Proceedings of ICRC 2001: 3971 © Copernicus Gesellschaft 2001

ICRC 2001

# The evolution of galactic cosmic ray element spectra from solar minimum to solar maximum: ACE measurements

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**Abstract.** The spectra of galactic cosmic ray (GCR) elements from Beryllium to Nickel in the energy range 40 - 500 MeV/nucleon at 1 AU are being continuously measured by instruments on-board the Advanced Composition Explorer (ACE). The collecting power of these instruments allows statistically precise spectra to be calculated every few months for most elements. Measurements of temporal variations in GCR spectra over the solar cycle are important for understanding solar modulation processes, and also for refining models of the near-earth radiation environment used to perform shielding and dose calculations for manned and unmanned space missions. We report on ACE observations of the evolution of GCR element spectra from solar minimum in 1997 through Spring 2001. We 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

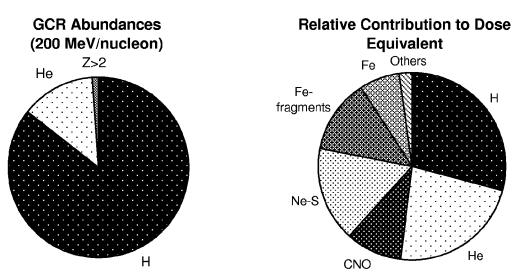


**Fig. 1.** (left) Abundances of cosmic–ray nuclei at 200 MeV/nucleon. (right) Contribution of the important galactic cosmic ray element groups to the BFO radiation dose behind 5 gcm$^{-2}$ of shielding at solar minimum (data from Wilson et al., 1997).

The radiation dose from galactic cosmic rays during a manned mission to Mars is expected to be comparable to the allowable limit for astronauts in low Earth orbit (LEO). Most of this dose would be due to galactic cosmic rays with energies $< 1$ GeV/nucleon, with important contributions from heavy nuclei in spite of their low abundance relative to H and He (see Figure 1).

The current annual exposure limit to the blood forming organs (BFO) for astronauts in LEO is 0.5 Sv/year (dose equivalent) (NCRP, 1989). This limit is 10 times the allowed annual limit for terrestrial radiation workers. Although exposure limits for interplanetary missions have not yet been defined, Wilson et al. (1997) find that for an interplanetary mission lasting a year or more, $\sim 30$ g cm$^{-2}$ of aluminum shielding 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 uncertainties 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.

## 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 envi-

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ronment 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). 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). 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. The 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 are 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), which relates solar cycle variations in cosmic ray intensities to the observed time history of the 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. With typical shielding, about 75% of the dose equivalent is due to nuclei with $E < 1$ GeV/nuc (L.W. Townsend, private communication, 1991). However, most of the published solar minimum measurements below 1 GeV/nuc were made during the 1970s by satellite instruments with small geometry factors or by balloon instruments with limited time coverage and sizeable systematic uncertainties.

## 3 GCR Element Spectra from ACE Compared with Previous Data and GCR Environment Models

Data from the the ACE mission (Stone et al., 1998a), can help make significant improvements to models of the GCR environment. ACE was launched in August 1997, during the most recent period of solar minimum activity, and has fuel to extend the mission until $\sim$2014. Two instruments on board ACE measure particle spectra at GCR energies: the Cosmic Ray Isotope Spectrometer (CRIS) and the Solar Isotope Spectrometer (SIS). CRIS measures elemental and isotopic composition for $Z$ = 2–28 from $\sim$ 50 to $\sim$ 500 MeV/nuc, with a geometry factor of $\sim$ 250 cm$^2$ sr, many times larger than previous instruments of its kind (Stone et al., 1998b). SIS measures elemental and isotopic composition for $Z$ = 2–28 from $\sim$10 to $\sim$100 MeV/nuc, with a geometry factor of 38 cm$^2$ sr (Stone et al., 1998c). The residual systematic uncertainty in the spectra measured by CRIS and SIS is conservatively estimated to be less than 10% for both instruments, and is probably less than 5%. Together, these instruments 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 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 $\sim$3 months of the present day.

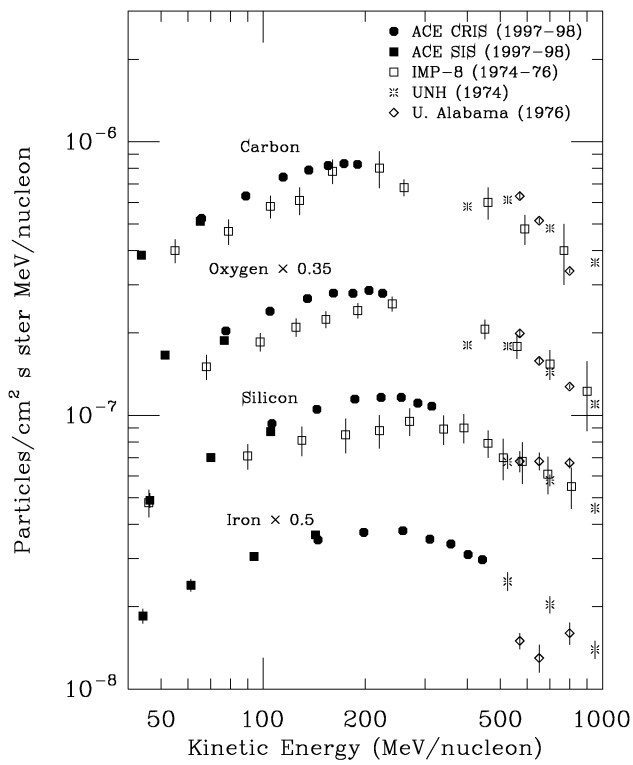


**Fig. 2.** Energy spectra of C, O, Si, and Fe measured by ACE (September 1997 through March 1998), IMP 8 (1974 – 1976) (Garcia-Munoz et al., 1977) and two balloon experiments (Lezniak and Webber, 1978; Derrickson et al., 1992). The error bars on the ACE data reflect statistical uncertainties only and are in most cases 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 2 shows solar minimum C, O, Si, and Fe spectra from ACE, gathered during the period August 28, 1997, through March 18, 1998, 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 – 1976 (Garcia-Munoz et al., 1977). 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. The University of New Hampshire (UNH) (Lezniak and Webber, 1978) and the

University of Alabama Huntsville (UAH) (Derrickson et al., 1992) spectra shown in Figure 2 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 2 shows that below $\sim 200$ MeV/nucleon the ACE spectra are as much as 20% higher than the IMP 8 spectra. This is perhaps not surprising, since there was a significant dip in neutron monitor count rates during 1974. Solar modulation is less important at higher energies, and above $\sim 300$ MeV/nucleon 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 between 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 $\sim 40$ to 500 MeV/nucleon. The ACE measurements also represent the highest flux levels ever reported for GCR heavy elements at 1 AU in this energy range.

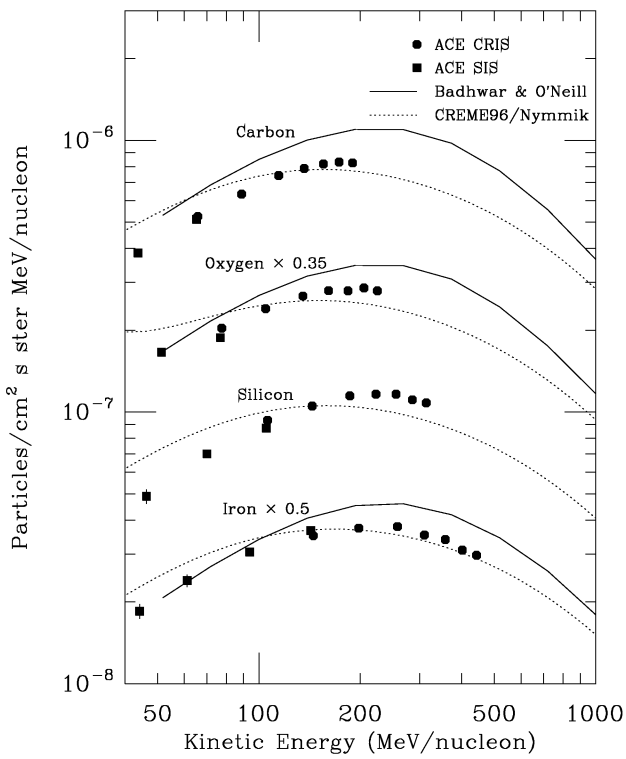


**Fig. 3.** Energy spectra of C, O, Si and Fe measured by ACE (September 1997 through March 1998), compared to 1997 solar minimum predictions of the CREME96/Nymmik (Tylka et al., 1996; Nymmik et al., 1996) and Badhwar & O'Neill (1996) models of the GCR environment.

In Figure 3, we compare the solar minimum ACE measurements with 1997 solar minimum predictions of the Badhwar & O'Neill and CREME96/Nymmik GCR environment models. (The Badhwar & O'Neill predictions were obtained by private communication, 2000; the CREME96/Nymmik predictions are available from the CREME96web site.) Above $\sim 120$ MeV/nuc, the CREME96/Nymmik 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 $\sim 120$ MeV/nuc, the CREME96/Nymmik spectra overestimate the cosmic ray intensity relative to the ACE data. The Badhwar & O'Neill spectra generally exceed the C, O, and Fe measurements, overestimating the intensities by $\sim 20\%$ at 200 MeV/nuc. 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.

Both the CREME96/Nymmik and the Badhwar & O'Neill models fit modulated spectra derived from model interstellar spectra to a database of cosmic–ray H, He, and heavy–ion spectra measured at 1 AU over the past $\sim 30$ years. 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.

## 4 Tracking Solar–Cycle Variations in the GCR Environment

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. Data available from CRIS and SIS on ACE now cover the period from solar minimum in 1997 to solar maximum in 2001, and these data can potentially continue to flow until $\sim 2014$.

Our group has been using a steady state leaky box model (eg. Cowsik et al., 1967) based on the formalism of Meneguzzi et al. (1971) to calculate model GCR spectra and compare them to the CRIS and SIS observations. Details of this model can be found in Davis et al. (2000, and references therein). The 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 (solar modulation) are calculated using the spherically symmetric model of Fisk (1971).

Figure 4 shows results of this model, fit to iron spectra from ACE during five time periods from August 1997 through February 2001. After fitting to the iron data, the model produces oxygen spectra that fit the ACE oxygen data to better than 5%, and the agreement with data for other key elements is of similar quality. The model tracks the changes in intensity and shape of the measured spectra as a function of solar modulation, and the model fits the data significantly better than the Badhwar & O'Neill or CREME96/Nymmik models

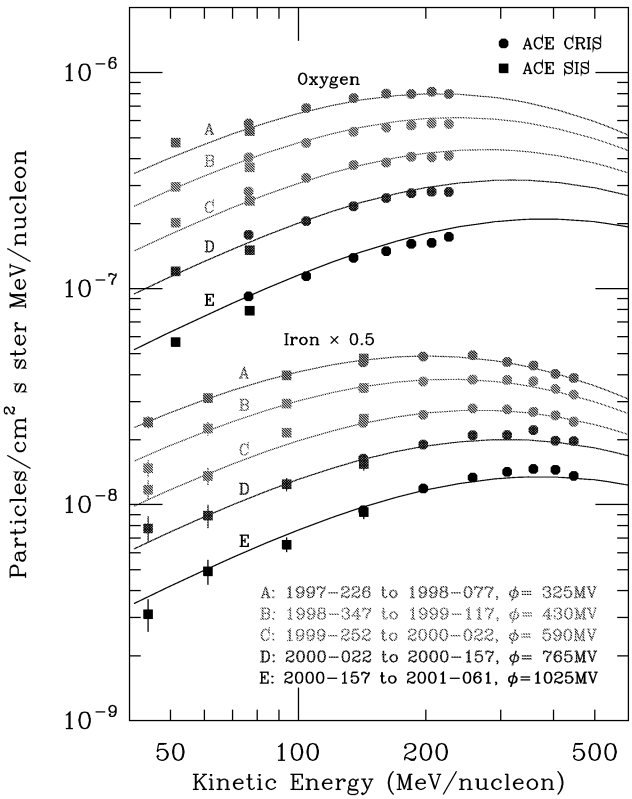


**Fig. 4.** A leaky box model of GCR propagation, fit to iron energy spectra measured by ACE during five time periods from August 1997 through February 2001. After fitting to the iron data, the model is also in reasonably good agreement with the ACE oxygen data, as well as data for the other major elements present in the GCRs.

at solar minimum. A comparison of the local–interstellar and 1 AU spectra produced by this leaky–box model with those used by the Badhwar & O'Neill and CREME96/Nymmik models would help to resolve the discrepancies between those models and the ACE measurements.

## 5 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. Given that these ACE spectra reflect true solar minimum conditions, it appears that neither of the two GCR radiation environment models currently in use correctly predicts the contribution of heavy ions to the radiation dose in interplanetary space. 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. The results of this model also match the observed changes in intensity and shape of the GCR spectra from solar minimum to solar maximum.

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 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. In future work, we plan to develop a predictive model of the GCR environment, by fitting these spectra over a complete solar cycle with our propagation/solar modulation model, and correlating the model parameters with neutron monitor and/or sunspot number data.

*Acknowledgements.* 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 Gautam D. Badhwar at NASA Johnson Space Flight Center for providing GCR environment model data, and to the developers of CREME96 for presenting their programs on the Web for public use,

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