THE 1973-1984 SOLAR MODULATION OF COSMIC RAY NUCLEI

M. Garcia-Munoz, K.R. Pyle and J.A. Simpson*
Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

ABSTRACT. As a continuation of our program of solar modulation studies we have carried out new measurements, with the University of Chicago cosmic ray telescope on the Earth satellite IMP-8, of the intensity time variations and the energy spectra of galactic cosmic ray protons, helium, carbon and oxygen from 1980 through 1984 including the recent solar maximum. In order to test the applicability of a steady state model of solar modulation during a period which includes times of rapidly changing modulation, we have compared these fluxes with the predictions of a conventional model of solar modulation which assumes equilibrium between modulation mechanisms. It is found that for a reasonable range of variations of the diffusion coefficient the model predictions can be made to agree with the measurements at essentially all times during the studied period. The model can account also for the observed hysteresis effects between cosmic rays of different rigidities.

1. **Introduction**. It has been observed that during the recent solar maximum the decreases and increases in cosmic ray intensity due to modulation level variations propagate outward from the Sun at approximately the solar wind velocity. (McDonald et al., 1981; McKibben, Pyle, and Simpson, 1982, 1985; Fillius and Axford, 1985). This fact together with the evidence that the radius of the modulation region is certainly greater than 30 A.U. and possibly as large as 50 to 150 A.U. implies that it takes to the disturbances responsible for these variations a time of the order of one year or more for propagation to the outer limits of the heliosphere. Therefore, at times of rapidly changing modulation, the modulation mechanisms may not be in equilibrium.

This work is a study of the modulation of cosmic ray nuclei in a time interval from 1973 through 1984, including the recent solar maximum. Measurements of the intensity time variations and differential energy spectra during this period are interpreted in the frame of a conventional model of solar modulation which assumes steady state (i.e. equilibrium) and absence of drifts. By using empirical diffusion coefficients and their time variations it is found that the model can reproduce at 1 A.U. the main features of time intensity variations and differential energy spectra of cosmic ray nuclei through the entire solar modulation cycle.

2. **The Modulation Model.** The model is described in Evenson *et al.* (1983). In it the solar wind velocity, V, is constant, and equal to 400 km/sec, and the diffusion coefficient is given by

$$k = \beta P^{\alpha} k(r); \qquad k(r) = k_o \exp[(r-1)/29] \qquad (1)$$

---

*and Department of Physics

where P is particle magnetic rigidity, r distance from the Sun in A.U., β particle velocity in units of velocity of light and k_o and α are functions of rigidity and time. It is assumed that the local interstellar electron differential spectrum is as deduced from

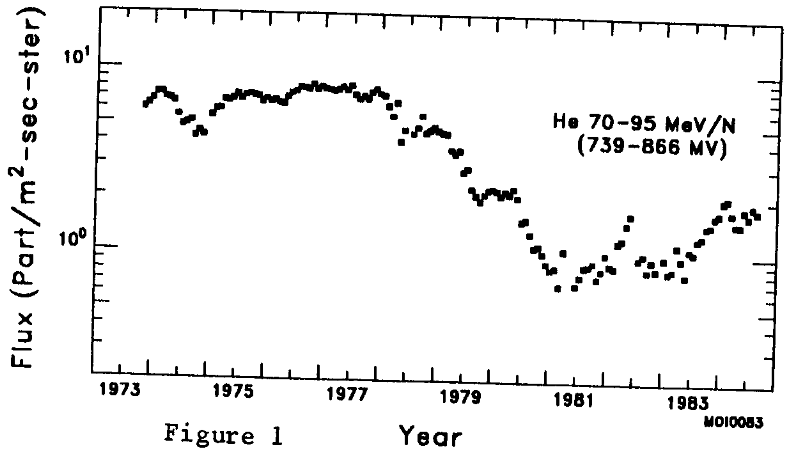

Figure 1

synchrotron radiation by Cummings et al. (1973). Comparison with measured differential nuclear and electron spectra at 1 A.U. during solar minimum leads to the local interstellar nuclear spectra. In this model the depth of modulation at a point r is given, for a heliosphere of radius R, by the force-field parameter, or modulation parameter

$$\phi(r) = \frac{1}{3}\int_r^R \frac{V}{k(r)}\, dr \qquad (2)$$

and thus it is independent of the specific functional form of k(r). Therefore, other k(r) functions different from the one selected in (1) could lead also to the same modulation depth.

Perko and Fisk (1983) have developed a time-dependent model of solar modulation in which the parameter varying with time is the frequency of outward propagating depressions in k(r) which simulate zones of increased scattering associated with solar flare shocks. In our calculations of cosmic ray intensities at 1 AU, k(r) appears only in integral form in the determination of the modulation depth ϕ.

3. **Measurements and Calculations.** Figure 1 shows the time dependence from 1973 through 1984 of the 70-95 MeV/n quiet time cosmic ray ^{4}He flux measured at 1A.U., averaged in solar rotation intervals. The data are from the University of Chicago instrument onboard the IMP 8 spacecraft. Note that the 70-95 MeV/n ^{4}He flux does not contain anomalous helium, even at times of solar minimum. The anomalous helium, when present, extends below about 60

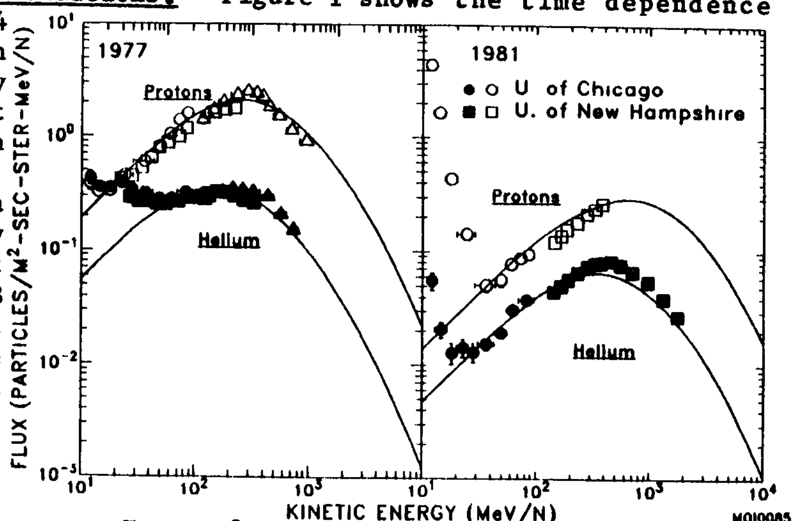

Figure 2

MeV/n. We have continued measuring the differential energy spectra of 10-95 MeV/n protons and helium from 1980 through 1984, adding to our previous measurements which extended up to 1979 (Evenson et al., 1983). Figure 2 shows the 1977 differential energy spectra at solar minimum, as reported by Evenson et al. (1983), and the 1981 spectra at solar maximum, where we have added the University of New Hampshire data (Webber et al., 1983). The curves in the figure are the fluxes predicted by the modulation model. Spectral measurements and theoretical fits have been obtained in this way from 1977 through 1984. The corresponding diffusion coefficients from solar minimum 1977 through solar maximum 1981, as the adjustable parameters, are shown in Figure 3. Each of these diffusion coefficients corresponds to a modulation depth ϕ and gives a modulated helium spectrum with a value for the 70-95 MeV/n helium flux. Therefore, there is a one-to-one relationship between ϕ and the 70-95 MeV/n helium flux.

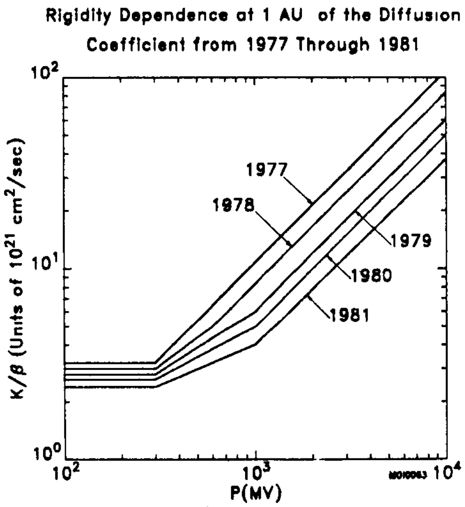

Figure 3

The next step is to use this relationship and use as input the 70-95 MeV/n He flux, from 1973 through 1984, in order to deduce the model predictions of the fluxes of protons, carbon, and oxygen cosmic rays in other energy (rigidity) intervals through the same period and compare these predictions with the IMP 8 measurements. Figure 4 shows, for the 1973-1984 time interval, the comparison of model predictions (histograms) and measurements (data points) for 63-95 MeV/n protons, 45-178 MeV/n carbon and 53-211 MeV/n oxygen. It can be seen that in general there is good agreement between model and measurements. The larger disagreements can be immediately traced to the very well known phenomenon of hysteresis (Cooper and Simpson, 1979) by which higher rigidities

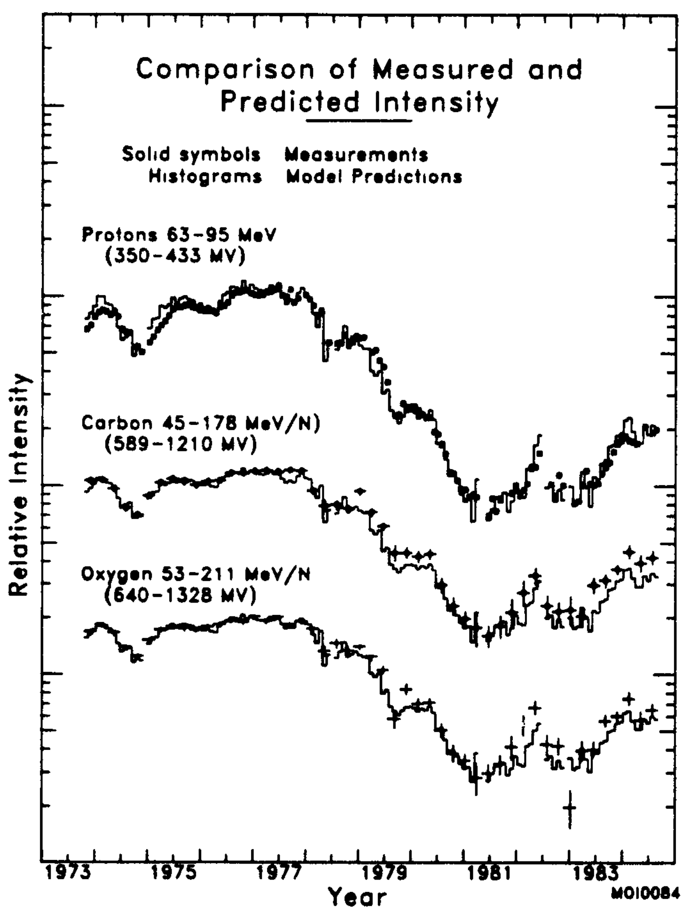

Figure 4

recover faster that lower rigidities as can by seen clearly in Figure 4 during the recoveries of the years 1982 and 1984. However, hysteresis can be easily incorporated in our simplified model by raising the high rigidity part of the diffusion coefficient relative to the low rigidities during the recovery phase. In this way a good fit to the 1983 and 1984 spectra is obtained, as is shown, for the particular case of protons and helium, in Figure 5.

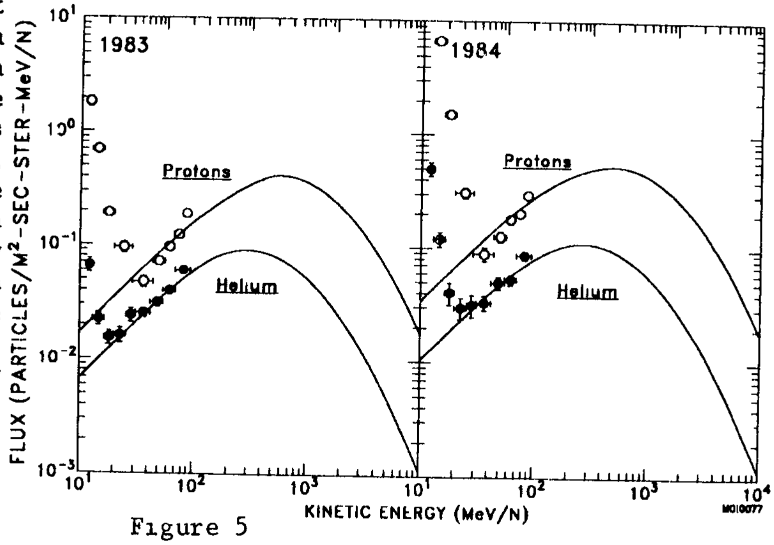

Figure 5

4. **Conclusions**. Empirical diffusion coefficients can be obtained by assuming at all times steady state in the heliosphere and fitting simultaneously the differential energy spectra of protons and helium at 1 AU in successive years from solar minimum 1977 through solar maximum 1981. These diffusion coefficients define a simple relationship between 70-95 MeV/n helium flux and depth of modulation. This relationship can be used to predict the main features at 1 AU of the intensity time dependence of other cosmic ray nucleons in different rigidity intervals from 1973 through 1984. The hysteresis effects can be accounted for by modification of the diffusion coefficients in selected rigidity intervals.

5. **Acknowledgements**. We thank James Beatty for data analysis and Scott Marusak for assisting in the preparation of the data. This research was supported in part by NASA Grant NGL 14-001-006 and NASA Contract NAS 5-28442.

References

Cummings, A.C., Stone, E.C., and Vogt, R.E. 1973., Proc. 13th Int. Cosmic Ray Conf. (Denver), 1, 335.
Cooper, J.F. and Simpson, J.A. 1979, Proc. 16th Intl. Cosmic Ray Conf. (Kyoto) 12, 176.
Evenson, P., Garcia-Munoz, M., Meyer, P., Pyle, K.R. and Simpson, J.A., 1983, Ap. J. Letters, 275, L15
Fillius, W. and Axford, I. 1985, J. Geophys. Res., 90, 517
McDonald, F.B., Lal, N., Trainor, J.H., Van Hollebeke, M.A.I, and Webber, W.R., 1981, Ap. J. Letters, 249, L71
McKibben, R.B., Pyle, K.R., and Simpson, J.A., 1982, Ap. J. Letters, L23
_______________, 1985, This conference, Paper SH 4.7-7.
Perko, J.S. and Fisk, L.A. 1983, J. Geophys. Res., 88, 9033
Webber, W.R., Kish, J.C. and Schrier, D.A. 1983, Proc. 18th Int. Cosmic Ray Conf. (Bangalore), 3, 35