THE RELATIVE ENERGY SPECTRA OF CARBON AND OXYGEN NUCLEI IN THE PRIMARY COSMIC RADIATION

T. T. VON ROSENVINGE* and W. R. WEBBER*
University of Minnesota, Minneapolis, Minn., U.S.A.

and

J. F. ORMES**
Goddard Space Flight Center, Greenbelt, Md., U.S.A.

(Received 22 August, 1968)

Abstract. Measurements of the energy spectra of carbon and oxygen nuclei in the primary cosmic radiation over the energy range from 140 MeV/nuc to 30 BeV/nuc are reported. An average C/O ratio of 1.11 ± 0.02 is obtained at the top of the atmosphere. This ratio is found to be constant to within ~ 5 % over the entire energy range. The energy spectra of these two nuclei are presented and compared with earlier measurements and with satellite observations at low energies. After correction for propagational effects in 4 g/cm^2 of interstellar hydrogen the 'source' C/O ratio is found to be ~ 0.9. The astrophysical implications of this C/O ratio are discussed.

1. Introduction

Carbon and oxygen nuclei are the most abundant constituents of the so-called 'heavy' cosmic rays (charge >2). Previous measurements above an energy of 1 BeV/nuc have indicated that carbon is the most abundant of the two. For example, a summary of all measurements relating to energies >1.5 BeV/nuc gives a C/O ratio ~ 1.5 (WEBBER, 1967a). A still earlier summary by WADDINGTON (1960) gives an even higher value of 1.8 for this ratio. On the other hand, the C/O abundance in most stellar sources is completely reversed, and characteristic values ~ 0.5 for this ratio in main sequence stars are observed (ALLER, 1961). An accurate measure of this ratio is thus of importance in attempting to isolate the source regions of cosmic rays. Recent measurements at low energies on satellites and rockets (FAN *et al.*, 1967; BALASUBRAHMANYAN *et al.*, 1966; REAMES and FICHTEL, 1967) indicate a C/O ratio ~ 1 or even less. The detailed balloon measurements of WEBBER and ORMES (1967, Paper I), covering the range from 200 MeV/nuc to upwards of 2 BeV/nuc substantiate the low-energy results and suggest a C/O ratio that increases from ~ 1 at the low-energy end of the range to ~ 1.4 above 1 BeV/nuc. The possibility of a substantial variation in the C/O ratio with energy would be of considerable astrophysical significance.

In this paper we shall examine the carbon and oxygen spectra and the C/O ratio from ~ 140 MeV/nuc to ~ 30 BeV/nuc as measured on balloon flights in the 1966–67 period. These new data are characterized by improved statistical accuracy, and charge

---

* Currently at the University of Adelaide, Adelaide, Australia.
** Presently a NRC-NASA Resident Research Associate.

Astrophysics and Space Science 3 (1969) 4–13; © *D. Reidel Publishing Company, Dordrecht-Holland*

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

TABLE I

Balloon-flight details

Date	Location	Instrument	Cut-off Rigidity[a] (BV)	Altitude (g/cm^2)	Collection Factor (ster m^2 sec)	Mt. Wash., N.M.
13 July 1966	Ft. Churchill, Canada	I	< 0.2	2.1	159	2337
25 July 1966	Ft. Churchill, Canada	I	< 0.2	2.8	196	2367
16 May 1967	Palestine, Texas	III	4.35	5.0	521	2332
3 June 1967	Palestine, Texas	III	4.95	5.0	854	2255
15 Sept. 1967	Queensland, Australia	II	11.2	6.2	756	2262

[a] Cut-offs determined using latest 2° × 2° world grid of Shea and Smart (private communication).

1969Ap&SS...3....4V

resolution. Also the background suppression is much improved over the data presented in Paper I.

2. Instrumentation and Balloon Flights

The data to be discussed here were obtained on balloon flights using three similar, but quite distinct, instruments. The details of the balloon flights are given in Table I. The operation of instruments is as follows:

A. INSTRUMENT I

This is basically a Čerenkov-scintillation counter telescope. It contains two thin scintillators, which form the telescope coincidence, followed by a 15 cm dia. UVT lucite Čerenkov detector, subsequently followed by another (range) scintillator. The first three telescope elements are all pulse-height analysed using separate 2048 channel analysers. This instrument, its response to charged particles and the method of unfolding the differential spectrum from the measured pulse-height distribution, have been described in detail in a previous publication (ORMES and WEBBER, 1968). It is used to obtain the differential energy spectra of the various nuclear species including carbon and oxygen from ~140 MeV/nuc to 1 BeV/nuc. This four-element system provides a substantial improvement in background suppression and charge resolution over the earlier two-element system, upon which the results of Paper I were based. The larger area and longer flight times provided more than 2 times the total area-time factor than in the entire earlier series of measurements.

B. INSTRUMENT II

This is a large-area double-scintillation counter telescope (diameter of individual elements $= 60$ cm). This system is used to obtain the integral intensity of nuclei at geomagnetic latitudes $\gtrsim 40°$, where only relativistic nuclei of each charge are present. The scintillators are optically compensated to obtain uniformity in light collection to within $\pm 2\%$. The technique for compensation, and the details of the charge resolution etc. are being reported in a separate publication (VON ROSENVINGE and WEBBER, 1968). The analysis of flight data using this instrument is particularly simple. Because of the good charge resolution and low background, each charge stands out as an individual clump of particles in the two-dimensional matrix of scintillator outputs.

C. INSTRUMENT III

This instrument is identical to II except that a 1.7-m long gas Čerenkov detector is inserted between the scintillation counter-telescope elements. Thus in addition to the integral intensity of particles above the rigidity threshold determined by the geomagnetic field at the location of the flight, the integral intensity of events above the gas Čerenkov threshold is obtained. In the two measurements with this instrument reported here, Freon gas was used at 2 atm and 1 atm pressure giving effective thresholds of 15 and 22 BeV/nuc respectively. A paper describing the operation of this system and a more complete discussion of the results obtained is now in prepara-

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1969Ap&SS...3....4V

tion. For these studies it is relevant to note that the gas threshold energy is quite sharp and rather clearly defined, particularly for heavy nuclei.

In the last analysis the ability to study the relative spectra of two nuclei such as carbon and oxygen depends on the degree of resolution of the different charges and on the statistical accuracy of the results. This in turn depends on the amount of 'background' present in the pulse-height matrix and the intrinsic resolution of the detector for adjacent charges. A pulse-height histogram for the charge range $Z = 3$–10 for the flight on 16 May, 1967 with instrument III is shown in Figure 1. Similar resolution is obtained for the other flights including the flights at Ft. Churchill with instrument I.

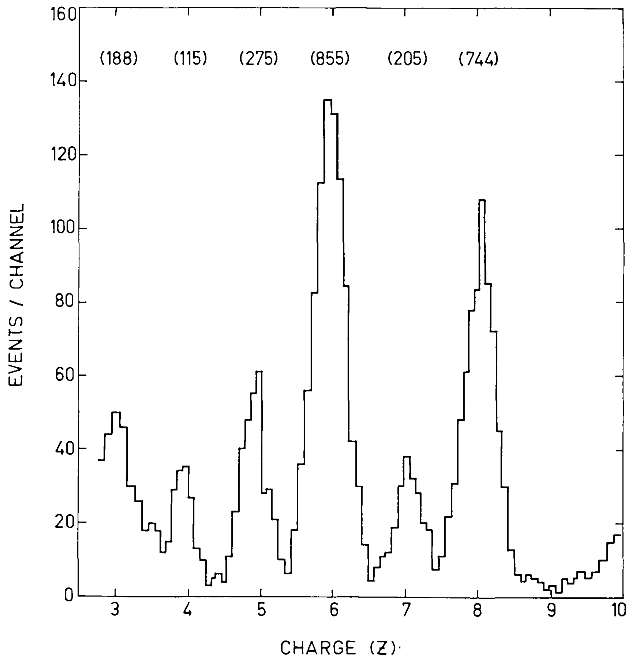

Fig. 1. Charge histogram in the range $Z = 3$–10, obtained from the flight on 16 May, 1967 at Palestine, Texas. Numbers refer to the actual number of nuclei assigned to each charge.

3. Atmospheric Corrections

The results obtained at floating altitude must be corrected for the effects of the residual atmosphere before we can make a definitive statement regarding the extraterrestrial C/O ratio. According to our direct atmospheric absorption measurements of these nuclei this correction is not a large one and does not introduce a significant uncertainty in the final result, contrary to some earlier suggestions (Reames and Fichtel, 1966). Since carbon and oxygen nuclei are individually the most abundant of the heavy nuclei by a factor of at least 3, fragmentation of still heavier cosmic-ray nuclei into them should not play an important role in the upper few g/cm^2 of the atmosphere. Thus the relative correction of the measured intensities of these two nuclei to the top

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1969Ap&SS...3....4V

of the atmosphere should be closely proportional to their interaction mean free paths. Calculations based on the geometrical cross-sections of these two cosmic-ray nuclei with air nuclei give an interaction mean free path for oxygen that is 2 g/cm^2 shorter than that for carbon. The direct measurements of the absorption of these nuclei in the atmosphere (Paper 1) indicate that the attenuation length for oxygen is 3 ± 1 g/cm^2 shorter than for carbon. In this paper we have corrected all carbon and oxygen data to the top of the atmosphere using measured attenuation lengths of 33 and 30 g/cm^2 respectively. This changes the C/O ratio by 0.02 in extrapolating through 5 g/cm^2 of atmosphere – a correction which is less than the statistical uncertainty in all but our most recent results.

TABLE II

Number of events and intensities of different charges observed in selected energy intervals

Energy of Rigidity	Counts and Intensity (particles/m^2 ster sec)				
	Carbon		Oxygen		Ratio
145–210 MeV/nuc	184		181		1.02 ± 0.10
210–340 MeV/nuc	360		361		1.00 ± 0.08
340–450 MeV/nuc	384		367		1.04 ± 0.08
	(156)		(160)		(0.98 ± 0.11)
450–600 MeV/nuc	448		393		1.14 ± 0.07
	(214)		(183)		(1.17 ± 0.11)
600–1000 MeV/nuc	685		610		1.13 ± 0.06
	(325)		(242)		(1.34 ± 0.12)
>1000 MeV/nuc	1190	3.24 ± 0.10	1006	2.78 ± 0.09	1.18 ± 0.05
	(612)		(535)		(1.14 ± 0.06)
>15 BeV/nuc	54	0.097 ± 0.014	54	0.097 ± 0.014	1.00 ± 0.17
>22 BeV/nuc	49	0.054 ± 0.008	43	0.047 ± 0.008	1.14 ± 0.18
>3.20 BV	(181)		(126)		(1.44 ± 0.15)
>4.35 BV	1372	2.63 ± 0.08	1237	2.27 ± 0.07	1.11 ± 0.04
>5.00 BV	1736	2.03 ± 0.06	1519	1.78 ± 0.05	1.14 ± 0.03
>11.1 BV	544	0.70 ± 0.03	568	0.72 ± 0.03	0.96 ± 0.06
$\Sigma >$ 1.0–1.5 BeV/nuc	4842		4330		1.12 ± 0.02
$\Sigma <$ 450 MeV/nuc	928		909		1.02 ± 0.05

4. Results

A summary of the numerical results of this study is given in Table II. The actual number of observed events is shown, along with the intensities corrected to the top of the atmosphere. The number of events upon which Paper 1 is based is shown in parentheses. The differential energy spectra of carbon and oxygen nuclei are shown in Figure 2. We have selected this spectral representation as being the most useful for comparison with other results. Differential and integral rigidity spectra may be derived from the data presented in Table II and Figure 2. It is of interest to note here that the exponent

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

on the integral rigidity spectrum of C and O nuclei in the 5–50 BV range is equal to 1.55±0.04.

The differential intensity measurements of these nuclei in the energy range 60–200 MeV/nuc obtained on satellites and rockets are also shown in Figure 2. These low-energy results fit quite well onto our spectra. Indeed the slightly higher intensities observed by the Chicago experimenters may be directly related to the fact that at the time of their measurements in 1965 the average neutron monitor rate was ~3% higher than for our measurements in 1966.

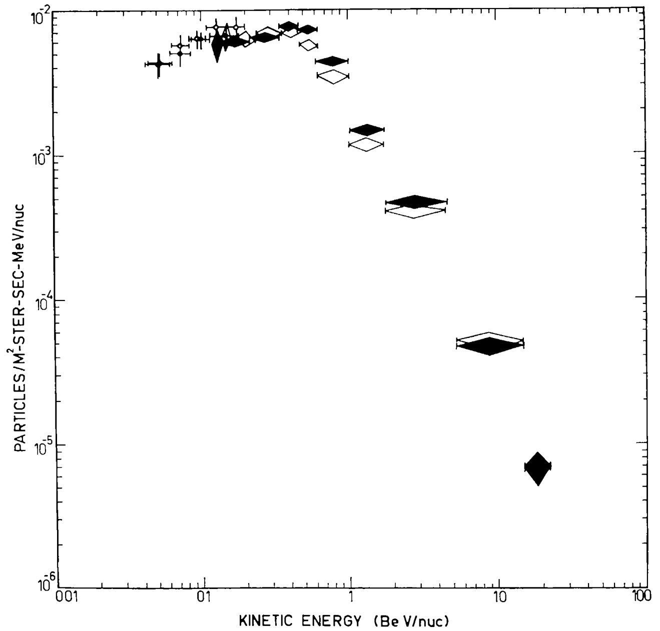

Fig. 2. Differential energy spectra of carbon and oxygen nuclei, derived from measurements made in 1966–67. Low-energy data on these nuclei from the work of FAN *et al.* (1967) and BALASUBRAHMANYAN *et al.* (1966) appropriate to 1965 are also shown. Carbon nuclei shown as solid diamonds and circles; oxygen nuclei as open diamonds and circles.

Our data show that carbon is only slightly more abundant than oxygen. Taking an integral or all of our measurements above 1–1.5 BeV/nuc, this ratio is 1.12±0.02. An integral above the lowest energy measured (~140 MeV/nuc) gives 1.10±0.02.

A more sensitive way of examining the comparative spectra of the two nuclei is to plot the carbon to oxygen ratio. This is done as a function of kinetic energy in Figure 3. It is immediately evident that according to our recent data no substantial variation of the C/O ratio with energy exists. Although the results of Paper 1 give somewhat higher values of C/O above ~600 MeV/nuc than are obtained in the recent survey, the two sets of measurements are consistent within the larger experimental errors of the earlier measurements.

Significant differences are apparent, however, between our current measurements

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

above ~1.5 BeV/nuc and those reported in the past as exemplified by the summary of Webber (1967a) and the individual observation of the N.R.L. group (O'Dell *et al.*, 1962). The N.R.L. observation is chosen because it not only exhibited the best charge resolution but was the most statistically significant (~260 carbon nuclei were identified) measurement at higher energies prior to this one and the one reported in Paper I. The summary of Webber (1967a) (which includes the N.R.L. result) is a compilation of measurements reported prior to 1965 which claim to have had adequate charge resolution. A wide variation of C/O ratios, ranging from more than 2 to ~0.8, are listed in this compilation. This variation is quite out of keeping with the claimed experimental errors and suggests that the charge resolution in some of these early measurements is not as good as was hoped by the authors. It is possibly significant that the early measurements of this ratio which seem to show the best charge resolution (e.g. low-nitrogen abundance) (Daniel and Durgaprasad, 1962; Kristiansson *et al.*, 1963) also give C/O ratios ~1. (In a compilation similar in spirit to the one of Webber but using a more highly selected set of data, Kristiansson (1966), arrives at mean value for the C/O ratio of 1.27 at energies above 1.5 BeV/nuc.)

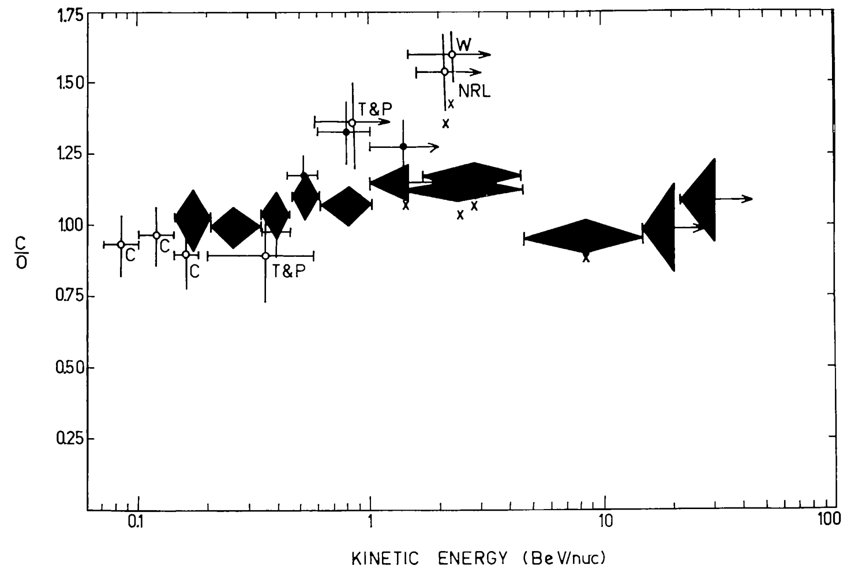

Fig. 3. Ratio of carbon to oxygen nuclei as a function of energy. The diamonds refer to the work reported here. The solid circles designate the results from Paper I. The letters refer to the following references: C: Fan *et al.* (1967); N.R.L.: O'Dell *et al.* (1962); T and P: Anand *et al.* (1966); W: Webber (1967). The ratios obtained at low energies by Balasubrahmanyan *et al.* (1966) and Reames and Fichtel (1967), coincide with the Chicago results and are not shown here. The arrows and crosses refer to the adjustments in the ratios needed if all carbon is C^{13}.

It is relevant to point out that the statistical accuracy of all of the other measurements listed in the survey by Webber is roughly comparable to that of the N.R.L. measurement alone. This consideration and the possibility of charge-resolution difficulties in some of the earlier measurements lead us to place less weight on the point labelled *W* in Figure 3 and more on the N.R.L. observation. At present the most plausible explanation for the discrepancy between our latest results and those of the N.R.L. group is simply one of statistics.* The C/O ratio obtained by the N.R.L. group is just less than three standard deviations above our value at ~ 1.5 BeV/nuc.

The most accurate contemporary emulsion measurement of carbon and oxygen nuclei, that of ANAND *et al.* (1966), is also shown in Figure 3. This does not help to resolve the issue, since within the experimental errors (~ 200 carbon nuclei were observed in this study) it is consistent with the other measurements.

It seems that our recent measurements set a new standard of precision for the measurement of the C/O ratio. Within this level no significant variation in this ratio exists with energy. It is worth noting, however, that the sum of our recent measurements below 450 MeV/nuc gives a C/O ratio $= 1.02 \pm 0.04$ as compared with the value of 1.12 ± 0.02, appropriate to energies above 1.5 BeV/nuc. The measurements at still lower energies also give a mean value of the C/O ratio $\lesssim 1.0$. If a variation of this small magnitude is to be confirmed still more accurate measurements will be needed at both low and high energies.

A further aspect relating to the interpretation of the C/O ratio concerns the possible presence of C^{13} in the cosmic radiation. We assume that all oxygen is O^{16} in keeping with known cosmic abundances. Previous attempts to measure the C^{13}/C^{12} ratio have been inconclusive; however, on astrophysical grounds an appreciable fraction of the carbon could be C^{13} (WEBBER, 1967a).

Consider the data presented in Figures 2 and 3. For nuclei with an A/Z ratio $= 2.0$ the energies corresponding to the cut-off rigidities of 4.35 BV, 5.00 BV and 11.1 BV are 1.42 BeV/nuc, 1.75 BeV/nuc, and 4.6 BeV/nuc respectively. For an A/Z ratio $= 2.17$ corresponding to C^{13} these energies are 1.26 BeV/nuc, 1.58 BeV/nuc, and 4.2 BeV/nuc.

In order to deduce an *energy* spectrum from the measurements which utilize the cut-off rigidity in the geomagnetic field, assumptions must be made regarding the A/Z ratio. Similar assumptions must be made in order to deduce a *rigidity* spectrum from measurements in which energy limits are determined by the instrument calibration (which depends on velocity).

The net effect of the possible presence of C^{13} on the results is best summarized in Figure 3, which shows the modifications necessary to the derived C/O ratios under the extreme assumption that all carbon is C^{13}. The adjustments affect our measurements and those of other workers in a like manner. They do not explain the differences between our measurements and earlier ones, nor do they greatly modify the C/O ratios.

---

* Solar modulation effects will not affect this ratio if all carbon is C^{12} and all oxygen is O^{16}. If there is an admixture of C^{13} then solar modulation effects on carbon nuclei would be expected to be slightly less than oxygen at the same energy. Calculations using representative solar modulation functions (WEBBER, 1967b) indicate that one would expect at most (assuming all carbon is C^{13}) a 3 % decrease in the C/O ratio above ~ 1.5 BeV/nuc between the time of the N.R.L. measurement and the time of our measurement due to such a differential solar modulation effect.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

5. Interpretation of the Results

Before the results on carbon and oxygen nuclei just discussed can be related to the source composition at least two further effects must be taken into account.

The first concerns the effect of a possible residual solar modulation operative even during the period 1965–66 near sunspot minimum when these measurements were made. The situation here is similar to our earlier discussion on solar modulation effects, except that we are now dealing with the very uncertain magnitude of the possible residual modulation. Using a residual modulation parameter $=0.5$ BV (WEBBER, 1967b) we obtain an extrasolar C/O ratio $\sim 5\%$ less than observed at the earth if all carbon is C^{13}. Thus this effect is relatively unimportant.

A much more important effect relates to the fragmentation which occurs as the cosmic-ray beam travels from its place of origin to us. Current estimates (SHAPIRO and SILBERBERG, 1967) place the material path length at 4 ± 1 g/cm^2 of hydrogen. In order to calculate the effect of this material on the C/O ratio we need to know the fragmentation probabilities of all heavier nuclei into carbon and oxygen. For this purpose a more detailed study of the fragmentation probabilities is needed than is currently available. However, those parameters presented by FICHTEL and REAMES (1968) will suffice to illustrate the problem. Assuming that these fragmentation parameters and the amount of material passed through are energy-independent, we have made a simple one-dimensional diffusion calculation. The resulting C/O ratio at injection is found to be reduced from the value of 1.10 observed at the earth to ~ 0.9.* This reduction in the C/O ratio is grossly similar to that encountered in extrapolation to the top of the atmosphere and results in large part from the fragmentation of the heavier oxygen nuclei into carbon.

Perhaps the most striking feature of the C/O ratio of 0.9 we have derived for the 'source' of galactic cosmic rays is that this value is significantly different than the value of 0.59 ± 0.07 found for these nuclei in solar cosmic rays (BISWAS and FICHTEL, 1965). A difference is also evident for our N/C 'source' ratio of 20.05 for galactic cosmic rays and the solar ratio of 0.19 ± 0.04. The measured solar cosmic-ray abundances of these nuclei closely mirror the solar abundances determined spectroscopically (DURGAPRASAD *et al.*, 1968) and therefore presumably those of other similar main-sequence stars. It has been argued that the equality of the solar cosmic-ray charge composition and the solar composition determined spectroscopically indicates that the heavier solar cosmic rays are not preferentially accelerated (BISWAS and FICHTEL, 1965). If this argument can be applied to galactic cosmic rays then the relative abundance of CNO in the galactic 'source' regions must be different than that in the sun. Indeed a significant modification of the solar CNO ratio by element building must have taken place in the galactic cosmic-ray source.

---

* For completeness in the ensuing discussion we should point out that the N/O ratio obtained by us at the top of the atmosphere in the same study is 0.29 ± 0.01. This ratio also appears to be independent of energy. When extrapolated to the source, using the fragmentation parameters given by FICHTEL and REAMES (1968), this becomes <0.05. Thus, cosmic-ray nitrogen may essentially be a fragmentation product just as are the L nuclei. If so, cosmic-ray N should have a large component of N^{15} resulting from O^{16} stripping reactions.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

Acknowledgements

This work was performed under NASA grant NSG-281-62, while the authors were at residence at the University of Minnesota.

References

ALLER, L. H.: 1961, *The Abundances of the Elements,* Interscience Publ., New York.

ANAND, K. C., BISWAS, S., LAVAKARE, P. J., RAMADURI, S., SREENIVASAN, N., BHATIA, U. S., CHOHAN, U. S., and PABBI, S. D.: 1966, *J. Geophys. Res.* **71,** 4687.

BALASUBRAHMANYAN, V. K., HAGGE, D. E., LUDWIG, G. H., and McDONALD, F. B.: 1966, *J. Geophys. Res.* **71,** 1771.

BISWAS, S. and FICHTEL, C. E.: 1965, *Space Sci. Rev.* **4,** 709.

DANIEL, R. R. and DURGAPRASAD, N.: 1962, *Nuovo Cimento* **23,** Suppl., 82.

DURGAPRASAD, N., FICHTEL, C. E., GUSS, D. E., and REAMES, D. V.: 1968, Proc. 10th Cosmic Ray Conf., Calgary, *Can. J. Phys.* **46,** S 749.

FAN, C. Y., GLOECKLER, G., and SIMPSON, J. A.: 1968, Proc. 10th Int. Cosmic Ray Conf. Calgary, *Can. J. Phys.* **46,** S 548.

FICHTEL, C.E. and REAMES, D.V.: 1968, *Phys. Rev.*

KRISTIANSSON, K.: 1966, *Arkiv Fysik* **32,** 285.

KRISTIANSSON, K., MATHIESON, O., and STENMAN, A.: 1963, *Arkiv Fysik* **23,** 479.

O'DELL, F. W., SHAPIRO, M. M., and STILLER, B.: 1962, Proc. 7th Int. Cosmic Ray Conf., Kyoto, *J. Phys. Soc. Japan*, Suppl. A III, 23.

ORMES, J. F. and WEBBER, W. R.: 1968, *J. Geophys. Res.* **73,** 4231.

REAMES, D. V. and FICHTEL, C. E.: 1966, *Phys. Rev.* **149,** 991.

REAMES, D. V. and FICHTEL, C. E.: 1967, *Phys. Rev.* **162,** 1291.

SHAPIRO, M. M. and SILBERBERG, R.: 1967, *High Energy Nuclear Reactions in Astrophysics*, Benjamin, New York.

VON ROSENVINGE, T. T. and WEBBER, W. R.: 1968, *Nuc. Inst. and Methods* (to be published).

WADDINGTON, C. J.: 1960, *Progr. Nucl. Phys.* **8,** 3.

WEBBER, W. R.: 1967a, in *Handbuch der Physik*, Vol. **46**-2, Springer-Verlag, Berlin, p. 181.

WEBBER, W. R.: 1967b, Survey Paper on Solar Modulation Effects Presented at the 10th Int. Cosmic Ray Conf., Calgary (unpublished).

WEBBER, W. R. and ORMES, J. F.: 1967, *J. Geophys. Res.* **72,** 5957.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System