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Solar cosmic rays

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1. Introduction

A wealth of data on many aspects of solar cosmic rays has been collected over the last decade. One of the most striking features of these events has been the tremendous variation in many of their characteristics and the related difficulty of precise interpretation. However, one feature of the solar cosmic rays which does seem to be constant from event to event and within an event is the relative abundances of the multicharged nuclei with the same charge: mass ratio. This paper will concentrate on observations of the composition of solar particles and their interpretation. A brief discussion on the propagation of the energetic solar particles including a few comments on the source region will also be given.

2. Multiply charged nuclei

The constancy of the relative abundances of the multiply charged nuclei of the same charge: mass ratio has been a concept which has developed from experimental results and been tested several times in a number of solar particle events. Of particular interest is the apparent general agreement between solar cosmic ray abundance measurements and solar spectroscopic results where comparison can be made. Because of the interesting possibility that these particles may represent a sample of the Sun, it seems worth while to review the existing experimental evidence related to this subject.

The energy per nucleon, or rigidity spectra of the medium ($6 \leqslant Z \leqslant 9$) and helium nuclei, have been the same within uncertainties each time they were measured in five different events (Biswas *et al.* 1962, 1963, 1966; Durgaprasad, Fichtel, Guss & Reames 1968; Bertsch, Fichtel & Reames 1970), even though the proton spectra were often quite different. An example of this feature is given in figure 1. In addition to having the same energy per nucleon spectra, the relative abundances of helium and medium nuclei in the same intervals have been measured in events and found to be the same within uncertainties. These results are summarized in table 1. Finally, 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, eight times in four events, although the uncertainties in some cases are quite large.

If the constancy of the relative abundances of multicharged nuclei in solar cosmic rays is accepted, the best estimate of these abundances is obtained by taking the average composition in the same velocity intervals from all of the data available. This procedure was followed and the results are presented in table 2 with a base of one chosen for oxygen. Among the nuclei with nuclear charges > 2, the medium nuclei (6 ⩽ nuclear charge ⩽ 9) are 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 generally the same within uncertainties as the solar photospheric 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 one nuclear species deserving particular mention is Fe, which is the only one whose charge: mass ratio differs slightly from the others. Because of the low abundance of Fe and the steep energy spectrum† the relative abundance of Fe has been measured only once (Bertsch

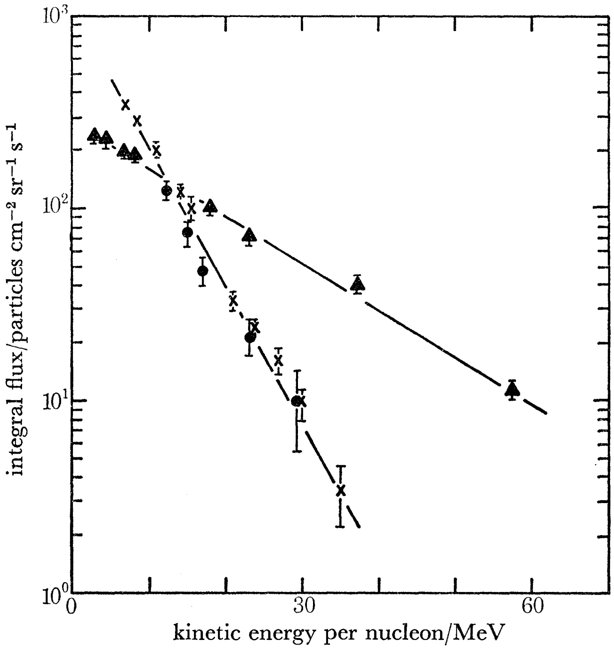

FIGURE 1. Integral energy per nucleon spectra measured at 14h43 U.T., 2 September 1966, for protons × 0.1 (▲), helium nuclei (●), and medium nuclei × 60 (×) (Durgaprasad *et al.* 1968).

TABLE 1. HELIUM: MEDIUM NUCLEI RATIO

time of measurements (U.T.)	energy interval per nucleon MeV	He:M	reference
14h08 3 Sept. 1960	42.5–95	68 ± 21	Fichtel & Guss (1961)
18h40 12 Nov. 1960	42.5–95	63 ± 14	Biswas, Fichtel & Guss (1962)
16h03 13 Nov. 1960	42.5–95	72 ± 16	Biswas, Fichtel & Guss (1962)
19h51 16 Nov. 1960	42.5–95	61 ± 13	Biswas, Fichtel, Guss & Waddington (1963)
06h00 17 Nov. 1960	42.5–95	38 ± 10	Biswas, Fichtel, Guss & Waddington (1963)
03h39 18 Nov. 1960	42.5–95	53 ± 14	Biswas, Fichtel, Guss & Waddington (1963)
13h05–19h18 18 July 1961	120–204	79 ± 16	Biswas, Fichtel & Guss (1966)
14h43 2 Sept. 1966	12–35	48 ± 8	Durgaprasad, Fichtel, Guss & Reames (1968)
22h33 2 Sept. 1966	14–35	53 ± 14	Durgaprasad, Fichtel, Guss & Reames (1968)
23h19 12 April 1969	18–40	47 ± 12	Bertsch, Fichtel & Reames (1970)
weighted average of above readings		58 ± 5	
12h25–23h45 12 July 1959	150–200	$\gtrsim 100 \pm 35$	Biswas (1961)
10h30–12h30 15 Nov. 1960	175–280	$\approx 100 \begin{cases} +100 \\ -50 \end{cases}$	Ney & Stein (1962)

† Because the rate of energy loss of a charged particle increases rapidly with charge, Z, the given minimum particle range needed for detection and identification corresponds to increasingly large energy per nucleon values as Z increases.

Fichtel & Reames 1969), although consistent upper limits of about 0.02 have been measured in other events (Biswas *et al.* 1962, 1963; Bertsch *et al.* 1970). Bertsch *et al.* (1969) have considered the effect of the small difference in the charge: mass ratio of ^{56}Fe and ^{16}O and concluded that the solar cosmic ray propagation process affects this ratio by no more than 30 % and probably much less on the basis of the study of the proton and helium propagation. These same authors noted that there is the additional possibility that there is bias in the acceleration process at a given energy per nucleon, or velocity, due to the different charge: mass ratio.

TABLE 2

element	solar cosmic rays	solar photosphere
^{2}He	107 ± 12	—
^{3}Li	—	$< 10^{-5}$
^{4}Be–^{5}B	< 0.02	$< 10^{-5}$
^{6}C	0.59 ± 0.07	0.60 ± 0.10
^{7}N	$0.19 \left\{ \begin{matrix} +0.04 \\ -0.07 \end{matrix} \right.$	0.15 ± 0.05
^{8}O	1.0	1.0
^{9}F	< 0.03	0.001
^{10}Ne	0.13 ± 0.02	0.11
^{12}Mg	0.042 ± 0.011	0.051 ± 0.015
^{14}Si–^{21}Sc	0.090 ± 0.020	0.097 ± 0.003
^{22}Ti–^{28}Ni	0.011 ± 0.003	0.006–0.1

A good theory which has been tested by experiment for the acceleration process does not exist. Biswas *et al.* (1963) pointed out that rigidity effects could and probably did enter into the acceleration process. This problem has been studied further by several authors including Wentzel (1965) and Fichtel & McDonald (1967). The general effect is to suppress the flux of more energetic particles with the smaller charge: mass ratio because for a given velocity they will have a larger rigidity and escape more easily from the accelerating region. Most estimates would suggest that this effect is small for particles whose charge: mass ratios are as nearly the same as for ^{56}Fe and ^{16}O in the energy interval being considered, but this is far from certain. Because these effects vary from event to event, and would vary markedly if they were important, it is very desirable to measure the relative abundance of Fe in other events. We hope to do this and have sounding rockets waiting at Fort Churchill. It should be noted, however, that the upper limits set in these other events 12 and 15 November 1960 and 12 April 1969 seem to speak against the Fe/O value exceeding about 0.02.

We are aware of the current controversy which exists over the estimate of Fe in the Sun based on spectroscopic measurements, which is due apparently more to uncertainty in oscillator strengths than to spectroscopic measurement uncertainties. We should like to summarize the estimates of the Fe abundance using the astronomical tradition of quoting the log of the abundance with a base of 12 for H. This is done in table 3. If the higher Fe value should prove to be accurate, the Fe abundance in solar cosmic rays would appear to be different. This important point clearly needs further study.

It has been indicated previously (Biswas *et al.* 1962; Fichtel & McDonald 1965; Durgaprasad *et al.* 1968) that the energetic solar nuclei coming from the Sun with charges ranging from that of helium through at least 20 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 2 may be used to estimate the helium and neon abundances in the Sun, as originally suggested by Biswas *et al.* (1962), whereas it is difficult to obtain a good estimate of the abundance of these two elements spectroscopically in the photosphere. The average helium:oxygen ratio is 107 ± 12, and the average neon:oxygen ratio is 0.13 ± 0.02. The neon:oxygen ratio is similar to the universal abundances estimated by Seuss & Urey (1956) and Cameron (1959), although a bit low. The helium:medium ratio is also typical, but the more interesting ratio is that of protons to helium. Because of the different energy spectra for particles with different charge:mass ratios, there is no simple reliable way to determine this ratio from solar cosmic rays alone. However, if the helium:medium ratio of 58 ± 5 is accepted as representative of the Sun, and the proton:medium value from spectroscopic data (Lambert 1967) is used, a proton:helium ratio of 16 ± 2 is obtained. The uncertainty in this number depends on the correctness of the assumption above and the uncertainty in the proton:medium ratio; hence the estimated error placed on this ratio is large. It is worth noting that this number agrees with structure calculations; however, it is well below the 100:1 value expected from current stellar activity, which suggests that the universe was quite different in the past (Hoyle 1965).

TABLE 3

Reference	$\lg A(\mathrm{Fe})$	source or region
Goldberg, Müller & Aller (1960)	6.57	photosphere
Goldberg, Kopp & Dupree (1964)	6.64	photosphere
Warner (1968)	6.51	photosphere
Garz & Koch (1969)	7.60	photosphere
Rogerson, Jr. (1969)	6.85	photosphere
Grevesse & Swings (1969)	7.50	photosphere
Jordan (1966)	7.75	corona
Pottasch (1967)	7.55	corona
Widing & Sandlin (1968)	7.70	corona
Nikolsky (1969)	7.30	corona
Bertsch, Fichtel & Reames (1969)	6.8*	solar cosmic rays

* Assuming 8.8 for oxygen.

TABLE 4

ratio	energetic solar particles	galactic cosmic rays
(C, N, O)/He	0.017 ± 0.002	0.075 ± 0.008
$(10 \leqslant Z \leqslant 20)$/He	0.0024 ± 0.0005	0.023 ± 0.003
$(22 \leqslant Z \leqslant 28)$/He	0.00010 ± 0.00003	0.0040 ± 0.0005

If these numbers are accepted, the distribution in mass between hydrogen, helium, and heavier nuclei becomes X:Y:Z: (0.79 ± 0.10):(0.198 ± 0.024):(0.014 ± 0.004).

The solar cosmic rays are markedly different in composition from the galactic cosmic rays, which are well known to be rich in the heavy elements, presumably due to the special nature of their origin. Table 4 shows that the heavy excess in galactic cosmic rays is an increasing function of charge. Relative to solar cosmic rays, galactic cosmic rays are about 4 times as rich in C, N, O nuclei, 10 times as rich in nuclei with charges of 10 to 20, and approximately 40 times as rich in the Fe group nuclei.

3. PROPAGATION

The propagation of energetic solar particles from the Sun to the Earth is now known to be a very complex problem. There appears to be good evidence to suggest a trapping region near the Sun, wherein there is diffusion around the Sun. One of the more important results which support this concept is the broad longitudinal range over which solar particles are observed at the orbit of the Earth for a given flare and the apparently low rate of longitudinal diffusion of solar cosmic rays in the interplanetary fields. These latter fields are now known to be generally spiral in motion, but also are twisted and have numerous irregularities which scatter the particles (see, for example, Ness, Scearce & Seek 1964).

The predominantly one-dimensional character of the diffusion along these field lines is deduced both from the large anisotropies observed at the Earth (McCracken 1962; Bartley, Bukata, McCracken & Rao 1966; Fan, Lamport, Simpson & Smith 1966), the solar longitudinal distribution of events, particularly electrons (Anderson & Lin 1966; Lin & Anderson 1967), and the small, but significant flux variations with time scales equivalent to the satellite moving a few particle gyroradii in solar longitude (see, for example, Bryant, Cline, Desai & McDonald 1965).

The picture of any particular event is further complicated by the peculiarities of the field structure at any given time and the outward motion of the hotter plasma associated with the flow which puts an outward moving kink in the interplanetary field lines, which become a kind of wall, generally a rather porous one, for the solar particles. Thus, the nature of the diffusion near the Sun and in interplanetary space, with respect to variation with position, the rigidity dependence of the diffusion coefficient, and the degree of twisting of the field lines, can be deduced in only a very general sense, if at all. Finally, the Sun rotates about 13° per day so that over the period of several days of observation of solar particles from an event, the Earth or the artificial satellite in question has moved substantially toward or away from the field lines connecting most directly to the flare region.

To construct this entire situation theoretically is obviously a virtually impossible task both due to its complexity and the lack of experimental information. However, various attempts have been made, and an increasingly sophisticated model is developing in the literature. Even before there were magnetic field measurements, solar-wind theory (Parker 1960) had predicted that the magnetic field in the interplanetary region would be in the form of generally spiral lines emanating from the Sun, with superimposed small-scale irregularities. The spiral nature of the field, of course, results from the field lines being drawn out radially by the solar wind while the base of the field line at the Sun rotates with the solar surface.

The first suggestion of a diffusion model for the propagation of energetic particles using magnetic irregularities as scattering centres was by Parker (1956) and Meyer, Parker & Simpson (1956). Starting with simple isotropic diffusion, theories which included both spatial variation of the diffusion coefficient and spatial dimensions less than three quickly followed (Parker 1963; Krimigis 1965). The complex problem of anisotropic diffusion was then considered by several authors.

A model with many of the features described earlier in this section was first suggested by Reid (1964) and Axford (1965). Reid assumed that there was a layer near the Sun which to a good approximation could be represented by a two-dimensional region in which particles diffuse and leak out into the interplanetary field lines at a rate proportional to the intensity at any point and time. Axford then treated the subsequent interplanetary diffusion problem in some depth. This picture has recently been made more general by Lin, Kahler & Roelof (1968), who also included the effect of solar rotation. Figure 2 illustrates this general picture.

A single form of the resulting mathematical expression for the intensity at the Earth, which assumes the diffusion coefficient near the Sun to be a constant K_1, and the diffusion coefficient in interplanetary space to be a constant K_0, is given by the following equation:

$$N(t) = \frac{C}{K_0 K_1}\int_0^\infty \frac{\mathrm{d}t'}{t'(t-t')^{\frac{3}{2}}} \exp\left\{-\frac{S^2}{4K_1 t'} - bt' - \frac{x^2}{4K_0(t-t')}\right\},$$

where S is the distance from the flare in the two-dimensional layer near the Sun and x is the distance along the interplanetary field line. The factor $1/t' \exp\{-S^2/4K_1 t'\}$ is related to diffusion near the Sun; the factor $\exp\{-bt'\}$ is related to loss from that region; and

$$1/(t-t')^{\frac{3}{2}} \exp\{-x^2/4K_0(t-t')\}$$

is related to the interplanetary diffusion. Studies of the proton and helium nuclei as a function of time in events clearly show that the diffusion coefficients are in fact functions of the rigidity of the particles (Biswas & Fichtel 1965; Durgaprasad *et al.* 1968). As an example, figures 3 and 4 show the variation of the proton:medium nuclei ratio as a function of time for particles in the same velocity interval and even the same rigidity times velocity interval (Durgaprasad *et al.* 1968). The rotation of the Sun is taken into account by relating S to the difference in solar longitude of the flare and the foot of the field line connecting the Sun to the Earth at any time. Lin *et al.* (1968) in their Fig. 12 illustrate the effect of the rotating Earth, which either stretches out the intensity-time profile or compresses it, depending on the relative location of the flare and the Earth.

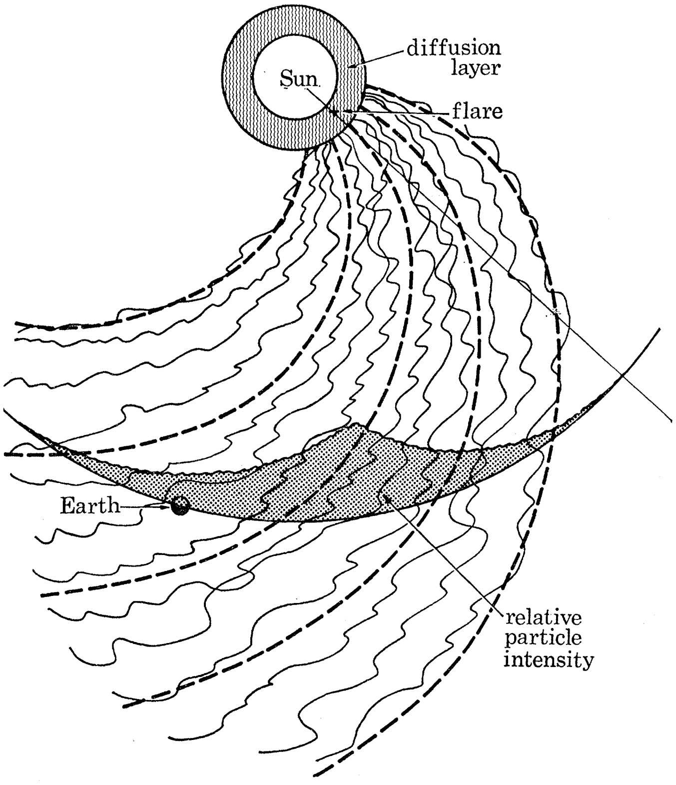

FIGURE 2. Schematic diagram of the solar particle propagation picture developed by Reid (1964), Axford (1965), and others.

As detailed as this model is, it still leaves the twisting of the field lines and the magnetic field kink introduced by the hot plasma from the flare region as other features yet to be painted in. Other contributions to the problem of anisotropic diffusion have been made by Burlaga (1966), Fibish & Abraham (1965), Parker (1965), Roelof (1966) and Fisk & Axford (1969). The latter point out the need for using a generalized form of the telegraph equation when the anisotropy is large.

Finally, it is worth noting specifically that all of the considerations discussed involve only the velocity of the particle and possibly its rigidity—through rigidity-dependent scattering; hence, particles with the same charge: mass ratio will propagate from the Sun to the Earth in the same manner if energy loss through interaction with matter is negligible, as it is unless the particles spend too much of their time very close to the flare region. The failure to see any marked change in the slope of the energy spectra of protons in several events down to energies as low as 1 MeV (S. M. Krimigis & P. Verzariu, personal communication 1970) together with the lack of any clear positive evidence for secondary particles and the similar energy/nucleon spectra of He and C, N, O nuclei, speak strongly against any significant energy loss of this type. An upper limit of about 2×10^{-4} g/cm^2 of material can be set from these results. If the average propagation time is taken as 10^4 to 10^5 s, the average density must be less than 10^7 to 10^6 atoms/cm^3. Further, if the average time in the accelerating region is about 100 s, the density there does not exceed 10^9 atoms/cm^3. There remains the possibility of Fermi acceleration or deceleration which may occur in interplanetary space. Even if it does exist, particles of the same charge: mass ratio will be affected in the same way with respect to changes in their velocity.

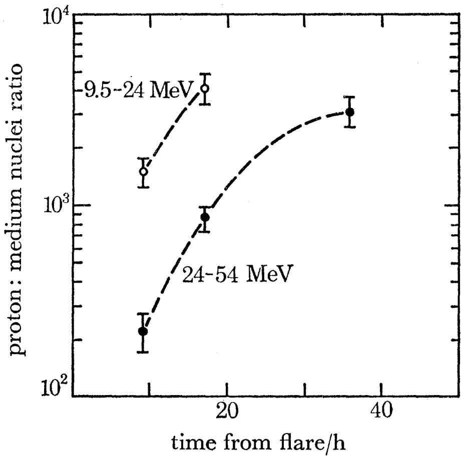

FIGURE 3

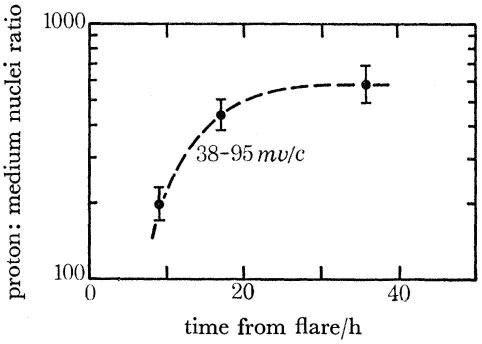

FIGURE 4

FIGURE 3. Ratio of protons to medium nuclei for the three flights for the two different energy per nucleon intervals shown, plotted as a function of time from the flare (Durgaprasad *et al.* 1968).

FIGURE 4. Ratio of protons to medium nuclei for the three flights for the βR (velocity in units of the velocity of light times particle rigidity) interval shown in the figure, plotted as a function of time from the flare (Durgaprasad *et al.* 1968).

Thus, both theoretical and experimental evidence speak against any effects in the propagation of solar particles which would alter the relative abundances of particles of the same charge: mass ratio. The experimental evidence also suggests there is no bias in the initial accelerating process. For the acceleration phase, it is possible and even reasonable to have no bias for particles of the same charge: mass ratio, although differences can occur when the nuclear charge: mass ratios differ as mentioned in the previous section.

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