

Fluences of solar, heliospheric, and galactic particles at 1 AU

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Abstract. We report energy spectra of He, O, and Fe nuclei from ~ 0.3 keV/nucleon to ~ 300 MeV/nucleon, integrated from late-1997 to mid-2000. These fluence measurements were made at 1 AU using data from instruments on ACE, and include contributions from fast and slow solar wind, coronal mass ejections, pickup ions, impulsive and gradual solar particle events, particles accelerated in corotating interaction regions and other interplanetary shocks, and anomalous and galactic cosmic rays. Fluence measurements of six additional species are presented from ~ 0.04 to ~ 100 MeV/nucleon. We discuss the relative contributions of various particle components, comment on the energy spectra, and consider the implications for particle acceleration processes, cosmic ray spectra and particles implanted in the lunar soil.

a few keV/nucleon to a few hundred keV/nucleon. These measurements are of interest to models of particle acceleration and transport processes on the Sun, in the heliosphere, and in the Galaxy, and to studies of long-term contributions of energetic-particles to the lunar soil, meteorites, and planetary atmospheres.

The first results of this study, covering a 33-month period have just been reported (Mewaldt et al. 2001a); in this paper we present a brief summary of these results, and consider some of the questions that they raise.

2 Fluence Measurements

The measurements were obtained with the SWICS (Gloeckler et al. 1998), ULEIS (Mason et al. 1999), SIS and CRIS (Stone et al. 1998b, 1998c) instruments on ACE. Energetic-particle data were summed over a 33-month period from 1997:280 to 2000:184. Fluences were obtained from hourly-average fluxes within many separate energy intervals, taking into account the relevant instrument live times and geometry factors (Mewaldt et al. 2000a). (ACE data such as these are available at <http://www.srl.caltech.edu/ACE/ASC/>). This period starts with solar-minimum conditions in 1997 and ends with solar-maximum conditions in 2000.

The SWICS data for this preliminary study were summed over the first 11 months in 1999. These 11-month fluences were multiplied by a factor of 3 to correspond to the 33-month period used by the other instruments. The solar wind is less variable than higher-energy solar and interplanetary particles and the 1999 period should provide a reasonable representation of the longer time interval. In general, data from the instruments agree reasonably well where they overlap, but some renormalization was necessary (Mewaldt et al. 2000a).

1 Introduction

Energetic particles in the heliosphere range in energy from solar wind energies of ~ 1 keV to cosmic rays with $>10^{20}$ eV. Included are particles accelerated on the Sun, in interplanetary space, and in the Galaxy, with more or less steady sources like the solar wind and galactic cosmic rays, as well as highly variable sources associated with solar flares, coronal mass ejections, and interplanetary shocks.

Using data from instruments on the Advanced Composition Explorer (ACE), we are investigating the integrated fluence of particles over an energy range that extends from ~ 300 eV/nucleon to ~ 300 MeV/nucleon. ACE is ideal for this study because it has continuous access to the interplanetary medium, and because its instruments cover a broad dynamic range in both composition and energy, including the relatively unknown suprathermal region from

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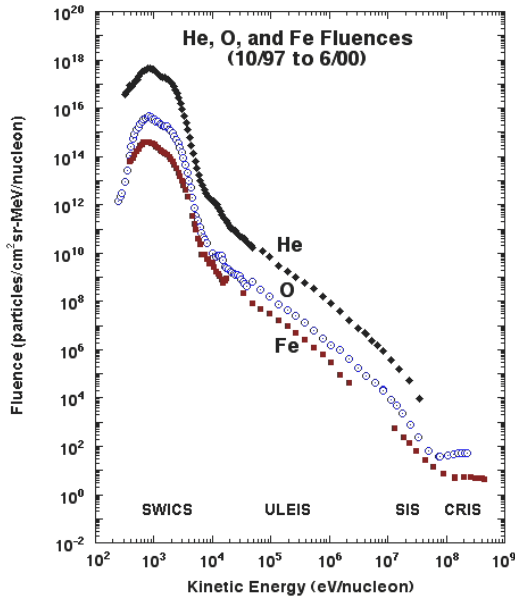


Figure 1: Fluences of He, O, and Fe nuclei measured over the period from 9/1997 to 6/2000 by the SWICS, ULEIS, SIS, and CRIS instruments on ACE. The SWICS fluences were measured over the first eleven months of 1999 and then multiplied by x3.

Measured fluences of He, O, and Fe extending from solar wind to cosmic ray energies are shown in Fig. 1. All three species clearly have common spectral shapes. The peak at ~ 0.8 keV/nucleon corresponds to slow solar wind with a mean velocity of ~ 400 km/sec. The contribution of occasional higher-speed streams of as high as ~ 1000 km/sec can also be seen. When the intrinsic thermal speed of the solar wind is folded in, the solar wind distribution extends to ~ 8 keV/nucleon. Beyond this a long, suprathermal tail extends with a power-law slope of -2 to ~ 10 MeV/nucleon. Near ~ 10 MeV/nucleon all spectra exhibit a gradual “knee” and briefly steepen. Above ~ 100 MeV/nucleon, the modulated fluence of galactic cosmic rays (GCRs) begins to dominate, continuing on for many more decades in energy.

5 Contributions to the Fluences

It is of interest to understand what particle components and acceleration processes contribute to the spectra in Fig. 1. In the intermediate region from ~ 30 keV/nucleon to ~ 30 MeV/nucleon the fluence spectra are a superposition of many separate “events”, examples of which are illustrated for oxygen in Fig. 2. At energies from ~ 3 to 30 MeV/nucleon most of the fluence comes from the largest solar particle events that occur a few times a year during solar maximum (e.g., the 11/97 event). Figure 3 illustrates how these events contribute to the 10 MeV/nucleon fluence. Note that anomalous cosmic rays make only a relatively small contribution to the fluence at 1 AU – contributions from large SEP events are considerably greater.

Impulsive solar flares and particles accelerated in corotating interaction regions (CIRs) contribute to the

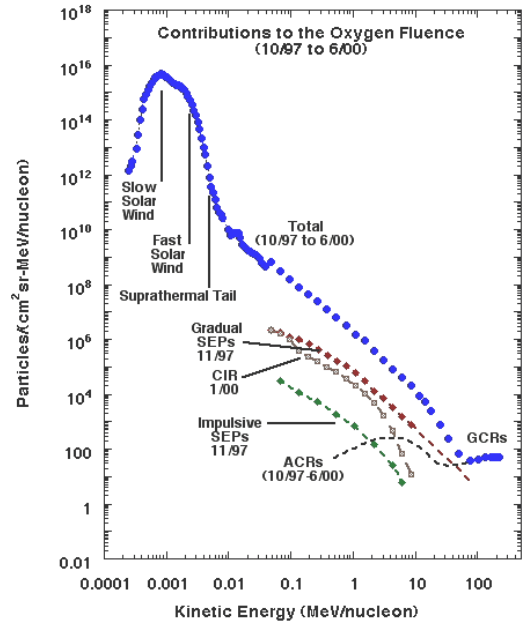


Figure 2: Illustration of some of the contributions to the oxygen fluence, including examples of impulsive and gradual SEP events, CIR-accelerated particles, and anomalous and galactic cosmic rays.

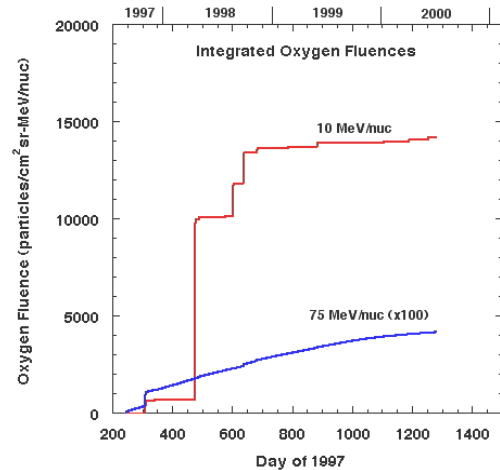


Figure 3: Time history of the integrated oxygen fluences at 10 and at 75 MeV/nucleon measured by SIS. In this case 27-day average fluxes were integrated. At 10 MeV/nucleon a few large SEP events contribute more than the continuous anomalous cosmic ray intensity, while at 75 MeV/nucleon the steady, continuous contribution of galactic cosmic rays is apparent.

energy range from ~ 0.1 to 1 MeV/nucleon. Although generally smaller in size than gradual SEP events, impulsive events occur much more frequently. At ~ 0.1 MeV/nucleon there are no large individual events that dominate – rather, there appear to be similar contributions from ~ 100 separate events of various kinds (see Fig. 4).

At even lower energies (~ 10 keV/nucleon to ~ 50 keV/nucleon, data from SWICS/ACE shows that suprathermal tails on the solar wind are continuously present (Gloeckler et al. 2000). The origin of these tails is

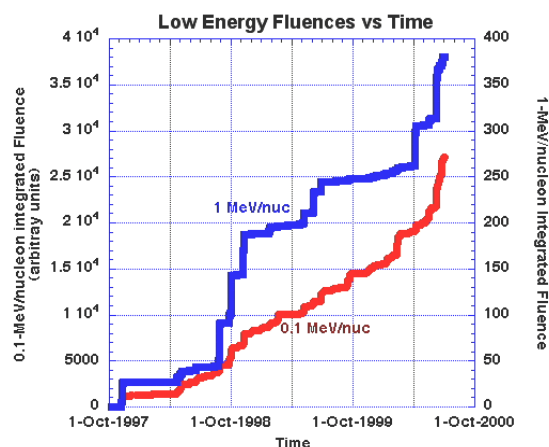


Figure 4: Time history of integrated daily oxygen fluences at 0.1 and 1 MeV/nucleon measured by ULEIS. Note that a large number of individual events contribute.

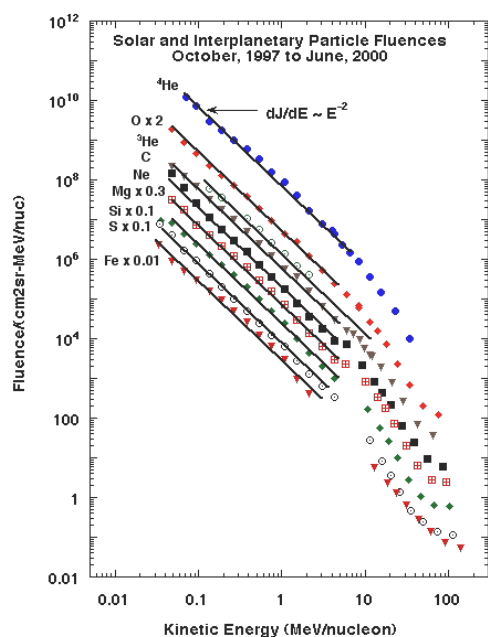


Figure 5: Solar and interplanetary fluences of nine species measured by ULEIS and SIS. The E^{-2} spectra were fit by eye.

presently a subject of investigation (see discussion below). The estimated intensity of interstellar and inner-source pickup ions at ~ 1 keV/nucleon is several decades lower than the solar-wind intensity (Gloeckler et al. 2000).

Using ULEIS and SIS data, fluence spectra have been computed from ~ 0.04 to ~ 100 MeV/nucleon for 9 species (see Fig. 5). It is rather remarkable that all of these species show the same E^{-2} power-law spectral shape over the entire energy range from ~ 0.04 MeV/nucleon to ~ 10 MeV/nucleon. The similar spectral shape suggests that these ions have a common origin. However, from Figures 3 and 4 it appears that while a continuous process (or processes) might explain the bulk of the particles observed isolated, individual events make most of the fluence at 1 MeV/nucleon and 10 MeV/nucleon.

Composition measurements provide some clues to the origin of the particles. The measured $^3\text{He}/^4\text{He}$ ratio above 100 keV/nucleon is ~ 0.01 to 0.02 , a factor of >30 greater than the corresponding ratio in the solar wind. While this suggests that impulsive ^3He -rich solar-flare events make an appreciable contribution to this energy region, ^3He is also overabundant in many gradual SEP events (Cohen et al. 1999, Mason et al. 1999), and it is likely that the ^3He fluence is due in part to the re-acceleration of remnant impulsive-flare material by interplanetary shocks (Mason et al. 1999; Desai et al. 2001).

The time period covered by this study ended just before the “Bastille Day” event on July 14, 2000, the largest SEP event during this solar cycle. One might ask to what extent inclusion of this event would modify the fluences in Figure 1. Using spectra compiled by Tylka et al. (personal communication, 2001) from several spacecraft including ACE and Wind, we find that the Bastille Day event contributes $\leq 10\%$ of the 33-month fluences below 0.1 MeV/nucleon. However, over the energy range from ~ 2 -3 to ~ 20 -30 MeV/nucleon (depending on species) this event contributes more than the other 33 months combined. The greatest relative contribution is to He, since this event was enriched in He relative to heavier ions. Addition of this contribution does not significantly alter the E^{-2} character of the O and Fe fluences in Figures 1 and 5, but it does flatten the He spectrum somewhat. Of course, other large events after June 2000 should also be included.

4 Solar Wind and Solar Particles in the Lunar Soil

Solar-wind noble gases and nitrogen implanted in lunar soils are a record of solar-wind variations over the history of the solar system. This record reveals an excess of the heavy isotopes of He, Ne, Ar, and Xe with respect to the present day solar wind, along with a depletion of ^{15}N (see, e.g., Wieler 1998 and Kerridge 1993). These anomalies were at first ascribed to solar energetic particles, and dubbed the “SEP” component, because they are implanted somewhat deeper in lunar samples than solar wind. However, it now appears that this component amounts to $\sim 10\%$ of the implanted solar wind in a given sample – orders of magnitude more than expected from the present-day frequency and size of SEP events.

Wimmer-Schweingruber and Bochsler (2000) have suggested an interstellar origin for the anomalies, pointing out that during the Sun’s journey around the Galaxy it has inevitably passed through dense interstellar clouds, whose pressure would cause the heliosphere to contract such that the termination shock may have been located at a few AU. Enhanced fluxes of pickup ions and ACRs are also expected (Zank and Frisch 1999). In this interpretation, the “SEP” component represents a sample of interstellar matter, isotopic anomalies result from galactic evolution effects since the birth of the solar system, and lunar soil provides a “travel diary” of the voyage of the solar system through the Galaxy.

A first attempt to calculate the depth profile of Ne isotopes implanted in lunar soil using measured energy spectra has been initiated (Mewaldt et al. 2001b). Note that both impulsive and gradual events observed by ACE are enriched in heavy isotopes such as ^{22}Ne on average (e.g., Leske et al. 1999). Although the results to date do not account for the apparently greater past intensity of the “SEP” component, they do determine the degree to which other explanations such as higher solar activity in the past or interstellar material from dense clouds may be required.

5 Energetic-Particle Spectrum from 10^2 to 10^{20} eV

The measurements presented here (with the addition of protons and intermediate species) make it possible to construct an all-particle spectrum of solar, heliospheric, and galactic particles extending continuously from several hundred eV to hundreds of MeV, and covering ~ 16 decades in intensity. This spectrum overlaps with surveys of the cosmic-ray all-particle spectrum from hundreds of MeV to $>10^{20}$ eV. We hope to present a spectrum from $\sim 10^2$ to $>10^{20}$ eV covering 46 decades in intensity at the conference.

6 Discussion

It is somewhat surprising that the fluences of ions from such a variable mix of sources show such a high degree of organization. All species have a common spectral shape. In particular, it is remarkable that a common power-law slope applies to the region from ~ 10 keV/nucleon, where the suprathermal tails on the solar wind dominate, to ~ 10 MeV/nucleon, where large SEP events contribute the most.

The origin of the suprathermal solar-wind tails remains a mystery. Although similar tails have been observed in association with CIRs (Chotoo et al. 2001) and other interplanetary shocks, ACE studies have shown that these tails are continuously present in the in-ecliptic solar wind, even when there are no shocks present (Gloeckler et al. 2000). Gloeckler et al. argue that they must originate in interplanetary space, not on the Sun, since tails are observed on interstellar pickup-ion distributions as well as on solar-wind species. As yet there is no consensus on their origin.

There are several similarities between these heliospheric spectra and those of higher-energy galactic cosmic rays. All heliospheric species have a common spectrum from ~ 10 keV/nucleon to ~ 10 MeV/nucleon, even though individual events contributing to these spectra often have non-power-law spectra with large composition variations. It is possible that GCRs also include contributions from several sources with differing spectra and composition, yet the primary GCR species from $\sim 10^9$ to $\sim 10^{13}$ eV/nucleon appear to be consistent with a single common source spectrum slightly steeper than -2 . In both cases the power-law regions end with a “knee”, followed at higher energy by an “ankle”. Although shock-acceleration processes are thought to be the main contributor to GCR spectra from 10^9 to 10^{14} eV/nucleon, their contribution to heliospheric spectra from 10^4 to 10^7 eV/nucleon is less clear.

7 Summary

The fluence spectra presented are the first continuous solar-wind, solar-particle, interplanetary, and cosmic-ray fluences from <1 keV/nucleon to >100 MeV/nucleon. Both solar minimum and solar maximum conditions are included, and these spectra should provide a good first approximation to the spectral shapes that would be obtained if such measurements were extended over an entire solar cycle.

All species are found to have a common spectral shape. Solar wind dominates the energy range up to ~ 8 keV/nucleon. From ~ 10 keV/nucleon to ~ 10 MeV/nucleon as many as 100 or more separate events somehow combine to produce $\sim E^{-2}$ power-law spectra for all species measured, including ^3He . From ~ 5 to ~ 50 MeV/nucleon intense, gradual SEP events make the largest contribution, while at higher energies galactic cosmic rays take over. It is not yet known what processes make the largest contributions to the region from ~ 10 keV/nucleon to ~ 1 MeV/nucleon. The possibilities include impulsive SEP events, CIR events, or other, as yet unidentified processes that occur continuously on the Sun or in the inner heliosphere.

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