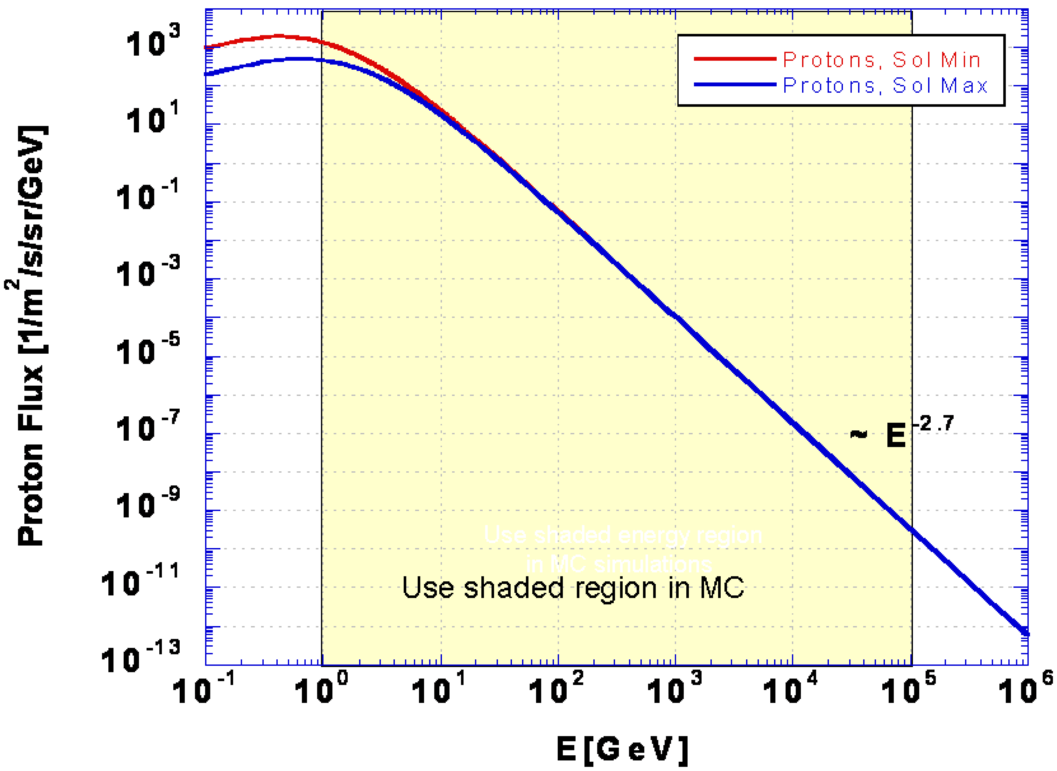


Figure 1: Spectrum of Galactic Protons incident on the top of the Earth's atmosphere [1].

the weighted sum of the solar-min and solar-max flux:

$$J(E)_{\mathrm{date}} = (1-x)J_{\mathrm{smin}}(E) + xJ_{\mathrm{smax}}(E)$$

where $x = |\sin(\pi\Delta T/T_{\mathrm{cycle}})|$, $T_{\mathrm{cycle}}$ = length of the solar cycle, and $\Delta T$ is the time (based on the date) since the beginning of the cycle.

## 3 Inter-Code Comparisons

Instead of relying on a single MC code to validate our results we ran some problems with three independently developed multi-purpose codes, i.e. Fluka2005, Geant4, and MCNPX 2.5.0. We implemented the same model of the atmosphere in each code, injected primary protons of fixed energy at the top and tallied the particles of interest (muons, neutrons, protons, gammas, electrons, and pions) at sea level.

Our conclusion is that the codes give almost equivalent spectra for all particles except neutrons below 1 MeV, where Geant4 predicts too small of a flux. Neutron transport at these energies has only recently been implemented in Geant4. On the other hand, Fluka and especially MCNPX have been heavily used and are considered verified and validated in this energy region.

Figures 2 and 3 show the tallied neutron and gamma spectra at sea level for incident proton energies of 1 TeV and 100 GeV respectively.

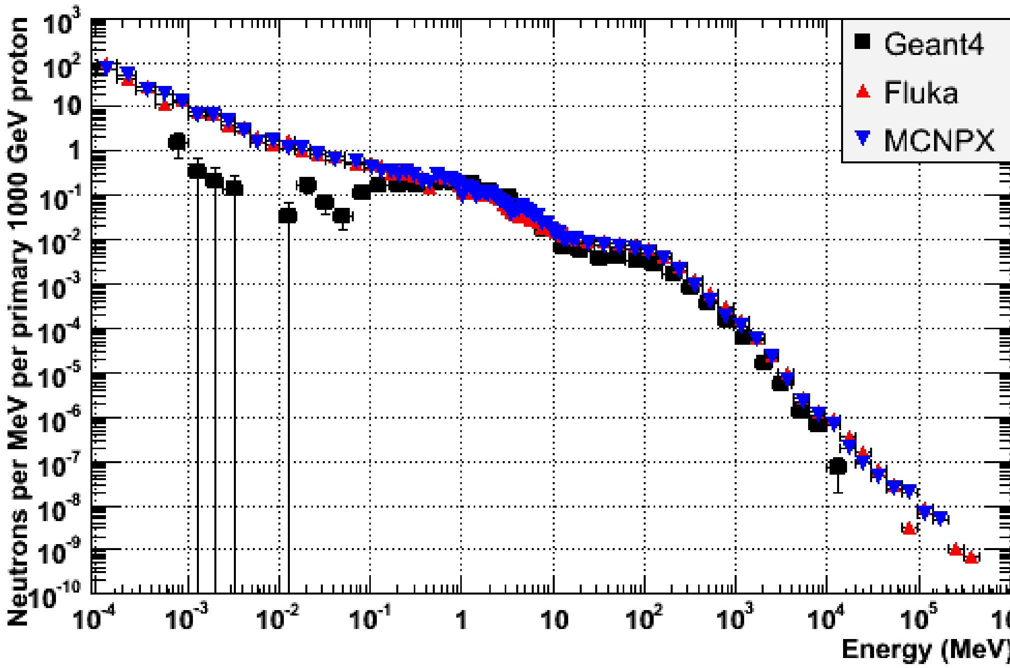


Figure 2: MC-generated neutron spectra at sea level. The incident proton energy is 1TeV.

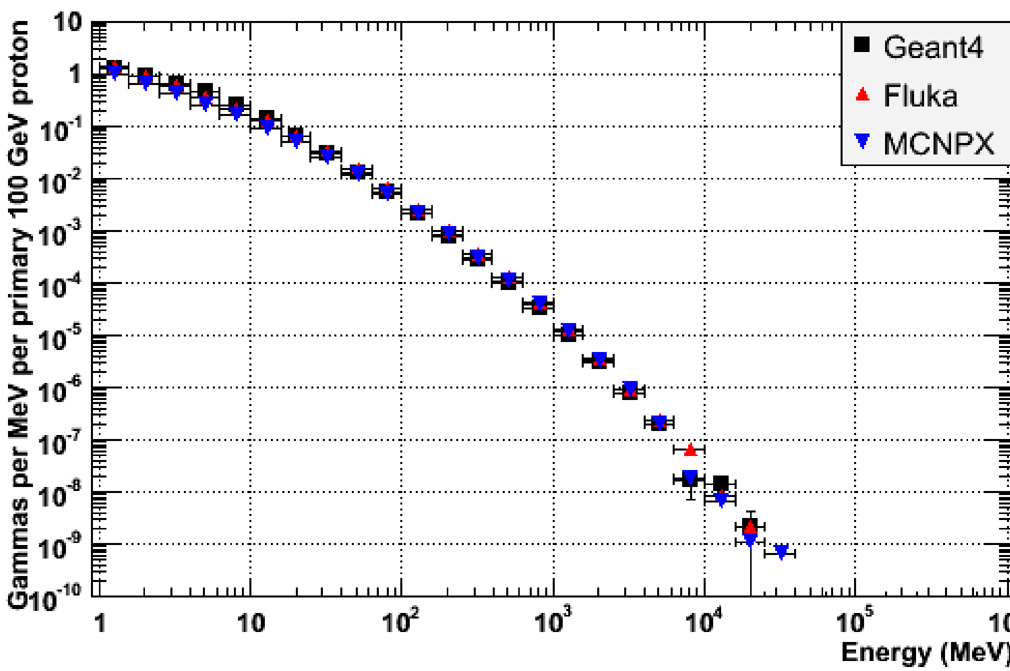


Figure 3: MC-generated gamma spectra at sea level. The incident proton energy is 100GeV.

## 4 Code-Data Comparisons

Most of our high statistics production runs were made with MCNPX 2.5.0 and comprise more than 10000 cpu-hrs. To compare our results with other Monte Carlo codes we divided the shaded region in Figure 1 into 33 energy groups: 14 equally spaced flat bins from 1 GeV to 15 GeV, plus 19 logarithmically spaced bins up to 100 TeV. The latter bins had a power law distribution within each bin with a spectral index of

2.7. All protons were sourced with an isotropic angular distribution and the atmosphere response functions were accumulated for each incident energy bin. By suitable weighting and co-adding of sub spectra, total absolute spectra at any position in the solar cycle and any value of the geomagnetic cutoff can be calculated.

Shown in Figures 4-7 are the predicted muon, proton, pion, and neutron fluxes for no geomagnetic cutoff and average solar modulation, along with the data points from Rastin[2], Brooke and Wolfendale [3], Ashton and Saleh [4], and Kornmayer et al [5] .

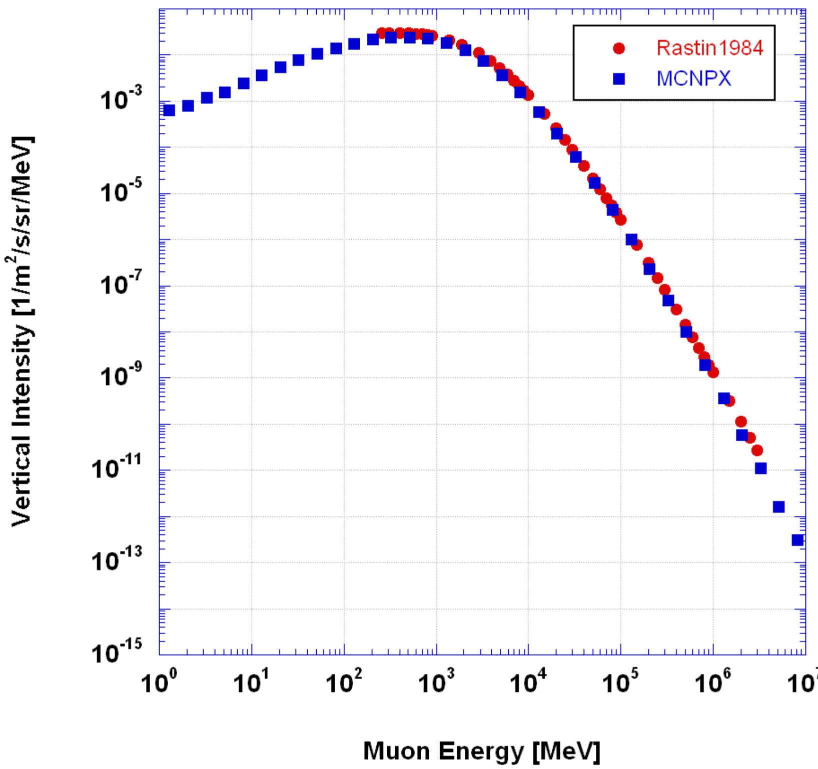


Figure 4: MC-generated muon spectrum and data measured at sea level.

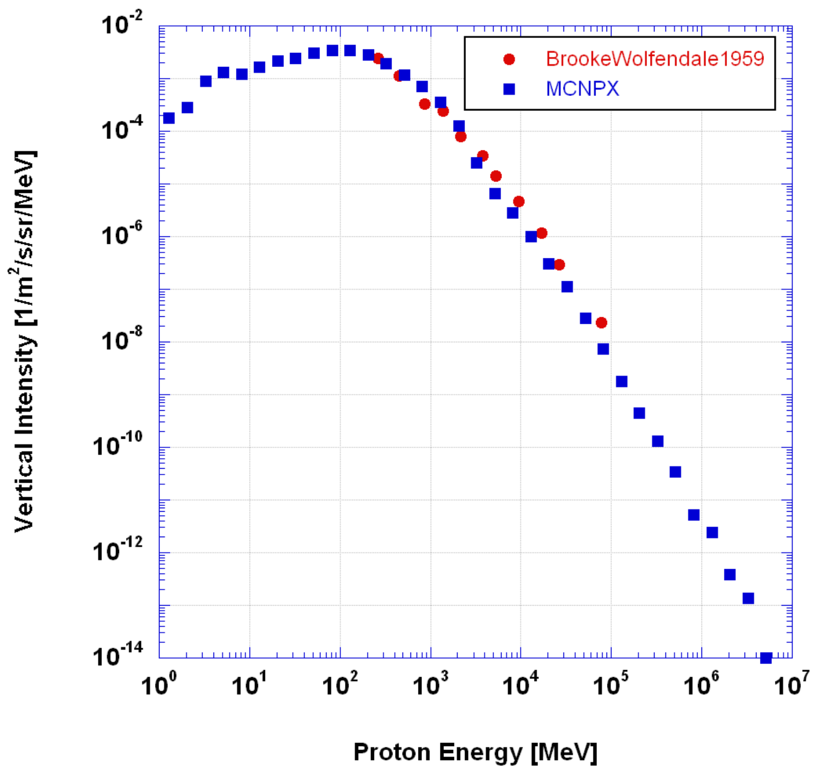


Figure 5: MC-generated proton spectrum and data measured at sea level.

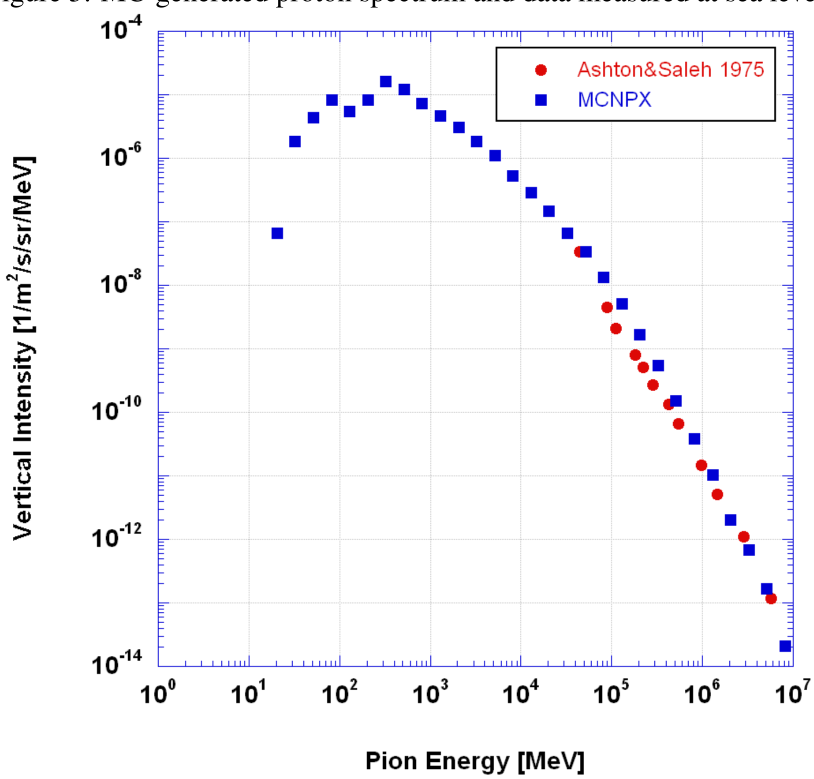


Figure 6: MC-generated pion spectrum and data measured at sea level.

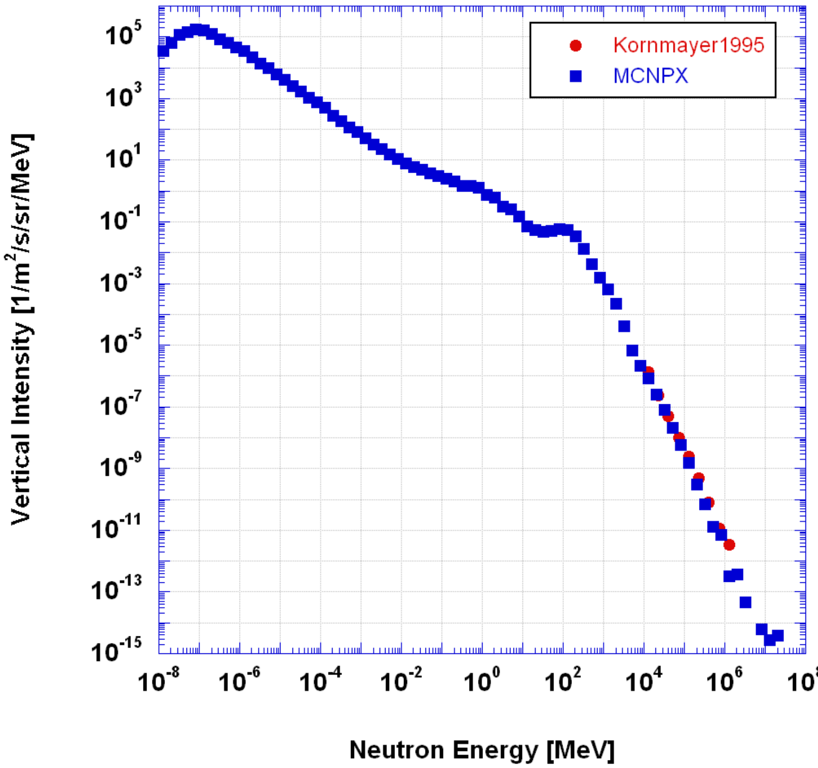


Figure 7: MC-generated neutron spectrum and data measured at sea level.

## 5 Conclusion

We have calculated cosmic-ray fluxes at sea level employing three different Monte Carlo codes. Except for low energy neutrons, all codes give essentially similar distributions of cosmic-ray secondaries. We have also compared our calculations to published data and found good agreement. Hence MC calculations should give quite reliable predictions of cosmic-ray distributions in situations where data are not available.

## References

[1] P. Papini, C. Grimani,and S.A. Stephens, Nuovo Cim C 19 , 367 (1996).

[2] B.C. Rastin, J. Phys. G: Nucl. Part. Phys. 10, 1609 (1984).

[3] G. Brooke and A. Wolfendale Proc. Phys. Soc. 83, 843 (1964).

[4] F.Ashton and A. Saleh PICRC 7, 2707 (1975).

[5] H. Kornmayer et al., J. Phys. G: Nucl. Part. Phys. 21, 439 (1995).

[6] D. J. Cook, Physical Review Letters, Vol 51 No 4, (1983).