Elemental Composition and Energy Spectra of Galactic Cosmic Rays

R. A. Mewaldt
California Institute of Technology
Pasadena, CA 91125

ABSTRACT

A brief review is presented of the major features of the elemental composition and energy spectra of galactic cosmic rays. The requirements for phenomenological models of cosmic ray composition and energy spectra are discussed, and possible improvements to an existing model are suggested.

1. INTRODUCTION

Over the past forty years, but especially during the past decade or so, a variety of spacecraft and balloon instruments have combined to measure the composition of galactic cosmic rays over essentially the entire periodic table (nuclear charge Z = 1 to 92), and the energy spectrum of abundant cosmic ray species from ~10 MeV/nuc to ~100 GeV/nuc. In this report we discuss aspects of these measurements that are relevant to phenomenological models of cosmic ray composition and its dependence on energy. Adams et al. (1981; see also Adams, 1986) have produced such a model and we suggest some minor improvements and updates that might be made to this model in an effort to improve its accuracy.

This report constitutes a written version of a presentation made at the *Workshop on the Interplanetary Charged Particle Environment* held at the Jet Propulsion Laroratory in March, 1987. The purpose of this workshop was to review current models of the interplanetary particle environment, in an effort to evaluate their accuracy and improve their predictive capability. Among the applications of such models are evaluations of the effects of energetic charged particles on microelectronic devices carried on spacecraft, and their effect on man in space.

2. COSMIC RAY COMPOSITION

Several experiments over the past decade or so have led to significant improvements in in our knowledge of the composition of galactic cosmic rays. There are now accurate measurements of the relative abundances of all elements from H to Zn (Z = 1 to 30; see, e.g., Engelmann et al., 1983, 1985; Dwyer and Meyer, 1985, 1987; Garcia-Munoz and Simpson, 1979). For the ultra-heavy (UH) elements with Z > 30, the recent HEAO-3 and Ariel missions (Stone et al., 1987; Fowler et al., 1985) have provided abundances of adjacent pairs of even and odd nuclei up to Z = 60, while for the upper one-third of the periodic table the abundances of various groups of charges have been reported. For recent reviews of these and other measurements see Simpson (1983) Mewaldt (1983), Meyer (1985), and Mason (1987).

Figure 1 and Table 1 summarize the relative elemental composition from Z = 1 to 92, normalized to Si = 10^6. Note that the relative flux spans more than 10 decades in intensity. To a rough approximation the relative abundances of the major elements in cosmic rays are in proportion to their distribution in solar system material, but there are also significant differences from the solar composition, including the great enhancement of "secondary" nuclei produced in cosmic rays by fragmentation (e.g., Li, Be, and B); the relative depletion (by a factor of ~5) of elements with high first ionization potential in cosmic rays (e.g., C, N, O, Ne, Ar); and the underabundance of H and He relative to heavier elements.

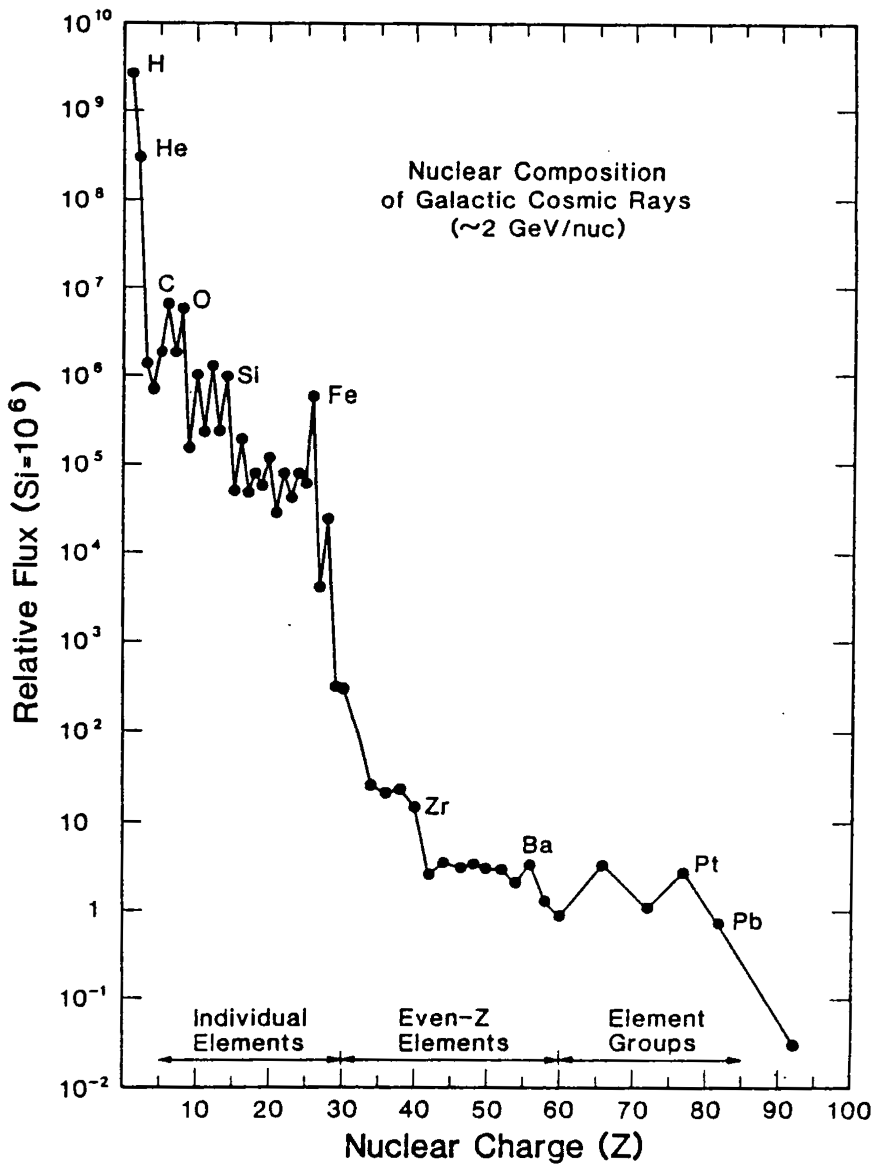

Figure 1: The relative flux of cosmic rays as a function of nuclear charge Z (see also Table 1).

Table 1 - Elemental Composition of Galactic Cosmic Rays (~1 GeV/nucleon)+

Nuclear Charge Z	Relative Abundance* (Si = 1000)	Nuclear Charge Z	Relative Abundance* (Si = 10^6)
1	3×10^6	29	381±88
2	$2.7 \pm 0.6 \times 10^5$	30	393±35
3	1360±30	31-32	63±12
4	670±20	33-34	26.4±2.3
5	1920±143	35-36	20.6±1.4
6	6400±211	37-38	22.4±1.4
7	1820±58	39-41	14.5±1.1
8	5930±107	42	2.4±0.5
9	143±7.4	43-44	3.6±0.6
10	993±26	45-46	3.0±0.5
11	224±8	47-48	3.4±0.5
12	1240±28	49-50	3.0±0.5
13	224±8	51-52	3.0±0.5
14	1000	53-54	2.1±0.4
15	51.1±3.5	55-56	3.4±0.5
16	189±8	57-58	1.3±0.3
17	47.1±3.4	59-60	0.9±0.3
18	79.5±4.9	62-69	3.5±0.4
19	57.0±3.7	70-73	1.1+0.4-0.3
20	124.4±6.3	74-80	2.7±0.4
21	28.5±2.6	81-83	0.6+0.3-0.2
22	82.1±4.8	90-96	0.03+.04-.03
23	41.0±3.3		
24	80.9±5.0		
25	59.9±4.1		
26	587±17		
27	3.3±0.5		
28	29.6±0.6		

\+ Based on Binns et al. (1982), Byrnak et al. (1983), Dwyer and Meyer (1985), Engelmann et al. (1983), Lezniak and Webber (1978), and Stone et al. (1987). Uncertainties in the relative abundance of widely separated charges may be somewhat greater than indicated.

* Note that the normalization is Si=10^6 for Z≥29 and Si=1000 for Z≤28.

In Figure 2 we show the "integral composition" of cosmic rays, the integrated flux of elements heavier than a given nuclear charge. Note in particular that the flux of the UH elements, which constitute the upper 2/3 of the periodic table, amount to only ~0.1% of that of Fe (Z = 26). In problems involving the effect of cosmic rays on micro-electronic devices there is often a threshold energy loss for a given device, such that only cosmic rays of a certain charge or greater are capable of triggering the device, since energy loss is proportional to Z^2. Figure 2 demonstrates the advantages of a high threshold, and shows that phenomenological models of cosmic ray composition should, at the very least, characterize accurately the abundance and energy spectra of certain key elements that represent significant increases or "breaks" in this integral distribution (e.g., H, He, O, Si, and Fe).

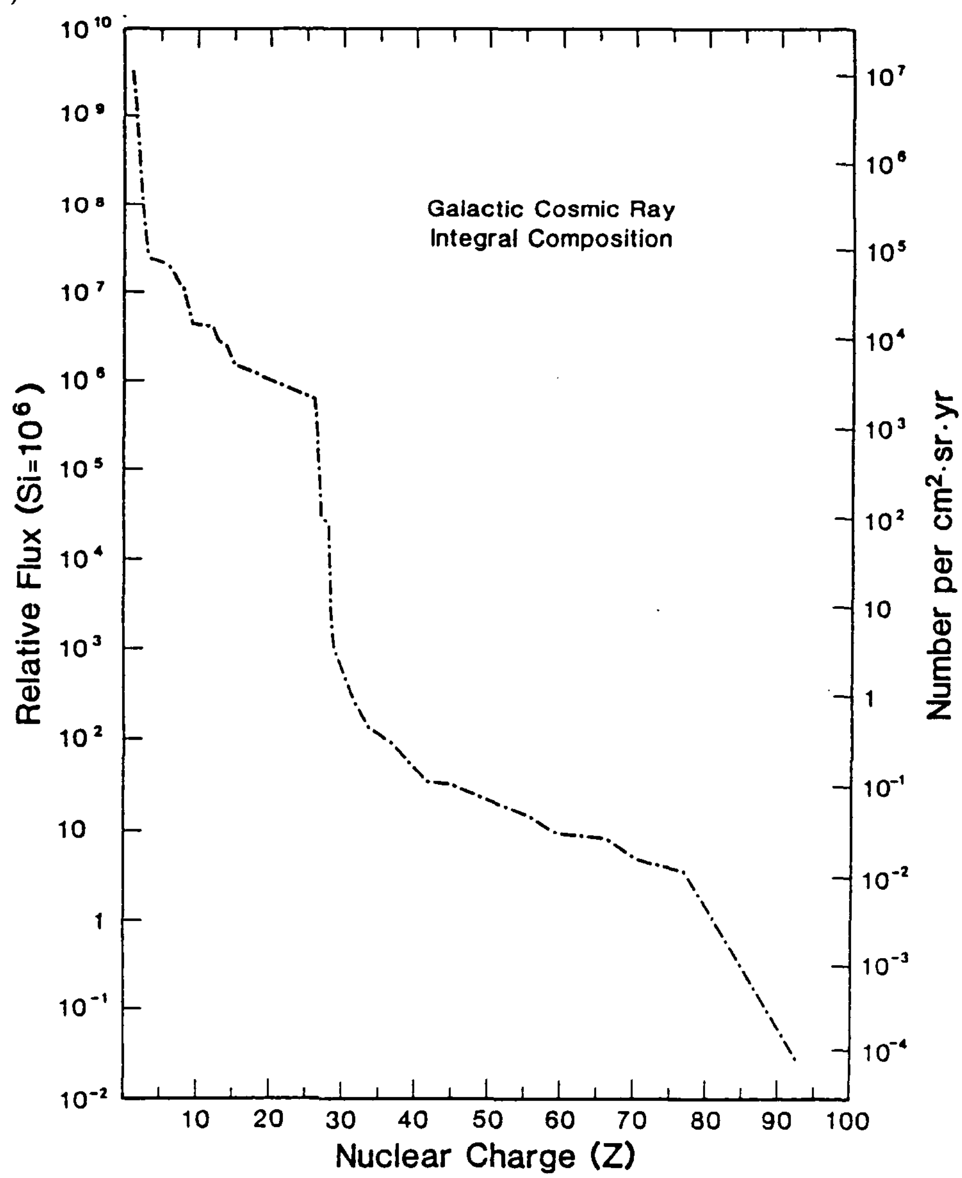

Figure 2: The relative flux of cosmic rays heavier than a given nuclear charge, as obtained by integrating the data shown in Figure 1.

3. ENERGY DEPENDENCE OF THE COMPOSITION

To a good approximation, the composition of cosmic rays can be considered independent of energy if the particle energy is measured in units of energy per nucleon (equivalent to comparing the composition at the same velocity). There are, however, some important differences. Figure 3 compares the composition measured at 0.2 and 15 GeV/nuc to that at ~2 GeV/nuc. The most obvious difference at 15 GeV/nuc is the generally lower abundance of "secondary" nuclei relative to primary nuclei, indicating that higher energy cosmic-ray nuclei (those with energies > several GeV/nuc) have passed through less material subsequent to their acceleration (see, e.g., Ormes and Protheroe, 1983). A possibly related feature is that the abundance of heavier "primary" nuclei such as Fe is more abundant at high energy.

The N_z(15 GeV/nuc)/N_z(2 GeV/nuc) ratio in Figure 3 is an indication of the extent to which the energy spectra of the various elements differ. Engelmann et al. (1983, see also Juliusson et al., 1983) have fit power laws in total energy/nucleon to the spectra of elements with $4 \leq Z \leq 28$ from ~0.8 to 25 GeV/nuc. This particular spectral shape gives a good approximation to the observed spectra of "primary" elements from ~2 to 10 GeV/nuc; at lower energies the (time dependent) effects of solar modulation are particularly important. They found that the typical spectral index for "secondary" elements over this energy range was steeper than that for primaries by about $\Delta\gamma = 0.2$.

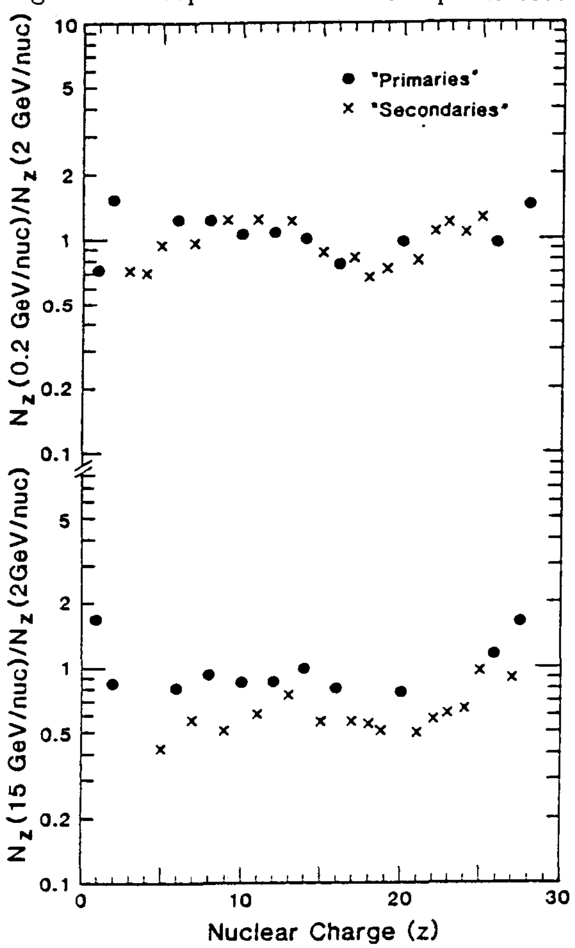

Figure 3: (Top) Comparison of the cosmic ray elemental composition measured at ~0.2 GeV/nuc (Garcia-Munoz and Simpson, 1979) relative to that at ~2 GeV/nuc Engelmann et al., 1983); (Bottom) Comparison of the ~15 GeV/nuc composition (Engelmann et al., 1983) with that measured at 2 GeV/nuc. Elements that are mainly of "secondary" origin, produced by cosmic ray collisions with the interstellar gas, are differentiated from "primary" species accelerated by cosmic ray sources.

At lower energies (0.2 GeV/nuc, see Figure 3) the differences in composition (from 2 GeV/nuc) are somewhat more difficult to characterize; they are likely due in part to the energy dependence of the various fragmentation cross sections, which vary more with energy below ~1 GeV/nucleon. Note that neither H or He seems to fit with the pattern of heavier nuclei. This is perhaps not surprising for H, since it has a different charge to mass ratio. It should also be pointed out, however, that even though H and He are the most abundant elements in cosmic rays, in many cases their abundance relative to heavier nuclei in less certain than the relative composition of heavier nuclei. This is because most of the experiments that measure the composition of heavy nuclei do not measure H and He (and vice versa) because of dynamic range considerations.

4. ENERGY SPECTRA

Figure 4 shows energy spectra for four abundant elements spanning several decades in energy/nucleon, up to the highest energies so far measured. At high energies ($\gtrsim 5$ GeV/nuc) the spectra approach the well known power law ($\sim E^{-2.7}$, where E is kinetic energy/nuc); at lower energies the effects of solar modulation are evident, and the intensity varies significantly over the solar cycle. These four

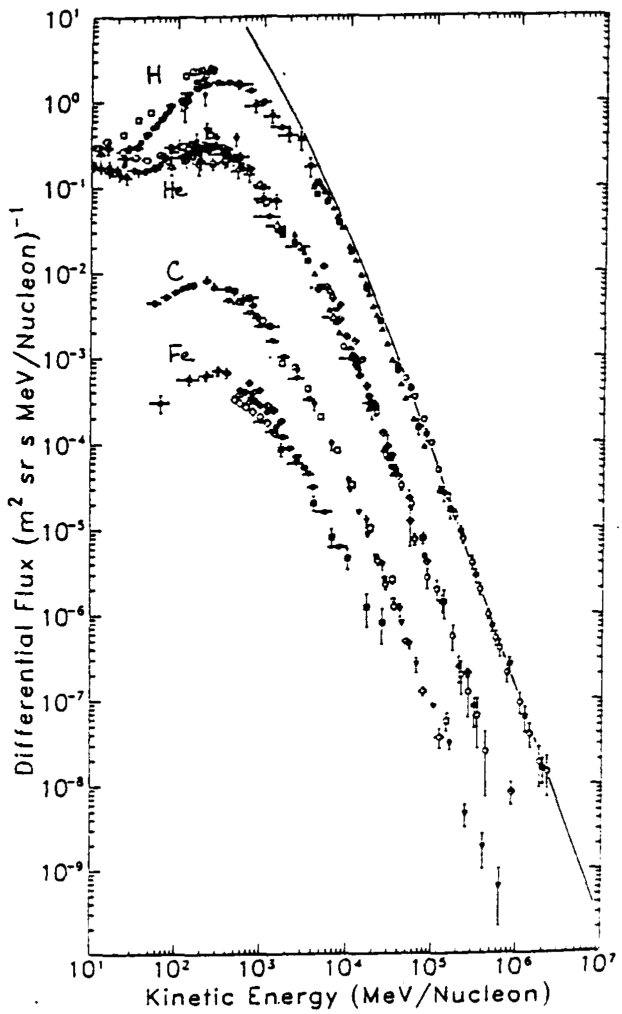

Figure 4: Measured cosmic ray energy spectra for the elements H, He, C, and Fe (from Simpson, 1983).

elements are among the most important to characterize accurately in phenomenological models of cosmic rays. Here again it is evident that all of these elements have approximately the same spectral shape, although the enhanced abundance of Fe at high energy and the relative depletion of H at lower energies is also evident.

At energies below ~100 MeV/nucleon, the composition becomes more complex, as indicated in Figure 5. The solar minimum spectra of several elements, especially He, N, O, and Ne contain anomalous enhancements at energies below ~50 MeV/nuc. This so-called "anomalous" cosmic ray (ACR) component has a separate origin from the higher energy galactic cosmic ray component. Its composition, and its spatial and temporal behavior was discussed at this workshop by Cummings (1987; see also the workshop summary by Mewaldt et al., 1987).

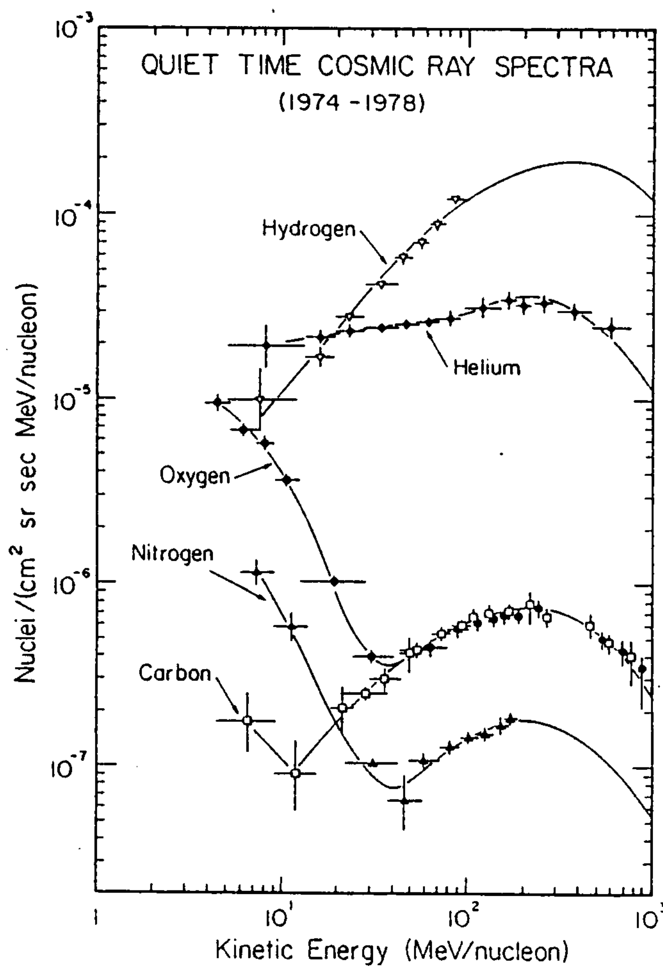

Figure 5: Quiet-time energy spectra for the elements H, He, C, N, and O measured at 1 AU over the solar minimum period from 1974 to 1978 (from Mewaldt et al., 1984). Note the "anomalous" enhancements in the low-energy spectra of He, N, and O. The data are from the Caltech and Chicago experiments on IMP-7 and IMP-8.

Figure 6 shows integral energy spectra for H and He (from Webber and Lezniak, 1974) appropriate to solar minimum. This figure demonstrates that the bulk of cosmic rays are in the energy range below a few GeV/nuc, and it is therefore this region that must be most accurately represented in modeling cosmic ray energy spectra. Unfortunately, this region is also the most sensitive to solar modulation effects. Note that only a few % of cosmic rays have energies $\gtrsim$ GeV/nuc. Figure 6 also demonstrates that H and He do not have exactly the same spectral shape (see also Figure 4).

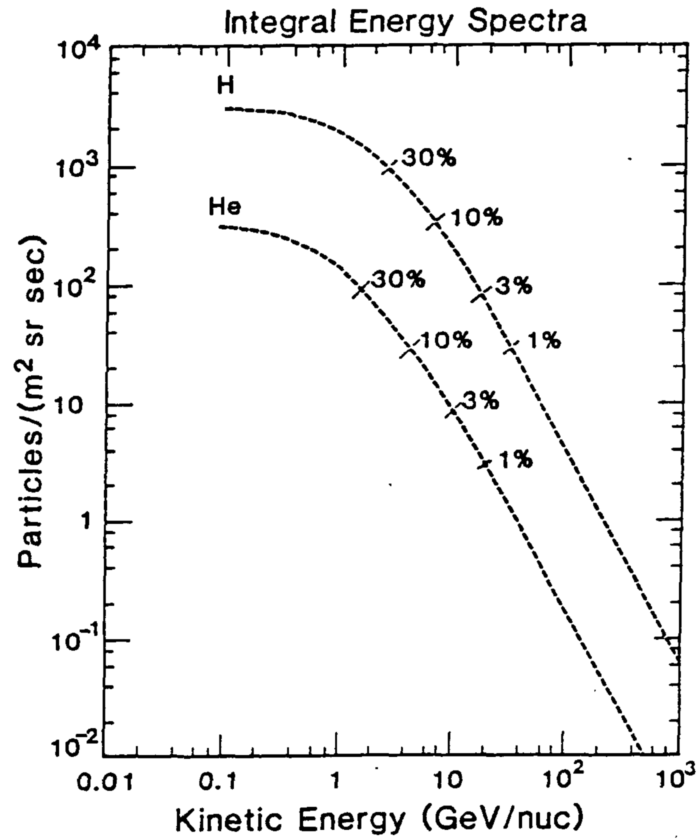

Figure 6: Integral energy spectra of H and He measured at solar minimum (adapted from Webber and Lezniak, 1974).

5. REQUIREMENTS FOR PHENOMENOLOGICAL COSMIC RAY MODELS

We discuss here the minimum requirements that should enter into phenomenological models of the composition and energy spectra of cosmic rays if the available data are to be represented in a reasonably accurate fashion.

a) Elemental Abundances: As a minimum the relative composition of elements with $1 \leq Z \leq 28$ with a typical energy of ~1 to 2 GeV/nuc should be included. If relevant to the application, the composition up through $Z \simeq 92$ can also now be easily included (e.g., Table 1). For the heaviest elements, where only charge groups have been measured, it would be possible to make a reasonable breakdown of the abundances of the charge group into individual elements using the results of a cosmic ray propagation model (see, e.g., Brewster et al., 1983).

b) Energy Spectra of Selected Species: There are at least four key primary species, H, He, C, and Fe, for which a differential energy spectrum (at solar minimum) is needed. There should also be at least one "generic" secondary spectrum to take into account the secondary/primary differences indicated in Figure 3.

c) Energy Spectra for other Elements: One method to obtain the energy spectra of other elements would be to use the relative composition from item (a) (e.g., Table 1) and choose the spectrum (from (b)) that is closest in shape. Thus, for example, the elements can be divided into the following five (minimum) groups:

H
He
C (C, O, Ne, Mg, Si, S)
Fe (Ca, and all $25 \leq Z \leq 92$)
"Secondary" (Li, Be, B, N, F, Na, Al, P
$Z = 17\text{-}19$, $Z = 21\text{-}24$)

d) Solar Cycle Dependence: To model the effects of solar modulation on the energy spectra there could be an energy and time dependent modulation factor scaled from observed neutron monitor rates (see, e.g., Mewaldt et al., 1987). Another possibility is to tabulate both solar minimum and solar maximum spectra for the various key species and then interpolate between these spectra using an observed (or predicted) neutron monitor rate.

e) Extrapolation to the Outer Heliosphere: Measurements by Pioneer and Voyager show that the composition of cosmic rays is only weakly dependent on distance from the Sun, with the exception of the anomalous cosmic ray component, which has a somewhat larger radial gradient than normal galactic cosmic rays, and thus becomes more important in the outer heliosphere. Because of the energy dependence of cosmic ray gradients, low energy cosmic rays gradually become relatively more numerous in the outer heliosphere (see the reports at this workshop by McKibben and Mewaldt et al.)

f) Mean Mass: Finally, a mean mass should be defined for each element based on the results of a cosmic ray propagation model that takes into account the source composition, nuclear interactions, and solar modulation. The mean mass parameter is needed to calculate various range-energy and rigidity-dependent effects.

The model of Adams et al. (1981; updated in Adams, 1986) is an example of a phenomenological model of cosmic rays like that described above which was derived for the near-Earth environment. This model does meet the various requirements described above and appears to provide a reasonably accurate characterization of cosmic ray composition and energy spectra. Since this model was last revised, there have been several new measurements reported that should be reviewed and, if appropriate, taken into account. For example, recent measurements of the energy spectra of H and He have been reported by Garcia-Munoz et al. (1987) and Webber et al. (1987a, 1987b). In the GeV/nuc energy range, the French-Danish experiment on HEAO-3 (Engelmann et al., 1985) and the balloon experiment of Dwyer and Meyer (1985, 1987) have provided precise measurements of the energy spectra of elements with $4 \leq Z \leq 28$. There is also new data HEAO-3 for both $Z=20$ to 28 and $Z>30$ nuclei (Binns et al., 1987, Stone et al., 1987). Incorporation of these recent results is suggested mainly for completeness; while they should improve the accuracy of the model, it does not appear likely that these updates will make a significant difference in the predictions of the model for most applications.

In addition, the following other improvements to the model of Adams et al. should also be considered. Their model uses the energy spectrum of He as a reference spectrum for elements with $3 \leq Z \leq 16$. However the He spectrum is contaminated by "anomalous" He at energies below ~ 100 MeV/nucleon, and, in addition, a significant fraction of He is known to be ^{3}He (see, e.g., Mewaldt, 1986), which has a different charge to mass ratio. For these reasons we suggest that the carbon spectrum be used as a reference for these light elements.

Perhaps the major uncertainty in the Adams et al. model is associated with the difficulty of predicting the time dependence of the cosmic ray flux due to solar modulation effects. A possible solution to this problem is discussed in the report by Mewaldt et al. (1987).

6. SUMMARY AND CONCLUSIONS

Available measurements now allow for a reasonably precise description of galactic cosmic ray composition and energy spectra. Thus, the relative composition of species with $1 \leq Z \leq 30$ is now known to $\sim 10\%$ accuracy, while the accuracy of measurements of $Z > 30$ nuclei is perhaps more like $\sim$20-30%. When combined with available knowledge of the energy spectra, quantities such as the integral flux of (relatively abundant) species above (e.g.) some cutoff rigidity can now be modeled to an accuracy of $\sim 20\%$ at solar minimum conditions. Because the model of Adams et al. appears to do a very reasonable job of accounting for cosmic ray composition and energy spectra, only minor updates and improvements to this aspect of the model are recommended; there is no apparent reason (within the context of this workshop) to derive a new model. The largest uncertainty in such descriptive models of cosmic rays results from the difficulty of predicting the level of solar modulation at some particular future time period, the effects of which are greatest at low energy. It is in this area of the temporal description of cosmic ray energy spectra that efforts at improvement can most profitably be directed.

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