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COMPOSITION OF RELATIVISTIC COSMIC RAYS NEAR THE EARTH AND AT THE SOURCES

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Data on cosmic-ray composition obtained in Gemini XI are combined with other recent measurements on several thousand relativistic nuclei ranging from Li to Ni. Improved charge resolutions has yielded more precise estimates of abundances for elements beyond oxygen. New results reduce the relative flux of Cr by ~ 3. Our latest distribution function of cosmic-ray path length [exp $(-0.23\,x)$, for $x > 1$ g cm^{-2}] together with newly measured and calculated cross sections yield a revised source composition. Relative to carbon (C $\equiv$ 1.00), the *source* fluxes are:
N = 0.12 ± 0.03; O = 1.02 ± 0.06; Ne = 0.20 ± 0.03; Mg = 0.27 ± 0.03; Si = 0.23 ± 0.03; S = 0.04 ± 0.02; Fe = 0.23 ± 0.05. The presence of small traces (~ 0.02) of Ar and Ca and (~ 0.01) of Na, Al, and Ni in the sources would improve the overall fit. Estimates of Mg and Si have increased noticeably in the *source* composition since our 1969 Budapest report, while Cr may be altogether absent.

1. Introduction

The composition of the nuclear component of the cosmic radiation has undergone considerable changes between the source regions and the top of the earth's atmosphere due to collisions with the interstellar gas which consists mostly of hydrogen. We have carried out calculations on the transformation of the cosmic ray composition in order to determine the relative abundances of the *primordial* cosmic rays at the source regions. A semi-empirical method of calculating nucleon–nucleus cross sections was designed for this purpose. The elemental abundances of the primordial cosmic rays reflect the chemical composition in the source regions. It may reveal which processes of nucleosynthesis have played a significant role in the evolution of the sources. We have used data obtained in Gemini XI [1], combined with other recent measurements on several thousand relativistic nuclei ranging from Li to Ni and new results on the iron group by Lezniak et al. [2] and Casse et al. [3].

2. Composition of Arriving Cosmic Rays

The primary cosmic radiation arriving at the top of the earth's atmosphere consists mostly of fast hydrogen and helium nuclei in the ratio 7:1, at comparable rigidities above 2 GV. (The term "rigidity" denotes momentum/charge; it is proportional to the radius of curvature of charged particles in a given magnetic field.) The flux of cosmic-ray helium is ten times that of all heavier nuclei combined. Among the latter, carbon and oxygen are the most abundant.

Fig. 1 shows the relative abundances of cosmic rays in the range of hydrogen to nickel. A comparison is made here with the composition of the solar system based on data from solar spectra and meteorites. (For some elements, the meteoritic values are not plotted if they nearly coincide with the solar data.) The solar and cosmic-ray abundances have been normalized with respect to carbon. The outstanding feature of Fig. 1 is the large "excess" of Li, Be, and B in cosmic rays (by about 5 orders of magnitude), compared with that in

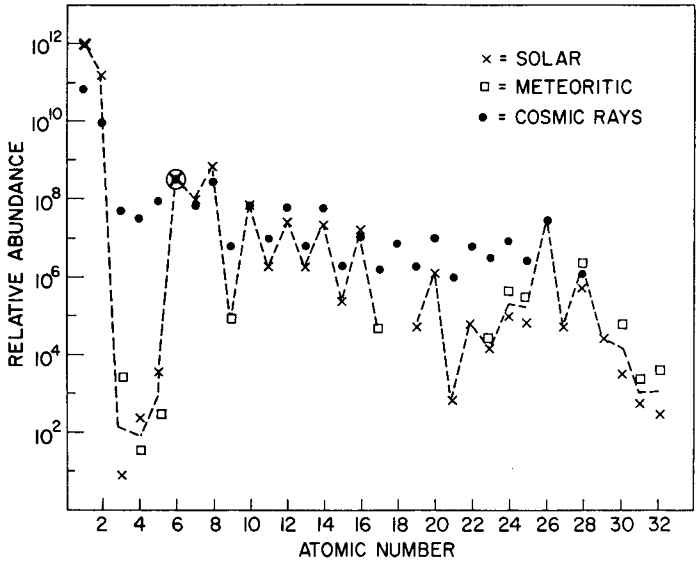

Fig. 1. A comparison of the relative abundances of elements in the cosmic radiation at the top of the earth's atmosphere, and in the solar photosphere, as well as in carbonaceous chondrites. The latter (meteoritic) values are shown only if they deviate appreciably from those of the sun. Solar data are normalized to hydrogen at 10^{12}; cosmic ray data were normalized so that the abundance of carbon coincides with solar carbon.

the solar system. Also, most elements ranging from Cl to Mn (with atomic numbers 17 to 25) are more plentiful in cosmic rays by a factor of about 100.

These overabundances are explained in terms of nuclear breakup of heavier nuclei upon collisions with the interstellar gas; the elements Li, Be and B in cosmic rays [4]* are largely derived from the breakup of carbon and oxygen, and those with $17 \leqq Z \leqq 25$ from the breakup of iron.

3. Transformation of the Primordial Compositions

The primordial composition of cosmic rays can be determined from the relative fluxes of the arriving nuclei including the secondaries generated en route. It is

* However, due to the low altitude of their balloon flight, and uncertainties in correcting for interactions in the atmosphere, these authors concluded that Li, Be and B are absent in cosmic rays above the atmosphere.

necessary, however, to know the partial cross sections for the various modes of breakup. Only a limited number of cross section values have been measured [5]. Most of the pertinent cross sections of nucleon–nucleus interactions have not yet been measured so one must resort to semi-empirical techniques for calculating

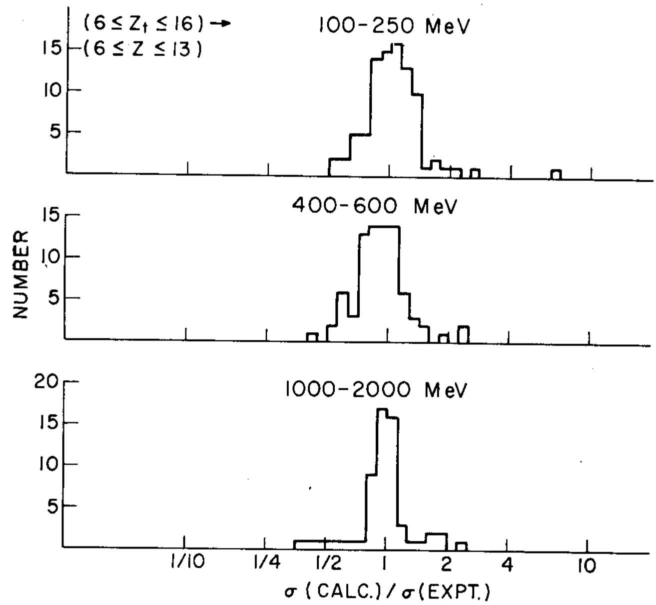

Fig. 2. A comparison of calculated and experimental cross sections, for targets and products in the range $6 \geqq Z \leqq 16$, in three energy intervals.

Table 1

Cross sections (mbn) for collision of heavy nuclei with hydrogen, $E \geqq 1.5$ GeV/nucleon

Product	Target				
	C	O	Ne	Mg	Si
Li	13	28	23	24	24
Be	20	16	15	15	15
B	65	37	27	23	19
C		44	32	23	18
N		76	41	30	23
O			72	53	39
F			45	19	14
Ne				69	55
Na				51	23
Mg					77
Al					52

the unmeasured ones.* For this purpose, we have modified and extended [6] the earlier empirical equations of Rudstam [7]. Fig. 2 shows the distribution in the ratios of calculated to experimental cross sections in three energy intervals, for targets ranging from carbon to sulphur. The standard deviation of these ratios from unity is about 20% for energies >1 GeV per nucleon; it increases to 30% at lower energies of the order of 150 MeV per nucleon.

Table 1 shows cross sections for the production of various elements from collision of carbon, oxygen, neon, magnesium and silicon with hydrogen at energies >1.5 GeV per nucleon. These are based on our detailed calculations of partial cross sections, and supplemented by experimental data when available. (It may be remarked that the semi-empirical equations used in the calculations were fitted to the available cross-section measurements.)

No unique value of path length satisfied *both* the abundance ratio of Li-Be-B to C-N-O nuclei, and the ratio $17 \leq Z \leq 25$ to iron nuclei. However, an expo-

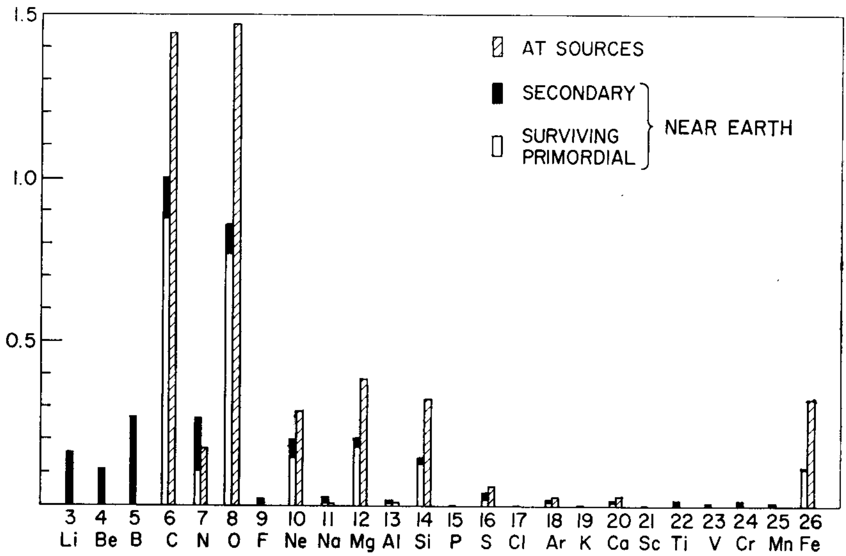

Fig. 3. The cosmic ray abundances at the sources and near earth. The blank portions represent the surviving primordial radiation, the shaded portions the contributions of secondary nuclei that arrive near the earth.

nential distribution in path lengths of the form $e^{-0.23x}$ for $x > 1$ g cm^{-2}, with a gradual rise between 0 and 1 g cm^{-2} satisfies *both* of the above ratios. Such an exponential distribution is to be expected: cosmic rays with longer potential path lengths leak out of the galaxy, and a drop-off at the shortest path lengths is likely if there are no cosmic ray sources relatively close to the solar system.

Next the calculated composition after traversal of an amount of matter (as shown in Fig. 3) was fitted to that observed at the top of the atmosphere. This process was carried out by iteration, adjusting the source composition and a provisional path length distribution function. Fig. 3 shows our newly revised cosmic-ray composition at the sources and near the earth. The arriving carbon is normalized to unity. The blank portions represent the contribution of the surviving primordial cosmic rays and the shaded portions those generated by breakup en route.

4. The Primordial Cosmic-Ray Composition versus the Composition of the Solar System

Table 2 shows the composition of the primordial cosmic rays, normalized to carbon. Hydrogen is the most abundant element—several hundred times more plentiful than carbon. Two values are shown for hydrogen; the smaller value is for a primordial spectrum that follows a power law in rigidity, while

Table 2

Primordial composition*
of the more abundant cosmic rays

H**	$\left.\begin{matrix}2\\5\end{matrix}\right\} \times 10^4$	Ne	20 ± 3
He	$(2.7 \pm 0.5) \times 10^3$	Mg	27 ± 4
C	100*	Si	23 ± 4
N	12 ± 3	Fe	23 ± 5
O	102 ± 6		

* Normalized to carbon

** The two values correspond to $\frac{dJ}{dR} \propto R^{-\gamma}$ and $\frac{dJ}{d\varepsilon} \propto \varepsilon^{-\gamma}$

the other corresponds to a power law in energy/nucleon. Helium is the next most common cosmic-ray element at the source regions, about 20 or 30 times

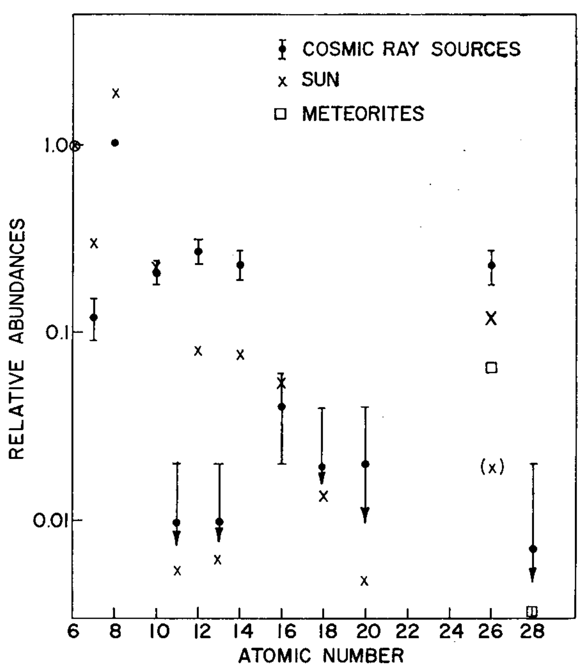

Fig. 4. The relative abundances of elements in the primordial cosmic radiation and in the solar photosphere. The data are normalized with respect to carbon.

as plentiful as carbon. Oxygen is as abundant as carbon. The flux of each of the four elements Ne, Mg, Si and Fe is about one quarter that of carbon. Other elements are scarcer, e.g. nitrogen, about 12% relative to carbon. The presence of small traces ($\sim$0.02) of Ar and Ca and ($\sim$0.01) of Na, Al and Ni in the sources would also improve the overall fit to the observation at the top of the atmosphere. Furthermore new results [2, 3] which have reduced the relative flux of Cr to one third of the early value [8], no longer suggest its presence at the sources.

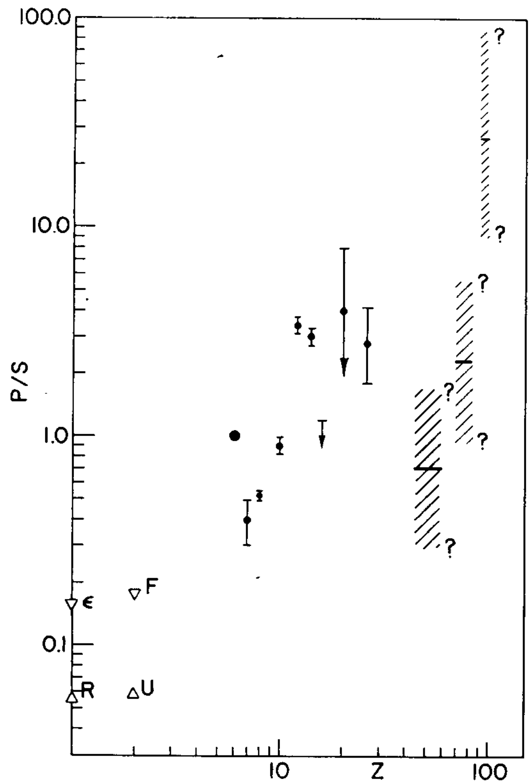

Fig. 5. The ratio of primordial cosmic-ray abundances to those in the solar system, as a function of atomic number Z. The ratios are normalized to unity at carbon. The values ε and R for hydrogen are based on assuming the cosmic ray spectrum to follow a power law in energy/nucleon and rigidity, respectively. The values F and U for helium are based on estimates of solar helium derived from the study of solar particles and solar spectra, respectively. (F denotes Fichtel's group [11]; U, Unsöld [10].) The shaded portions on ultra-heavy nuclei are based on the work of Fowler et al. [15].

In Fig. 4 the primordial abundances of cosmic rays ranging from carbon to nickel are compared with those of the solar photosphere [9–12] and of meteorites [13]. The values are normalized to carbon. Nitrogen and oxygen are relatively somewhat less plentiful in cosmic rays than in the sun. On the other hand, heavier elements like Mg, Si and Fe are notably overabundant in cosmic rays. Also shown in Fig. 4 are the elements Na, Al, Ca and Ni, while our [8, 14] abundance estimates of Mg and Si have been up-dated.

The overabundance of heavier elements in the primordial cosmic rays is even more marked if the comparison is extended all the way from hydrogen to the uranium group. Fig. 5 presents the *ratio* of primordial cosmic-ray abundances to those in the solar system, normalized to unity for carbon. The shaded values for the ultraheavy nuclei are based on the primordial abundance estimates of Fowler et al. [15]. The general trend of larger relative abundances of heavier elements in the primordial cosmic rays is evident. However, some oscillations are superimposed on the trend, e.g. for N and O beyond carbon, for S beyond silicon, and for a set of elements beyond iron.

5. Conclusions

It has been recognized for some time that the comparison with solar composition favours cosmic-ray origin in highly evolved stars, in which the processes of element synthesis have reached an advanced stage, e.g., in supernovae. The latest measurements [2, 3] indicate that the amount of chromium in the primordial cosmic rays (relative to iron) is not anomalously high; special conditions of nucleosynthesis for producing chromium are no longer needed. The preliminary (and statistically limited) data on nuclei of the uranium group ($90 \leqq Z \leqq 96$) indicate that the increase with atomic number in the ratio of primordial cosmic ray abundances to those of the solar system continues beyond iron.

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