

# Time Variations of Galactic Cosmic Ray Intensities Near Earth: 1997 to 1999

M.E. Wiedenbeck<sup>1</sup>, W.R. Binns<sup>2</sup>, E.R. Christian<sup>3</sup>, C.M.S. Cohen<sup>4</sup>, A.C. Cummings<sup>4</sup>,  
J.S. George<sup>4</sup>, P.L. Hink<sup>2</sup>, J. Klarmann<sup>2</sup>, R.A. Leske<sup>4</sup>, M. Lijowski<sup>2</sup>, R.A. Mewaldt<sup>4</sup>,  
P.L. Slocum<sup>1</sup>, E.C. Stone<sup>4</sup>, T.T. von Rosenvinge<sup>3</sup>, and N.E. Yanasak<sup>1</sup>

<sup>1</sup>*Jet Propulsion Laboratory, Pasadena, CA 91109, USA*

<sup>2</sup>*Washington University, St. Louis, MO 63130, USA*

<sup>3</sup>*NASA / Goddard Space Flight Center, Greenbelt, MD 20771, USA*

<sup>4</sup>*California Institute of Technology, Pasadena, CA 91125, USA*

## Abstract

The time dependences of the intensities of low-energy galactic cosmic ray (GCR) nuclei have been investigated using instrumentation carried aboard the Advanced Composition Explorer (ACE). The intensities of these low energy particles near Earth began to decline from solar minimum levels in late-1997/early-1998, shortly after the launch of ACE, and have been continuously monitored by the Cosmic Ray Isotope Spectrometer (CRIS) instrument since that time. We find that the variations are well correlated with variations of higher energy cosmic rays, as indicated by neutron monitor observations. The relative magnitude of the GCR variations is significantly less than previously reported for anomalous cosmic rays. We also compare the fluctuations observed for different energies and different nuclides.

## 1. Introduction:

The temporal variations of galactic cosmic ray intensities over solar cycle time scales have been extensively studied and provide important constraints on models of solar modulation. On shorter time scales, neutron monitors make possible studies of the variability of multi-GeV cosmic rays on time scales as short as days, but without differentiating among the various particle species or energies. It is of interest to determine the temporal response of individual cosmic ray nuclides in restricted energy intervals to the interplanetary variations that modulate these particles, since such data should be sensitive to parameters such as the rigidity dependence of the interplanetary diffusion.

Until recently space instruments have lacked the combination of large geometrical factor and good mass resolution required to address the question of the variation on short time scales of individual nuclides other than H and He. At solar minimum, the Cosmic Ray Isotope Spectrometer (Stone et al., 1998) collects  $\sim 5000$  heavy nuclei ( $Z > 2$ ) per day with energies  $\sim 50$  to  $\sim 500$  MeV/nuc. This makes possible statistically accurate measurements of intensities of major isotopes on time scales of a solar rotation or less.

## 2. Time Variations GCR Oxygen and Carbon:

Figure 1 compares a time-intensity plot of GCR  $^{16}\text{O}$  at  $\sim 160$  MeV/nuc from CRIS with the temporal dependence of the Climax neutron monitor rate over the same time interval. Periods of significant solar activity have been eliminated from the CRIS data. The same major features are seen in both plots: a sizable downward step in the intensities in April 1998, a gradual recovery between June and October 1998, and a slow decline after October. To study these correlated variations in greater detail we have calculated averages over successive Bartels rotations and examined the deviations from the average values over the period September 1997 through April 1999. We calculate the quantity  $\Delta X \equiv \ln(X/\langle X \rangle)$ , where  $X$  stands for the quantity of interest and  $\langle X \rangle$  is its average over the entire time period studied. Figure 2 shows the correlation between the variations of the GCR oxygen flux and those of the Climax rate. From the slope of the straight line fit to these correlated variations we find the power law index  $\alpha$  in the relation  $(\Delta \text{GCR } ^{16}\text{O}) \propto (\Delta \text{Climax NM})^\alpha$ . Similar

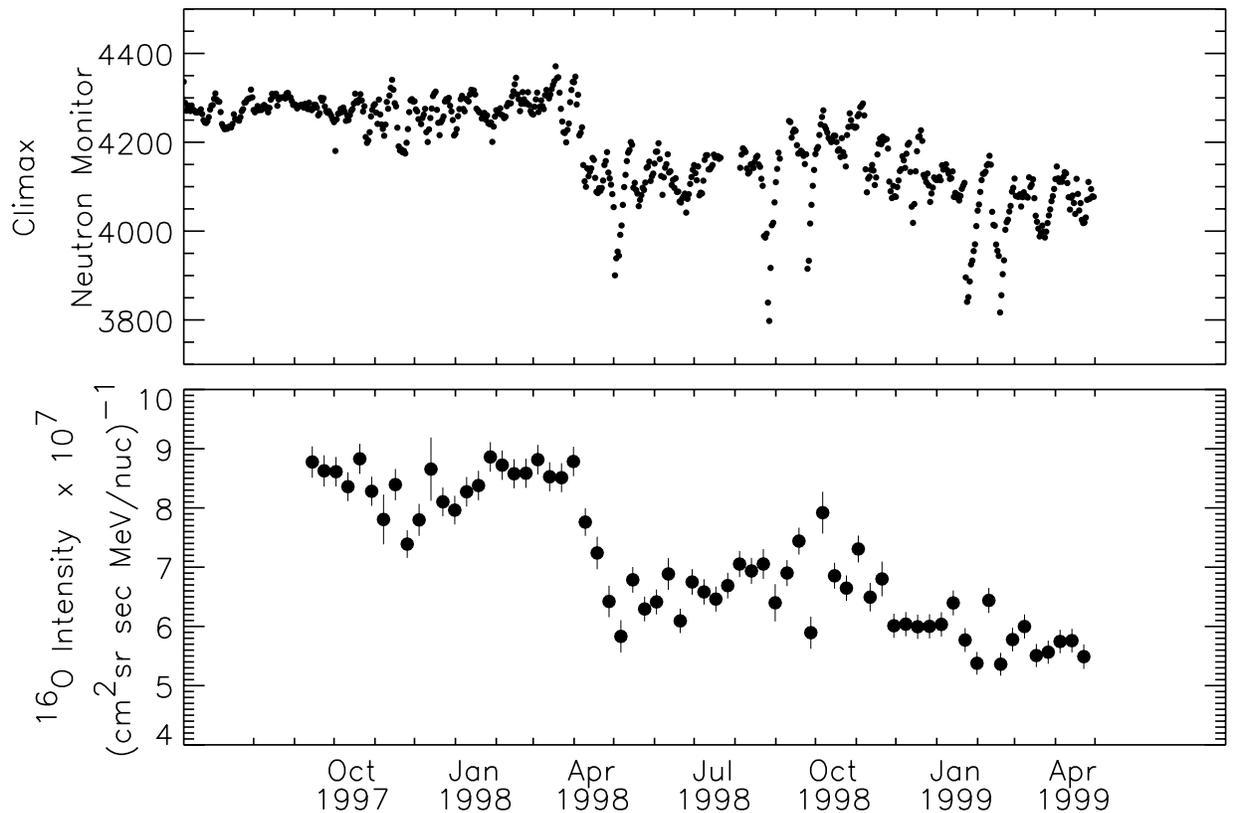


Figure 1. Comparison of time series for the Climax neutron monitor (upper panel) and for 160 MeV/nuc GCR  $^{16}\text{O}$  measured with CRIS.

correlations are found for each of seven GCR energies between 70 and 230 MeV/nuc that we have examined with CRIS.

Figure 3 shows the dependence of this power law index on particle energy for  $^{16}\text{O}$  (filled circles) and for  $^{12}\text{C}$  (open circles). The magnitude of the power law index,  $\sim 7$ , is significantly less than has previously been found for the correlation between variations of anomalous cosmic ray (ACR) intensity and variations of the Climax neutron monitor. Mewaldt et al. (1993) found an exponent  $\sim 25$  for this latter correlation. Although the uncertainties are large, both the  $^{16}\text{O}$  and  $^{12}\text{C}$  data suggest a decrease of the amplitude of the CRIS variations with increasing energy. The two lowest energy points in Fig. 3 indicate larger variations of  $^{16}\text{O}$  than of  $^{12}\text{C}$ . This may be the result of a small contribution of ACR oxygen, with its much stronger variations, to the observed oxygen.

### 3. Variations of Other GCR Isotopes:

Interplanetary diffusion coefficients used in modeling the solar modulation of cosmic rays commonly have the form  $\kappa \propto \beta R^n$ , where  $R$  is the particle's magnetic rigidity (momentum/charge) and  $n$  is some positive exponent. From such a form for the diffusion coefficient one expects the amount of modulation to decrease with increasing rigidity, and therefore at a fixed energy per nucleon one should see the intensities of the higher-mass isotopes of an element vary less than lower-mass isotopes of the same element.

To test this prediction we investigated the correlations between the time variations of  $^{16}\text{O}$  and of nine other GCR isotopes:  $^{10}\text{B}$ ,  $^{11}\text{B}$ ,  $^{12}\text{C}$ ,  $^{14}\text{N}$ ,  $^{15}\text{N}$ ,  $^{20}\text{Ne}$ ,  $^{22}\text{Ne}$ ,  $^{24}\text{Mg}$ , and  $^{28}\text{Si}$ . For reasons of convenience, the comparisons were done using isotopes at equal range in the CRIS detector, rather than at equal energy per nucleon. Thus to interpret any trends in the slopes of the observed correlation functions one must take into account the effect of differences in energy as well as different

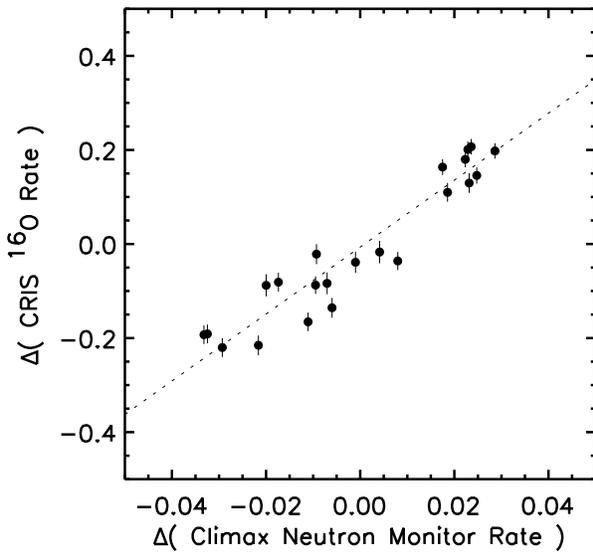


Figure 2. Correlation between time variations of the Climax neutron monitor rate and variations of the intensity of GCR  $^{16}\text{O}$  at 160 MeV/nuc.

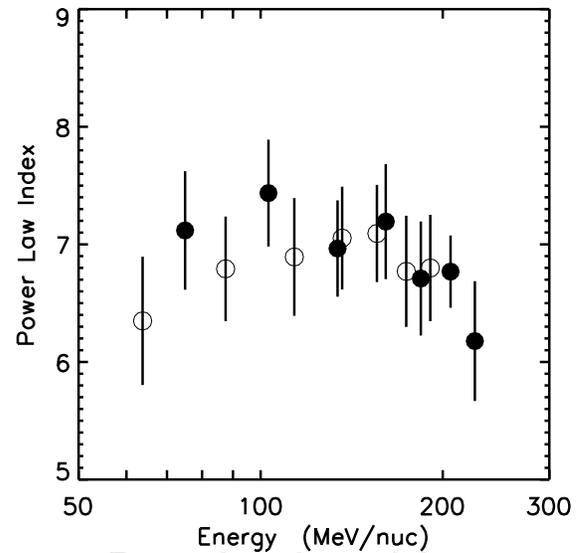


Figure 3. Energy dependence of the power law index relating variations of the Climax neutron monitor rate and variations of low-energy cosmic ray intensities. The index for  $^{16}\text{O}$  is shown by the filled points and the index for  $^{12}\text{C}$  is shown by the open points.

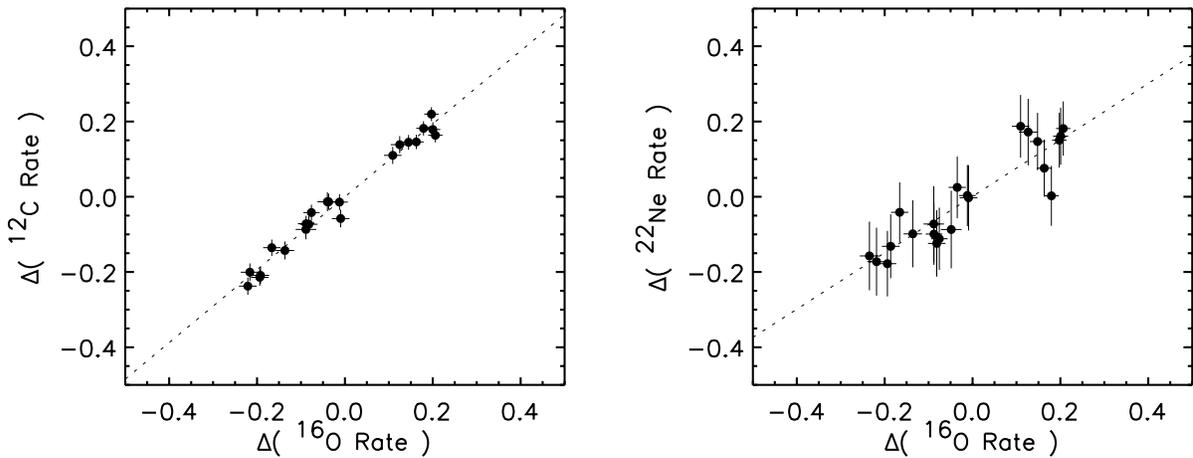


Figure 4. Correlation between time variations of different isotopes measured with CRIS. The left panel compares variations of  $^{12}\text{C}$  and  $^{16}\text{O}$  while the right panel compares  $^{22}\text{Ne}$  and  $^{16}\text{O}$ .

mass-to-charge ratios.

Figure 4 shows two representative correlation plots,  $\Delta^{12}\text{C}$  versus  $\Delta^{16}\text{O}$  and  $\Delta^{22}\text{Ne}$  versus  $\Delta^{16}\text{O}$ . Each of these plots contains data for just one of the seven CRIS ranges (“range 5”) that was investigated. The higher statistics available for  $^{12}\text{C}$  and  $^{16}\text{O}$ , as compared to the other isotopes studied, are responsible for the better definition of the correlation line in the plot of  $\Delta^{12}\text{C}$  versus  $\Delta^{16}\text{O}$ . In this plot, the cluster of points with positive values of  $\Delta^{12}\text{C}$  and  $\Delta^{16}\text{O}$  corresponds to measurements before the step decrease of intensities in April 1998 (see Fig. 1). The same correlation line adequately

describes both this large step and the smaller, short term variations on either side of the step.

Note that while the slope of the correlation line between  $\Delta^{12}\text{C}$  and  $\Delta^{16}\text{O}$  is close to unity, the line relating  $\Delta^{22}\text{Ne}$  and  $\Delta^{16}\text{O}$  is distinctly shallower. Figure 5 is a plot of the slopes of the correlation lines for each isotope's variations relative to  $^{16}\text{O}$  as a function of the ratio of rigidity for the two nuclides. For each isotope, the plotted point is the average of the values obtained from the seven analyzed ranges (or energies). The error bars on the correlation slopes represent the rms spread among the seven points, while the horizontal bars indicate the spread of the rigidity ratios among the seven averaged values. Note that the slope of  $\Delta^{12}\text{C}$  versus  $\Delta^{16}\text{O}$  is close to unity in spite of the difference of nearly 10% in rigidities caused by the difference of energies for the equal-range data that were compared. For all of the other isotopes the correlation slopes are smaller, indicating smaller amplitude variation for those isotopes than for  $^{16}\text{O}$  and  $^{12}\text{C}$ .

The data in Fig. 5 are consistent with a decrease of the correlation slope by  $\sim 5$  to 10% for in 30% increase in the rigidity ratio. However, this conclusion depends critically on the  $^{12}\text{C}$  point with its small uncertainty. Lacking the  $^{12}\text{C}$  result, the remaining points would not indicate any clear dependence on the rigidity ratio.

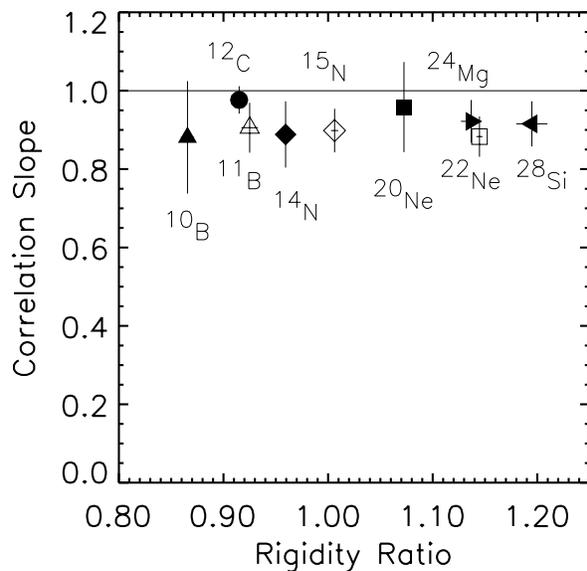


Figure 5. Power law index relating the variations of various isotopes relative to those of  $^{16}\text{O}$  is plotted as a function of the ratios of the rigidities between the isotope and  $^{16}\text{O}$ . Comparisons are done for equal ranges in the instrument.

### Further Investigations:

Additional studies can aid in understanding the results reported here and help to exploit this information to constrain models of solar modulation. Studies of correlations between the fluctuations of various isotope intensities at equal energy per nucleon should be useful for identifying the parameter(s) that control the amplitude of the intensity modulation. For example, any difference between the modulation of the various nuclides having  $M/Z = 2$  at equal energy per nucleon cannot be accounted for by a process dependent only on particle velocity and rigidity. It will also be of interest to determine how the correlation slopes depend on the time scale over which the data are averaged since the spatial extent of the structures in the heliosphere that control the modulation on short time scales must be smaller than those that produce longer term effects. The statistical accuracy of the ACE data should enable these and other investigations which would not have been possible with previous, smaller instruments.

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