CONFERENCE—Dr. Larry Pinsky, professor and chair of the Department of Physics (*c.*), discusses problems of space radiation with Dr. Thomas Wilson, NASA co-investigator associated with the Astromaterials Research and Exploration Science Office (ARES) (*r.*), and Kerry Lee, graduate student in physics (*l.*). Radiation can seriously affect astronaut safety.

Development of a Space-Radiation Monte-Carlo Computer Simulation Based on the FLUKA Code

Abstract— FLUKA is the best currently available integrated Monte-Carlo radiation transport code. It has been continuously enhanced by a team of authors over the last decade and a half and will continue to be updated and improved over the coming years. While doing an excellent job with the physics incorporated within the scope of the code, FLUKA as it currently exists is not adequate to simulate the space radiation environment. Its major deficiency is the lack of provisions for heavy ion (nuclei with charge ≥ 2) interactions during transport. In addition, the user interface to the current version of FLUKA is quite cumbersome. This project has embarked on an effort to remedy these problems and produce a code that will accurately simulate the radiation environment. As a first step, the interaction code DPMJET has been incorporated into FLUKA to handle heavy-ion interactions above 3-5 GeV/A. Researchers have used this improved version of the code to simulate the data from the ATIC balloon-borne cosmic-ray experiment in order to be able to compare UH results with actual data. Work is proceeding on the inclusion of a second interaction code, RQMD, to handle the interactions below 3 GeV/A. ISSO funding was used, in part, as a source of matching funds in obtaining a NASA grant to pursue this project. That grant is currently in force and will continue through November 2003.

Our environment is constantly being traversed by what is known by the umbrella term of “radiation.” In general, it includes individual charged particles, which span the spectrum in energy from those that are unable to penetrate the skin to those which are capable of penetrating miles of rock. It also includes the highest energy photons, which we term gamma-rays, along with their lower energy cousins, the X-rays. Even neutral particles such as neutrons and neutrinos fit under this umbrella term. At the surface of the Earth, we sit in an environment that includes all of these constituents to some extent. For example, the average person’s body is traversed by approximately 100 relativistic muons per second, and neutrons and gamma-rays bombard our bodies from the decay of various radioactive nuclides that we ingest in our food and in the air we breathe. In space beyond the Earth’s atmosphere, the radiation environment is significantly more intense. There are contributions from Galactic Cosmic Rays (GCRs), which diffuse throughout our galaxy and impinge upon us after auguring their way first through the fringes of the Sun’s effects, and then through the Earth’s magnetic field. The Sun itself contributes a constant stream of lower-energy particles along with occasional outbursts in the form of directional flares which can be so intense as to be lethal, potentially even to astronauts inside a typical spacecraft. The Earth’s magnetic field provides both a shield of sorts from the lower-energy incoming charged particles, but at the same time it indirectly provides another source of radiation when it acts to funnel charged particle into the intense regions of trapped particles known as the radiation belts. Finally, there is an albedo of particles coming upward from the Earth itself. In large part, this is a result of the interactions of the GCRs with the atmosphere, but even some contribution comes from sources at or near the surface. One should also mention the potential for sources that will come from within the spacecraft material and components themselves, along with an albedo, emanating from the spacecraft as viewed from outside. For astronauts within a spacecraft, the greatest radiation threat typically comes from the net enhancement to the radiation flux's capability to cause biological damage that occurs as that flux passes through moderate amounts of matter, such as in the spacecraft walls.

We have made great strides in categorizing and measuring the nature and composition of each of these sources, as they exist in the native environments. However, it is the nature of these particles that they interact in very complex and transformative ways as they traverse matter. This is the primary subject of study in the field of elementary particle physics. While the number of experiments done in the history of that field is staggering, attempts have been made to provide succinct mathematical models that include the transport for all of these kinds of particles traversing all forms of material. Given the probabilistic nature of the interactions, individual events are best modeled through the use of stochastic processes based on pseudo-random number generators whose expectation values coincide with the physics observable being modeled. Such simulations are termed Monte Carlo calculations.

We have chosen FLUKA as the Monte Carlo code to be employed because it is currently the most accurate integrated code available. FLUKA was originated by Professor Johannes Ranft beginning in 1970 for simulating particle cascades (FLUKA is acronym formed from the German for "Fluctuating Cascade"). Professor Ranft has ceded control over the continued development of FLUKA to the INFN (Instituto Nazionale di Fisica Nucleare—the Italian National Nuclear Physics funding agency) group at the University of Milan. Individuals primarily responsible are a husband and wife team, Drs. Alfredo Ferrari and Paola Sala. FLUKA in its present version is a fully integrated code, completely capable of simulating a wide range of physics. FLUKA also provides for "plug-in" capabilities to add physics that is not already integrated, such as a full treatment of all possible heavy-ion interactions.

The internal ability to simulate the transport of all of the ions up to iron is the most glaring shortcoming of FLUKA in its present form in terms of its usefulness for simulating the space radiation environment. In addition, FLUKA's interface is very difficult to use, and the output formats available are limited by the current implementation of the code's output interface. We are thus also developing a substantial upgrade of the user-friendliness of FLUKA by melding its interface into the new ROOT data analysis infrastructure being developed at CERN.

The general problem of providing an event generator to simulate interactions for all heavy ions of interest in the cosmic-ray flux is formidable. In fact, NASA has embarked on an associated program (in which UH researchers are active participants) to take the data necessary and provide the modeling required to obtain this capability. The projected time frame for this ambitious project is about ten years. In the interim, we have chosen to employ several existing codes that have been modified for internal use within FLUKA. While this solution is not perfect, it will allow us to begin exploring the possibilities with the available resolution and based on the currently available data. As the longer term NASA project unfolds, we will, of course, incorporate those improvements into the future releases of our code.

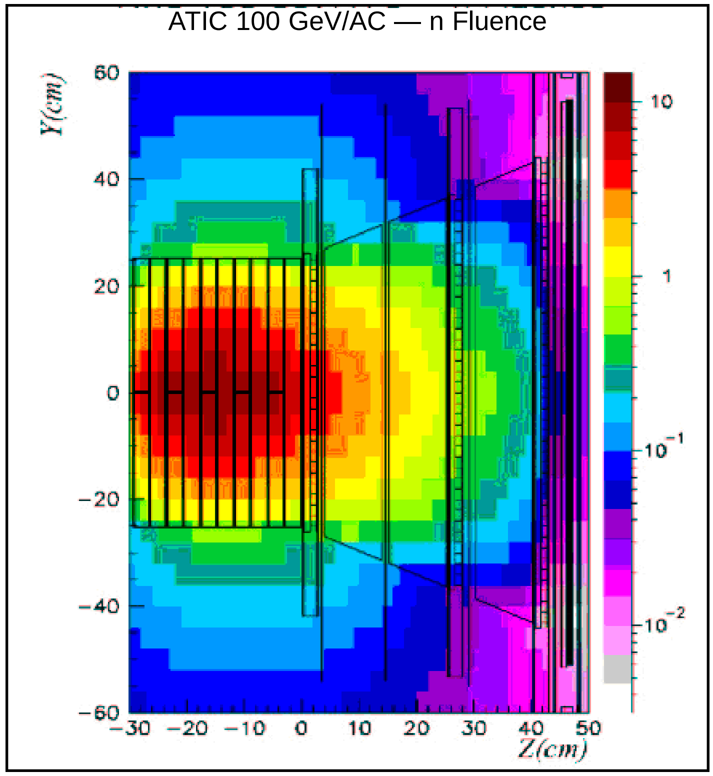

Figure 1. A plot of neutron fluences due to 100 GeV/A incident carbon in the ATIC experiment as calculated with FLUKA/DPMJET.

At the highest energies, we have succeeded in incorporating the DPMJET code into FLUKA. DPMJET is an application program that acts as an event generator for incident nuclei above 3 GeV/A, and is fairly good for all incident and target nuclear combinations. The accuracy of the generator is actually beginning to degrade at energies below about 25 GeV/A but is still respectable down to about 5 GeV/A. Between 5 and 3 GeV/A, the results worsen to the point where they cannot be trusted any lower than that.

In order to validate this version of FLUKA we have performed simulations of the ATIC experiment. ATIC is a balloon-borne experiment designed to look at the cosmic-ray composition in the 100 GeV/A to 10 TeV/A range. It consists of a telescope of silicon strip detectors on top of a set of carbon interaction targets followed by a Bismuth-Germanium-Oxygen (BGO) calorimeter, with triggering scintillators interspersed at various points. The experiment was flown near the top of the atmosphere for an extended time last year in Antarctica. Our interest is in determining if FLUKA with DPMJET is sufficient to simulate the actual data accurately. One must stress that we are not collaborators on the ATIC experiment and are most grateful to the ATIC collaboration for giving us access to much useful information about their experiment. Figure 1 displays a fluence plot of some of the FLUKA results. It represents the total neutron fluence

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ASTROMATERIALS RESEARCH—Dr. Thomas L. Wilson, NASA/JSC co-investigator, explores the accuracy of computer codes in assessing data of inelastic nuclear collisions. RMQD codes may be incorporated into FLUKAcodes.

through A raster of pixels due to 1000 simulated 100 GeV/A carbon nuclei normally incident close to the central axis of the experiment. An outline of the ATIC hardware is superimposed on the plot. Color-coded levels are logarithmic and represent five levels per decade. Fluence is the net flux and is expressed as the total path-length of neutrons of all energies through each pixel. One can use this plot to evaluate the potential for neutron backscatter contamination in the entire detector from events of this type. Such contamination represents a potential background for subsequent events of interest.

In order to deal with the lower-energy heavy-ion interactions, we are currently exploring the accuracy with which the RQMD code replicates the existing data down to the limit for inelastic nuclear collisions. If RQMD is deemed to do an acceptable job through these energies, it will be incorporated into FLUKAin the same fashion as DPMJET has been. We have already determined that such an incorporation is practical. In the event that RQMD is found to have unacceptable inaccuracies, our fall-back solution would be to extend the Pre-Equilibrium model called PEANUT, which is already employed internally by FLUKA to generate the interactions of singly-charged incident particles on nuclear targets.

In addition to the efforts to include the heavy-ion physics within FLUKA, we are also supporting work on the existing geometry package to the extent that the use of logical parentheses will be added to the current set of combinatorial tools. After that work is completed, work will continue to transfer the existing scoring and analysis tools that have been developed over the years to evaluate the FLUKAoutputs into a ROOT analysis environment. ROOT is an object-oriented software analysis infrastructure developed at CERN. Following the completion of that task, work will begin on producing a ROOT-based Graphical User Interface for the creation of the required inputs for FLUKA, with the ultimate goal of combining both end-packages into the same seamless environment.

Publications

Pinsky, L., J. MacGibbon, G. Badhwar, and T. Wilson. “A Space Radiation Monte-Carlo Computer Simulation using the FLUKA Code,” *J. Geophys. Res*. (*Accepted for publication*.)

Presentations

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Funding and proposals

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“Radiation Transport Code Development for Space Radiation Shielding Applications.” NASA NRA-01-OBPR-05, Aug. 1, 2002-July 31, 2006, $680,374; *pending*.