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Acceleration processes of heliospheric particle populations

Through space exploration an amazing variety of populations of energetic particles have been discovered in our Sun's surroundings. Wherever we look in the heliosphere, we find processes that can accelerate ions and electrons of the local plasma to energies of ~0.01 to ~1000 MeV, or even more.

The heliosphere is that volume of space surrounding the Sun and filled by the solar wind, the ionized gas expanding from the Sun at supersonic speed and embedding all planets. This region was named the 'heliosphere' by Dessler (1967) and originally defined 'as the region of interplanetary space where the solar wind is flowing supersonically'. The current definition refers to that region of space where the solar plasma dominates: the heliosphere extends beyond the heliospheric (solar wind) termination shock, believed to lie about 100 AU from the Sun. Beyond this is the heliopause, the division between solar and interstellar plasma and magnetic fields.

That the space between Sun and Earth (and beyond) is not completely a vacuum has been recognized for nearly a century (or even slightly more), ever since discussions started about the observed relationships between solar activity and geomagnetic variations (see e.g. historical sources in Chapman and Bartels 1940). That the heliosphere is populated with 'energetic particles' – electrons, protons, and heavier ions with a few tens of keV energy to tens of MeV energy – was not known until the advent of the flight of appropriate detectors on spacecraft that travelled beyond the boundaries of the Earth's magnetosphere, beginning in the 1960s.

In the early years of space exploration, the heliosphere was viewed as a passive domain for energetic particles. Solar energetic particles were known to be injected periodically at its centre, galactic cosmic rays continually penetrated from outside, and occasional energetic particles leaked from the Earth's magnetosphere. The heliosphere was considered to be responsible for merely dispersing and decelerating (cooling) these particle populations. It was a degrading receptacle.

However, in the last thirty years our view of the heliosphere has changed dramatically. The discoveries of several new energetic particle populations in the 1960s and early 1970s produced convincing evidence that the interplanetary medium is the site of large-scale and nearly continuous acceleration of charged particles to energies as high as ~30 to ~100 MeV per atomic mass unit (amu). The heliosphere is not simply a mostly passive medium that transports solar particles, modulates galactic cosmic rays and occasionally accelerates particles to modest energies by interplanetary shocks.

The great variety of new energetic particle populations accelerated at different sites throughout the heliosphere is illustrated in Figure 1: solar energetic particles (SEPs); particles associated with travelling shocks (the discovery of 'energetic storm particles' goes back to the earliest era of space science); 'upstream particles' accelerated at the bowshocks of Earth and other planets; 'corotating' ion events associated with the forward and reverse shocks bounding 'corotating interaction regions' (CIRs) in the

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George Gloeckler and Klaus-Peter Wenzel, The Century of Space Science, 963–1005

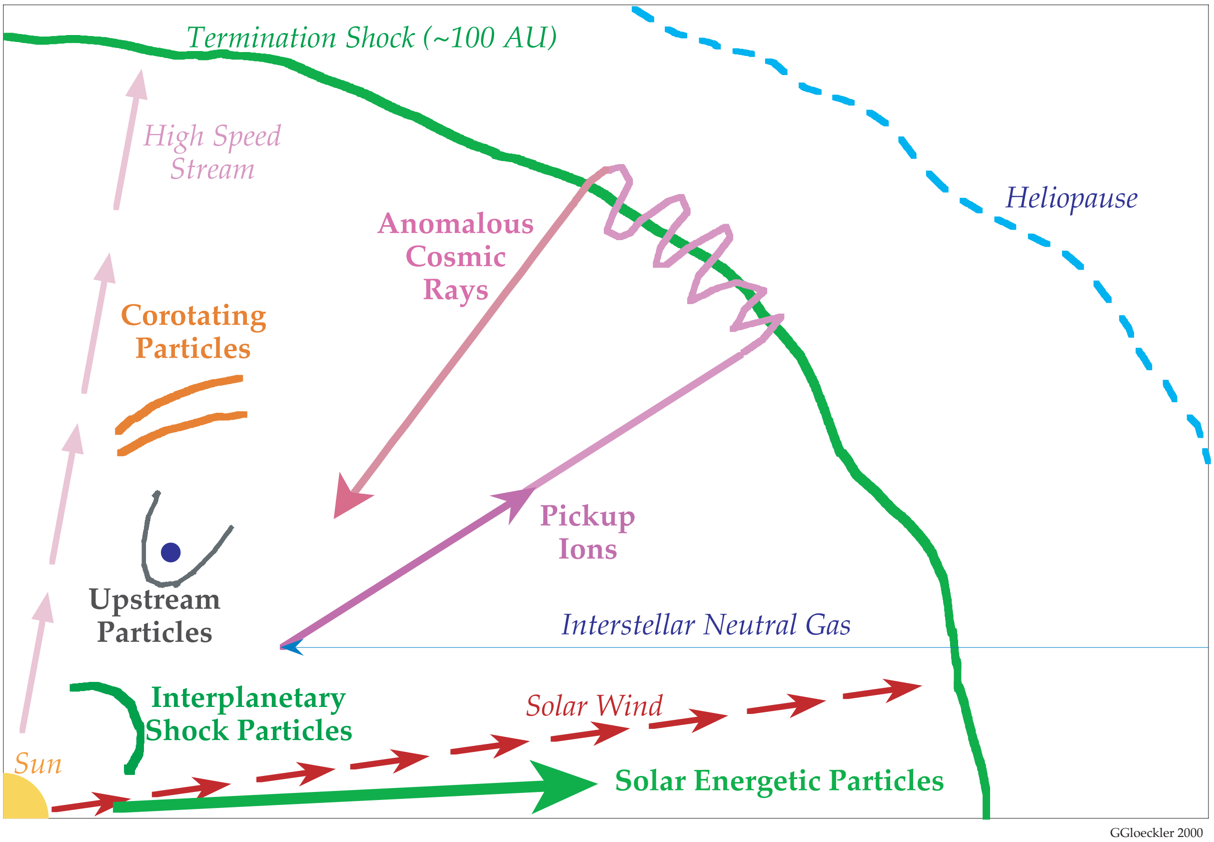

Figure 1 Schematic illustration of heliospheric energetic particle populations (bold labels). Solid curves indicate shocks.

solar wind; the anomalous cosmic ray (ACR) component; and pickup ions. These particles often propagate over great distances, carrying information on the nature, location and composition of their sources and about the physics of particle acceleration in their energy spectra, ionization states, and abundance of elements and isotopes.

Most of these heliospheric energetic particle populations are directly associated with collisionless shock waves. The prime acceleration site of the ACR component is thought to be the solar wind termination shock. With the exception of impulsive SEP events and interstellar pickup ions, there is nearly a one-to-one correspondence between shocks and energetic (upwards of several hundred keV) particle populations in the heliosphere. Since the solar wind is supersonic, it is not surprising that it is riddled with shock waves. But originally it came as a surprise that the shocks are such prolific particle accelerators. Thus, for more than three decades, the heliosphere has provided a gigantic and effective astrophysical laboratory for intense studies of particle acceleration processes by means of direct measurements. These *in situ* studies of particle acceleration have formed a basis for our understanding of acceleration processes throughout the Universe, for example, for the problem of the origin of galactic cosmic rays (see Chapter 29).

Typical intensity spectra as a function of energy per amu (energy/nucleon) for the different populations of energetic particles are illustrated in Figure 2. We will discuss these, with the exception of galactic cosmic rays, in later sections.

SPACECRAFT AND INSTRUMENTATION

The first energetic particle signatures that were found in the heliosphere were detected as a 'target of opportunity' by spacecraft that had another prime objective, including Mariner 2, Explorer 12 and Explorer 14. Later spacecraft that played a key role in the discovery and study of the various heliospheric ion populations included the Interplanetary Monitoring Platform (IMP) series, in particular IMPs 7 and 8; Helios 1 and 2 in the inner heliosphere; the International Sun–Earth Explorers (ISEE 1, 2, 3); Pioneers 10 and 11 and Voyagers 1 and 2 in the outer heliosphere; Ulysses, exploring the three-dimensional heliosphere; and Wind and the Advanced Composition Explorer (ACE). Most of

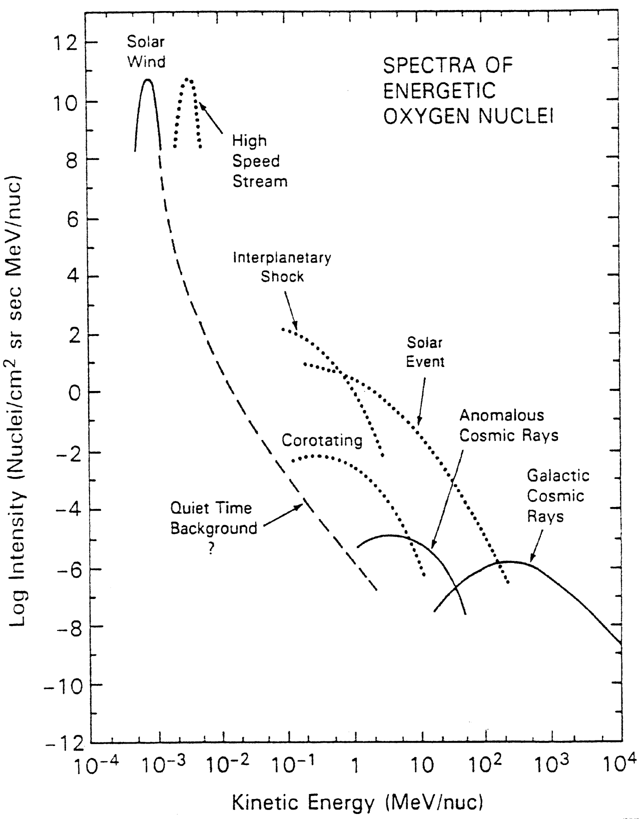

Figure 2 Typical oxygen differential spectra for different populations of heliospheric particles. (After Figure 2.1 of von Rosenvinge *et al.* 1995.)

these spacecraft were spinning, thus being able to provide information on the arrival direction of the particles measured.

By the end of the twentieth century we had explored the heliosphere in three dimensions, mapping the spatial distributions of the solar wind, of CIRs and of coronal mass ejections (CMEs) as Ulysses flew over the solar poles. Energetic particles accelerated at CIR shocks have been followed to latitudes far higher than the shocks themselves, thus serving as probes of the magnetic topology in the solar corona and high-latitude heliosphere. The Voyager spacecraft have tracked the modulation of the spectra of the ACRs out beyond 75 AU. Observations with the large-area detectors on Wind and ACE near 1 AU provide new insights into the physical processes of acceleration of SEPs. And we must not forget those spacecraft that continue to operate for long periods of time, such as IMP 8, which has been providing data for 30 years. These give us a complete perspective on solar-cycle variations that underlie the physical processes we study.

Table 1 lists the space missions that have made major contributions to the study of heliospheric particle populations.

Detectors for energetic particles used in the very early days of space exploration included Geiger counters, nuclear emulsions, proportional counters and scintillators with photomultiplier tubes. Semiconductor (solid-state) detector developments, reducing weight and enhancing reliability of instruments, began in the late 1950s and early 1960s. At lower energies space plasma detectors used Faraday cups. These

Table 1 Space missions that played a key role in studies of heliospheric particle populations

Spacecraft	Operation	Orbit	Achievements
Explorer 12	1961–1962	Elliptical Earth orbit	First detection of 'energetic storm particles'
Mariner 2	Aug–December 1962	Reached Venus in Dec. 1962	First observation of an interplanetary shock
IMP 7	1972–1978	Circular, $\sim 30\ R_E$	Discovery of ACR oxygen; first measurement of ionization states of energetic particles
IMP 8	1973–now	Circular, $\sim 30\ R_E$	Discovery of ACR He; 1 AU reference mission due to long orbital life
Helios 1/2	1974/76–1986/1980	Inner heliosphere to 0.3 AU	Spatial structures of SEP events; CIR radial gradients from 1 to 0.3 AU
Pioneer 10/11	1972–1999	Outer heliosphere	ACRs; CIR radial gradient beyond IAU
Voyager 1/2	1977–now	Outer heliosphere	ACRs
ISEE 1/2	1977–1987	Elliptical Earth orbit	Earth's bow shock and upstream particles
ISEE 3	1978–1982	215 R_E Sunward of Earth	Interplanetary shock particles; two classes of SEP events
AMPTE/IRM	1984–1986	Elliptical Earth orbit	Discovery of He^+ pickup ions
Ulysses	1990–now	Solar polar orbit (1.3 to 5.4 AU)	Discovery of H^+ and heavier pickup ions; CIRs at high latitudes
SAMPEX	1992–now	Earth polar orbit	Charge states of ACRs
Wind	1995–now	Upstream of Earth	Large area detector systems
ACE	1997–now	215 R_E Sunward of Earth	High-resolution composition (elemental and isotopic and charge states) with large collection area

early instruments provided a measure of the total ion flux and could only resolve protons from helium and heavier ions.

In the course of time, instruments have improved enormously, in sensitivity (e.g. larger collecting areas and lower energy thresholds), in resolution (e.g. better separation of different species) and in high-speed on-board processing. Where we once measured event-averaged abundances and energy spectra in SEP events or across CIR shocks, we can now probe the time-dependent spectral evolution in such events for many particle species over 4–5 orders of magnitude in energy.

What led to the many discoveries and provided progress in the detailed understanding of the different particle populations were – besides new spacecraft on different trajectories probing new regions in the heliosphere – new space-borne instruments capable of measuring the composition of particles at increasingly lower energies. The most common composition-resolving particle detectors were so called 'energy loss *v*. energy' ($\mathrm{d}E/\mathrm{d}x$ *v*. E) telescopes, using stacks of solid-state detectors (see Gloeckler (1970) for descriptions of these and other particle detection techniques). In these particle telescopes, the amplitudes of the coincident signals from the thin front $\mathrm{d}E/\mathrm{d}x$ detector and the thick back E detector (or stack of detectors) were digitized (or pulse-height analysed) and transmitted to Earth. When the pulse heights of both detectors were plotted against each other for many recorded particles, distinct tracks would appear for each resolved nuclear species, with the separation between tracks depending on the combination of nuclear charge (atomic number) and mass. In this way the atomic number and mass of the nucleus were determined. Ever lower energy limits were reached by decreasing the thickness (but not the area) of the $\mathrm{d}E/\mathrm{d}x$ detectors. This was done by, for example, using thin-window proportional counters of the Ultra-Low Energy Telescope (ULET) (Hovestadt and Vollmer 1971) provided by the Max-Planck-Institut (Garching) as part of the University of Maryland Experiments on IMPs 7 and 8 (Tums *et al.* 1974), or a mosaic of ultra-thin solid-state detectors in the Low Energy Charged Particle (LECP) experiment on Voyagers 1 and 2 (Krimigis *et al.* 1977). Large-area, position-sensitive solid-state detectors made it possible to resolve individual isotopes of many of the elements in the various particle populations (e.g. von Rosenvinge *et al.* 1995, Stone *et al.* 1998).

To reach even lower energies (tens of kilo-electronvolts), large-area plastic sheets were exposed in space and then returned to Earth for analysis (Price *et al.* 1967). This technique makes use of the fact that highly ionizing, heavy particles will damage the plastic material along their track. Once retrieved from space, these tracks become visible after chemical etching, and from the size and shape of the cones etched into the material, information on the nuclear charge and energy of the particle is obtained. The main disadvantage of plastic track detectors is their lack of good time resolution and the need to recover them.

A different approach to measure the composition of particles in the low-energy range between about 0.1 to 10 MeV/amu uses the 'time-of-flight *v*. energy' (TOF–E) technique (Gloeckler and Hsieh 1979). The start detector, a thin foil, is separated from the stop detector (usually a solid-state detector) by 10–50 cm. Secondary electrons, emitted from the respective surfaces of the start and stop detectors, are guided, typically by electric fields, to microchannel plates that detect these fast electrons and produce the start and stop signals for the TOF analysis. Measurements of the speed of the particle using TOF analysis combined with measurement of its energy (E) in the stop detector yields its mass. Composition instruments of this type were flown on the Wind (Gloeckler *et al.* 1995) and ACE spacecraft (Mason *et al.* 1998).

Even lower energies are reached by combining TOF–E with electrostatic analysis, as is done in the Solar Wind Ion Composition Spectrometer (SWICS) instrument on Ulysses, Wind and ACE (Gloeckler *et al.* 1992, 1995, 1998). Such instruments provide composition measurements from less than 1 to more than 100 keV/charge and measure, in addition to the mass, the charge or ionization state of the particle. This class of instruments is used to measure solar wind composition and the velocity distribution of pickup ions.

The most recent set of instruments to measure the composition of the solar wind, solar energetic particles and galactic cosmic rays with large collection areas and excellent elemental and isotopic resolution are assembled on ACE. It includes, besides SWICS (essentially the same instrument as its counterpart on *Ulysses*; see below), the Ultra Low Energy Isotope Spectrometer (ULEIS), the Solar Energetic Particle Ionic Charge Analyzer (SEPICA), the Solar Isotope Spectrometer (SIS) and the Cosmic Ray Isotope Spectrometer (CRIS). These state-of-the-art ACE instruments are described in Russell *et al.* (1998).

The acceptance of novel and technically advanced experiments for spaceflight has not always been easy, and the road to the pioneering measurements that were eventually made was often tortuous and lengthy. For example, there was considerable resistance to the use of ultra-thin solid-state detectors that were eventually flown in the LECP experiment (Krimigis *et al.* 1977) on Voyagers 1 and 2, yet these detectors make it now possible to measure the lowest energy ACRs in the outer heliosphere.

The TOF technique found it particularly difficult to gain acceptance in flight experiments. TOF instruments were proposed for an Explorer mission and again for Galileo, but were not selected by NASA because the technology was considered unproven and too risky for flight. However, in http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0