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POST-LAUNCH DATA ANALYSIS FOR THE COSMIC RAY ISOTOPE EXPERIMENT ONR-604 IN THE "COMBINED RELEASE AND RADIATION EFFECTS SATELLITE" (CRRES)

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I. INTRODUCTION

The NASA Grant NAGW-2368 (for "Post-Launch Data Analysis for the Cosmic Ray Isotope Experiment ONR-604 in the Combined Release and Radiation Effects Satellite [CRRES]") has supported, from its beginning in October 1990 to its termination in September 1994, a program of research and analysis which has continued the research carried out during many years in the Laboratory for Astrophysics and Space Research of the University of Chicago on the origins, acceleration mechanisms and the propagation modes of the hierarchy of energetic charged particles found in a wide range of astrophysical settings, extending from the cosmic rays arriving from the depth of the galaxy to the energetic particles in the heliosphere and in the near Earth environment.

In particular this grant has been a vital support in the investigation of the particle radiations in the Earth's magnetosphere

The ONR-604 instrument was launched in July 1990 aboard the*CRRES* spacecraft. The CRRES mission has been a joint program of the National Aeronautics and Space Administration and the U. S. Air Force Space Test Program which has provided launch support and telemetry coverage. The spacecraft was placed into a low-inclination eccentric orbit with a period of ~10 hours, and thus measured charged particle fluxes in both interplanetary space and in the Earth's trapped radiation. ONR-604 performed extremely well, both in interplanetary space and in the intense radiation belt environment. Indeed, we were able to make detailed measurements of interplanetary fluxes and composition into L=4, or for more than 50% of the orbital period. Thus the experiment produced two valuable datasets, one set outside of L=4 for interplanetary studies, and one set inside of L=4 for radiation belt studies. The data returned by the University of Chicago ONR-604 instrument has been the base for 10 papers on magnetospheric and galactic energetic-particle research.

II MAGNETOSPHERIC STUDIES.

We have carried out magnetospheric studies, in active collaboration with Co-Investigators at Louisiana State University and Lockheed Co. One exciting topic has been an investigation of charged particle access to the Earth's magnetosphere, both during solar quiet times and during solar flare periods. We have introduced novel aspects involving the use of isotopic measurements as tools in the understanding of charged-particle access mechanisms.

a) Heavy Energetic Nuclei in the Earth Magnetosphere.

(Papers 1, 3, 9).

A part of this research has been the mapping of the intensities of heavy energetic nuclei along the CRRES orbit to determine their distributions in space and time in the Earth's magnetosphere as well as correlation of the intensities of heavy energetic nuclei with the single event upsets registered by the Microelectronics Package Experiment on CRRES (see "CRRES Microelectronics Test Package" by E. G. Mullen and K. P. Ray, IEEE Trans. Nuc. Science, 40, 228, 1993)

b) Cosmic Ray Model.

(Papers 7, 8, 9).

The data from the ONR-604 experiment has been used to construct a Cosmic Ray Model that can predict the intensity of energetic heavy ions in the near Earth's space at a given time and can be used in particular to asses the damage (e. g. single event upsets, SEU) that such heavy ions ions can inflict to the microelectronics at the hearth of space vehicles.

The heavy ion energetic (>10 MeV/nucleon) particle population in the vicinity of the Earth is dominated by three components:

1. Solar energetic particles (SEP), which are associated with solar flare eruptions. This component was particularly important during the CRRES mission which occurred at times of maximum solar activity.
2. Galactic cosmic rays (GCR), which originate outside the heliosphere.
3. The anomalous components (AC), which have been measured in a few elements (He, N, O, Ne) and are only present at low energies (<60 MeV/nucleon). In the interplanetary space near Earth these components are only significant at times of low level of solar modulation.

To predict the absolute abundance spectrum of the particle population in the Earth's vicinity our group at the University of Chicago, together with groups at Louisiana State University, and the Lockheed Co. has developed a model based on our current understanding of GCR, SEP and AC

astrophysics. This model has been designated CHIME (for "CRRES/SPACERAD Heavy Ion Model of the Environment").

The model includes the SEP maximum fluency, time dependent behavior, heavy ion content, and energy spectrum. For the GCR it starts from the assumption of a cosmic ray source composition, then follows the evolution of the cosmic ray composition during interstellar transport and partial leakage from the Galaxy until arrival to the local interstellar space. The modifications due to solar modulation are taken into account through the values of the force-field parameter F. For the AC, differential energy spectra (assumed to originate at the edge of the heliosphere) have been deduced from measurements at 1 AU and other radial distances from the Sun, and the spectra at Earth calculated using the parameter F.

CHIME predicts the energy spectra of all stable and long-lived species, from ^{1}H to ^{58}Ni over an energy range from 10 to 50,000 MeV/nucleon.

c) Validation of the CHIME Model.

The Cosmic Ray Model has been based in previous energetic particle measurements over many years, at different radial distances from the Sun and based on a growing understanding of the nature and dynamics of solar energetic particles, galactic cosmic rays and anomalous components. An outstanding part of this data base originated in the past from measurements carried out by University of Chicago satellites in the IMP missions and in the Pioneer probes.

For a validation of the model and a final adjustment of its parameters we used data from the CRRES ONR-604 instrument taken inside the Earth's magnetosphere and complemented by data taken near Earth outside the magnetosphere by the University of Chicago experiment on the IMP-8 satellite. A first step has been to determine the correctness of the fluxes calculated using the ONR-604 data taken beyond $L>4.75$ by comparing them with IMP-8 fluxes.

III. CHARGED-PARTICLE ISOTOPIC MEASUREMENTS

(Papers 2, 3, 4, 5).

ONR-604 returned high-quality charged-particle isotopic measurements until the *CRRES* spacecraft failed in October 1991.

Although the number of events available for isotopic composition was severely limited because the mission lasted only 15 months instead of the anticipated 3-5 years, we have attained using the ONR-604 dataset the best isotopic resolution yet achieved. We have reported the results on the isotopic composition of cosmic ray C through Si at the World Space Congress in 1992 and to the 23rd International Cosmic Ray conference in Calgary, Canada in 1993. We are now finishing a comprehensive paper on these isotopic investigations for publication in the Astrophysical Journal.

IV INTERPLANETARY AND HELIOSPHERIC PROPAGATIONS.

(Papers 4, 5).

We have updated in collaboration with the LSU Group our programs to calculate energetic particle propagation in interplanetary space and developed our techniques and software to perform solar modulation calculations. Both the propagation and modulation calculations have been essential to interpret our isotopic and elemental measurements in terms of galactic source composition. The CRRES mission has ocurred during the highest solar modulation level registered to date thus providing an opportunity to study an exceptionally dynamic state of the heliosphere.

APPENDIX 1

PUBLICATIONS SUPPORTED BY THE GRANT

1. *"The Access of Heavy Ions into the Earth's Magnetosphere Measured by the ONR–604 Instrument on the CRRES Satellite"*,

   D. L. Chenette, J. F. Cooper, M. Garcia-Munoz, T. G. Guzik, O. E. Pruet, K. R. Pyle, Y. Sang, J. A. Simpson, and J. P. Wefel, *Proc. XXII Int'l Cosmic Ray Conf., (Dublin),* **3**, 613, 1991.

2. *"The Isotopic Composition of Galactic Cosmic Rays From The ONR-604 Experiment on the CRRES Satellite"*,

   M. Garcia-Munoz, K. R. Pyle and J. A. Simpson, *"World Space Congress, Book of Abstracts"* , Paper E.7-M.1.15X, page 508. Washington D. C., 28 August - 5 September 1992.

3. *"The $^3He/^4He$ Ratio Outside and Inside the Magnetosphere from the University of Chicago Experiments on the IMP-8 and CRRES Spacecraft"*,

   J. Chen, J. F. Cooper, T. G. Guzik, M. Garcia-Munoz, K. R.. Pyle, Y. Sang, and J. P. Wefel, *"World Space Congress, Book of Abstracts"* , Paper E.7-M.1.16X, page 508. Washington D. C., 28 August - 5 September 1992.

4. *"The Isotopic Composition of Ne, Mg, and Si Cosmic Rays from the ONR-604 Experiment on the CRRES Mission"*,

   M. A. DuVernois, M. Garcia-Munoz, K. R. Pyle, and J. A. Simpson, *Proc. XXIII Int'l Cosmic Ray Conf., (Calgary),* 1, 563, 1993.

5. *"The Isotopic Composition of Cosmic Ray C, N, O: Source Abundances Derived from the ONR-604 Experiment on the CRRES Mission"*,

   M. Garcia-Munoz, K. R. Pyle, J. A. Simpson, and M. Thayer, *Proc. XXIII Int'l Cosmic Ray Conf., (Calgary),* 1, 543, 1993.

6. *"A Model of Solar Energetic Particles for Use in Calculating LET Spectra Developed from ONR-604 Data"*,

   J. Chen, D. Chenette, T. G. Guzik, M. Garcia-Munoz, K. R. Pyle, Y. Sang and J. Wefel, *Adv. Space Res.*, 14, 676 1994.

7. *"A Model of Galactic Cosmic Rays for Use in Calculating Linear Energy Transfer Spectra"*,

J. Chen, D. Chenette, R. Clark, M. Garcia-Munoz, T. G. Guzik, K. R. Pyle, Y. Sang and J. Wefel., *Adv. Space Res.*, 14, 765, 1994.

8. *"The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particle Effects on Electronic and Biological Systems"*,

D. Chenette, J. Chen, E. Clayton, T. G. Guzik, J. P. Wefel, M. Garcia-Munoz, C. Lopate, K. R. Pyle, K. P. Ray, E. G. Mullen, and D. A. Hardy, *"Proceedings of the 31st Annual International Nuclear and Space Radiation Effects Conference"*, paper G-1, Tucson, Arizona, July 18-22, 1994.

9. *"The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particle Effects on Electronic and Biologic Systems in Space"*,

D. L. Chenette, J. Chen, E. Clayton, T. G. Guzik, J. P. Wefel, M. Garcia-Munoz, C. Lopate, K. R. Pyle, K. P. Ray, E. G. Mullen, and D. A. Hardy, *IEE Trans. Nucl. Science*, 41, 2332, 1994.

10. *"The Isotopic Composition of Cosmic Ray C, N, O, Ne, Mg, and Si: The CRRES Satellite Mission Investigations"*,

M. DuVernois, M. Garcia-Munoz, K. R. Pyle, J. A. Simpson, and M. Thayer, to be submitted for publication in the *Astrophysical Journal*, 1995.

APPENDIX 2.

SELECTED REPRINTS OF PUBLISHED PAPERS SUPPORTED BY THE GRANT

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A MODEL OF SOLAR ENERGETIC PARTICLES FOR USE IN CALCULATING LET SPECTRA DEVELOPED FROM ONR-604 DATA

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ABSTRACT

A model of solar energetic particles (SEP) has been developed and is applied to solar flares during the 1990/1991 CRRES mission using data measured by the University of Chicago instrument, ONR-604. The model includes the time-dependent behavior, heavy-ion content, energy spectrum and fluence, and can accurately represent the observed SEP events in the energy range between 40 to 500 MeV/nucleon. Results are presented for the March and June, 1991 flare periods.

INTRODUCTION

Ionization caused by an incident energetic particle, particularly heavy ions, in a sensitive region of a satellite instrument can damage the logic circuits and upset computer memories or control mechanisms. This effect is known as a Single Event Upset (SEU). The Microelectronics Package on board the CRRES mission was designed to study the SEU effects for a variety of chips. Solar Energetic Particles (SEP's) with energy between 10-500 MeV/nucleon are one source of SEU's. It is, therefore, important to model SEP events, in order to calculate the Linear Energy Transfer (LET) spectra needed for predicting the occurrence of SEU's. The solid state detector telescope ONR-604 /1/ on CRRES can measure heavy ions from helium (40-100 MeV/nucleon) to iron (185-500 MeV/nucleon). Heavy ions (neon and above) were analyzed with highest priority in the instrument and are called P1 particles.

Adams *et al.* /2/ determined the solar energetic heavy-ion fluxes by scaling from solar proton spectra and by utilizing a flare relative composition dataset measured at low energies. In a summary of SEP observations made by IMP-8 during 1973-83, Chenette and Dietrich /3/ pointed out that, for most SEP's, the spectra have a similar shape at energies 10-400 MeV/nucleon for the various ions heavier than boron. This result was confirmed at low energies (2-25 MeV/nucleon) by Reames *et al.* /4/, who showed that heavy ions and Helium have similar spectral shapes. However, the shape of the proton spectrum is usually different from that of the heavy ions /5/. Two different types of SEP events can be distinguished according to their heavy-ion content: "rich" and "normal" /2/. The heavy ion "rich" events tend to be impulsive events while "normal" events tend to be gradual in their onset time history /6/. In the following sections a SEP model is developed and applied to solar flares during the 1990/1991 CRRES mission.

MODELING SEP EVENTS

There are five steps in modeling a SEP event: (1) Determine the time-intensity profile including the start, peak and end of the SEP event. (2) Obtain peak and average fluxes for helium and protons and fit each to a power-law form:

$$dJ/dE = A(E/E_0)^{-\gamma}, \tag{1}$$

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where E_0 is a "representative energy" for each SEP event. The spectral index γ is assumed to be the same as the helium index for all the heavy elements. (3) Calculate the fluence (in particle/cm^2-sr-MeV/nucleon). (4) Find the heavy-ion enrichment parameter δ, defined /3/ as $\delta = (\ln(Fe/O) - \ln 0.155)/18$, where 0.155 is the mean solar corona Fe/O abundance ratio /7,8,9/. (5) Apply the δ parameter to scale the solar heavy-ion fluxes of different species from the solar helium spectra. Then the LET spectra can be calculated for various thicknesses of shielding.

THE OBSERVATIONS

Helium: Time Histories

From the helium counting rates, a total of 26 SEP events have been identified during the CRRES mission, of which the March and June, 1991 events are the largest. The 12 major SEP events, with peak helium counts per orbit > 100, are tabulated in Table 1, and each SEP event is associated with a specific solar flare. Table 1 also lists the start, peak and end time at Earth of each SEP event. The SEP particles are believed to be accelerated to energies of tens to hundreds of MeV/nucleon by a shock wave and then move outward through the corona and diffuse along the magnetic field lines into interplanetary space. Therefore, although a solar flare event lasts seconds to hours, as observed in the H_α line, X-ray, Gamma-ray, and radio spectral regions, a SEP event at Earth can last from hours to more than a week, with a typical period of 2-3 days.

TABLE 1. Major SEP Events During the CRRES Mission

Event Number	Peak Orbit	Start (Day)	Peak (Day)	End (Day)	Peak He (cnt/orb)	P1/He (10^{-4})	Assoc. Flare (Day/UT)
1	451	26.0	27.2	29.3	201	-	Jan 25/0630
2	462	31.3	31.7	32.4	481	-	Jan 31/0230
3	522	56.4	56.5	57.6	235	-	Feb 25/0819
4	586	82.1	82.6	84.0	10000	9±2 1.7	Mar 22/2247
5	593	84.6	85.4	87.6	3234	-	Mar 24/2046
6	710	133.1	133.4	135.0	517	-	May 13/0144
7	774	153.0	159.6	162.1	23404	1.7±0.5	Jun 04/0352
8	783	162.1	163.4	165.5	19135	2.9±0.7	Jun 11/0209
9	792	166.3	167.2	173.6	11918	10±2 1.6	Jun 15/0821
10	829	179.5	183.0	188.3	1648	-	Jun 28/0626
11	842	188.4	188.6	190.3	450	-	Jul 07/0223
12	961	238.7	239.7	241.4	156	-	Aug 25/0115

The March and June events have helium counting rates that increase two orders in magnitude, and these events, 4 and 7 in Table 1, are used as examples to illustrate the model. The time-intensity profiles of these two SEP periods are plotted in Figure 1a. The peak helium fluxes occurred at orbit 586 for the March event and at orbits 774, 783, and 792 for the June events. These multiple peaks in the SEP events are actually associated with different particle injections, as listed in Table 1. The March event includes two major solar flares and the June period contains at least three large solar flares.

The CRRES satellite was in a geosynchronous transfer orbit (GTO) and traveled through the magnetosphere from a perigee of ~ 350 km to an apogee of ~ 33,580 km with an inclination of 18.2 degrees. Helium with different energies observed at various positions in the orbit (i.e., different L shells) will experience different geomagnetic cutoff effects. Figure 1b displays the helium counting rate as a function of L shell for orbits 586 (top) and 774 (bottom). Helium above 40 MeV/nucleon can freely access L > 5, in agreement with the transmission function calculations. In addition, most helium is detected at L > 6 since the spacecraft spends the most time at high L shells.

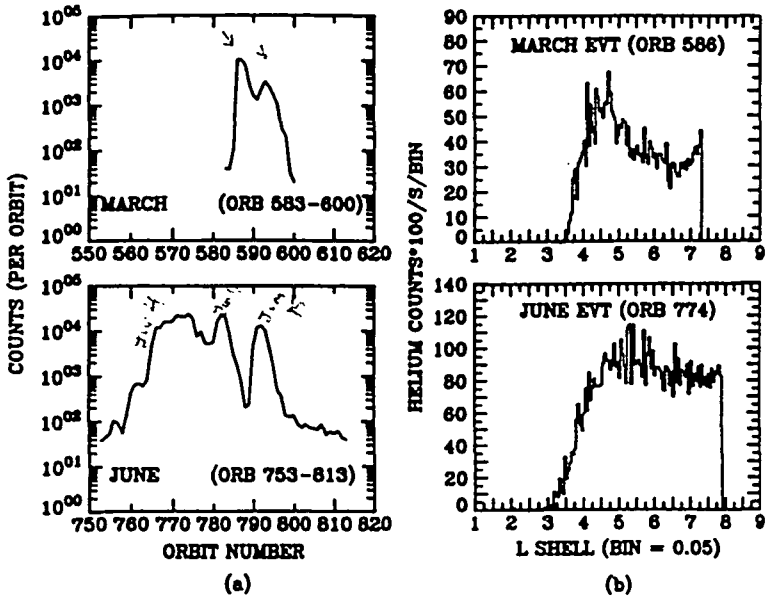

Fig. 1. (a) Time-intensity profiles for the March (top) and June periods (bottom). Multiple peaks in the profiles are associated with different solar flares. (b) Helium rate as a function of L shell for orbits 586 (top) and 774 (bottom). Each bin is 0.05 L unit.

Helium: Energy Spectra and Fluence

The helium (L > 6) energy spectra (after corrections for the geometry factor of the instrument and the detector efficiency) are shown in Figure 2 for the peak flux orbits 586 and 774. The ONR-604 energy range for helium is 45-90 MeV/nucleon, and E_0 has been chosen as 66 MeV/nucleon. The two solid lines are the least-squares fit to equation (1) which is an excellent representation of the observed data. The spectral index γ is the most important parameter and is listed in column 3 of Table 2. The peak spectral amplitude A^p_{He}, listed in column 2, is the peak helium flux at energy E_0. Also given are the spectral index and amplitude, denoted as γ^a and A^a_{He}, for the duration of each SEP event, with A^a_{He} again the average flux at energy E_0. The estimated errors for both spectral index and amplitude are from least-squares fitting.

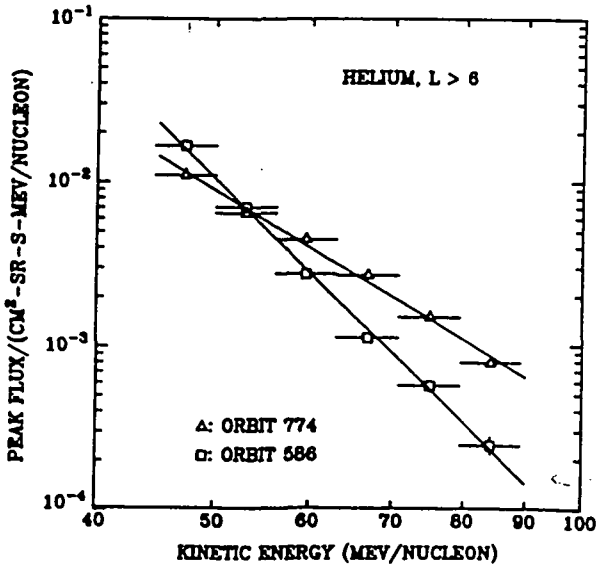

Fig. 2. Helium energy spectra at L > 6 for orbits 586 (square) and 774 (triangle). The straight lines are the least-squares fit to Eq. (1).

The average fluence, column 6 of Table 2, is simply the product of the average flux and the duration, which represents the intensity of a SEP event, another important parameter in the model.

TABLE 2. Helium Spectrum and SEP Model Parameters

Event	Peak Spectra A^p_{He}*	γ^p	Average Spectra A^a_{He}*	γ^a	Fluence** (at E_0)	Duration (Days)	Fe/O	δ
March (4)	13.9±0.5	7.3±0.2	10.7±0.5	6.8±0.2	175.7×10^4	1.9	4.37	0.186
June (7)	26±1	4.5±0.2	9.6±0.4	4.3±0.2	754.8×10^4	9.1	0.098	-0.025

* in particles/m^2-sr-s-MeV/nucleon; ** in particles/m^2-sr-MeV/nucleon.

Heavy-Ion Content

Since the collecting power of ONR-604 is not sufficient to obtain enough heavy ions at the energies sampled by the instrument, it is difficult to obtain an Fe/O ratio directly for the SEP events. Therefore, the ratio of P1 to helium is used as an indicator of the SEP heavy-ion enrichment. The P1 particles contain heavy ions from neon to nickel with the dominant elements being magnesium, silicon and iron. Due to the steep spectra of SEP ions and to the high energy detection ranges of ONR-604, we expect to be able to detect P1 particles only from the largest solar flares. Figure 3 illustrates the heavy-ion content for 200 orbits around the June events. The top panel is the P1 counts/orbit, middle panel is the helium counts/orbit, and the bottom panel is the ratio, $P1/He$. The P1 rate usually peaks one or two orbits before that of helium. Figure 3 also shows that the P1/He ratio during quiet times (i.e., galactic cosmic rays) is much higher than during solar flares. For each of the four largest SEP events we calculated the upper-limit of the P1/He ratio (since no subtraction of the GCR background from the P1 flux was made) by averaging over four consecutive orbits for the event. The results are tabulated in column 7 of Table 1.

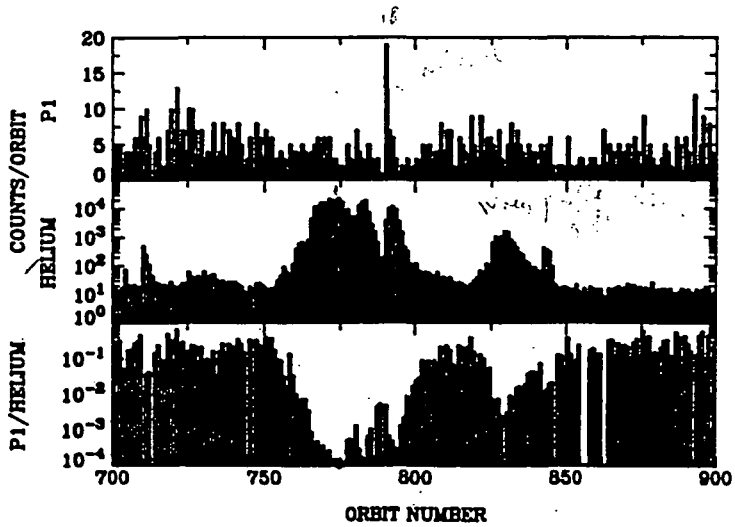

Fig. 3. Heavy-ion content for 200 orbits around the June events. The top panel is the P1, and the middle panel the helium in counts per orbit, and the bottom panel shows the ratio between them. P1 contains heavy ions from ~ neon to nickel.

It is noted that the energy range of P1 (100-500 MeV/nucleon) is different from that of helium (45-90 MeV/nucleon) and that the detector efficiency varies for different SEP events as well as for different ion species. The ratio of P1 to He after correcting for the energy range and instrument efficiency is $(P1/He)_0 = c(P1/He)$ where c is the correction factor and $(P1/He)$ is the observed value listed in Table 1. The (Fe/O) ratio is then obtained through

$$Fe/O = (Fe/P1)(P1/He)_0(He/O), \tag{2}$$

where $He/O \sim 55.2$ for SEP's /8,9/ being independent of the energy /10/ and $Fe/P1 = 0.192$ and 0.370 for heavy-ion "normal" and "rich" flares, respectively /2/. For events 4 and 7 the factor c is estimated to be 238 and 54, respectively. The corresponding Fe/O ratios and δ values are summarized in Table 2. For comparison, the average value of the Fe/O is 1.0 for heavy-ion "rich" events and 0.155 for "normal" events /11/, observed at lower energies (< 10 MeV/nucleon). This ratio can vary by several orders of magnitude at higher energies from flare to flare.

Compared to the variations of other ion abundances, the ratio He/O does not vary much for different SEP events /10/. It is therefore possible to scale the fluxes of different heavy-ion species directly from that of helium instead of oxygen /3/ through

$$A_X = (A_{He}/55.2)\,(X/O)_{SEP}\,e^{\delta(ZX-8)}, \tag{3}$$

where X represents a specific heavy-ion element, Z_X its charge, and $(X/O)_{SEP}$ the X/O abundance ratio for "normal" SEP (i.e. solar corona) matter. Figure 4 plots the predicted spectra for oxygen and iron. The March flare is a heavy-ion "rich" case with the spectral amplitudes for oxygen and iron $A_O = 2.5 \times 10^{-5}$ and $A_{Fe} = 1.1 \times 10^{-4}$ (cm^2-sr-s-MeV/nucleon)$^{-1}$, respectively. Orbit 774 (event 7 in Table 1) is a heavy-ion "normal" case, and its predicted oxygen and iron spectra (Fig. 4b) have $A_O = 4.7 \times 10^{-5}$ and $A_{Fe} = 4.6 \times 10^{-6}$ (cm^2-sr-s-MeV/nucleon)$^{-1}$. It is interesting to note that event 4 corresponds to an impulsive helium time-intensity profile with only 0.5 days from start to peak, while event 7 has a gradual helium time profile with more than 6.5 days from start to peak (Table 1). Such a correspondence between heavy ion content and flare time history has been seen in other events /6/.

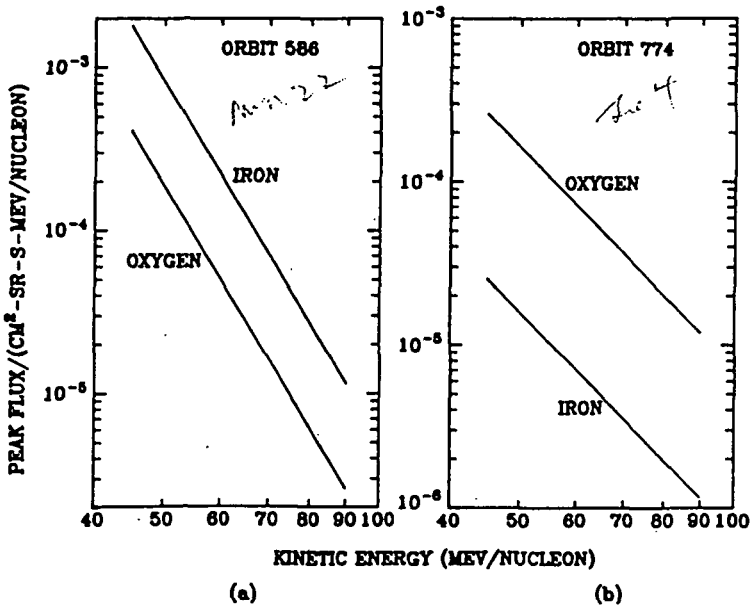

Fig. 4. Predicted energy spectra for oxygen and iron scaled from the solar helium fluxes for orbits 586 (a) and 774 (b).

The proton data, supplied by National Geophysical Data Center, are from the geosynchronous GOES-7 satellite and cover an energy range of 15-500 MeV. The power-law spectrum assumed in the SEP model is also a good representation for the protons. The inferred proton spectral parameters for events 4 an 7 are $A = 2.7 \pm 0.9$ and 0.22 ± 0.04 particles/cm^2-sr-s-MeV/nucleon and $\gamma = 4.7 \pm 0.4$ and 3.1 ± 0.2. It is noted that the proton spectral indices are significantly different from that of helium, which may be due to the charge/mass ratio difference between these two species. Therefore, scaling from proton spectra is not an accurate method to predict heavy-ion fluxes.

SUMMARY

Solar energetic particle events can be separated into two groups according to their heavy-ion content. The 1991 March SEP event is heavy-ion "rich" and is associated with an impulsive solar

flare, while the first event in June 1991 is "normal" and is associated with a gradual type flare. It is found that the solar proton spectral indices are different from that of helium. The solar heavy-ion spectra can be obtained by employing the enrichment parameter δ and by scaling from the solar helium spectrum. The SEP model developed here provides a good representation of the observations made by ONR-604 and GOES-7 for the energy range 45-90 MeV/nucleon for helium and 15-500 MeV for protons. The model can be generalized into a predictive tool for calculating the heavy-ion fluxes, LET spectra and SEU rates of space instruments during solar flares.

ACKNOWLEDGEMENT

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A MODEL OF GALACTIC COSMIC RAYS FOR USE IN CALCULATING LINEAR ENERGY TRANSFER SPECTRA

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ABSTRACT

The galactic cosmic rays (GCR) contain fully stripped nuclei, from Hydrogen to beyond the Iron group, accelerated to high energies and are a major component of the background radiation encountered by satellites and interplanetary spacecraft. This paper presents a GCR model which is based upon our current understanding of the astrophysics of GCR transport through interstellar and interplanetary space. The model can be used to predict the energy spectra for all stable and long-lived radioactive species from H to Ni over an energy range from 50 to 50,000 MeV/nucleon as a function of a single parameter, the solar modulation level ϕ. The details of this model are summarized, ϕ is derived for the period 1974 to present, and results from this model during the 1990/1991 CRRES mission are presented.

INTRODUCTION

CRRES (Combined Release and Radiation Effects Satellite) was launched on July 25, 1990, in part, to study and characterize the effects of energetic charged particles incident upon electronic devices. As charged particles pass through or stop within the sensitive volume of a microelectronic circuit a large amount of ionization may be produced, simulating a logic state change and causing a single event upset (SEU). In principle, the SEU rate for a particular chip geometry can be calculated if the linear energy transfer (LET) spectra (a convolution of the particle environment composition, energy spectrum and stopping power) is first determined. The CRRES mission carried a Microelectronics Package (MEP) to measure the SEU phenomenon for a variety of chips and an additional series of instruments which were used to characterize the in-situ energetic particle environment.

One such instrument, ONR-604, was designed to measure high energy, heavy ions covering the charge range $1 \leq Z \leq 28$ and the energy range 40 - 100 MeV/nucleon for Helium up to 180 - 500 MeV/nucleon for Iron. The abundance of heavy ions in a particle population can be only a fraction of H or He, but ionization energy is deposited in proportion to charge squared and, hence, the high charge species constitute an important component of the LET spectra. To properly determine the LET, full energy spectra for all isotopes are needed, however, an instrument such as ONR-604 will deliver, for short integration time periods (< 6 months), a spectrum segment for the most abundant species. Thus, a model must be used to fill in the gaps, matching the available data and providing energy spectra over energy and charge regions not covered by the measurements.

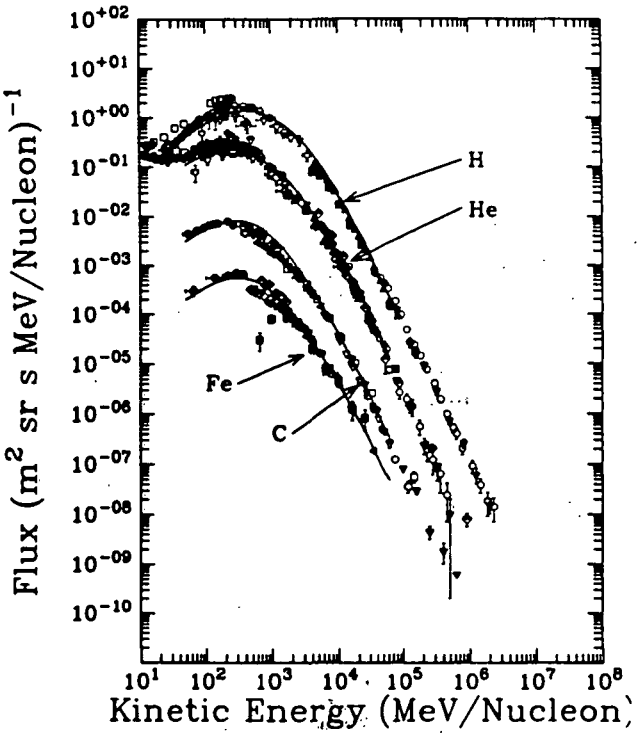

Fig. 1. Energy spectra measurements and model predictions for H, He, C and Fe.

The energetic (>50 MeV/nucleon) heavy ion particle population in the vicinity of Earth is generally dominated by two principal components; the Solar Energetic Particles (SEP) which are associated with solar flare eruptions and the Galactic Cosmic Rays (GCR) which originate outside the heliosphere. This paper describes a GCR model which is based upon our current understanding of cosmic ray astrophysics. Companion papers at this conference describe a SEP Model /1/ and application of the SEP / GCR model results to calculations of the LET spectrum for the CRRES mission /2/.

THE GCR MODEL

The GCR spectra outside the heliosphere in local interstellar space (LIS) are expected to be constant over very long time periods, but in the vicinity of Earth the cosmic ray intensity at energies less than ~5 GeV/nucleon can vary dramatically according to the level of solar activity. The GCR model makes use of this fact and consists, simply, of a LIS database input to a program that calculates the effects of solar modulation. Once the LIS database is determined, using a full calculation of cosmic ray interstellar transport and requiring a fit to available measurements, the near-Earth GCR spectra for a given time period can be derived by adjusting, in essence, a single parameter representing the appropriate level of modulation. Such a model is founded upon our current understanding of cosmic rays and assures compliance with the particle measurements. The energy spectra resulting from the model covers the energy range 50 - 50,000 MeV/nucleon for each isotope from H to Ni contained in the galactic cosmic ray population and can be directly used to compute the LET spectrum as a function of time /2/.

Determining the GCR Local Interstellar Spectrum

Over the years a wealth of data on cosmic ray spectra near the orbit of Earth has been collected as illustrated in Figure 1 which shows available data for a selected set of elements. Much of the lower energy data (i.e. < 1 GeV/nucleon) in the figure was obtained during an extended period of minimum solar modulation conditions (~1975 - 1978) when the cosmic ray flux was at a maximum. Similar measurements are available for almost every element in the cosmic rays, with varying accuracy and energy coverage. These are the primary data used to provide multiple constraints when deriving the GCR local interstellar spectra. In addition, elemental ratio measurements augment the spectra data, and isotopic ratio measurements are also available. The most accurate isotope results are for elements with charge less than Sulfur at energies less than ~600 MeV/nucleon.

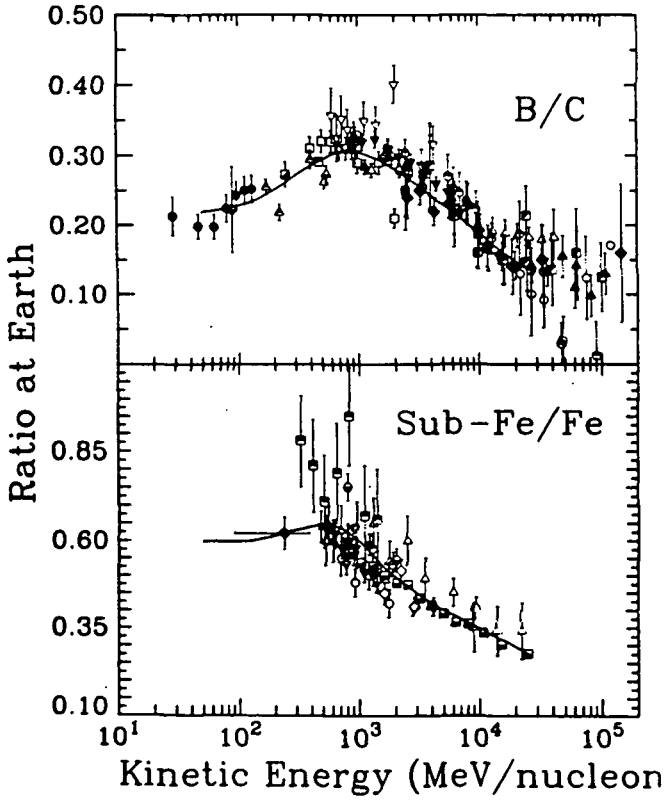

Fig. 2. Secondary/Primary ratio measurements and model predictions.

The curves in Figure 1 show the GCR model predictions using a solar modulation level appropriate to solar minimum. The LIS were calculated with a numerical simulation of cosmic ray transport through interstellar space with the GCR source and propagation characteristics adjusted until a good fit to the measurements were obtained. The numerical simulation is based upon the weighted-slab propagation technique /3/ and is described by Garcia-Munoz et al. /4/. This technique involves calculating the effects of ionization energy loss, radioactive decay, electron pickup and loss, and nuclear interaction fragmentation loss, production and kinematics for a series of thin slabs of interstellar matter. The slab results are then integrated over a pathlength distribution (PLD) which can be related to particular astrophysical models /5/. In practice, the PLD is usually determined empirically by fitting ratios of secondaries (little or no abundance at the cosmic ray source) to primaries (present at the source). Secondary components are produced entirely from the fragmentation of primary species and are particularly sensitive to details of cosmic ray transport. Such ratios include B/C and (Sc+Ti+V+Cr+Mn)/Fe as shown in Figure 2 along with the predictions of the GCR model.

Determining the Solar Modulation Level

With the baseline LIS determined, the effects of solar modulation must be calculated for each time period of interest. The program used for this calculation is a spherically symmetric model of the heliosphere that includes the effects of diffusion, convection and adiabatic deceleration /6/ and has been used successfully to model the modulation of electrons, protons and heavier nuclei over several solar cycles /7,8/. The level of modulation at a heliospheric radius r is given by the parameter

$$\phi(r) = \frac{1}{3}\int_r^R \frac{V(r')}{K(r')}dr' \qquad (1)$$

where V(r') is the solar wind velocity, K(r') is the radial part of the diffusion coefficient and R is the radius of the heliosphere. It is this single parameter,which specifies the modulation intensity and values of R, r, V and K yielding the same value of ϕ will result in similar modulated spectra /9/.

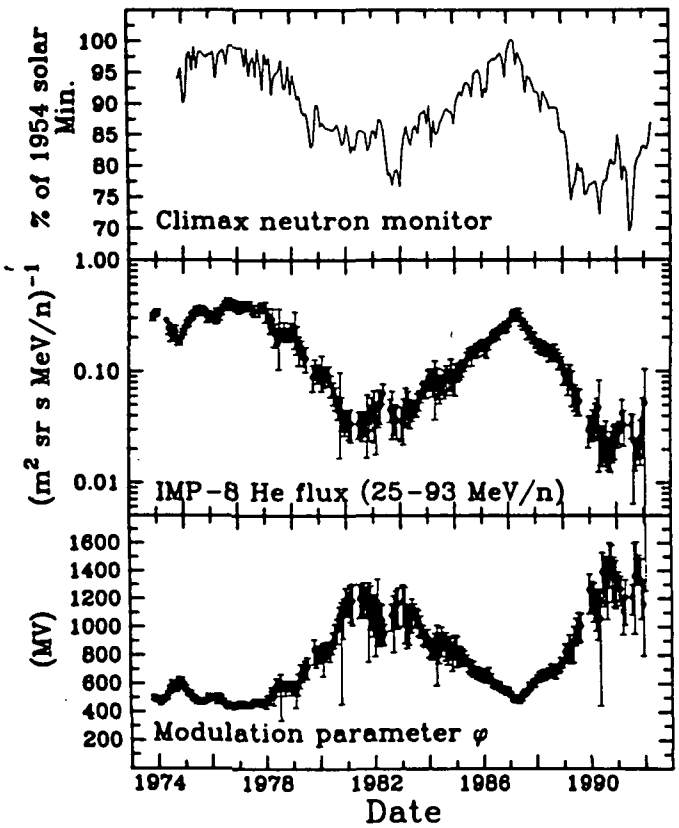

Fig. 3. The solar variations from 1973 to present for the Climax neutron monitor (top), the IMP-8 25-93 MeV/nucleon Helium flux (middle), and the solar modulation level (bottom).

For this GCR model, ϕ is determined from a portion of the Helium spectrum measured by the IMP-8 interplanetary spacecraft. Monthly averages, cleaned of solar flare periods and anomalous rate spikes, are shown in the middle panel of Figure 3. These data track the solar cycle with maximum flux values during solar minima (~1975-1979 and ~1987-1988) and a minimum flux level during solar maxima (~1980-1983 and ~1990-1992). The error bars show the variance of the He flux over the time period, and these fluctuations are largest for solar maximum conditions. Further, periods of low solar activity ("quiet time") are not frequent during solar maximum, resulting in occasional gaps in the time coverage. The top panel of Figure 3 shows results from a Univ. of Chicago ground based neutron monitor located at Climax, Colorado over the same time period. The neutron monitor is sensitive to the high energy (>3 GV) cosmic ray flux at Earth, and there is a clear correlation with the lower energy interplanetary Helium flux.

The bottom panel of Figure 3 shows the derived value of ϕ using a method similar to that of Garcia-Munoz et al. /8/. The Helium LIS is fixed, and ϕ is adjusted until the calculated spectrum matches the flux measurements. We have compared the results of Figure 3 with previous work /4,7/ that determined ϕ over the time period 1974 - 1980 and the results are in good agreement. As an additional cross check we also determined ϕ from Oxygen spectra measured by IMP-8 over a time period (8/90 to 3/91) during the recent solar maximum. A chi-squared minimization fit to these data yield ϕ = 1444 ± 42 MV which is consistent with ϕ = 1330 ± 110 MV derived from the Helium measurements. In later releases of this model we expect to use ONR-604 flux measurements to refine the level of modulation determined here.

MODEL RESULTS FOR CRRES

Figure 4 shows GCR model results for 1990 and 1991. The CRRES operational lifetime from its launch on 25 July 1990 till an unrecoverable systems failure on 12 October 1991 is shown as the horizontal line on the bottom panel of Figure 4. Throughout this period ONR-604 on-board CRRES performed well and the data analysis is well underway. The top panel of Figure 4 presents the Helium count rate derived from the ONR-604 pulse height analysis P2 rate for "quiet times" and for L > 6. When these data are compared with the IMP-8 Helium measurements (bottom panel, filled circles) the same relative trend is evident, indicating a good correlation between the interplanetary measurements and the ONR-604 results within the magnetosphere.

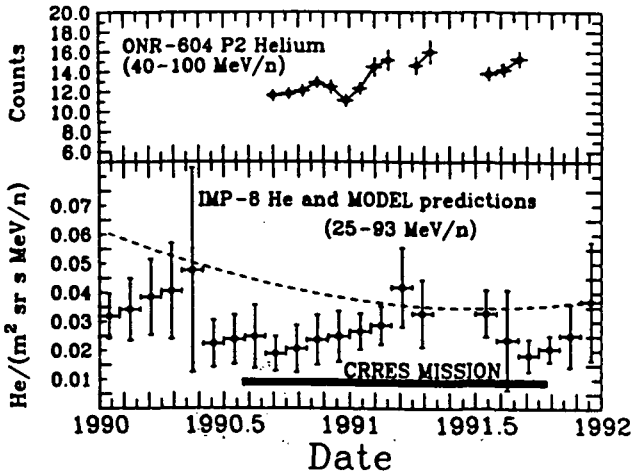

Fig. 4. The top panel shows the ONR-604 P2 Helium count rate during the CRRES mission and the bottom panel shows the IMP-8 Helium flux compared with the CREME model predictions (dashed curve).

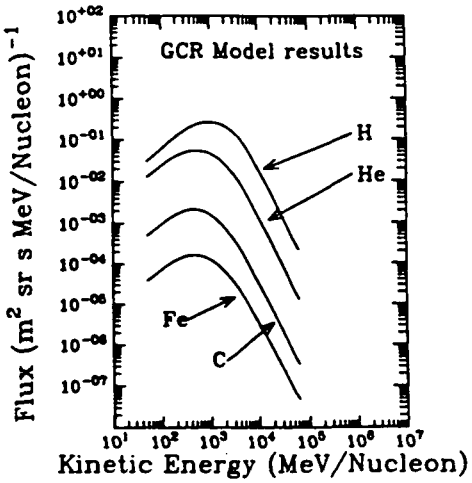

Fig. 5. The GCR model energy spectra predictions for the average solar modulation conditions during the CRRES mission.

A large gap in the monthly averaged IMP-8 Helium flux during the CRRES mission is apparent in the bottom panel of Figure 4. This was a period of intense solar activity and solar energetic particles dominate the measured particle population /1/. The flux predictions of the CREME model /10/ are shown as the dashed curve. CREME (Cosmic Ray Effects on Microelectronics) was developed in the early 1980's to provide a model of the near-Earth particle environment for calculating LET and SEU rates. This particle environment is expressed by a series of analytic formula for the energy spectra and solar cycle variations. While CREME predicts a minimum He flux during the 1991 period of intense solar activity the general trend does not follow the actual measurements. Further, for the time period 8/90 to 3/91 CREME over-estimates the Helium measurement by about 60% and the IMP-8 Oxygen flux by about a factor of two. Thus, it is expected that CREME will predict enhanced LET spectra and SEU rates for the CRRES mission /2/.

The average value of ϕ during the CRRES lifetime is ≈1330 MV and a selection of GCR model energy spectra for this level is shown in Figure 5. These spectra can be compared to the data and curves of Figure 1, which are for solar minimum conditions. At 100 MeV/nucleon the two sets of curves can differ by almost an order of magnitude. For CRRES the heavy ion fluxes at low energy (~100 MeV/nucleon) are at a ~20 year low as can be seen from Figure 3. In fact, over this time period the modulation level follows a very complex curve and it is not evident how future trends can be reliably predicted. What seems clear, however, is that if accurate spectra are required then a GCR model directly tied to in-situ particle measurements, such as described here, must be used.

CONCLUSIONS

A model of the galactic cosmic rays, based upon current understanding of cosmic ray astrophysics and constrained by available measurements, has been developed to predict the energy spectra of each species over a broad energy range for any quiet-time period from 1974 to the present by adjusting a single parameter; the solar modulation level ϕ. Within the CRRES time period, this model follows interplanetary measurements of the Helium and Oxygen fluxes at 100 MeV/nucleon while the CREME model overestimates these values by 60% to a factor of two. In later versions of this model we expect to improve upon the prediction accuracy by requiring simultaneous fits to heavy ion spectra measurements from IMP-8 and ONR-604.

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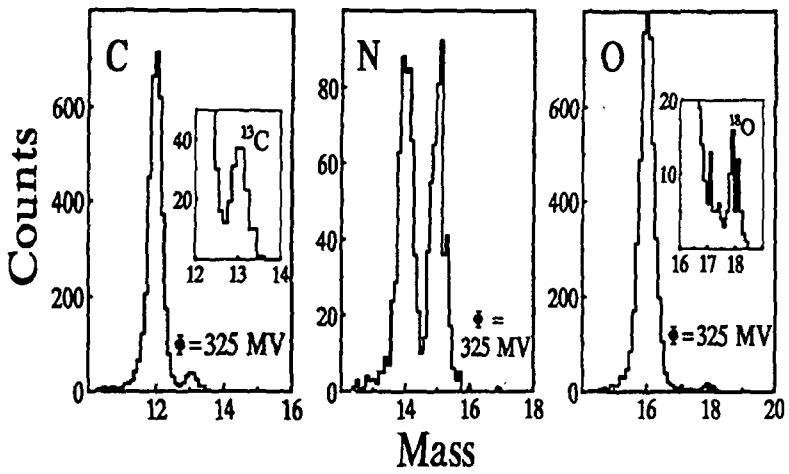

Figure 1 Mass histograms for elements with 6≤Z≤8 . Two inserts show the separation of the ^{13}C from ^{12}C and ^{18}O from ^{16}O.

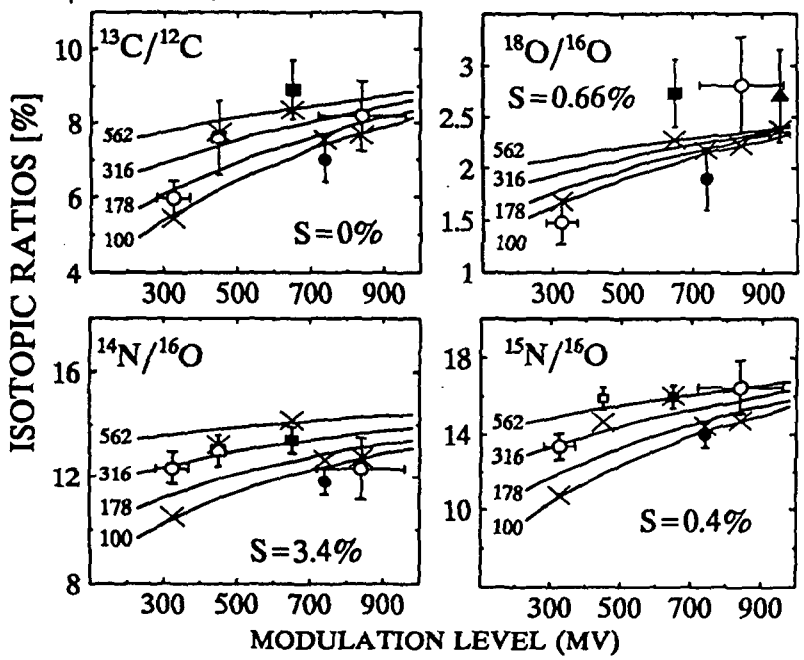

Figure 2 Observed and predicted isotopic ratios for C, N and O elements. Solid lines refer to propagation calculations for energies of 100, 178, 316 and 562 MeV/nucl. The value S is the abundance ratio at the cosmic ray source used in the calculations. Open circles are this measurement; open squares, Webber,1982; solid squares, Gibner et.al., 1992;solid circles,Wiedenbeck and Greiner,1981a,b and Krombel and Wiedenbeck, 1988;solid triangles, Webber 1985. Crosses are the isotopic ratios from propagation calculations calculated at energies and modulaton values of the individual experimental measurements.

Proc. 23rd International Cosmic Ray Conference (Calgary), 1, 543, 1993

THE ISOTOPIC COMPOSITION OF COSMIC RAY C, N, O: SOURCE ABUNDANCES DERIVED FROM THE ONR-604 EXPERIMENT ON THE CRRES MISSION.

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ABSTRACT

We have measured the isotopic composition of the cosmic ray elements C, N, O, in the energy interval 98-245 MeV/nucleon using data received from July, 1990 to October 1991 from the University of Chicago ONR-604 experiment on board the NASA/DoD Combined Release and Radiation Effects Satellite. The experiment average mass resolution for these isotopes is σ = 0.14 amu. The measured abundances have been extrapolated back to the source using the propagation model developed by Garcia-Munoz et al. (1987). It is found that relative to the abundance of the major isotope in the element, the source abundances of ^{13}C, ^{15}N, ^{17}O, and 18O are consistent with those of the solar system or with absence from the source. The source ratio ^{14}N/^{16}O is about a factor 3.6 smaller than in the solar system abundances.

1. INTRODUCTION

In order to constrain models of cosmic ray origin a knowledge of the elemental and isotopic composition of the cosmic ray at their source is needed for comparison with solar system abundances and models of nucleosyntesis processes. In the particular case of C, N, O, the low abundances of the heavier isotopes, ^{13}C, ^{17}O, ^{18}O, requires a high mass resolution for complete isotopic separation. In addition, because of the high secondary content at Earth of the less abundant isotopes, an accurate correction for propagation effects is needed to determine the abundances at the source.

2. THE MEASUREMENTS

A new technology based in semi-conductor detector arrays for the determination of particle trajectory has been developed at the University of Chicago to achieve complete isotopic separation in the measurements reported here. The ONR-604 particle telescope on CRRES is similar to the "Ulysses" mission instrument described in Simpson et al. (1992) and Connell and Simpson (1993). A description of the ONR-604 experiment and the CRRES mission is given in DuVernois et al. (1993) and in Gussenhoven et al. (1985).

The CRRES satellite was launched on July 25,1990, into a geocentric orbit with an inclination of 18^0, and altitude of 33,600 Km at apogee (geosynchronous altitude) and 350 Km at perigee. The data presented here were taken in the portion of the orbit with a McIlwain parameter L>4 (altitude >26,000 Km) where the background of magnetospheric particles was at its minimum level. Thus these data were recorded during half of each orbital period (≈10 hours) and the total data taking time extended from July 28, 1990, until the satellite failed on October 12, 1991.

Contamination of the selected data by particles of solar origin is negligible. Unfortunately the mission period included the lowest cosmic ray flux recorded during the recent solar modulation cycles, and therefore the accuracy of the data is limited by statistics.

Figure 1 shows mass histograms for the elements C, N, O. Maximum likelihood fits give an average mass resolution of σ = 0.14 amu for the isotopes. The relative abundances of the isotopes are calculated from the histograms. A correction (from 3 to 9%) is applied for the differences in the isotopic energy intervals considered in the analysis.

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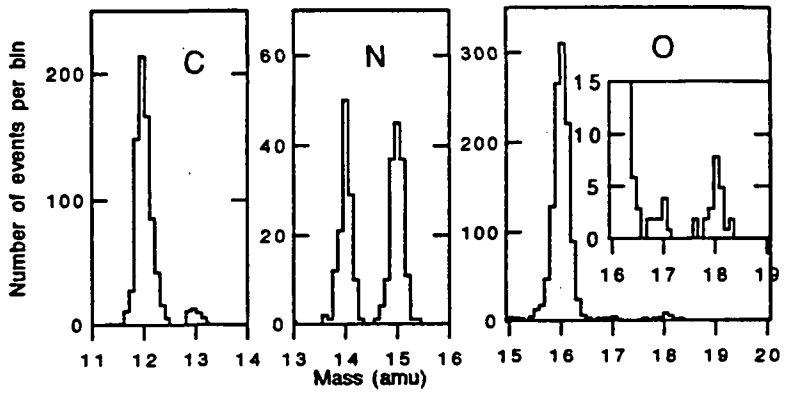

Figure 1. U. of Chicago CRRES Experiment.
Mass histograms of cosmic ray C, N, and O.

3. COSMIC RAY SOURCE ABUNDANCES.

To derive the CRS abundances from the measurements it is necessary to determine the change that the abundances at the source experience during interstellar propagation in the galaxy and the effects of solar modulation in the heliosphere. We have used a modified leaky box model of cosmic rays propagation as developed by Garcia-Munoz et al. (1987). In this model, below about 1 GeV/nucleon the exponential pathlength distribution (PLD), that can be represented by a combination of two exponential functions ("double exponential" PLD) is deficient in short pathlengths and this deficiency increases as the energy decreases. The mean of the pathlength distribution decreases with increasing energy above a few GeV/nucleon and, below this energy, decreases with decreasing energy. The interstellar medium is assumed to have solar system composition and the calculations take into account spallation reactions, ionization energy loss and radioactive decay.

This model has been shown to give a good fit simultaneously to the measured energy dependence of the B/C ratio and also to the available experimental values of the sub-Fe/Fe ratios. We have used in this calculation the same elemental source abundances and the same set of fragmentation cross sections employed by Garcia-Munoz et al. (1987).

For the average level of solar modulation during the period of measurement, July, 1990-October, 1991 (times of the strongest solar modulation in recent history) we have used $\Phi = 700$ MeV/nucleon. This level has been obtained from measurements of the galactic cosmic ray proton and helium spectra by the University of Chicago IMP-8 experiment during the same period.

The observed isotopic abundances are plotted in Figure 2 as a function of the energy. They are listed in Table 1 together with the energy intervals of the measurements (from incident particle energies triggering detector K2 to energies just failing to trigger the anticoincidence A), the deduced abundances at the CRS, and the solar system abundances given by Cameron (1982). The uncertainties assigned to the source abundances are only the propagated observed uncertainties. Further uncertainties in the propagation model are in the fragmentation cross sections, pathlength distribution, source spectral shape, and modulation level. The largest uncertainty is, by far, in the fragmentation cross sections that are estimated to be from 10% to 35%. A detailed study of these uncertainties is given in Garcia-Munoz et al. (1987). Figure 2 and Table 1 show also for comparison other recent results reported in the literature which have comparable mass resolution and statistics.

Using the above propagation parameters we have calculated the isotopic ratios that would have been observed at Earth assuming that the CRS has the same isotopic composition as the solar system abundances. They have been plotted as a function of energy in Figure 3 (solid curves) for comparison with the measured ratios. We have also plotted propagation results using the pure exponential PLD (dashed curves) to show the difference from the calculations using the PLD deficient in short pathlenghs.

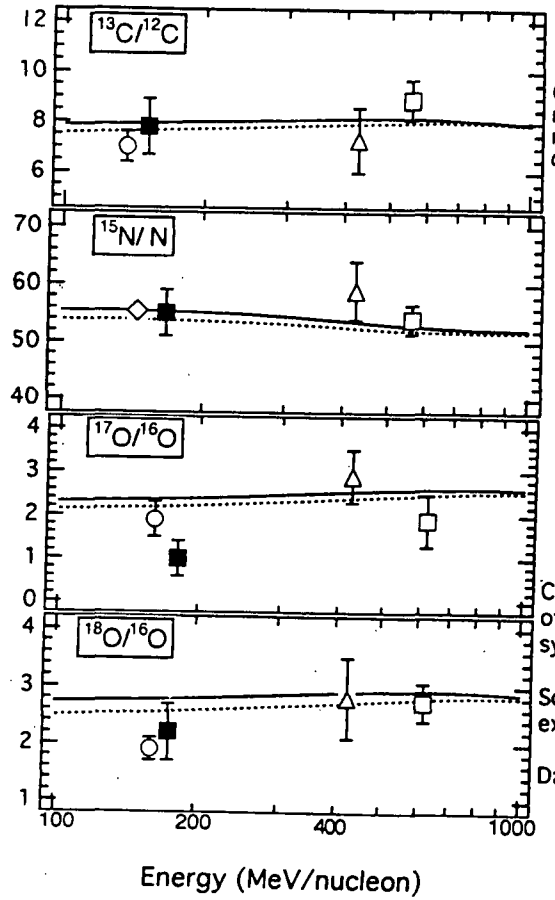

Figure 2

Comparison of measured isotopic ratios (in percent) of cosmic ray C, N, O

■ U of Chicago CRRES

○ Wiedenbeck and Greiner, 1981a,b.

□ Gibner et al., 1992.

△ Webber et al., 1985; Webber, 1982.

◇ Krombel and Wiedenbeck, 1988.

Curves: Propagation of source with solar system abundances.

Solid: double exponential PLD.

Dashed: exponential PLD.

4. CONCLUSIONS

Consideration of Table 1 and Figure 2 lead to the following conclusions:

1. ^{13}C is present in the CRS with solar system abundance. This result allows a small probability of absence from the source.
2. The abundances of ^{15}N and ^{18}O are consistent with CRS abundances similar to those of the solar system or with absence from the source.
3. The very low measured abundance of ^{17}O strongly suggests absence from the source.
4. The ratio $^{14}N/^{16}O$ is about a factor 3.6 smaller than in the solar system abundances. This is consistent with results reported by previous investigators.

As can be seen in Figure 2, given the accuracy of measurements and calculations, using in the calculations a PLD purely exponential (dashed curves) changes very little the above conclusions.

Connell and Simpson (1993) reach the same conclusions based on the "Ulysses" measurements which have higher statistical accuracy.

Gibner et al. (1992) have compared a set of experimental results similar to that of Figure 2 with propagation calculations that use a leaky box model with input parameters that differ from the ones used in this work.

TABLE 1. - ISOTOPIC FRACTIONS

Ratio	This Work			(a)	(b)	(c)	(d)
	Near Earth		C R Source	C R Source			Solar System
	Energy (MeV/n)	Fraction (%)	Fraction (%)	Fraction (%)	Fraction (%)	Fraction (%)	Fraction (%)
C-13/C-12	98-204	7.8±1.1	1.0±1.0	2.1±0.6	0.5(+1.1,-0.5)		1.12
N-15/N	108-225	55±4					0.37
N-14/O-16	112-234	13±2	3.5±2.0	3.7±1.7	4±1.4		12.6
N-15/O-16	108-225	16±2	<2.2	<5.2	<4		0.046
O-17/O-16	117-245	1.0±0.4	0	0.4(+0.4,-0.3)	<0.7	0.8±0.6	0.037
O-18/O-16	113-238	2.2±0.5	<0.5	0.2±0.2	1.15±0.38	0.7±0.6	0.20

(a) Wiedenbeck and Greiner, 1981a,b; Krombel and Wiedenbeck, 1988;
(b) Gibner et al. 1992; (c) Webber et al., 1985; (d) Cameron,1982.

Comparing our measurements with their propagation curves it is found that the above conclusions remain unchanged except in the case of ^{18}O for which Gibner et al. find a significant source overabundance relative to the solar system. We conclude that this is mainly due, on one hand to the relatively high experimental accuracy that they report, and on the other hand to the use in their propagation calculations of different experimental cross sections and the empirical algorithm used to estimate unmeasured cross sections. Work is continuing in this Laboratory to resolve differences in the propagation models and cross sections and in the implication of the C, N, O, source composition for cosmic ray origin.

5. ACKNOWLEDGMENTS

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The *Ulysses* Cosmic Ray Isotope Experiment I: Source Abundances of C, N and O Derived from High Resolution Measurements.

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ABSTRACT

We present the initial report on measurements of the isotopic composition of C, N, and O obtained from the High Energy Telescope (HET) of the Cosmic and Solar Particle Investigation (COSPIN) aboard the *Ulysses* Spacecraft. These measurements combine exceptional mass resolution (~0.10 amu at C to ~0.13 amu at O) with high statistical significance. We compare these data with the results of a propagation model to estimate source abundances. We conclude that the source composition of the heavier isotopes of C and O (i.e. ^{13}C, ^{17}O and ^{18}O) is consistent with solar abundances or with absence from the source. This source composition of C and O provides important constraints on models for the origin of the cosmic ray source material.

1. INTRODUCTION

The Ulysses Mission is a joint NASA and ESA project. The spacecraft was launched on Oct. 6, 1990 on the shuttle *Discovery* and inserted into a trajectory to Jupiter at 5.2 AU and thence into an orbit which will reach a south heliographic latitude of ~82° in 1994. *Ulysses* will be the first spacecraft to visit the polar regions of the Sun. The University of Chicago High Energy Telescope (HET) is part of the Cosmic and Solar Particle Investigation (COSPIN) described in detail in Simpson et al. (1992). The measurements in this paper cover the period from launch to the end of 1992 at ~25° South ecliptic latitude.

Since the measured heavier isotopes of C and O have relatively small abundances, only with high mass resolution measurements is it possible to obtain meaningful estimates of their cosmic ray source composition.

2. MEASUREMENTS

The high mass resolution measurements reported here are based on our technology of position-sensitive semi-conductor detector arrays in the HET to determine the trajectories of the cosmic rays as described in detail in Simpson et al. (1992). In brief, the HET consists of two sets of three position sensing Si detectors (PSD's) of ~1100 μm thickness arranged to determine the trajectory of incident particles. Six 5000 μm Si detectors (K's) provide mass and charge determination by the multiple dE/dx versus residual energy method for events stopping in the second through sixth K. A Si detector identifies penetrating events while a scintillator shield identifies side penetrating events. Consistency requirements were made on the energy loss in the PSD's and in the mass determinations in the K detectors. To eliminate events stopping in the detector support structure, the trajectory of each particle, when projected beyond the apparent stopping detector, was required to end its range in an active detector region. This was the only constraint on the angle of incidence. Figure 1 shows mass histograms of C, N and O. Mass resolution varies from ~0.10 amu for C to ~0.13 amu for O based on maximum likelihood fits. These data, together with the comparable CRRES data [Garcia-Munoz, et al. 1993], have the highest mass resolution reported to date. The histograms contain a total of 3169 C, 847 N and 3938 O events. Table 1 summarizes the measured isotopic abundance ratios with

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The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particle Effects on Electronic and Biological Systems in Space

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Abstract

We present a new time-dependent model of the interplanetary heavy ion environment and a new set of software based on this model to calculate energy deposit (LET) spectra and resulting single event upset rates.

I. INTRODUCTION

Accurate estimates of the frequency of single event effects require accurate models of the fluxes of heavy ions which cause them. These flux models must account for the multifarious temporal variations of ion flux intensity (Fig. 1), and their significant energy- and species-dependencies.

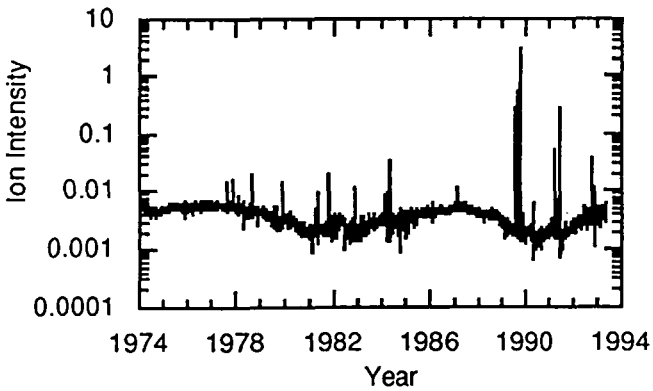

Fig. 1: The intensity of carbon and heavier ions near earth with energies greater than 10's of MeV/nucleon measured by The University of Chicago instrument aboard IMP-8 [1].

The intensities of galactic cosmic rays vary inversely with solar activity, with minima in years of solar activity maxima (1982, 1990). The sun, in solar flares, provides impulsive fluxes of heavy ions with peak intensities over 1000 times that of the galactic cosmic ray background. The largest such events of the past 20 years were in October 1989.

Over a decade ago, in response to growing awareness of and interest in the problem of single particle effects in microelectronics, a pioneering model of the near-earth cosmic ray and solar particle heavy ion environment was developed at the Naval Research Laboratory and incorporated into a software package called "Cosmic Ray Effects on MicroElectronics" (CREME [2]). Since its initial release CREME has become a standard and is in widespread use for engineering calculations of single particle effects.

Studies of the CREME model and comparisons of its predictions with direct measurements of the heavy ion environment near earth have demonstrated a number of deficiencies [3,4,5], some of which have significant effects on the results of the model. For example, CREME is based on analytic function fits to only a few ion species. Energy spectra for other ions are scaled by constants. Also, to account for variations due to the solar activity cycle, fits were determined at times corresponding to minimum and maximum cosmic ray flux intensities. For other times the model interpolated between the minimum and maximum spectra assuming a sinusoidal variation with an 11-year period.

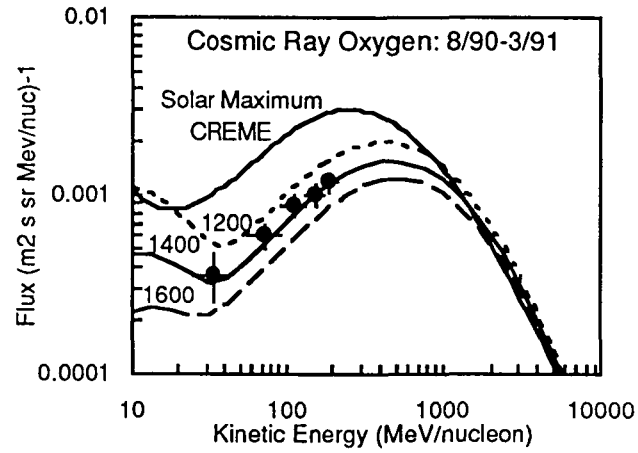

Fig. 2: The cosmic ray oxygen spectrum measured by The University of Chicago instrument aboard the IMP-8 satellite at solar maximum, compared to the CREME model and a set of solar modulation model results for Φ=1200, 1400, 1600 MV.

Figure 2 compares the CREME model prediction for the galactic cosmic ray oxygen flux at solar maximum to the flux measured by The University of Chicago instrument aboard IMP-8 in 1990-91, the most recent period of solar maximum. During this period the oxygen flux predicted by the CREME model was approximately double the measured oxygen flux at energies near 100 MeV/nucleon. For comparison, oxygen energy spectra based on a solar modulation model [6] are shown for solar modulation parameter values of 1200, 1400, and 1600 MV. The measured flux is well-represented by the solar modulation model at 1400 MV, or slightly less.

The flight of the Combined Release and Radiation Effects Satellite (CRRES), which included both state-of-the-art instrumentation to measure the heavy ion environment [7] as well as a comprehensive MicroElectronics Package (MEP) for on-orbit tests of single-event upsets [8], provided both the impetus and the opportunity to develop an improved model of the near-earth heavy ion environment. This is a preliminary report and description of this model, the CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME). A more complete and detailed description is in preparation.

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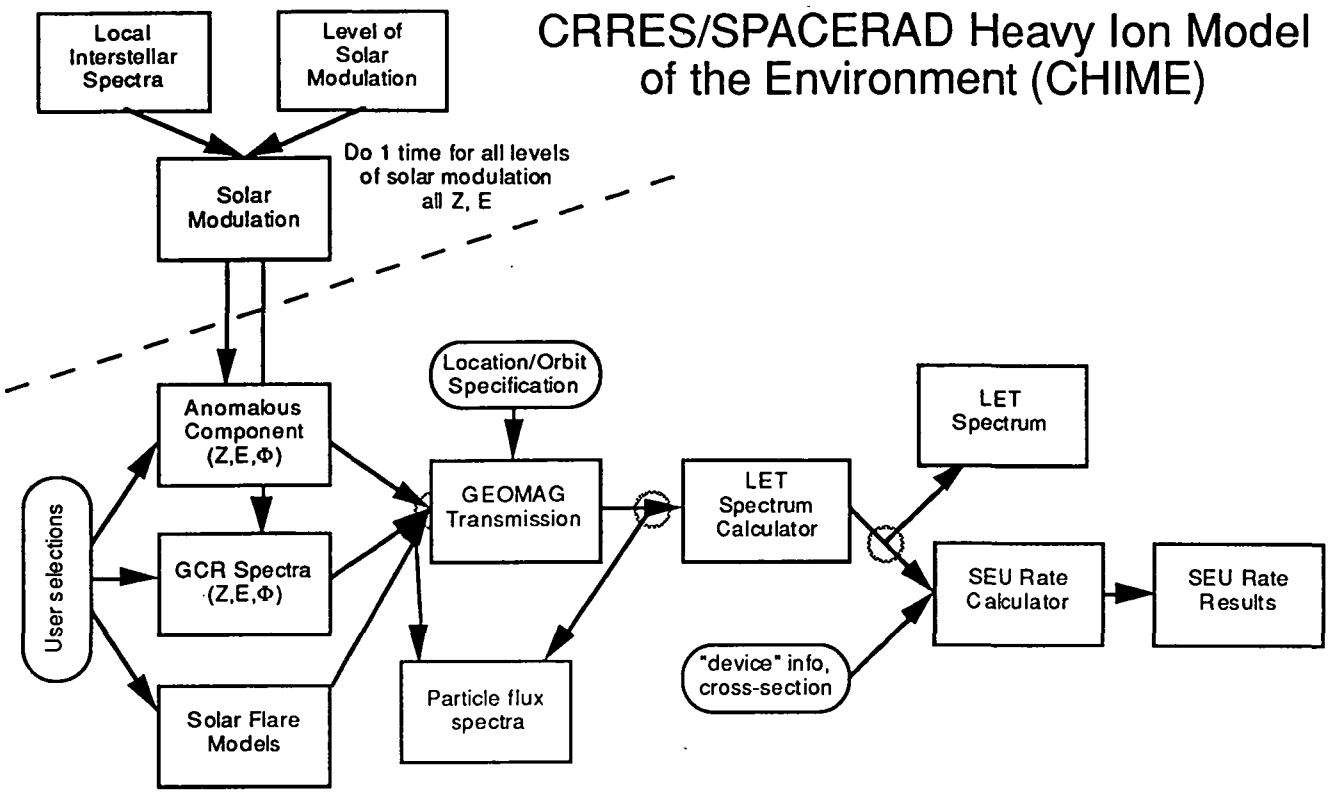

Fig. 3: A flowchart describing the major modules of the CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME).

II. Model Components

A. Overview

The major components of the CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) are indicated in Figure 3. The model covers the energy range from 10 MeV/nucleon to 60 GeV/nucleon for all stable elements, and includes the known major sources of heavy ions in the near-earth interplanetary medium over this energy range: galactic cosmic rays, the anomalous component [9], and heavy ions from solar energetic particle events (SEP). With this new model we sought to address the following major objectives and improvements to the existing state-of-the-art:

(1) to provide an accurate representation of the heavy ion flux environment and its temporal variations near earth as measured over the past two solar activity cycles,
(2) to provide a physically-based method to extrapolate this environment into the future which also can be adapted based on future knowledge of the solar activity cycle,
(3) to improve the calculation of the geomagnetic cutoff and shielding effects, and
(4) to package these elements together in a form which would be easy to use by the space radiation effects community.

The original motivation for the CHIME model was to provide the most faithful possible description of the flux intensities of energetic heavy ions and their variations near earth (outside the radiation belts), and to describe the specific heavy ion environment during the period of the CRRES mission [10, 11] by using the heavy ion flux measurements made by instruments of the CRRES payload [12]. It was quickly recognized that the best application of the CRRES payload flux measurements would be to use them to establish the parameters of a suitable time- and energy-dependent model which accurately describes the effects of solar activity on a fixed source. The knowledge accumulated over the past three decades or more of cosmic ray physics, which has very accurately determined the relative abundances and energy spectra of the elements, can be incorporated in the model in this way. Contemporary measurements establish the epoch which is associated with a specific level of solar activity.

B. Galactic Cosmic Ray and Anomalous Component

The time- and energy-variations of the galactic cosmic ray and anomalous component heavy ions near earth are well understood as the result of a "modulation" by the sun of a set of "local interstellar spectra" (LIS) at the outer boundary of the heliosphere [13, 14]. In a spherically-symmetric model the solar modulation at a distance r from the sun, is described by a single modulation parameter, $\Phi(r)$, for all cosmic rays [15]:

$$\Phi(r) = \frac{1}{3}\int_r^B \frac{V(r')}{\kappa(r')}dr' \quad (1)$$

where V is the speed of the radial solar wind, κ is a radial transport particle diffusion coefficient, and the range of integration extends from the observer at r to the outer boundary of the heliosphere, B. In the "force-field approximation" this modulation parameter corresponds to a potential, and it has become customary to use it in potential units, e.g. megavolts (MV).

For CHIME, the LIS were determined by a complete calculation of cosmic ray propagation in the galaxy [16]. The resulting spectra were then modulated and compared to the ensemble of cosmic ray measurements, taking into account the level of modulation associated with each observation. Source composition and galactic propagation model parameters were adjusted to achieve the best agreement. The LIS of secondary cosmic ray ions, and low-abundance ions which are not yet well measured across the entire energy spectrum, are calculated in this galactic propagation model. These LIS are the current best estimates of the galactic cosmic ray and anomalous component sources available.

Having established the LIS for all ions, the solar modulation model was run for a wide range of solar modulation levels. The results of these runs were tables of the local (1 astronomical unit from the sun) fluxes of all elements (labeled by atomic number, Z) as a function of energy (E) for each value of Φ. The database in CHIME is a compressed collection of these tables representing the heavy ion environment near earth, $F[Z,E,\Phi(1AU)]$. The fluxes are tabulated for values of E and Φ as necessary to insure that the interpolation error based on a cubic spline in log-log space is less than 1%.

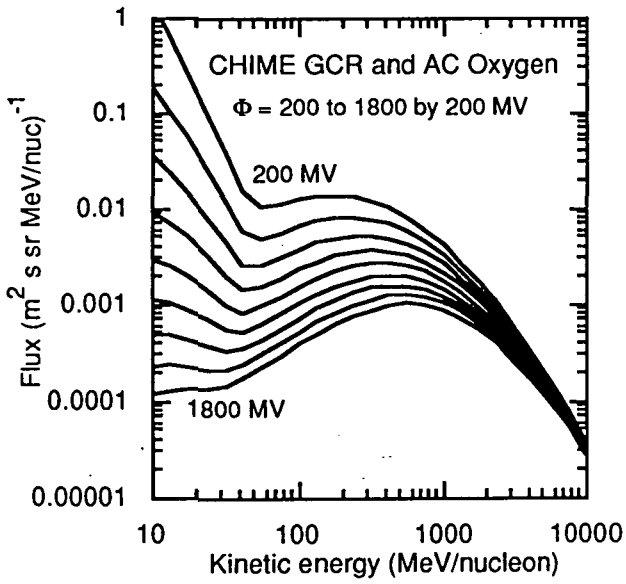

Fig. 4: The full range of oxygen spectra as a function of solar modulation level, combining the GCR and AC sources.

For the elements He, N, O, and Ne, an additional component, the anomalous component (AC) [9], is calculated using the same solar modulation code and for the same range of solar modulation as the galactic cosmic ray flux. Due to the nature of the AC source, however, the AC-LIS decrease much more rapidly with increasing energy and therefore do not extend to higher energies compared to the GCR-LIS. Additionally, in the solar modulation calculation the AC is treated as singly charged. These differences are sufficient to accurately model the AC and its time- and energy-variations using the same solar modulation calculation and parameters selected to model the GCR spectra. An example of the combined GCR+AC flux for oxygen over the full range of modeled solar modulation conditions is presented in Figure 4.

C. Solar Modulation Level Variations

Given the full tabulation as described above of the GCR and AC fluxes for all probable levels of solar modulation, the actual environment appropriate to any specific time is defined completely by the solar modulation level $[\Phi(1AU,t)]$. Many proxies of solar activity could be used to determine this function, including space-based observations, ground-based cosmic ray measurements from neutron monitors, or potentially even sunspot number. For the CHIME model the flux of helium ions at 70-95 MeV/nucleon was used. There are several advantages to this choice. In this energy range the sensitivity of the flux to the level of solar modulation is high. Due to the relatively high intensity of these ions this method has high statistical accuracy. Also, the Charged Particle Instrument operated by The University of Chicago aboard the IMP-8 satellite [1] has provided a continuous record of this flux over the past two solar cycles, since late 1973.

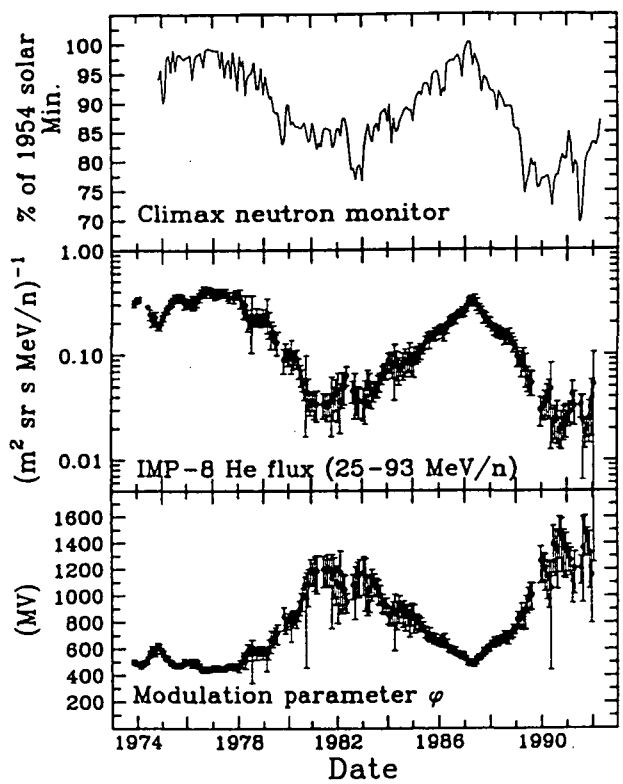

Fig. 5: Three indicators of solar modulation level. The solar modulation parameter is calculated from the He flux data [10].

The calculated level of solar modulation vs time from 1973 through 1993 is shown in the lower panel of Figure 5 [after 17]. In the middle and upper panels are shown, respectively, the measured flux of helium at 70-95 MeV/nucleon, on which the solar modulation level calculation is based, and the intensity measured by The University of Chicago's neutron monitor at Climax Colorado. The obvious correlation between the neutron monitor and helium flux measurements indicates how the CHIME database could be used based on other solar modulation level indices. However, since the solar modulation calculation is based on a time-independent solution it should not be used to model short-term (up to 10's of days) temporal variations.

The solar modulation level vs time model incorporated into CHIME is shown in Figure 6. This is based on the results from Figure 5 during the period of the actual measurements. The extrapolation into the future is based on a time series analysis of the 1973-1993 data. This extrapolation captures well the differences between even- and odd-numbered solar cycles which have been attributed to the effects of particle drifts due to the change in polarity of the solar and interplanetary magnetic field [18]. It predicts, for example, a long period of solar minimum conditions, like that of 1973 - 1978, and a relatively broader but less intense maximum in solar modulation, peaking in 2003.

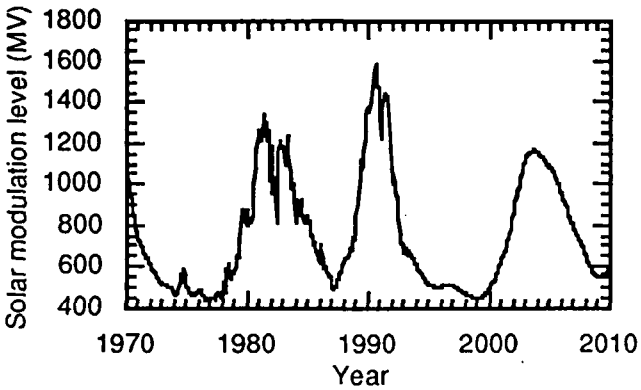

Fig. 6: The solar modulation level as a function of time as modeled and incorporated in CHIME.

A user of the CHIME model may either select a time period or a specific solar modulation level to specify the GCR and AC flux. If a time period is selected, the software computes the average of the flux over the specified time period, using the monthly values of the solar modulation parameter. This is necessary since the flux is not a linear function of the solar modulation parameter. The average flux over some period is not equal to the flux at the average value of the solar modulation parameter.

D. Solar Energetic Particle Flux Database

In addition to the external sources, galactic cosmic rays and the anomalous component, the sun is a significant source of heavy ions as a result of solar energetic particle (SEP) events. The relative importance of the SEP component is evident in Figure 1. Each of the spikes above the smoothly-varying galactic cosmic ray background level is due to an SEP event.

Several different SEP models are incorporated in CHIME. These include both models based on measurements made during the CRRES mission and models based on statistical distributions of energetic solar proton event intensities. The user of CHIME may select any one of these models to add to the GCR and AC database.

A total of 26 SEP events were observed during the CRRES mission which had peak fluxes of more than three times the galactic cosmic ray flux level, for helium ions at energies >40 MeV/nucleon. Daily average intensity models for all 26 of these events are incorporated in CHIME. They are based on measured proton and helium spectra and measured heavy ion enhancement factors [19]. Combined with the external source models, accurate representations of the interplanetary heavy ion flux for any day of the CRRES mission, July 1990 through October 1991, can be constructed with these results.

The two largest SEP events observed during CRRES occurred in March and June 1991. The March event was an "iron-rich" event, but with a significantly softer spectrum that the June event [11]. Due to their significance during the CRRES mission period, these events are made available for separate use in CHIME. The user can select either the peak flux or the 24-hour average flux for these events, and can add the result for either event to the GCR and AC spectra.

For predictive purposes CHIME provides heavy ion fluence models as a function of mission duration and probability of occurrence. These models are based on the "Interplanetary Proton Fluence Model: JPL 1991" [20]. This is a statistical description of the observed distribution of energetic solar proton event sizes. For a given mission start date and duration, the model provides a proton fluence spectrum which would be exceeded at a probability of occurrence or confidence level selected by the user (from 50% to 0.1%). Heavy ion fluxes are scaled from the proton spectrum using a table of average solar energetic particle event ion composition [21]. This method has a well-defined statistical basis for the overall SEP size distribution, based on the proton results. Since the largest SEP events generally have more normal composition characteristics [21], this statistical distribution of fluences is probably good also when scaled for the heavy ions. Additional analysis of SEP heavy ion observations, especially at higher energies, will be useful to better support this supposition. As additional results describing the distributions of heavy ions in SEPs are published they will be added to CHIME as appropriate.

E. The Geomagnetic Shielding Calculation

For earth-orbiting satellites at low altitude, the earth's magnetic field and the solid earth itself provide significant additional protection from the interplanetary heavy ion environment. While the physics of this shielding effect is simply the Lorentz force on a moving charge, an exact calculation is complicated by the complex particle trajectories which can result, especially in the transition region where the shielding effect becomes important. The earth's magnetic field produces an east-west asymmetry in the flux arriving at some observing location (magnetic radius and latitude r, λ) such that for a dipole magnetic field, particles with a specific momentum per unit charge (rigidity, $\rho = p/Z$) only arrive from a cone of directions surrounding the west (for positive charges) with an angular extent ω given by

$$\cos(\omega) = 2Y / \cos(\lambda) - Y^2 \cos(\lambda) \quad (2)$$

where $Y^2 = M/(c\rho r^2)$, M is the magnetic moment of the earth, and c is the speed of light. The solid angle corresponding to this cone is equal to $2\pi\ (1 + \cos\omega)$.

To account for the shielding due to the solid earth, the access cone solid angle is reduced by the fraction obscured by the earth at altitude h to obtain a total solid angle factor [22]:

$$\Omega = \pi(1+\cos\omega)\{1+\cos(\arcsin(R_e / [R_e + h]))\} \quad (3)$$

The vertical cutoff rigidity approximation often employed to estimate the geomagnetic shielding effect is a simplification of this procedure. It approximates the access function as a step function at the rigidity corresponding to a cone angle of 90°.

The GEOMAG Transmission function in CHIME calculates this access solid angle as a function of the ion energy and applies this filter function to the interplanetary heavy ion flux calculated by the procedures described in the previous sections. The user may select a location, an orbit, or a series of orbits over some period of time. When an orbit is specified the access filter is calculated as a time-weighted average. The transmission filter is applied separately to the anomalous component, which is treated as singly charged (Z=1) in this part of the calculation.

F. The Linear Energy Transfer Spectrum Calculator

The LET spectrum calculator in CHIME employs an integral method and a two-part (shield and target) spherical geometry model. The thicknesses of the shield and the target may be specified by the user in column density units (mg/cm2). Since the range depends on the density of the target and only weakly on the target composition, this approach permits the model to be used with different materials, e.g. GaAs. Working from the sensitive region out, and for each ion species, minimum and maximum incident ion energies are calculated corresponding to pre-defined LET thresholds. At each threshold LET, the integral LET spectrum is calculated by integrating the heavy ion flux spectrum over this energy range and summing over all particle species.

In this implementation, the ion LET in the target and the ion energy outside the shield are both calculated using differences of the range function, R(E,Z,M), for an ion with kinetic energy E, atomic number Z and mass M. The range function is scaled at ion energy E/M by MZ^{-2} from the range tabulation for protons in silicon of Janni [23]. It does not depend on the charge state of the ion before it strikes the shield or target. A range extension is applied to account for the ion charge state at low velocities within the material based on the results of Heckman, *et al.* [24]. One advantage of this method is that it fully accounts for the slowing-down of the incident ions within the target, including the low-energy ions which stop in the target. Such ions have ranges less than the target thickness after penetrating the shield. The effects of nuclear interactions are not included in this model. For thick shields, when the effects of these interactions become important, this LET spectrum will over-estimate the real spectrum at high LET and underestimate the real spectrum at low LET.

A final module in CHIME combines the LET spectrum calculated as described above, together with user specifications or measurements of the upset cross-section, and a model for the geometry for a specific device, to calculate a single-particle upset rate. This module incorporates a rectangular parallelepiped (RPP) model like that of Pickel and Blandford [25] to estimate the geometric factor of the sensitive region as a function of path length. It improves on the "step function" approximation to the upset cross-section by integrating a tabulation of this cross-section as a function of LET provided by the user. The only restriction on this tabulation is that it must be monotonic non-decreasing with increasing LET. This method and its sensitivity to assumptions of the geometry model have been described previously [26, 27]. Petersen and co-workers have reviewed methods used for single event effect calculations [28] and of the geometrical factors affecting these calculations [29].

III. FLUX DATABASE COMPARISONS

The major difference between CHIME and CREME is in the particle flux model database. Important improvements have been made both in the fidelity of the particle spectra models and in the methods provided to model the effects of solar modulation as necessary to tailor the spectra to a specific time period. One significant example of these improvements is evident by the model comparisons with the measured solar maximum oxygen spectrum as shown in Figure 2. In this section we provide additional examples covering both the cosmic ray and solar SEP flux models.

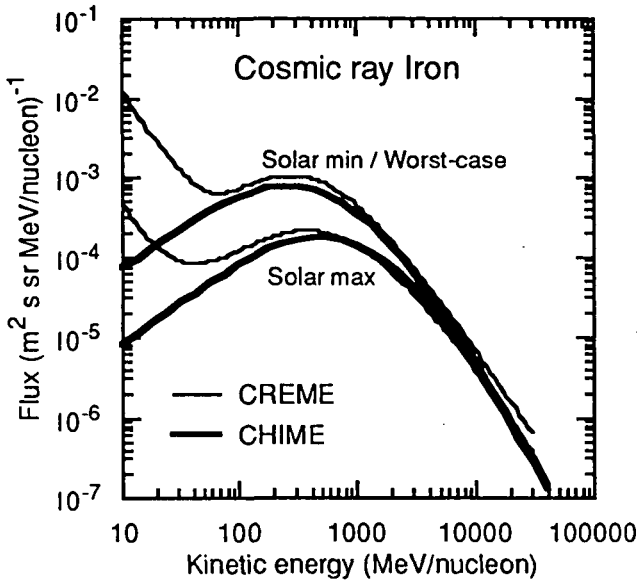

Fig. 7: CHIME and CREME model cosmic ray iron spectra for solar maximum and solar minimum conditions.

In contrast to the significant difference in the oxygen spectra, the iron spectra in CREME are much closer to the CHIME model results. CHIME does not include the low energy turn-up in the flux which is in the CREME model below 60 MeV/nucleon. In CHIME, this feature is attributed to SEP events and is not part of the GCR database. The overestimate of the iron flux in this region by CREME has been discussed elsewhere [27].

SEP event peak fluxes for oxygen and iron are compared in Figures 8 (for oxygen) and 9 (iron). In both cases the CREME model results shown are the 10% worst case peak fluxes for SEP events for both the normal (weather index 7) and worst-case (weather index 8) composition. The CHIME model results are the peak oxygen and iron flux intensities during the SEP events of 23 March and 4 June 1991. These are the two largest events observed during the CRRES mission. Of a total of 26 identified events these two events should be most comparable to a 10% worst-case model prediction.

Within CHIME, the SEP energy spectra for all of the events observed during the CRRES mission by The University of Chicago's ONR-604 instrument are described as power-laws in kinetic energy. The March 1991 event is an iron-rich event but has a softer energy spectrum. The measured energy spectrum of the June event is harder and that event is more typical of normal SEP composition. Above an energy of

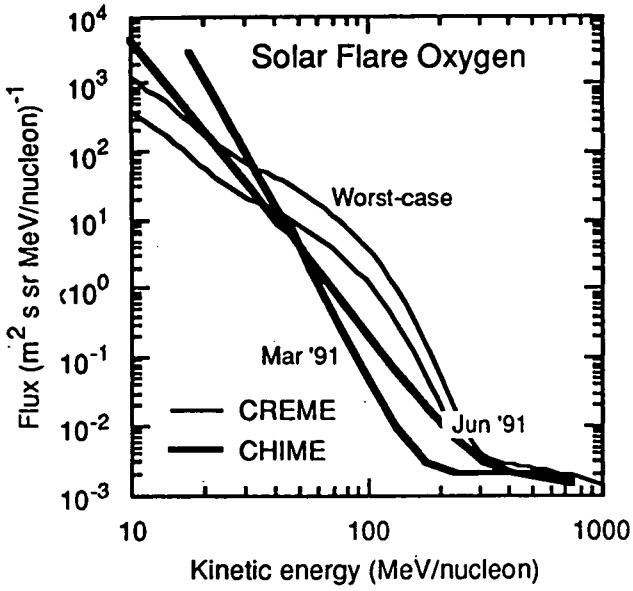

Fig. 8: CHIME and CREME model SEP peak oxygen spectra. The CREME models are the 10% worst-case for both normal and worst-case composition. The CHIME models are for the 23 March and 4 June 1991 SEP events from CRRES.

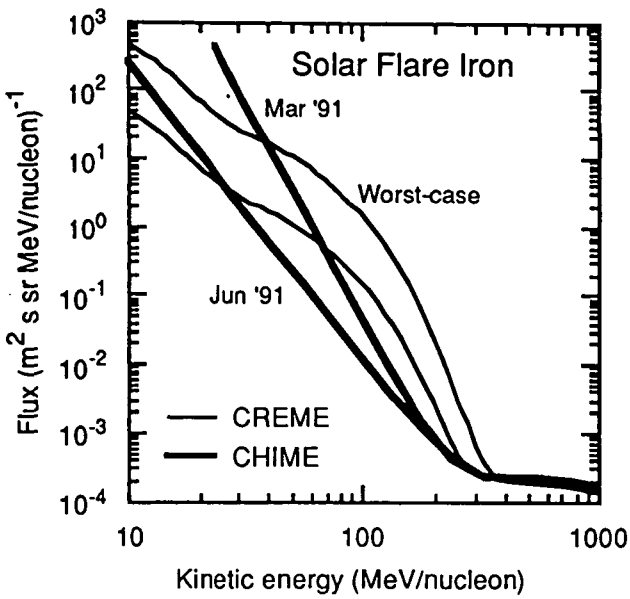

Fig. 9: CHIME and CREME model SEP peak iron spectra. The CREME models are the 10% worst-case for both normal and worst-case composition. The CHIME models are for the 23 March and 4 June 1991 SEP events from CRRES.

a few hundred MeV/nucleon these SEP models merge into the solar minimum GCR flux background flux at levels of a few x10^{-3} (for oxygen) or x10^{-4} (for iron).

Compared to the power-law models in CHIME, the CREME models include a significantly larger flux for both oxygen and iron in the energy range near 100 MeV/nucleon. This feature of the CREME model has been noted in other discussions of SEP heavy ion models. One effect of this will be a significant increase in the predicted SEU rate due to such events for moderate amounts of shielding.

Over the past two full solar cycles, a period when reliable and consistent long-term satellite observations have been continuously available, the largest SEP events have been those of August 1972, and September and October 1989. In terms of the heavy ion flux intensities at high energy, the SEP events of the CRRES mission period in March and June 1991 are next in order of decreasing intensity. Additional work is presently underway to better quantify the statistics of the heavy ion flux intensities.

Several other cosmic ray models have been offered since the release of CREME. Each addresses a different set of problems and improvements. Badhwar and O'Neill [4] used a method similar to that described here to model the H, He, and Fe GCR spectra. They demonstrated significant improvements in the quality of the fits of these elements to measured spectra. Nymmik, *et al.* [5] provided an analytic model of cosmic ray spectra and addressed the time variations in a new way, including a time scale that depends on particle rigidity. They also provided a method to predict the cosmic ray intensity from the sunspot number. Neither of these models includes the anomalous component. CHIME provides for the first time a comprehensive description of all species and all sources of heavy ions in the interplanetary medium important at energies above 10 MeV/nucleon which is based on physical models of the sources and their time variations. CHIME also includes a predictive component to address the expected variations in cosmic ray intensity over the next full solar cycle.

IV. Sample SEU Rate Results

Initial comparisons have been performed between the predictions of CHIME and the single event upset rates measured by the Micro-Electronics Package (MEP) aboard CRRES. The 93L422 is a bipolar static RAM which has been the subject of several studies of SEU [e.g. 25, 28]. In the MEP this part exhibited an upset rate of 2.8x10^{-4} per bit per day based on 201 events averaged over the whole mission. This result excluded all periods when CRRES was in the inner zone proton belts and during the two major SEP events.

The CHIME model calculation was based on the entire period from late July 1990 through mid-October 1991. An isotropic shielding thickness of 886 mils aluminum equivalent (6.08 g cm^{-2}) was used to calculate the LET spectrum. The 93L422 was modeled as described in [25 and 26] using the measured cross-section for the AMD part and assuming a sensitive volume per bit of 39x39x1 μm. The upset rate calculated using CHIME is 4.1x10^{-4} per bit per day. This is 46% higher than the observed rate. The extreme range of calculated SEU rate for the 93L422, based on the accuracy and extent of the cross-section measurements is from 2.9 to 6.1x10^{-4} per bit per day. While the lower limit of this range is consistent with the observed rate to within 1σ of the measurement, it is unlikely that uncertainties in the flux, uncertainties in the measured SEU cross-section, or uncertainties in the geometry model (based on the analysis in [25]) can account for this discrepancy unless coincidentally

they should all happen to be in the right direction. Thus we conclude that the calculated SEU rate is close, but higher than the measured rate by 40% to 50%.

Two important factors, which have traditionally been neglected in SEU rate calculations, have not been taken into consideration in this estimate based on CHIME. They are the distribution of shielding and the effects of nuclear interactions in the shield [22].

Since the LET spectrum intensity is not linear with changes in the shielding thickness, precise calculations must take into account the distribution of shielding thicknesses surrounding the device.

More important, perhaps, is the effect of nuclear interactions. The 886 mil Al average shield thickness provides about 10^{24} target nuclei per cm^2. Nuclear reactions start to become significant at this thickness if the total average inelastic nuclear cross-section for heavy ions per target nucleus is of the order of 1 barn (10^{-24} cm^2).

The MEP is not centered within CRRES. If the average shield were composed of two parts at half and double the average shielding thickness, the slight increase in the flux due to the reduced shielding in one half would be more than compensated-for by the significant increase in nuclear interactions in the other. For thickly shielded devices, therefore, the effects of nuclear interactions in the shield must be considered. These interactions tend to reduce the average LET of the transmitted beam.

V. Summary

The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) is a significant new tool for the calculation of single event effects due to interplanetary heavy ions. The model incorporates the most accurate and up to date database currently available for galactic cosmic ray and anomalous component heavy ion fluxes over the past two solar cycles. It also provides a predictive model for these fluxes through the next two solar activity minima, to the year 2010.

Several different models are provided within CHIME to describe the SEP heavy ion fluxes. These include both "peak instantaneous" and "24-hour average" flux intensity models for two typical large SEP events (March and June 1991). Additionally, daily average SEP heavy ion fluxes for each day of the CRRES mission are included. For predictive purposes a statistical model, the JPL 1991 interplanetary proton fluence model, is used and scaled to heavy ions using observed average SEP event composition.

CHIME provides the capability to select or average the heavy ion flux models for any time or period desired by the user from 1970 through 2010 and beyond. The geomagnetic and solid earth shielding model in CHIME is based on an offset magnetic dipole approximation. The resulting heavy ion flux energy spectra are converted to an LET spectrum using an integral method based on the range-energy relation. Finally, a module is provided which integrates the LET spectrum together with device characteristics, including a measured SEU cross-section, to calculate expected SEU counts or rates.

The CHIME model, including a user's manual with more complete documentation, is available for a variety of different computer platforms, including IBM PCs and compatibles, Macintosh, UNIX (Sun and other workstations), and DEC VAX/VMS. Distribution is being handled through one of the co-authors, E.G. Mullen at the Phillips Laboratory, to whom all requests should be directed.

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