Chapter 19: Developing of a New Atmospheric Ionizing Radiation (AIR) Model

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Towards a New Atmospheric Ionizing Radiation (AIR) Model

Preface

As a result of the research leading to the 1998 AIR workshop and the subsequent analysis, the neutron issues posed by Foelsche et al. and further analyzed by Hajnal have been adequately resolved. We are now engaged in developing a new atmospheric ionizing radiation (AIR) model for use in epidemiological studies and air transportation safety assessment. A team was formed to examine a promising code using the basic FLUKA software but with modifications to allow multiple charged ion breakup effects. A limited dataset of the ER-2 measurements and other cosmic ray data will be used to evaluate the use of this code.

INTRODUCTION

The earth is continually bathed in high-energy ionizing radiation that comes from outside the solar system, called galactic cosmic rays which consist of roughly 90% protons and 8% helium nuclei (also called alpha particles, though of different origin) with the remainder being heavier nuclei and electrons [Gaisser, 1990]. When these particles penetrate the magnetic fields of the solar system and the Earth and reach the Earth's atmosphere, they collide with atomic nuclei in air and create cascades of secondary radiation of every kind [Reitz, 1993]. The intensity of the different particles making up atmospheric cosmic radiation, their energy distribution, and their potential effect on avionics and aircraft occupants vary with altitude, location in the geomagnetic field, and time in the sun's magnetic activity cycle [Reitz, 1993; Wilson, 2000; Heinrich et al., 1999]. The atmosphere provides shielding, which at a given altitude is determined by the mass thickness of the air above that altitude, called atmospheric depth. The geomagnetic field provides a different kind of shielding, by deflecting low-momentum charged particles back into space. The minimum momentum per unit charge (magnetic rigidity) a vertically incident particle can have and still reach a given location above the earth is called the geomagnetic vertical cutoff rigidity (vertical cutoff) for that point.

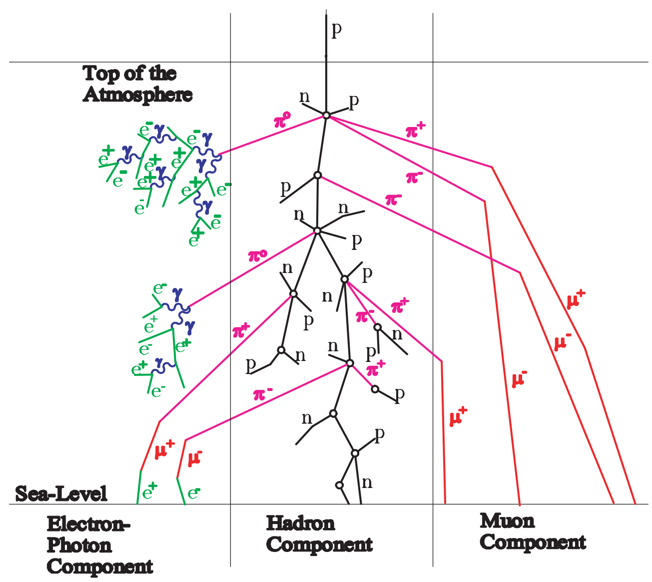

Fig. 1 Cascading particles produced by high-energy protons at the top of the atmosphere.

The local flux of incident cosmic rays at a given time varies widely with geomagnetic location and the solar modulation level. When solar activity is high, GCR flux is low and vice versa. Anti-correlation between cosmic rays fluxes and the level of solar activity (solar modulation) is caused by magnetic field irregularities in the solar wind that push charged particles out of the solar system or decelerate them [Clem et al., 1996 and references therein]. Solar modulation of cosmic ray fluxes has roughly a 22-year cycle, which must be considered to accurately predict the spectrum at any given time. The modulated spectrum is generally determined by solving the Fokker-Planck equation for a spherical symmetric model of the heliosphere incorporating diffusion, adiabatic acceleration and convection.

METHOD

The propagation of primary particles through the Earth's atmosphere has been calculated with a three dimensional Monte Carlo transport program FLUKA [Fasso, et al., 1993; Clem and Dorman, 2000]. Primary protons and alphas are generated within the rigidity range of 0.5GV-20TV uniform in $\cos^2\theta$. For a given location, primaries above the effective cutoff rigidity are transported through the atmosphere. Since FLUKA does not transport nuclei, helium ions are initially transported with a separate package called HEAVY to simulate fragmentation [Engel et al., 1992]. This package interfaces with FLUKA to provide interaction starting points for each nucleon originating from a helium nucleus

The primary cosmic ray spectrum used in this calculation was determined through an analysis of simultaneous proton and helium measurements made on high altitude balloon flights [Seo et al., 1991; Papini et al., 1993; Boezio et al., 1999; Menn et al., 2000; Sanuki et al., 2000] or space craft [Alcaraz, et al., 2000a; 2000b] as shown in Figure 2. These flights occurred during different times and different levels of solar modulation resulting in a variation of spectra shapes. To provide a continuous relationship between solar modulation level and the expected spectra shape for both cosmic ray protons and helium, a global fit was performed on this data using the solution to the Fokker-Plank equation assuming the shape of the spectrum of cosmic rays in the local interstellar medium (outside the solar system) is a power law in rigidity multiplied by an ionization energy loss term to account for the effects expected

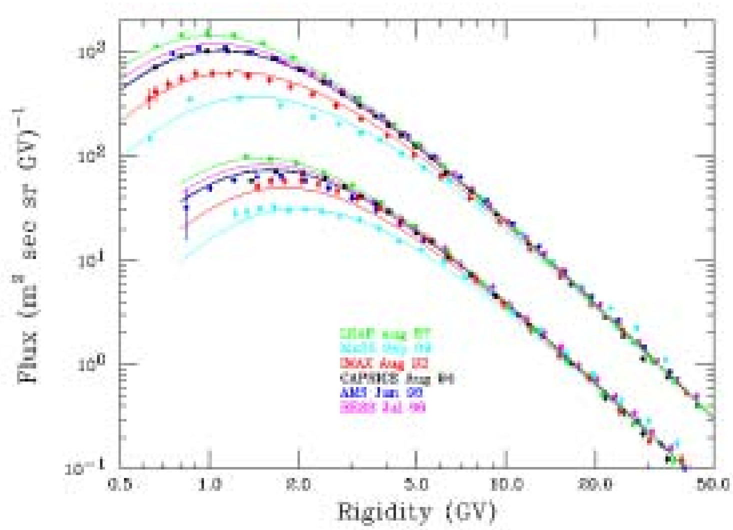

Figure 2. Results of balloon and space-craft measurements of the rigidity spectra of primary cosmic ray protons (upper spectra) and Helium ions (lower spectra) above of the Earth's atmosphere (points) and global fit to all the spectra (curves).

$$dF/dR = k1R^{-k2} \ (1-e^{-k3\beta})$$

from galactic propagation. The free parameters (k1, k2, k3) in the fit include the power index and normalization of the local interstellar spectra of protons and alpha particles. Initially, the diffusion coefficient ($\boldsymbol{\kappa}$) was modeled in the standard way as

$$\boldsymbol{\kappa} = \boldsymbol{\kappa_0}\, e^{(r-1)/rd} \beta R$$

where R is the rigidity of the particle, β is the speed of the particle normalized to the speed of light, r is the distance from the sun in astronomical units and rd is the diffusion length scale. In this model, the quantities $\boldsymbol{\kappa}$ and $\boldsymbol{\kappa_0}$ are vectors and each component of $\boldsymbol{\kappa_0}$ is a free parameter representing the diffusion coefficient value for each data set (same value for both particle species) used in the global fit. Although this unique method provided promising results, the chi square of the fits had a rigidity dependence resulting in systematic errors. As an attempt to reduce the systematic effects, the above diffusion coefficient model is modified to

$$\boldsymbol{\kappa} = \boldsymbol{\kappa_0}\, e^{(r-1)/rd} \beta\, f_n(R)$$

where $f_n(R)$ is an nth order polynomial in rigidity with the lowest order term forced to zero and the coefficient on the linear term forced to one. Second order results are shown in Figure 2. Even though this technique has decreased the chi square per degree of freedom by ~30%, the average residual (the difference fit - data divided by the data error) is 3.5 sigma based on the published errors of the spectra. Therefore, some work is needed to improve this procedure including the possibility of modifying the current local interstellar spectrum model. The recent work of Badhwar et al. [2001] may be helpful.

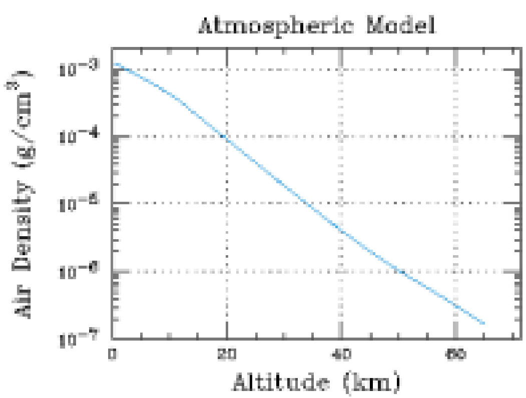

Fig. 3 Standard atmosphere density as a funciton of altitude.

The atmosphere is divided into 180 (bottom boundary radius = 6378.14km) concentric spherical shells with differing radii and density to simulate the actual density profile with a vertical total 1035g/cm2 column density for sea level and 305g/cm2 for 9.1km (30,000ft) [4]. Air density changes ~5% with each adjacent spherical shell, but within each shell the material has a uniform density. Above 2000 meters the atmospheric composition is constant with a 23.3% O2, 75.4% N2 and 1.3% Argon distribution by mass while below 2000 meters a varying addition of H2 from 0.06% at sea-level to 0.01% by mass at 2000 meters is included to account for the abundance of water vapor. The outer air-space boundary is radially separated by 65 kilometers from the inner ground-air boundary. A single 1cm2 element on the air-space boundary is illuminated with primaries. This area element defines a solid angle element with respect to the center of the Earth which subtends a slightly smaller area element at different depths. Particle intensity at various depths is determined by superimposing all elements on the spherical boundary defining the depth. Due to rotational invariance this process is equivalent to illuminating the entire sky and recording the flux in a single element at ground level, but requires far less computer time [5]

COMPARISON WITH OBSERVATION

As a check, the calculated particle fluxes are compared to published data. The absolute normalization of the simulated flux is determined from the number of generated primaries, weighted according to the expected primary spectrum (no free parameters in the comparison). The particle types compared are muons, protons and neutrons. The neutron measurements were performed aboard an ER-2 high altitude airplane by Goldhagen's group during one of the lowest solar modulation periods (highest radiation levels) of the previous solar cycle (Jun-13 1997) [6]. As shown observations were taken at 56.5 and 101g/cm2 atmospheric depths at high latitude locations with rigidity cutoffs less than 1GV. The calculation agrees fairly well particularly in high energy regime, however the flux measurements are systematically higher at lower energies. This discrepancy could be the result of T value used for the ambient temperature and/or treatment of the thermalization process. Also shown are observations of sea-level protons and muons as published in Allkofer and Grieder 1984 [7]. Again the calculation seems to agree with the observations fairly well however there are systematic differences. These difference could be explained by the limitation of a digitized atmospheric model that produces an enhancement in pion interactions. In any case, it appears that the use of this version of FLUKA is a reasonable choice.

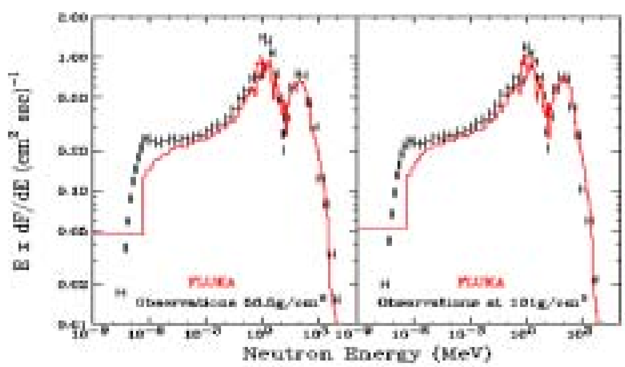

Figure 4. Measured and calculated neutron spectra at 20 km altitude and 0.8 GV cutoff.

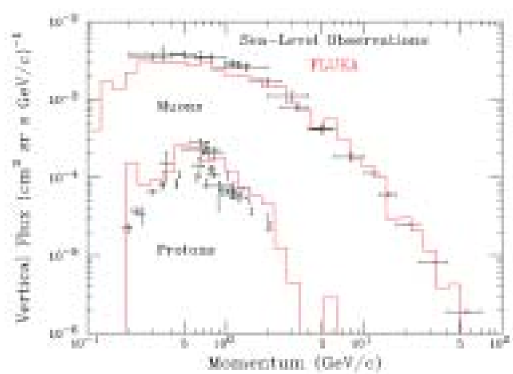

Figure 5. Sea-level observations of protons and muons [Allkofer and Grieder 1984] compared to this calculation.

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