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ENERGETIC SOLAR PARTICLES

S. Biswas

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Tata Institute of Fundamental Research
Bombay 400005
INDIA

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S. Biswas
Tata Institute of Fundamental Research, Bombay 400 005

1. Introduction

It has been known for about three decades that the sun is capable of accelerating particles to high energies. However, during the past sixteen years, energetic solar particles have been studied directly using detectors in balloons, rockets and satellites and these have contributed greatly to our present knowledge of energetic nuclei emitted by the sun during solar events. The studies of energetic solar particles, which are also called solar cosmic rays, have been pursued with great interest because these yield important information on several aspects of solar physics and interplanetary physics. In most of the solar events the energies of accelerated particles lie in the energy range of about 1 to 100 MeV/amu; however in some very large events these extend to relativistic energy range, $\sim$ 10 GeV/amu.

In this review, I shall briefly discuss some of the important aspects of energetic solar particles and their relation to solar physics. This will enable us to identify the major aspects of solar cosmic ray studies currently under investigation and to focus our attention to the problems of the physical processes in the sun which may be responsible for these phenomena. At present, our understanding of these physical processes in the sun is rather rudimentary and incomplete.

The studies of the composition and energy spectra of solar cosmic ray nuclei are related to the basic problem of particle acceleration process in sun and to the composition of elements in solar atmosphere.

The composition of higher energy (> 20 MeV/amu) multiply charged nuclei of He, C, N, O, Ne, Mg, Si and Fe give information on the abundance of elements in the solar atmosphere. At lower energies ($\sim$ 1-10 MeV/amu) the abundances of these elements show enhancements relative to solar abundances and these enhancements are believed to be due to particle acceleration mechanisms operative in the sun which are not fully understood at present.

Another type of information is provided by the studies of the relative abundances of H^2, H^3 and He^3 isotopes and Li, Be, B nuclei in the solar cosmic rays. The relative abundances of H^2, H^3 and He^3 in solar cosmic rays are rather small, in general, and these are produced by the nuclear interactions of accelerated solar particles in the solar material. Therefore, the relative abundances of these isotopes yield information on the amount of material traversed by the accelerated particles in the solar atmosphere.

The most recent observations of anomalously high He^3 abundances in many small solar events, some of which also show anomalously high abundances of heavy nuclei, particularly Fe, are rather puzzling at present. These probably represent an entirely new type of phenomenon in the active region of the sun, which are not understood at present.

In the last section, we shall briefly discuss the question of the relationship of the accelerated particles in the sun to the optical flare phenomena. Several authors have suggested in recent years that accelerated solar electrons, protons and other nuclei may be responsible for the heating of solar plasma by ionisation loss process and for the optical flare. In this model accelerated particles may play the primary role in solar flare phenomena. Further studies of different aspects of these phenomena may give important clues to a wide ranging phenomena in the active sun.

Before discussing these results and their implications, it is useful to note briefly the observational methods employed for these studies. This is discussed in the next section. The earlier results of the composition of energetic solar particles and their implications have been discussed in the review papers by Biswas and Fichtel (1965) and by Biswas (1972).

II. Observational Methods

As the solar cosmic ray nuclei have rather steeply falling spectrum and are rapidly absorbed in the upper layers of the atmosphere, only solar protons and helium nuclei can be detected in balloon altitudes and all other heavier nuclei are studied outside the earth's atmosphere by means of rockets and satellites. The composition of solar cosmic ray nuclei was studied extensively for over one decade 1960-72 by means of nuclear emulsion detectors flown in NASA sounding rockets during many major solar events and these provided almost entire data on solar cosmic-ray composition during this decade. The rocket payloads with detector assemblies are kept in readiness on 24 hour standby basis at Ft. Churchill, Canada, and these are fired at appropriate times during a solar particle event (Biswas et al, 1962). Since 1971 plastic detectors such as stacks of lexan and cellulose triacetate sheets have been used in these sounding rockets to study low energy heavy nuclei in the energy range of 1-20 MeV/amu, which were not accessible in earlier detectors (Crawford et al, 1975, Nevatia and Biswas, 1975). Counter telescopes in satellites have been used since 1971 for the studies of nuclear composition of solar particles. These detector systems using semiconductor counters have high resolving power for heavy nuclei of energies > 10 MeV/amu, and these have been also used to identify isotopes of H^2, H^3 and He^3 (Teegarden et al, 1973; Anglin et al., 1973). Recently, thin-walled proportional counter combined with silicon surface barrier detectors have been successfully used in IMP-7 and IMP-8 satellites to measure the composition of very low energy (0.6-4 MeV/amu) heavy nuclei from solar particle events (Hovestadt et al., 1973).

III. Composition of Energetic Solar Particles in Large Solar Events

During the years 1960-72, a large number of sounding rocket flights were made by NASA, Goddard Space Flight Center during many major solar events to study the composition of solar cosmic rays (Biswas and Fichtel, 1965; Durgaprasad et al., 1968; Bertsch et al., 1972, 1973 and 1974). These studies showed that the relative abundances of multiply charged nuclei of energy > 20 MeV/amu of He, C, O, Ne and Mg and some heavier ones, having same mass to charge ratios, remained essentially the same in spite of large differences in the size of the events and very large variations of proton to helium ratios which have different mass to charge ratios. These results indicated that these nuclei are fully ionised and the acceleration process do not discriminate the nuclei having the same mass to charge ratios. Therefore, the relative abundances of these nuclei in energetic solar particles represent an unbiased sample of elements in the solar atmosphere. This conclusion was confirmed from the observation that the relative abundances of carbon, nitrogen, oxygen and magnesium nuclei in the solar cosmic rays are the same as those obtained by spectroscopic means for these nuclei. Therefore, from solar cosmic ray observations the helium and neon abundances in the sun were estimated (Biswas and Fichtel, 1965) which could not be obtained earlier spectroscopically in the photosphere. Recent measurements of solar helium abundance from chromospheric studies (Hirayama, 1971) and of neon abundances from UV observations (Lambert, 1969) are in excellent agreement with those from solar cosmic ray studies. Thus, it is seen that energetic nuclei coming from the sun with charges ranging from He to Fe reflect the composition of elements on the solar surface. The relative abundances of the elements in the energetic solar cosmic rays and in solar photosphere are shown in Table 1 and these are plotted in Fig.1 including coronal abundances.

The solar hydrogen to helium ratio in the photosphere cannot be directly determined from solar cosmic rays because these have different mass to charge ratios. Therefore, we used the He/O ratio in solar cosmic ray particles and H/O ratio (= 1690) from solar spectroscopic data (Lambert, 1967) to obtain solar hydrogen to helium ratio as 16 ± 2). This ratio is in agreement with solar model calculations. Hence, the mass ratios of hydrogen, helium and heavier nuclei in the solar atmosphere are determined as $X : Y : Z = 0.79 : 0.20 : 0.013$ (Biswas, 1969).

When the measurements of solar cosmic ray composition were extended to lower energies, in the range $\sim$1-20 MeV/amu, it was found that the abundances of heavy nuclei such as Ne, Mg, Si and Fe relative to O were enhanced as compared to solar abundance values. The first evidence of this phenomenon was detected from the observations of etched tracks of low energy Fe nuclei in the Surveyor glass sample which had an exposure of 2.4 years on the lunar surface (Price et al., 1971). Since then, several direct measurements in solar events have established the enhancement of abundances at low energies (Mogro-Campero and Simpson, 1972; Crawford et al., 1972; Bertsch et al., 1973; Bertsch et al., 1974; Crawford et al., 1975; Nevatia and Biswas, 1975).

A summary of the enhancement factors of some of the elements in the energy interval of 5-10 MeV/amu are shown in Table 2 for medium and large events. Here we have defined the enhancement factor ξ as the ratio of the abundance of an element Z in the low energy solar cosmic rays (5-10 MeV/amu) measured relative to oxygen, to that in the higher energy solar cosmic rays of energy > 25 MeV/amu. The composition of the latter corresponds to the solar abundances within experimental uncertainties as discussed earlier. It is seen in Table 2 that for He the value of ξ is less than unity, which means that at low energies oxygen is enhanced relative to helium. Furthermore, He/O ratios at low energies ($\sim$ 10 MeV/amu) show variability by a factor of about two in some solar events (Bertsch et al., 1974). Therefore, the two values for helium are shown to take into account this effect. In case of Fe nuclei the ratios of Fe/O at low energies may b variable by a factor of about two, which is indicated by the uncertainty of the value of the enhancement factor. The other elements, Ne, Mg and Si do not show any significant variation from event to event (Nivatia and Biswas, 1975). These data are plotted in Fig.2, which show that enhancements are probably not a monotonically increasing function of the atomic number Z. Large enhancements of Fe-group nuclei observed from the summing of the data of several small events (Mogro-Campero and Simpson, 1972) probably belong to another type of process associated with small solar events as discussed in the next section.

The question naturally arises as to the cause of the enhancement of abundances at low energies. This is most probably due to acceleration process of heavy ions. At energies less than $\sim$ 20 MeV/amu, the heavy nuclei are not fully stripped of orbital electrons and hence their equilibrium charges are less than their nuclear charges, as shown in Fig.3.

Hence, these low energy nuclei which have different mass to charge ratios are expected to show biased abundances relative to those of fully stripped nuclei. However, detailed understanding of the process are not available at present. An interesting approach to the problem was made by Ramadurai (1973) who calculated a Fermi acceleration spectra in the presence of ionisation loss. He found that at low energies the energy spectra of low energy heavy nuclei were increasingly steeper with increasing nuclear charge Z of the accelerated particle, and hence increasing enhancements should occur at low energies. There are several features of this phenomenon which need further examination. A more complex model was proposed by Cartwright and Mogro-Campero (1972).

In summary, it may be noted that the problems of acceleration of particles in the sun and the enhancements at low energies are highly interesting ones and these are far from understood at present. In recent years, a great deal of new experimental data have been available on these phenomena and it is important to make fresh attempts towards the understanding of the processes responsible for these phenomena in sun.

Now let us turn our attention to the weak components in energetic solar particles, viz. Li, Be, B nuclei and H^2, H^3 and He^3 isotopes. In large solar events the abundances of these nuclei are very small. These nuclei and isotopes can occur in solar cosmic rays due to fragmentation and nuclear reactions of the accelerated solar particles in the solar material. From the upper limit of $(Be + B)/O < 0.01$, amount of material traversed by accelerated solar particles was calculated as < 0.1 g.cm^{-2} of solar material. If the density in the accelerating region is assumed to be $10^{11} - 10^{13}$ atoms of hydrogen/cm^3, acceleration time is calculated as about 100 sec. or less (Biswas and Fichtel, 1965).

The abundance ratio of H^2/H^1 and H^3/H^1 are less than $10^{-3} - 10^{-4}$ which in general agrees with calculated values. On the other hand He^3/He^4 ratio measured in several flare events show rather complex behavior. Some events show very small abundances of He^3 ($He^3/He^4 \lesssim 3 \times 10^{-3}$); these are called He^3 'poor' events. In many other small events large ratios of He^3/He^4 were measured as $\sim(1-10) \times 10^{-2}$ (Anglin et al., 1973; Garrad et al., 1973); those are called He^3 'rich' events. The reasons for such large variations are not known. These are ascribed as due to variations in pathlength for nuclear interaction in solar atmosphere and due to other processes. Traversal of several gm.cm^{-2} of solar material are necessary to produce He^3/He^4 ratio of a few percent, as observed in He^3 'rich' events (Ramaty and Kozlovsky, 1974).

IV. Anomalous Abundances of He^3 and Fe-group Nuclei

Now we turn our attention to the most recent results of He^3 isotope which were obtained in the interplanetary space with IMP-6 and 7 satellites by the NASA, Chicago and Caltech groups. These results are most astonishing in several respects, because in a large number ($\sim$20) of small solar events, He^3/He^4 ratios were measured to be unexpectedly large, 0.2 to 1; and in one instance, the ratio was as high as 1.5 (Balasubrahmanyan et al., 1975; McDonald et al., 1975) and in two other events the ratio was very high, 6 and 8 (Hurford et al., 1975). In Fig.4 we show the example of He^3/He^4 ratio of 1.5. Such a high abundance of He^3 nuclei among the accelerated particles of energy 3-10 MeV/amu cannot be understood in terms of secondary production of He^3 nuclei by nuclear interactions of accelerated solar nuclei in the solar atmosphere. This process would require extremely large amount of material traversed by solar particles, about 100 gm./cm^2 of hydrogen which is clearly not possible. Therefore, it is clear that we are dealing here with an entirely new type of physical processes in the sun. Before one attempts to interpret these unusual and surprising observations, it is necessary to obtain additional information on the properties of these anomalous particles. From the results available at present, we summarise the properties of these anomalous He^3 component as follows:-

(1) Anomalously high He^3 abundances in energetic solar particles are associated with small solar flares of magnitude 1^- or with subflares and not with large solar events.

(2) These events persist over many hours and the data on He^3/He^4 ratio were collected for about 10 to 60 hours in different events.

(3) When He^3 abundances were high, H^2 and H^3 abundances were very small or undetectable and only upper limit of the ratios of H^2/He^3 and H^3/He^3 could be obtained.

(4) In some instances, anomalously high He^3 events have been associated with the observations of anomalously large abundance of solar heavy nuclei of Fe-group. This type of events is discussed later.

These observations cannot be understood according to the presently known ideas of the energetic solar particles. In the new hypothesis by Kocharov (1973, 1975), it is suggested that there is mixing between the outer convective layer and the interior of the sun whereby He^3 may be transported into the outer convecting zone and to the solar photosphere on some particular occasion when they are subjected to particle acceleration process. This hypothesis was suggested to account for some of the other features of solar physics, such as relatively high abundance of He^3 in solar wind. Stephens and Balasubrahmanyan (1975) have examined the possibility of mixing process by which He^3 from the interior of the sun may occasionally surface out and give rise to variable and anomalously high He^3 abundance. Clearly, further studies are necessary to understand this entirely new type of phenomenon in the energetic solar particles.

Now we discuss another class of solar particle events in which anomalously high abundance of Fe-group nuclei were measured. These have been detected very recently, in 1974, by IMP-8 satellite in the interplanetary space. The fluxes of heavy nuclei of helium to iron of energies 0.7 to 4 MeV/amu were measured during the solar 'quiet' period in 1974. It was found that on three occasions each lasting for 3 to 15 days, unusually high abundances of low energy heavy nuclei of neon to iron was observed (Gloeckler et al., 1975; Hovestadt et al., 1975). During this period, abundances of neon to iron nuclei increased by a factor of about 10 to 20 relative to the composition of normal solar cosmic rays. In these three occasions, iron abundances relative to oxygen were $\gtrsim 1.0$. The example of the unusual composition of iron nuclei is shown in Fig.5. The remarkable feature of the phenomena is that such abnormal composition is not associated with any solar particle events as such, but a region of space seems to be populated with these low energy heavy nuclei with unusual composition. As the satellite enters this region, it encounters these solar particles of unusual composition which may persist for a period of a few days to 15 days, after which normal particle population is recorded. From the measurements available at present, we note the following properties of this anomalous high heavy ion emissions:-

(1) These are probably associated with very small solar activities, or subflares or no visible flares which may be responsible for the emission of these particles.

(2) The three instances observed so far are strongly co-related with He^3 enhancement events.

At present, we do not know the origin of this phenomenon and further studies are necessary to understand this new class of phenomenon of solar particles.

Konyakhina et al (1971) reported several increases in the heavy nuclei fluxes of energy 400-600 MeV/amu with cerenkov detectors and not associated with solar events of usual type. These events were not seen with other types of detectors and these are apparently of a different nature.

V. Energetic Solar Particles and Optical Flares

In this section, we briefly discuss the relationship of the energetic solar particles to optical flares. In early investigations, it was presumed that optical flare phenomena was the primary process which initiated the acceleration of particles. However, beginning with Giovanelli (1948), it has been suggested by several investigators (e.g. Syrovatskii and Sheleva, 1972) that particle acceleration process in the sun is the primary process which provide the energy of the optical flare by the ionisation loss of the accelerated particles. In these calculations, it has been shown that energy loss of the accelerated electrons could be responsible for the heating of the solar plasma which manifest as optical flare. Svestka (1970) suggested that white light flares were produced by ionisation loss of accelerated protons moving downwards. The energy loss of the accelerated protons and heavier ions in the solar atmosphere, the total energy dissipation by this process and the energy spectrum of particles escaping from the sun have been calculated by Biswas and Radhakrishnan (1973). It was shown that when the energy spectrum of accelerated protons escaping from the sun can be determined from observed data, the energy dissipation in the solar atmosphere can be evaluated under some plausible assumptions and this can be compared with observed energy release in optical flare. The uncertain parameter in these calculations is the fraction of lines of force which forms closed loop..It is found that ions and electrons can provide sufficient energy for the heating of solar plasma in optical flare when the fraction of closed tubes of force at acceleration level is $\sim$99%. This picture of large fraction of magnetic lines of force forming closed loop structure, where accelerated particles are trapped and spend most of their energy, is strongly supported by the recent X-ray photographs of the sun. These high resolution X-ray photographs of the sun taken from rockets show a large number of arched tubes of force emitting X-rays which must originate from accelerated electrons confined in the arched tubes of force (Van Speybroeck et al., 1970).

This model can also explain the phenomenon of large variability in the size of solar particle events which is apparently not related to the magnitude of the optical flare event. It is shown in Fig.6 that for a typical event with a given number of accelerated protons, the number of escaping protons from the sun varies by a large factor of $\sim 10^2$ depending on the value of a fraction of lines of force which forms closed loop structure. The amount of energy deposited by the accelerated particles by the ionisation loss process, however, does not vary significantly for different values of the fraction of closed lines of force and for different heights of accelerating region.

It is clear that further studies of different aspects of the phenomena would be able to reveal many unsolved aspects of the particle acceleration process and of the optical flare phenomena in the sun.

VI. Concluding Remarks

In this talk, I have reviewed some of the recently discovered aspects of energetic solar particles and their relationship to solar physics. These are expected to be studied with great interest during the coming years of increasing solar activity. It is to be noted that several new types of phenomena are associated with small flare events and therefore systematic studies of these small events, in addition to larger ones, can be of much value. The newly established Udaipur Solar Observatory can play an important role in some of these studies of solar active regions.

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Table 1.

Relative Abundance of Elements normalised to a base of 1.0 for Oxygen

Z	Elements	Solar Cosmic Rays of E > 20 MeV/amu	Solar Photosphere
		Ref.(a)(b)(c)(d)	Ref.(e)
2	He	103 ± 10	110 ± 25*
3	Li	< 0.02	-
4	Be	< 0.02	-
5	B	< 0.02	-
6	C	0.56 ± 0.06	0.60 ± 0.10
7	N	0.19 ± 0.03	0.15 ± 0.05
8	O	1.0	1.0
10	Ne	0.16 ± 0.03	0.13 ± 0.03+
12	Mg	0.056 ± 0.014	0.051 ± 0.004
14	Si	0.028 ± 0.010	0.060 ± 0.007
16	S	0.008 ± 0.006	0.028 ± 0.004
18	A	< 0.017	-
20	Ca	< 0.010	0.004 ± 0.0005
22	Ti		
24	Cr		
26	Fe	0.050 ± 0.020	0.045 ± 0.015

(a) Biswas and Fichtel, 1965

(b) Durgaprasad et al., 1968

(c) Bertsch et al., 1972, 1973.

(d) Bertsch et al., 1975.

(e) From Review by Pagel (1973), and data of Lambert and others.

* From Chromospheric & prominence data by Hirayama (1971)

\+ Lambert (1967), UV data of upper Chromosphere and lower corona.

Table 2.

Summary of Abundance Enhancements at E = 5-10 MeV/amu

Element	Enhancement Factor at E = 5-10 MeV/amu $\xi = \frac{[A(Z)/A(O)]\ \text{Low Energy}}{[A(Z)/A(O)] > 20\ \text{MeV/amu}}$	References
He	0.3 - 0.75	(a)
	0.33 ± 0.06	(b)
C	~ 1.0	(a)
O	≡ 1.0	
Ne	1.5 ± 0.4	(c)
Mg	3.6 ± 1.2	(c)
Si	4.6 ± 1.7	(c)
Fe	2.9 ± 1.2	(d),(a)

(a) Bertsch, Biswas and Reames, 1974.

(b) Durgaprasad, Nevatia and Biswas, 1975.

(c) Nevatia and Biswas, 1975.

(d) Crawford et al., 1974.

Captions for Figures

Fig.1. Relative abundances in solar cosmic rays of energy > 20 Mev/amu relative to oxygen = 1.0, and from spectroscopic data of solar photosphere and corona. Solar cosmic ray data are from Biswas and Fichtel, (1965), Durgaprasad et al (1968), Bertsch et al (1972, 1973, 1974); spectroscopic data are from the review by Pagel (1973).

Fig.2. Abundance enhancement factors in solar cosmic rays at low energies, 5-10 MeV/amu.

Fig.3. Equilibrium charge vs energy/amu for multiply charged nuclei of He to Fe.

Fig.4. Mass histogram of He^3 and He^4 nuclei in the solar particle event on May 28, 1969 and November 2, 1969. Note the extremely high ratio of $He^3/He^4 = 1.5 \pm 0.1$ on May 28, 1969 event. In Nov.2 event He^3/He^4 ratio was 0.08 (Balasubrahmanyan et al., 1974).

Fig.5. Time average differential energy spectra for iron and oxygen nuclei during May 7 to 17, 1974, showing very large ratio of Fe/O ≈ 1.35 in 0.7-4 MeV/amu interval (Gloeckler et al.,1975).

Fig.6. Energy dissipation in solar atmosphere by accelerated solar particles and energy flux of escaping particles, for Sept.28, 1961 event for different values of f, the fraction of open lines of force. The dotted line decides measured escaping flux suggesting $f \approx 1\%$ (Biswas and Radhakrishnan, 1973).

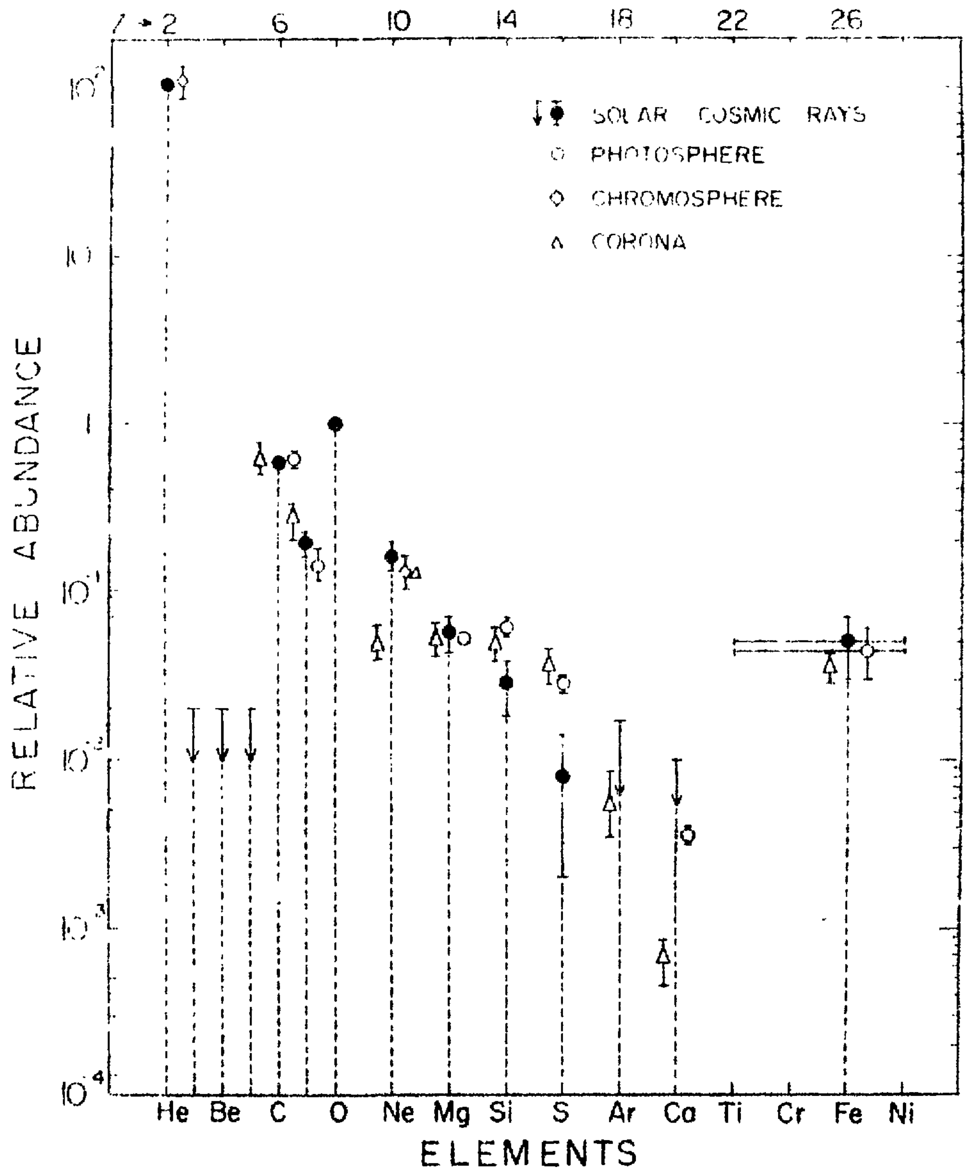
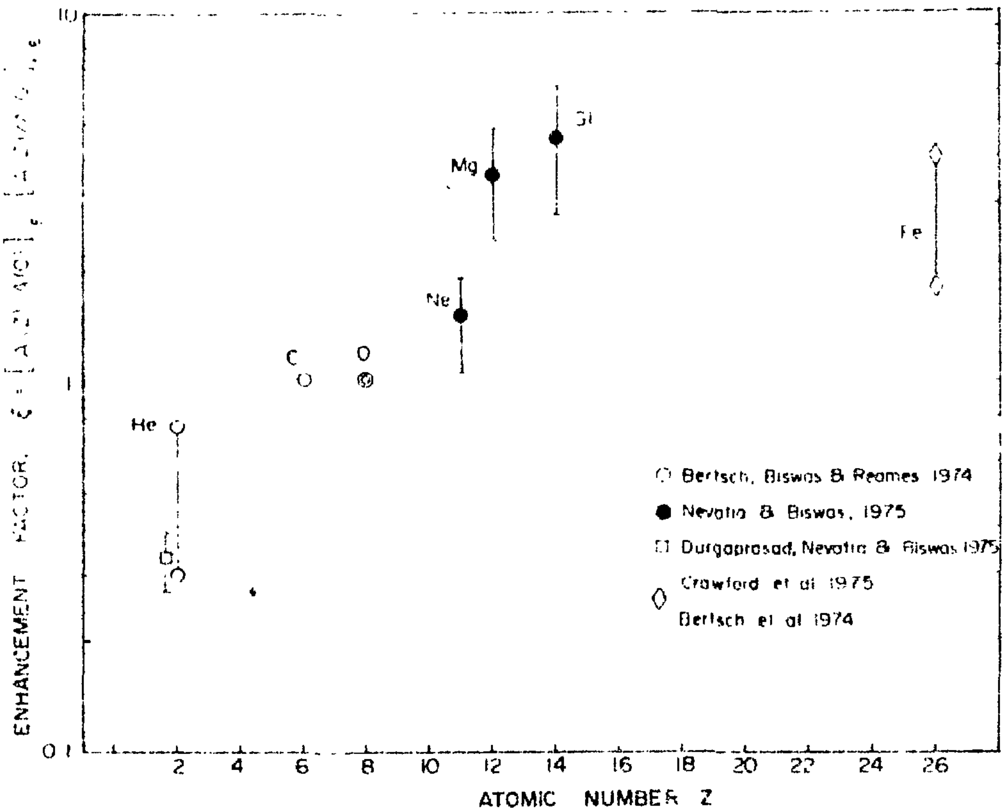

Z → 2
6
10
14
18
22
26
SOLAR COSMIC RAYS
PHOTOSPHERE
CHROMOSPHERE
CORONA
RELATIVE ABUNDANCE
He
Be
C
O
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
Ni
ELEMENTS

Fig. 1



ENHANCEMENT FACTOR
10
1
0.1
2
4
6
8
10
12
14
16
18
20
22
24
26
ATOMIC NUMBER Z
He
C
O
Ne
Mg
Si
Fe
Bertsch, Biswas & Reames 1974
Nevatia & Biswas, 1975
Durgaprasad, Nevatia & Biswas 1975
Crawford et al 1975
Bertsch et al 1974

Fig. 2

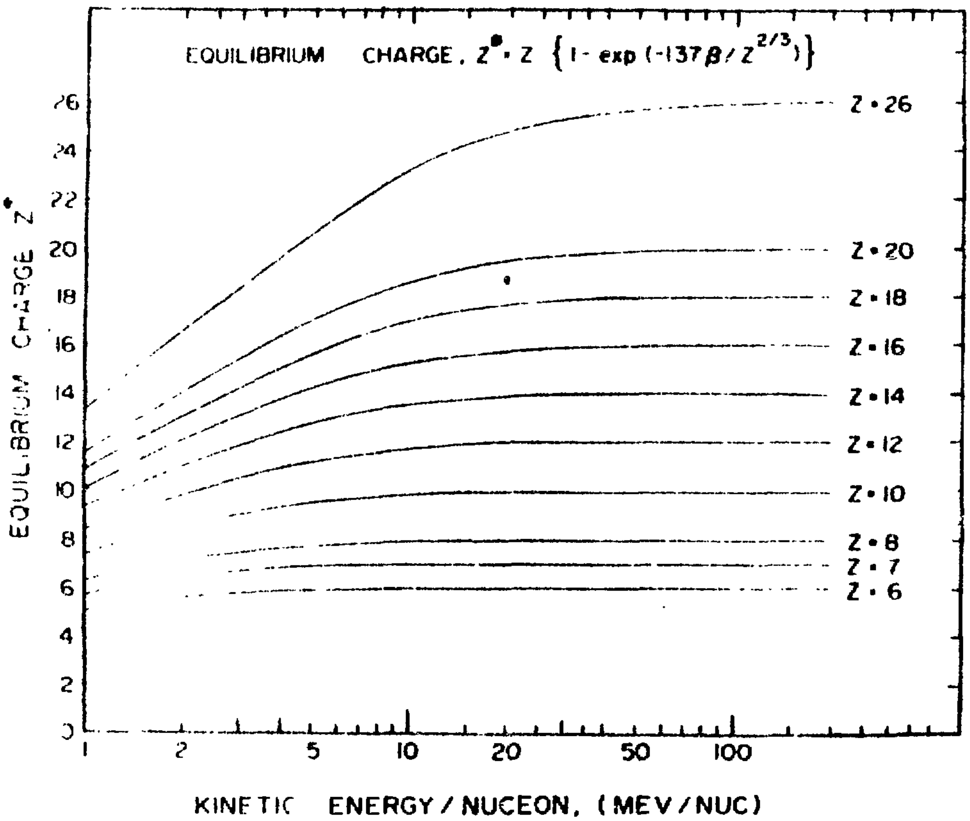

EQUILIBRIUM CHARGE, Z* = Z {1 - exp (-137β / Z^{2/3})}
Z = 26
Z = 20
Z = 18
Z = 16
Z = 14
Z = 12
Z = 10
Z = 8
Z = 7
Z = 6
EQUILIBRIUM CHARGE Z*
KINETIC ENERGY / NUCEON, (MEV / NUC)

Fig. 3

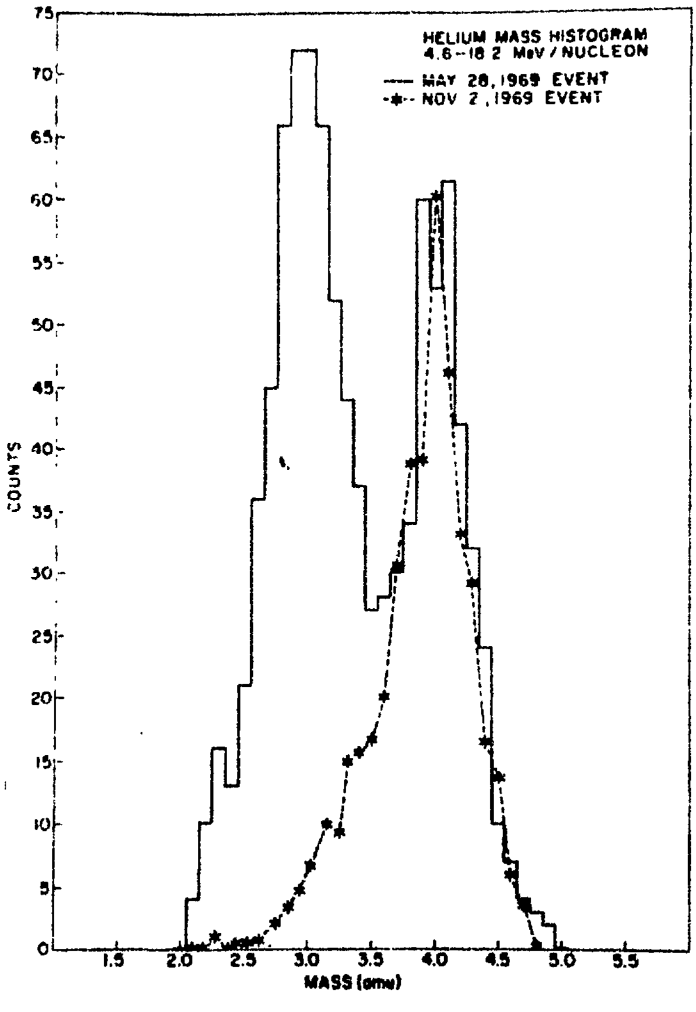

HELIUM MASS HISTOGRAM
4.6 – 18.2 MeV / NUCLEON
MAY 28, 1969 EVENT
NOV 2, 1969 EVENT
COUNTS
MASS (amu)

Fig. 4

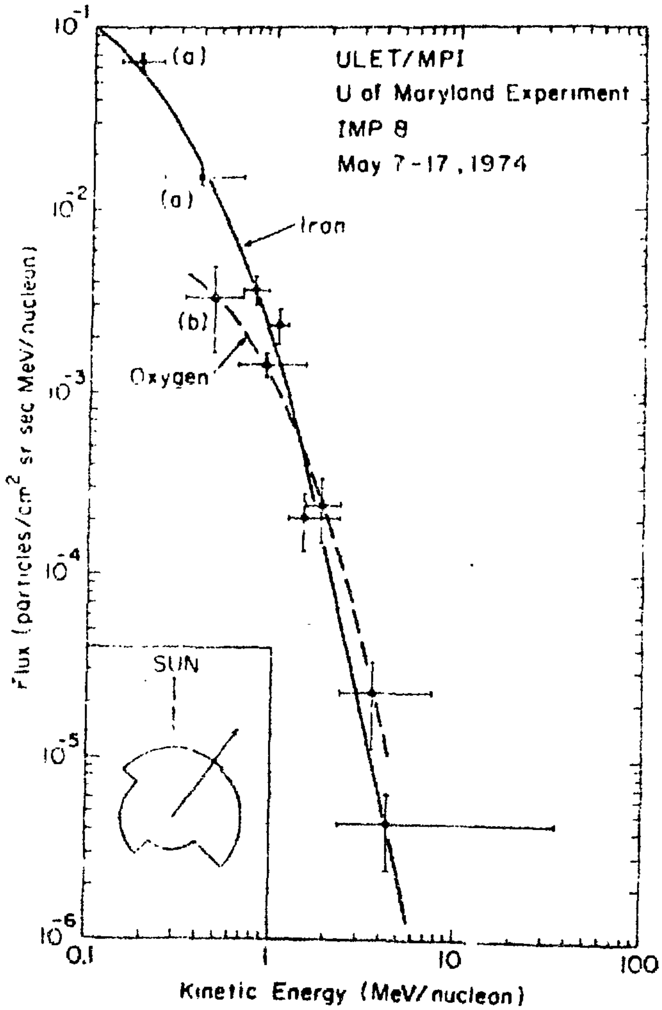

ULET/MPI
U of Maryland Experiment
IMP 8
May 7-17, 1974
Iron
Oxygen
(a)
(a)
(b)
SUN
Flux (particles/cm2 sr sec MeV/nucleon)
Kinetic Energy (MeV/nucleon)

Fig. 5

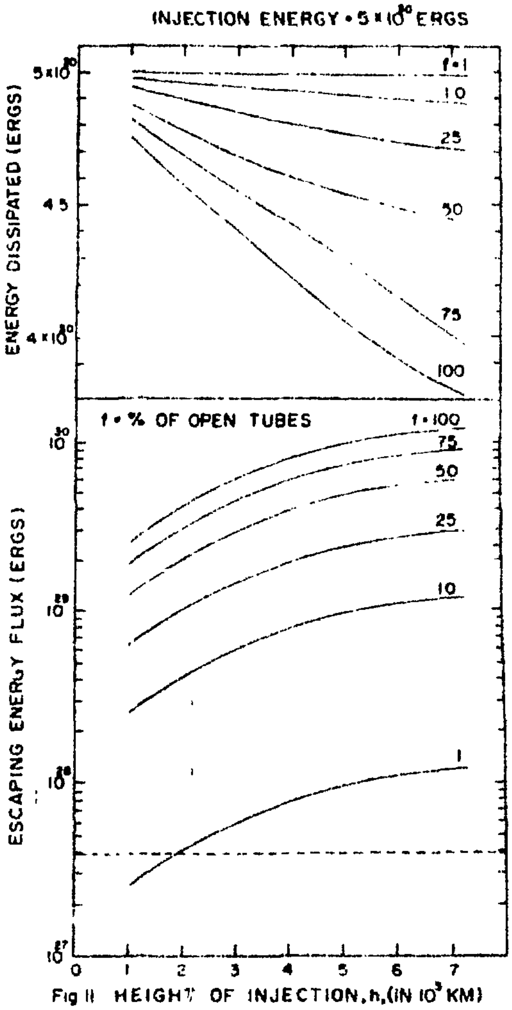

INJECTION ENERGY = 5 × 10^30 ERGS
ENERGY DISSIPATED (ERGS)
5×10^30
4.5
4×10^30
f=1
10
25
50
75
100
f = % OF OPEN TUBES
f=100
ESCAPING ENERGY FLUX (ERGS)
10^30
10^29
10^28
10^27
0
1
2
3
4
5
6
7
Fig II HEIGHT OF INJECTION, h, (IN 10^3 KM)

Fig. 6