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The chemical composition of energetic charged particles in interplanetary space

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The particle population in the heliosphere is briefly reviewed. Next the chemical composition of the charged fraction is reviewed by discussing three classes. The galactic cosmic rays and high energy solar flare particles above 100 MeV/nucleon are mentioned. The anomalous component in the range 1–100 MeV/nucleon, prompt solar flare particles, energetic storm particles and corotating events are discussed. The anomalous variations in isotopic (^{3}He) and chemical composition (iron-rich events) at energies below 10 MeV are reviewed. A discussion on the ionic charge state of these particles concludes this overview.

1. THE PARTICLE POPULATION IN INTERPLANETARY SPACE

The particle population in interplanetary space has various sources, the Sun being the most important one. It releases solar wind plasma continuously, which in fact sustaines the heliospheric cavity in the stellar wind. The Sun also occasionally emits charged particles accelerated to very high energies in 'flares' which are manifestations of the most rapid energy conversion. As a fraction of the solar atmosphere is in a neutral charge state, it is also likely that neutral gas escapes from the Sun into the heliosphere. There are other emitters of charged and neutral particles (atoms, molecules) in the solar system: all planets lose neutral gas from their atmospheres. However, they also lose plasma from their magnetospheres, and at least some of them (Mercury, Earth, Jupiter) are known to emit fairly energetic charged particles into their environment.

Within the Earth's magnetosphere those ions that form the ring current have a good chance to pick up electrons, move as neutrals unrestricted by magnetic fields, and eventually become ionized again. This mechanism is supposed to feed the low energy proton population in the inner radiation belt. Obviously, particles of the same origin will be found in interplanetary space. It is likely that similar mechanisms exist in the magnetospheres of other planets. Shock waves propagating through the interplanetary medium are known to accelerate charged particles to very high energies (particles with energies above 50 MeV have been observed to be affected). So besides the Sun and the planets, identified as particle emitters, we have to recognize that in interplanetary space processes are at work that change the energy distribution of particle populations sometimes or even permanently. The heliosphere, on the other hand, is bombarded by cosmic ray particles from outside. The solar magnetic fields carried with the solar wind flow exclude particles of lower energies ($E \lesssim 100$ MeV/nucleon) from penetrating into the inner part of the solar system. So at Earth, for example, only highly energetic primary cosmic ray particles may be observed (plus secondaries at lower energies from local nuclear interactions). Neutral gas of interstellar origin, however, may also penetrate into the heliosphere with velocities of about 20 km/s relative to the Sun. Finally, comets and meteorites should be mentioned as further sources of dust and gas in the heliosphere.

2. Chemical composition above 100 MeV/nucleon

At high energies the charged particle population is mostly due to the galactic cosmic ray source except during intense solar flares, where a solar component might be superimposed.

Cosmic ray particles diffuse from their sources through the galactic disk, thereby undergoing collisional interactions with interstellar gas and dust. Their composition as measured in interplanetary space is remarkably constant if corrected for the history *en route* and for solar modulation effects, and is for the more abundant elements in reasonable accord with what is called the relative abundance of elements in the Universe, as compiled by Cameron (1968, 1973) (based on abundances in carbonaceous chondrites which show little evidence of chemical fractionation, and on neutron shell calculations). Their composition includes all elements in the periodic table at least up to Ni and probably up to and beyond $Z = 40$. There are discrepancies (figure 1) for the light nuclei: cosmic rays are depleted in H and He, but show abundances for, for example, Li, Be and B that are orders of magnitudes larger than universal abundances, which is also true for almost all elements between Cl and Mn ($17 \leqslant Z \leqslant 25$), which are believed to be generated also in break-up reactions of heavier nuclei in collisions with the

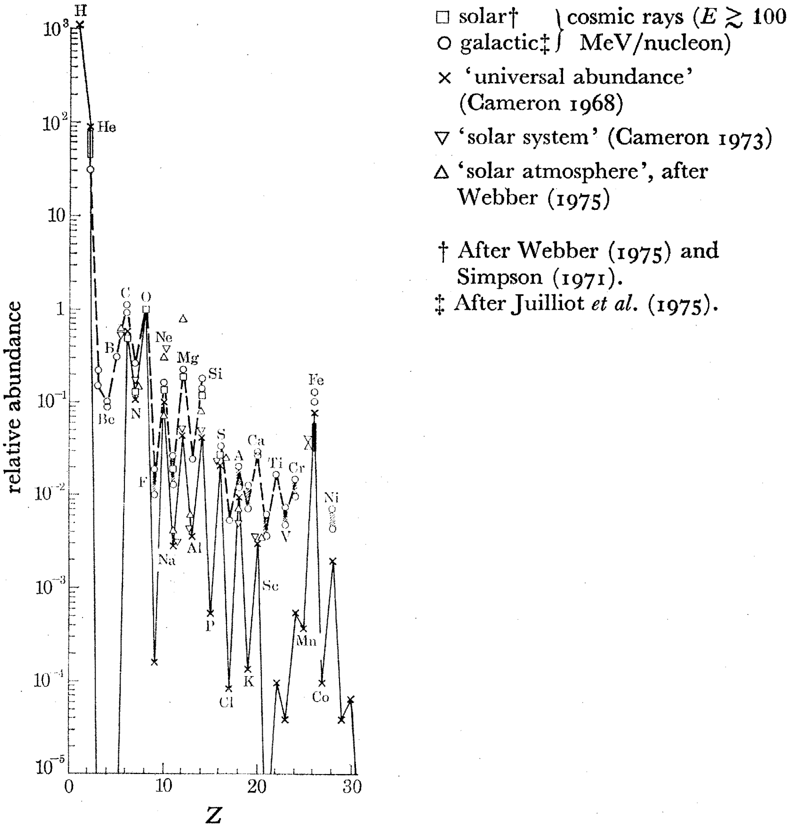

Figure 1. Relative abundance of elements plotted against nuclear charge, Z, normalized to ^{16}O (= 1) in solar and galactic cosmic rays at high energies ($E > 100$ MeV/nucleon). Full line connects 'universal abundance'-points, broken line connects solar particle data. Two points of the same kind at one element indicate range of data.

interstellar gas. The solar flare particle composition of major elements in this energy range is close to the cosmic ray composition and also close to solar abundancies as derived from optical measurements; this is illustrated also in Figure 1.

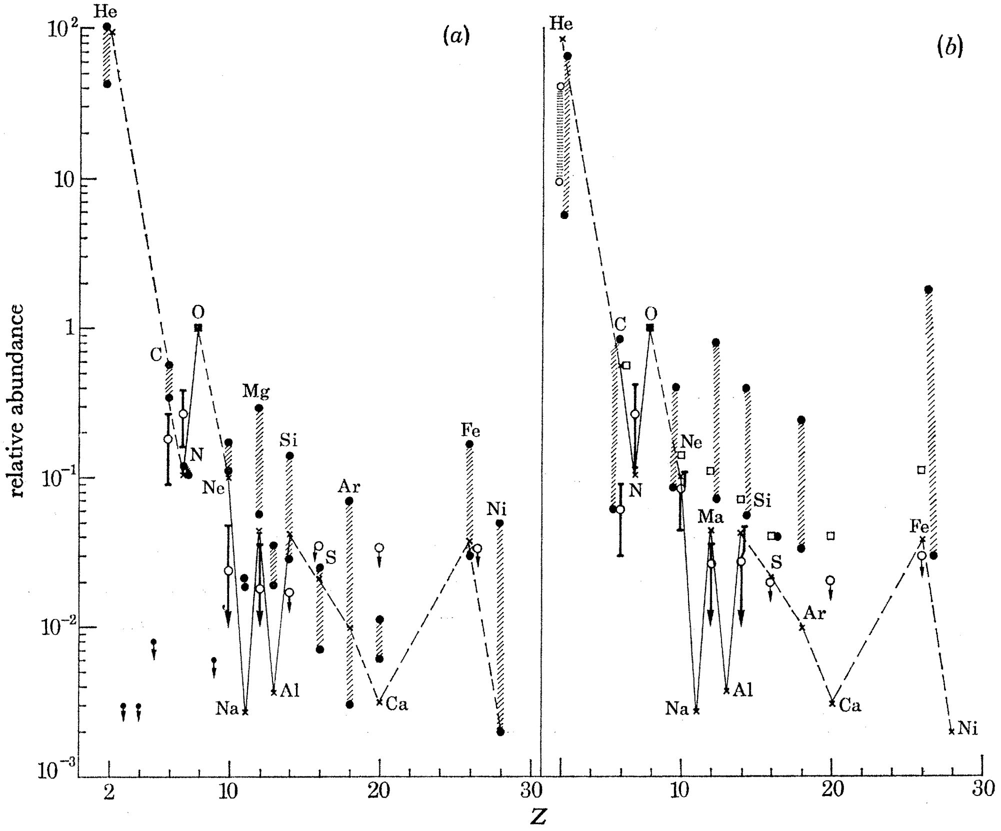

FIGURE 2. Relative abundance of elements plotted against nuclear charge, Z, normalized to ^{16}O (= 1). Lines connect data points giving universal abundances, which are also shown in figure 1. Hatched bars indicate range of data points compiled from papers shown below.

(*a*) Energy range $10 \leqslant E \leqslant 50$ MeV/nucleon. Symbols: ○, quiet times ('anomalous component') (after Klecker *et al.* 1977); ●, prompt flare particles (hatched bars represent range); ×, universal abundance (Cameron 1968). Includes flare data from Bertsch *et al.* (1972), Teegarden *et al.* (1973), Sullivan *et al.* (1973), Webber *et al.* (1975), Mogro-Campero & Simpson (1972*a*, *b*), Price *et al.* (1971), Klecker *et al.* (1977) and Crawford *et al.* (1975).

(*b*) Energy range $E < 10$ MeV/nucleon. Symbols: §, quiet times ('anomalous component') (after Klecker *et al.* 1977); §, quiet times (solar component, after Klecker *et al.* 1977); §, flare associated particles, §, universal abundance (Cameron 1968). Includes flare data from Nevatia & Biswas (1975), Sullivan *et al.* (1973), Woods *et al.* (1975), Klecker *et al.* (1977), Lanzerotti (1972) and Scholer *et al.* (1977) (event 7 only).

3. CHEMICAL COMPOSITION BELOW 100 MeV/NUCLEON

At lower energies, typically in the range 1–100 MeV/nucleon, over the last 10 years during quiet times an 'anomalous component' was isolated. In this energy range, the energy spectra of He, N, O and Ne revealed a second 'hump' (below the one due to the exclusion of low energy cosmic ray particles from the inner heliosphere). At even lower energies the spectra turn up again. It was therefore suggested (Hovestadt *et al.* 1973) that even during quiet times, weak fluxes of charged particles are emitted from the Sun. The origin of the anomalous component, however, is certainly not solar. Several observations support this conclusion: (1) the chemical composition in this energy range shows a solar cycle variation consistent with singly charged ions; (2) ^{3}He and ^{2}H, which are believed to be secondaries from high energy interactions show the $j \approx E^{+1}$ energy spectrum unchanged, and thus cannot be decelerated from higher energies; (3) nitrogen is ^{14}N only; if it would have been of the same origin as cosmic radiation, ^{14}N and ^{15}N should have been present in about equal abundances. This also excludes the possibility that the 'anomalous' particles are related to any nucleosynthesis process nearby; i.e. they cannot be of solar origin.

Several groups of workers have investigated this effect. It is now believed that the 'anomalous component' originates from interstellar neutral gas molecules that, after being ionized in the inner part of the solar system, are accelerated by some wave–particle interactions and may, owing to their higher rigidity (singly charged), diffuse back into the inner part of the solar system. Different ionization potentials should then discriminate between elements: atoms with high ionization potentials have a good chance of penetrating deep into the solar system and consequently could become more effectively accelerated. This mechanism, proposed by Fisk (1976) is in good agreement with observation (see Klecker (1977) and references therein).

The relative abundance of elements in this energy range reflects then just this special effect. It is therefore not surprising when the relative abundance of elements (based on a comparison at the same energy per nucleon) becomes meaningless. It would in this case be more appropriate to compare the elemental abundance when integrated over the full energy range. This is, however, difficult because at low energies fluxes may be of solar origin, and secondaries from cosmic ray nuclear interactions give additional background over this energy range.

4. The energy range below 10 MeV/nucleon

Early studies of solar particles in interplanetary space have led to the definition of three classes of solar particles: prompt particles, energetic storm particles (e.s.p.), and corotating particles. This last category of events has been analyzed in the last years only in more detail. These studies (Barnes & Simpson 1976; Pesses *et al.* 1978; McGuire *et al.* 1978; Van Hollebeke *et al.* 1978; Scholer *et al.* 1979) revealed that these events, which typically last a few days at 1 AU, were observed in close association with fast solar wind streams. They are identified primarily from the fact that no dispersion is seen, that they cannot be related to solar events but reappear in subsequent solar rotations, that their energy spectra are steep and that their anisotropy is, in the solar wind frame, directed towards the Sun with indications for large positive gradients (maximum intensities between 2 and 4 AU). The alpha particle:proton ratio in these events is fairly constant and does not vary as in flare events ($\alpha/p \approx 0.07$–0.1), carbon and helium are overabundant relative to oxygen when compared with flare particles. These features suggest that these corotating streams were not of solar origin in the strict sense, but may be thought to be accelerated somehow in interplanetary space, for example in connection with turbulence associated with fast solar wind streams. The fact that not all fast solar wind streams contain such energetic particle populations has led to the tentative introduction of the term 'interplanetary active region' to identify regions which contain such particles.

For the e.s.p. particles mentioned above, it is not clear whether they are released from the Sun after some acceleration or whether they are accelerated by the shock that passed through the region. It is well known that the post-shock region is dominated by waves, so, to some extent, these particles stay with the shock as it propagates outward. Shocks in general affect particles up to several tens of megaelectronvolts, and also affect the composition (see, for example, Armstrong & Krimigis 1973). For the time being it is therefore not very promising to go into a discussion of the various observations obtained at e.s.p. particles as their instantaneous composition is known to have been affected by shocks and eventually also by other effects.

Prompt particles from flares are then the only energetic particle species that are known to be accelerated in the flare process to relatively high energies. Above energies of some 10 MeV/nucleon their chemical composition is known to be fairly constant from flare to flare but also in the course of an event if one excludes dispersion effects during the onset phase. Also the relative abundance of elements is similar with abundances known from optical observations in the photosphere and lower corona.

However, when observations at energies much below 1 MeV/nucleon were made, we learned that with decreasing energy the composition of solar particles no longer remains constant. Instead, it varies from flare to flare and also in the course of a particular flare event. The p/α ratio is probably the most widely used quantity to demonstrate this variability. Optical observations, solar wind data and energetic solar flare particle data give values ranging from 16 to 22, and solar neutrino theory requires at least $p/\alpha = 16$. But for solar particles at low energies the ratio has been observed to vary by more than three orders of magnitude! Also, subsequent flares from the same active region tend to show increasing p/α ratios (Briggs *et al.* 1978). It was, after all, completely unexpected to find also events with ^{3}He more abundant than ^{4}He. While in the solar wind the $^3\mathrm{He}/^4\mathrm{He}$ ratio is about 6×10^{-4}, and even smaller in material from the Moon and gaseous meteorites, in such events values up to 2 have been observed, first reported by Garrard *et al.* (1973). While Price *et al.* (1971) had already noted that heavy elements seem to be overabundant at low energies, Gloeckler *et al.* (1975) reported dramatic enrichments in heavy elements with iron abundances comparable to those of oxygen. Subsequently these events have been named 'iron-rich events'. Both were characterized as follows: (1) all flares with high ^{3}He contents are small flares (fluxes less than 0.1 $(\mathrm{cm^2\ s\ sr})^{-1}$), eventually subflares; (2) most of the ^{3}He ions have energies in the 0.1–1 MeV/nucleon range; (3) all ^{3}He-rich events are also rich in elements from the iron group, but not all iron-rich events are rich in ^{3}He; (4) the overabundance of heavier particles increases with decreasing energy and increasing nuclear charge, Z; (5) these events typically show large and prolonged anisotropies away from the Sun and seem to appear in low-speed solar wind régimes; (6) their energy spectra are comparable with flare spectra; (7) it seems as if all ^{3}He-rich events are accompanied by relativistic electrons.

Enrichment in heavy elements or/and in ^{3}He over solar abundances cannot be explained by propagation effects in the interplanetary medium. Varying composition at low energies has been suggested to reflect different chemical composition in source regions (mechanisms producing chemical fractionation were already proposed). On the other hand, up to now more than 50 ^{3}He-rich events have been observed, which means that this is not a rare type of event.

There is no consistent explanation of these observations as yet. Part of this deficit is due to our poor understanding of the flare process proper which leads to the acceleration of particles. In addition, our knowledge of the charge state of the particles observed in interplanetary space is based on only a few observations (and some of them are indirect conclusions). We also note that most instruments cannot distinguish the charge state; they even respond to neutrals.

5. CHARGE STATE OF SOLAR PARTICLE NUCLEI

Ions in a plasma of a given electron temperature have a well defined distribution of charge states, which rapidly follows electron temperature changes. So a particle population at a given height in the solar atmosphere has a charge state distribution characteristic of the local temperature. Ions moving through neutral material have an effective charge Z^* given by $Z^* = Z(1-\exp(-130\beta/Z^{\frac{2}{3}}))$. At energies above some 10 MeV, ions are practically fully stripped ($Z^* \approx Z$). At 5 MeV/nucleon, iron charge states have been reported from etched tracks to be +21. This is in general agreement with indirect findings, where the charge state has been inferred from rocket observations in the Earth's magnetosphere. Direct charge state measurements at lower energies have been reported by Sciambi *et al.* (1977 and other references therein). They use an electrostatic analyzer to determine E/Q of incoming particles. In the energy range 15–600 keV/nucleon, an effective charge of 5.7 was reported for carbon, 6.2 for oxygen on average from 10 'ordinary' solar particle events. The charge state did not vary during the events, nor with energy. For an iron-rich event these authors also determined an iron charge state of 11.6 (charge states 9–13 were observed). For ^{3}He-rich events, no charge state measurements have yet been reported. These observations show that M/Z is close to 2 for 'ordinary' events, where the abundances are close to those observed at higher energies (where $M/Z \approx 2$ for most elements). For the iron-rich event, M/Z is much larger (4.8), which might indicate that the acceleration process could produce the 'strange' abundances, if it operates in regions of different temperature. One eventually has to consider a solution for the ^{3}He-rich events along the same lines, if one excludes ^{3}He production. On the other hand, production of ^{3}He in proton collisions (Ramaty & Kozlowsky 1974) requires ^{2}H production at the same time at comparable rates. ^{2}H has never been observed at energies below 1 MeV, but this does not necessarily mean that ^{2}H is not there. The only positive identification of deuterium during flares was reported at energies above 1.2 MeV (Hsieh & Simpson 1970; Anglin *et al.* 1973). At lower energies, present instruments fail in the detection of deuterium owing to system noise. However, we note that at high temperatures deuterium is effectively destroyed by proton collision through $p + {}^2H \rightarrow {}^3He + \gamma$ which produces additional ^{3}He. Therefore, ^{3}He-rich events may alternatively stem from very hot flaring regions.

6. SUMMARY

In this short overview of our knowledge on the composition of energetic charged particles present in interplanetary space we have seen that the interesting questions related to high energy phenomena are now complemented at very low energies by fascinating new and unexpected observations. We are far from understanding all of the observations. However, clarification has been reached at least for the 'anomalous component', and progress towards an understanding of the corotating particle events – manifestation of ongoing interplanetary acceleration processes – was made. New models and theories are needed, to bring some order into the present state of apparent chaos in the field of chemical composition of solar flare particles, but also more observations with improved resolution and sensitivity.

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