OBSERVATIONS ON THE ABUNDANCE OF NITROGEN IN THE PRIMARY COSMIC RADIATION

J. A. LEZNIAK, J. F. ORMES,* T. T. VON ROSENVINGE, and W. R. WEBBER
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minn., U.S.A.

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Abstract. New measurements of the intensity and spectrum of cosmic ray nitrogen nuclei made by instruments flown on balloons and on the Pioneer-8 space probe are reported. The nitrogen spectrum is found to be identical with that of the other medium nuclei, carbon and oxygen, over the range of measurement from 100 MeV/nuc to >22 GeV/nuc. The ratio of N to all M nuclei is found to be $=0.125$, constant to within 10% over this energy range. This ratio is extrapolated to the cosmic-ray source using the most recently obtained abundances of oxygen and heavier nuclei and fragmentation parameters for the production of nitrogen from these nuclei. Taking an average material path length of 4 g/cm^2 of hydrogen constant with energy, as required to make the abundance of L nuclei $\rightarrow 0$ at the cosmic-ray source, the resulting N/M source ratio is $\leqslant 0.03$. In other words, to the same degree that the so-called L nuclei are absent in the cosmic-ray sources, N nuclei are also absent. This nitrogen abundance is therefore different from the estimated solar atmospheric abundance of ~ 0.10 for the N/M ratio which is believed to represent the integrated effects of nucleo-synthesis in the galaxy at the time of the formation of the sun. Nevertheless under certain conditions in the CNO bi-cycle that operates for the production of nitrogen in stellar objects a negligible production of nitrogen might be expected. It is suggested that these conditions exist in the cosmic-ray sources. The C/O ratio of 0.9 deduced for cosmic-ray sources is compatible with the observed low nitrogen abundance arising in this CNO bi-cycle.

The so-called M nuclei, carbon, nitrogen and oxygen, are the most abundant nuclei in cosmic rays with the exception of hydrogen and helium. In spite of this advantage, previous measurements have not produced a well defined agreement as to their relative abundances. This is particularly true in the case of nitrogen. A summary of experimental results available up to 1965 found an average C:N:O abundance ratio 160:74:100 ($O \equiv 100$) applicable at energies $\gtrsim 1$ GeV/nuc (Webber, 1967). The resulting N/M ratio is thus $=0.22$. This data was 'selected' to include only those experiments that supposedly could resolve these nuclei, however, in 5 of the 13 experiments summarized nitrogen was actually found to be more abundant than oxygen. This variation is quite out of keeping with the claimed experimental errors and suggests that the charge resolution in some of these earlier experiments is not as good as was hoped by the authors. It is possibly significant that the measurements which seemed to show the best charge resolution also had the lowest nitrogen abundance. For example, Daniel and Durgaprasad (1962) found $N/M = 0.16$ and O'Dell *et al.* (1962) obtained $N/M = 0.17$ as opposed to the higher value of 0.22 implied by the summary above. In a compilation similar in spirit to the one of Webber but using a more highly selected set of balloon data, Kristiansson (1966) arrived at a mean value for the N/M ratio of 0.14 at energies above ~ 1.5 GeV/nuc.

* NRC-NASA Resident Research Associate at Goddard Space Flight Center.

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Recent measurements at low energies on satellites and rockets (Fan *et al.*, 1968; Balasubrahmanyan *et al.*, 1966; Reames and Fichtel, 1967), tend to support a 'low' N/M ratio of $\sim$0.10. The balloon measurements of Webber and Ormes (1967, Paper I) covering the range from 200 MeV/nuc upwards to $>$2 GeV/nuc substantiate these low energy results.

The possibility of a 'low' N/M ratio would have an important bearing on the abundances of these nuclei in cosmic-ray sources and on the relative effects of nuclear spallation of the cosmic rays enroute to the earth from their regions of origin.

We have recently extended the balloon measurements reported in Paper I. This new data is characterized by improved statistical accuracy and charge resolution and covers an energy range from $\sim$140 MeV/nuc to $>$22 GeV/nuc. We have reported the results on the relative spectra and intensities of carbon and oxygen in a separate publication (von Rosenvinge *et al.*, 1969). In that paper the instrumentation, balloon flights, and atmospheric corrections were discussed in detail.

In order to extend the significance of the data reported here we have also included the results on the spectrum of nitrogen and other M nuclei obtained from the University of Minnesota experiment aboard the Pioneer-8 spacecraft. This instrument is a six-element solid-state Cerenkov telescope. It is described in a separate publication (Lezniak and Webber, 1969). The spacecraft data was obtained during a 100-day period January–March, 1968. Solar modulation effects are in evidence – corresponding to a greater modulation in early 1968 than in 1966–67 when the balloon flights were made. However, since all M nuclei have mass to charge ratios $\cong$2.0 these solar modulation effects are not expected to alter the N/M ratio from that existing in nearby interstellar space (von Rosenvinge *et al.*, 1969).

A summary of the numerical results of this latest study on the spectrum of nitrogen nuclei is given in Table I. The actual number of observed events is shown along with the appropriate differential or integral flux. The differential spectrum of nitrogen nuclei observed in 1966 and 1968 is shown in Figure 1. The differential intensity measurements of these nuclei obtained on satellites and rockets at low energies are also shown in this figure.

A sensitive way of examining the comparative spectrum of nitrogen is to plot the ratio of these nuclei to all M nuclei. This is carried out as a function of kinetic energy in Figure 2. We have used our own recently published data on the C and O spectra at higher energies in deriving this ratio. In the case of the other measurements shown in the figure we have used the authors own measurements of the ratio.

The mean of our measurements gives an N/M ratio $=0.125$. The Chicago and NASA results at lower energies are consistent with a value between 0.10–0.15. Most importantly the N/M ratio observed in all of the current 'high-resolution' studies is significantly lower than the consensus of many earlier measurements would suggest.

This ratio appears to be constant as a function of energy to within $\sim\pm10\%$.

Since the spectra of all M nuclei appear to be identical we may transform the N/M ratio into a N/O ratio by a simple numerical factor that depends on the relative abundance of CNO nuclei. For the C and O abundances given by von Rosenvinge

TABLE I

Number of events and intensities of nitrogen nuclei observed in selected energy intervals

Energy or rigidity	Balloon		Pioneer-8	
	Events	Intensity (particles/ m^2-ster-sec)	Events	Intensity (particles/ m^2-ster-sec)
135–210 MeV/nuc	33	0.17 ± 0.03	54[a]	0.067 ± 0.009
210–340 MeV/nuc	78	0.39 ± 0.04	41[b]	0.050 ± 0.08
340–450 MeV/nuc	62	0.31 ± 0.04	96	0.12 ± 0.012
450–600 MeV/nuc	77	0.38 ± 0.04	135	0.165 ± 0.015
600–1000 MeV/nuc	97	0.49 ± 0.05	289	0.36 ± 0.020
1000–1500 MeV/nuc			196	0.24 ± 0.03
>4.35 GV	246	0.67 ± 0.05		
>5.0 GV	375	0.62 ± 0.04		
>11.1 GV	105	0.19 ± 0.02		
>1000 MeV/nuc	167	0.93 ± 0.08	736	0.81 ± 0.03
>1500 MeV/nuc			540	0.57 ± 0.025
>15 GeV/nuc	18	0.038 ± 0.008		
>22 GeV/nuc	8	0.010 ± 0.003		

[a] Energy interval 128–220 MeV.
[b] Energy interval 290–340 MeV.

et al. (1969) this numerical factor is 2.34 yielding a N/O ratio $=0.29$. For many applications the N/O ratio is of more interest than the N/M ratio since O will be the principal progenitor of N in interactions as the cosmic-ray beam traverses matter. We shall use the ratios interchangeably here.

The arguments presented in the paper by von Rosenvinge *et al.* (1969) allow us to equate the N/M ratio and its constancy near the earth with the situation existing in nearby interstellar space. To now estimate the abundance of nitrogen in the cosmic-ray sources we must consider the effects of the fragmentation which occurs as the cosmic-ray beam travels from its point of origin to us. This fragmentation will result in the production of secondary spallation nuclei of lower charge but of approximately the same energy as the progenitor nuclei. This fragmentation is the generally accepted reason for the presence of appreciable quantities of Li, Be, B in the cosmic radiation at the earth – it being assumed that these nuclei are absent in the cosmic-ray source regions.

Utilizing recent measurements of the abundances of Li, Be, B in cosmic rays and taking the appropriate fragmentation parameters for the production of these nuclei from heavier nuclei, a passage of the heavier nuclei through an average material path length of 4 ± 1 g/cm^2 of hydrogen is required to produce the observed abundances if the hydrogen is traversed at approximately the same energy at which the various L nuclei are observed (Shapiro and Silberberg, 1967; Beck and Yiou, 1968; Fichtel and

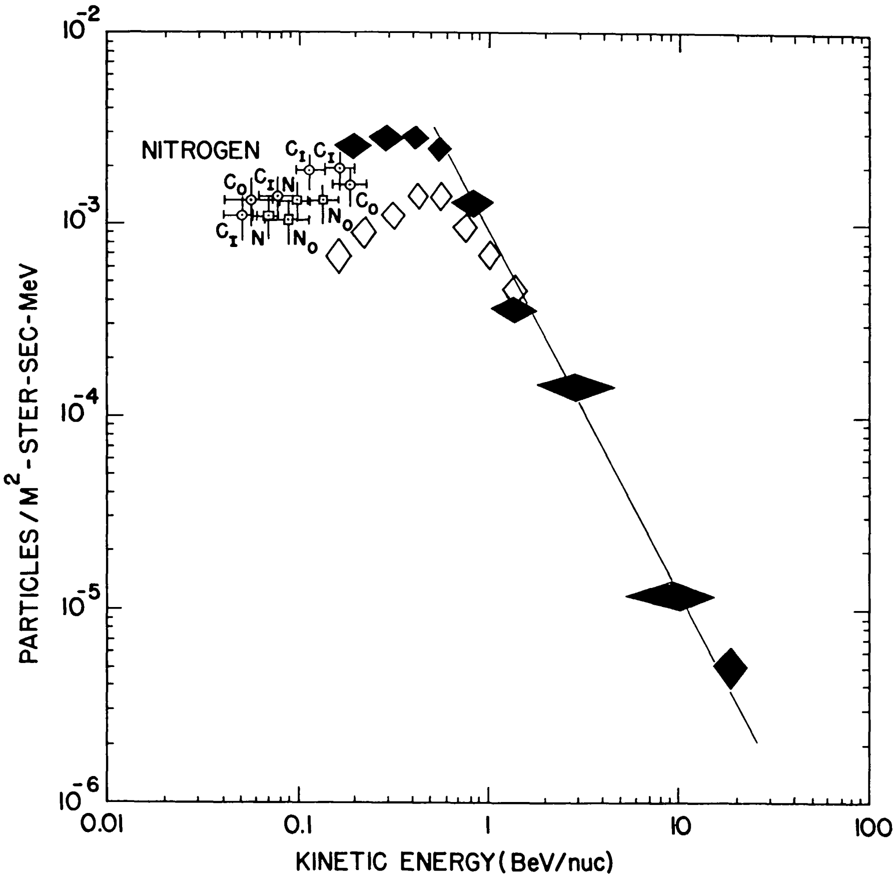

Fig. 1. Differential spectra of nitrogen nuclei measured on balloons in 1966 (solid diamonds) and on the Pioneer-8 space probe in 1968 (open diamonds). Measurements at low energies include Chicago OGO-I, C_0 (Comstock *et al.*, 1969), Chicago Imp III, C_I (Fan *et al.*, 1968), NASA satellite, N (Balasubrahmanyan *et al.*, 1966), NASA OGO-I, N_0 (Hagge *et al.*, 1968).

Reames, 1968; von Rosenvinge *et al.*, 1969.) Furthermore the (lack of) energy dependence of the L/M ratio is consistent with this average path length being constant with energy (von Rosenvinge *et al.*, 1969). These conclusions represent a substantial improvement in precision over previous estimates – partly because of the improvement in the cosmic-ray measurements themselves but mainly because of greatly improved knowledge of the relevant spallation cross-sections for the production of the L nuclei. This cross-section work has been carried out in a number of laboratories particularly at Orsay (Yiou *et al.*, 1968) and has most recently been summarized by Beck and Yiou (1968) and Fichtel and Reames (1968). In the case of the production of L nuclei, carbon and oxygen nuclei are the dominant progenitors and cross-sections for proton induced spallation from these nuclei have been particularly well studied.

Oxygen is the dominant progenitor for any secondary nitrogen that might be produced. The cross-section $O^{16}(p, pn)O^{15}$ which subsequently decays to N^{15} has been studied in detail as a function of energy (Adouze *et al.*, 1967). It is large, running approximately 30–40 mb at energies >150 MeV/nuc increasing below 100 MeV/nuc to a maximum ~ 75 mb at ~ 50 MeV/nuc. This is $\sim 1/4$ of the total oxygen loss cross-section of ~290 mb. (The mean free path of O nuclei in hydrogen is ~6 g/cm^2.) Thus in ~25% of all oxygen interactions N^{15} will be produced. Additional nitrogen is produced from oxygen via a (p, pd) process which directly produces N^{14}. Since this isotope is stable its cross-section is more difficult to measure. Beck and Yiou (1968); Fichtel and Reames (1968) and Waddington (1969) have estimated the cross-section for this reaction using the (modified) semi-empirical formula of Rudstam (1966).

We have used the total cross sections for the production of N from O and the various heavier nuclei (Ne, Mg and Si are the principle progenitors heavier than O) given by Beck and Yiou (1968) and Fichtel and Reames (1968). These are listed in Table II along with the computed source distribution of heavier nuclei taken from a paper in publication (von Rosenvinge, 1969). The production of nitrogen is strongly dominated by the $O^{16} \to N^{15}$ reaction, which supplies nearly 50% of all nitrogen at all energies. The predicted M/N abundance as a function of energy for a (slab approximation) matter traversal of 4 g/cm^2 of hydrogen is shown in Figure 2. The curve labeled 1 in this figure uses the fragmentation parameters given by Fichtel and Reames, the curve labeled 2 the parameters given by Beck and Yiou. We believe a comparison of these two curves provides a measure of the uncertainty in the expected N/M ratio due to fragmentation.

It is important to note that the amount of matter here is the same as is required to separately reproduce the observed abundances of Li, Be and B in cosmic rays. The rough equality between the observed N/M abundance and that predicted on the basis of nuclear spallation means that we can say, to the same degree we can argue that the L nuclei are absent in the cosmic-ray source, *so must nitrogen also be absent*. If we use a N/M ratio of 0.125 and allow for a 20% uncertainty in the fragmentation parameters

TABLE II

Nuclear cross-sections in mb and source abundances used in this work

		Target				
		O	Ne	Mg	Si	Fe
Source Abundance→		1.0	0.13	0.24	0.21	0.30
Product:						
200 MeV/nuc	N^{14}	25				
	N^{15}	50				
Total N		75[a]		Avg = 20		0
2 GeV/nuc	N^{14}	25				
	N^{15}	50				
Total N		75[a]	35	30	25	6
				Avg = 30[b]		

[a] Beck and Yiou (1968) use a value of 70 mb for this cross-section at 2 GeV/nuc: Fichtel and Reames take a value of 90 mb at both energies.
[b] For Mg Beck and Yiou (1968) use a value of 32 mb, for Fe 6 mb.

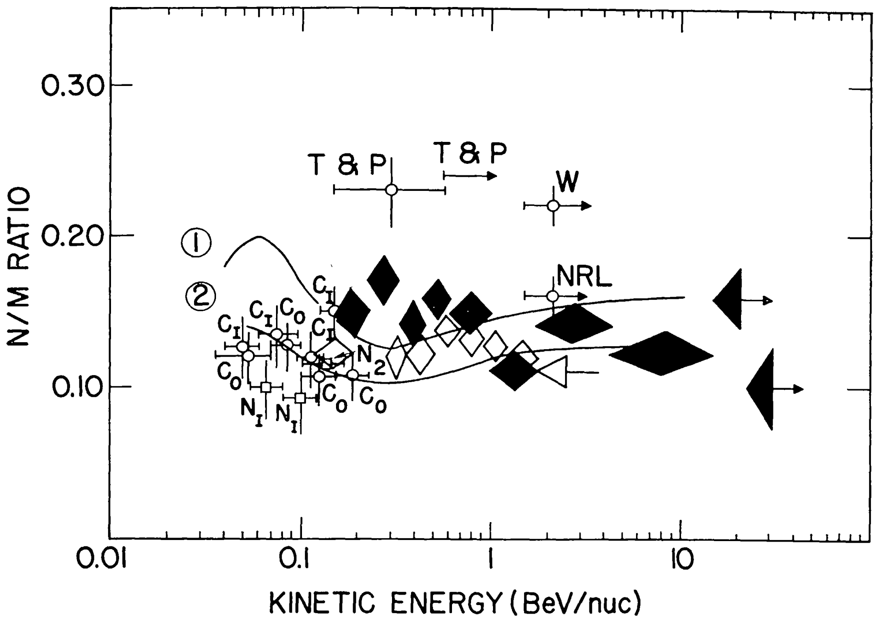

Fig. 2. Ratio of nitrogen to all M nuclei as a function of energy. 1966 balloon measurements shown as solid diamonds, 1968 Pioneer-8 measurements as open diamonds. Measurements at low energies include Chicago OGO-I, C_0 (Comstock *et al.*, 1969), Chicago Imp III, C_I (Fan *et al.*, 1968), NASA satellite, N_I (Balasubrahmanyan *et al.*, 1966), NASA OGO-I, N_2 (Hagge *et al.*, 1968). Other ratios at high energies include, T and P (Anand *et al.*, 1966); NRL. (O'Dell *et al.*, 1962), W (Webber, 1967). The expected N/M ratio for a passage of cosmic rays through a slab length of hydrogen $=4$ g/cm^2 constant with energy is shown for two sets of fragmentation parameters as described in the text.

of heavier nuclei and O and C into both N and the L nuclei we can place an upper limit for the N/M ratio in the cosmic-ray sources of 0.03 if it is assumed concurrently that L nuclei are not present to any significant extent in these same sources. This is a rather surprising conclusion. The only other determination of the 'source' abundance of N that we are aware of, made using the contemporary fragmentation parameters has been made by Beck and Yiou (1968). They take an N/M ratio of 0.15 at earth which is not appreciably different from ours. More significantly, however, they utilize an N/O ratio at earth $=0.43$. Their extrapolated source N/O ratio is 0.12. Thus the difference in our conclusions is almost entirely due to our new value for the N/O ratio at earth of 0.29. This in turn is due only partly to the low nitrogen abundance we observe. Equally as important is the relatively high oxygen abundance (C/O ratio ~ 1.1 instead of ~ 1.5 as previously believed) reported by von Rosenvinge *et al.* (1969) and confirmed in the Pioneer-8 space probe measurements.

The possibility that nitrogen in cosmic rays is principally the result of nuclear spallation of high energy cosmic rays has two important manifestations that are amenable to measurements: (1) The ratio N^{15}/N^{14} should be $\gtrsim 1$, possibly approaching 2 at low energies. For the usual element building processes occurring in nucleosynthesis N^{15}/N^{14} is $\ll 1$. Unfortunately it has not yet been possible to measure the isotopic composition of nitrogen in the cosmic rays. (2) The N/M ratio should increase by a factor ~ 1.5 at energies <100 MeV/nuc as a result of the increased spallation cross-sections at low energies if the simple slab picture is a valid model for the matter traversal of cosmic rays. This is evidently not observed. It should be noted here that variations in spallation cross-sections at low energies should also produce variations in the Li/M and B/M ratios in cosmic rays as a function of energy. This is also not observed (von Rosenvinge *et al.*, 1969). This suggests that the slab length approximation may not be correct. Fichtel and Reames (1968) have considered propagation models in which distributions of path lengths arise. The presence of a large number of path lengths for particles of a given energy tends to smear out the effects of the energy dependence of the fragmentation parameters. It may be that this is the reason that the expected increase in the N/M and other ratios at low energies is not observed.

Our conclusions do not depend on the model taken for the propagation of cosmic rays or even on the average path length of matter traversed however. The only requirements we have are: (1) The intensity of L nuclei in the source is ~ 0 and (2) The propagation conditions for the progenitors of N and the L nuclei are the same. This latter requirement is certainly reasonable since the progenitor nuclei themselves are for the most part the same.

Let us now examine more closely the consequences and implications of a cosmic ray source N/M ratio that is $\lesssim 0.03$. The reader should be aware of the situation with regard to solar cosmic rays. Data on the nuclear composition of these particles has been summarized by Durgaprasad *et al.* (1968). An average N/M ratio of 0.11 ± 0.03 is obtained, representing observations in some 4 solar cosmic-ray events using large areas of emulsion flown on rockets. This ratio appears to be the same in all events. The actual charge resolution obtained in these measurements is quite limited; however, the NASA workers believe that this represents a finite flux of nitrogen present in solar cosmic rays (Fichtel, 1969). Most observers conclude that the solar cosmic rays have passed through very little matter after acceleration, probably $\ll 0.1$ g/cm^2 (Biswas and Fichtel, 1965). Therefore this nitrogen is unlikely to have a nuclear spallation origin as in the case of the galactic nitrogen. It must be a sample of nitrogen present in situ in the solar atmosphere. The N/M ratio in the solar photosphere is reported to be 0.09 (Lambert, 1968). In the solar corona Pottasch (1965) derives a value of 0.05 for this ratio. In general therefore the abundance of nitrogen in the solar cosmic rays appears to mirror the abundance found spectroscopically in the solar atmosphere. Possibly the solar cosmic-ray abundance somewhat more closely resembles that observed in the photosphere although this is an open question. At any rate the nitrogen abundance observed in solar cosmic rays is not inconsistent with either of the spectroscopic abundances quoted above.

It has been argued that the equality of abundances of elements in the outer layers of the sun and those observed in solar cosmic rays implies that the process of acceleration, whatever it may be, shows no charge-dependent preference (Biswas and Fichtel, 1965). This is the cornerstone of arguments regarding the acceleration of galactic cosmic rays as well. In this view, features of the composition of galactic cosmic rays should be related to the features of the chemical composition in the sources rather than to details of the acceleration process itself.

The deduced upper limit of N/M <0.03 for nitrogen in the galactic cosmic-ray sources (and by implication in the chemical composition of the cosmic-ray sources as well) would seem to be different from values pertaining to the sun which range from ~ 0.05 to 0.11. It is possible that agreement in the ratios could be achieved but only by stretching all observations to their limit. Let us suppose that this is a real discrepancy and that the galactic cosmic ray sources represent a different evolution of the CNO abundance than is indicated on the sun. What possibilities exist in this regard? First we should note that, with our present knowledge of the central temperature of the sun and of the various mechanisms of nucleo-synthesis, element building beyond that accompanying normal hydrogen burning to helium is not of major importance (Davis *et al.*, 1968). Thus the solar surface abundance of nitrogen and other elements heavier than helium probably fairly accurately reflects the integrated effects of nucleo-synthesis up to the time of the formation of the sun. It should be noted that this element distribution probably represents a mixture of substances created in a number of stars in which the nuclear reactions were quite possibly not identical (Bashkin, 1965).

Actual experimental observations of the relative nitrogen abundance in non-solar objects are meagre. For example, in supernova, which are considered possible cosmic-ray sources, the experimental situation with regard to chemical composition is summarized by Zwicky (1965). The few optical spectra that are available are very difficult to interpret and although it may be possible to make some general remarks concerning abundances, details of individual elemental abundances such as N are very uncertain.

In order to place the low nitrogen abundance deduced for cosmic-ray sources in its proper perspective it is necessary to examine the theoretical picture regarding the nucleo-synthesis of nitrogen. This is believed to be principally accomplished through the CNO bi-cycle which becomes important in stellar interiors at $\sim 1 \times 10^7$ K. (e.g. Caughlan and Fowler, 1962). If the bi-cycle has been active long enough to attain equilibrium, the abundance of N^{14} should be very large compared to the abundances of all the other CNO nuclei. The ratio of nitrogen to carbon at equilibrium depends on the temperature at which the bi-cycle has been active and ranges from 386 at $T = 10^7$ K to 12 at $T = 10^8$ K (Caughlan and Fowler, 1962). An enhancement of nitrogen of this magnitude is not generally observed in stellar objects. Caughlan (1965) has studied the *approach* to equilibrium in the CNO bi-cycle and finds that if the bi-cycle has operated for a time short compared to the mean lifetime of C^{12} for proton capture, a ratio of N/C of less than or equal to 1 can be explained. Caughlan also examines the effect of different initial relative abundances of C^{12} and O^{16} on the nitrogen abundances. In massive stars where helium burning has been operating for some time in the core, much of the C^{12} will be processed into O^{16} so that nearly equal initial abundances of C^{12} and O^{16} might exist. The situation where the initial abundances of these two nuclei are equal seems to be appropriate for our observations. As the bi-cycle proceeds from this initial situation the C/O ratio gradually decreases from 1 reaching a value <0.01 when at least one proton has been consumed per initial $C^{12} + O^{16}$ nucleus. Meanwhile the nitrogen abundance is increasing from zero to a N/M value

$=0.5$ at the same time. Conditions when the N/M ratio is <0.03 exist only in an early part of the cycle when the number of protons consumed per initial $C^{12}+O^{16}$ nucleus is small. At this same time the initial C/O abundance is almost unchanged at a value ~ 0.9, which is the abundance found in cosmic rays at the source. This particular situation is achieved in a time $=0.1$ of the lifetime for proton capture by C^{12}.

The above sequence of events is nearly independent of temperature as long as $10^7\,K \leqslant T \leqslant 10^8\,K$, although the rapidity of the cycle is strongly temperature dependent.

It is interesting to note that the solar cosmic-ray ratios C/O$=0.6$, N/M$=0.11$ can also be reproduced in the CNO bi-cycle for the same initial conditions. These ratios are achieved in a time $=0.25$ of the lifetime for proton capture by C^{12}. To convert these times to times in sec during which the bi-cycle has been operative requires a knowledge of the temperature and the local proton density. Caughlan (1965) provides the necessary tables for this purpose. For temperatures $\sim 10^8$ K the lifetime for proton capture by C^{12} may be $\gtrsim 1$ year in stellar interiors, therefore the time scales required to reproduce a low nitrogen abundance could indeed be very rapid in some instances. It should be realized, however, that the eventual nitrogen abundance arising from this process will be strongly dependent on the interplay of all of the nuclear processes occurring in the star as well as the details of the distribution of the element building throughout the star.

Upon comparing the solar N/M ratio and that appropriate to the cosmic-ray sources it is tempting to suggest that the CNO bi-cycle has operated for a shorter time in the cosmic-ray sources than in the sources associated with elements which now appear in the sun. This is suggestive that a different class of objects is responsible for the nucleo-synthesis in each case.

In essence our main objective in presenting and discussing these results is, (1) to further stimulate measurements of the nitrogen abundance in the sun and in solar cosmic rays to confirm that this is, in fact, different than that to be associated with cosmic-ray sources and, (2) to encourage efforts to understand the possibility of a very low nitrogen abundance in cosmic-ray sources. This may lead to a better understanding of the features of nucleo-synthesis in these sources and indeed may give us an important clue regarding the identity of the cosmic-ray sources themselves.

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