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# COMPOSITIONS OF ENERGETIC PARTICLE POPULATIONS IN INTERPLANETARY SPACE

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## I. Introduction

Although the study of the composition of low-energy particles in the interplanetary medium is a relatively new subject, our knowledge in this field has been advancing rapidly. Discoveries of pronounced anomalies in the compositions of solar flare particles and low-energy "cosmic-rays", and of large-scale interplanetary acceleration regions beyond several AU have been followed by more systematic investigations aimed at characterizing each of the components of the interplanetary energetic particle population.

The discoveries may be attributed to a combination of three favorable circumstances: (a) availability of sophisticated instruments capable of performing composition measurements at low energies, (b) properly instrumented deep space probes exploring the outer and inner heliosphere, and (c) a favorable time period in the solar activity cycle during which the discovered phenomena were especially prominent. Composition measurements not only have played a key role in the initial discoveries, but have also contributed significantly to our understanding of the acceleration processes responsible for the production of energetic particles which populate interplanetary space.

Rather than being a comprehensive review of the extensive literature on the subject, this report will highlight the major developments in this area emphasizing observations of helium and heavier particles with energies below about 10 to 20 MeV/nucleon. Not included in the present discussion are solar and Jovian electrons, solar neutrons, observations dealing mostly with protons, and locally produced particles such as energetic storm particles (ESP) or upstream magnetospheric bursts. For more comprehensive surveys of various observational and theoretical aspects of these subjects the reader is referred to recent reviews by Fisk (1977), Ramaty, et al. (1979) and Gloeckler (1975).

In this report we will summarize advances in our knowledge and assess important questions which are likely to be investigated in the near future for each of three dominant constituents of interplanetary particles: solar flare particles, co-rotating particle streams, and the so-called "anomalous cosmic ray" component. The recent discovery of a class of solar flare particle events with unusual enrichments of  $^3\text{He}$  and heavy elements indicates highly selective solar injection mechanisms. Systematic examination of the compositions of these particle events and comparisons with abundances in normal flare particle populations should provide a clearer understanding of these mechanisms. Observations of positive radial intensity gradients and anisotropies in co-rotating particle streams suggest the existence of large-scale interplanetary acceleration in a region extending from  $\sim 2$  to 4 AU. Studies of the elemental and charge state composition should resolve current questions as to what material is accelerated and how. The discovery of the "anomalous cosmic ray" component in 1972-74 was completely unexpected. Although present observations exclude the sun as a direct source of these energetic particles, their origin is still debated. Whether these particles are accelerated in the outer heliosphere or come from a local interstellar source may not be known until the charge states of these particles have been determined.

## II. The Composition of Solar Flare Particles

An important motivation for the initial measurements of the composition of charged particles accelerated in solar flares was the establishment of more precise solar elemental abundances using this "direct" sample of the solar atmosphere. Indeed, the results of early studies by the Goddard Group (e.g. Biswas and Fichtel, 1965) using nuclear emulsions carried on sounding rockets launched during large solar flare particle events supported this expectation. Analysis of data taken during 8 major flares from about 1960 to 1970 indicated that for elements heavier than hydrogen the composition of solar particles with energies above  $\sim 20$  MeV/nucleon remained fairly constant and reflected the composition of the solar atmosphere for elements where such comparison could be made.

Improvements in experimental techniques and the availability of satellites made it possible to study flare particle compositions at lower energies, in small flare particle events, and as a function of time in large events. These

developments led to the discoveries of dramatic compositional anomalies, especially in smaller flare particle events, and the realization that the composition varies not only from one flare event to the next but also during a given event. Thus, a major emphasis of current compositional studies is to systematically examine a large number of solar flare particle events in order to isolate the variable from the repeatable features and to understand the causes for the anomalies in the solar particle abundances.

### Normal Flare Particle Events

Substantial progress has been made in recent years in characterizing compositional aspects of solar flare particles by carefully examining a large number (about 30) of flare events especially at energies extending down to  $\sim 1$  MeV/nucleon. This has provided us with the first abundance measurements of such rare elements as Na, Al, Ar and Ca, isotopes of H, He, C, O and Ne, and better upper limits for Li, Be, B, F and P.

Elemental and Isotopic Abundances. Average values of the elemental abundances of  $\geq 1$  MeV/nuc solar particles in relatively large solar flare events (peak intensities exceeding  $\sim 100$  protons/cm<sup>2</sup> sec sr MeV) with a "normal" composition are given in Table 1 and shown in Figure 1 as solid bars, open rectangles (element groups) and solid triangles (upper limits). The abundances relative to oxygen of the individual elements or element groups are derived from results reported for a number of individual flare particle events by Crawford et al. (1972), Bertsch et al. (1973), Teegarden et al. (1973), Hovestadt (1974), Webber (1975), McGuire et al. (1977) and Mason et al. (1979a). The vertical extent of the solid bars and open rectangles indicates the degree of variability in the compositions from one flare to the next, which for the more abundant elements (H, He, C, N, Ne, Mg, Si and Fe) is considerably larger than the statistical uncertainties to which the abundances of these elements can be determined for individual flare events. Despite these variabilities the basic compositional features of solar flare particles are similar to those of the solar corona and photosphere whose abundances are also given in Table 1 and shown in Figure 1. There is the overall agreement in the abundances of He, C, N, and S through Fe, the elements Li, Be, B,

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F, and P are seen to be rare, and the odd  $Z$  ( $Z$  is the atomic number) elements N, F, Na, Al and P are far less abundant than their even  $Z$  neighbors. It should be noted, however, that solar particles seem to be consistently enriched in the elements Na to Si and the solar flare C/O ratio, although consistent with the solar photospheric abundance is lower than the coronal value. Little is known about elements heavier than iron except that their abundances are very low.

The composition of solar particles in the medium and small intensity "normal" events is basically similar to that in the more intense flares. There is, however, a tendency for the He/O ratio to be somewhat larger ( $\sim 70$  to  $90$ ) than the corresponding ratio in the large flare particle events (Gloeckler, 1979).

Our knowledge of the isotopic composition of solar flare particles is at this time rather limited and generally confined to the lighter elements. Typical values of the H and He isotopic ratios at  $\sim 1$  to  $10$  MeV/nucleon averaged over a number of solar flare particle events are:  $^2\text{H}/^1\text{H} = 7(+10, -6) \cdot 10^{-6}$ ,  $^3\text{H}/^1\text{H} \sim 3 \cdot 10^{-6}$  and  $^3\text{He}/^4\text{He} \sim (9 \pm 4) \cdot 10^{-3}$  (Hurford, 1975; Hurford et al., 1975a). These values are consistent with earlier results of Anglin (1975), Anglin et al. (1973) and Hsieh and Simpson (1970). The isotopic abundances of solar flare Ne in the energy range from  $11$  to  $60$  MeV/nucleon have recently been reported by Mewaldt et al. (1979a) and Dietrich and Simpson (1979) to be

$$^{20}\text{Ne}/^{22}\text{Ne} = 7.6^{+2.0}_{-1.8} \text{ and } 7.7^{+2.3}_{-1.5} \text{ respectively.}$$

This value is significantly lower than the comparable and well established solar wind ratio of  $13.1 \pm 0.6$  (Geiss et al., 1970) and poses interesting problems for the acceleration of solar material. The low abundances of  $^{13}\text{C}$ ,  $^{17}\text{O}$ ,  $^{18}\text{O}$ , and  $^{21}\text{Ne}$  ( $^{13}\text{C}/^{12}\text{C} \sim 10^{-2}$ ,  $^{17}\text{O}/^{16}\text{O} < 3 \cdot 10^{-3}$ ,  $^{18}\text{O}/^{16}\text{O} \sim 2 \cdot 10^{-3}$ ,  $^{21}\text{Ne}/^{20}\text{Ne} < 10^{-2}$ ) indicate that element production by nuclear spallation reactions in the solar atmosphere is not significant (Mewaldt et al., 1979b).

**Charge States.** Direct and indirect determinations of the ionization states of solar particles indicate incomplete stripping of the heavy ions over an extended energy range up to at least  $\sim 5$ - $10$  MeV/nucleon. Direct measurements (Sciambi et al., 1977; Gloeckler et al., 1973, 1975a, 1976) have shown that in general the

charge states of C, O and Fe below  $1$  MeV/charge in solar flares are (a) consistent with the ionization states of these elements in the solar wind (charge states of  $6$ ,  $6$  and  $12$  for C, O and Fe respectively), (b) do not vary substantially from flare to flare, and (c) remain constant over the energy range of the measurements of  $\sim 50$  to  $1000$  keV/charge. A number of indirect determinations of charge states of iron at higher energies ( $\sim 1$  to  $10$  MeV/nucleon) also indicate partial ionization. For example, with the assumption that the charge states of He, C, O and Fe are  $2$ ,  $6$ ,  $6$  and  $11$  respectively one can explain in the simplest manner the time-dependent variations of the relative abundances of these elements often observed during the initial phase of flares (O'Gallagher et al., 1976; Scholer et al., 1978). Under similar assumptions the apparent energy-dependence of the Fe/O and O/He ratios computed at equal energy per nucleon (Price et al., 1973) disappears when these ratios are computed at equal rigidities.

**Variability in the Composition.** It has now been established beyond any doubt that there is significant variability in the composition of normal flare particle events, not only from one event to the next but often also during a given event. In Figure 1 we indicate by the vertical extent of the solid bars and rectangles the degree of the variability in the event-averaged ratios of H, He, C, Na, Mg, Si, S-Ca and Fe relative to oxygen. The magnitude of the variations is seen to be largest for elements whose atomic number  $Z$  differs most from oxygen, reaching a factor of about ten for protons and iron.

Systematic changes in the elemental composition have been observed during individual solar particle events and in successive flares from the same active region. O'Gallagher et al. (1976) find that in addition to the well known velocity dispersion (Cline and McDonald, 1968), there is a charge-to-mass dependent dispersion in the time-to-maximum for elements having equal velocities. They report that  $1$  to  $1.6$  MeV/nucleon iron, for example, reaches maximum intensity some eight hours before  $1$  to  $1.6$  MeV/nucleon oxygen. The ratios often continue to change with time as an event progresses (Armstrong et al., 1976; Scholer et al., 1978). Recently Briggs et al. (1979) have reported H/He enhancements in second and third as compared to the first particle producing flares

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which occurred in the same McMath active plage region. Such enhancements seem to be transient and are not seen for multiple flares separated by more than about 100 hours.

**Energy Dependence in the Composition.** Ratios of Fe/O and O/He (computed at equal energy/nucleon) in normal solar flare particle events are often found to increase with decreasing energy, especially below  $\sim 1$  MeV/nucleon (Price et al., 1973, Scholer et al., 1978). Such energy-dependent variations in the ratios may, however, be artificial. By assuming solar wind ionization states for solar flare He, O and Fe (2, 6 and 11 respectively) and computing the ratios at equal particle magnetic rigidities the variations generally disappear.

For two large solar particle events (4 July 1974 and 24 September 1977) large Fe/O ratios as well as systematic enhancements in other heavy elements were reported at energies above  $\sim 15$ –20 MeV/nucleon (Bertsch and Reames, 1977, and Dietrich and Simpson, 1978). For these same two events the composition as measured by the University of Maryland/Max Planck Institut experiment on IMP-8 was more nearly normal at 1 to 4.6 MeV/nucleon with no large energy dependence over this range. These results indicate a significant energy dependence in the ratios above  $\sim 5$  MeV/nucleon, and increasing enrichments of the heavy elements with increasing energy, implying that the energy spectra of heavier elements become progressively flatter (Hamilton and Gloeckler, 1978).

### $^3\text{He}$ -Rich and "Fe" Rich Solar Particle Events

The  $^3\text{He}/^4\text{He}$  abundance in "normal" solar particle events is typically  $\sim 10$  to 30 times larger than the value of  $\sim 10^{-4}$  estimated for the photosphere (e.g. Ramaty et al., 1979). Such enrichment of He can generally be explained in terms of production in nuclear reactions of energetic particles with the solar atmosphere. The discovery of a class of solar flare events in which  $^3\text{He}/^4\text{He}$  often exceeds unity, and where Fe and other heavy elements are highly overabundant came as a surprise since nuclear production mechanisms could not explain such drastic departures from the "normal" flare composition. Although the number of such anomalous events for which detailed composition measurements are available is small, one can already begin to see their overall characteristics.

The abundances of elements relative to oxygen averaged over a number of small "Fe- $^3\text{He}$ -rich" events (Hovestadt et al., 1975; Mason et al., 1979b) are shown in Figure 1 as shaded bars and shaded rectangles (element groups). These abundances computed in the 1 to 4.6 MeV/nucleon range are compared in Table 1 and Figure 1 to the compositions of "normal" flare particles, the solar corona and the photosphere. Iron rich events, defined here to have Fe/O ratios larger than 0.5, are seen to be systematically enriched not only in Fe but also in Ne, Mg, Si and S-Ca. Protons, helium and carbon, on the other hand, are typically underabundant. The composition is seen to be variable (see Figure 1) although systematic trends in the variabilities noted for "normal" events cannot be established from the small sample of events available at this time. The extent of departure from a normal composition is illustrated in the May 14–15, 1974 solar flare particle event where the 0.6–1.6 MeV/nucleon C/O and Fe/O ratios are  $0.01^{+0.07}_{-0.01}$  and  $2.58 \pm 0.57$  respectively (Mason et al., 1978, 1979c, d). Systematic enhancements of Fe and other heavy elements have also been observed in certain large flares at higher energies by Bertsch and Reames (1977) between 15 and 30 MeV/nucleon and by Dietrich and Simpson (1978) at energies as high as 200 MeV/nucleon.

Solar particle events in which the  $^3\text{He}/^4\text{He}$  ratio is unusually large ( $\gtrsim 0.1$ ) are also found to be overabundant in iron and other heavy elements. Despite considerable scatter in the data there is in fact a positive correlation between, e.g., the Fe/He and  $^3\text{He}/^4\text{He}$  ratios in some 40 solar particle events compiled by Anglin et al. (1977). This correlation, as well as the enormous enrichments of  $^3\text{He}$  cannot be successfully explained in terms of nuclear production models (e.g. Ramaty et al., 1979). Fisk (1978), on the other hand, has described a plasma heating mechanism which can simultaneously produce large  $^3\text{He}/^4\text{He}$  ratios ( $\gtrsim 1$ ) and Fe enhancement in small solar flare particle events.

Data from about 30  $^3\text{He}$  rich events reported since 1968 indicate that the  $^3\text{He}/^4\text{He}$  ratio is variable, ranging from  $\sim 0.1$  to  $\sim 10$ , with  $^3\text{He}/^4\text{He} \gtrsim 0.5$  in over half of the cases (Ramaty et al., 1979; Gloeckler, 1975). No measurable amounts of  $^2\text{H}$  or  $^3\text{H}$  have been found in any of the 30 events; typical upper limits range from  $4 \cdot 10^{-3}$  to 0.04. It should be noted that the proton intensity in  $^3\text{He}$ -rich events is generally small, i.e., less than  $\sim 10^{-1}$  protons/( $\text{cm}^2 \text{ sec sr MeV}$ ) at 10 MeV, and that positive association



with solar optical flares cannot always be established for such microevents (e.g. Ramaty et al., 1979).

Abundance ratios as a function of energy have been measured in only a few  $^3\text{He}$ - and Fe-rich events. From this limited sample one finds that there is no pronounced energy dependence in the Fe/O and He/C ratios in the range 0.5 to 4 MeV/nucleon (Gloeckler et al., 1976). In contrast,  $^3\text{He}/^4\text{He}$  increases, with increasing energy by a factor of  $\sim 5$  (Gloeckler, 1978) in the May 7, 1974  $^3\text{He}$ -rich event where the He intensities were sufficiently large to allow energy spectrum measurements.

#### Requirements for Solar Flare Particle Acceleration Mechanisms

The explanation of the rich variety, systematic changes, and dramatic deviations in the composition of solar flare particles must be one of the outstanding challenges for solar flare theories. Enormous deviations from "normal" abundances, especially for  $^3\text{He}/^4\text{He}$ , C/O and Fe/O cannot be simply accounted for in terms of compositional variability in the source material or by nuclear production models (Ramaty and Koslovsky, 1974; Rothwell, 1976; Colgate, et al., 1977a, b), but are far more likely to be caused by preferential heating and injection into the acceleration mechanisms (Fisk, 1978; Kocharov and Kocharov, 1978). In a model proposed by Fisk (1978) a common plasma instability is invoked to excite electrostatic ion cyclotron waves which can then resonantly heat  $^3\text{He}$ , and certain ions of O, N and Fe to far greater temperature than ambient  $^4\text{He}$ , and carbon. Direct acceleration of ions in the high-energy tail of the Maxwell-Boltzmann distribution to energies  $\gtrsim 1$  MeV would then result in dramatic enhancements of these preferentially heated ions. This model not only accounts for the observed absence of  $^2\text{H}$  and  $^3\text{H}$  in the anomalous flares but could also explain the compositional variabilities since the selection of ions which are preferentially heated depends critically on the coronal temperature in the acceleration region. Furthermore, it can be argued that the observed composition in the larger flares is more "normal" because in the extended acceleration regions averaging effects, due to e.g., the variations in plasma temperature and B, over a large region would tend to wash out large deviations in the composition.

The temporal variations in the composition observed in the post-maximum phase of flare particle events cannot be explained solely by interplanetary propagation effects, but requires a continuous rather than impulsive release of particles from the flare site. Compositional changes could be introduced either by changing conditions in the acceleration region (e.g., changing coronal temperature, varying H/He ratios in the ambient material), by a rigidity-dependent acceleration and escape mechanisms, or both.

It remains to be seen to what extent the average composition of solar flare particles reflects the composition of the source material in the photosphere or corona. Aside from the variability, the solar particle abundances are seen to be somewhat enriched in elements heavier than oxygen. Once the systematic character of these enhancements is more fully understood it may be possible in fact to improve and extend our knowledge of solar abundances by using the average flare particle composition, which can be determined in great detail. In the immediate future, however, composition studies will have the greatest impact on our understanding of the dynamical processes on the sun which lead to the heating, acceleration and escape of solar flare particles.

#### III. Corotating Energetic Particle Streams

Modest increases in the intensity of  $\gtrsim 1$  to  $\sim 20$  MeV/nucleon protons and  $\alpha$ -particles, which persist for three to six days and often reappear a number of times at 27-day intervals, were first observed during the 1965 solar minimum (Bryant et al., 1965; Fan et al., 1965). It was soon established that these corotating or 27-day recurrent increases are not associated with solar flares and do not exhibit the velocity dispersion often observed at the onset of solar flare particle events (Cline and McDonald, 1968), but are correlated with high-speed solar wind streams and interplanetary magnetic field structures corotating with the sun. Pioneer 10 observations during the 1974-76 solar minimum (McDonald et al., 1976) which revealed that the peak intensity of  $\sim 1$  MeV protons in corotating particle streams increases with increasing radial distance from the sun, provided the first clue that these particles are not of solar origin but rather are accelerated in the interplanetary medium beyond several AU. A number of more recent measurements of radial gradients (Van Hollebeke et al., 1978, 1979; Kunow et al., 1977; Christon and Simpson,

1979) and particle anisotropies (Mewaldt et al., 1978a; Ipavich et al., 1978) in corotating events combined with the temporal-spatial correlations observed at  $\sim 4$  to 5 AU between the  $\sim 1$  MeV/nucleon corotating particles (Barnes and Simpson, 1976; Pesses et al., 1978) and the magnetic field and plasma turbulence (Smith and Wolfe, 1976) in the corotating interaction regions (CIR) provide further evidence for the existence of large-scale and continuous acceleration of particles in the interplanetary medium between  $\sim 2$  and 5 AU.

Although the existence of interplanetary acceleration is now fairly well established, questions on the nature of the acceleration mechanisms and as to what ambient material is accelerated are just beginning to be examined. The acceleration mechanisms discussed most frequently include both statistical processes resulting from magnetic and plasma turbulences which are generated when high and low speed solar wind streams collide in the CIR (Fisk 1976a, b), and acceleration at the forward and reverse shocks (Palmer and Gosling, 1978; Armstrong and Decker, 1979; Pesses and Van Allen, 1979) which bound the CIR (Hundhausen and Gosling, 1976; Smith and Wolfe, 1976).

Of the possible sources for the corotating energetic particles the most likely candidates are either the high-energy tail of the solar wind or an as yet undetected, low energy ( $\lesssim 200$  keV/nucleon) residual particle population, presumably of solar origin. Comparing the elemental and charge state composition in corotating events with that in the postulated sources may be the best way to resolve the question of origin. It should be emphasized, however, that to make such comparisons most meaningful one must find a representation in which the composition remains unchanged as a function of particle parameters (e.g., energy, rigidity or velocity).

#### Composition of Energetic Particles in Corotating Streams

It has been shown recently (Gloeckler, 1979; Gloeckler et al., 1979a) that the relative abundances of H, He, C, O and Fe in corotating particle streams remain constant when the energy spectra of these elements are expressed as distribution functions (number density in phase space) of velocity  $v$ . These distribution functions are found to have the simple form  $f = f_0 \exp(-v/v_0)$  over the entire velocity (or energy) range of the measurements ( $\sim 0.16$  to 10 MeV for protons), and the characteristic speed,  $v_0$  (typically  $3 \cdot 10^8$  cm/sec) is observed to be the same within experimental uncertainty for all elements examined in each of the corotating

events studied. Furthermore, distribution functions computed from energy spectra reported by Van Hollebeke et al. (1979) and Mewaldt et al. (1978b) for  $\sim 1$  to 10 MeV protons in a large number of corotating events also have exponential forms with characteristic velocities around  $3 \cdot 10^8$  cm/sec. Measurements of helium above  $\sim 1$  MeV/nucleon by these groups, however, differ from those of Gloeckler et al. (1979a) and distribution functions derived from helium spectra reported by Van Hollebeke et al. (1979) and Mewaldt et al. (1978b) have characteristic velocities which are generally 30 to 40% smaller than those observed for H, C, O and Fe. This discrepancy in the helium measurements has not yet been resolved.

The average relative abundances obtained from the distribution functions of various elements in corotating particle streams (Gloeckler et al., 1979a, b) are shown in Table 1 along with the compositions of solar flare particles, the solar corona (Withbroe, 1971) and photosphere (Ross and Aller, 1976). Unlike the case for solar flare particles, the relative abundances in corotating events appear in general to be less variable from one event to the next (Gloeckler, 1979; Gloeckler et al., 1979b). It may be seen from Table 1 that the composition of recurrent events is characterized by a relatively large abundance of He and C relative to oxygen (Ipavich et al., 1978; McGuire et al., 1978; Scholer et al., 1979; Gloeckler et al., 1979a, b), and in this respect deviates noticeably from the typical abundances of solar flare particles. On the other hand the corotating particle composition reflects most closely the composition of the solar corona (and thus presumably that of the solar wind). The agreement is particularly striking for H, He, C, Si and Fe. The Mg/O, (S-Ca)/O and especially Ne/O seems, on the other hand, to be more abundant in corotating events than in the solar corona. It is not known at present to what extent the solar wind Ne/O, Mg/O and (S-Ca)/O ratios could systematically deviate from the respective coronal values.

On the basis of presently available composition measurements it would appear that the high-energy tail of the solar wind distribution is the most likely source material for the corotating particles. If one further assumes that the composition of the solar wind and of its high-energy tail are similar, then the measured relative abundances in corotating events provide at present the best information about the elemental composition in the solar wind, and, in particular, would suggest that C/O = 1 in the solar wind. As



pointed out by Gloeckler et al. (1979a) the observed exponential dependence of the particle distribution function on velocity may imply that the acceleration of corotating particles in or near the corotating interaction regions is predominantly by a statistical process.

#### IV. The Anomalous Cosmic Ray Component

At the onset of the last solar minimum in 1972 anomalies began to appear in the energy spectra and composition of  $\sim 70$  MeV/nucleon cosmic rays. This is illustrated in Figure 2 where we show the energy spectra of H, He, C and O between  $\sim 0.5$  and  $>100$  MeV/nucleon measured in the interplanetary medium during quiet times (when neither solar flare or corotating particles were present). Particles in the low-energy rising portion of the spectra might be predominantly interplanetary in origin. Galactic cosmic rays are observed for H above 10 MeV, for He above 60-80 MeV/nucleon and for C and O above  $\sim 30$  MeV/nucleon. In the intermediate energy range ( $\sim 2$  to  $\sim 30$  MeV/nucleon) appears the anomalous component. The helium spectrum above  $\sim 2$  MeV/nucleon is relatively flat and between  $\sim 5$  and 30 MeV/nucleon He is more abundant than protons (Garcia-Munoz et al., 1975, 1977a, b). The oxygen spectrum shows an unusual hump between  $\sim 2$  and 20 MeV/nucleon with no comparable feature for carbon (Hovestadt et al., 1973, Klecker, et al., 1975, 1977) and at  $\sim 5$  MeV/nucleon oxygen is some 10 to 20 times more abundant than carbon. In addition to helium and oxygen, nitrogen and neon are observed to be more abundant in the anomalous component than in the  $\sim 100$  MeV/nucleon galactic cosmic rays (McDonald et al., 1974a; Klecker et al., 1975, 1977; Webber et al., 1975a; von Rosenvinge and McDonald, 1975; Mewaldt et al., 1975a).

The abundances relative to carbon of the major elements in the anomalous component are compared to the composition of galactic cosmic rays in Table 2. Assuming that 2-30 MeV/nucleon carbon is predominantly galactic during quiet times, the elements H, He, N, O, Ne and possibly Fe are from 5 to 20 times more abundant in the anomalous component than they are in cosmic rays. Within statistical uncertainties the composition of the other elements is comparable to that of the galactic particles. Available measurements of the isotopic abundances of anomalous He, N and O indicate an essentially pure  $^4\text{He}$  (Garcia-Munoz et al., 1975),  $^{14}\text{N}$  and  $^{16}\text{O}$  (Webber et al., 1975a; Mewaldt et al., 1976a) composition.

Measurements of the variations in intensity of the anomalous helium and oxygen with time and heliocentric distance prove conclusively that these particles are of non-solar origin. One observes, for example, that the radial intensity variation (Webber et al., 1975a, 1977; McKibben et al., 1979) and the solar modulation or temporal changes (Mewaldt et al., 1975b; von Rosenvinge and McDonald, 1975; Garcia-Munoz et al., 1975; McKibben, 1977) of the anomalous component are similar to those of galactic cosmic rays. The recent Pioneer 10 and 11 results of McKibben et al. (1979) indicate in addition a large off-ecliptic or latitude gradient for the anomalous helium and provide convincing evidence that the source of the anomalous component is located not only beyond 10 AU but possibly also above  $\sim 10^\circ$  in heliographic latitude.

Both a galactic and an interplanetary origin have been proposed for the anomalous component. The galactic origin hypothesis, originally suggested by McDonald et al. (1974a), has interesting and far-reaching consequences. It would require a nearby interstellar source with a composition highly enriched in He, N, O and Ne. These elements would presumably be fully ionized, and would experience relatively little solar modulation. Although it is possible under special conditions to produce stellar material depleted in carbon, the predicted isotopic composition of C, N and O in such stellar objects is highly enriched in the rare isotopes of these elements (e.g., Hoyle and Clayton, 1974) which is contrary to what is observed in the anomalous component.

The interplanetary origin hypothesis has been proposed by Fisk et al. (1974). In their model the anomalous component results from interstellar neutral gas which has been ionized and then accelerated in the interplanetary medium. Neutral H, He, N, O and Ne atoms are swept into the heliosphere by the motion of the solar system through the interstellar medium and because of their relatively high first ionization potential and/or charge-exchange cross sections, are able to reach the inner heliosphere before being singly ionized by solar UV and charge exchange with the solar wind. These singly charged ions are quickly picked up and convected outward by the solar wind and on their way out slowly gain energy by statistical acceleration in the turbulent interplanetary field. By the time they reach heliocentric distances of  $\sim 50$  AU they have energies of  $\sim 10$ -20 MeV/nucleon. These energetic singly ionized particles have a relatively high rigidity and can thus penetrate back into the inner solar system, undergoing little solar modulation, to be observed as the anomalous component. Highly

ionized particles of comparable energies, such as low-energy galactic cosmic rays or accelerated solar material, will be essentially excluded from reaching the inner heliosphere because of the strong modulation of these low rigidity particles.

A firm prediction of the interplanetary acceleration model is that the particles in the anomalous component are singly ionized. Although no direct measurements of the ionization states are available, indirect evidence based on the detailed comparison between the observed and predicted solar modulation (von Rosenvinge and McDonald, 1975; McKibben, 1977) and radial intensity gradient (Webber et al., 1977) of this component favors low ionization states. Only by direct measurements of the charge states and through out-of-ecliptic observations will it be possible to make a decisive choice between the two alternative sources of origin for the anomalous component.

#### V. Future Advances

**Solar Flare Particles.** Significant advances in our knowledge of solar particle composition are expected in the very near future when results from the International Sun-Earth Explorer spacecraft ISEE-3 stationed at 1 AU become available. Of particular interest will be the more extensive, direct measurements of the charge states (Hovestadt et al., 1978) and of the isotopic composition (Althouse et al., 1978) for elements up to and including iron in solar flare particle events. Charge states and isotopic ratios should provide information on conditions (such as temperature and density) at the acceleration sites.

With the analysis of extensive IMP-7 and 8 satellite data set spanning the 1972-1977 solar minimum nearing completion, several questions dealing with the systematic behavior of the variabilities of the composition in solar flare events will be addressed. For example, Mason et al. (1979a) have recently studied the dependence on the nuclear charge  $Z$  of the magnitudes of the standard deviations,  $S(Z)$ , of the distributions of event-averaged ratios of H, He, C, Ne, Mg, Si, S-Ca and Fe relative to oxygen for 12 large solar flare particle events during the 1974-1977 solar minimum. They observe that  $S(Z) \propto |Z^{1/3} - Z_{\text{oxygen}}|$  and that there is a correlation between the abundance of an element relative to oxygen and the Fe/O ratio. This correlation is positive for Ne/O, Mg/O, Si/O and (S-Ca)/O, and becomes progressively stronger as the atomic number of the element approaches that of iron. On the other hand C/O shows a negative

correlation with Fe/O, especially for Fe/O  $\gtrsim$  0.1. No correlation is evident for H/He vs He/O or for He/O vs. Fe/O.

Another area where advancement is anticipated is in the correlated studies using data from remote sensing instruments on the Solar Maximum Mission and the ISEE 1 and 3 particle experiments. Such studies are essential for obtaining a more complete picture of solar flare phenomena and are bound to reveal new and interesting features not evident in isolated measurements.

As the frequency of large solar flare particle events increases with the approach of solar maximum activity, high-mass and charge resolution particle experiments on the ISEE and Voyager spacecraft will provide us with detailed information on the systematic and variable aspects of the compositions in large events, information which is essential for developing realistic acceleration models. Similar studies of  $^4\text{He}$ - and Fe-rich events and of elements beyond iron must, however, await development and flight (in the mid 1980's) of large-area, low-energy instruments with sensitivities several orders of magnitude greater than those presently available. It is expected that the systematic investigation of the anomalous micro-flares during the next solar minimum (late 1980's) will lead to a clearer understanding of injection mechanisms and the acceleration processes.

**Corotating Particle Streams.** The existence of large-scale, relatively time-independent and uncomplicated interplanetary acceleration in a region of space where it is now possible to make *in situ* observations has far reaching consequences for our general understanding of acceleration mechanisms. The systematic examination of these processes should therefore be of the highest priority and will undoubtedly be pursued. Our knowledge of the composition in corotating particle streams is at present still rudimentary, and the lack of solar wind abundance measurements makes it difficult to establish firmly the source material from which these energetic particles are accelerated.

With the successful launch of the ISEE-3 spacecraft it will soon be possible to obtain routinely the composition of major elements in both the low-speed (Coplan et al., 1978) and high-speed (Hovestadt et al., 1978) solar wind streams. In addition, initial measurements of the charge states of corotating particles should become available using the Max-Planck-Institut/University of Maryland experiments (Hovestadt et al.,

1978) on ISEE 3. The ability to compare the measured compositions and distribution functions in the high-speed solar wind streams, the high-energy tail of these streams, and energetic particles for the same corotating event should lead to a far more definitive identification of the source material and the acceleration process. This, combined with simultaneous in situ measurements of the accelerated particles and the plasma-magnetic field turbulence which will be possible with instruments on the Voyager 1 and 2 spacecraft (Krimigis et al., 1977; Behannon et al., 1977; Bridge et al., 1977) will provide rich opportunities for developing detailed models of the acceleration process.

The very detailed composition measurements of corotating particles, including isotopes and the rarer elements will not be done, however, until large-area, high-sensitivity, low-energy composition instruments are developed and flown. Such measurements will not only advance substantially our understanding of corotating particle streams but could provide us with the most comprehensive knowledge of the isotopic and elemental composition of the source material—presumably the solar wind.

The Anomalous Component. One of the more essential measurements yet to be made will be that of the charge states of elements in the anomalous component, since this will be decisive in establishing the origin (galactic vs. interplanetary) of these energetic particles. This measurement, while difficult because of the very low fluxes, could be made, for example, with a large-area ( $>500 \text{ cm}^2 \text{ sr}$ ) low-energy composition instrument on a polar orbiting earth satellite using the geomagnetic field as a particle rigidity selector. Finding the anomalous He, N, O and Ne singly charged would establish the existence of interplanetary acceleration in the outer heliosphere. Measurements of the elemental abundances to greater precision, of the rare elements (including e.g. carbon) and of the isotopes of N, O and Ne, (all these measurements require a large-area detector) are necessary not only for constructing more realistic models of acceleration mechanisms and solar modulation, especially at low energies, but would also provide us with a detailed knowledge of the source material composition, possibly the isotopic composition of N, O, Ne in the interstellar gas.

It should be remarked that there was no evidence for anomalous He, at least above 20 MeV/nucleon, during the 1965 solar minimum (e.g. Gloeckler and Jokipii, 1967). (No low energy N, O or Ne measurements were available at that time.)

McKibben et al. (1979) have used this observation and the large latitude gradients they measured to suggest that the appearance of the anomalous component at earth may depend on the sign of the sun's dipole field. In fact, Jokipii et al. (1977) have investigated the role of large-scale gradient and curvature drifts on particle modulation and found that for the current sign of the sun's dipole field such drifts take positively charged particles toward the solar equatorial plane, whereas during the 1965 solar minimum such particles were transported toward the solar poles. It will therefore be extremely interesting both for studies of solar modulation and the determination of the source location to verify the existence of this 22-year cycle for He and for the other anomalous elements observed near earth and to examine the intensity variations of these particles over extended heliographic radial distances ( $\sim 1$  to  $>20 \text{ AU}$ ) and latitudes ( $\sim +90^\circ$  to  $-90^\circ$ ). Instruments on the International Solar Polar Spacecraft (NASA and ESA), on the two deep-space Voyager spacecraft and the interplanetary ( $\sim 1 \text{ AU}$ ) ISEE-3 spacecraft have been designed to perform many of these exploratory measurements.

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Table 1

Average Abundances Relative to Oxygen of Energetic  
Particle Populations in the Interplanetary Medium

Element	Solar Flare Particle Events		Corotating Particle Streams(c) (1-10) (f)	Solar Material	
	Normal(a) (1-20) (f)	Iron-Rich(b) (1-5) (f)		Corona(d)	Photosphere(e)
H	4600	300	2800	1780	1445
He	70	40	170	150 <sup>(h)</sup>	91
Li	<0.0005(g)				$\sim 1.4 \cdot 10^{-8}$
Be	<0.0007(g)				$\sim 2 \cdot 10^{-8}$
B	<0.0007(g)				$< 1.8 \cdot 10^{-8}$
C	0.54	0.23	1.05	1.0	0.6
N	0.13			0.2	0.126
O	$\approx 1$	$\approx 1$	$\approx 1$	$\approx 1$	$\approx 1$
F	<0.002(g)				
Ne	0.16	0.39	0.2	0.063	0.054
Na	0.016			0.005	0.0028
Mg	0.18	0.54	0.13	0.079	0.050
Al	0.016			0.005	0.0048
Si	0.13	0.44	0.087	0.079	0.065
P	<0.002(g)			0.0005	0.0005
S	0.026			0.0251	0.023
Ar	<0.004(g)	0.33	0.06	0.01	0.0015
Ca	0.012(g)			0.0045	0.0032
Fe	0.15	1.3	0.095	0.093	0.05

(a) Derived from measurements of Crawford et al., (1972); Bertsch et al., (1973), Teegarden et al., (1973), Hovestadt, (1974), Webber (1975), McGuire et al., (1977), and Mason et al., (1979a).

(b) Hovestadt et al., (1975); Mason et al., (1979b).

(c) Derived from measurements of Gloeckler et al., (1979b).

(d) Wichbroe (1971).

(e) Ross and Aller (1976).

(f) Approximate energy range of measurements in MeV/nucleon.

(g) Data of McGuire et al., (1977).

(h) Derived from the solar wind He/O ratio, Bame (1972).

ORIGINAL FILED IN  
OF POOR QUALITY

Table 2

Abundances Relative to Carbon of the  
Anomalous Component and Galactic Cosmic Rays

Element	Anomalous Component (2-30)(a)	Galactic Cosmic Rays (b) (>100)
H	$40 \pm 4$ (c,d)	275
He	$90 \pm 10$ (c,d,e)	50
C	$\approx 1$	$\approx 1$
N	$3 \pm 1$ (d,e,f)	0.255
O	$18 \pm 4$ (d,e,f)	1.0
Ne	$1.3 \pm 0.4$ (e,f)	0.175
Mg	$0.3 \pm 0.2$ (e,f)	0.23
Si	$0.2 + 0.25$ (e,f) $- 0.15$	0.17
Fe	$0.6 \pm 0.2$ (e)	0.12

(a) Approximate energy range of the measurements  
in MeV/nucleon.

(b) Cartwright et al. (1971).

(c) Garcia-Munoz et al. (1975).

(d) Mewaldt et al. (1975a).

(e) Klecker et al. (1977).

(f) Webber et al. (1975a).

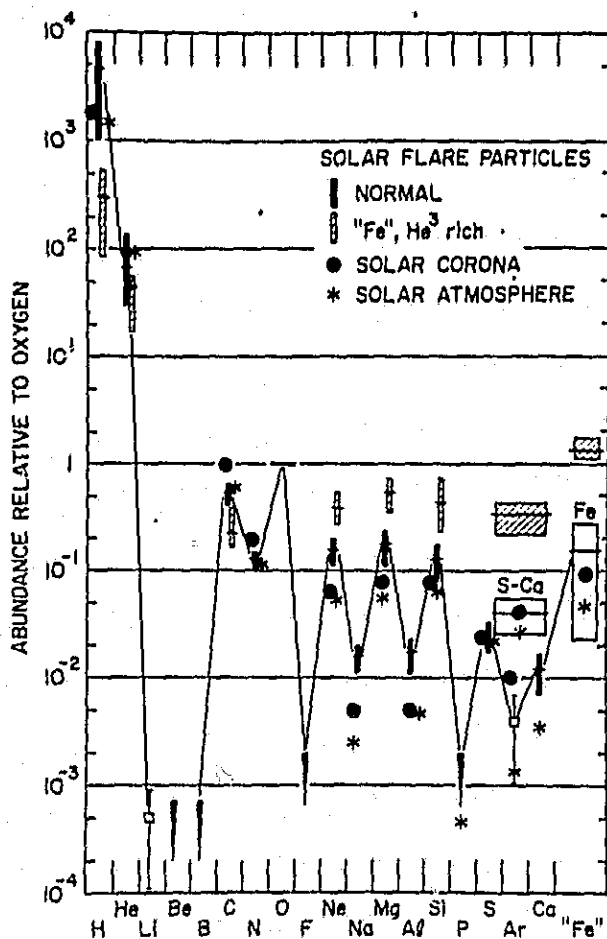


Figure 1. Abundances of elements and element groups normalized to oxygen in the solar corona (filled circles), solar atmosphere or photosphere (stars) and in solar flare particle events. The abundances for relatively large (peak intensities  $\geq 100$  protons/cm<sup>2</sup> sec sr MeV) flare particle events with a normal composition are indicated by solid vertical bars, solid triangles (upper limits), open squares (single measurement with error bars) and open rectangles (element groups). These abundances were derived from measurements reported by Crawford et al. (1972), Bertsch et al. (1973), Teegarden et al. (1973), Webber (1975), McGuire et al. (1977), and Mason et al. (1979a). The composition for "Fe"-rich (also <sup>3</sup>He-rich) solar flares particle events is indicated by cross hatched bars and rectangles and is based on abundance measurements in the 1 to 4.6 MeV/nucleon range reported by Hovestadt et al. (1975) and more recently by Mason et al. (1979b,c, d). The vertical extent of the bars for H, He, C, N, Ne, Mg, Si, S-Ca, and Fe in both the normal and Fe-rich events indicates the degree of variability in the composition between different solar flare particle events. See text for a fuller discussion of this figure.

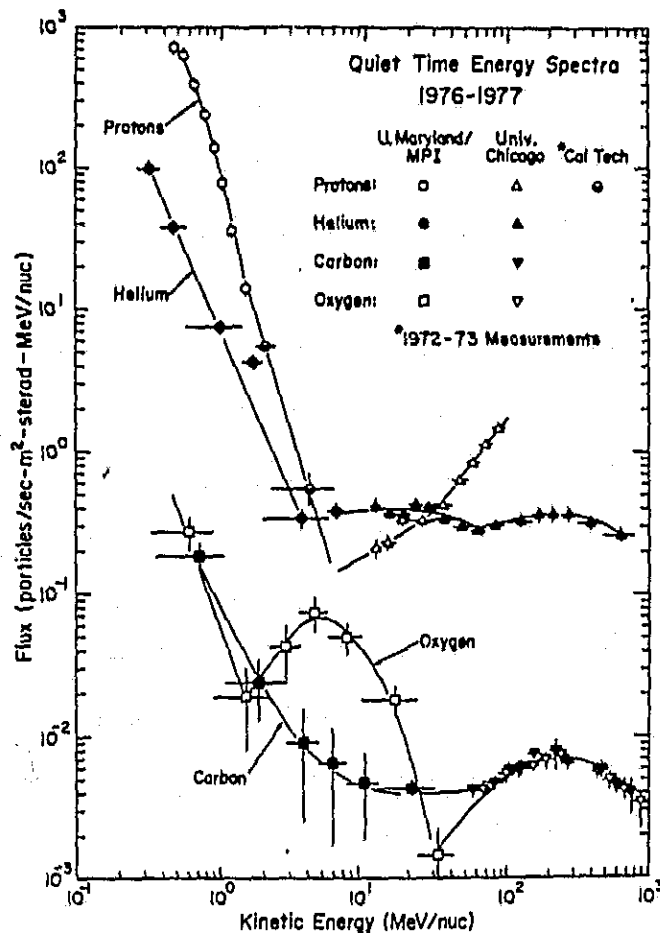


Figure 2. Differential energy spectra of hydrogen, helium, carbon and oxygen observed in the interplanetary medium near 1 AU during the solar minimum in 1976-1977 during quiet-times. The "anomalous cosmic ray" component appears between  $\sim 2$  and  $\sim 30$  MeV/nucleon and is characterized by large overabundance of He and O compared to H and C respectively. Data represented by  $\circ$ ,  $\bullet$ ,  $\square$ , and  $\blacksquare$  taken from Mason et al., (1977, 1979e); by  $\Delta$  and  $\blacktriangle$  from Garcia-Munoz et al., (1977b); by  $\nabla$  and  $\blacktriangledown$  from Garcia-Munoz et al., (1977c); and by  $\odot$  from Mewaldt et al. (1975c).