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COMPOSITION OF SOLAR COSMIC RAYS

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I. INTRODUCTION

For over two decades, it has been known that the sun is capable of accelerating particles to high energies in association with major solar disturbances. The existence of these energetic particle events was first realized by Forbush (1946) as a result of ground level observations; subsequently, the results of several experiments have shown that there are many of these events and that they occur most frequently during the years of high solar activity (e.g. McDonald, 1963; Roederer, 1964; and Webber, 1964). The known events have varied in size from those whose intensities are just barely detectable to events where, for one day, the flux of particles with energies greater than 20 Mev exceeded 10^3 particles/(cm²ster.sec.). The normal non-solar cosmic ray intensity above 20 Mev is about 0.2 particles/(cm²ster.sec.). Although protons are the most numerous particles in a given velocity interval, many other types of particles are known to exist, and their presence, energy spectra, and relative abundances are of considerable importance not only in the study of solar cosmic rays, but also solar physics and non-solar cosmic rays.

The study of the composition of solar cosmic rays was pursued with considerable success during the most recent solar maximum (approximately

1957 to 1962). Already many of the general features seem to be clear, and some detailed knowledge is emerging. Detailed studies of the proton energy spectra as a function of time now exist for several events from 3 to 600 Mev as a result of the scintillation counter experiments flown on Explorers XII and XIV (Bryant, Cline, Desai and McDonald, 1962; 1963). In addition less complete time histories of solar proton spectra exist for some earlier events from measurements made with simple electronic detectors and nuclear emulsions flown on balloons, sounding rockets, and satellites (e.g. McDonald, 1963.). The energy spectra of solar protons and helium nuclei have been measured simultaneously on several occasions using nuclear emulsion detectors flown on balloons (Biswas, Freier and Stein, 1962; Biswas and Freier, 1961; Ney and Stein, 1962; Freier and Webber, 1963; Freier, 1962; Freier, 1963) and in rockets (Biswas, Fichtel and Guss, 1962; Biswas, Fichtel, Guss and Waddington, 1963). In spite of their limited number, these measurements are of particular interest because the different charge to mass ratio of He^4 and H^1 permits the separation of velocity and rigidity (momentum/charge) effects. Turning to the isotopic composition, detectable fluxes of deuterons have been seen in two events (McDonald, Balasubrahmanyam, Brunstein, Hagge, Ludwig, and Palmeira, 1965) and relatively severe upper limits have been set in two others (Biswas, et al., 1963 and Freier and Waddington, 1965). Results on the presence of tritium and He^3 in the solar particle radiation have been obtained by Fireman, DeFelice, and Tilles (1961), Tilles, DeFelice and Fireman (1963) and Schaeffer and Zahringer (1962).

Smaller quantities of nuclei with higher charges have also been seen in several events (Fichtel and Guss, 1961; Biswas, Fichtel, and Guss, 1962; Yagoda, 1961; Pomerantz and Witten, 1962; Kurnosova, Razorenov, and Fradkin, 1962; Biswas et al., 1963; Biswas and Fichtel, 1962; and Biswas et al., 1965), and it seems likely that these heavier nuclei are always present since they have been observed every time the intensity of the event was sufficiently great to expect to be able to detect them on the basis of their abundances in other events. Detailed charge studies (Biswas, et al., 1963; Biswas and Fichtel, 1963) seem to indicate that the multiply charged component (the nuclear charge, $Z > 2$) has a composition similar to that of the sun, and hence dissimilar to that of the cosmic radiation coming from beyond the solar system. Energetic electrons are very rare (Earl, 1962; Yates, 1963; Ney and Stein, 1962; Cline, Ludwig, and McDonald, 1964), and positive evidence for them exists in only one solar cosmic ray event (Meyer and Vogt, 1962), and even then their intensity was very low compared to that of the protons. There is no direct evidence for neutrons.

This review of solar particle composition will begin with a summary of our present knowledge of the charge spectrum of the nuclear component, the energy spectra of the various nuclear components, the isotopic composition of the hydrogen and helium nuclei, and the available information on other possible components such as electrons and neutrons. This will be followed by a discussion of the relation of these measurements to the theories of solar particle propagation and acceleration.

Finally, the insight which these results can give into the relative abundances of elements on the sun and the origin of the cosmic rays coming from beyond the solar system will be discussed

II. EXPERIMENTAL OBSERVATIONS ON THE COMPOSITION OF SOLAR COSMIC RAYS

This section will be divided thus: First, the charge spectrum of the solar nuclei and the energy spectra of different nuclear charge groups will be discussed. Then, the available data on the isotopic composition of the two principal charge species, hydrogen and helium, will be presented. Finally, the experiments to detect other components will be summarized.

A. CHARGE SPECTRUM OF SOLAR NUCLEI AND THEIR ENERGY AND RIGIDITY SPECTRA

At the present time it seems to be meaningful to speak of the charge composition of multiply charged nuclei, but there seems to be no simple relationship between the abundances of protons and the nuclei of higher charge. This picture develops from the similar composition, independent of energy, of the multiply charged nuclei at different times and in different events, and the correspondingly large variations in the proton to helium ratio. The remainder of this section, IIA, will be devoted principally to the analysis of the complicated proton-helium problem and a description of the energy and rigidity spectra. A detailed discussion of the charge spectrum of the multiply charged nuclei will be left until the next section, IIB.

The data for the study of the solar nuclei, much of which is summarized in Tables 1 and 2, comes from a variety of detectors and

experiments flown on balloons, sounding rockets, and satellites. In the case of balloon borne detectors, the lowest energy particle which can be measured is determined either by the air cutoff (typically 75 Mev for protons) or in some cases by the geomagnetic cutoff. In general, the lower limit of the detectable energy in sounding rocket experiments flown from regions close to the magnetic poles and satellite experiments is caused by the detector system itself and is therefore usually 10 Mev or less.

Since the particle distribution that is being examined consists not only of nuclei of different types, but also nuclei of different velocities, it is necessary to examine both the composition and the velocity distribution as a function of time in an event. In addition, possible event to event variations must also be considered before meaningful statements about the relative abundances can be made. Finally, it is desirable to proceed even further and separate the effects of velocity and rigidity because in general the acceleration and the propagation of solar cosmic rays could depend on both of these parameters.

In proceeding to analyze the data, it must be remembered that the charge to mass ratio of the proton differs by a factor of two from most of the nuclei of higher charge, such as He^4 , C^{12} , O^{16} , and Ne^{20} , and, therefore, for a given velocity, the rigidity of a proton is less than the other nuclei. Here, we are assuming that the helium nuclei observed are mostly He^4 .

For those times when data on both hydrogen and other nuclei exist it is possible to find simple mathematical expressions for both the energy per nucleon and the rigidity spectra in the limited intervals where data exist for both types of particles being considered.

These representations are as follows:

$$dJ/dW = C(A,Z,t)(W/W_0)^{-\gamma(A,X,t)} , \quad (1)$$

$$dJ/dR = K(A,Z,t) \exp [-R/R_0(A,X,t)] , \quad (2)$$

where J is the integral particle flux, A the atomic number, Z the nuclear charge, t the time in the event, W the total energy, W_0 the rest energy, and R the rigidity. Although these equations are adequate representations for the limited intervals where nuclear composition data exists, it should be mentioned that neither equation (1) nor (2) holds for all energies and times, although equation (2) is better than equation (1) for energies below about 35 Mev. Measured values of γ and R_0 are given in tables 1 and 2 for those instances where data are available for more than one component.

Freier and Webber (1963) were the first to show that an exponential rigidity spectrum of the form given by equation (2) was an excellent representation of the data. They showed further that the rigidity spectra of protons and helium nuclei are often similar in shape; that is R_0 of equation (2) is approximately the same for the two nuclear species. An example of this effect is shown in Fig. 1. However, they are not always exactly the same. In two instances, at 1603 UT on November 19, 1960 and at 1405 UT and 0930-1700 UT on September 3, 1960, when the spectra of protons and multiply charged particles could be measured over a wide rigidity

interval, the R_0 values were significantly different. An analysis of the data (Biswas and Fichtel, 1963) indicated that there was less than a 0.1% chance of R_0 values of protons and helium nuclei being the same. Fig. 2 is an example of spectra which have different R_0 values. The measurements were made using nuclear emulsions flown on balloons and sounding rockets and the references are given in table 2. In the balloon experiments, the measurements covered an energy range from about 300 to 800 Mev for the protons and about 80 to 300 Mev/nucleon for the helium nuclei, while in the latter studies protons and helium nuclei were measured in the energy intervals from about 15 to 300 Mev and 30 to 130 Mev/nucleon respectively.

When proton to helium ratios are compared, it is found that, although the helium and hydrogen nuclei seem to have similar rigidity spectra, the ratio of the two components in the same rigidity interval varies greatly from one event to another and from one time in an event to another. Above approximately 0.8 Mev rigidity, the proton to helium ratio has varied from $\geq 50:1$ to $1:1$ with smaller ratios tending to be more common. Table 2 gives some of the ratios that have been observed by experimenters. These data are taken largely from the summaries of Freier and Webber (1963) for the rigidity range above approximately 0.8 Bv and Biswas and Fichtel (1963) for the rigidity range from approximately 0.5 to 1.0 Bv. Additional measurements included in Table 2 were made recently by McDonald, et al. (1965) using a scintillator telescope flown on the IMP satellites.

In all the instances where the fluxes of the proton and helium nuclei could be measured in the same energy per nucleon interval, the

He nuclei energy/nucleon spectrum had a much steeper slope than the proton one. Fig. 3 shows a typical example of this effect and Table 1 gives the γ values calculated from Equation (1). Figures 4a and 4b show the energy/nucleon spectra for protons, helium nuclei, and medium nuclei for those instances when all three nuclear species have been observed at the same time.

In considering the hydrogen to helium nuclei ratio within a given velocity increment, then, the interval must be specified since the ratio varies markedly with energy, as shown in Fig. 5. In addition to this ratio varying appreciably with energy per nucleon in one event, there is now some evidence to indicate that for a given velocity interval there can also be considerable variation in this ratio from one event to another as shown in Fig. 5. Table 2 gives the ratios which have been measured at times when comparisons could be made in the same energy per nucleon interval. Unfortunately, the high and uncertain magnetic cutoff at Minnesota prevents the calculation of this ratio in many cases when helium nuclei data were available because the protons in the same kinetic energy interval as the observed He nuclei were partially or entirely forbidden by the magnetic field.

B. MULTIPLY CHARGED NUCLEI

The data on heavy nuclei ($Z \geq 3$) are more limited but easier to summarize. Because of their short ranges, almost all of the information on energetic solar heavy nuclei has come from sounding rockets and satellites, and in only two cases has it even been possible to detect them at balloon altitudes. Heavy nuclei were first detected in the

September 3, 1960 solar cosmic ray event in nuclear emulsions flown on sounding rockets from Fort Churchill (Fichtel and Guss, 1961). They were subsequently seen again in the November 1960 events in nuclear emulsions flown on balloons, sounding rockets, and satellites by Biswas et al. (1962), Yagoda et al. (1961), Ney and Stein (1962), Biswas et al. (1963), and Biswas and Fichtel (1963) with an ionization and Cerenkov counter system flown by Pomeranz and Witten (1962), and in the July 18, 1961 event with nuclear emulsions flown on a balloon (Biswas, et al., 1965).

The evidence which exists at present indicates that the energy per nucleon spectra of the medium nuclei and the helium nuclei are the same. The γ values of Equation 1 for helium and medium nuclei as calculated by Biswas and Fichtel (1963) are given in Table 1 and are seen to be the same within uncertainties. Further, since all of the medium nuclei which occur in detectable amounts have the same charge to mass ratio as He^4 , the rigidity spectra of these two nuclear species are also the same, assuming of course that the nuclei have been completely stripped of their electrons. Figs. 1, 2, 3, and 4 all show the similarity of the helium and medium spectra. In addition to having the same rigidity spectra, the relative abundances of helium and medium nuclei in the same rigidity intervals have been measured several times in three events and found to be the same within uncertainties, as indicated in Table 3. The variation of one of the helium to medium ratios from the average by two standard deviations is not thought to be significant both because one such deviation in a sample of six is not

too unlikely and because the other two ratios measured in the same event are within one standard deviation. Since the helium to medium ratio is constant, the proton to medium ratio varies in a manner similar to the proton to helium one, which was shown in Fig. 5.

The relative abundances among the heavy nuclei for those nuclei which could be measured in the same energy per nucleon intervals have been found to be the same each time a measurement was made, namely, five times in two events (Biswas et al., 1962 and Biswas et al., 1963). These data are summarized in Table 4. This result, of course, suggests that if these other nuclei had been present in sufficient numbers to measure a rigidity spectrum, their rigidity spectrum would have been the same as the medium and helium nuclei.

The results summarized in the last two paragraphs indicate that it is possibly meaningful to speak of relative abundances of solar cosmic ray multiply charged nuclei, and that the best estimates of these abundances would be obtained by taking the average composition in the same velocity intervals from all of the data available. Therefore, the average composition of the multiply charge nuclei in the same velocity intervals as measured in the five flights mentioned above is presented in Table 5 with a base of one having been chosen for oxygen. Among the heavy nuclei (those with nuclear charges greater than two), the medium nuclei ($6 \leq \text{nuclear charge} \leq 9$) are seen to be the most abundant, while Be and B are so rare that only upper limits can be set. A closer examination shows that the relative abundances of the energetic solar particles are the same within uncertainties as the solar abundances determined by spectroscopic means. Since the

solar and universal abundances are similar, although not the same, the solar cosmic ray composition is also similar to the universal abundances. The solar cosmic rays are, however, markedly different in composition from the galactic cosmic rays which are well known to be rich in the heavy elements. The possible significance of these results will be discussed in some detail in the next two sections of this paper, i.e. III and IV.

Kurnosova, Razorenov, and Fradkin (1962) have reported a few increases of heavy nuclei above cosmic ray background in the relativistic region lasting on the order of two to twenty minutes and not associated with a solar particle event of the usual variety. These measurements were made on a satellite with a Cerenkov counter system. Although other experiments which would have detected this type of increase have been flown (McDonald, 1965), no other increase of relativistic heavy nuclei has been reported. Since these events are apparently of a different nature from the low energy solar particle events being discussed here and nothing more is yet known about them, they will not be treated further.

C. ISOTOPIC COMPOSITION OF SOLAR HYDROGEN AND HELIUM NUCLEI

As mentioned earlier, protons are by far the most abundant singly charged nuclei. However, experiments have been performed to look for the possible presence of deuterons and tritons. Attempts to detect deuterons have been made in four events. In a rocket flight on November 12, 1960, Biswas et al. (1962) found the deuteron to proton ratio was less than 3×10^{-3} in the energy interval from 25 to 48 Mev/nucleon and subsequently Freier and Waddington (1964b) found a limit of

2×10^{-3} in the interval above 50 Mev/nucleon in the July 18, 1961 event. Both of these measurements were made with nuclear emulsions. McDonald et al. (1965) found the proton to deuteron ratio to be about 5×10^{-3} for protons with energies from 15 to 75 Mev and deuterons with energies from 20 to 100 Mev in both the March 16, 1964 and February 5, 1964 events. Since the particle energy spectra decreases rapidly with energy, the proton to deuteron ratio in the same energy nucleon interval is somewhat less than this number, but still finite. These particles were detected in the IMP scintillation counter telescope mentioned previously. Perhaps it is important to note that the latter two events in which deuterons were actually seen were small events during a period near solar minimum, whereas the other two events were much larger ones.

Small quantities of tritium were detected by radiochemical studies of materials recovered from a satellite and sounding rockets flown in the November 12, 1960 event (Fireman et al., 1961 and Tilles et al., 1963). The observed particles represent the combination of tritons formed in interactions in the material above the detector, tritons temporarily trapped in the radiation belts, and any primary tritons which might be present. In trying to make a quantitative estimate of the triton abundance, the situation is further complicated by having no direct measure of the integrated proton flux in the case of the satellite, Discoverer 17. Assuming the majority of the tritons are

solar, as Tilles et al. suggest, and an integrated proton flux above 30 Mev of between $10^9/\text{cm}^2$ (estimated by the authors on the basis of riometer data and direct particle measurements at a few times during the event) and 4×10^9 (estimated by Lal, Rajagopalan, and Venhatavaradan, 1963, from radiochemical data) a triton to proton ratio of $(1 \text{ to } 4) \times 10^{-3}$ above 30 Mev/nucleon is obtained. Lal et al. (1963), on the basis of radioactivity data, concluded that more than 80% of the tritons were secondaries, in which case the ratio might be as small as 2×10^{-4} . In a sounding rocket payload Tilles et al. (1963) measured an integrated triton flux of about $8 \times 10^4/\text{cm}^2$ in the energy interval from approximately 0 to 27 Mev/nucleon. From the scintillation counter results of Ogilvie et al. (1962), the integrated flux of protons in the energy interval from 2 to 27 Mev was about $8 \times 10^7/\text{cm}^2$ during the rocket flight. Therefore, the ratio H^3/H^1 is $\leq 10^{-3}$ for solar particles in the energy range from approximately 0 to 27 Mev/nucleon. Direct measurements by Biswas et al. (1962) in nuclear emulsions flown in the same sounding rocket on November 12, set an upper limit to the triton flux in the interval from 20 to 45 Mev/nucleon of $< .7 \text{ H}^3/\text{cm}^2 \text{ ster sec}$. The flux of protons measured in the same flight (Biswas et al., 1962) was $0.9 \times 10^3 \text{ protons}/\text{cm}^2 \text{ ster sec}$ in the same interval (20-45 Mev). Therefore, the triton to proton ratio was $\leq 10^{-3}$ in the energy interval 20-45 Mev/nucleon. In the July 18, 1961 event, Freier and Waddington (1964b) using nuclear emulsions flown on a balloon, set an upper limit to the triton to proton ratio of 0.6×10^{-3} in the energy region above 50 Mev/nucleon.

On the basis of the above analysis, we feel that the present experimental results indicate that the deuteron to proton ratio for solar particles in the approximate interval from 10 to 10^2 Mev/nucleon is on the order of a (few) $\times 10^{-3}$ or less and the triton to proton ratio is probably less than 10^{-3} . Variations in these ratios from event to event probably occur; so there is nothing too surprising about the limit in one event being more severe than the ratio measured in another. The ratio might also be expected to vary with the velocity interval.

Relatively little is known for certain about the relative abundance of the helium isotopes. Schaeffer and Zahringer (1962) reported the presence of He^3 in a radiochemical study of some of the components of the Discoverer 17 satellite and estimated the He^3/He^4 ratio to be 0.2 with an uncertainty of a factor of three. However, they observed larger concentrations of He^3 at greater depths of material. This result is surprising if the majority of these particles are primaries because the steep energy spectrum should have predominated over any effect of the variation of the geomagnetic cutoffs with satellite position to give a decreasing He^3 flux with depth. Further, the abundance of He^3 in the experiment mentioned corresponds to a flux which seems to be about ten times larger than the total helium flux in the energy range from 40 to 105 Mev/nucleon estimated from the work of Biswas et al. (1962), namely about 4×10^7 He/cm^2 . Because of these uncertainties, it seems best not to state a He^3/He^4 ratio at this time.

D. ELECTRONS

The abundance of very energetic electrons is expected to be small due to the high rate of energy loss by synchrotron radiation at large relativistic energies; so, even if there were large numbers of these energetic electrons initially, they would soon lose their energy.

Although the flux of very energetic solar electrons is known to be relatively small, appreciably less than the proton component, positive evidence for electrons does exist for at least one event (Meyer and Vogt, 1962). In the July 18, 1961 event, the flux of electrons greater than 100 Mev was measured to be $0.04 \text{ el./}(\text{cm}^2 \text{ster sec})$, or a few percent of the proton flux in the same kinetic energy region. In other events, September 3, 1960 (Meyer and Vogt, 1962; Earl, 1962), November 12, 1960 (Yates, 1963), and November 15, 1960 (Ney and Stein, 1962), and March 16, 1964 (Cline, Ludwig and McDonald, 1964), there was no positive of electrons. On September 4, 1960, Earl (1962) obtained an upper limit of 0.0025 for the rigidity interval greater than 450 Mev/c; the other limits in a similar rigidity range are less severe. During the March 16, 1964 solar event the 3 to 8 Mev electron flux increased less than 50% while the 15 to 75 Mev proton flux increased by several orders of magnitude (Cline et al., 1964). Considering the flux levels and the general shape of the spectra, these results suggest an electron to proton ratio at about 5 Mev of much less than 1%.

In addition to the experiments related to direct measurements at the earth, Stein and Ney (1963) have shown that the continuum electromagnetic radiation from large solar flares is consistent with the

interpretation that this radiation is due to the synchrotron radiation of electrons. They have further shown that the number of electrons needed to produce the observed intensity is of the same order as the estimated number of protons accelerated in a large solar flare and that the necessary magnetic field is of the order of 500 gauss, which seems to be a conservative estimate of typical field strengths (Aller, 1953). Therefore, present indications suggest that in fact the electrons are accelerated at the sun along with the protons, but lose their energy quickly by synchrotron radiation so that only a relatively few high energy electrons ever reach the earth.

Relatively large fluxes of low energy electrons (kinetic energy > 1 Mev) have also been observed. Hoffman et al. (1962) detected 3×10^6 el/(cm² ster sec) between 10 and 35 kev. for about ten minutes on September 30, 1961, associated approximately with the arrival of the sudden commencement. Except for that period the flux was less than the detectable limit of 2×10^5 el/(cm² ster sec).

E. NEUTRONS

No positive evidence is available at present for neutrons of solar origin. Anderson et al. (1959) obtained an upper limit of 0.02 for the ratio of neutrons above 120 Mev to protons above 100 Mev in a study during the August 22, 1958 solar particle event. Energetic neutrons are not particularly expected, because, being uncharged, the most likely acceleration mechanisms will have no effect on them. However, the need for more experiments in this area is clearly evident.

The possibility of solar neutrons from secondary processes during relatively quiet solar periods has been suggested in the literature.

This question arose in connection with the apparent observation of a continuous quiet time flux of protons of energy less than ~ 200 Mev which was steady for a time period of several weeks during the years 1960 and 1961 when solar activity was relatively high (Meyer and Vogt, 1963a; and Stone, 1964). Satellite experiments seem to indicate that in 1961 the differential flux was almost constant from about 10 to 130 Mev (Stone, 1964), and the results of Meyer and Vogt suggested the possibility of a rising spectra at low energies. In order to explain this phenomena, Simpson (1963) suggested that these low energy protons could be decay products of neutrons emitted from the sun. These solar neutrons might be produced, if protons and He particles were accelerated more or less continuously and suffered collisions deep in the solar atmosphere. The neutron flux expected on the basis of this hypothesis has been calculated under various assumptions (Lingenfelter and Flamm, 1964). However, there is strong evidence resulting from nuclear emulsion experiments flown on balloons to indicate that in the years 1960 and 1961 there was not a continuous quiet time flux (Freier and Waddington, 1965; Fichtel, Guss, Stevenson, and Waddington, 1964), and further there has been a systematic difference, where comparisons are available between the results of Meyer and Vogt and other experimentalists in the years 1962 through 1964 (Brunstein, 1964; Fichtel, Guss, Kniffen, and Neelakantan, 1964; Balasubrahmanyam, and McDonald, 1964; Freier and Waddington, 1964a; Ormes and Webber, 1964; Fichtel, Guss, and Durgaprasad, 1965; McDonald and Ludwig, 1964; Meyer and Vogt, 1963b).

III. RELATIONSHIP OF THE COMPOSITION OF SOLAR COSMIC RAYS TO OTHER ASTROPHYSICAL PROBLEMS

In this section, the significance of the experimental data will be discussed in terms of four related problems. The first of these is the study of the propagation of solar particles in interplanetary space and the bearing of the composition data on this problem. Then, going back a step farther in the solar particles' history, a look will be taken at the acceleration of high energy solar particles. Thirdly, the relationship of the solar cosmic ray composition to that of the sun will be examined. Finally, there will be a discussion of the difference between the composition of the solar and galactic cosmic rays in detail in order to try to understand the importance of these differences in terms of the particles' origin and history.

A. PROPOGATION OF SOLAR PARTICLES

Beginning now with the propagation, there are two aspects which will be given some attention. The first is the type of propagation which occurs and the second is the amount of material which the particles have traversed before reaching the earth.

With regard to the former, it is realized now that the propagation of solar particles is not a simple matter. The function which describes the rise and fall of the particle intensity and the energy spectrum in principle, can depend on the particle velocity, rigidity, positron, and direction. Since the multiply charged particles have a different charge to mass ratio by a factor of two from that of the protons, they also have a very different rigidity from that of the protons for a given velocity. Thus, if the absolute differential energy spectra of

both protons and helium nuclei, for example, could be measured throughout an event, together with their angular distribution, very significant insight could be obtained into the propagation characteristics because comparisons of fluxes at the same time could be made rather than having to compare fluxes of different velocities at different times as is the case of singly charged particles. In the last case, variations of the interplanetary conditions as a function of time can further complicate the picture. Unfortunately, only a few simultaneous measurements of the spectra of the two types of particles exist.

Even with these limited data, however, it seems clear that a purely rigidity dependent propagation can be excluded. As was shown earlier, the proton to helium ratio in the same rigidity intervals has been seen to vary appreciably from one time in a given event to another. Further, this ratio has varied very markedly from one event to another, while the helium to medium ratio has been the same in each of the three events it was measured.

Therefore, other general classes of propagation besides the pure rigidity one must be examined. One approach to the problem was the development of a simple diffusion model for solar cosmic rays wherein the scattering centers were magnetic inhomogeneities (Parker, 1956; Meyer, Parker, and Simpson, 1956; Parker, 1963b). Although the diffusion coefficient in general can depend on both the particle's velocity and rigidity, Parker suggests that the propagation depends primarily on its velocity below 1 Bev in the inner solar system because in this region the radius of gyration is less than the scale length of the

magnetic field disordering. Considerable experimental evidence has now been accumulated to indicate that the time history of the energy spectrum does follow approximately the predictions of simple diffusion equations (Bryant, Cline, Desai, and McDonald, 1962; Hoffman and Winckler, 1963; Bryant, Cline, Desai and McDonald, 1965; Krimigis, 1965) and that at least early in an event the propagation is primarily velocity dependent (Bryant et al., 1962; Biswas et al., 1962; Bryant et al., 1965).

During the declining phase, a somewhat different picture appears. The fact that an exponential decay of particle flux is often, or usually, seen late in an event (Webber, 1964; Bryant et al., 1962) suggests that particles are escaping from the region in which they are being held (Parker, 1962). It is unlikely that this boundary is absolutely sharp, but rather consists of a volume in which the magnetic field irregularities are less frequent and weaker.

However, the primarily garden hose nature of the magnetic field which has now been measured (Ness, Searce, and Seek, 1964) cannot be ignored, and the diffusion theory must take into account the superimposed effects of magnetic irregularities and the semiregular fields. Theoretical calculations aimed at beginning to solve this problem have been made (Fibish and Abraham, 1965). One interesting result is the conclusion that the time history expected from other field configurations may bear many similarities to simple diffusion (Boldt, 1964). The anisotropy, however, can be very different.

Turning now to the amount of material traversed, there are a number of ways in which this parameter could be determined from the composition. These methods consist, for the most part, in measuring the abundances of some isotope or charge species which presumably exist in only a negligible amount on the sun, but is formed by fragmentation in the acceleration region or during the interplanetary propagation. Other less quantitative means of estimating the material traversed are related to the study of the energy spectra and relative abundances of various components. In the next several paragraphs the estimates of the amount of material traversed using several different approaches will be discussed.

The upper limit to the relative abundances of Be and B nuclei given in Table 5 sets a limit on the number of these nuclei which could have been formed by the fragmentation of S nuclei (nuclear charge ≥ 6). In accordance with the available data on cross sections and the analysis used to supplement the existing data presented by Badhwar, Daniel, and Vijagalakshmi (1962) and Badhwar and Daniel (1963), the cross-sections for producing Be and B from C, N, O, and Ne at 55 Mev/nucleon (the mean of the experimental results) are 320, 133, 100, and 40 mb respectively. The uncertainties of these values could be as high as a factor of about two. The contribution from $Z \geq 10$ nuclei is small. Using the relative abundances of solar particle radiation as given in Table 5, the above cross-section values, and the observed limit of the abundance of Be and B, the amount of matter traversed is found to be $< 0.1 \text{ gm/cm}^2$ of H. Assuming the uncertainty of the cross-section

to be a factor of two, the limit becomes $< 0.2 \text{ gm/cm}^2$ of hydrogen.

Tritons are another particle species which must be formed primarily by fragmentation. Using the cross-section data assembled by Tilles et al. (1963) and Flamm et al. (1962) and a H to He ratio of 20, which seems typical for the energy interval of interest, the limit to the H^3/H^1 ratio obtained earlier, namely $< 10^{-3}$, gives an upper limit to the amount of material traversed of 0.5 gm/cm^2 . In this calculation, $\sigma[\text{He}^4(\text{p,d})\text{H}^3]$ was assumed to be 30 mb.

In the events where only an upper limit could be set to the deuteron flux the results are similar, and, in the two events where a small deuteron flux was observed, the calculated amount of material would be about the same as the upper limit in the other events or a little larger. However, this approach may not be too meaningful for the events in which McDonald et al. (1965) detected deuterons because the upper limit to the helium flux is so small ($\text{H}^1/\text{He}^4 > 200$) that it seems very unlikely that deuterons were formed by He^4 fragmentation, unless the helium nuclei are subsequently suppressed for some reason.

The ratio of He^3/He^4 in the solar beam is somewhat uncertain as previously discussed. However, if the accelerated solar particles traversed $< 0.1 \text{ gm/cm}^2$ of hydrogen, the cross-section data of Tilles et al. (1963) and Flamm et al. (1963) lead to a He^3/He^4 value of $< 3 \times 10^{-3}$. This value is about 70 times smaller than the reported value of 0.2, which had an uncertainty of a factor of three. The observed value gives the amount of matter traversed as 6_{-4}^{+12} , which is inconsistent with other observations in the November 12, 1960 event.

However, as Fireman (1963) points out, it may also be possible that the He^3 were formed in thermonuclear reactions as suggested by Severniji and Shabanskii(1960). Energetic H^3 and He^3 can be produced in this way, but not H^2 nuclei which are the thermal energy parent particles.

There is other evidence which argues strongly against the amount of material traversed being as large as several gm/cm^2 in the large events. First, if the particles had passed through an amount of material approaching several gm/cm^2 , the source energy/nucleon spectrum of the medium nuclei would have to be substantially different from that of the helium nuclei with a very much steeper spectrum in the vicinity of 100 to 200 Mev/nucleon. Further, the $M/(Z \geq 10)$ ratio would be greater than the expected solar ratio rather than equal to it. It seems more reasonable to assume that the observed composition and energy spectra are a result of an unbiased acceleration of all nuclei rather than the coincidence of a biased acceleration and a just properly compensating amount of material traversed before reaching the earth. Finally, observations of solar proton spectra in the energy interval of about 2 to 80 Mev by detectors in satellites (Bryant, Cline, Desai, and McDonald, 1965) during several events do not show any flattening or decline of the proton spectrum below about 50 Mev, as would have occurred if the radiation had a smooth spectrum at the source and traversed a few gm/cm^2 of hydrogen. Bryant et al. (1965), in fact, suggest that the amount of material traversed may be less than .001 gm/cm^2 from studies of the proton energy spectrum.

If it is postulated that the amount of material traversed, after the acceleration phase has begun is less than a few tenths of a gm/cm^2 then this amount of material is not sufficient to affect the relative abundances of the multiply charged nuclei in the measured energy interval by a detectable amount. Further, it was shown earlier in this section that the relative abundances of particles with the same charge to mass ratio in a given velocity interval will remain unaffected by the propagation since they have the same velocity for a given rigidity. The constancy of the helium to medium ratio both with time and energy and the contrastingly large variations in the proton to helium ratio then strongly suggest that the medium and helium nuclei have the same ionized charge to mass ratio. The only reasonable conclusion then is that these nuclei are fully ionized, since it is not likely that oxygen nuclei would have four electrons removed and helium only one, for example. We are then led to the conclusion that the constancy of the relative abundances of the multiply charged component exists after the acceleration phase at the sun and before propagation to the earth.

The interesting question which immediately presents itself is whether or not the relative abundances of the multiply charged nuclei reflect those at the sun. This will be discussed after the next section's treatment on acceleration phenomena.

It should also be mentioned that if there is interplanetary acceleration, which presently seems to be small compared to the initial acceleration, it probably has the same characteristics as the acceleration at

the sun, which will be discussed in the next section. Therefore, it will have no effect on the above discussion of the constant ratios.

B. ACCELERATION OF SOLAR PARTICLES

The problem of the solar acceleration of particles to high energies is one that is far from solved. Various possible acceleration mechanisms have been examined in some detail previously (Parker, 1957; Parker, 1958; Alfven, 1959; Freier and Webber, 1963), and it has been concluded that there are three accelerating mechanisms which seem to be possibilities. They are the Fermi mechanism (Fermi, 1949; Fermi, 1954; Parker, 1958), the betatron effect (Alfven, 1959), and the magnetic field annihilation method including associated electric fields (Sweet, 1958; Dungey, 1958). Each of these three in turn permits a large number of variations depending on the individual model selected. In addition, there may be important special injection mechanisms, such as thermonuclear reactions (Severnji and Shobanskii, 1960).

The Fermi mechanism is divided into two phases, injection and acceleration which is achieved by particles being reflected from moving magnetic inhomogeneities. Since the energy necessary for injection in a given physical situation can be a function of the charge and atomic weight of the nucleus, it is possible to have a biased composition; however, if the effective temperature is such that the mean particle energy is greater than that necessary for injection, no bias will occur. The nuclei may be ionized in other ways, for example by high energy electrons; however, the expected electron density makes this latter possibility seem unlikely. In the subsequent accele-

ration, the first order Fermi theory leads to a particle spectrum which is a function of velocity only, regardless of its charge to mass ratio— it being only necessary that the particle be charged. Previously it has been shown (Biswas, Fichtel, and Guss, 1962) that in a particular situation such as the sun one can obtain a spectrum which is both a function of velocity and rigidity, with a particle having a smaller charge to mass ratio having a steeper energy spectrum at high energies. This modified Fermi mechanism would lead to similar spectra for all the nuclei with the same charge to mass ratio but different spectra for protons and helium nuclei, as observed.

The study of the problem of acceleration of cosmic rays has also been investigated by Hayakawa, Nishimura, Obayashi, and Sato (1965). For solar cosmic rays, they conclude that the Fermi process predominates for the acceleration of nuclear particles in the non-relativistic region. The injection energy is assumed to be 10^3 ev corresponding to a thermal energy for which $T = 10^7$ °K, which is large, but possibly present in the source region. The energy gain then proceeds in the normal Fermi manner by the particles having collisions with magnetic irregularities moving with Alfvén velocities, and the rate of change of energy is proportional to the total energy. This process ends when the particle escapes from the accelerating region. Their calculation shows that the final rigidity is proportional to M/Z and is therefore the same for all multiply charged nuclei, but is different for protons and helium nuclei, for example. Their theory is also consistent with an exponential spectrum at low rigidities.

A number of attempts have been made to find an astrophysical situation in which betatron acceleration can occur. Parker (1958) suggests that realistic calculations for sunspot regions indicate that the betatron effect by itself is not an important process because the energy gained is too small and the process is reversible. Even, if one includes a scattering effect to partially eliminate the complete reversibility, as Alfven (1959) has, the betatron effect still does not seem too likely because of the necessity of having to go through several cycles of very large scale magnetic field fluctuations in a relatively short time.

The magnetic field annihilation-electric field acceleration method has not been pursued very far generally because of the difficulty in understanding how it would be possible to obtain the necessary acceleration in a region whose physical parameters are similar to those which the photosphere, the chromosphere, or even the corona are thought to have. An excellent discussion of this problem is given by Parker (1963a).

Recently, McDonald et al. (1965) have suggested the possibility of a two-phase acceleration, in which the particles gain some energy while passing through a considerable amount of material in the first phase and then pass through relatively little during the final phase. This type of process would explain the presence of H^2 , H^3 and He^3 and yet permit a smooth steep final proton spectrum and similar heavy nuclei spectra. The possible variation in composition among H^1 , H^2 , H^3 and He^4 suggests there may be important differences in the

acceleration processes in different events. A complete picture remains to be developed, but these ideas should perhaps be explored further.

In general, the study of the multiply charged nuclei can aid greatly in the examination of the acceleration problem because it provides some definite facts which any proposed mechanism must explain. The results on H^2 , H^3 , and He^3 must certainly be accounted for. Further, since the discussion in the preceding section indicated that the propagation mechanism probably would not affect the relative abundances of the multiply charged nuclei within a given velocity interval, the following features related to the observed characteristics then also apply to the particles immediately after acceleration. Firstly, the multiply charged nuclei have had the same relative abundances in the same velocity intervals within uncertainties each time a measurement was made, whereas this has not been true for the protons and helium nuclei which have different charge to mass ratios. Secondly, insofar as comparisons can be made this composition reflects that of the sun. Thirdly, the helium and medium nuclei have had the same energy per nucleon spectrum in the two events where measurements could be made at the same time, whereas the proton and helium nuclei spectra in the same events were very different.

These results place important restraints on any acceleration theory and should aid in determining the true accelerating mechanism. For a further discussion of the solar particle acceleration problem,

besides the references already mentioned see Dungey (1964), Gold (1964), Jaggi (1964), Parker (1957), Parker (1964), Petschek (1964), Severney (1960), Sweet (1964), and Wentzel (1964).

Finally, a tentative estimate of the time of acceleration may be obtained in the following manner. Assume that the solar cosmic rays have not passed through more than 0.1 gm/cm^2 , i.e., 6×10^{22} atoms of hydrogen/ cm^2 , during the final acceleration phase as indicated by some of the data presented earlier. Since the amount of material traversed in interplanetary space is negligible compared to that in the solar atmosphere, this limit for the material traversed applies to the solar region. The density of matter at the flare site is poorly known, but has been estimated as being $10^{11} - 10^{13}$ atoms of hydrogen/ cm^3 (Gold and Hoyle, 1960; and Parker, 1957). A particle with an average energy between 10 and 50 Mev/nucleon has a velocity between 0.4×10^{10} and 1.0×10^{10} cm/sec. Hence, the acceleration time with these assumptions is not more than a few minutes and probably less. On the other hand if the amount of material traversed were of the order of 3 gm/cm^2 , the time would be in the range from .3 to 70 minutes. However, since the early phase of the acceleration may occur in the more dense regions, the lower limit may be closer to the true value.

C. RELATION TO SOLAR COMPOSITION

There are a number of pieces of experimental data which suggest that the abundances of the multiply charged nuclei in the range ($2 \leq Z \leq 20$) reflect those of the sun. Before processing further, these features will be summarized. First, the experimentally observed

values for the relative abundances of the multiply charged energetic solar particles were the same as those obtained by spectroscopic means for those nuclei where a comparison could be made, namely carbon, nitrogen, oxygen, and some of the larger nuclei, and the upper limit of the Be and B flux was certainly consistent. The results show further that within the uncertainties the same relative abundances of helium, carbon, oxygen, neon, and larger nuclei have been obtained in a total of five exposures in two different events. Also, in a third event, when the fluxes were very small, at least the ratio of helium to medium nuclei was the same. Next, the helium nuclei are seen to have the same energy per nucleon, or velocity, spectrum as the medium nuclei at five times in two different events, every case when a measurement could be made. This is very good evidence to support the contention that they also have similar velocity spectra at the source. This last result together with the very different velocity spectra for protons suggest that the helium and medium nuclei were affected in the same way by the acceleration process.

Thus, the energetic solar nuclei coming from the sun with charges ranging from that of helium through at least about twenty do seem to reflect the composition of the solar surface. If the composition of these nuclei is accepted as representative of the sun, the relative abundances given in Table 5 may be used to estimate the helium and neon abundances in the sun, whereas it is not possible to obtain a good estimate of the abundance of these two elements spectroscopically in the photosphere. The average helium to oxygen ratio is 107 ± 14 and

the average neon to oxygen ratio is 0.13 ± 0.02 (Biswas and Fichtel, 1963). The neon to oxygen ratio is similar to the universal abundances estimated by Suess and Urey (1956) and Cameron (1959), although a bit on the low side. The helium to medium ratio is typical, but of course, the more interesting ratio would be the proton to helium one. For the reasons mentioned above associated with the different energy spectra and charge to mass ratio, there is no simple reliable way to determine this ratio from solar cosmic rays alone. If the helium to medium ratio of 60 ± 7 is accepted as representative of the sun and the proton to medium value from spectroscopic data, namely 650 (Aller, 1961; Goldberg, Muller, and Aller, 1960), is used, a proton to helium ratio of 11.5^{+7}_{-5} is obtained. The uncertainty in this number depends on the correctness of the assumption above and the uncertainty in the proton to medium ratio. Hence, the estimated error placed on this ratio is large.

It is beyond the intended scope of this review article to discuss the relationship of these abundance ratios to solar models. Sears (1964) has discussed this question in some detail, and the reader is referred to this article.

D. RELATION TO GALACTIC COSMIC RAYS

Until a few years ago, it was generally accepted that most stars could not be important sources of cosmic rays for a number of reasons. Within the last several years it had been noted that, since the sun produced large quantities of particles whose energies were well above the injection energy needed for the Fermi theory to be operative in

the galaxy (Fermi, 1949; Fermi, 1954), it might be possible that ordinary stars were an important source of cosmic rays. Relatively generous estimates of particle production by the stars indicated that protons could be supplied at a rate sufficient to account for the ordinary cosmic rays, and these particles could then be accelerated in the galaxy by the Fermi method. There remained the problem of the charge composition of cosmic rays being different from normal stellar abundances, but it was thought that there might possibly be favorable acceleration of the larger nuclei.

The results of the experiments on the multiply-charged component have shown that their abundances are just a reflection of those in the sun. There are at least four important differences within the heavy nuclei group between solar cosmic rays and ordinary cosmic rays. Two of these, the carbon to oxygen ratio of $3/5$ in solar cosmic rays compared to $3/2$ in ordinary cosmic rays and the light to medium ratio of $< 1/100$ in solar cosmic rays compared to $1/4$ in ordinary cosmic rays may be attributed to the fact that ordinary cosmic rays have gone through a few gm/cm^2 of material wherein the light nuclei are formed by fragmentation, and there is at least an increase in the carbon to oxygen ratio. Also relatively minor variation in the source composition may aid in explaining the inverse C/O value. The other two, the different helium to medium nuclei ratios and the different ratios between the helium nuclei and those in the high charge group are only enhanced by fragmentation. The helium to medium nuclei ratio is more than four times larger for the accelerated solar particles, about

(60 ± 7):1 as compared to (14 ± 2):1 for ordinary cosmic rays, and the ratio of the helium nuclei to those in the charge group with $11 \leq Z \leq 18$ is (803 ± 93):1 in the solar cosmic rays as compared to (48 ± 7):1 in the galactic cosmic rays—a difference of 16 ± 3 . Finally, the helium to iron nuclei ratio is $\leq 5 \times 10^3$ in the solar cosmic rays compared to 171 ± 26 in the galactic cosmic rays—a difference of more than 25.

At galactic cosmic ray injection energies, the proton to medium ratio in solar cosmic rays is seen to be approximately $1:10^3$ or larger. The proton to medium ratio for ordinary cosmic rays is about 250 for the same energy per nucleon intervals at very high energies and 100 for the same rigidity intervals. Thus, the proton to medium ratio for solar cosmic rays is 4 to 10 times the ordinary cosmic ray ratio and the difference would be slightly increased by fragmentation in interstellar matter. The differences in the ratios of the proton flux to that of either the medium nuclei or heavier nuclei are much greater as can be seen by an examination of the ratios in the previous paragraph.

Thus, since the sun has abundances typical of most ordinary stars* in the respects mentioned here and since these abundances are reflected in solar cosmic rays, it seems reasonable to conclude that the difference in the charge composition between galactic cosmic rays and ordinary stars* being considered as the sole primary source of galactic cosmic rays. Thus, galactic cosmic rays probably have a very special origin, perhaps in supernovae [See for example Ginzburg and Syroratsky (1961)].

*Here the term ordinary star refers to the great majority of stars with normal cosmic abundances and specifically excludes the unusual ones such as nova and supernovae which may be important cosmic ray sources

IV SUMMARY

The general features of the solar particle composition now seem to be clear. The two most abundant components, protons and helium nuclei, have different velocity spectra, similar, but not exactly identical rigidity spectra, and varying relative abundances. The multiply charged nuclei, on the other hand, appear to have the same spectral shape and relative abundances each time measurements are made, at least in the region from 42 to 135 Mev/nucleon. Further, these relative abundances seem to reflect those of the sun insofar as comparison can be made. Electrons are rare, but high energy electrons are not expected to be plentiful due to the probable high rate of energy loss caused by synchrotron radiation at the sun. Energetic neutrons were also not expected in large quantity and have not been observed. Finally, there is positive evidence that very small quantities of deuterons and tritons exist, probably in an amount which is about 10^{-3} or less of the proton abundance.

The experimental data indicate that the propagation phenomenon is not purely rigidity dependent. Although the propagation of solar particles is still not well understood, the development of theories which take into account both the general magnetic field and the inhomogeneities in the field seem to hold some promise of explaining the experimental results. The composition data have also established important restraints which any acceleration theory must satisfy, and thereby contributed greatly to the very difficult problem of determining the acceleration mechanism.

The similarity of the relative abundance of the energetic solar particles and the nuclei in the sun's photosphere suggested the possibility of having a new means of estimating the solar neon and helium abundances. This very interesting possibility will have to be explored by further testing of the composition of future solar particle events. Finally, it was seen that the composition was a very strong argument against most stars being the principal source of high energy non-solar cosmic rays, and, therefore, special sources, such as supernovae or possibly quasistellar objects, should be considered as much more likely prospects for the origin of cosmic rays.

The results which have been obtained thus far on the composition of solar cosmic rays have indicated that further research in this area of study should be very rewarding and of value to many fields of physics. Further data on the composition and relative, as well as absolute, energy spectra of the various components are needed throughout many events. More experiments also should be performed to determine the properties of the rare components, deuteron, tritons, He^3 , electrons, neutrons, and the heavier nuclei. When these experiments are complete, the knowledge which is needed to aid in answering the solar and astrophysical problems discussed in this review should be at hand.

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Table 1

Values of γ (Equ. 1) and R_0 (Equ. 2) of Energy/nucleon and Rigidity Spectra ofProton, Helium and Medium nuclei

Time of Measurements	γ			R_0		Ref. ⁺
	P	Helium	Medium ($6 \leq Z \leq 9$)	P	He & M	
1408 UT & (0930 - 1700)UT, Sept. 3, 1960	-11.9 ± 0.4	-27.0 ± 2.1	-	169.6 ± 6.9	$132.6 \pm 7.2^*$	a,b,c
1840 UT, Nov.12, 1960	-20.7 ± 2.4	-56.3 ± 7.2	-61.8 ± 9.6	119.3 ± 7.0	103 ± 9.9	c,d
1603 UT, Nov.13, 1960	-37.4 ± 2.2	-59.7 ± 8.2	-64.4 ± 8.9	78.0 ± 3.9	109.2 ± 6.7	c,d
1030-1230 UT Nov.15, 1960	-	-	-	175	$\sim 175^*$	e
1430-1730 UT Nov.16, 1960	-	-	-	100	$> 100^*$	e
1951 UT, Nov.16, 1960	-26.5 ± 3.4	-70.8 ± 10.8	-63.8 ± 8.4	103.3 ± 10.0	107.2 ± 10.4	c,f
0600 UT, Nov.17, 1960	-32.4 ± 2.1	-63.8 ± 9.9	-71.0 ± 11.0	89.7 ± 5.7	102.9 ± 12.4	c,f
0339 UT, Nov.18, 1960	-36.7 ± 2.6	-60.8 ± 8.4	-60.7 ± 12.3	81.3 ± 6.4	113.9 ± 15.5	c,f
1535-1750 UT July 18, 1961	-	-	-	160	$\sim 160^*$	8
2110-2330 UT July 18, 1961	-	-	-	125	$\sim 125^*$	8

* He nuclei only

+ (a) Fichtel and Guss (1961)

(b) Biswas, Freier and Stein (1961)

(c) Biswas, and Fichtel (1963)

(d) Biswas, Fichtel and Guss (1962)

(e) Ney and Stein (1962)

(f) Biswas, Fichtel, Guss and Waddington (1963)

(g) Freier and Webber (1963)

Table 2

Proton to Helium and Proton to Medium Nuclei Ratios

Flare date & onset Time	Date and Time of measurement UT	Vehicle	Energy Interval, E, in MeV/nucleon	R(P,He,E)*	Rigidity Interval, R, in BeV/c	R(P,He,R)*	R(P,M,R)*	Ref
July 10, 1959 0210 UT	July 11, 0755 -1625	Balloon	≥ 80	59 ± 6	≥ 0.79	1.4 ± 0.2	-	g,h
	July 12, 1225 -2345	Balloon	≥ 80	430 ± 70	≥ 0.79	5.0 ± 0.8	-	g,h
	May 4, 1700 - (5)0200	Balloon	-	-	0.7 -1.6	≥ 50	-	g,i
	Sept 3, 0930 -1700	Balloon	-	-	0.4 -0.6	31	-	b
Sept 3, 1960 0037 UT	Sept 4, 1650 -2320	Balloon	115-180	> 185	0.4 -0.6	19	-	b
	Sept 3, 1408	Rocket	42.5-95	43 ± 14	0.57-0.87	20 ± 7	1100 ± 380	a,f
	Nov 12, 1840	Rocket	42.5-95	32 ± 6	0.57-0.87	5 ± 1	300 ± 55	d
	Nov 13, 0400	Satellite	-	-	1.5 - 2	-	$\sim 260^{***}$	j
Nov 12, 1960 1322 UT	Nov 13, 0543	"	-	-	2 - 2.5	-	$\sim 260^{***}$	j
	Nov 13, 1603	Rocket	42.5-95	36 ± 7	0.57-0.87	1 ± 0.2	68 ± 14	d

Table 2 Continued

Nov 13, 2306	Satellite	-	-	-	-	1.1-1.9		~ 260	j
Nov 15, 0024	"	-	-	-	-	1.0-1.2		260 ***	j
Nov 15, 1030-1230	Balloon	-	-	-	-	0.81-1.08	1	~ 100 **	e
Nov 15, 1430-1730	Balloon	-	-	-	-	> 0.8	1.6	-	e
Nov 16, 1951	Rocket	42.5-95	23 ± 5	1410 ± 200	0.57-0.87	1.7 ± 0.5	100 ± 23	f	
Nov 16, 1951	Rocket	3 - 17.5	9.5 ± 2.5	-	0.15-0.36	1.6 ± 0.6	-	k	
Nov 16, 1951	Rocket	0.55-2.5	-	-	0.064-0.137	3.7 ± 0.9	-	k	
Nov 16, 2338	Satellite	-	-	-	.85-1.5	-	~ 260 ***	j	
Nov 17, 0600	Rocket	42.5-95	59 ± 13	2230 ± 370	0.57-0.87	2.5 ± 0.6	95 ± 19	f	
Nov 17, 2314	Satellite	-	-	-	.6-1.0	-	~ 1000 ***	j	
Nov 18, 0339	Rocket	42.5-95	51 ± 11	2720 ± 560	0.57-0.87	1.7 ± 0.5	92 ± 24	f	
July 18, 1535-1750 UT	Balloon	-	-	-	.8-1.3	6 ± 1	-	g, 1	
July 18, 1305-1918 UT	Balloon	115 - 195	-	(1.9 ± .6) 10 ⁴	.95-1.27	-	212 ± 68	m	
July 18, 2110-2330 UT	Balloon	-	-	-	.8-1.3	6 ± 1	-	g, 1	
Most of event	Satellite	15-75	> 200	-	-	-	-	n	
Mar 16, 1964 1555 UT									
Feb 5, 1965 1750 UT	Satellite	15-75	> 200	-	-	-	-	n	

Table 2 Continued

* $R(i,j,k)$ is the ratio of the flux of particles of type i in the interval k to the flux of particles of type j in the same interval.

** Rigidity interval for M-nuclei was 1.18 - 1.45 BV

*** $R(P,M+H,R)$

(a) Fichtel and Guss (1961)	(h) Freier (1962)
(b) Biswas, Freier and Stein (1961)	(i) Biswas and Freier (1961)
(d) Biswas, Fichtel and Guss (1962)	(j) Pomerantz and Witten (1962)
(e) Ney and Stein (1962)	(k) Davis and Ogilvie (1962)
(f) Biswas, Fichtel, Guss and Waddington (1963)	(l) Freier (1963)
(g) Freier and Webber (1962)	(m) Biswas, Fichtel, and Guss (1965)
	(n) McDonald, Balasubrahmanyam, Brunstein, Hagge, Ludwig, and Palmeira (1965)

Table 3

Helium to Medium Nuclei Ratio

Time of measurements	Energy Interval Mev/nucleon	$R(\text{He}, M, E)^*$	Ref ^{***}
1408 UT, Sept 3, 1960	42.5 - 95	68 ± 21	a, f
1840 UT, Nov.12, 1960	42.5 - 95	63 ± 14	d
1603 UT, Nov.13, 1960	42.5 - 95	72 ± 16	d
1951 UT, Nov.16, 1960	42.5 - 95	61 ± 13	f
0600 UT, Nov.17, 1960	42.5 - 95	38 ± 9	f
0339 UT, Nov.18, 1960	42.5 - 95	53 ± 14	f
<hr/> Average <hr/>	<hr/> 42.5 - 95 <hr/>	<hr/> 60 ± 7 <hr/>	
1030-1230 UT, Nov.15, 1960	175 - 280	$\sim 100^{**}$	e
1225-2345 UT, July 12, 1959	150 - 200	$\geq 100 \pm 35$	o

* $R(i, j, k)$ is the ratio of the flux of particles of type i in the interval k to the flux of particles of type j in the same interval.

** Uncertainty of the value is a factor to two.

*** (a) Fichtel and Guss (1961)
 (d) Biswas, Fichtel and Guss (1962)
 (e) Ney and Stein (1962)
 (f) Biswas, Fichtel, Guss and Waddington (1963)
 (o) Biswas (1962)

Table 4

Relative Abundances of Heavy Nuclei with a Base of 10 for

Oxygen, in the same energy per Nucleon Interval*

Nuclear charge	4 & 5	6	7	8	9	10	11 - 18
1840 UT, Nov 12, 1960	< 0.2	4.8 ± 1.0	1.7 ± 0.7	10	< 0.3	1.4 ± 0.5	1.1 ± 0.2
1603 UT, Nov 13, 1960	< 0.2	7.1 ± 1.5	1.9 ± 0.8	10	< 0.3	1.2 ± 0.5	1.6 ± 0.2
1951 UT, Nov 16, 1960	< 0.3	6.5 ± 1.3	2.9 ± 0.9	10	< 0.5	2.0 ± 0.8	1.2 ± 0.2
0600 UT, Nov 17, 1960	< 0.3	6.0 ± 1.8	2.1 ± 1.0	10	< 0.6	2.0 ± 1.1	1.7 ± 1.2
0339 UT, Nov 18, 1960	< 0.5	4.9 ± 1.9	1.0 ± 0.7	10	< 1	0.7 ± 0.7	1.0 ± 1.0
Average or best limit	< 0.2	5.9 ± 0.7	1.9 ± 0.4	10	< 0.3	1.5 ± 0.3	1.3 ± 0.4

* From Biswas Fichtel and Guss (1962) and Biswas, Fichtel, Guss and Waddington (1963).

Table 5
Relative Abundances of Nuclei Normalized to a Base
of 1.0 for Oxygen

Element	Solar Cosmic Rays	Sun ⁺	Universal ⁺ Abundances ⁺	Galactic Cosmic Rays**
^2He	107 ± 14	?	150	48
^3Li	-	$< 10^{-5}$	$< 10^{-5}$	0.3
$^4\text{Be}-^5\text{B}$	< 0.02	$< 10^{-5}$	$< 10^{-5}$	0.8
^6C	0.59 ± 0.07	0.6	0.26	1.8
^7N	0.19 ± 0.04	0.1	0.20	$\lesssim 0.8$
^8O	1.0	1.0	1.0	1.0
^9F	< 0.03	0.001	$< 10^{-4}$	$\lesssim 0.1$
^{10}Ne	0.13 ± 0.02	?	0.36	0.30
^{11}Na	-	0.002	0.002	0.19
^{12}Mg	0.043 ± 0.011	0.027	0.040	0.32
^{13}Al	-	0.002	0.004	0.06
^{14}Si	0.033 ± 0.011	0.035	0.045	0.12
$^{15}\text{P}-^{21}\text{Sc}$	0.057 ± 0.017	0.032***	0.024	0.13
$^{22}\text{Ti}-^{28}\text{Ni}$	$\lesssim 0.02$	0.006	0.033	0.28

+ The uncertainty of the values in this column is probably of the order a factor of 0.5 sec. Aller (1961) or Goldberg, Muller, and Aller (1961)

+ The uncertainty of the values in this column is hard to estimate, but is probably at least a factor of 0.5 in some cases. See Suess and Urey (1956) and Cameron (1959)

** The uncertainty of the values in this column varies from 10 to about 30 percent. See Waddington (1960)

*** A 5/2 ratio for the abundance of ^{16}S relative to ^{18}A was assumed, the relative abundance of ^{18}A being unknown.

Captions for Figures

Fig. 1. Differential rigidity spectra of solar protons, helium, and medium nuclei at 1951 UT, November 16, 1960 (Biswas, et al., 1963). O: Protons; Δ : He Nuclei; \square : (Medium Nuclei) 60

Fig. 2. Differential rigidity spectra of solar protons, helium, and medium nuclei at 1603 UT, November 13, 1960 (Biswas and Fichtel, 1963). O: Protons; Δ : He Nuclei; \bullet : (Medium Nuclei) 60

Fig. 3. Differential energy spectra of solar protons, helium, and medium ($6 \leq Z \leq 9$) nuclei as a function of total energy/rest energy at 1951 UT, November 16, 1960. Note that the abscissa is an expanded logarithmic scale (Biswas, et al., 1963). O: Protons; Δ : He Nuclei 10; \bullet : (Medium Nuclei) 600

Fig. 4. (a) Differential energy spectra for solar protons as a function of total energy for those instances where proton, helium, and medium spectra were observed simultaneously.

A - 1400 UT	Sept. 3, 1960	———○———
B - 1840 UT	Nov. 12, 1960	—·—△—·—
C - 1603 UT	Nov. 13, 1960	———□———
D - 1951 UT	Nov. 15, 1960	·····▽·····
E - 0600 UT	Nov. 16, 1960	—·—◇—·—
F - 0339 UT	Nov. 17, 1960	—·—●———

Captions for Figures (Continued)

Fig. 4. (b). Differential energy spectra for solar helium and medium nuclei as a function of total energy for those instances where proton, helium, and medium spectra were observed simultaneously.

	Time	He	M X 60
A -	1400 UT Sept. 3, 1960	—○—	—●—
B -	1840 UT Nov. 12, 1960	—□—	—■—
C -	1603 UT Nov. 13, 1960	—△—	—▲—
D -	1951 UT Nov. 16, 1960	—▽—	—▼—
E -	0600 UT Nov. 17, 1960	—◇—	—◆—
F -	0339 UT Nov. 18, 1960	—◐—	—◑—

Fig. 5. The proton-to-helium nuclei ratio as a function of kinetic energy per nucleon at several different times. For curves A through F, the curves represent data taken from the work of Biswas, et al., (1962), Biswas, et al., (1963), Biswas, (1961), and Biswas and Fichtel, (1963). Uncertainties in the ratios range from 25 to 50 per cent. The data represented by G are the lower limits set by McDonald, et al., (1965). The times at which the measurements were made are as follows: A - 1840 UT, Nov. 12, 1960; B - 1603 UT, Nov. 13, 1960; C - 1961 UT, Nov. 16, 1960; D - 0600 UT, Nov. 17, 1960; E - 0339 UT, Nov. 18, 1960; F - 1408 UT, Sept. 3, 1960; G - March 16, 1964 and Feb. 5, 1965.

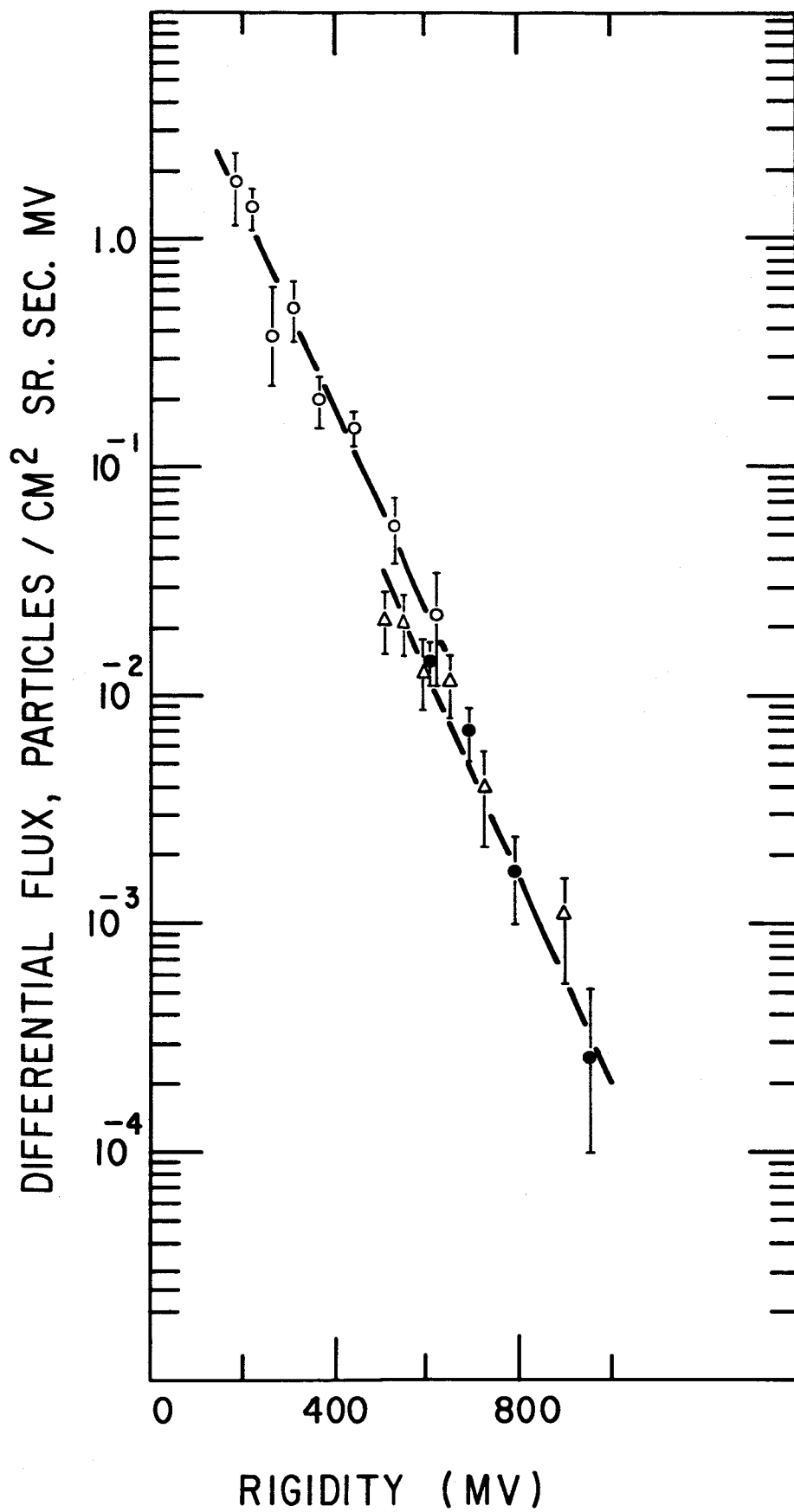


fig.1

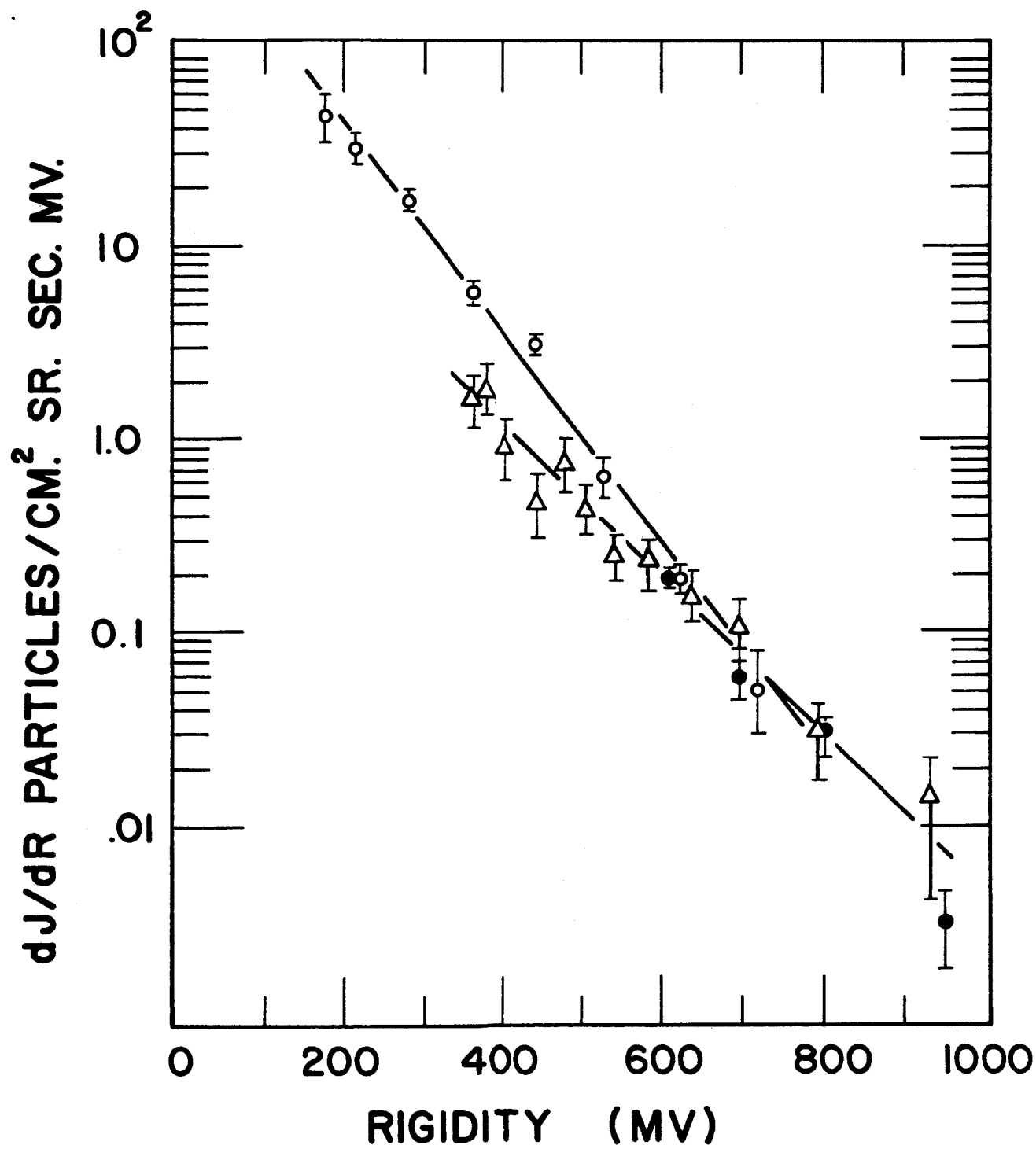


fig. 2

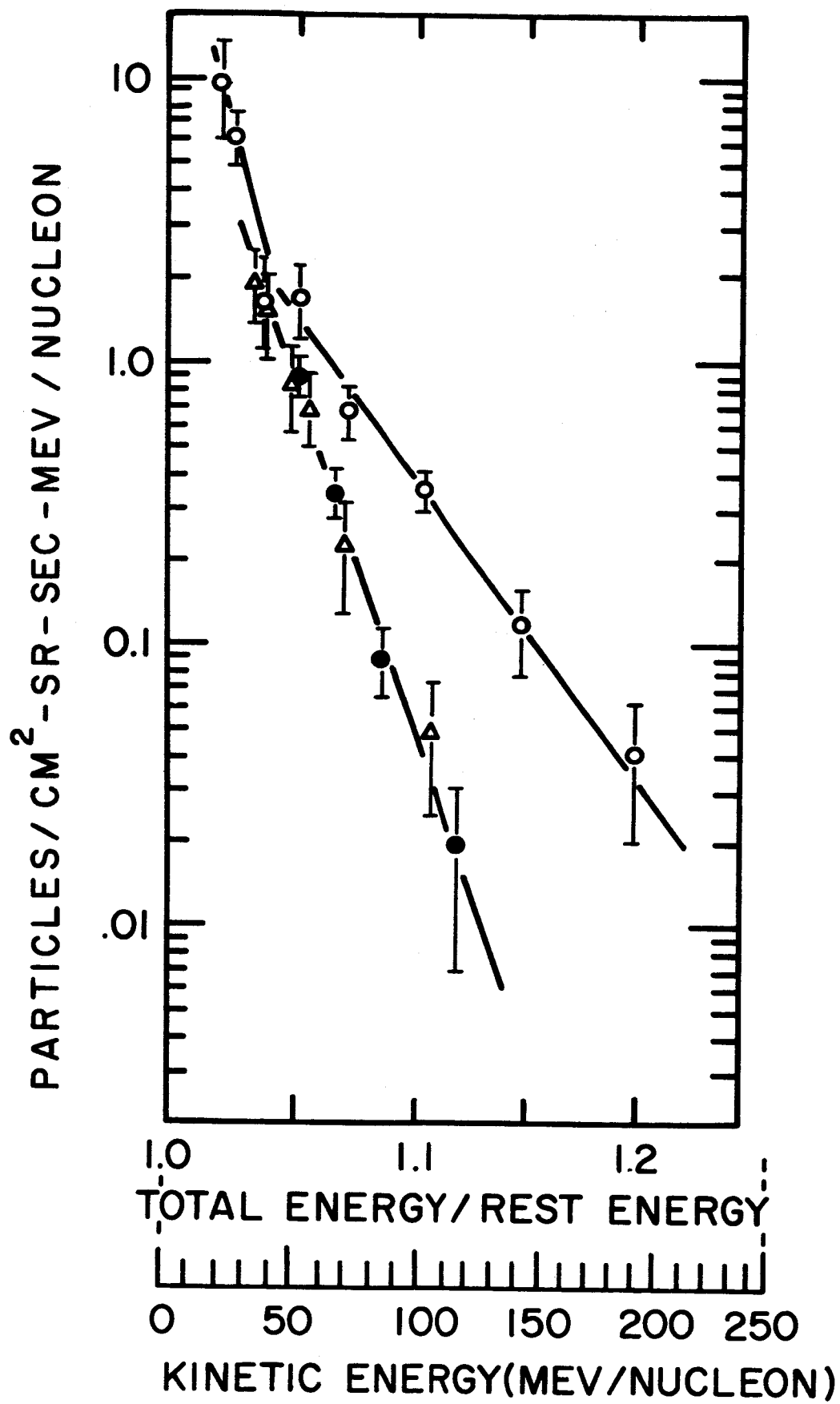


fig. 3

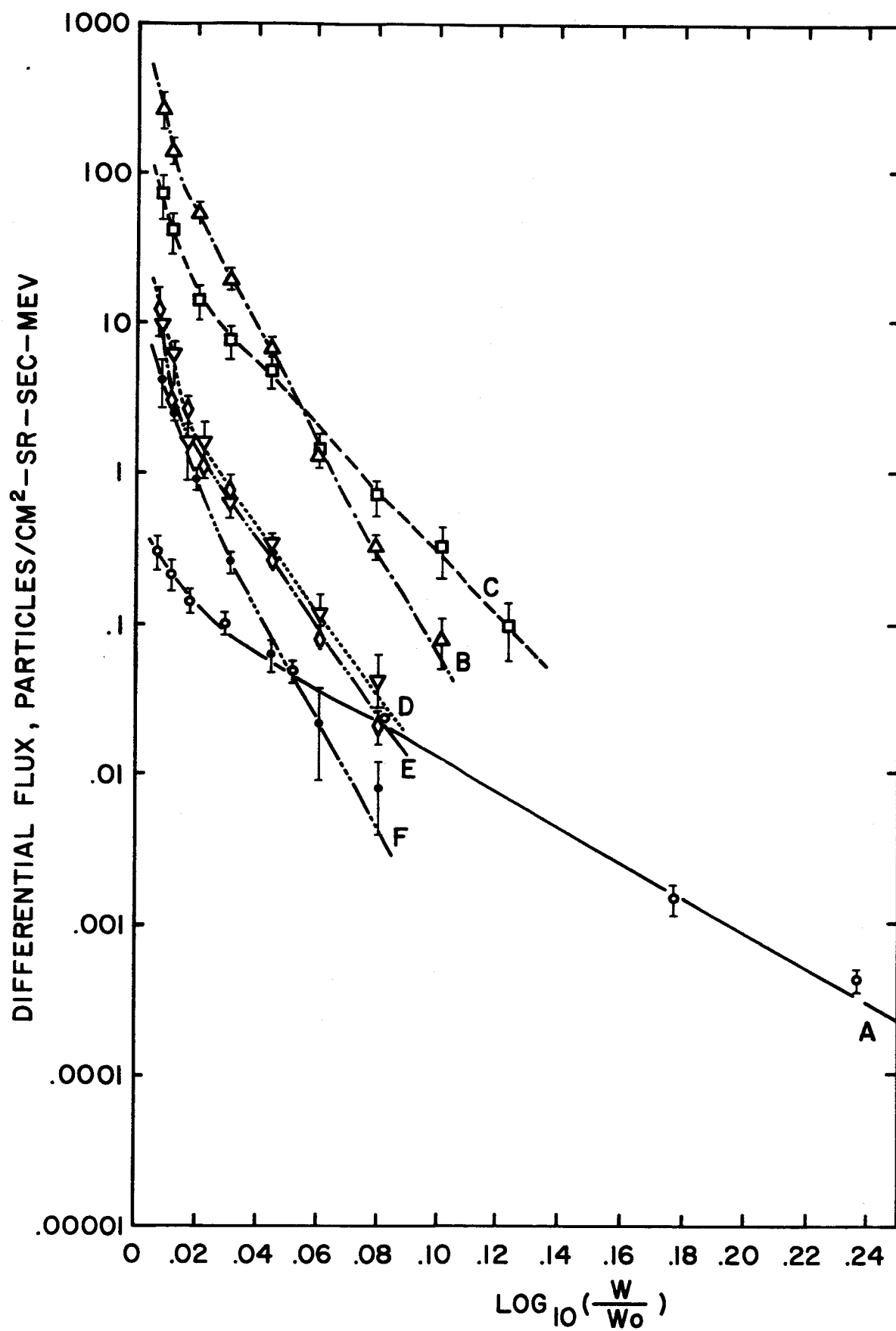


fig. 4a

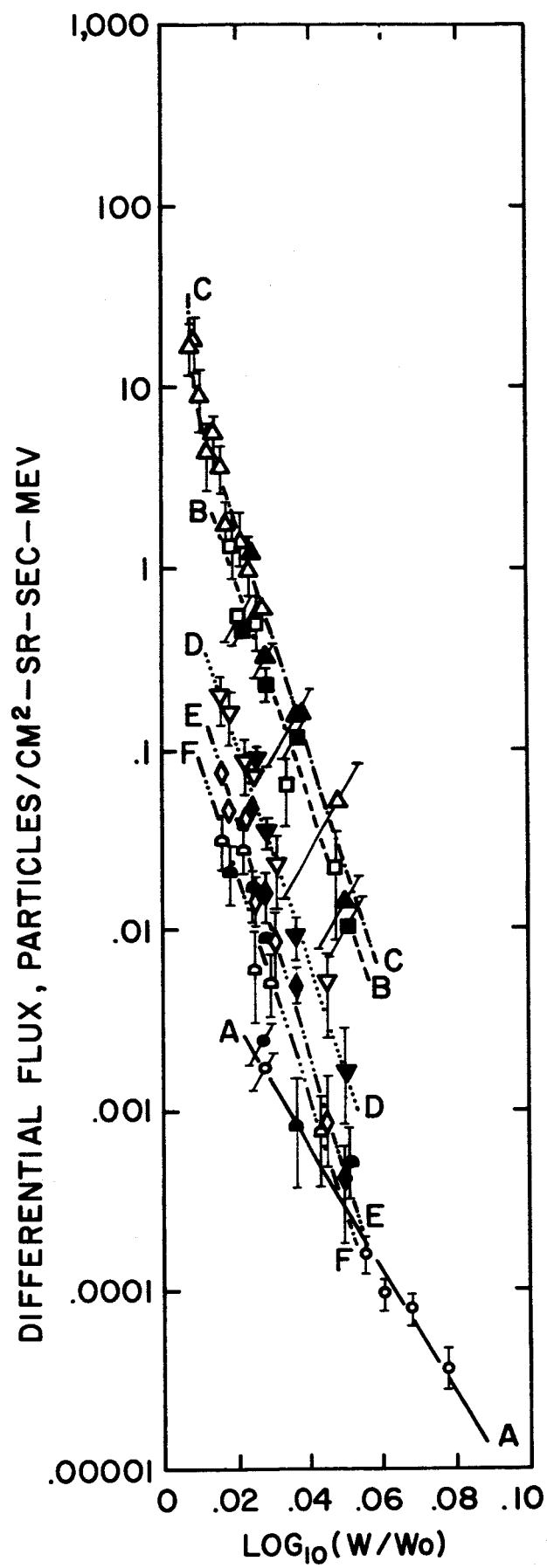


fig. 4 b

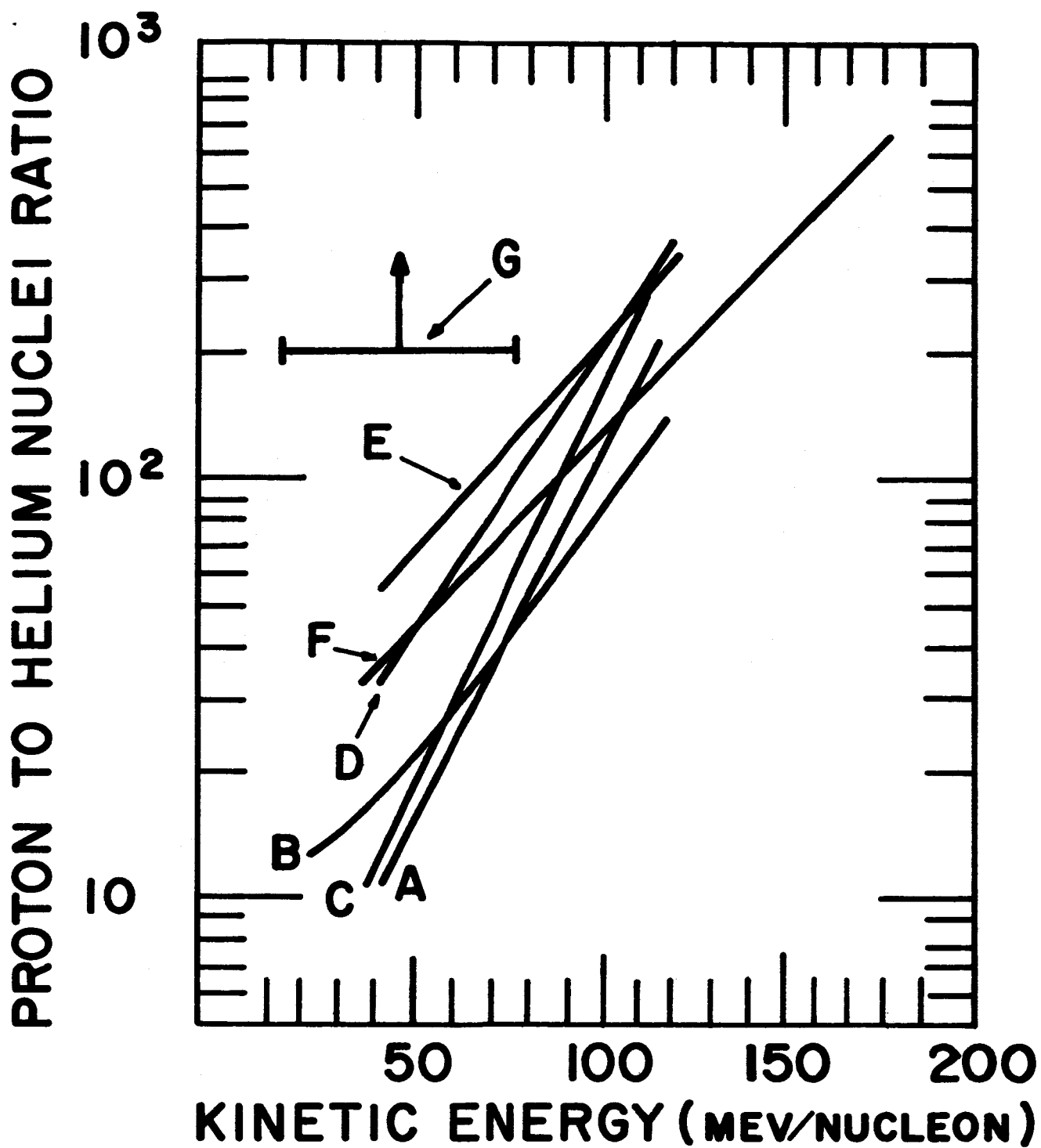


fig. 5

Errata and Changes for
COMPOSITION OF SOLAR COSMIC RAYS

by

S. Biswas and C. E. Fichtel

N65 31552

Page 2, line 1

Change "1957 to 1962)." to "the years 1957 through 1962)."

Page 3, line 3

Change "Yagoda, 1961" to "Yagoda, Filz, and Fukui, 1961"

Page 5, line 1

Change "experiments" to "experimental systems"

Page 5, line 20

Change "proton differs" to "proton (H^1) differs"

Page 6, equations (1) and (2)

Replace "X" in " $\gamma(A, X, T)$ " and " $R_0(A, X, T)$ " by "Z"

Page 6, second to last line

Change "1405" to "1408"

Page 7, line 3

Change "--chance of R_0 values of protons--" to "--chance for the R_0 values of the protons--"

Page 7, line 10

Change "--15 tp 300--" to "--15 to 300--"

Page 7, Line 16

Change "0.8 Mev" to "0.8 Bv"

Page 7, line 21

Change "Biswas and Fichtel (1963)" to "Biswas and Fichtel (1964)"

Page 9, line 6

Change "--Fichtel (1963) with--" to "--Fichtel (1964) and with--"

Page 10, line 18

Change "charge" to "charged"

Page 10, line 22

Change "medium nuclei ($6 \leq \text{nuclear charge} \leq 9$)--" to "medium nuclei, M, ($6 \leq Z \leq 9$)"

Page 11, lines 8-11

Replace "Kurnosova ----- usual variety." by "Kurnosova, et al. (1962) have reported a few two to twenty minute increases of heavy nuclei above cosmic ray background in the relativistic region, not associated with a solar particle event of the usual variety."

Page 11, line 13

Change "experiments" to "experimental systems"

Page 11, last line

Delete "subsequently"

Page 12, line 3

Change "proton to deuteron" to "deuteron to proton"

Page 12, line 7

Change "--same energy" to "same energy/"

Page 13, line 4

Change " 4×10^9 (estimated by Lal, Rajagopalan, and Venkatavaradan," to " $4 \times 10^9 / \text{cm}^2$ (estimated by Lal, Rajagopalan, and Venkatovaradan,"

Page 14, line 14

Change "0.2 with" to "0.2 at about 50 Mev/nucleon with"

Page 15, line 5

Change "lose their energy" to "lose most of their kinetic energy"

Page 15, line 15

Change "positive of electrons" to "positive evidence for electrons"

Page 15, Line 16

Change "0.0025 for the rigidity" to "0.0025 for the electron to proton ratio in the rigidity"

Page 15, second to last line

Change "continuum" to continuum

Page 16, second to last line

Change "neutrons from" to "neutrons arising from"

Page 16, lines 12

Change "> 1 Mev" to "< 1 Mev"

Page 16, last line

Change "suggested in the literature" to "suggested (Simpson, 1963)."

Page 17, lines 17 and 18

Change "continuous quiet time flux" to "continuous quiet time flux of low energy protons which increased at low energies"

Page 17, second to last line

Change "Fichtel, Guss, and Durgaprasad" to "Durgaprasad, Fichtel, and Guss"

Page 18, line 21

Change "positron" to "position"

Page 20, line 6

Change "propogation" to "propagation"

Page 20, lines 9 and 10

Change "--flux is often, or usually, seen--" to "--flux is usually seen--"

Page 21, last line

Change "of H" to "of hydrogen"

Page 22, line 8

Change "--, $\sigma[\text{He}^4(p,d)\text{H}^3]$ was assumed to be 30 mb." to "-- $\sigma[\text{He}^4(p,2p)\text{H}^3]$ was assumed to be 10 mb".

Page 22, line 10

Change "deuteron" to "deuterons"

Page 22, second to last line

Change " 6^{+12}_4 , which--" to " 6^{+12}_4 gm/cm², which--"

Page 23, line 2

Change " He^3 " to " He^3 nuclei"

Page 23, line 3

Change " H^3 and He^3 " to " H^3 and He^3 nuclei"

Page 23, line 17

Change "amoung" to "amount"

Page 23, line 19

Change "by detectors in" to "from detectors flown in"

Page 24, line 21

Change "at the sun" to "of the solar atmosphere"

Page 25, line 11

Change "--fields (Sweet--" to "--fields at a neutral point (Giovanelli, 1948; Sweet--"

Page 25, line 14

Change "thermonuclear" to "thermonuclear"

Page 26, line 22

Change "M/Z" to "the mass to charge ratio"

Page 26, line 24

Delete, "for example"

Page 27, last line

Change " He^4 suggests there" to " He^4 nuclei suggests that there"

Page 29, Line 13

Change "Parker, 1957" to "Parker 1957a"

Page 29, line 18 to 20

Replace "However, since the early-----true value." by "Other experimental evidence, including the very prompt arrival of high energy solar particles in many events, suggests that the major portion of the acceleration is completed within a few minutes."

Page 29, second line from bottom

Change "--Before processing further," to "--Before proceeding farther,"

Page 29, second to last line

Change "sun" to "solar atmosphere"

Page 30, lines 4 and 7

Change "larger" to "heavier"

Page 30, line 19

Change "about twenty" to "about charge twenty"

Page 33, line 8

Change " $1:10^3$ " to " $10^3:1$ "

Page 33, line 22

Change "stars* being" to "stars* remains as a serious objection to ordinary stars being"

Page 33, Line 24

Change "Syroratsky" to "Syrovatsky"

Page 34, line 9

Change "sun" to "solar atmosphere"

Page 34, line 15

Change "deutrons" to "deuterons"

Page 35, line 17

Change "deuteron, tritons, He^3 , electrons" to "deuterons, tritons, He^3 , nuclei, electrons"

References, page 1

After "Aller, L. H.: 1953---" add "Aller, L. H.: 1961, The Abundance of the Elements, Interscience Publishers, New York.

References, page 2

Change "Fichtel, C. E., D. E. Guss, and N. Durgaprasad, 1965: to be published" to "Durgaprasad, N., C. E. Fichtel, and D. E. Guss: 1965, to be published."

Table 2, heading on columns 5, 6, 8, 9 and footnotes * and ***

Change " $R(i,j,k)$ " to " $RA(i,j,k)$ "

Table 3, heading on column 3 and footnote *

Change " $R(i,j,k)$ " to " $RA(i,j,k)$ "

Table 3. second footnote (**)

Change "factor to two" to "factor of two"

Table 5. first footnote (+)

Change "0.5 sec." to "0.5."

Change "Goldberg, Muller and Aller, 1961" to "Goldberg, Muller,
and Aller, 1960"

Captions for Figures, Fig. 1, line 3 & Fig. 2, line 3

Change "(Medium Nuclei) 60" to "(Medium Nuclei) x 60"

Captions for Figures, Fig. 3, line 5

Change "He Nuclei 10;0: (Medium Nuclei) 600" to "(He Nuclei) x 10;0:
(Medium Nuclei) x 600"

Captions for Figures, Fig. 5, line 4

Change "--(1963), Biswas, (1961), and Biswas and Fichtel (1963)--"
to "--(1963), and Biswas and Fichtel (1964)--"

Additional Errata and Changes for

COMPOSITION OF SOLAR COSMIC RAYS

by

S. Biswas and C. E. Fichtel

Page 3, line 4

Change "--Biswas and Fichtel, 1962--" to "--Biswas and Fichtel, 1964--"

Page 7, line 2

Change "Biswas and Fichtel, 1963" to "Biswas and Fichtel, 1964"

Page 15, line 17

Change "Mev/c" to "Mv"

References, page 1

Change "Biswas, S. and C. E. Fichtel: 1963" to "Biswas, S. and C. E. Fichtel: 1964"

Table 1, heading to third major column

Change " R_0 " to " $R_0(\text{Mv})$ "

Table 1, second through fourth minor columns

Delete minus sign before all numbers

Table 2, heading to column 7

Change "BeV/c" to "Bv"