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Long-Term Fluences of Solar Energetic Particles from H to Fe

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Abstract Data from ACE and GOES have been used to measure Solar Energetic Particle (SEP) fluence spectra for H, He, O, and Fe, over the period from October 1997 to December 2005. The measurements were made by four instruments on ACE and the EPS sensor on three GOES satellites and extend in energy from ∼0.1 MeV/nuc to ∼100 MeV/nuc. Fluence spectra for each species were fit by conventional forms and used to investigate how the intensities, composition, and spectral shapes vary from year to year.

Keywords Sun: particle emission · Sun: solar wind · Sun: abundances · Acceleration of particles

1 Introduction

In 2001, Mewaldt et al. combined He, O, and Fe data from four instruments on NASA's Advanced Composition Explorer (ACE) and presented fluence spectra that extended from solar wind to galactic cosmic ray energies. As shown in Fig. 1, all three species had very similar spectral shapes, including power-law spectra with a slope of about −2 extending from ∼10 keV/nuc to ∼10 MeV/nuc. Six additional species had similar E^{-2} fluence spectra (right panel of Fig. 1). This was unexpected because this energy interval included contributions from many separate solar energetic particle (SEP) events that varied in intensity, spectral hardness, and composition (Mewaldt et al. 2001, 2005a). In this paper we present new yearly fluence spectra for H, He, O, and Fe extending from ∼0.1 to ∼100 MeV/nuc for the period from late-1997 through 2005. The yearly fluence spectra are dominated by each

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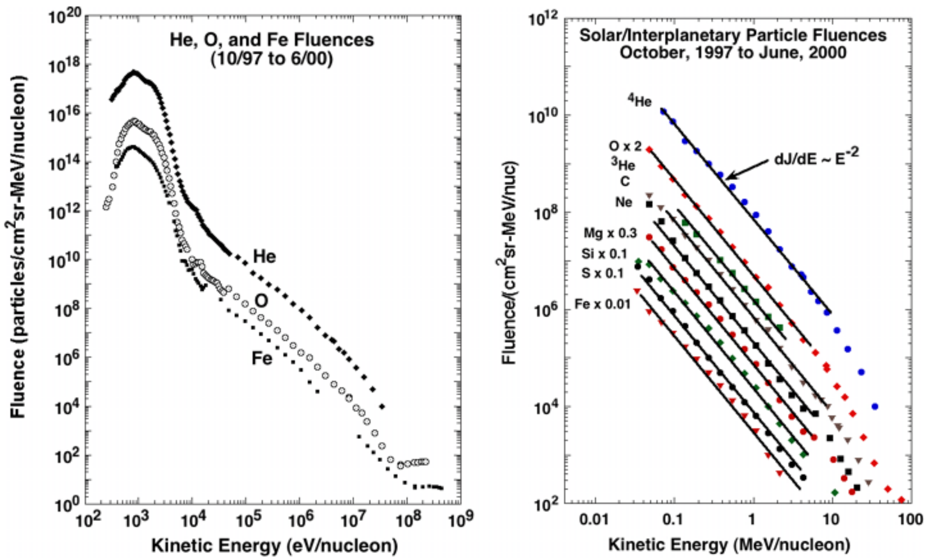


Fig. 1 *Left*: Fluence spectra for He, O, and Fe nuclei from October 1997 to June 2000, measured by four instruments on ACE (Mewaldt et al. 2001). *Right*: In the October 1997 to June 2000 period it was found that the fluences of nine species had the same E^{-2} spectral slope from ~0.05 to ~5 MeV/nuc (adapted from Mewaldt et al. 2001)

year's large SEP events. We use these measurements to examine how the low-energy fluence spectra (~0.1 to ~2 MeV/nuc) vary from year to year in spectral slope and to investigate whether the composition varies as a function of energy and/or with time.

2 Fluence Spectra: Observations and Fits

The measurements presented here cover the period from the launch of ACE in late 1997 to the end of 2005. We combined the last 3 months of 1997 with 1998, giving a total of 8 "yearly" fluence spectra. Most of the data are from three instruments on ACE, the Solar Isotope Spectrometer (SIS; Stone et al. 1998a), the Ultra Low-Energy Isotope Spectrometer (ULEIS; Mason et al. 1998), and the Electron, Proton, Alpha Monitor (EPAM; Gold et al. 1998). In addition, H and He data were obtained from the EPS sensors on NOAA's GOES-8, 10, and 11 satellites (Onsager et al. 1996). Finally, galactic cosmic-ray (GCR) measurements from the Cosmic Ray Isotope Spectrometer (CRIS) instrument on ACE (Stone et al. 1998b), and the BESS balloon-borne instrument (Shikaze et al. 2003) were used to estimate GCR contributions to the fluences. Table 1 summarizes the species and energy coverage of the instruments used for the reported fluence spectra.

Spectra from separate instruments for the largest SEP events (Mewaldt et al. 2005a; Cohen et al. 2005), and for 2000 and 2001 did not agree as well as during less active years, apparently due to intensity-related instrumental effects during the largest SEP events. To reconcile these differences the ULEIS spectra were multiplied by 1.6 in 2000 and 0.55 in 2001, and the SIS He spectra for 2003 were multiplied by 2.3 as in (Mewaldt et al. 2005a). Proton and He spectra from GOES were obtained by summing fluences from the NOAA event list at http://umbra.nascom.nasa.gov/SEP/seps.html, including differential proton and He spectra from 4.2 MeV to 200 MeV. Additional (though not independent) proton points were

Table 1 Species and energy coverage

Instrument	H (MeV)	He (MeV/nuc)	O (MeV/nuc)	Fe (MeV/nuc)
ACE/EPAM	0.047–4.75			
ACE/ULEIS		0.065–7.24	0.040–7.24	0.040–2.56
ACE/SIS		6.13–41.2	7.05–89.8	10.5–117.5
GOES-8,10,11	4.2–200	2.5–125		

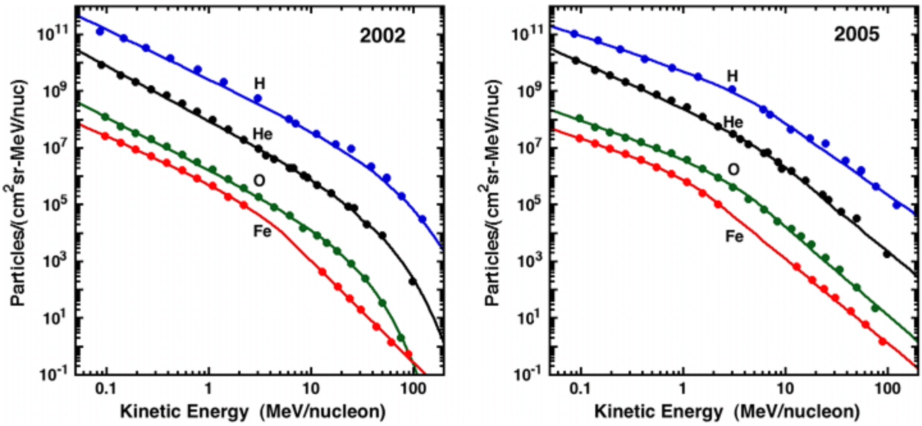


Fig. 2 Fluence spectra for 2002 and 2005, fit with the double power-law form of Band et al. (1993). Note that the spectral breaks are ordered by species

obtained by differentiating GOES integral spectra for >5 to >100 MeV (Tylka et al. 2005; Mewaldt et al. 2005a). Following attempts to fit the GOES He spectra with a smooth spectrum, and the comparison of He spectra from SIS, GOES, and the SOHO/ERNE instrument (Torsti et al. 1995), we divided the GOES 16–45 MeV/nuc He points by 2, and multiplied the SIS He spectra by 1.3 for all years except 2003 (see above and Mewaldt et al. 2005a).

In order to isolate the SEP contributions, we corrected the measured fluence spectra for O and Fe using GCR spectra from the ACE/CRIS instrument in conjunction with a cosmic-ray modulation model (Davis et al. 2001). The GCR and instrumental background corrections to the GOES H and He spectra were based on pre-event background levels from GOES.

The yearly SEP fluence spectra for H, He, O and Fe were fit with the double-power-law spectrum of Band et al. (1993), which has provided excellent fits to fluence spectra from individual SEP events (Tylka et al. 2005; Mewaldt et al. 2005a). Examples of the yearly spectra are shown in Fig. 2; the 8.25-year sum is shown in Fig. 3. The low-energy spectra were fit separately with a power-law between 0.1 and 2 MeV/nuc. The resulting spectral slopes are summarized in Fig. 4.

3 Results and Discussion

The spectral indices in the suprathermal energy range (Fig. 4) show correlated variations from year to year in all four species. This portion of the spectrum includes contributions from

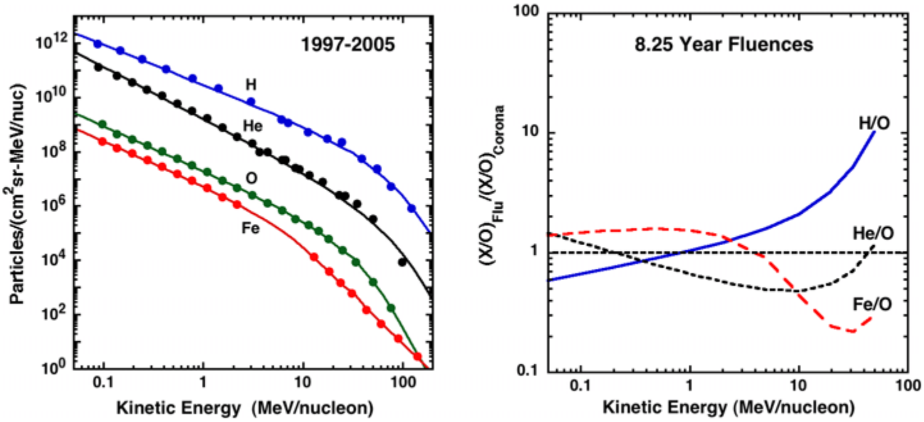
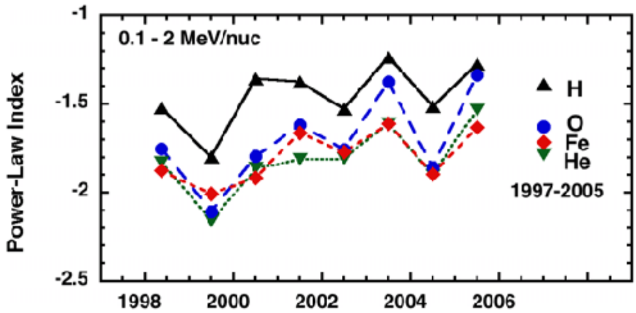


Fig. 3 *Left*: Fluence spectra summed over the 8.25-year period from October 1998 to December 2006. *Right*: Ratios of H/O, He/O and Fe/O derived from fits to the 8.25-year spectra shown at the left. Each ratio has been divided by the coronal abundances of Feldman and Widing (2003)

Fig. 4 Yearly power-law indices based on 0.1 to 2 MeV/nuc data from EPAM (protons) and ULEIS (He, O and Fe). Statistical uncertainties are comparable to the size of the data points. He spectral slopes are somewhat more uncertain than the other species



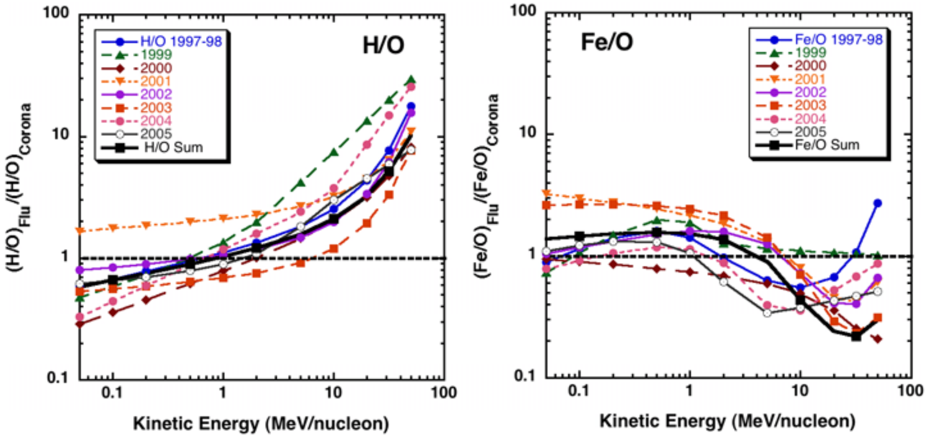


Fig. 5 Energy dependence of the yearly H/O and Fe/O ratios, each normalized to the coronal abundances of Feldman and Widing (2003)

many separate events, large and small (Mewaldt et al. 2001, 2005a), with typical spectral indices of -1 to -2 in the largest events, and with heavy-ion spectra typically somewhat softer than proton spectra (see examples in Cohen et al. 2005; Mewaldt et al. 2005a). During solar maximum years (2000–2005) the fluence spectra reflect the large events that had the hardest spectra. In many years the He and O indices below a few MeV/nuc are similar, as expected since they have similar Q/M ratios. In other years the He spectra are significantly softer than O (see Fig. 2), which is unexpected. The detection efficiency of He in ULEIS is smaller and less certain than that of heavier ions, so apparent differences between He and O should be treated with caution.

Gloeckler et al. (2000) find that quiet and moderately-quiet suprathermal spectra ($\sim$0.01 to 1 MeV/nuc) all tend to have spectral indices of -1.5, and they suggest an interplanetary acceleration process that could be responsible for these suprathermal tails (Fisk and Gloeckler 2006). However, their time periods were chosen to exclude shocks, while our suprathermal fluence spectra are due mainly to SEP events accelerated by CME-driven shocks, where the spectral index is expected to depend on the shock strength (e.g., Lee 1983).

The spectra from all years show evidence of species-dependent spectral breaks, with H breaking at the highest energy/nuc and Fe at the lowest energy/nuc (Figs. 2 and 3). This is because the fluence spectra >1 MeV/nuc during any one year are dominated by the largest SEP events of that year, which typically have spectral breaks that depend on the charge-to-mass (Q/M) ratio of the species (e.g., Tylka et al. 2000; Cohen et al. 2005, Mewaldt et al. 2005a, 2005b; Cohen et al. 2007).

Using fits to the spectra it is easy to examine the energy dependence of the relative abundances of these species as shown in Figs. 3 and 5. Below $\sim$1 MeV/nuc the H/O ratios increase with energy while the Fe/O ratios show little variation. At energies between $\sim$1 and $\sim$30 MeV/nuc the H/O ratios turn sharply up, and the Fe/O ratios turn sharply down as a result of the Q/M-dependent spectral breaks discussed above. The above trends are consistent with the Q/M-dependent patterns in large SEP events, and can be understood if higher-rigidity particles escape upstream of the shock more easily and are therefore less efficiently accelerated (e.g., Li et al. 2005). The low-energy He/O behavior is unexpected (see above), but the >5 MeV/nuc patterns follow the expected Q/M-dependent behavior.

There are several years in which the Fe/O ratio increases above 30 MeV/nuc (Figs. 2 and 5) due to SEP events with hard spectra that are enriched in heavy elements such as Fe (Cohen et al. 1999; Dietrich and Lopate 2001; Tylka et al. 2005; Mewaldt et al. 2006). In 1997–98 the Fe-rich 6 November 1997 event dominates at high energies; in 2004 the Fe-rich 11 April 2004 event contributes most of the >30 MeV/nuc fluence. The Fe/O ratio in 1999 is flat; in this year there were several Fe-rich events but no-large Fe-poor events (Cane et al. 2006). There is also an increase in Fe/O above 30 MeV/nuc in the 8.25-year fluences (Fig. 3). Cane et al. (2003) interpreted high-energy Fe enrichments in well-connected SEP events as contributions of "flare-accelerated particles". Tylka et al. (2005) concluded that these Fe enrichments are due to selective acceleration (by quasi-perpendicular shocks) of remnant suprathermal material from earlier Fe-rich SEP events.

The abundance ratios in Figs. 3 and 5 were normalized to the coronal abundances of Feldman and Widing (2003). Our long-term (8.25-year) ratios are within a factor of two of coronal values between $\sim$0.05 and $\sim$5 MeV/nuc, with somewhat larger year-to-year variations. However, the observed energy dependence of the abundance ratios suggests that there is no one energy interval where one can be confident that fluence spectra uniformly sample the coronal composition (see also Desai et al. 2006).

4 Summary

The fluence spectra reported here extend those in Mewaldt et al. (2001) by adding H and by showing how SEP fluences vary from year to year. Although the year-to-year spectral shapes are similar, and all are well fit by a double-power-law, there are significant spectral-slope and abundance variations. In the 0.1 to 2 MeV/nuc interval the power-law slopes vary from -1.3 to -2.1 with the hardest spectra in years with the largest SEP events. At higher energies the fluence spectra have Q/M-dependent spectral breaks that reflect the behavior of the largest SEP events of the year. This leads to composition variations with heavier species generally depleted above $\sim$3 MeV/nuc. An exception to this is Fe; in some years (and the 8.25-year sum) the Fe/O ratio reverses the lower-energy trend and increases above $\sim$30 MeV/nuc due to occasional Fe-enriched events with hard power-law spectra at high energies. The observed energy-dependent composition suggests that there is no single energy region in which long-term measurements of SEP fluence spectra can, by themselves, provide a reliable measure of the coronal composition.

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