296 DEVELOPMENT OF A PROXY DATA SET FOR THE ENERGETIC HEAVY ION SENSOR (EHIS) IN THE GOES-R SPACE ENVIRONMENT IN-SITU SUITE (SEISS)

Ranjeetha Bharath[1], Juan V. Rodriguez*, Janet C. Green, and William F. Denig
National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, Colorado

1. INTRODUCTION

Energetic heavy ions of solar origin can adversely affect a variety of human operations including but not limited to aircraft, satellites, and spacecraft. In addition, energetic heavy ions can pose a threat to human health, particularly for astronauts beyond Earth's protective atmospheric layer. NOAA has monitored solar energetic particles (protons and alpha particles) since 1975 from geostationary orbit. The Energetic Heavy Ion Sensor (EHIS), which is part of the GOES-R Space Environment In-Situ Suite (SEISS, http://www.goes-r.gov/spacesegment/seiss.html), will augment this longstanding capability. In support of NOAA's goal of a Weather Ready Nation, EHIS will measure elemental ion fluxes from hydrogen (atomic number = 1) to nickel (atomic number = 28) in energy ranges capable of penetrating normal satellite shielding and causing single event effects. The NESDIS National Geophysical Data Center (NGDC) will derive a Level 2 product from EHIS fluxes in which the observed spectra of flux versus energy are transformed into spectra of flux versus linear energy transfer (LET) or stopping power in silicon. A flux-LET spectrum summed over all energetic ion species is more useful to the spacecraft design and testing communities than flux-energy spectra by particle type. Iron ion fluxes are of particular concern because they typically dominate the high end of the LET spectrum up to ~30 MeV cm^2 mg^{-1}.

In support of the development and testing of the Level 2 LET algorithm, we have developed a proxy data set of energetic heavy ion fluxes from measurements by the Solar Isotope Spectrometer (SIS) aboard the Advanced Composition Explorer (ACE) satellite (Stone et al., 1998). ACE is located at the L1 Lagrangian point; the heavy ion fluxes measured by GOES-R are expected to be similar to those observed at L1, particularly at higher energies. The SIS Level 2 product available from the ACE Science Center includes fluxes of the fourteen most abundant elements from helium to nickel in eight energy bands that vary by element but lie in the range from 4 to 150 MeV/nucleon.

The upper four SIS energy bands overlap the lower part of the EHIS energy range. In order to generate the proxy data, a method has to be developed for interpolating or extrapolating the SIS fluxes to the EHIS energy bands. For the initial proxy data set, we have fit energy spectra of heavy ion differential flux integrated over entire solar energetic particle (SEP) events to an analytical expression derived from the physics of particle acceleration in solar flares. This expression fits well most of the observed spectra for all fourteen elemental ions. The resultant fits can be used to estimate the fluxes in the EHIS channels. In this paper, we describe the method for calculating the proxy data set and associated errors, and results of this analysis.

2. METHOD

2.1 *Calculation of Event Fluences*

In order to analyze the SIS heavy ion data, several steps were taken in this study that involve time, flux, and particle count information. The first step is to integrate the fluxes in time to obtain elemental fluences, or equivalently time-averaged fluxes, over entire SEP events. Flux, j, in this context, has units of $[\text{steradian}\cdot\text{sec}\cdot\text{cm}^2\cdot(\text{MeV/nuc})]^{-1}$. The integral with respect to time is approximated by

$$\text{fluence} = \sum_i j(t_i)\,\Delta t \qquad (1)$$

In the cases here, using the SIS Level 2 data, it sufficed to sum the hourly fluxes and multiply by Δt = 3600 seconds to calculate the event fluence values. For each SEP event, fluence was calculated for each element (helium-4, carbon, nitrogen, oxygen, neon, sodium, magnesium, aluminum, silicon, sulfur, argon, calcium, iron, and nickel) in each of the energy ranges provided in the ACE Science Center data.

One important question arises from this method of integrating fluence with respect to time for each element and energy band: How is the time range for an event determined? Cane et al. (2006) list all the large SEP events that took place during Solar Cycle 23 from 1997

---

[1] NOAA Hollings Undergraduate Scholar, Massachusetts Institute of Technology, Cambridge, Massachusetts

* *Corresponding author address:* Juan V. Rodriguez, NOAA National Geophysical Data Center, E/GC2, 325 Broadway, Boulder, CO 80305;
e-mail: juan.rodriguez@noaa.gov

to 2005. The largest twenty-two events from this list were chosen for analysis in the present study, as determined by the peak >10 MeV integral flux. Cane et al. (2006) provide approximate event date and hour ranges for the SEP events in their list. However, these time ranges were determined based on protons, not heavier ions. In order to determine the proper time range for calculating event fluence, it is necessary to plot a running fluence integral with time, showing fluence as it increases over time to determine whether it levels off by the end of a time interval (Mazur et al., 1992). In this manner, we checked each range given by Cane et al. (2006) and modified event time ranges as needed. In addition, intervals given in fractions of hours needed to be rounded to integral hours to accommodate the hourly fluxes used in the analysis.

An example of the checks performed on the intervals given by Cane et al. (2006) is given in Figure 1. This plot displays the running neon ion fluence integral as a

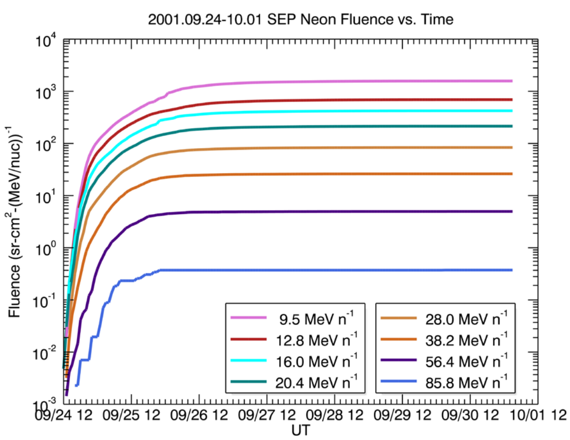

Figure 1. Neon running fluence as a function of time during the SEP event that commenced on September 24, 2001, as measured by ACE SIS.

function of time during the SEP event that commenced on September 24, 2001. It is clear from the plot for each neon energy band that by the end of the event, the fluence has reached a plateau. This signifies an acceptable choice of time interval for the event. In cases in which the fluence continued to rise past the end time given by Cane et al. (2006), the time interval was increased hourly until the fluence curves reached a plateau at all energies.

Figure 2 displays the fluence-energy spectrum by element for the September 24, 2001 SEP event. The error bars are plotted on each data point. The Poisson counting statistical error in each energy-elemental channel was calculated in units of fluence as the fluence divided by the square root of the number of counts measured during the event.

2.2 *Curve Fits*

Using a stochastic acceleration model with rigidity-dependent diffusion, Mazur et al. (1992) derived an expression for the energy-spectrum of differential number flux arising from the differential equation relating particle number density to particle energy per nucleon and time. The diffusion equations yield, when combined and limited to steady state, the following equation:

$$j(T)=N_0\, T^{(5-2b)/4}\, K_\nu(\beta T^{2-b}) \quad (2)$$

Here, T is the energy per nucleon. The parameter ν is the order of the modified Bessel function of the second kind K_ν and is given by

$$\nu = (2b-1)/[4(2-b)] \quad (3)$$

The parameter β is related to the diffusion coefficients and is given by

$$\beta = \Delta/(2-b) \quad (4)$$

where Δ is a function of the charge-to-mass ratio as well as of other parameters independent of time, particle energy, mass and charge. The three fit parameters are b, Δ, and N_0. Note that simply having three parameters is not sufficient to achieve a good fit to these spectra. For example, a shock acceleration model with three parameters is often too soft (predicted fluxes too low) in the energy range of interest here (Mazur et al., 1992; Mewaldt et al., 2005).

This physics-based expression can be fit to the fluence energy spectra and associated error bars (for each element and each event) using nonlinear regression. However, in this study, the primary goal was to fit the spectrum as accurately as possible at higher energies, above which the SIS data do not cover the EHIS range. Therefore, a more accurate fit for high energies was obtained by fitting the base 10 logarithm of the fluences to the base 10 logarithm of Equation 2. Namely, the *nlinfit* curve fitting function in MATLAB, based on a Levenberg-Marquardt (Press et al., 1988) nonlinear regression approximation, takes the logarithm of Equation 2 as its objective function along with the logarithm of the fluence-energy spectra and returns a three-parameter fit. This achieves the effect of equal weighting of all eight energy channels rather than weighting by counting statistics, which would underemphasize the highest energy channels (i.e., those with the lowest count rates).

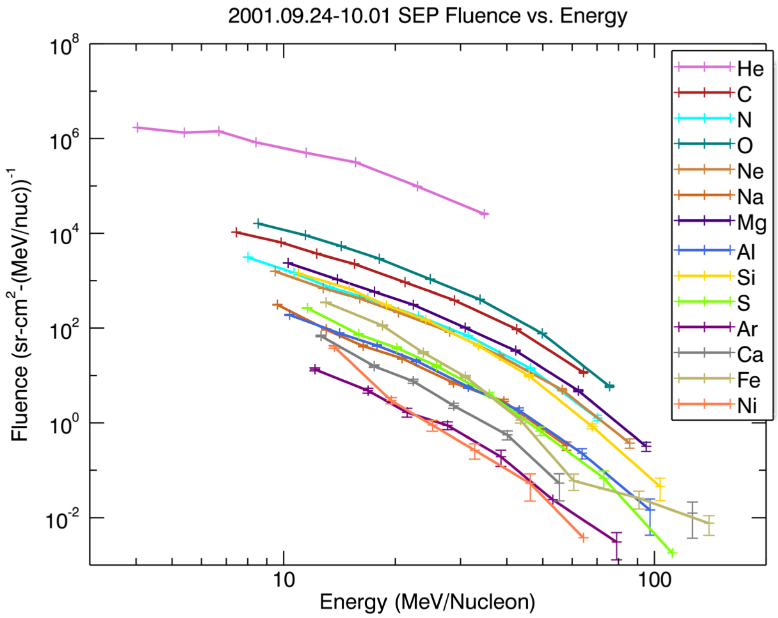

Figure 2. Heavy ion event-fluence spectra for the SEP event that commenced on September 24, 2001, as measured by ACE SIS. Error bars represent Poisson uncertainties.

Originally, the intent was to describe curve fit quality using errors on each of the three parameters derived from the covariance matrix calculated by the Levenberg-Marquardt routine. However, such statistical error analysis applies solely to Gaussian errors (Press et al., 1988). Because this analysis was performed on the logarithm of the fluxes, such error analysis is in principle not valid, and we found that the standard deviations determined from the diagonal elements of the covariance matrix did not make sense. However, the normalized root-mean-squared (RMS) error, using relative values for equal weighting, is an appropriate measure and is the one used here. It is defined as:

$$\text{RMS error} = \text{norm}[(\text{residuals}/\text{Y-values})^2]/(n-p) \qquad (5)$$

where n is the number of data points and p is the number of fit parameters, and residuals are the differences between the curve-fit Y-value and the data point Y-value (where the Y-values are the logarithms of the fluxes).

2.3 *Elemental Abundance*

The last analysis performed on the data is a relative elemental abundance study for each SEP event. Using the results of the curve fits, the fluence equation (Equation 1) is integrated over the energy range 12—60 MeV/nuc. This energy range is chosen for consistency with much of the published work in this field (e.g., Cohen et al., 2005). The resulting integral fluence for each heavy ion species is then normalized to the result for oxygen (e.g., Gloeckler, 1979; Reames, 1998).

3. RESULTS AND DISCUSSION

The fourteen heavy ion event-fluence energy spectra were analyzed from the twenty-two selected large SEP events of Solar Cycle 23. Of the 308 spectra analyzed, 89% of the spectra had an RMS error less than 1. Of the remainder, three (for the low-abundance elements argon, calcium and nickel) had only 1-3 data points and therefore could not be fit or did not have a meaningful error. Of those that could be fit, 30 spectra had a normalized RMS error greater than 1, indicating that the three-parameter Bessel function model did not fit the data well, or that there were as few as 4 points in the spectrum.

As an example, the fit results and normalized RMS errors for the September 24, 2001 SEP event, whose spectra are plotted in Figure 2, are listed in Table 1. The values of β are calculated from b and Δ according to Equation 4. The values of b range from 1.29 (for helium) to 1.85 (for calcium). The normalized RMS errors are all less than 1 except for nickel. The RMS error for the fit to the nickel spectrum is 2.08, due to the low energy tail that is evident in Figure 2. Figure 3 shows four examples of these curve fits (carbon, neon, sodium and iron), representing RMS errors spanning four orders of magnitude. The fits to the carbon and neon spectra have very small RMS errors (2×10^{-4} and 2×10^{-3}, respectively). The normalized RMS error in the fit to the

	N_0	b	Δ	β	RMS
He	2.60E+06	1.29	0.347	0.49	8.50E-05
C	2.12E+05	1.50	0.678	1.35	2.06E-04
N	1.15E+05	1.52	0.774	1.61	4.02E-02
O	1.79E+05	1.42	0.551	0.95	4.69E-04
Ne	3.66E+04	1.48	0.649	1.24	2.30E-03
Na	3.87E+07	1.75	1.709	6.77	2.86E-02
Mg	5.11E+04	1.46	0.611	1.13	8.45E-04
Al	1.13E+04	1.50	0.753	1.52	7.40E-03
Si	6.33E+04	1.46	0.675	1.24	9.65E-02
S	2.26E+04	1.48	0.775	1.48	7.10E-03
Ar	1.79E+04	1.59	1.125	2.73	6.07E-01
Ca	7.17E+11	1.85	2.364	16.23	1.06E-01
Fe	1.45E+12	1.82	2.536	13.89	9.96E-01
Ni	5.45E+11	1.79	2.854	13.59	2.08E+00

Table 1. Parameters for Equation 2 from fits to heavy ion fluence spectra from the SEP event commencing on September 24, 2001.

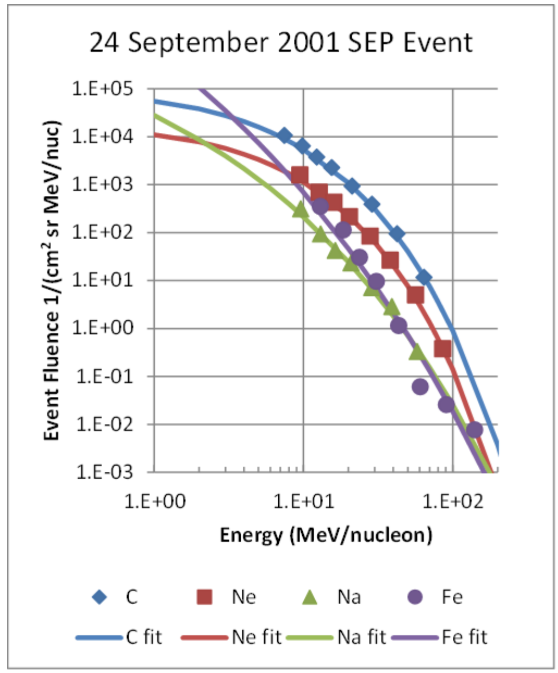

Figure 3. Three-parameter Bessel function curve fits to the carbon, neon, sodium and iron fluence energy spectra from the September 24, 2001 event.

sodium spectrum is also small (0.03), but in this case the fitting routine returned a warning to the effect that the result is insensitive to at least one of the three parameters (see discussion below).

For this particular event, the iron spectrum exhibited a high-energy tail (Figure 3), a phenomenon observed occasionally in the present study, as well as by Mazur et al. (1992). The three-parameter fit (normalized RMS error ~ 1) cannot capture the break in the curve, and it underpredicts the flux at higher energies. In such cases, in order to produce accurate proxy data as well as for scientific purposes, the data should be fit to a higher-order expression, such as a sum of the three-parameter Bessel function curve at lower energies and a power law at higher energies. More generally, curve fits with RMS errors approaching unity should be examined carefully before being used as proxy data.

In some cases, the shape of the curve may be adequately described by a two-parameter power-law fit, but the three-parameter Bessel function expression still provides a useful, accurate fit. For example, in the event that started on April 15, 2001 (Figure 4), the spectra appear to follow a power law. The RMS errors of the fits to Equation 2 are generally low (the largest error was 0.645, for carbon). However, the MATLAB non-linear fitting routine warned (after the fit converged) that the resulting curves were insensitive to some of the parameters, which suggests that they would be adequately described by a two-parameter power-law fit.

When the results from all 22 events are compared with the results of Mazur et al. (1992), a similar picture arises of the behavior of the heavy ion spectra. From analysis of hydrogen, helium, oxygen and iron spectra from ten SEP events, Mazur et al. (1992) determined that b was not strongly species-dependent. Therefore, we compare the species-averaged b. The median and upper- and lower-quartile values of b are similar between the two studies (Table 2). For the three elements that are analyzed in both studies (He, O and Fe), there are significant differences in the medians and quartiles of β between the two studies. One possible explanation for this difference is that both studies show a large degree of event-to-event variability in this parameter, and the tails of the distributions for the same species do overlap. Both studies also share an increasing trend in β from helium to iron that is more pronounced in the present study.

The difference between the energy ranges of the data used in the two studies suggests that event-to-event variability is not the only explanation, however. The helium energy range is considerably narrower in this study, 4-35 MeV/nuc vs. 0.3-80 MeV/nuc in the earlier study. The oxygen energy range extends to higher energies in this study, 8.5-76 MeV/nuc vs. 0.5-50 MeV/nuc in the earlier study. The iron energy ranges have little overlap, 13-140 MeV/nuc in this study vs. 0.3-

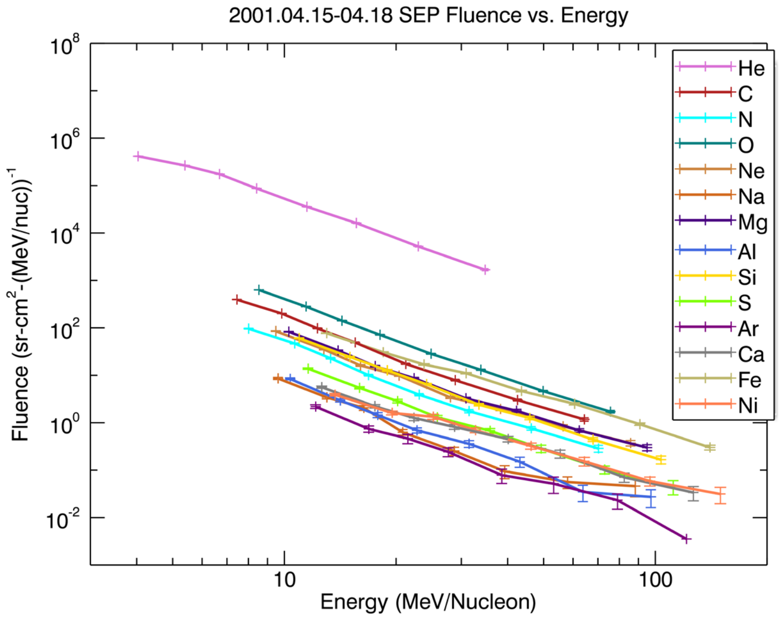

Figure 4. Heavy ion event-fluence spectra for the SEP event that commenced on April 15, 2001, as measured by ACE SIS. Error bars represent Poisson uncertainties. Over the SIS energy range, the spectra in this event appear to follow power laws.

30 MeV/nuc in the earlier study. These comparisons suggest that, while b is relatively insensitive to the energy range, estimation of the parameter β would benefit from inclusion of lower energy Level 2 fluxes from the Ultra-Low Energy Isotope Spectrometer (ULEIS) on ACE, which are available for helium-4, carbon, oxygen, neon-sulfur combined, and iron.

Percentile	25%	50%	75%
b, Species-Average			
Mazur et al. 1992	1.64	1.68	1.78
This Study	1.59	1.74	1.79
β, Helium			
Mazur et al. 1992	4.79	6.30	8.57
This Study	0.48	1.13	3.96
β, Oxygen			
Mazur et al. 1992	4.85	6.37	8.44
This Study	1.00	5.78	12.78
β, Iron			
Mazur et al. 1992	6.38	8.14	9.27
This Study	8.48	13.58	17.19

Table 2. Comparison of fit parameters b and β from this study with the results of Mazur et al. (1992).

4. HEAVY ION ABUNDANCES

The relative abundances of heavy ion species in SEP events have been studied extensively (e.g., Gloeckler, 1979; Reames, 1998; Cohen et al., 2005; Cane et al., 2006). Abundances are shown here in order to illustrate their variability from event to event, particularly that of iron. Abundances relative (to oxygen) in the 12-60 MeV/nuc range, calculated by integrating the three-parameter curve fits, are plotted in Figure 5 for all twenty-two SEP events analyzed here. Consistent with earlier results, the heavier elements, including iron, exhibit greater variability. Iron-to-oxygen ratios are often compared to the Reames (1998) average of 0.134 (in the 5-12 MeV/nuc range) for gradual SEP events. Figure 5 shows Fe/O ratios ranging from an order of magnitude above to an order of magnitude below this average, consistent with the results of Cane et al. (2006). This result underscores the importance of flying EHIS on GOES: heavy ion abundances cannot be predicted accurately from observations of solar energetic protons and alpha particles (helium-4), which are available from GOES 13-15 and prior series.

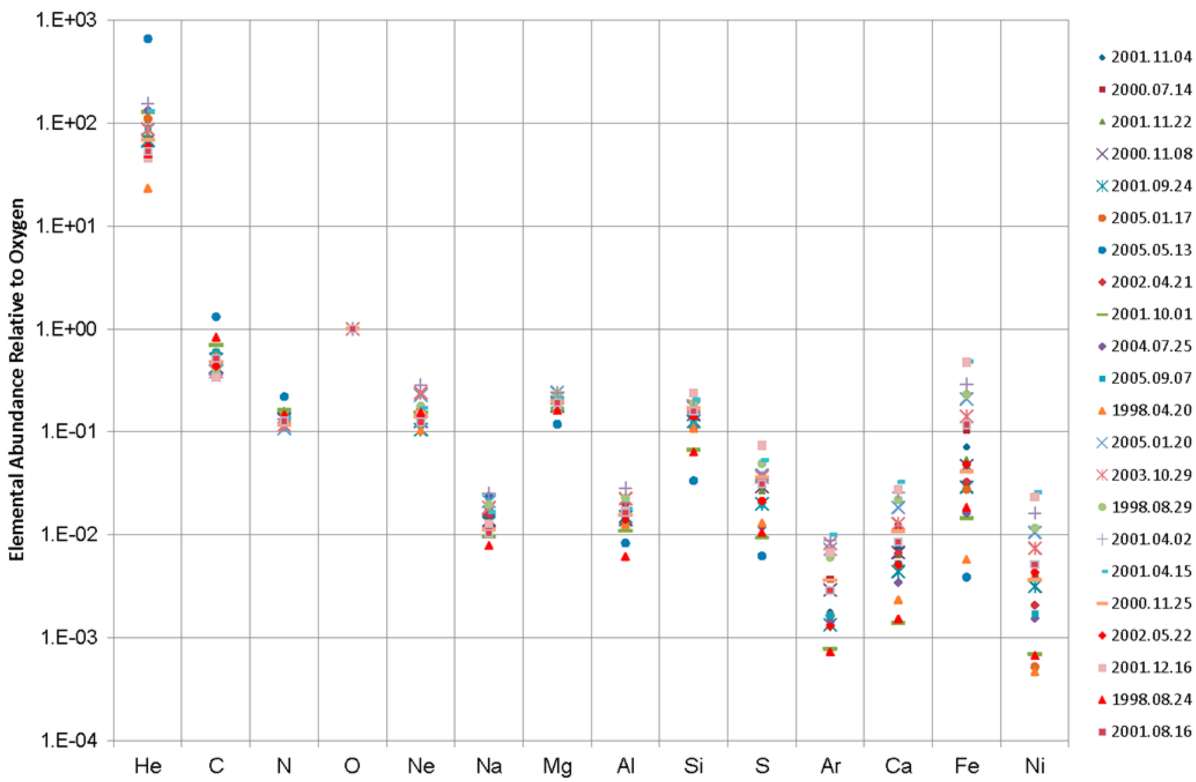

Figure 5. Abundances of heavy ion fluxes in the 12-60 MeV/nuc range relative to oxygen for the twenty-two SEP events from Solar Cycle 23 analyzed in this study.

5. SUMMARY AND FUTURE WORK

We have found that a three-parameter model derived from the physics of particle acceleration in a solar flare (Mazur et al., 1992) can fit well the majority of heavy ion spectra from twenty-two large solar energetic particle events during Solar Cycle 23. This data set, from ACE SIS, includes fourteen elements between helium and nickel, including iron which is of particular concern for causing single-event effects. These are the most abundant elements (apart from hydrogen) that will be measured by the GOES-R Energetic Heavy Ion Sensor (EHIS).

Several improvements to this proxy data set are possible, including: analyzing more large SEP events, including those in Solar Cycle 24; adding a power law to represent high energy tails; deriving a 1-hour data set in order to capture variability during individual events; and incorporating lower energy ACE ULEIS fluxes for several of the elements to test the robustness of the fit parameters. These proxy spectra can be run through an instrument model in order to simulate the effect of the geometrical factor on the observations at various cadences.

ACKNOWLEDGMENTS

Ranjeetha Bharath was supported during this work by a NOAA Hollings Undergraduate Scholarship. Other support was provided by the GOES-R Risk Reduction Program. We thank the SIS Team for producing the Level 2 fluxes and making them available via the ACE Science Center.

REFERENCES

Cane, H. V., R. A. Mewaldt, C. M. S. Cohen, T. T. von Rosenvinge, 2006: Role of flares and shocks in determining solar energetic particle abundances. *J. Geophys. Res., 111*, A06S90, doi:10.1029/2005JA011071.

Cohen, C. M. S., E. C. Stone, R. A. Mewaldt, R. A. Leske, A. C. Cummings, G. M. Mason, M. I. Desai, T. T. von Rosenvinge, M. E. Wiedenbeck , 2005: Heavy ion abundances and spectra from the large solar energetic particle events of October-November 2003. *J. Geophys. Res., 110,* A09S16, doi:10.1029/2005JA011004.

Gloeckler, G., 1979: Compositions of energetic particle populations in interplanetary space. *Rev. Geophys., 17*, 569-582.

Mazur, J. E., G. M. Mason, B. Klecker, R. E. McGuire, 1992: The energy spectra of solar flare hydrogen, helium, oxygen, and iron: evidence for stochastic acceleration. *Ap. J., 401*, 398-410.

Mewaldt, R. A., C. M. S. Cohen, A. W. Labrador, R. A. Leske, G. M. Mason, M. I. Desai, M. D. Looper, J. E. Mazur, R. S. Selesnick, D. K. Haggerty, 2005: Proton, helium, and electron spectra during the large solar particle events of October–November 2003. *J. Geophys. Res., 110,* A09S18, doi:10.1029/2005JA011038.

Press, W. H., B. P. Flannery, S. A. Teukolsky, W. T. Vetterling, 1988: *Numerical Recipes in C*

Reames, D. V., 1998: Solar energetic particles: Sampling coronal abundances. *Space Sci. Rev., 85*, 327-340.

Stone, E. C., et al., 1998: The Solar Isotope Spectrometer for the Advanced Composition Explorer. *Space Sci. Rev., 86,* 357-408.