JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. A12, PAGES 29,979–29,987, DECEMBER 1, 2001

Solar minimum spectra of galactic cosmic rays and their implications for models of the near–earth radiation environment

A. J. Davis,[1] R. A. Mewaldt,[1] C. M. S. Cohen,[1] A. C. Cummings,[1] J. S. George,[1] R. A. Leske,[1] E. C. Stone,[1] M. E. Wiedenbeck,[2] N. E. Yanasak,[2] E. R. Christian,[3] T. T. von Rosenvinge,[3] W. R Binns,[4] and P. L. Hink[4]

Abstract. The radiation dose from galactic cosmic rays during a manned mission to Mars is expected to be comparable to the allowable limit for space shuttle astronauts. Most of this dose would be due to galactic cosmic rays with energies < 1 GeV nucleon^{-1}, with important contributions from heavy nuclei in spite of their low abundance relative to H and He. Using instruments on NASA's Advanced Composition Explorer (ACE) spacecraft, we have made the most statistically precise measurements to date of the solar minimum energy spectra of cosmic ray nuclei with charge $Z = 4$–28 in the energy range $\sim$40–500 MeV nucleon^{-1}. We compare these measurements obtained during the 1997–1998 solar minimum period with measurements from previous solar minima and with models of the near-Earth radiation environment currently used to perform shielding and dose calculations. We find that the cosmic ray heavy–element spectra measured by ACE are as much as 20% higher than previously published solar minimum measurements. We also find significant differences between the ACE measurements and the predictions of available models of the near–Earth radiation environment, suggesting that these models need revision. We describe a cosmic ray interstellar propagation and solar modulation model that provides an improved fit to the ACE measurements compared to radiation environment models currently in use.

1. Introduction

The radiation environment in interplanetary space differs significantly from that inside the Earth's magnetosphere. In interplanetary space, astronauts are protected only by their vehicle or spacesuit and are subject to the full galactic cosmic ray (GCR) energy spectrum, as well as transient solar energetic–particle events. For long-duration missions it is quite possible that the radiation dose to astronauts from one or both of these sources will reach or exceed the allowed annual exposure limits currently defined for low Earth orbit (LEO).

The flux of galactic cosmic rays at 200 MeV nucleon^{-1} varies by a factor of $\sim$5 over the 11-year solar sunspot cycle. This solar modulation of cosmic rays is inversely related to the sunspot number, and so cosmic ray intensities are highest at solar minimum, when the sunspot number is lowest. Thus accurate measurements of the spectra of cosmic rays at solar minimum are important, since these spectra represent the "worst case" GCR radiation for which missions must be designed.

The current annual exposure limit to the blood forming organs (BFO) for astronauts in LEO is 0.5 Sv/year (dose equivalent)[*National Council on Radiation Protection and Measurements*, 1989]. This limit is 10 times the allowed annual limit for terrestrial radiation workers. Exposure limits for interplanetary missions have not yet been defined, however *Wilson et al.* [1997] find that for an interplanetary mission lasting a year or more, ~ 30 g cm^{-2} of aluminum shielding (more than 10-cm thickness) would be required to bring the BFO dose equivalent from solar–minimum cosmic rays below the LEO exposure limit. This is $\sim$6 times the shielding used for the Apollo missions, and if required, the extra mass could add significantly to the cost of a manned mission to Mars [*Wilson et al.,* 1993].

There are large uncertainties in the human biological response to highly charged, high-energy particles, such as those present in the cosmic rays, and also in the radiation transport through shielding materials [*Wilson et al.,* 1997]. Aside from these problems, there remain sizeable uncertainties ($\sim$10–30%) in the absolute intensities of all cosmic ray species and in the variation of cosmic ray spectra as a function of solar modulation. Depending on the applicable radiation limits, these uncertain-

---

[1] Physics Department, California Institute of Technology, Pasadena, California.

[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

[3] NASA Goddard Space Flight Center, Code 661, Greenbelt, Maryland.

[4] Physics Department, Washington University, St. Louis, Missouri.

Paper number 2000JA000325.
0148-0227/01/2000JA000325$09.00

ties in the radiation environment can potentially lead to significant uncertainties in shielding requirements, because shielding material is not very effective at attenuating the dose equivalent due to cosmic rays beyond the first few g cm^{-2} [*Wilson et al.,* 1997]. Therefore accurate spectra of key cosmic ray elements are needed to improve the accuracy of models that attempt to assess the radiation hazard due to cosmic rays. In this paper we focus on cosmic ray heavy–element spectra measured by instruments on ACE during the 1997–1998 solar minimum, and on their implications for models of the radiation dose in interplanetary space.

2. Existing Models and Measurements of the GCR Environment

In order to calculate the radiation dose due to cosmic rays behind a given shield configuration and during a given time period, one must combine a model of the GCR radiation environment with a radiation transport code. Several groups have developed advanced radiation transport codes. Examples include the HZETRN code[*Wilson et al.*, 1994, 1997, and references therein], developed at NASA/Langley Research Center, and the CREME96 code, developed at the Naval Research Laboratory [*Tylka et al.,* 1996]. These codes take the entire energy spectrum of the incident cosmic rays into account, and they include the effects of charged projectile fragments produced in the shielding. The HZETRN code also includes the effects of neutron production and the knockout of target constituents in the shielding. However, these codes are generally run using different models of the radiation environment. The HZETRN code commonly uses the GCR environment model of *Badhwar and O'Neill* [1996] (hereafter referred to as the Badhwar & O'Neill model), which is based on the diffusion–convection theory of the solar modulation of cosmic rays in the heliosphere [*Parker,* 1985]. In this model, estimates of the modulation level are computed by fitting the theory to observed cosmic ray spectra at 1 AU. The modulation estimates are then correlated with ground–based neutron monitor counting rates. These neutron monitors are sensitive to the reaction products of $\sim$1–20 GeV primary cosmic rays in the Earth's atmosphere. After allowing for the polarity of the interplanetary magnetic field during the observations, the resulting regression lines can be used to predict the level of modulation (and hence the GCR environment) at later times from the nearly continuous neutron monitor record.

The CREME96 code uses a representation of the GCR radiation environment based on the model of *Nymmik et al.* [1992, 1996] (hereafter referred to as the CREME96/Nymmik model), which relates solar cycle variations in cosmic ray intensities to the observed time history of the Wolf (sunspot) number. The Badhwar & O'Neill and CREME96/Nymmik models are similar in approach, but they differ in their implementation of solar modulation theory, and probably in the methods used to model the observed cosmic ray spectra.

All models of the GCR environment have been limited up to now by the relatively small number of high–quality cosmic ray spectral measurements made at 1 AU during solar minimum conditions. With typical shielding thicknesses, about 75% of the dose equivalent is due to nuclei with $E < 1$ GeV $\mathrm{nucleon}^{-1}$ (L.W. Townsend, private communication, 1991). However, most of the published solar minimum measurements below 1 GeV $\mathrm{nucleon}^{-1}$ were made during the 1970s by satellite instruments with small geometry factors or by balloon instruments with limited time coverage and sizeable systematic uncertainties. Furthermore, although H and He account for more than 98% of all GCRs, the heavier nuclei become much more important when their greater rate of energy loss (proportional to Z^2) and greater biological effectiveness are taken into account. Figure 1 shows GCR abundances at 200 MeV $\mathrm{nucleon}^{-1}$, compared to the relative contribution of the various element groups to the BFO dose equivalent behind 5 g cm^{-2} of shielding at solar minimum (data from *Wilson et al.* [1997], calculated using the HZETRN transport code). Taken as a group, the heavy elements with $Z > 2$ account for $\sim$48% of the dose equivalent, H accounts for $\sim$29%, and He accounts for $\sim$23%. Clearly, the key elements whose spectra must be measured accurately to evaluate radiation risk include Fe, Fe fragments (Z = 17–25), Ne, Mg, Si, C, and O, as well as He and H.

3. Measurements of GCR Element Spectra by ACE

Data from the the ACE mission, launched in August 1997, can help make significant improvements to models of the GCR environment. The ACE spacecraft is in orbit about the L1 libration point, about 1.5 million km sunward of the Earth [*Stone et al.,* 1998a]. The spacecraft carries nine instruments, sampling particles from solar wind to GCR energies ($\sim$0.1 to $\sim$500 MeV $\mathrm{nucleon}^{-1}$), and has consumables to extend the mission to cover a full solar cycle or more. Two instruments on board ACE measure particle spectra at GCR energies: the Cosmic Ray Isotope Spectrometer (CRIS) and the Solar Isotope Spectrometer (SIS). CRIS consists of four silicon solid–state detector stacks and a scintillating fiber–optic trajectory system, with a combined geometry factor of $\sim$ 250 cm^2 sr, many times larger than previous instruments of its kind [*Stone et al.,* 1998b]. The instrument measures elemental and isotopic composition for Z = 2–28 from $\sim$50 to $\sim$500 MeV $\mathrm{nucleon}^{-1}$. SIS consists of two silicon solid–state detector telescopes with a combined geometry factor of 38 cm^2 sr [*Stone et al.,* 1998c]. This instrument measures elemental and isotopic composition for Z = 2–28

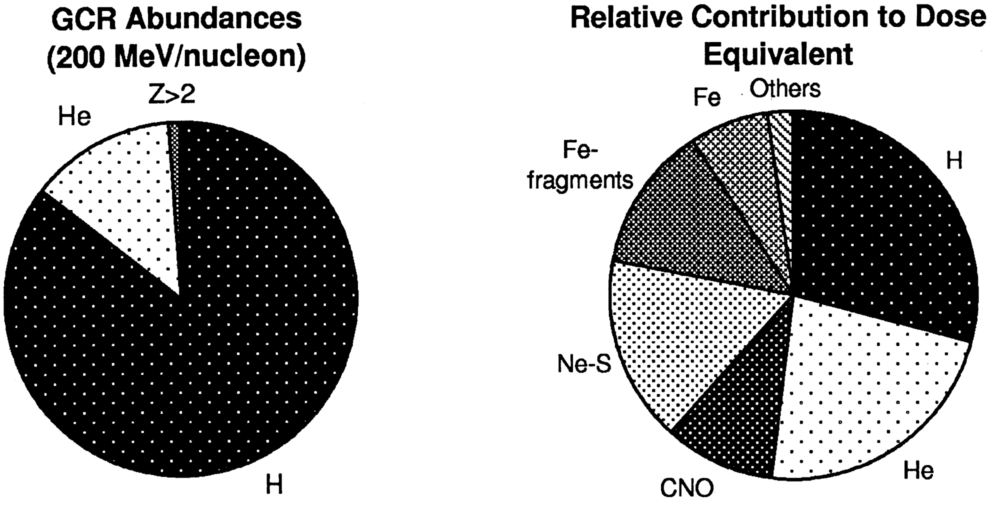

Figure 1. (left) Abundances of cosmic–ray nuclei at 200 MeV nucleon^{-1}. (right) Contribution of the important galactic cosmic ray element groups to the blood–forming organs dose equivalent behind 5 gcm^{-2} of shielding at solar minimum (data from *Wilson et al.,* [1997]).

from ~ 10 to ~ 100 MeV nucleon^{-1}. Estimates of the residual systematic uncertainties in the absolute spectra obtained from these instruments are derived from accelerator calibrations and multiple, independent calculations of the geometry factors and detector efficiencies. We conservatively estimate the residual systematic uncertainty to be less than 10% for both instruments, and probably less than 5%.

Together, CRIS and SIS cover the element and energy range most important for evaluating the radiation risk due to heavy cosmic rays. Element spectra from both these instruments are available from the ACE Science Center web site http://www.srl.caltech.edu/ACE/ASC. At the time of writing, the CRIS data on the Web included all elements from B through Ni, while the SIS data included He, C, N, O, Ne, Mg, Si, S, and Fe. Hourly, daily, and 27-day averages are available, from a few days after launch to within ~ 3 months of the present day.

ACE was launched during the most recent period of minimum solar activity, when GCR intensities reached their highest levels. Figure 2 shows University of Chicago Climax neutron monitor daily count rates and IMP 8 helium fluxes from 169 to 456 MeV nucleon^{-1} since the launch of IMP 8 in 1973 [see, e.g., *McDonald et al.* 1998]. These data clearly show the variation in cosmic ray intensity over the 22–year solar magnetic cycle. The data also indicate that intensities during 1997 were as high as those reached during the 1976 solar minimum, which is the period when most previous solar minimum heavy–element GCR spectra were obtained. Note also that even though the neutron monitor rates are greater in 1987 than in 1976 or 1997, the IMP 8 helium flux is similar for all three solar minima. The ACE spectral data presented in this work were gathered during the period August 28, 1997, through March 18, 1998, indicated by the shaded area on the right in Figure 2. Twenty–seven–day averages of the cosmic ray intensity measured by CRIS were constant to within a few percent during this period, and the cutoff time was chosen before the drop in intensity during April 1998, evident in Figure 2.

4. Comparison of ACE Spectra with Previous Data and GCR Environment Models

Figure 3 shows solar minimum C, O, Si, and Fe spectra from ACE, compared with spectra obtained by other experiments during the 1976–1977 solar minimum. The IMP 8 spectra were obtained using the University of Chicago instrument during 1974 through 1976 [*Garcia-Munoz et al.,* 1977] (indicated by the shaded area on the left in Figure 2). Prior to the launch of ACE, these data represented the best available solar minimum heavy–ion spectra in the energy range $\sim$50–1000 MeV nucleon^{-1}. Unfortunately, additional heavy–ion spectra from this instrument for other time periods have not been published. The University of New Hampshire (UNH) [*Lezniak & Webber,* 1978] and the University of Alabama Huntsville (UAH) [*Derrickson et al.,* 1992] spectra shown in Figure 3 are from high–altitude balloon measurements. The UNH balloon flight was in the fall of 1974 and the UAH flight was in the fall of 1976.

Figure 3 shows that below $\sim$200 MeV nucleon^{-1} the ACE spectra are as much as 20% higher than the IMP 8 spectra. This is perhaps not surprising, given the significant dip in the neutron monitor count rates and IMP 8 helium fluxes during 1974 (see Figure 2). Solar modulation is less important at higher energies, and above $\sim$300 MeV nucleon^{-1} it appears that the agreement between the various measurements is generally quite good. Considering the low statistical uncertainties relative to the previous measurements, and the good agreement be-

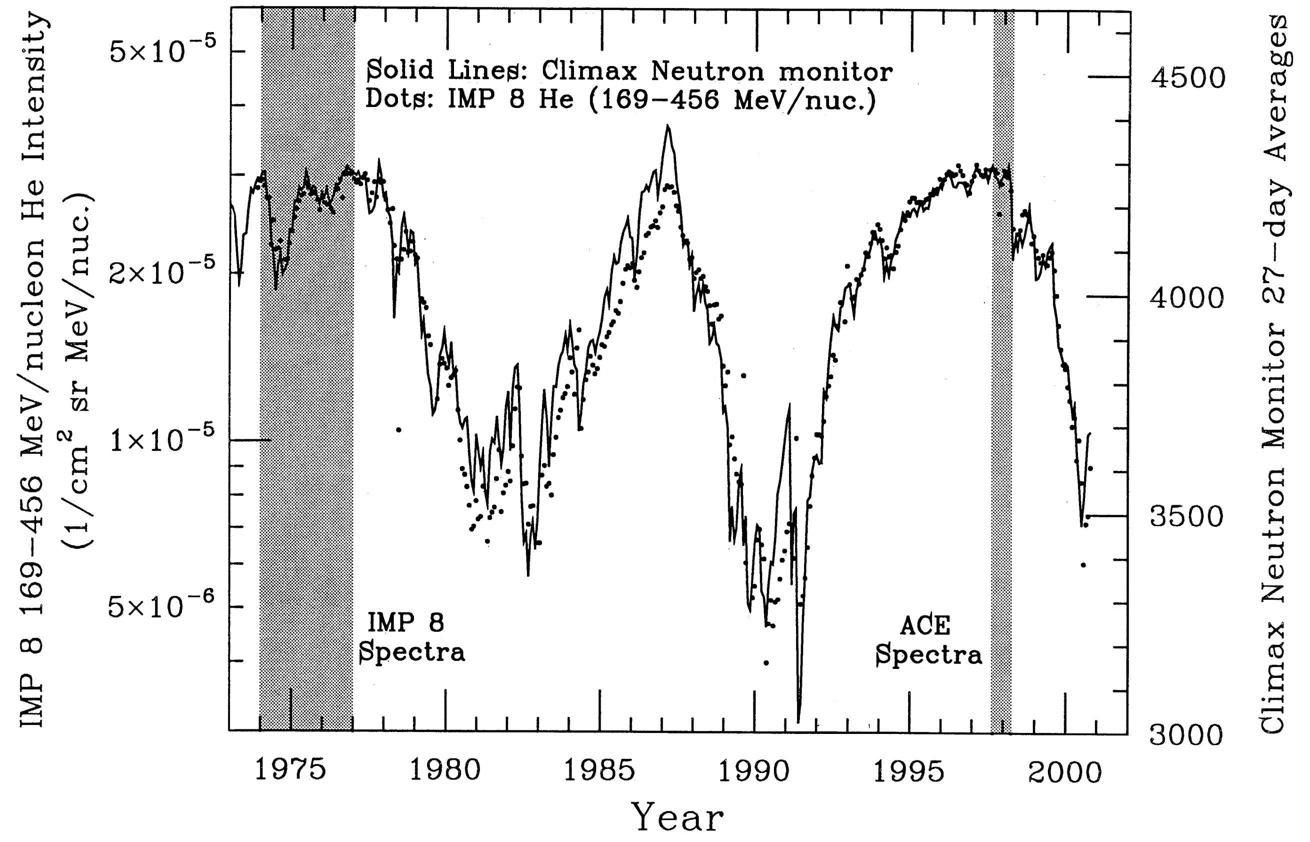

Figure 2. Climax neutron monitor 27-day average count rates and IMP 8 helium fluxes from 169–456 MeV nucleon^{-1} since the launch of IMP 8 in 1973. ACE spectra presented in this paper were obtained during the time period indicated by the shaded area on the right. IMP 8 spectra were obtained during the period indicated by the shaded area on the left.

tween the spectra from the CRIS and SIS instruments on ACE, we believe that the ACE measurements are a significant improvement over previous measurements of GCR heavy–element spectra in the energy range from ~40 to 500 MeV nucleon^{-1}. The ACE measurements also represent the highest flux levels ever reported for GCR heavy elements at 1 AU in this energy range.

In Figure 4, we compare the ACE measurements with 1997 solar minimum predictions of the Badhwar & O'Neill and CREME96/Nymmik GCR environment models. (The Badhwar & O'Neill model predictions for C, O, and Fe were obtained by private communication, 2000; the 1997 CREME96/Nymmik model predictions are available from the CREME96 web site.) Above ~120 MeV nucleon^{-1}, the CREME96/Nymmik model spectra agree quite well with the ACE C and Fe measurements, but they underestimate the O and Si intensities by as much as 15%. Below ~120 MeV nucleon^{-1}, the CREME96/Nymmik model spectra overestimate the cosmic ray intensity relative to the ACE data. The Badhwar & O'Neill model spectra generally exceed the C, O, and Fe measurements, overestimating the intensities by ~20% at 200 MeV nucleon^{-1}. It appears that the CREME96/Nymmik model will underestimate the solar minimum contribution of heavy ions to the radiation dose, while the Badhwar & O'Neill model will overestimate this contribution. The reasons for the differences between these models and the ACE measurements are unclear. The models are derived from a database of cosmic–ray H, He, and heavy–ion measurements accumulated over the past ~30 years at a variety of solar modulation levels.

Both the CREME96/Nymmik and Badhwar & O'Neill models fit empirical functions to observed cosmic–ray H, He, and heavy–ion spectra. Therefore the new ACE measurements will undoubtedly help to make improvements in these models, since the data include all the elements from B to Ni in the energy range of interest with good statistical accuracy, including the less–abundant secondary elements produced during the propagation of primary cosmic rays in the interstellar medium.

However, an alternative approach to improving on these models, suggested by *Mewaldt* [1994], and *Adams and Lee* [1996] is to make use of our knowledge of the astrophysical processes that determine the composition and energy spectra of cosmic rays and that cause some elements to have different spectra than others. Much effort has been devoted in recent years to the development of models of the acceleration, propagation through the galaxy, and subsequent penetration of cosmic rays into the heliosphere [see, e.g., *Simpson*, 1983, and references therein; *Wefel*, 1988, and references therein]. Typically, it is assumed that cosmic rays are accelerated with common energy spectra from some source population whose composition is one of the free parameters of the model. The model then determines how the composition and spectra of these primary cosmic rays are altered during propagation through the interstellar medium. This results in a set of local–interstellar GCR spectra that includes both surviving primaries and secondary cosmic rays, produced by fragmentation of the primaries on interstellar H and He. The models can account for the observation that the spectra of the secondaries have significantly different energy spectra than the primaries. The local–interstellar spectra serve as input for solar modulation calculations that take into account diffusion, convection, and adiabatic energy loss in the heliosphere, as well as the effects of the 22–year solar magnetic cycle [see, e.g., *Potgieter,* 1998]. The results of these calculations are then compared with observations, and iterated as necessary to produce good fits to the observations.

The simplest model of cosmic ray propagation that actually does a good job of reproducing the observations is the "leaky box" model [*Cowsik et al.,* 1967], in which cosmic rays diffuse freely inside the galaxy and are reflected at the boundaries. At each encounter there is some probability for escape from the galaxy. This results in an exponential path length distribution (PLD) for cosmic rays in the galaxy. The mean of this PLD is $\Lambda_{\rm esc}(E)$ (where E denotes energy per nucleon) and the energy dependence of $\Lambda_{\rm esc}(E)$ is adjusted to account for the observed cosmic ray secondary/primary ratios and energy spectra.

To illustrate the advantages of making use of a GCR propagation model for shielding and dose calculations, we present here the results of a steady state leaky box model based on the formalism of *Meneguzzi et al.,* [1971], details of which can be found in the work of

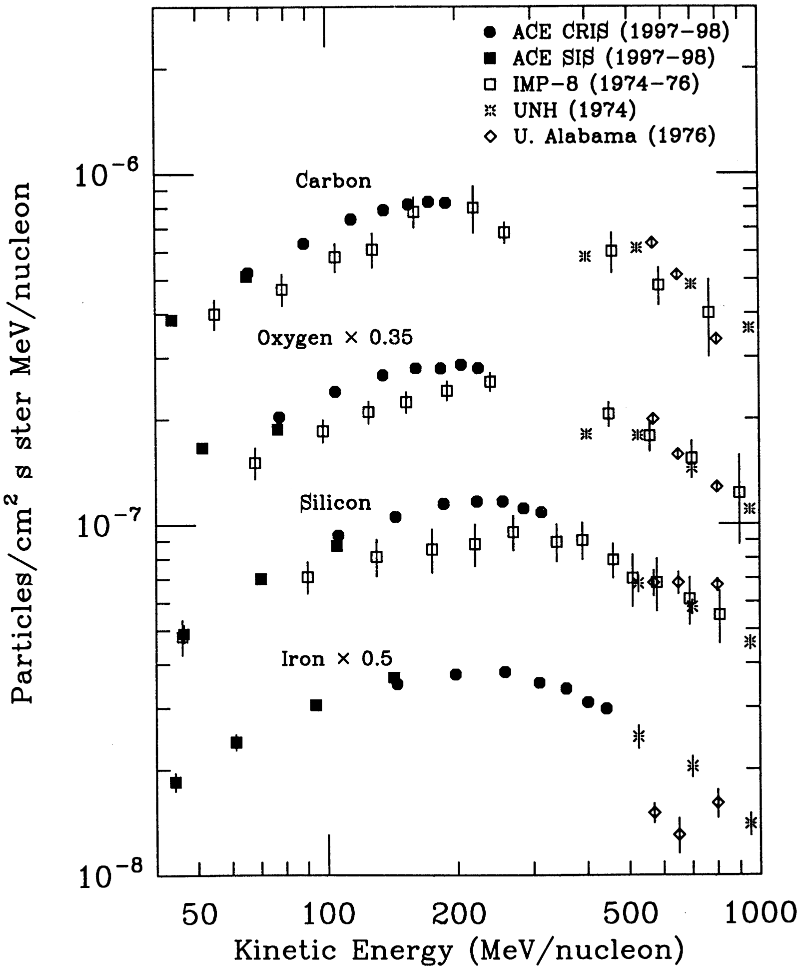

Figure 3. Energy spectra of C, O, Si, and Fe measured by ACE (September 1997 through March 1998), IMP 8 (1974 - 1976) [*Garcia-Munoz et al.,* 1977] and two balloon experiments [*Lezniak and Webber,* 1978; *Derrickson et al.,* 1992]. The error bars on the ACE data reflect statistical uncertainties only and are generally smaller than the data points. Systematic uncertainties in the absolute spectra of GCRs measured by ACE are conservatively estimated to be less than 10%.

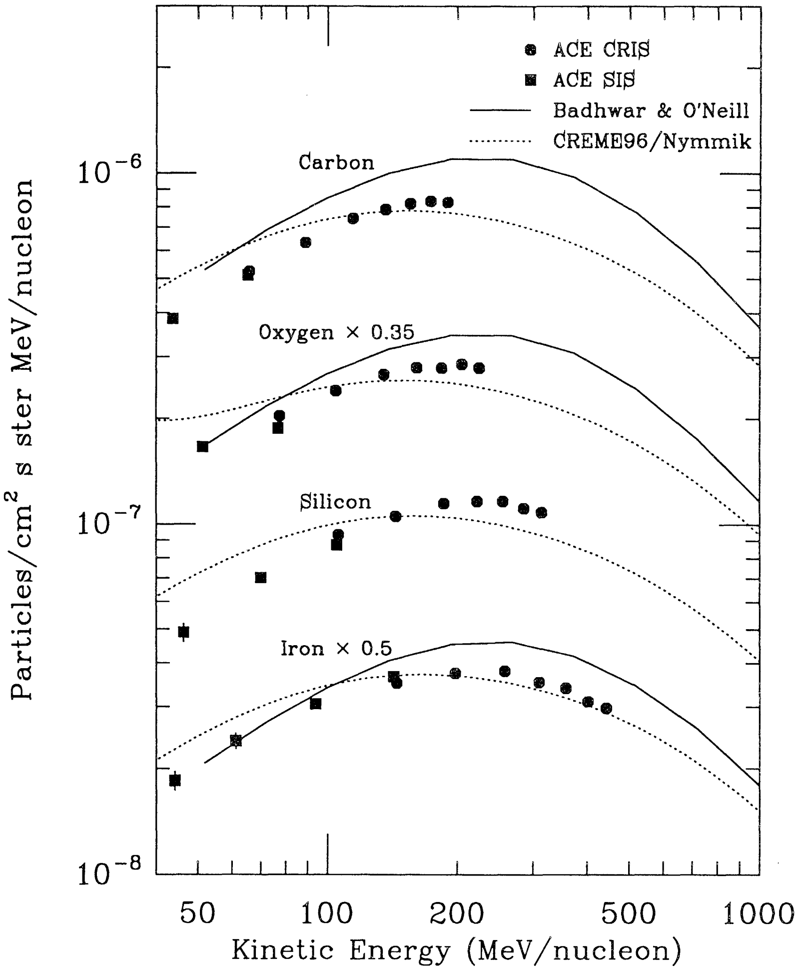

Figure 4. Energy spectra of C, O, Si and Fe measured by ACE (September 1997 through March 1998), compared to 1997 solar minimum predictions of the CREME96/Nymmik [*Tylka et al.,* 1996; *Nymmik et al.,* 1996] and *Badhwar & O'Neill* [1996] models of the GCR environment.

Davis et al. [2000, and references therein]. This model includes the effects of escape from the galaxy, ionization energy losses in and nuclear interactions with the interstellar medium, and decay of radioactive species. The effects of cosmic ray transport in the heliosphere are calculated using the spherically symmetric model of *Fisk* [1971]. Figure 5 shows the results of this model, fit to B, C, (Sc + Ti + V), and Fe spectra from ACE. Both C and Fe are examples of primary cosmic rays, while B, Sc, Ti and V are cosmic-ray secondaries. Fits to O, Si and other key elements are of similar quality. The GCR propagation model fits the data significantly better than the Badhwar & O'Neill or CREME96/Nymmik models, across the full energy range spanned by the ACE measurements.

Extrapolations and interpolations from this model should be reliable, since the local-interstellar spectra it generates are based on the underlying physics, and the comic-ray modulation parameters are selected to fit energy spectra measured over a wide range of solar activity. In addition, a comparison of the local-interstellar and 1 AU spectra produced by this leaky-box model with those currently used by the Badhwar & O'Neill and CREME96/Nymmik models should help to decide whether the discrepancies between these models and the ACE measurements are related to the input spectra, or to differences in representing the level of solar modulation.

5. Characterization of the GCR Environment Throughout a Complete Solar Cycle

The radiation risks for long-duration missions have generally been evaluated using a solar minimum GCR environment as input. However, if the radiation risk due to GCRs at solar minimum turns out to be too great, it may be necessary to consider planning long-duration missions for times in the solar cycle when cosmic ray intensities are lower. High-quality cosmic ray spectra obtained at regular intervals throughout a solar cycle would be very useful for such studies. The ACE spacecraft will be able to provide these spectra over the next few years, as we pass through the maximum in solar activity and the associated minimum in cosmic ray intensity.

Figure 6 shows 27–day average fluxes of O and Fe at ~ 200 MeV nucleon^{-1}, from September 1997 through December 2000. The effects of increasing levels of solar modulation are evident, and it is clear that high–quality spectra of the key heavy elements can be generated from the ACE data with a time resolution of ~3 months. If used as input to any of the GCR environment models discussed above, such data should result in a significant improvement in the reliability of the model predictions throughout the solar cycle. For instance, our leaky box model could be used to fit the ACE spectra for each 3–month period, producing a set of modulation parameters that could be correlated with neutron monitor counting rates to allow for a predictive capability.

6. Conclusions

The galactic cosmic ray spectra measured by ACE during September 1997 through March 1998 represent the highest flux levels ever observed for GCR heavy elements at 1 AU. Neutron monitor count rates and IMP 8 helium intensities since 1973 confirm that the ACE data were obtained during solar minimum and show that GCR intensities reached during both the 1977 and 1987 solar minimum were no higher than the 1997–1998 ACE observations.

The ACE measurements presented here can lead to improved models of the GCR radiation environment and improved predictions of the solar minimum radiation levels expected during long–duration interplanetary space flights. Given that these ACE spectra reflect true solar minimum conditions, the Badhwar & O'Neill model currently overestimates the solar minimum intensities of heavy cosmic rays by as much as 20% in the energy range ~100 to ~500 MeV nucleon^{-1}, while the CREME96/Nymmik model underestimates the environment by a slightly smaller margin. It appears that neither model will correctly predict the contribution of heavy ions to the radiation dose in interplanetary space.

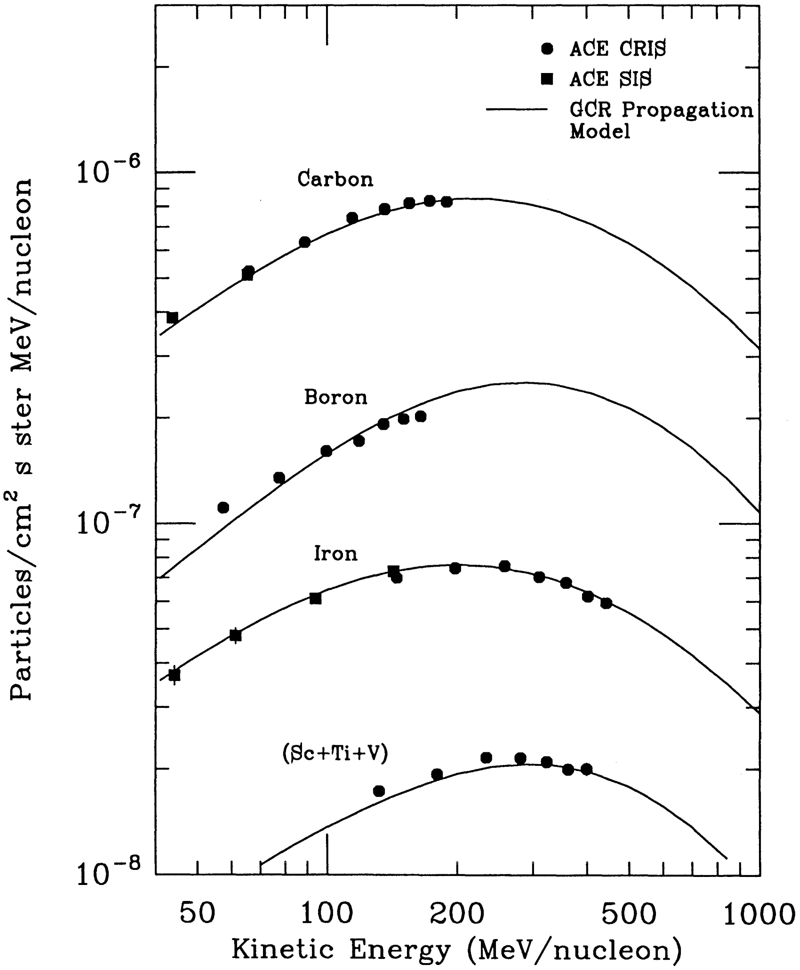

Figure 5. A leaky box model of GCR propagation, fit to B, C, (Sc+Ti+V), and Fe energy spectra measured by ACE. Details of the propagation mode can be found in the work of *Davis et al.,* [2000].

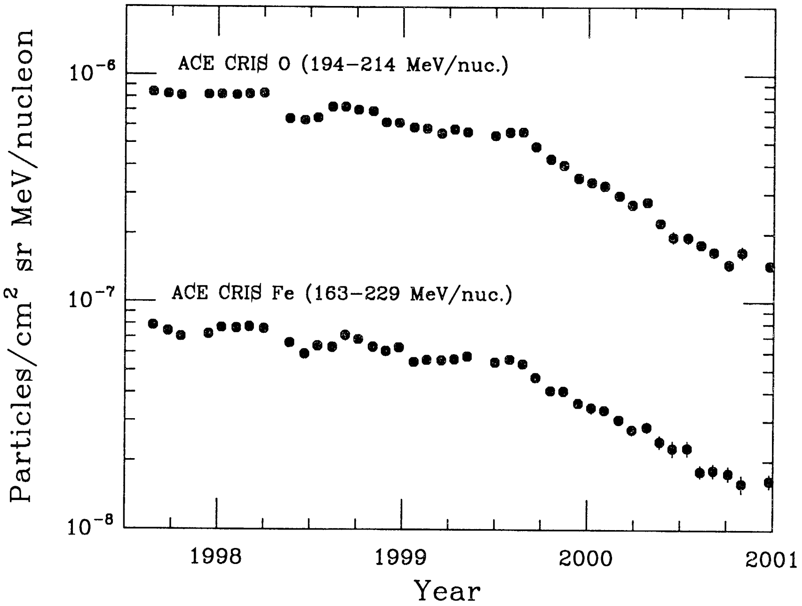

Figure 6. Measured intensities of ~200 MeV nucleon^{-1} O and Fe, from September 1997 through December 2000. Galactic cosmic ray intensities at these energies have decreased by a factor of ~4 over this time period. The error bars reflect statistical uncertainties only. Major tick marks on the x axis indicate the beginning of each year.

Therefore both models could be usefully updated taking into account the new measurements.

The reliability of predictions of the GCR radiation environment (and radiation dose estimates calculated from these predictions) could be further improved by making use of cosmic ray propagation models that incorporate knowledge of the astrophysical processes that determine cosmic ray composition and spectra. As an example, it is shown that a leaky box propagation model coupled with a solar modulation model produces cosmic ray spectra that fit the ACE measurements significantly better than the predictions of the Badhwar & O'Neill and CREME96/Nymmik models. A detailed comparison of the local–interstellar spectra used to generate these predictions with the spectra produced by the leaky box model should lead to a better understanding of the discrepancies between the model predictions and the new ACE measurements.

The CRIS and SIS instruments on the ACE spacecraft are capable of measuring high–quality spectra of the key elements averaged over intervals of several months or less for the duration of the mission, which may well extend to the next solar minimum. Element spectra from both these instruments are available from the ACE Science Center web site. These data can significantly improve our ability to evaluate the GCR radiation environment at any given time in the solar cycle.

Acknowledgments. This research was supported by NASA at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, the Goddard Space Flight Center, and Washington University. We are grateful to the large group of dedicated and talented individuals who made the ACE mission possible and contributed to the development of the CRIS and SIS instruments (as acknowledged by *Stone et al.* [1998b, 1998c]. University of Chicago neutron monitor operations and research activities are supported by the National Science Foundation (grant ATM-9912341). IMP 8 GME helium data are provided on the IMP 8 GME web site by Robert E. McGuire, NASA Goddard Space Flight Center. We are grateful to the developers of CREME96 for presenting their programs on the Web for public use, and we are grateful to Gautam D. Badhwar at NASA Johnson Space Flight Center for providing GCR environment model data.

Janet G. Luhmann thanks Lawrence W. Townsend and another referee for their assistance in evaluating this paper.

References

Adams, J. H., and J. Lee, A model of the primary cosmic ray spectra, *Radiat. Meas.*, *26*, (3), 467–470, 1996.

Badhwar, G. D., and P. M. O'Neill, Galactic cosmic radiation model and its applications, *Adv. Space Res.*, *17*, (2), 7–17, 1996.

Cowsik, R., P. Yash, S. N. Tandon, and R. P. Yerma, Steady state of cosmic–ray nuclei — Their Spectral shape and path length at low energies, *Phys. Rev.*, *158*, (5), 1238, 1967.

Davis, A. J., et al., On the low energy decrease in galactic cosmic ray secondary/primary ratios, in *Acceleration and Transport of Energetic Particles Observed in the Heliosphere*, edited by R. A. Mewaldt et al., *AIP Conf. Proc.*, *528*, 422–425, 2000.

Derrickson, J. H., T. A. Parnell, R. W. Austin, W. J. Selig, and J. C. Gregory, A measurement of the absolute energy spectra of galactic cosmic rays during the 1976–77 solar minimum, *Int. J. Radiat. Appl. Instrum., Part D*, *20*, 415–421, 1992.

Fisk, L. A., Solar modulation of galactic cosmic rays, *J. Geophys. Res.*, *76*, 221, 1971.

Garcia–Munoz, M., G. M. Mason, J. A. Simpson, and J. P. Wefel, Charge and energy spectra of heavy cosmic rays at intermediate energies, *Proc. 15th Int. Cosmic Ray Conf.*, *1*, 230–233, 1977.

Lezniak, J.A., and W. R. Webber, The charge composition and energy spectra of cosmic–ray nuclei from 300 MeV per nucleon to 50 GeV per nucleon, *Astrophys. J.*, *223*, 676–696, 1978.

McDonald, F. B., N. Lal, and R. E. McGuire, Cosmic ray recovery and solar minimum phase of solar cycle 22: An interim report, *J. Geophys. Res.*, *103*, 373–379, 1998.

Meneguzzi, M., J. Audouze, and H. Reeves, The production of the elements Li, Be, B by galactic cosmic rays in space and its relation with stellar observations, *Astron. Astrophys.*, *15*, 337–359, 1971.

Mewaldt, R. A., Galactic cosmic ray composition and energy spectra, *Adv. Space Res.*, *14*, (10), 737–747, 1994.

National Council on Radiation Protection and Measurements, Guidance on radiation received in space activities, *Rep. 98*, Bethesda, MD, July 31, 1989.

Nymmik, R. A., M. I. Panasyuk, T. I. Pervaja, and A. A. Suslov, A model of galactic cosmic ray fluxes, *Nucl. Tracks Radiat. Meas.*, *20*, 427–429, 1992.

Nymmik, R. A., M. I. Panasyuk, and A. A. Suslov, Galactic cosmic ray flux simulation and prediction, *Adv. Space Res.*, *17*, (2), 19–30, 1996.

Parker, E. N., The passage of energetic charged particles through interplanetary space, *Planet. Space Sci.*, *13*, 9–49, 1985.

Potgieter, M. S., The modulation of galactic cosmic rays in the heliosphere: theory and models, *Space Sci. Rev.*, *83*, 147–158, 1998.

Simpson, J. A., Elemental and isotopic composition of the galactic cosmic rays, *Annu. Rev. Nucl. Particle Sci.*, *33*, 323–381, 1983.

Stone, E. C., et al., The Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 1–22, 1998a.

Stone, E. C., et al., The cosmic ray isotope spectrometer for the Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 285–356, 1998b.

Stone, E. C., et al., The solar isotope spectrometer for the Advanced Composition Explorer, *Space Sci. Rev.*, *86*, 357–408, 1998c.

Tylka, A. J., J. H. Adams, P. R. Boberg, B. Brownstein, W. F. Dietrich, E. O. Flueckiger, E. L. Petersen, M. A. Shea, D. F. Smart, and E. C. Smith, CREME96: A revision of the cosmic ray effects on micro–electronics code, *IEEE Trans. Nucl. Sci.*, *44*, (6), 2150–2160, 1996.

Wefel, J. P., An overview of cosmic ray research: Composition, acceleration, and propagation, in *Genesis and Propagation of Cosmic Rays*, edited by M. M. Shapiro and J. P. Wefel, 1–40, D. Reidel, Norwell, Mass., 1988.

Wilson, J. W., J. E. Nealy, W. Schimmerling, F. A. Cucinotta, and J. S. Wood, Effects of radiobiological uncertainty on vehicle and habitat shield design for missions to the moon and mars, *NASA Tech. Pap.*, *3312*, 1993.

Wilson, J. W., L. W. Townsend, J. L. Schinn, F. A. Cucinotta, R. C. Costen, F. F. Badavi, and S. L. Lamkin, Galactic cosmic ray transport methods: Past, present and future, *Adv. Space Res.*, *14*, (10), 841–852, 1994.

Wilson, J. W., F. A. Cucinotta, H. Tai, L. C. Simonsen, J. L. Shinn, S. A. Thibeault, and M. Y. Kim, Galactic and solar cosmic ray shielding in deep space, *NASA Tech. Pap.*, *3682*, 1997.

W. R. Binns and P. L. Hink, Washington University Physics Dept., Campus Box 1105, St. Louis MO 63130. (wrb@howdy.wustl.edu)

E. R. Christian and T. T. von Rosenvinge, NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771. (tycho@lheamail.gsfc.nasa.gov)

C. M. S. Cohen, A. C. Cummings, A. J. Davis, J. S. George, R. A. Leske, R. A. Mewaldt, and E. C. Stone, Mail Code 220-47, California Institute of Technology, Pasadena, CA 91125. (ad@srl.caltech.edu)

M. E. Wiedenbeck and N. E. Yanasak, Mail Stop 169-327, Jet Propulsion Laboratory, Pasadena, CA 91109. (mew@heag1.jpl.nasa.gov)

(Received August 24, 2000; revised November 15, 2000; accepted November 28, 2000.)