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 g cm⁻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, ∼ 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 ∼ 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 (∼ 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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environment with a radiation transport code. Several groups have
developed advanced radiation transport codes. Examples in-
clude 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 Re-
search Laboratory (Tylka et al., 1996). However, these codes
are generally run using different models of the radiation en-
vironment. 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 ~1–20 GeV pri-
mary 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 en-
nvironment) 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 cos-
mic 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 im-
plementation 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 cos-
mic 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 commu-
nication, 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 Pre-
vious 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 ~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 un-
certainty in the spectra measured by CRIS and SIS is conser-
vatively 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 evalu-
ating 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 aver-
geages are available, from a few days after launch to within
~3 months of the present day.

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 ~50–1000 MeV/nucleon. The University of
New Hampshire (UNH) (Lezniak and Webber, 1978) and the

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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 ~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 ~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 ~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.

~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 ~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 ~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 ~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 ~2014.

Our group has been using a steady state leaky box model (e.g. Cowax 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.
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 CREAM96/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.

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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

References