

Treatment of Heavy Ions ($Z \geq 3$)

Predictions for the heavy ion spectra from lithium to uranium are based on abundance ratios with respect to helium. The following outlines the method used to determine these abundance ratios, and further details can be found in reference [1].

ACE/SIS observations of C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni

The primary source is data from the Solar Isotope Spectrometer (SIS) flown on the ACE (Advanced Composition Explorer) spacecraft. Data relating to 13 ion species have been used, for each ion species the spectra being defined over different energy ranges (with eight bin energy resolution):

- Carbon: 7.4 to 64.4 MeV/nuc
- Nitrogen: 8 to 70.2 MeV/nuc
- Oxygen: 8.5 to 75.7 MeV/nuc
- Neon: 9.5 to 85.8 MeV/nuc
- Sodium: 9.6 to 88.2 MeV/nuc
- Magnesium: 10.3 to 95 MeV/nuc
- Aluminium: 10.4 to 97.3 MeV/nuc
- Silicon: 11 to 103.6 MeV/nuc
- Sulphur: 11.6 to 111.7 MeV/nuc
- Argon: 12.1 to 121.2 MeV/nuc
- Calcium: 12.6 to 126.6 MeV/nuc
- Iron: 13 to 140.4 MeV/nuc
- Nickel: 13.7 to 149.7 MeV/nuc

Data from 110 events were visually inspected leading to the selection of 14 events for which data for most of these elements could be used for calculating the event-averaged spectra. These event spectra were cleaned, de-spiked and gap-filled, and event-integrated fluences fitted to Band functions in energy per nucleon which allowed interpolation/extrapolation to each of the SEPEM bin energies [2]. From these, the average abundance ratios for the ions with respect to He were determined for the 11 SEPEM energy bins.

Abundance ratios for other heavy ions

For titanium, chromium and zinc ($Z=22, 24$ and 30 respectively), the ACE/SIS-based abundance ratios for iron have been scaled by those determined by Reames [3] based on ISEE-3 measurement data for large SEPs over 5-12 MeV/nuc. For all remaining ions $Z \geq 3$, the ACE/SIS-based abundance ratios for the ions with the nearest Z were scaled according to the photospheric abundances of Asplund *et al* [4].

Note that the abundance ratios for the following ion species are deliberately set to zero since there is no stable isotope, and nor do they have an extremely-long-lived (*i.e.* primordial) radioisotope such as ^{232}Th , ^{235}U , and ^{238}U : technetium ($Z=43$), promethium (61), polonium (84), astatine (85), radon (86), francium (87), radium (88), actinium (89), protactinium (91).

Ion charge states

For analysing of conventional shielding effects (*e.g.* using MULASSIS), the ionisation state of the initial incident ion (Q) can be considered irrelevant, since within the material, charge state is determined by the ion velocity and the interaction with the electrons in the medium. However, the ion charge state is important when calculating the geomagnetic shielding effects as it defines the particle's rigidity. SEPEM provides three options for defining Q :

- “Fully ionised”: For all ions, the charge state equals the atomic number ($Q=Z$).
- “CREME96 and half ionised”: The charge state of the ions is based on the algorithm in CREME96 for ions up to zinc ($Z=30$) [5], whilst for ions with $Z=31$ to 92, the charge state is assumed to be $Q=Z/2$.
- “CREME96 and fully ionised”: This is identical to the second option, except for ions with $Z=31$ to 92, the charge state is assumed to be fully ionised ($Q=Z$).

For a given ion, the charge state algorithm in CREME96 provides an estimate the fraction of ions at each charge state from $Q=1$ to fully-ionised ($Q=Z$), these fractions based on observations of SEP ions in interplanetary space. For H, He, Li and Be, the ions can be considered fully charged, whilst for heavy ions up to zinc, the Q approaches $Z/2$. For this reason, and because if one assumes the ions to be fully ionised it leads to only a *best-case estimate of the environment* (*i.e.* maximum geomagnetic shielding), it is recommended that “CREME96 and half ionised” is selected for most analyses.

References

- [1] Athina Varotsou and Anne Samaras, “Creation off a cleaned ACE Heavy Ion database and deffinition of ion abundance ratios (WP3100),” TRAD Technical Note TRAD_ESA_SEP_TN1_AV_170214 Rev.2, February 2015.
- [2] Band **et al**, “BATSE observations of gamma-ray burst spectra. I - Spectral diversity,” *ApJ*, **413**, 28, pp 281-292, 1993.
- [3] Donald V Reames, “Solar energetic particles: Sampling coronal abundances,” *Space Sci Rev*, **vol 85**, pp327-340, 1998.
- [4] Martin Asplund, Nicolas Grevesse, A Jaques Sauval and Pat Scott, “The chemical composition of the Sun,” *Annual Rev Astron Astrophys*, **47**, pp 481-522, 2009. Also in arXiv:0909.0948v1.
- [5] A J Tylka, J H Adams, Jr, P R Boberg, et al, “CREME96: A revision of the Cosmic Ray Effects on Micro-Electronics code” *IEEE Trans Nucl Sci*, **44**, pp2150-2160, 1997.