THE ASTROPHYSICAL JOURNAL, 457:435–439, 1996 January 20

NEW HIGH-STATISTICAL–HIGH-RESOLUTION MEASUREMENTS OF THE COSMIC-RAY CNO ISOTOPES FROM A 17 YEAR STUDY USING THE *VOYAGER 1* AND *2* SPACECRAFT

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Received 1995 May 10; accepted 1995 July 28

ABSTRACT

We have now analyzed 17 yr of *Voyager 1* and *Voyager 2* data and derived isotopic composition ratios for C, N, and O elements in cosmic rays with a statistical accuracy exceeding that of the sum of all previously published spacecraft measurements. We have also used newly measured cross sections in the propagation calculations to derive the source composition of these elements. We find (1) the source $^{13}C/^{12}C$ ratio is 2.5 σ lower than the solar ratio of 1.1%. (2) For N we find the source $^{14}N/^{16}O$ ratio to be 5.0% and the source $^{15}N/^{16}O$ ratio to be 0.97%—about 1 σ larger than the ratio of 0.37% expected for a solar composition. (3) The source $^{18}O/^{16}O$ ratio is determined to be $0.24 \pm 0.17\%$, including both measurement and propagation errors, almost exactly the solar ratio of 0.23%. The implications of these results for cosmic-ray origin theories are discussed.

Subject headings: cosmic rays — ISM: abundances — Sun: abundances

1. INTRODUCTION

Determining the isotopic composition of C, N, and O in cosmic rays is of crucial importance for understanding the sources of cosmic rays and the nucleosynthesis occurring therein. Already there have been numerous reports of differences in the isotopic composition of these elements with respect to the solar composition that may suggest, for example, that Wolf-Rayet stars contribute significantly to the cosmic-ray population. Recent improved measurements from the *Voyager* spacecraft and other spacecraft as summarized by Lukasiak et al. (1994) suggest differences of 2–3 σ or larger in the key cosmic-ray and solar $^{13}C/^{12}C$, $^{15}N/^{16}O$, and $^{18}O/^{16}O$ ratios.

In this paper we report new measurements of these ratios using 17 yr of available *Voyager 1* and *2* data—resulting in $\sim$3 times more events than the previous analysis by Lukasiak et al. (1994). These new data have been interpreted using new measurements of the key cross sections into ^{13}C, ^{15}N, and ^{18}O from the Transport (Chen et al. 1995) and the New Mexico-French cross section collaborations (Webber et al. 1995) that reduce the cross sectional errors by a proportional amount. In the light of these new data, significant compositional differences still exist between the cosmic-ray sources and solar ^{13}C, but not ^{15}N or ^{18}O. We further examine just what limits on the compositional differences of these elements can be set by future improved cosmic-ray data, along with the limitations of the present cross section database which is unlikely to be significantly improved in the future.

2. INSTRUMENTATION, DATA ANALYSIS, AND RESULTS

The data from the High Energy Telescope (HET) of the cosmic-ray science (CRS) experiment on both the *Voyager 1* and *2* spacecraft have been used in this analysis. The experiment has been extensively described previously (Stone et al. 1977). The HET is a double-ended telescope consisting of a combination of solid-state detectors (see Fig. 1). The cosmic-ray nuclei considered in this paper are events which have entered the B end and stop in either one of the first three C detectors. The HET data are from the low-gain mode, which allows the analysis of all events from He to Ni. The separation of different chemical species and isotopes in these telescopes is achieved by using the multiple dE/dx versus residual energy E technique.

The first step in the analysis of the experimental data is the removal of background events which is accomplished by using the two dE/dx counters B_1 and B_2 to reject events for which the two pulse heights are not consistent. We start with the charge assignment which relies on the well-known dE/dx versus E technique. Using an energy loss program we calculated the theoretical tracks for each element. These theoretical tracks are fitted to the data for the elements from carbon to silicon. For every event we have determined a charge value from the position of an event in respect to the closest tracks corresponding to two sequential charges as described by Ferrando et al. (1991). Elements from C to O were separated with a charge resolution of $\sim$0.04 charge units.

In the next state of data analysis we used these charge data to determine for each event two mass values, A_1 and A_2, corresponding to an analysis of B_1 versus ΣC and B_2 versus ΣC pulse height data.

For the mass analysis a mass value was determined for every event from the position of an event with respect to the closest mass track. A mass consistency criterion for the two determined A_1 and A_2 values was used to reject background events. We kept all the events with $|A_2 - A_1|$ smaller than 3 times the standard deviation. The number of events rejected by using this mass consistency criterion was 8%. The simulation tracks were then further adjusted to fit the distribution of events corresponding to different isotopes and to optimize the mass resolution. The HET has four dead layers between the C counters and the events from the regions of these layers have mass values which are not well resolved. To improve the mass resolution further we removed all events stopping in these dead layers. Figure 2 shows the mass histograms obtained for the elements C, N, and O in the combined *Voyager 1* and *2* space-

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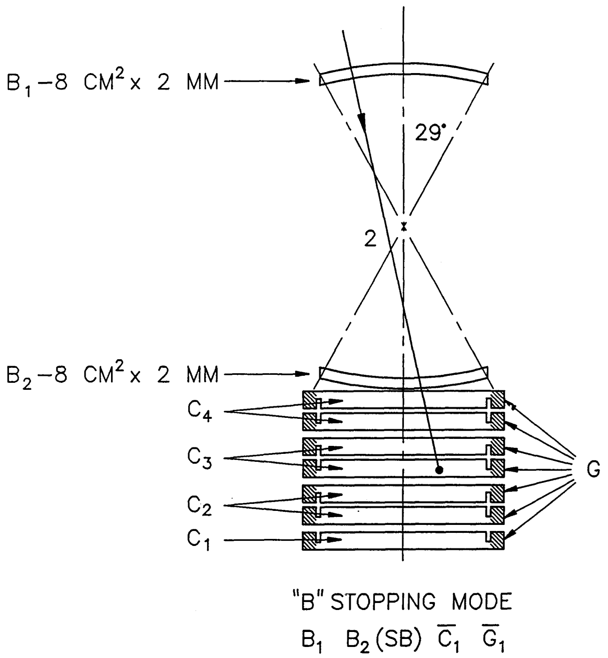

FIG. 1.—Schematic drawing of B—stopping part of the *Voyager* cosmic-ray telescope.

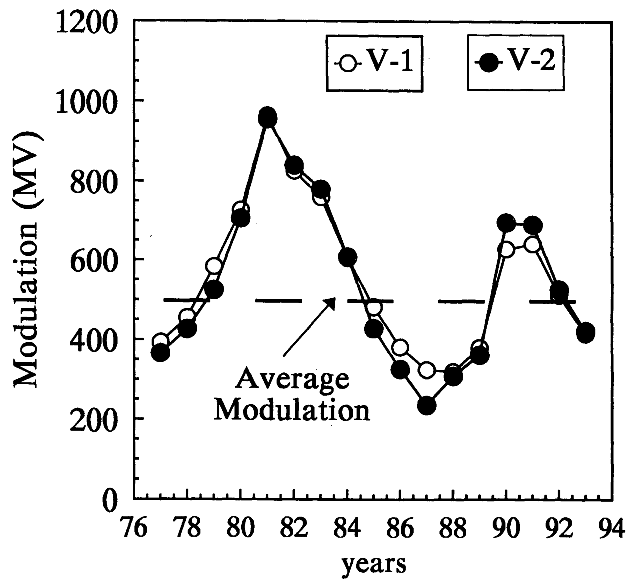

FIG. 3.—The yearly levels of the solar modulation constant Φ for *Voyager 1* and *Voyager 2* as determined from the yearly average He spectra.

craft cosmic-ray measurements. The inserts in this figure emphasize the separation of the ^{13}C from ^{12}C and ^{18}O from ^{16}O isotopes. The solid lines in Figure 2 correspond to a fit of a multi-Gaussian function to the isotope distribution. The mass resolution of the HET telescope is $\sigma = 0.2$ amu for C.

The energy interval for each isotope is mass dependent and the energy limits for different isotopes are given in Table 1. In the calculations of isotopic ratios we corrected for these differences in the energy intervals by using a spectral index $\gamma = 0.8$ for all charges. In addition, corrections of 5.6% and 3.5% are made for ^{14}N and ^{16}O, respectively, for the contribution of the anomalous component in the lowest energy channels. The results from this study for the isotopic composition are given in Table 1. They correspond to the level of solar modulation $\Phi = 500$ MV which corresponds to the average for 17 yr using the same interstellar He spectrum and modulation model as in Ferrando et al. (1991). The values of Φ for each year as determined from the measured yearly He spectrum and the weighted average for all 17 yr are shown in Figure 3.

3. INTERPRETATION OF THE RESULTS

To use our results to determine the source composition of the C, N, and O isotopes we have used the "leaky box" model with an exponential distribution of path lengths. While this model provides a very simplified physical interpretation of the propagation of cosmic rays it can be used with accurate cross sections to predict a "reference" propagation. This reference propagation may be used, for example, to fit the well-measured B/C ratio, thus giving a measure of the net effect of galactic

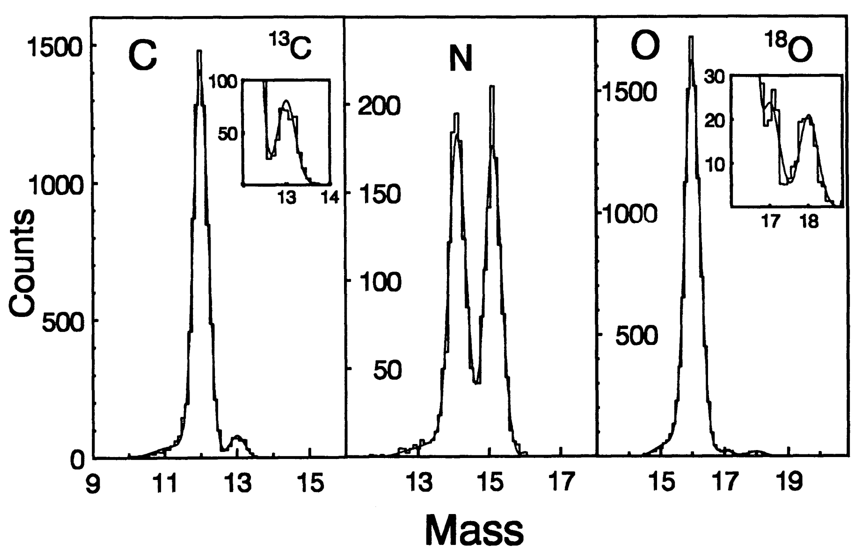

FIG. 2.—Mass histograms for cosmic ray C, N, O from summed *Voyager 1* and *2*, 17 yr average. Solid curves are a result from the multiparameter x^2 fitted to the histograms.

TABLE 1

Isotopic Composition (Voyager 1 and 2, 1977–1993, Φ = 500 MeV)

Isotope (1)	Number of Events (2)	Mass Resolution (amu) (3)	Energy Interval MeV nucleon^{-1} (4)	Isotopic Ratio (5)	Measured Ratio (%) (6)	Secondary Contribution (%) (7)	Ratio at Source (%) (8)
^{12}C	7709	0.200	50–132				
^{13}C	443	0.200	48–126	^{13}C/^{12}C	6.29 ± 0.33	6.19 ± 0.23	0.10 ± 0.39
^{16}O	10263	0.236	59–155				
^{17}O	145	0.236	57–150	^{17}O/^{16}O	1.57 ± 0.16	1.25 ± 0.06	0.32 ± 0.19
^{18}O	130	0.236	55–145	^{18}O/^{16}O	1.54 ± 0.14	1.30 ± 0.06	0.24 ± 0.17
N	2549	...	53–141	N/O	24.9 ± 0.54		
O	12126	...	59–155				
^{14}N	1109	0.229	54–144	^{14}N/^{16}O	11.98 ± 0.41	7.02 ± 0.23	4.96 ± 0.46
^{15}N	1109	0.229	52–138	^{15}N/^{16}O	13.65 ± 0.47	12.68 ± 0.45	0.97 ± 0.62
B	915	...	44.2–80.0	B/C	24.9 ± 0.90		
C	4666	...	50–91				
B	896	...	80–114	B/C	24.7 ± 0.90		
C	4707	...	91–131				

propagation since B is known to be absent in the cosmic-ray sources. Thus, in effect, the production of any secondary isotope during galactic propagation can be predicted to essentially the same accuracy with which the measured B/C ratio can be predicted (±3%) as discussed by Webber & Soutoul (1989). The fit to the B/C ratio made by incorporating the latest cross sections is shown in Figure 4. It is important to note that this fit must be made at all energies and in particular at the low energies where the C, N, and O isotopic measurements are made. For this reason we have derived values of the B/C ratio from the same *Voyager* data set as the C, N, and O isotopes and these values are shown in Table 1 and Figure 4 along with the measurement at low energies of comparable accuracy from Wiedenbeck & Greiner (1981). The best-fit path length is $\lambda_e = 31.6\beta R^{-0.60}$ g cm^{-2} for rigidities greater than 4.7 GeV and $\lambda_e = 12.5\beta$ g cm^{-2} for lower rigidities (for a modulation parameter $\phi = 500$ MV corresponding to the 17 yr average). This path length is slightly different than our earlier value discussed in Lukasiak et al. (1994) and arises for two reasons: (1) We require a fit to the low-energy data points as well as the higher energy *HEAO 3* data of Engelmann et al. (1990). (2) We have used updated cross sections including new measurements of the French-New Mexico and Transport collaborations (Webber et al. 1995; Chen et al. 1995) in addition to the earlier

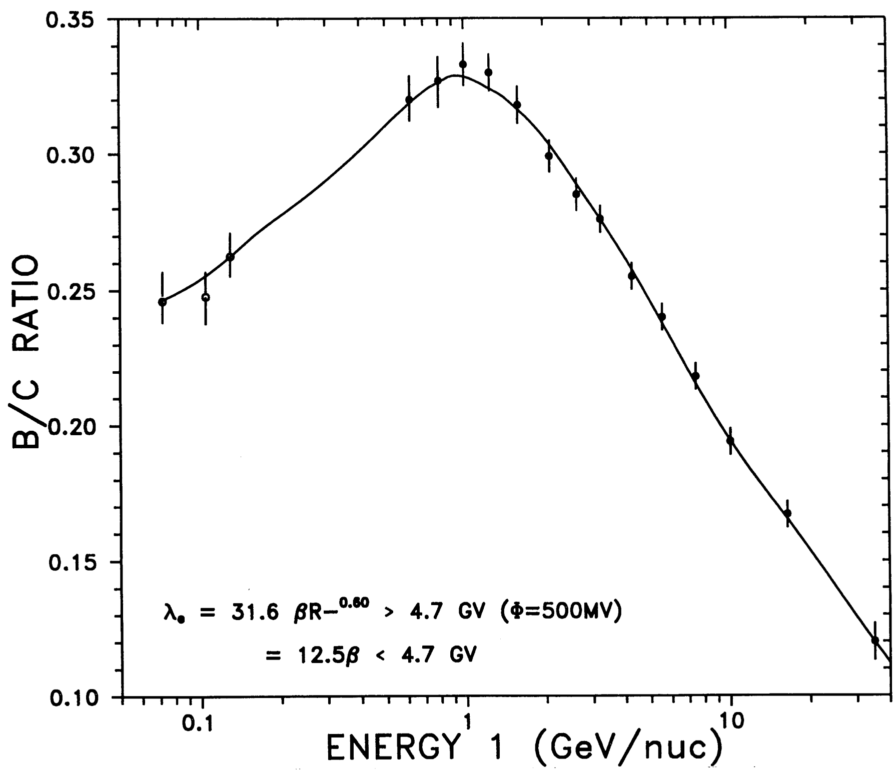

Fig. 4.—Measurements and predictions of the B/C ratio. Prediction is for $\lambda_e = 31.6\ \beta R^{-0.60} > 4.7$ GV and $= 12.4\beta$ for $R < 4.7$ GV. Solid points are from Engelmann et al. (1990), x is from Wiedenbeck & Greiner (1981), and open circles are from this measurement.

set of measurements and semiempirical calculations of Webber, Kish, & Schrier (1990) for hydrogen and Ferrando et al. (1988) for helium. The new cross sections incorporated in this calculation include those obtained using ^{11}B, ^{12}C, ^{14}N, ^{15}N, ^{16}O, ^{19}F, ^{20}Ne, and ^{22}Ne beams, all relevant to the production of B, C, N, and O secondaries. In fact, for the isotopes in question direct measurements of cross sections now exist for ~95% of the total secondary production.

In the propagation calculations the input spectra of all species are assumed to be the same with exponent $= -2.30$, and the interstellar medium is assumed to be 90% hydrogen and 10% helium. Additional energy loss due to the large amount of ionized hydrogen in the disk is also included in the calculations (Soutoul, Ferrando, & Webber 1990). As described in Lukasiak et al. (1994), we consider three sources of error in the determined source abundances. The first is just the statistical fitting error in the measured isotopic ratios as shown in column (6) of Table 1. The second includes the cross section uncertainties for the secondary production of the relevant isotopes. The third, which is combined with the second in column (7) of Table 1, relates to the uncertainties in the B cross sections and their effect on the chosen value for λ_e.

We illustrate the total cross sectional uncertainties in Table 2 which shows the total production of ^{18}O by heavier elements. In this calculation we show the estimated cross section and its uncertainty. This when multiplied by the relative abundance of the progenitor isotope (a full propagation calculation is used) gives the relative contribution of the particular isotope. So, for example, ^{24}Mg, ^{20}Ne, ^{19}F, ^{28}Si, and ^{22}Ne produce ~75% of all ^{18}O and all of these cross sections have now been measured.

The direct error in secondary production is then added in quadrature with the error introduced by fitting the B/C ratio to get the final result of 1.30 ± 0.06% for the ^{18}O/^{16}O production ratio shown in column (7) of Table 1. Similarly the secondary production ratios are found for the other isotopes and then subtracted from the measured ratios to get the source ratios in column (8).

We now discuss these source ratios in more detail.

^{13}C/^{12}C.—For this source ratio we find 0.10 ± 0.39%. This error is now ~0.6 times the previous error given by Lukasiak et al. (1994), which was the best yet reported up to 1994—and the ^{13}C/^{12}C ratio itself is slightly smaller. This result is 2.5 σ smaller than the solar ratio of 1.1%. In this case the largest error is the measurement error itself so improved cosmic-ray data will help to elucidate this difference. It should be noted that all other high-quality measurements of this ratio also give a lower than solar value as summarized by Lukasiak et al. (1994). In fact, the summary of all of the other measurements of ^{13}C/^{12}C given in the above paper is −0.2 ± 0.6%. We believe that a stronger case can now be made for a deficiency of ^{13}C in the cosmic-ray source (CRS) relative to the solar.

^{14}N/^{16}O.—Our measurement of this source ratio is 4.96 ± 0.46%. This is almost the same as our earlier measurement but with ~0.5 times the error. So taken with other earlier measurements a strong case can be made for a ^{14}N/^{16}O ratios at the CRS of ~5% or about 0.4 of the solar ratio of 12%.

^{15}N/^{16}O.—For this source ratio we find 0.97 ± 0.62%. This is slightly smaller than our earlier value (Lukasiak et al. 1994)—but now with only ~0.55 times the error. Other measurements of this ratio described in Lukasiak et al. (1994), give a smaller value consistent with the solar ratio of 0.37%. Our measurement is ~1 σ above the solar ratio. And now ~95% of the cross sections into ^{15}N have been measured. Overall, we must conclude that there is no significant evidence for a source abundance of ^{15}N different from the solar ratio.

It is interesting to note that in this case the cross section measurement errors and the propagation errors are about the same. Further improved measurements of this ratio in cosmic rays may thus still be limited in their interpretation by cross sectional uncertainties—particularly for potential source abundance ratios ≤1%.

^{18}O/^{16}O.—Our value for this source ratio is 0.24 ± 0.17%. This value is slightly smaller than our earlier value but with only 0.6 times the error. This smaller ratio is mainly due to the larger production of ^{18}O from the new cross sections, such as ^{22}Ne used in this new calculation. (The net effect of the new cross sections at a fixed level of modulation is an increase of 8% in secondary production of ^{18}O). This new source ratio is now completely consistent with the solar ratio of 0.23% as are the other earlier spacecraft measurements summarized in Lukasiak et al. (1994).

The ^{17}O abundance is also of interest since its solar source abundance is essentially zero (0.04%) and therefore it can be used as a tracer for secondary production calculations assuming the CRS ratio is also solar. Our value for this CRS ratio is 0.32 ± 0.19%—consistent with zero.

TABLE 2

PRODUCTION OF ^{18}O AT 400–600 MEV NUCLEON^{-1}

Transition	σ(mb)	$\Delta\sigma$(%)	Fractional Contribution (%) to ^{18}O
F19 →	50.5	8	16.0
Ne20 →	25.4	3	16.9
Ne21 →	17.2	8	6.1
Ne22 →	19.6	5	7.7
Ne23 →	14.2	6	6.2
Mg24 →	16.3	4	22.5
Mg25 →	10.2	5	3.5
Mg26 →	6.3	10	4.7
Al27 →	7.1	5	2.4
Si28 →	8.2	4	10.9
Si29 →	5.6	8	1.2
Si30 →	3.8	10	0.8
S32 →	6.3	5	1.2

4. SUMMARY AND DISCUSSION

New *Voyager* measurements with improved statistics along with newly measured cross sections are used to derive more accurate source abundance ratios for the very important cosmic-ray isotopes ^{13}C, ^{14}N, ^{15}N, and ^{18}O. These measurements are particularly difficult because of the small values of these ratios—thus requiring both accurate data and cross sections to derive meaningful source ratios. But it is crucial to determine these ratios because of their important role in stellar nucleosynthesis in the source of cosmic rays themselves, and also because significant differences between solar and galactic source composition for all of these isotopes have been reported at one time or another in the past.

The low ^{13}C/^{12}C ratio in the CRS we find here could be evidence for an enrichment of ^{12}C in these sources rather than a depletion of ^{13}C. A contribution to cosmic ray ^{12}C from Wolf-Rayet stars in which ^{12}C is enhanced in the winds of WR-type receives support from these measurements. In fact, a fractional contribution from these stars sufficient to produce the already observed enhancement of ^{22}Ne/^{20}Ne in the CRS (e.g., Prantzos et al. 1986; Webber et al. 1990) would give a reduced ratio of $^{13}C/^{12}C$ $\sim$0.4% in the CRS, consistent with what we and others measure.

The fact that no significant enhancement in the $^{18}O/^{16}O$ ratio is observed in our data is relevant to this discussion since simulations of W-R star evolution indicate a large $^{18}O/^{16}O$ excess during core He burning although the total injected output that eventually becomes cosmic rays may not contain an excess (Prantzos et al. 1986). Measurements of both the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios for the CRS could in principle be used as an additional diagnostic of the W-R contribution to the sources of cosmic rays. To fully exploit this approach better estimates are needed of the elemental and isotopic composition of W-R ejecta over their lifetime.

The authors wish to thank the *Voyager* project office at JPL for their support through contract No. 959213 at the University of Maryland and contract No. 959160 at New Mexico State University.

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