# Energetic particles in the heliosphere

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***Abstract*—The energetic particle population in the heliosphere is highly variable in space and time, intensity, energy, and composition. Over the last decades advanced instrumentation onboard many spacecraft extended our ability to explore the energetic particle populations in the inner and outer heliosphere. We are now able to measure intensity-time profiles and anisotropies, energy spectra, elemental and isotopic abundances, and the ionic charge of particles over an extended energy range of ~0.1 to 100 MeV/nuc and for a large dynamic range of particle intensities. These measurements provide crucial information for understanding the sources of the particle populations and the acceleration and propagation processes involved. In this paper we provide an overview of the various particle populations observed in the heliosphere, with emphasis on particles accelerated at the Sun, at interplanetary shocks, in co-rotating interactions regions, and in the outer heliosphere.**

## 1. INTRODUCTION

THE energetic particle populations in the heliosphere cover a large energy range from < 1 keV/amu for the solar wind to > 1 GeV/amu for Galactic Cosmic Rays (GCR). In their energy spectra, elemental, isotopic, and ionic charge composition these particle populations carry fundamental information on the source region and their acceleration and propagation processes. Figure 1 shows schematically the energy spectra of oxygen ions in the heliosphere [1]. Spanning ~6 decades in energy and ~20 orders of magnitude in intensity it is evident that the measurement of these particle populations requires multi-sensor systems as shown for the ACE spacecraft in Fig. 1.

The various particle populations are, from low to high energy, as shown in Fig. 1: (1) the slow and fast solar wind, (2) energetic particles predominantly locally accelerated at interplanetary shocks (ESP for energetic storm particles), (3) particles accelerated at corotating interaction regions (CIR), (4) particles accelerated at coronal and interplanetary shocks and in the flare process near the sun (solar energetic particles), (5) Anomalous Cosmic Rays (ACRs), accelerated at the terminations shock of the heliosphere (or beyond), and (6) Galactic Cosmic Rays (GCRs), accelerated in the galaxy, possibly at supernova shocks [2], and propagating into the inner heliosphere. In this paper we provide an overview of the various particle populations observed in the heliosphere, with special emphasis on particles accelerated at the sun, and in the inner and outer heliosphere.

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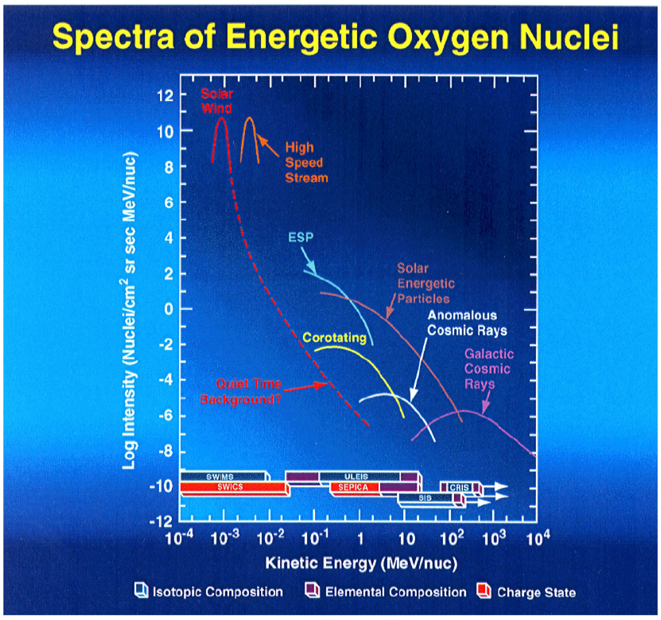


Fig. 1: Typical energy spectra of energetic oxygen ions from various particle populations in the heliosphere. The energy ranges of various ACE instruments are indicated at the bottom [1].

## 2. SOLAR ENERGETIC PARTICLES

High-energy particles originating at the Sun were first reported about 60 years ago [3]. At that time there was little doubt that these particles were closely related to contemporary solar flares. Later it became clear that acceleration at coronal and interplanetary shocks is also an efficient mechanism for particle acceleration (e.g. [4]). In the early 70s a new type of event was discovered that showed enhanced $^3$He abundances with $^3$He/$^4$He>1 [5], while the corresponding ratio in the corona or solar wind is ~5x10$^{-4}$ [6], [7]. Such events were later found to exhibit also enhancements of heavy ions by an order of magnitude relative to coronal abundances [8]. Based on these observations, characteristic differences of, for example, the electron to proton ratio, the intensity-time profiles, the distribution in solar longitude as observed from the near-Earth environment, and the mean ionic charge of heavy ions, solar energetic particles (SEP) were classified as *impulsive* and *gradual*, following a classification of flares based on the duration of soft X-ray emission [9]. In this scenario *impulsive* SEP events were related to flares and the *gradual* SEP events were related to coronal mass ejection (CME) driven coronal and interplanetary shocks (e.g. [10],

[11]), as schematically shown in Fig. 2.

However, new results with advanced instrumentation from several missions (e.g. WIND, SAMPEX, SOHO, ACE) have shown that this picture was oversimplified. New composition and ionic charge measurements show that enrichments in $^3$He are also common in interplanetary shock accelerated populations [12], that enrichments in heavy ions are often observed in large events at high energies (e.g. [13]), and that high charge states of Fe are also observed in events usual classified as *gradual* [14], [15]. Therefore, the classification into two distinct types of events is presently in question and the relative contributions of flares and coronal / interplanetary shocks are under debate.

In this chapter we will summarize the new observations of SEP composition and charge states and their implications.

### A. $^3$He-rich Solar Energetic Particle Events

The large enrichments of $^3$He and heavy ions found in event-integrated abundances of $^3$He- and heavy ion-rich events have been used as one of their defining characteristics as *impulsive* events. Although some of the characteristics (e.g. enrichment of $^3$He relative to solar wind and coronal abundances, see section 3) are observed to some extend also in large (*gradual*) events, several signatures of the $^3$He- and heavy ion rich events are unique, suggesting a different acceleration process and warrant a classification as a separate class of event.

*Time Dispersion:* The high sensitivity of new instrumentation provides unprecedented statistics for small events. Figure 3 shows as an example the energy versus time profile for several events in August 1998 as observed with the ULEIS experiment onboard ACE [16]. This type of display, plotting the arrival time of individual ions versus their energy, shows velocity dispersion that can be compared with scatter-free propagation along the interplanetary magnetic field, and allows the identification of individual injections at the Sun. This display also demonstrates that to correctly evaluate ion spectra and elemental and ionic charge composition in these events, start and stop times for the averaging of data need to be energy dependent, as indicated by the "boxes" enclosing individual injections. Figure 3 also shows that some events are suddenly cut off because of a loss of the magnetic connection to the acceleration site. These well defined injection profiles can also be used to infer large-scale diffusion parameters of ions in the heliospheric magnetic field [17], [18].

*Energy Spectra:* In a survey of energy spectra of ions in $^3$He-rich events in the mass range He to Fe and in the energy range 80 keV/amu to 15 MeV/amu two classes of events have been identified [19]. Class 1 events exhibit power laws that often steepen above ~1MeV/amu; in some cases the major species $^3$He, $^4$He, O, Fe have similar spectral slopes, while in other cases the $^3$He slope below ~1 MeV/nuc is distinctly harder than the others. Class 2 events curved $^3$He and Fe spectra at low energies, while $^4$He has power law spectra (Fig.

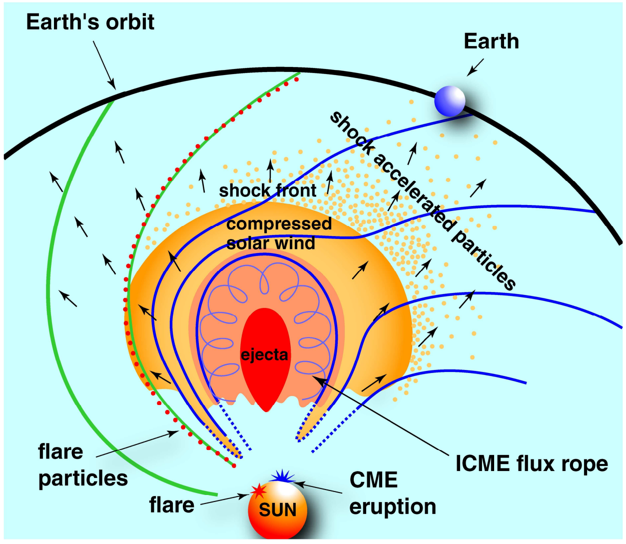


Fig. 2: Illustration of different sources of solar energetic particles: (1) particle acceleration at a CME-driven coronal and / or interplanetary shock ("shock accelerated particles"; (2) particle acceleration by a flare ("flare particles" in the corona (adopted from the Multimedia STEREO/IMPACT web site at http://sprg.ssl.berkeley.edu/impact/multimedia.html).

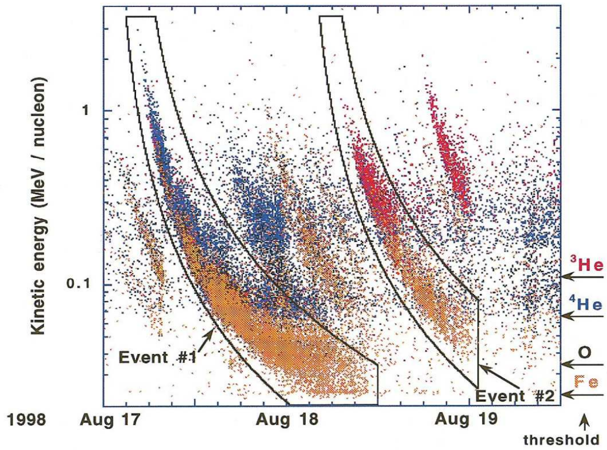


Fig. 3: Ion velocity spectrogram for 1998 August 17-19 from ACE/ULEIS showing ion species 3He, 4He, O, and Fe. *Thin lines:* Event "boxes" indicating individual ion injection events at the sun [16].

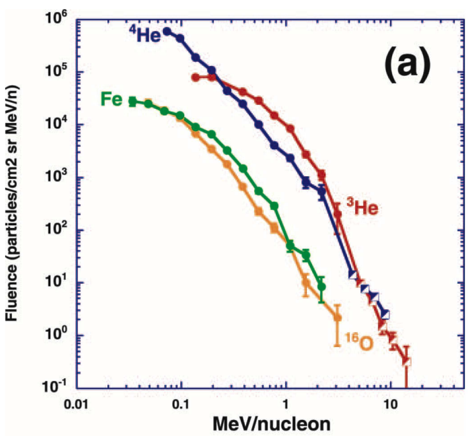


Fig. 4: Fluence of $^3$He, $^4$He, O, and Fe for the Class-2 $^3$He-rich solar energetic particle event of March 21, 1999 [19].

4). As a consequence of the different spectral shapes of $^3$He and $^4$He the $^3$He/$^4$He-ratio in Class 2 events is strongly energy dependent; also the largest $^3$He/$^4$He-ratios are observed in this class of events. It is known since the early measurements of heavy ion composition in $^3$He-rich events that these events exhibit also an enrichment in heavy ions by an order of magnitude (for Fe), relative to coronal abundances [8], [20], with a systematic increase of the enrichment factor with mass. With advanced instrumentation onboard the Wind and ACE spacecraft the measurements of heavy ions in these events has been extended to trans-iron elements [21], [22]. Figure 5 (from [22]) shows the enhancement of elemental abundances relative to coronal abundances in the mass range 4 to ~220 amu. Figure 5 demonstrates that the enhancement factor is monotonically increasing to ~200 for high masses. An estimate of the mean ionic charge of the ultra-heavy ions shows ([22], [23]) that the enhancement factor is also ordered by mass per charge [22].

In addition to the information on the composition of heavy ions by particles escaping from the acceleration site in the corona into interplanetary space, γ-ray line observations provide information on the composition of heavy ions interacting with the ambient corona. It was found that the composition of interacting heavy ions is similar to the abundances in $^3$He-rich SEP events as observed in interplanetary space [25].

*Ionic Charge States:* Because of the large differences between the mean ionic charge of iron ions, $Q_{Fe}$, in the MeV/amu energy range in events identified as *gradual* ($Q_{Fe}$ ~14) and *impulsive* ($Q_{Fe}$ ~20) [26]-[29], the ionic charge states were also used as a defining characteristic for this classification. However, new measurements of ionic charge states with instruments of improved sensitivity over a wide energy range (SAMPEX, SOHO, ACE) have shown that this picture was oversimplified. The new measurements (Fig. 6) show a systematic increase of the mean ionic charge of Fe from ~12 at ~10-100 keV/amu to ~15-19 at 550 keV/amu [30]-[32]. This large increase of the mean ionic charge of iron in the energy range ~10-550 keV/nuc can only be explained in terms of impact ionization by protons and electrons in a dense environment in the low corona (e.g. [33], [34]). The dashed lines in Fig. 6 show the equilibrium ionic charge of iron in the energy range 0.01 - 2 MeV/amu, computed for electron temperatures of 1.2 and 1.4 $10^6$ K, respectively, taking into account impact ionization by therrmal electrons and protons, and radiative and di-electronic recombination [31]. Figure 6 demonstrates that a simple equilibrium model does provide qualitatively the systematic increase of the mean ionic charge as observed, however, the increase of $Q_{Fe}$ with energy is at somewhat higher energy than observed. More realistic models, including the effect of stochastic acceleration, coulomb energy loss, and charge changing processes during acceleration, in combination with energy loss by adiabatic deceleration during interplanetary transport [35] are needed to quantitatively

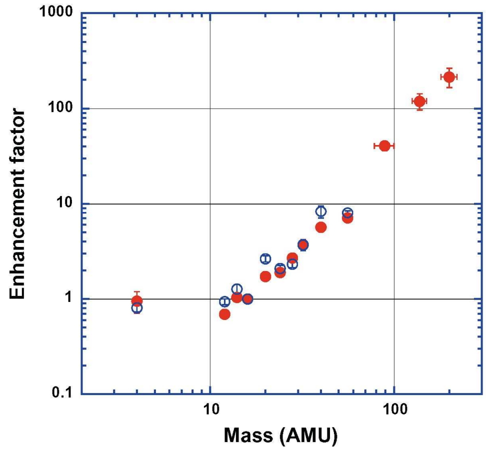


Fig. 5: *Filled circles:* Enhancement factor for heavy ion abundances in $^3$He-rich events, compared with gradual SEP ions and solar system abundances [22]. *Open circles*: Values from [24]

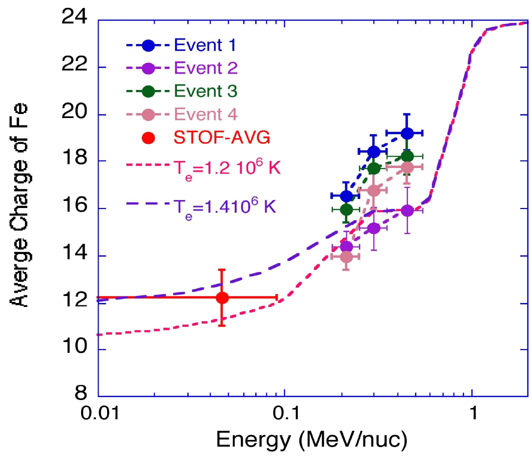


Fig. 6: Mean ionic charge of Fe as a function of energy for four impulsive events and energy dependence obtained for equilibrium conditions in a charge stripping model (adopted from [31]).

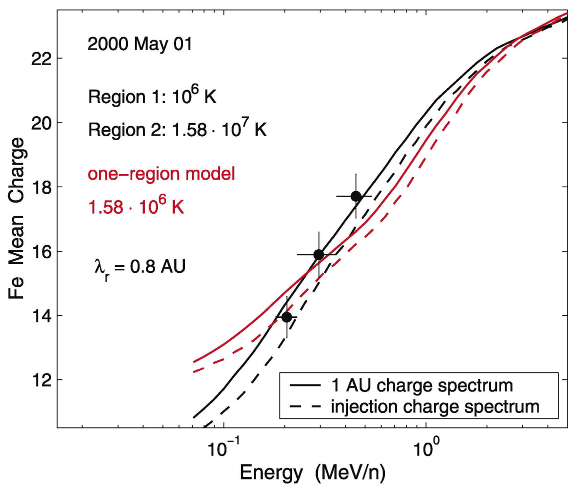


Fig. 7: Calculated and observed mean ionic charge of Fe during the May 1, 2000 $^3$He-rich solar energetic particle event [37].

reproduce the observed strong energy dependence of the heavy ion ionic charge states (see e.g. [36] for a recent review). Figure 7 shows as an example of such a model calculation that simultaneously fits the intensity-time and anisotropy-time profiles, the heavy ion energy spectra and the mean ionic charge as a function of energy, the results for $Q_{Fe}$ as a function of energy [37]. The model calculations show that at low energies, below ~100 keV/amu, the mean ionic charge is essentially determined by the electron temperature. At energies above ~200 keV/amu charge stripping effects are dominating and result in a strong increase of the mean ionic charge of Fe at energies <1 MeV/nuc (Fig. 7). One of the important parameters obtained from fitting the observed charge spectra with the model is the product $N_p\tau_A$, with proton density $N_p$ and acceleration time scale $\tau_A$. With $N_p\tau_A$ ~$10^{10}$-$10^{11}$ s cm$^{-3}$ [37] and assuming acceleration time scales of ~1-10 s, this corresponds to densities of ~$10^9$-$10^{11}$ cm$^{-3}$ at the acceleration site. This is similar to the density range of (0.6-10) x$10^{10}$ cm$^{-3}$ inferred from radio and electron measurements for the density of the acceleration region of electrons ([38], and references therein), i.e it indicates an acceleration in the low corona, at altitudes $\leq$ 0.2 solar radii above the photosphere.

*Acceleration Processes:* In order to cope with the large enrichments of $^3$He and heavy ions by up to factors of $10^4$ (for $^3$He) and ~10 (for Fe) and ~100 (for Ultra-Heavy ions) two stage processes have been invoked. Such scenarios include selective heating by resonant wave-particle interactions as a first step (e.g. [39]-[41]), followed by a second step that could involve shock acceleration [41]. Curved spectra at low energies as observed for $^3$He and Fe in Class 2 events can arise from stochastic acceleration processes by Alfvén turbulence. At low energies these processes have been shown to provide good fits to the data [42], [43]. However, the spectra reported by [19] are much harder at high energies (e.g. above ~1 (10) MeV/amu for Fe and $^3$He, respectively) than obtained with a stochastic acceleration model [19]. Models based on cascading MHD turbulence ([44], and references therein) provide promising fits to the heavy ion spectra [19]. However, in this model a different mechanism is needed for $^3$He and charge changing processes for heavy ions are not yet included.

### *B. Large (gradual) solar energetic particle events*

*Intensity-Time Profiles:* The intensity-time profiles of energetic particles in SEP events depend on the magnetic connection of the acceleration site with the observer. Therefore, the large variability of the intensity-time profiles and the longitude distributions of SEP events can qualitatively be explained by the extended longitudinal range of CME-driven interplanetary shocks and by the relative location of the observer to the presumed source location of the CME [45], [46]. Early in the event, much before the shock arrival, many large SEP events show a maximum-intensity plateau not exceeding several 100 protons per (cm$^2$ s sr MeV/amu) at 1 MeV. This plateau level can be explained by the scattering of escaping particles by the proton-amplified waves, limiting the intensity of escaping particles (the ‘streaming limit’) to a specific value (e.g. [47], and references therein).

Correlated with the arrival of the interplanetary shock, the particle intensities increase by up to several orders of magnitude, dependent on energy. A typical example of oxygen ion intensities in the energy range 0.14 to 51 MeV/amu as observed on ACE is shown in Fig. 8 [48].

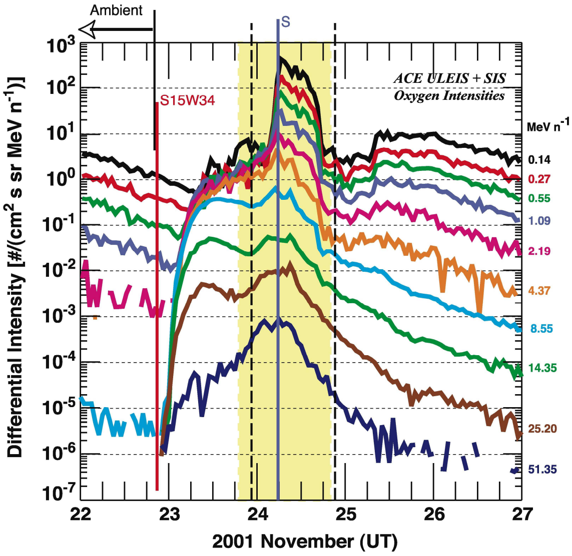


Fig. 8: Hourly averages of the oxygen intensity between ~0.15 and 50 MeV/amu measured by ULEIS and SIS onboard ACE for the time period November 22 - 27, 2001 [48].

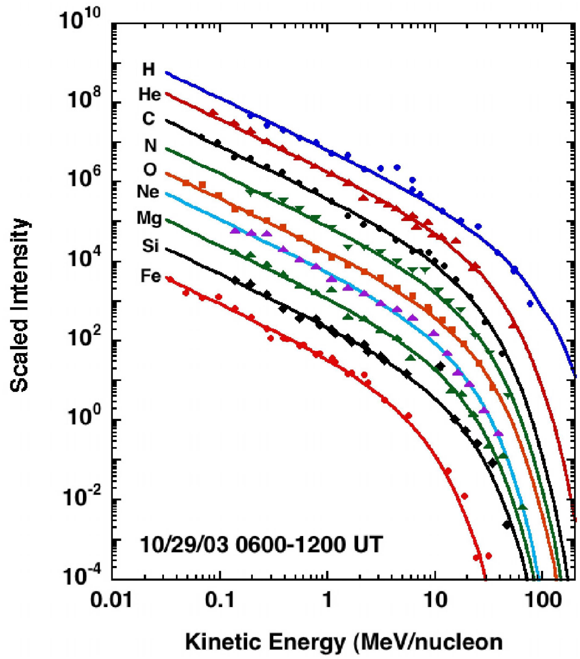


Fig. 9: Spectra from the 6-hour period following the shock on 29 October 2003. Data are from ACE and GOES-11 [55].

*Energy Spectra:* The energy spectra as observed in interplanetary space are the result of acceleration and propagation processes between the acceleration site and the observer. Power laws with exponential roll-over at high energies can often fit energy spectra in large events, with the e-folding energy systematically varying with mass per charge (Fig. 9). These spectral forms are suggestive of shock acceleration: in the ideal case of an infinite and planar shock geometry and steady state conditions, the particle differential intensity dJ/dE can be described by a power law: dJ/dE ~ $E^{-\gamma}$, where $\gamma$ is related to the shock compression ratio (e.g. [49], [50]). However, because coronal and interplanetary shocks are not planar, and because only a limited time is available for acceleration, steady state will not be reached, in particular at high energies. Thus, non steady-state conditions [51] and losses due to particle escaping upstream will result in a roll-over of the power law differential ion intensities at high energies (e.g. [52[, [53]). This spectral form is often observed and can be fitted by

$$dJ/dE = E^{-\gamma} \exp(-E/E_0) \qquad (1)$$

where $E_0$ depends on mass M and ionic charge Q of the ions and may be approximated by a power-law dependence [54]

$$E_0 \sim (Q/M)^{\alpha} \qquad (2)$$

These mass per charge dependent spectral breaks have successfully been used to infer the ionic charge of heavy ions [54]. The observed value of the exponent $\alpha$ in equation (2) is in the range ~1-1.75 [54], [55], i.e. somewhat smaller than $\alpha$=2, predicted by an SEP acceleration and transport model [55], [56].

*Fractionation Effects:* Event integrated elemental and isotopic SEP abundances have been related to photospheric, coronal, and solar wind abundances or have been used to infer solar system abundances that may not be accessible otherwise (e.g. [57]). When comparing SEP abundances with photospheric abundances it has been realized since many years that both coronal and SEP abundances show a dependence on the first ionization potential (FIP) or first ionization time [57]-[59], suggesting ion-neutral separation in the chromosphere as an important fractionation mechanism (see [60], for a recent review).

Furthermore, abundances in individual large SEP events show fractionation effects that monotonically depend on mass (M) and mass per charge (M/Q), usually approximated as a power law in M/Q [61]. This M/Q fractionation is observed for both elemental and isotopic abundances (e.g. [62]) and the correlation between isotopic and elemental abundances in individual events has been used to infer the abundance of the coronal source [63].

Mass per charge dependent fractionation has also been used to relate the elemental abundances observed at ~0.4 MeV/amu at interplanetary shocks to their source. The observation that the abundances at interplanetary shocks, relative to slow solar wind abundances, do not show a monotonic dependence on mass per charge [64] provides an argument that the bulk solar wind is not the source of the accelerated population. On the other hand, when compared with the upstream pre-event suprathermal population (see for example the population labeled 'ambient' in Fig. 8), a monotonic dependence of the abundance

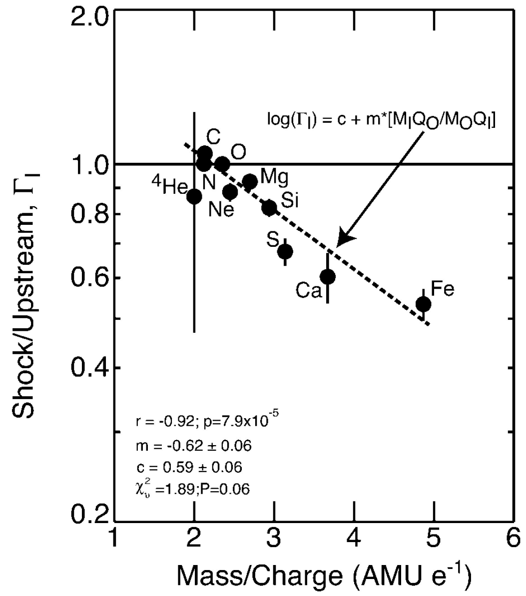


Fig. 10: Ratio $\Gamma_i$ of interplanetary shock abundances relative to the correspoding mean abundances measured upstream vs particle mass per charge [64].

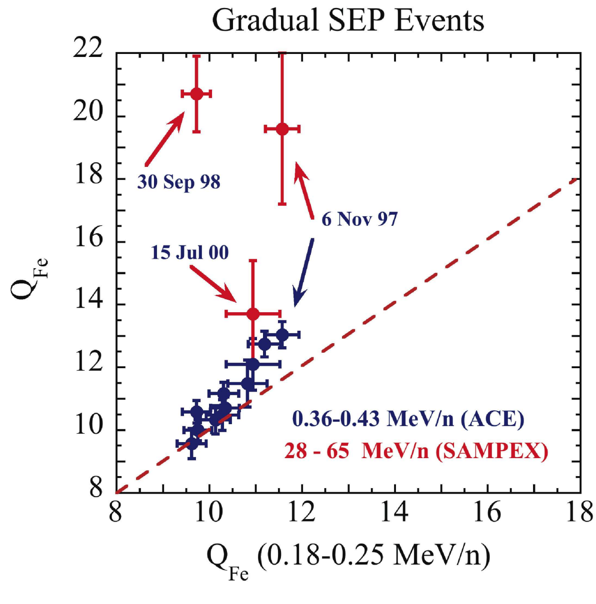


Fig. 11: Mean ionic charge of Fe ($Q_{Fe}$) at 0.18-0.25 MeV/amu vs. 0.36-0.43 and 28-65 MeV/amu [73].

ratios on M/Q is observed (Fig. 10), supporting the argument of acceleration of a remnant suprathermal component by the interplanetary shock [48], [64], [65].

*Ionic Charge States:* New measurements with high sensitivity over an extended energy range show a large event-to-event variability of the ionic charge distributions of heavy ions in large, interplanetary shock related (*gradual*) events, most pronounced for iron ions. At low energies (<200 keV/amu) the mean ionic charge of Fe is usually ~9-11 [66], similar to solar wind charge states [67]. The mean ionic charge of Fe at energies <1 MeV/amu is mostly constant, only in a view events it increases with energy by up to 4 charge units [68], [69]. At higher energies a large variability is observed. At energies above ~10 MeV/amu, the mean ionic charge is often observed to be significantly larger than at low energies, with $Q_{Fe}$ ~15-20 [70]-[74]. The variation of $Q_{Fe}$ with energy is illustrated in Figure 11, showing event averages in three energy ranges between 0.18 and 65 MeV/amu for several large events. These results indicate that the previous interpretation of heavy ion charge states being solely related to the plasma temperature was too simplistic and needs to be reconsidered (see below). The compilation of Fe/O-ratios and heavy ion charge states in Fig. 12 shows that the observed variability of the mean charge of Si and Fe at E $\geq$ 10 MeV/amu is strongly correlated with the relative abundance of Fe [72].

*The Observation of 'Flare' material in gradual events:* Large enrichments of heavy ions and high charge states of iron found in event-integrated abundances of $^3$He and heavy ion-rich events have been used in the past as one of their defining characteristics as impulsive events. Some of these signatures have now been also observed in gradual events or at interplanetary shocks. At sub-MeV energies, small and moderate enhancements of $^3$He relative to $^4$He, with $^3$He/$^4$He in the range of $10^{-3}$ to 0.24 have been observed in 12 large gradual events [65] and at interplanetary shocks [12]. At higher energies (> 5MeV/amu) $^3$He/$^4$He a factor of 10 larger than in the solar wind has been observed [75], and a statistical survey using daily averages of $^3$He and $^4$He fluxes in the energy range 15-30 MeV/amu as measured by the XXX experiment onboard SOHO showed for the years 1999 to 2002 an average value of $^3$He/$^4$He ~0.015, also significantly higher than in the solar wind or corona [76].

Furthermore, large abundances of Fe at energies of ~1 MeV/nuc [77]) and at energies of 12-60 MeV/nuc [78] and 25-80 MeV/nuc [13] have been observed in many large events. Furthermore, high charge states of $Q_{Fe}$~20 at energies >10 MeV/nuc, another tracer for ions accelerated in impulsive events close to the Sun, are not uncommon (see above). Apparently, the previous classification of SEP events into two distinct classes, i.e. *impulsive* and *gradual*, needs to be reconsidered and possible scenarios are discussed in the following section.

As a possible source of $^3$He in large, interplanetary shock related events remnant suprathermal particles from previous impulsive events have been suggested [65], serving as seed particles for the injection at the interplanetary shock. In this scenario also high (and variable) heavy ion abundances (e.g. Fe/C, Fe/O) could be interpreted as a mixture of two sources: suprathermal heavy ions from previous impulsive events and from gradual events. This suggestion is also supported by the finding that the interplanetary particle composition during quiet times shows enhancements in the $^3$He/$^4$He and heavy ion composition: enhancements by a factor of ~10 over the coronal value were found for Fe/O in the energy range ~1-10 MeV/amu during quiet times [79], and during times of moderate interplanetary fluxes $^3$He/$^4$He (4-15 MeV/ amu) and Fe/C (8-20 MeV/amu) were found to be enhanced by two orders of magnitude and by a factor of ~8, respectively [80]. The observational evidence that the interplanetary shock related heavy ion population at energies of ~1MeV/amu is not directly accelerated from the bulk solar wind, as shown above [64], would also support this view.

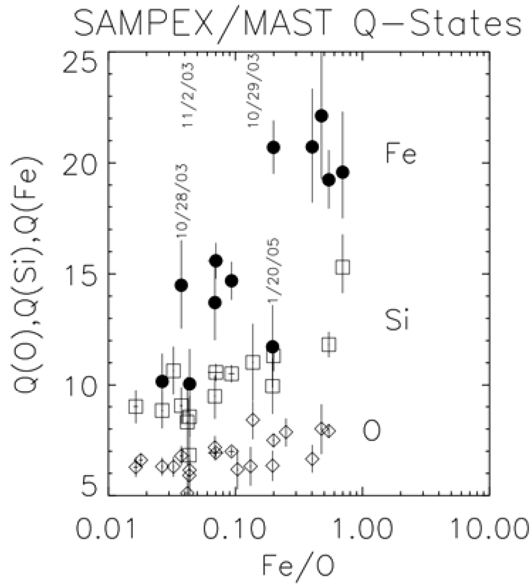


Fig. 12: Correlation of iron abundances relative to oxygen and charge states of O, Si, and Fe at >10 MeV/amu [72].

*Scenario 1:* In this scenario the large variability of spectral, compositional, and ionic charge state features at high energies (i.e. above 10s of MeV/amu) in large gradual SEP events arises from the interplay of two factors: shock geometry and the mixture of two seed populations with coronal / solar wind composition and 'flare' composition, i.e. a composition as observed in $^3$He- and heavy ion-rich events, respectively. In this scenario the shock geometry plays an important role. It is, in particular, assumed that quasi-perpendicular shocks require a higher initial speed of the ions for effective injection and therefore preferentially accelerate suprathermal seed particles from flares, whereas quasi-parallel shocks can draw their seed particles from the corona / solar wind suprathermals. In this model the shock geometry - via the injection threshold -

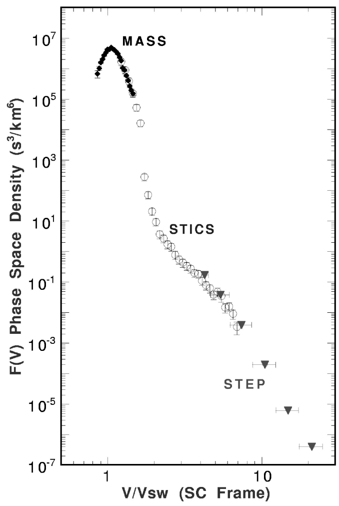


Fig. 13: Helium phase space density as a function of speed, normalized to solar wind speed, using data from the MASS, STICS and STEP sensors of the WIND spacecraft. The CIR spectrum shows a smooth transition from the solar wind to an approximate power law at suprathermal energies [88].

determines which of the two components dominates and thus determines spectral shapes, heavy ion abundances and ionic charge states at high energies [81] - [83].

*Scenario 2:* In an alternative scenario, direct injection of the particles, accelerated in the CME related flare, has been proposed (e.g. [11], and references therein; [13], [84]). In this scenario, gradual events generally consist of two populations: (1) a population at low energies predominantly accelerated at the coronal / interplanetary shock, and (2) a high energy component (above ~10s of MeV/amu), probably flare generated, with composition and charge states similar to impulsive events, possibly re-accelerated in the CME related shock. The relative intensity of the two components as observed at Earth will vary from event-to-event, dependent on the shock parameters (e.g. speed), the flare size and location, and the magnetic connection between the acceleration site and the observer. However, at high energies the second component usually dominates, giving rise to the heavy ion enrichment and high charge states at high energies [13], [85].

## 3. Corotating Interaction Regions

Long-lived streams of low energy (~0.01-10 MeV/amu) ions and ~40-300 keV electrons near corotating interaction regions (CIR) result from the interaction of high-speed solar wind overtaking slow-speed solar wind, forming forward and reverse waves. If the waves are sufficiently strong, a shock pair is formed, with the forward shock (FS) propagating outward and the reverse shock (RS) propagating inward. These shocks have been known for a long time to accelerate particles efficiently (e.g. [86]) and it was found that the particle intensities at CIRs peak at a few AU. For recent reviews of the plasma and energetic particle aspects of CIRs, including observations in the inner and outer heliosphere, at high solar latitudes, and the origin, injection and acceleration of CIR particles see [87] - [92].

Figure 13 shows as an example for typical CIR ion spectra at low energies the composite CIR spectrum of helium obtained on May 30, 1995 with the MASS, STICS and STEP sensors onboard the WIND spacecraft [88]. The measurements show a smooth transition from the solar wind to a power-law spectrum at suprathermal energies. Recent measurements with increased sensitivity and resolution provide energy spectra and composition for ions in the mass range of protons to Fe over the wide energy range of <0.1 to ~30 MeV/amu (Fig. 14). These measurements show power-law spectra at low energies with a roll-over at >1 MeV/amu, similar for all ions in the mass range He to Fe, resulting in heavy ion composition that is independent of energy [93]. The composition was found to be similar to the composition of the solar wind (Fig. 15), with the exception of He and Ne, which are overabundant by factors of 3.5±1.5 and 2.9±0.4, respectively [93].

Thus, the question arises, whether there are sources other

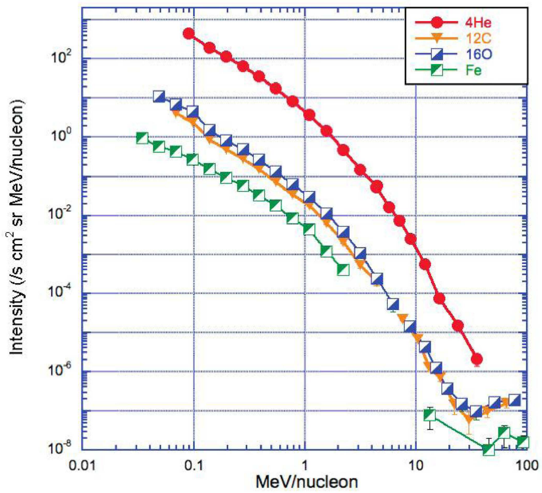


Fig. 14: Spectra of $^4$He, C, O, and Fe obtained with ULEIS and SIS onboard ACE during the CIR on March 22, 2000 [93].

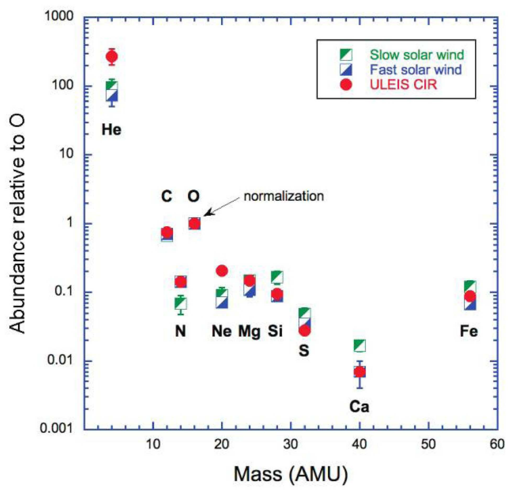


Fig. 15: Average CIR abundances in the energy range 0.32-0.45 MeV/amu, normalized to O, and compared to average solar wind values from slow speed streams and fast streams [93].

## 4. ANOMALOUS COSMIC RAYS

The anomalous component of low energy cosmic rays (ACR) has been discovered in the early 70's in the inner heliosphere. The 'anomalous' feature was the flat energy spectrum of $^4$He between 10 and 80 MeV/amu, and the 'hump' in the quiet-time cosmic ray energy spectrum of heavy ions (predominantly N, O, and Ne, see Fig. 16) at energies of ~3-20 MeV/amu, with unusual composition (C/O < 0.1). The early measurements showed He [99], O [100], [101], N [101] and Ne [102] in anomalous cosmic rays. Later, in the outer solar system, also Ar, and H was identified in ACRs. The early measurements also showed a positive radial gradient and modulation similar to galactic cosmic rays, suggesting a source in the outer solar system. For reviews of the early and recent observations, see [103]-[105].

Because all elements initially identified as ACRs had high first ionization potential (He, N, O, Ne), interstellar neutral particles were suggested as a source, that are singly ionized in the inner solar system, picked up by the solar wind, convected with the solar wind into the outer heliosphere, and accelerated in the outer heliosphere [106] and at the termination shock [107].

A comparison with detailed numerical models, including acceleration at the termination shock, convection, radial diffusion, and gradient and curvature drift effects showed that the hypothesis of an interstellar origin was consistent with these models for acceleration and propagation of ACRs [108], [109]. It was also found that taking drift effects into account is essential for explaining the different radial and latitudinal gradients in subsequent solar cycles with different polarity of the helio-spheric magnetic field [108]. The full confirmation of an inter-stellar origin of ACRs was obtained by the direct measurement of the ionic charge of ACR O, N, and Ne ions. These ions were found to be predominantly singly ionized at energies <20 MeV/amu; at higher energies doubly and triply charged ions dominate which can be explained by charge exchange in the outer heliosphere [110], [111].

The models that are assuming acceleration at the termination shock (TS) predicted the unfolding of the ACR energy spectra into single power law spectra with maximum intensity at the TS, characteristic for local shock acceleration. However, the measurements of the Voyager 1 spacecraft that encountered the TS in 2004 did not show the expected peak ACR intensities at the TS [112]. Possible explanations are that the acceleration at the termination shock may not be locally, where Voyager 1 crossed the TS, but, due to its blunt, non-spherical structure, the acceleration may be on the flanks, as illustrated in Fig. 17 [113], [114]. Other scenarios discussed are transient effects (e.g. [115], [116]), or acceleration at larger distances, i.e. in the distant heliosheath (e.g. [117]-[119]).

## 5. SUMMARY

There is now a wealth of observations of energetic ions in the atomic mass range from hydrogen to iron, covering a wide energy range from solar wind energies to 100s of MeV/amu.

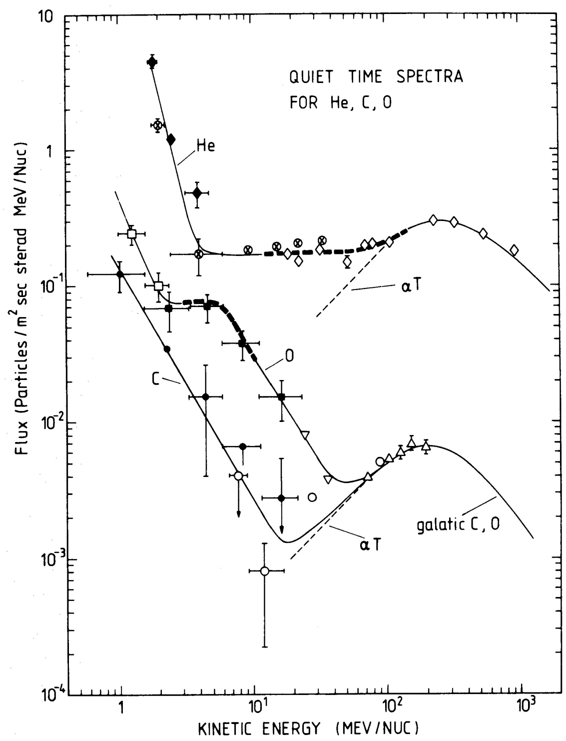


Fig. 16: Quiet-time spectra of He, C and O during 1973 to 1975. The characteristic features of ACRs are the flat energy spectrum of He and the "hump" in the oxygen spectrum, resulting in C/O < 0.1 at ~2-10 MeV/amu, different from spectra and composition of solar- and galactic cosmic rays (compilation of ACR data from [101]).

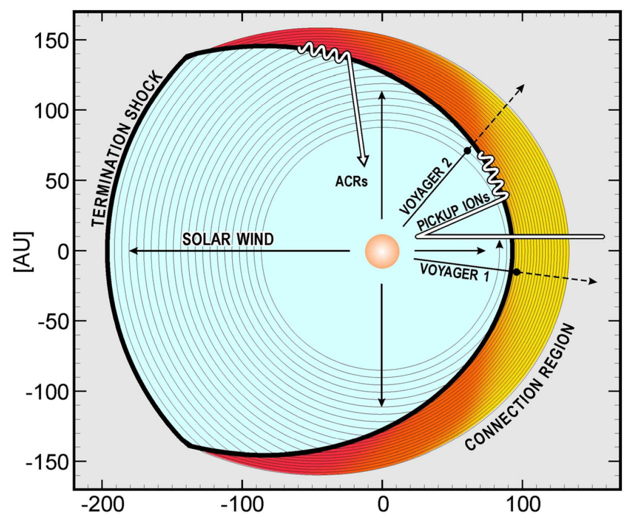


Fig. 17 Schematic diagram of an equatorial cut through the TS with the approximate positions of Voyager 1 and 2, illustrating the enrgization of pickup ions at the flanks of the TS [113].

New observations with instruments of much improved resolution and sensitivity onboard several spacecraft provide detailed information on the time-intensity profiles, energy spectra, elemental, isotopic, and ionic charge composition of energetic particles, accelerated in solar flares, at CME-driven coronal and interplanetary shocks, at CIRs, and at the termination shock and beyond. The particle signatures carry fundamental information on the particle source, and on the injection, acceleration and propagation processes. However, with the particle observations being in general remote from the actual acceleration site, we have to keep in mind that we always observe the combined effect of acceleration and transport processes that are in general difficult to disentangle.

Although there is considerable progress in our understanding of SEPs, there are a number of open questions that still need to be addressed in the future. We have, for example, time-resolved measurements of both SEPs (electrons and ions) and particles interacting in the solar atmosphere (hard X-rays, gamma-rays, radio), but due to transport effects between the source and the observation at 1 AU the SEP time profiles are smeared out and cannot easily be compared with electromagnetic signatures.

Further improvement in our understanding will also require more modeling efforts. In particular, three dimensional simulation of CMEs and ICMEs, including the effect of particle acceleration in the dynamically evolving magnetic field configuration with parallel and perpendicular shock geometries could provide important clues for the understanding of the observations. Also, unfolding injection, acceleration and propagation processes would provide a better understanding of the fractionation effects observed in elemental and isotopic abundances.

Significant progress in our understanding of SEP propagation and acceleration can be expected from multispacecraft measurements, combining, for example, measurements from the two STEREO spacecraft separated in longitude by now 45° with near-Earth measurements from SOHO and ACE ([120[-[122]).

Future missions like the Solar Orbiter (e.g. [123]-[125]) and the Sentinels [126] with perihelion distances of ~0.2 AU, or the Solar Probe with a perihelion distance of ~10 solar radia [127], will provide a close-up look at CMEs and solar active regions and allow a much better correlation of the electromagnetic signatures and the characteristics of ions and electrons, because interplanetary propagation effects are minimal at this distance.

In the outer heliosphere the Voyager spacecraft on their way through the heliosheath are continuing to provide valuable information on ACR dynamics that could, in combination with model calculations, help to solve the puzzle where ACRs as actually accelerated.


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