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ABSTRACT

The abundance of Fe-group nuclei in the energetic solar particles was measured twice in the January 24, 1971 event and once in the September 2, 1971 event. Including earlier results from the September 2, 1966 event, the experimental series being discussed in this article has found the Fe-group abundance to be in the range from 3% to 6% of the oxygen nuclei in the energy interval from 21 to 50 MeV/nucleon, in those events where the Fe-group abundance could be measured. Fe-nuclei have a different charge-to-mass ratio from that of the C, N, O nuclei; so small variations in the Fe abundance in solar particles are expected. In the three exposures where the statistics were adequate to construct an energy spectrum, the Fe-group nuclei were seen to have an energy/nucleon spectrum similar to that of the C, N, O nuclei; however, the energy/nucleon range was limited. The abundance for the Fe-group nuclei mentioned above is consistent with the present solar spectroscopic abundance estimates.

I. INTRODUCTION

Continued studies of energetic solar particles emitted in conjunction with large solar flares have led to the determination of the

Fe-group nuclei abundance relative to oxygen nuclei in three separate solar particle events, and significant upper limits for the Fe-group nuclei exist in two other events. The measurements have been made using nuclear emulsion detectors carried aboard sounding rockets flown from Fort Churchill, Canada. Although the sun is a frequent emitter of energetic particles, nuclei with charges greater than two are relatively rare as expected (e.g. Biswas and Fichtel, 1965) and nuclei of the Fe-group, were not seen until the September 2, 1966 event (Bertsch, Fichtel, and Reames, 1969). Subsequently, they have been detected several times (Price et al., 1971; Fleischer et al., 1971; Crozaz and Walker, 1971; Crawford et al., 1972; Bertsch et al., 1971; Teegarden et al., 1971; Simpson and Mogro-Campero, 1972) although it has not always been possible to relate their abundance to other species in a very direct way. In this paper, the final results from measurements on the Fe-group nuclei detected in the January 24, 1971 and the September 2, 1971 events will be reported and discussed together with the other results.

The abundance of iron in the sun as deduced from spectroscopic measurements is presently the subject of a controversy involving differences of more than an order of magnitude. Therefore, the abundance of the Fe-group nuclei (defined here as charges 24 to 28, but presumably predominantly 26) in solar cosmic rays is of particular interest, especially if the abundance there can be related to that of the sun. The relationship between the two Fe abundances, i.e. that of the sun and that of the energetic solar particles, is not completely straightforward, however, in part because Fe nuclei have a different charge-to-mass ratio from C, O, Ne, Si and other nuclei with which its abundance can be compared. This problem will be discussed later in the paper.

II. EXPERIMENT DESCRIPTION

The SPICE (Solar Particle Intensity and Composition Experiment) payloads and their Nike-Apache vehicles are kept on standby at the Fort Churchill Research Range in Manitoba, Canada and fired when it is determined that an event of interest is in progress. Each payload has two nuclear emulsion stacks consisting of 24 pellicles with lateral dimensions 6.4 cm x 7.1 cm. A thin cover of stainless steel having a total thickness equivalent to 72 microns of emulsion, separates the outermost pellicle from the particle radiation. This first pellicle is 200 microns thick. It is followed by three 300-micron and approximately twenty 600-micron pellicles. Experience has shown that this arrangement of thicknesses is advantageous since the high density of solar proton tracks in the outer pellicles of the stack makes it difficult to analyze tracks in a 600-micron plate. The two stacks have different sensitivities: one is composed of Ilford K.5 emulsions sensitive to minimum ionizing events, and the other of Ilford K.2 emulsions sensitive to protons of energy less than 40 MeV.

During the flight, the nosecone of the payload is opened while the payload is above about sixty kilometers yielding an exposure time of 245 seconds. By means of spin stabilization, the emulsion detectors are held in a vertical plane. A total useful exposure of about 1.5 x 10^4 cm^2-sr-sec. is obtained.

In order to identify the iron nuclei, the surface of the top 200 micron plate was scanned to locate the tracks of heavy nuclei with at least 78 microns of projected length and dip angles between 10° and 60°. Tracks formed by Fe-group nuclei were separated from tracks of lower charged nuclei with the aid of a digitized-television-microscope system operating on-line to a computer. The basic measurement is the total opacity per unit length of track, which is a measure of the rate of energy loss per unit length. The data are recorded at selected depths in the nuclear emulsion to avoid depth effects due to any variations in development or light illumination. The total opacity per unit length corrected for dip angle is then plotted against the residual range of the particle track to separate the Fe-group nuclei from the others. More details on the digitized-television-microscope system and its use are given by Ehrmann and Reames (1969).

In addition to the charge identifying measurements just described, the charge of each particle under consideration was also determined with a second estimate of the rate of energy loss. In most cases, the measurement made was a delta-ray count, although in one sample a track width measurement was made. The agreement between the two methods of charge identification was excellent; the few tracks for which discrepancies did exist could affect the Fe abundance quoted by no more than one part in twenty, even if all the wrong choices were made.

Information on the C, N, O nuclei was obtained by scanning the outer surface of the nuclear emulsions and using conventional measurement techniques, described in previous articles (e.g. Bertsch et al., 1971). This latter article also describes the approach to the remainder of the data analysis; so it will not be repeated here.

III. RESULTS

The first event in which Fe-group nuclei were detected and compared to the C, N, O group was the September 1966 event (Bertsch et al., 1969)--the first event also in which the improved sounding rocket payloads, permitting the observation of lower energy particles, were used. As mentioned in the introduction, Fe has been seen recently by several groups. These results will be discussed after the presentation of the results to date from the SPICE experiment series being discussed here. With regard to these measurements, the January 24, 1971 and September 2, 1971 events are the second and third events in which Fe-group nuclei have been detected, and in which the flux of Fe-group nuclei can be compared directly to the abundance of C, N, O nuclei in the same energy/nucleon interval. A sounding rocket nuclear emulsion exposure was also obtained in the April 12, 1969 solar particle event, but only an upper limit to the Fe-group abundance was obtained.

Fig. 1 shows the differential energy/nucleon spectra of the C, N, O and the Fe-group nuclei that have been obtained from three flights into two particle events. In the third event, September 2, 1971, the number of detected Fe-group nuclei was too small to permit construction of a spectrum although an abundance relative to oxygen was determined in the same energy/nucleon interval. In each of the three measurements, the C, N, O spectra and the iron spectra appear to have similar shapes, although the energy/nucleon spectral range of the Fe-group nuclei is small. The figures do show, however, that the Fe data agree with the curve obtained by multiplying the C, N,O nuclei energy/nucleon spectrum by the ratio of the C,N,O and Fe-group nuclei for the particular event.

We wish to call particular attention to the September 2, 1966 result. The final revised ratio reported here based on detailed measurements is about two and one-half times higher than reported previously (Bertsch et al., 1969). The change is due primarily to an improper scanning threshold for the preliminary work although increased statistics contributed also, the problem relates only to the Fe nuclei scan in the September 2, 1966 event.

Table I summarizes the Fe-group abundance measurements relative to oxygen obtained thus far in the SPICE experiment series. Note that conversion from the C, N, O nuclei to just oxygen introduces a factor of 1.75, based on the observed C, N, O to oxygen ratio.

The data in Table I suggest that the Fe-group abundance relative to O may vary slightly from event to event. For the events before 1966 a different type of rocket payload was used and the low energy threshold was much higher. Because of the steep energy/nucleon spectra, there were generally not enough particles to measure the Fe nuclei flux or set an upper limit of any significance. The one exception was an exposure obtained near maximum intensity of the relevant energy/nucleon interval in the November 12, 1960 event. This result is shown in Table I.

On the low side, there are two events with a 95% confidence upper limit of five percent for the iron to oxygen ratio, as well as the September 1966 value of three percent. These can be compared to the January 1971 measurements of about six percent. A small variation in the iron abundance is not surprising and is presumed to be the result of the fact that iron nuclei have a charge-to-mass ratio about seven percent less than the constant charge-to-mass ratio of the lighter, even-charged nuclei. Hence, slightly different acceleration and propagation effects would be expected, since both may be rigidity dependent. These effects have been mentioned previously with regard to the Fe abundance in solar cosmic rays (Bertsch et al., 1969). The variation in the ratio due to the propagation effect is probably no more than a factor of two and probably much less. There appears to be no certain way of estimating theoretically the bias in the ratio introduced by rigidity effects in the accelerating process if any, since the specific acceleration process for solar particles is not known.

Other results on the Fe-group nuclei will now be summarized. Fleischer et al. (1971) measured the energy spectrum of Fe-group nuclei from solar cosmic rays impinging on an optical filter of the Surveyor 3 spacecraft for 2.6 years prior to its return by the Apollo 12 astronauts on November 20, 1969. They deduced an E^{-3} differential spectrum from 1 to 100 MeV/nuc., but had no direct means of comparing the Fe-group nuclei to other species. Price et al. (1971) used both the Surveyor-3 camera lens and a piece of the Apollo 12 spacecraft window and deduced a similar Fe spectrum. These latter authors attempted to compare their results to the integrated He flux from other data. They deduced an Fe abundance in the 6 to 10 MeV/nucleon range about a factor of three higher than the larger values reported in this paper. A factor of three is probably within the uncertainties in this difficult comparison of two different experimental results wherein the energy/nucleon spectra are very steep. It should also be noted that the energy/nucleon interval is lower than those for the results being reported in this paper. Crozaz and Walker (1971) have shown that the Surveyor-3 results are consistent with lunar rock results, implying that the solar particle production rate has been the same on the average for a very long period.

Crawford et al. (1972) measured the energy/nucleon spectra of Fe-group nuclei using plastic detectors flown aboard the second of the two SPICE sounding rocket shots in the January 24, 1971 event. The measured energy/nucleon spectra in the same energy/nucleon interval as that of the present experiment agree within the uncertainties.

Teegarden, McDonald, and von Rosenvinge (1972) flew a low energy solid state detector telescope on IMP VI. To date, they have solar particle composition measurements in two events. Relative to oxygen, they measure an Fe-group abundance of 3% based on about 30 detected nuclei in the September 1, 1971 event consistent within uncertainties with the result given in Table I. When comparing the IMP-VI results with the SPICE measurements, it should be noted that the satellite experiment integrates over the whole event while the sounding rocket exposure is only 245 seconds in duration. Small time variations in the abundance ratio, Fe/O, are expected due to the rigidity dependence of solar particle propagation. Teegarden et al. (1971) observed an iron-to-oxygen ratio of .17 $\pm$.10 in the April 1971 event, but that was based on only 3 iron-group nuclei.

The one result which is apparently markedly different from the values reported here and mentioned above is related to data from the OGO-5 satellite experiment of Simpson and Mogro-Campero (1972). They deduce an average Fe/O value of .79 $\pm$.29 for many events from 1968 to 1971.

IV. DISCUSSION

Before proceeding with the Fe discussion, a brief review of a few features of the solar particle composition will be given. One aspect of the energetic solar particle composition, which has been seen in an examination of the experimental results of the sounding rocket nuclear emulsions series, is the apparent constancy of the relative abundances of particles with the same charge-to-mass ratio within experimental errors in all events where a comparison could be made at energies where the nuclei are fully ionized (e.g. Biswas and Fichtel, 1965; Fichtel, 1971; Bertsch et al., 1972). This constancy prevails within the fifteen to twenty percent statistical uncertainty of the individual measurements despite large variations in the intensity, changes in the spectral shape, and large differences in the proton-to-helium ratio. The weighted average of the He/M ratio is 58 ± 5. The energy region spanned by the measurements is from 10 to 200 MeV/nucleon, although most measurements are either in the range of 42 to 95 or 12 to 50 MeV/nucleon. Fig. 2 summarizes the abundance measurements made with the sounding rocket nuclear emulsion experiment series, and compares them with the abundances measured in the photosphere and corona by spectroscopic techniques. The photospheric and coronal abundances shown in Fig. 2 are those adopted by Withbroe (1971). Note the good agreement of these cosmic ray measurements with solar spectroscopic measurements where comparisons are possible.

With regard to comparisons to other solar particle measurements there is generally good agreement for C, N, O, and Ne. For Mg and heavier nuclei Simpson and Mogro-Campero (1972) obtain generally higher results. Teegarden et al. (1971) differ from the values reported here for Mg and Si, but agree with the values or limits for S, A, Ca, and Fe. There are also some differences in the He abundance reported, but this question will be addressed in a separate paper.

Assuming that the slightly different charge-to-mass ratio for Fe or other effects do not affect the abundance in a significant way during the acceleration or propagation phase as discussed earlier, the Fe-group abundance in solar cosmic rays seems to be generally in agreement with the more recent spectroscopic estimates of several percent of the oxygen abundance--at least in the energy/nucleon region where Fe is nearly fully ionized--although there is one experiment that suggests that the Fe group abundance in solar cosmic rays is nearly equal to that of oxygen. There also appears to be a difference from the several percent figure for Fe relative to O at very low energies, but here (a few MeV/nucleon or less) the Fe nuclei may be far from fully ionized and serious propagation effects might come into the picture. Thus, the question of the Fe abundance in the energetic solar particles following solar particle flares is still far from answered, but in the energy/nucleon range above about 10 MeV/nucleon an Fe/O ratio in the range of several hundredths seem to be developing, at least as the most common value for large solar particle events. More experimental results are clearly desired, however.

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FIGURE CAPTIONS

Fig. 1 Differential energy/nucleon spectra for C, N, O - nuclei (solid circles) and for Fe-group nuclei (open circles) obtained with nuclear emulsions on three sounding rocket flights. Solid curves are fit to the C, N, O spectral data and dashed curves are obtained by renormalizing the C, N, O curves to the Fe-group data using the factors indicated. In (C) the Fe-group spectral points of Crawford et al. (1972) obtained with plastic detectors on the same flight are shown (open triangles) for comparison.

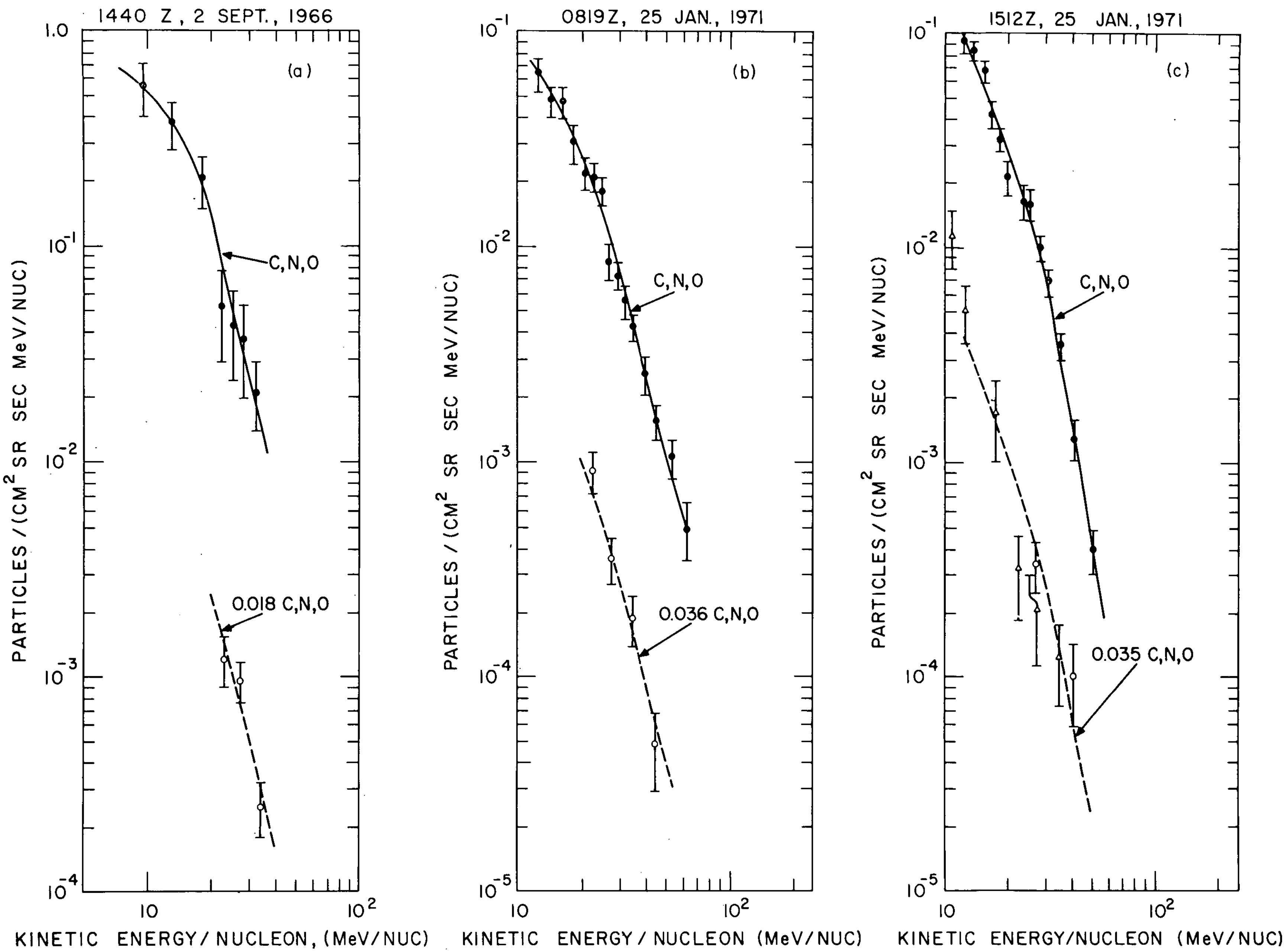
Fig. 2 Solar abundances relative to oxygen determined from solar cosmic-ray measurements and from spectroscopic measurements of the solar photosphere and corona. Solar particle composition data quoted in the above figure comes from the nuclear emulsion sounding rocket program only as discussed in the text. The data for Be through Ca is summarized from Fichtel and Guss (1961); Biswas et al. (1962); Biswas et al. (1963); Bertsch et al. (1972) and the present work. The data on He are summarized from the above references and Biswas et al. (1966). The data on Fe are from the present work. Photospheric and coronal abundances are those adopted by Withbroe (1971) and their error bars reflect the precision suggested by that author.

TABLE I

SUMMARY OF IRON GROUP MEASUREMENTS

DATE AND TIME OF MEASUREMENT		Fe / O IN %	ENERGY INTERVAL	NUMBER OF Fe GROUP NUCLEI DETECTED
NOV. 12, 1960	1840 UT	≤ 5 *	77-150 MeV/NUC	0
SEPT. 2, 1966	1443 UT	3.1 ± 1.0	21-40 MeV/NUC	66
APRIL 12, 1969	2319 UT	≤ 5 *	21-50 MeV/NUC	0
JAN. 25, 1971	0819 UT	6.3 ± 1.4	21-50 MeV/NUC	70
JAN. 25, 1971	1512 UT	6.0 ± 1.5	21-50 MeV/NUC	22
SEPT. 2, 1971	0758 UT	5.9 ± 1.8	21-50 MeV/NUC	14

*95 % CONFIDENCE UPPER LIMIT



1440 Z, 2 SEPT., 1966
(a)
C,N,O
0.018 C,N,O
PARTICLES / (CM^2 SR SEC MeV/NUC)
KINETIC ENERGY/ NUCLEON, (MeV/NUC)
0819Z, 25 JAN., 1971
(b)
C,N,O
0.036 C,N,O
PARTICLES / (CM^2 SR SEC MeV/NUC)
KINETIC ENERGY / NUCLEON (MeV/NUC)
1512Z, 25 JAN., 1971
(c)
C,N,O
0.035 C,N,O
PARTICLES / (CM^2 SR SEC MeV/NUC)
KINETIC ENERGY/NUCLEON (MeV/NUC)

FIG. 1

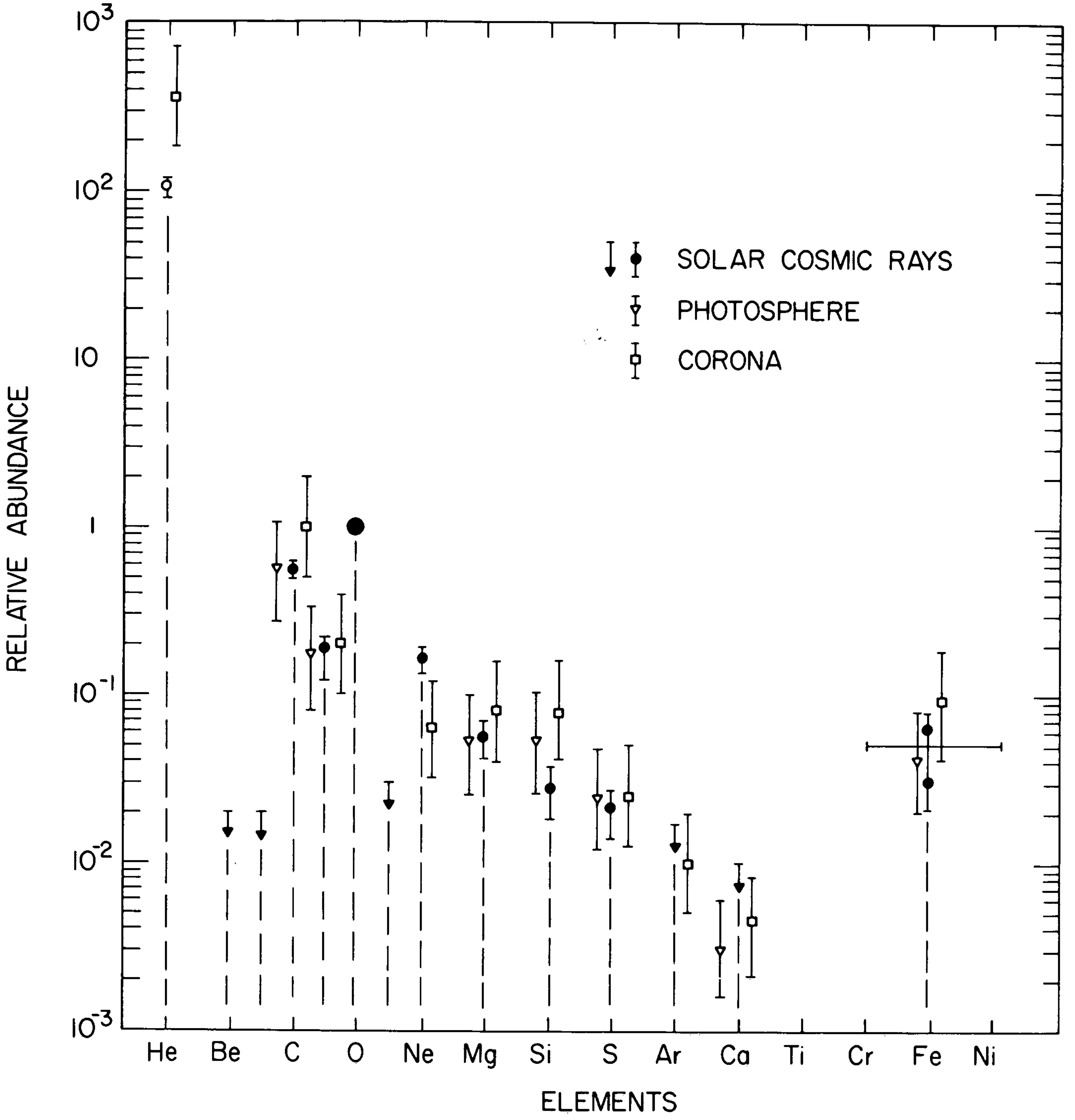

SOLAR COSMIC RAYS
PHOTOSPHERE
CORONA
RELATIVE ABUNDANCE
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
He
Be
C
O
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
Ni
ELEMENTS

FIG. 2