



Quiet-time Spectra of Suprathermal Heavy Ions near 1 au in Solar Cycles 23 and 24

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Abstract

We report on the annual variation of quiet-time suprathermal heavy ion spectral indices for C through Fe in the energy range 0.3–1.28 MeV nuc^{-1} during Solar Cycle 23’s rising phase through Solar Cycle 24’s declining phase. These Advanced Composition Explorer/Ultra-Low Energy Isotope Spectrometer measurements cover 1998–2019. We show that the average quiet-time suprathermal spectral index across species is $\gamma = 2.5 \pm 0.3$. Such observations may imply that quiet-time suprathermals are the result of a superposition of various underlying acceleration and transport processes that accelerate suprathermal ions. As such, they may be remnants of particles from discrete events like large and impulsive solar energetic particle events along with corotating interaction regions that have decayed in intensity.

Unified Astronomy Thesaurus concepts: Solar energetic particles (1491); Solar wind (1534); Adaptive interferometry (19); Interplanetary particle acceleration (826); Heliosphere (711)

1. Introduction

Charged particles in the heliosphere cover more than 16 decades in intensity, ranging from thermal plasma at solar wind energies of below a few keV up to and above MeV for energetic particles (McComas et al. 2018). Between the solar wind and energetic particles lies the suprathermal population (i.e., a few keV to MeV). ³He from impulsive solar energetic particle events (ISEP; Hovestadt et al. 1984a, 1984b) and He⁺ interstellar pickup ions (Blum & Fahr 1970; Holzer & Axford 1971; Feldman et al. 1974; Möbius et al. 1995; Mason & Gloeckler 2012) in large graduate solar energetic particle events (GSEP; Mason et al. 1999; Desai & Mason 2001; Desai et al. 2006b), interplanetary shocks (IP shocks; Desai et al. 2003), and corotating interaction regions (CIRs; Chotoo et al. 2000; Wijsen et al. 2023) suggest that suprathermal material from a variety of sources including those listed (Desai et al. 2003, 2004, 2006a, 2006b, 2006c, 2007; Dayeh et al. 2009, 2016, 2017; Filwett et al. 2017, 2019) and the heated solar wind (Gloeckler 1999, 2003; Fisk & Gloeckler 2006, 2014) contribute to the seed population of these events.

While suprathermals are likely an energetic particle seed population, the mechanisms that produce these ions are yet to be determined. Broadly, suprathermal sources fall into two categories: continuous processes and discrete events. Continuous processes are present throughout the heliosphere, are always active, and energize solar wind ions, which contributes to the low-energy range of the suprathermal regime. Proposed mechanisms include compressional turbulence (Fisk & Gloeckler 2006, 2008, 2012, 2014; Gloeckler et al. 2008), velocity fluctuations (Fahr et al. 2012), and magnetic reconnection (Drake et al. 2013; Zank et al. 2014). Discrete events accelerate particles to high energies, with the lower-energy portion of this solar energetic particle (SEP) regime contributing to the suprathermal tail. The relevant

mechanisms are coronal mass ejection (CME) driven shocks (GSEP events; Jones & Ellison 1991; Reames 1999; Desai & Mason 2001; Desai et al. 2003, 2006c; Zank et al. 2006; Dayeh et al. 2009, 2017; Mewaldt et al. 2012; Kahler & Ling 2019; Lario et al. 2019), ISEP events (Mason et al. 2002, 2016), and CIRs (Fisk & Lee 1980; Richardson 2004; Desai et al. 2006c; Mason et al. 2008; Dayeh et al. 2009, 2017; Zeldovich et al. 2011, 2018, 2021; Ebert et al. 2012; Allen et al. 2019). For a summary of known sources and acceleration mechanisms, see Desai & Giacalone (2016, Table 2).

Suprathermal tails behave like power laws. The continuous mechanism lead to tails that scale as v^{-5} or, equivalently, $E^{-1.5}$. Such a power-law index may imply that (1) suprathermals are the superposition of various underlying states that collectively behave like an ideal gas with a polytropic index 5/3 (Schwadron et al. 2010), (2) the stationary state characterizing suprathermal ions requires a fixed inner boundary with a free escape outer boundary (Zhang 2010; Antekci et al. 2013), (3) suprathermals are generated by Coulomb interactions (Randol & Christian 2014), or (4) acceleration of particles to suprathermal energies is due to a compressional process (Fisk & Gloeckler 2006, 2008, 2012, 2014; Gloeckler et al. 2008). Jokipii & Lee (2010) argue that, when compressional models account for particle conservation, they cannot produce spectra steeper than v^{-3} or E^{-1} . Rather, they argue that “the quiet-time suprathermal ion population is composed predominantly of remnant ions from these events (GSEP events and CIRs) as well as a contribution from impulsive SEP events (Jokipii & Lee 2010).”

Quiet times are periods without particle enhancements related to the discrete processes like CME-driven shocks, solar flares, and CIRs. They are also intervals when the local, continuous mechanisms are minimally active (Gloeckler 2003). Observations by Desai et al. (2006c), Dayeh et al. (2009, 2017), and Alterman et al. (2023) of abundances and spectra support the inference of Jokipii & Lee (2010) that suprathermals are remnants of higher-energy events. These observations suggest that the dominant discrete acceleration mechanism changes with solar activity. During solar maxima, it



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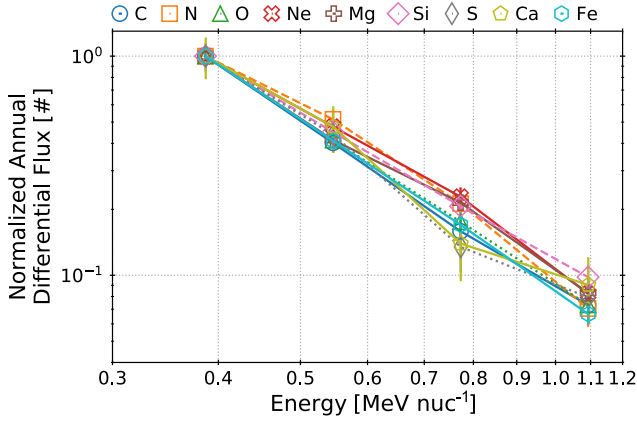


Figure 1. Examples of spectra from the year 2004 for all species normalized to their lowest energy value. Points are connected to aid the eye.

is likely CME-driven shocks with flares contributing at higher energies. During solar minima, CIRs are likely the dominant suprathermal source (Allen et al. 2019; Alterman et al. 2023). These processes lead to spectral indices in the range ~ 1.5 to ~ 3.0 (Dayeh et al. 2017), which is softer than that cited for the continuous processes. However, these studies typically focus on higher energies than those for which the local, continuous processes are active (Desai et al. 2016, Figure 2).

This study utilizes Advanced Composition Explorer (ACE; Stone et al. 1998) observations from the Ultra Low Energy Ion Spectrometer (ULEIS; Mason et al. 1998) to characterize the spectral index of suprathermal ions in quiet times. Our observations cover the years 1998–2019, which covers Solar Cycle 23’s rising phase through Solar Cycle 24’s declining phase, and the energy range $0.3\text{--}1.28\text{ MeV nuc}^{-1}$. We show that the typical quiet-time spectral index across species and solar activity is $\gamma = 2.5 \pm 0.3$.

2. Observations

We use Alterman et al.’s (2023) definition of quiet times. Alterman et al. (2023, Figures 1 and 2) calculate the 24 hr mean and variance of the cumulative C to Fe intensity when sorted by increasing intensity. They identify quiet times based on an inflection in this variance plotted as a function of the mean. This criterion is distinctive from Dayeh et al.’s (2017) in that Alterman et al. (2023) use nonlinear fitting to identify this inflection point whereas Dayeh et al. (2017) identify the inflection based on manual inspection of the data. We use Alterman et al.’s (2023) criterion because their results are not very sensitive to small changes in the threshold they derive. Selecting for quiet times ensures that our observations are not dominated by discrete events and allows us to study suprathermals in the absence of enhancements due to discrete events like CMEs, shocks, CIRs, and other SEP events (Dayeh et al. 2017).

Figure 1 plots the annual differential energy spectra of all species during quiet times in 2004 over the energy range of $0.3\text{--}1.28\text{ MeV nuc}^{-1}$. To facilitate comparison of the spectral shapes, each species’s spectrum is normalized to its lowest energy data point. Data points are connected to aid the eye. All spectra exhibit power-law behavior of the form $j \propto E^{-\gamma}$, with no spectral breaks or rollovers in this energy range. The

spectra for 2004 are representative of the behavior in other years.

We have performed weighted least-squares power-law fits to the spectra for all species in each year. Table 1 contains the annual spectral indices for each species along with the uncertainties from their fits. Missing entries in the table indicate fits that failed to converge. There are insufficient quiet-time Ca counts in 2008 to resolve a discernible Ca peak and so Ca in 2008 is excluded our analysis. To characterize the variation of the spectra with time, Figure 2 plots the oxygen spectral index as a function of time. The right-hand axis plots the annual sunspot number (SSN; SILSO World Data Center 2023) for reference. All observations are plotted at the middle of the year. In general, the oxygen spectral index $\gamma_{\text{O}} \sim 2.5$. As shown below, the spectral indices for all species are distributed around this value. Therefore, we plot the minimum and maximum spectral index across all species as error bars. Years without a marker indicate years when the oxygen fit did not converge. Per Table 1, only Ne and Si return meaningful spectral indices in 2009 and, as such, this year should be interpreted with the appropriate caution. During solar minima, count rates are markedly lower and fewer fits converge. We calculate the correlation and rank correlation coefficients between each spectral index and SSN. Only the correlation coefficients of γ_{Ne} and γ_{Ca} indicate a significant relationship to SSN (p -value < 0.05). In the case of Ca, the rank coefficient is 0.58 with a p -value of 0.03. Ne’s rank coefficient is -0.49 with a p -value of 0.02.

Figure 3 plots the spectral indices of carbon (γ_{C} , circles) and iron (γ_{Fe} , triangles) as a function of the oxygen spectral index (γ_{O}). Carbon and iron are chosen because they provide the largest difference in M/Q (Reames et al. 1994; Mason et al. 2004; Alterman et al. 2023). The diagonal black dotted line indicates unity. In general, both carbon and iron are organized along the diagonal with iron showing more scatter than carbon. The correlation coefficient between carbon and oxygen $\rho(\gamma_{\text{C}}, \gamma_{\text{O}}) = 0.93$ is significant (p -value < 0.05), while the coefficient between iron and oxygen $\rho(\gamma_{\text{Fe}}, \gamma_{\text{O}}) = 0.51$ is not (p -value > 0.05). However, it is worth noting that if we exclude the two γ_{Fe} for which the uncertainty is > 0.1 the correlation coefficient increases to 0.67 with a p -value < 0.008 . These two spectra are from the declining phase of Solar Cycle 23 and have low counts at in higher-energy bins. The bottom of Table 1 also includes the correlation coefficients between each species’s spectral indices and oxygen’s, the coefficient’s p -value, and the number of observations in the coefficient calculation. In general, Su and Si similarly show significant scatter as a function of O.

In addition to all γ , Table 1 includes the weighted mean of each species’s spectral index with the standard error of the weighted mean as it is uncertainty along with the standard deviation for each species. In general, the spectral index across species and over the 1998–2019 period is $\gamma = 2.5$ with a standard deviation of 0.3. Figure 4 is a stacked histogram of all species spectral indices. The legend gives the order in which the species are stacked with carbon on the bottom and iron on the top. The figure’s abscissa is constrained to the same range as Figure 3 and excludes the few extreme values. The white circle at the bottom of the figure indicates the distribution’s mean; error bars are the standard deviation. The median across γ for all years is 2.4 ± 0.2 .

Table 1
Annual Quiet-time Spectral Indices over the Energy Range 0.3–1.28 MeV nuc⁻¹

	C	N	O	Ne	Mg	Si	S	Ca	Fe
1998	2.64 ± 0.08	2.37 ± 0.07	2.57 ± 0.06	2.56 ± 0.08	2.83 ± 0.06	2.23 ± 0.14	2.13 ± 0.12	...	...
1999	2.84 ± 0.07	2.4 ± 0.06	2.69 ± 0.03	2.54 ± 0.03	2.74 ± 0.05	2.69 ± 0.03	2.59 ± 0.09	...	2.57 ± 0.03
2000	...	2.05 ± 0.07	2.25 ± 0.07	2.22 ± 0.05	2.32 ± 0.06	2.42 ± 0.05	2.79 ± 0.08	3.49 ± 0.08	2.44 ± 0.04
2001	2.52 ± 0.09	2.4 ± 0.12	2.44 ± 0.03	2.37 ± 0.07	2.32 ± 0.07	2.61 ± 0.05	...	2.57 ± 0.34	2.56 ± 0.02
2002	2.64 ± 0.06	2.43 ± 0.06	2.46 ± 0.03	2.37 ± 0.11	...	2.41 ± 0.04	2.32 ± 0.09	3.43 ± 0.12	2.48 ± 0.01
2003	2.24 ± 0.09	...	2.33 ± 0.03	2.16 ± 0.02	...	2.51 ± 0.05	2.89 ± 0.11	2.62 ± 0.14	2.43 ± 0.05
2004	2.63 ± 0.06	2.25 ± 0.11	2.51 ± 0.01	2.16 ± 0.13	2.39 ± 0.05	2.26 ± 0.03	2.45 ± 0.1	2.33 ± 0.14	2.58 ± 0.04
2005	2.24 ± 0.03	1.96 ± 0.08	2.17 ± 0.02	2.21 ± 0.01	2.23 ± 0.03	2.2 ± 0.07	2.32 ± 0.07	2.03 ± 0.14	2.23 ± 0.05
2006	...	2.59 ± 0.1	2.83 ± 0.02	2.99 ± 0.07	2.72 ± 0.11	2.47 ± 0.21	2.66 ± 0.1	2.04 ± 0.15	2.59 ± 0.1
2007	2.81 ± 0.04	2.55 ± 0.09	2.69 ± 0.05	2.61 ± 0.02	2.67 ± 0.18	...	...	2.18 ± 0.28	...
2008	2.29 ± 0.07	2.3 ± 0.08	2.33 ± 0.04	2.43 ± 0.1	...	...	...	...	2.78 ± 0.13
2009	...	...	...	3.45 ± 0.05	...	3.06 ± 0.18	...	...	...
2010	...	2.51 ± 0.07	2.6 ± 0.02	2.52 ± 0.04	2.5 ± 0.05	2.37 ± 0.11	1.97 ± 0.28	...	...
2011	2.6 ± 0.07	2.41 ± 0.1	2.58 ± 0.02	2.55 ± 0.05	2.44 ± 0.04	2.47 ± 0.05	2.65 ± 0.17	2.06 ± 0.15	2.55 ± 0.04
2012	2.47 ± 0.04	2.35 ± 0.09	2.46 ± 0.02	2.46 ± 0.07	2.47 ± 0.06	2.35 ± 0.04	2.45 ± 0.08	2.2 ± 0.08	2.43 ± 0.05
2013	2.74 ± 0.05	2.45 ± 0.03	2.6 ± 0.02	2.36 ± 0.05	...	2.38 ± 0.04	...	2.04 ± 0.18	2.44 ± 0.04
2014	2.32 ± 0.05	2.43 ± 0.08	2.39 ± 0.03	2.39 ± 0.05	2.46 ± 0.06	2.13 ± 0.03	2.53 ± 0.08	3.51 ± 0.5	2.37 ± 0.03
2015	...	2.44 ± 0.09	2.57 ± 0.06	2.44 ± 0.04	2.55 ± 0.07	2.67 ± 0.07	2.34 ± 0.17	...	...
2016	2.19 ± 0.02	2.12 ± 0.05	2.24 ± 0.03	2.14 ± 0.03	...	...	...	...	2.54 ± 0.05
2017	2.29 ± 0.04	1.91 ± 0.06	2.27 ± 0.02	2.39 ± 0.09	2.16 ± 0.04	2.14 ± 0.07	...	2.72 ± 0.28	2.31 ± 0.06
2018	3.1 ± 0.05	2.51 ± 0.01	2.79 ± 0.04	2.55 ± 0.17	2.6 ± 0.19	...	...	2.05 ± 0.26	...
2019	3.1 ± 0.08	2.82 ± 0.07	...	2.67 ± 0.18	2.78 ± 0.12	...	2.13 ± 0.13	...	...
W. Mean	2.5 ± 0.01	2.487 ± 0.006	2.487 ± 0.005	2.352 ± 0.007	2.43 ± 0.01	2.40 ± 0.01	2.50 ± 0.03	2.63 ± 0.04	2.488 ± 0.008
STD	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.6	0.1
Corr.	0.93	0.8	...	0.74	0.81	0.37	-0.08	-0.5	0.51 ^a
<i>p</i> -value	2 × 10 ⁻⁴	4 × 10 ⁻⁴	...	2 × 10 ⁻⁴	6 × 10 ⁻⁴	0.1	0.8	0.08	0.06 ^a
N	16	19	20	20	15	16	13	14	15

Notes. The average value (W. Mean) is the weighted mean of the converging fits with the standard error of the mean as the uncertainty. The standard deviation (STD) gives the variability of the spectral indices. The overall mean is $\gamma = 2.5 \pm 0.3$. We also include each species' spearman rank correlation coefficient with oxygen (Corr.), the *p*-value, and number of observations in the coefficient (*N*). Missing γ are from fits that failed to converge or, in the case of Ca in 2008, for which there was no discernible peak in the mass histogram.

^a If γ_{Fe} is excluded when the uncertainty is >0.1 , $\rho(\gamma_{\text{Fe}}, \gamma_{\text{O}}) = 0.67$ and the *p*-value = 0.008.

3. Discussion

Suprathermal ions suffuse the heliosphere (Tsurutani & Lin 1985; Desai et al. 2003; Wiedenbeck 2003). Although their intensities vary with solar activity, they are continuously present throughout the solar cycle (Desai et al. 2006c; Dayeh et al. 2009, 2017; Zeldovich et al. 2011, 2018, 2021; Alterman et al. 2023). Broadly, there are two types of processes that produce suprathermals. In the continuous class, processes like bulk velocity fluctuations, compressional turbulence, magnetic field waves and turbulence, and reconnection between magnetic islands continuously accelerate charged particles. In the discrete case, there are CME-driven shocks (GSEP events), flare related SEPs (ISEP events), and CIRs. See Desai et al. (2016a, Table 1) for references.

A suprathermal ion's history includes a combination of its origin, acceleration, and transport. Desai et al. (2006c), Dayeh et al. (2009, 2017), and Alterman et al. (2023) address how suprathermal ion origins change with solar activity. While this work does not consider origin, spectral indices carry the imprint of acceleration and transport processes.

Figure 1 reveals that the quiet-time suprathermal spectra in the observed energy range are power laws in energy and that their shape does not depend on species. The lack of rollover is unsurprising because our observations cover a limited energy range above where this rollover is usually observed (Desai et al. 2016, Figure 2). Therefore, quiet-time suprathermal

spectra indices in the 0.3–1.28 MeV nuc⁻¹ energy range are independent of M/Q. However, we must note that aggregating quiet-time observations into annual bins may obscure small but varying spectral breaks or those that are specific to individual events. As such, individual events must be analyzed to characterize if such behavior is universal to all events.

Figure 2 and Table 1 show that, due to low solar activity in the minimum of Solar Cycle 24 and corresponding lower suprathermal intensities, there are fewer years with statistically significant quiet time γ . More quantitatively, all but two species' spectral index γ do not have a significant correlation coefficient (ρ) with SSN. We consider a strong correlation coefficient to be $|\rho| \geq 0.6$ and require a *p*-value < 0.05 for statistical significance. The two species with significant *p*-values are moderately correlated with SSN at best ($|\rho| < 0.6$), which is insufficient to draw a conclusion. From this, we infer that the suprathermal γ in the reported energy range is independent of solar activity, which is consistent with Dayeh et al. (2017).

Figure 3 and Table 1 shows that some species γ have a statistically significant correlation with γ_{O} . However, there is no systematic organization for these correlations and the year-to-year variations in γ between species are all similar.

The stacked histogram in Figure 4 shows that quiet-time suprathermal spectral indices across all species from 1998 to 2019 are distributed around a central value. Table 1 includes

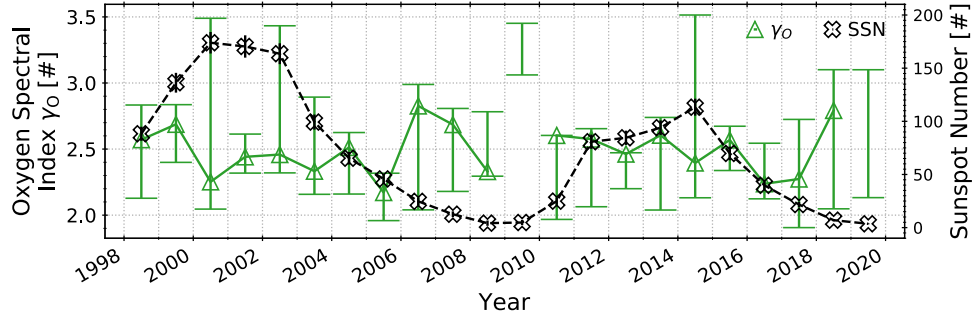


Figure 2. Annual oxygen spectral indices (triangles, left). Error bars are the minimum and maximum spectral index observed across all species. Annual sunspot number is plotted on the right (Xs) for reference.

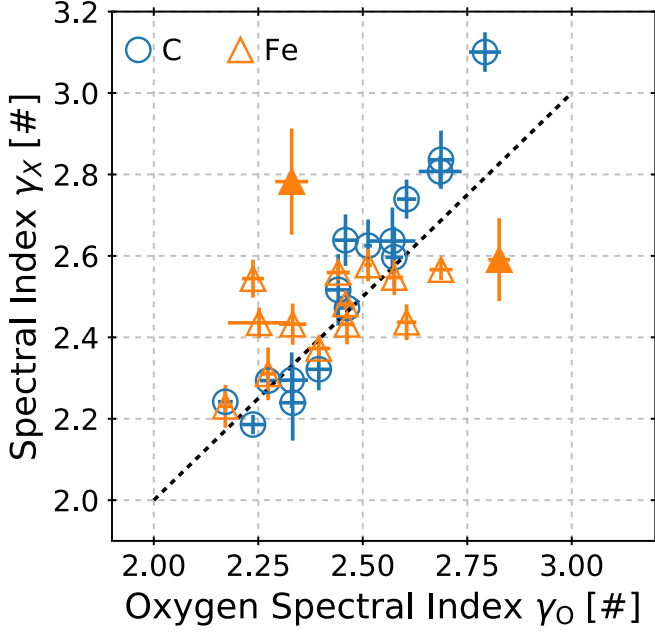


Figure 3. Carbon and iron spectral indices as a function of oxygen spectral index. The dotted line indicates unity. The two filled triangles indicate γ_{Fe} for which the uncertainty is ≥ 0.1 .

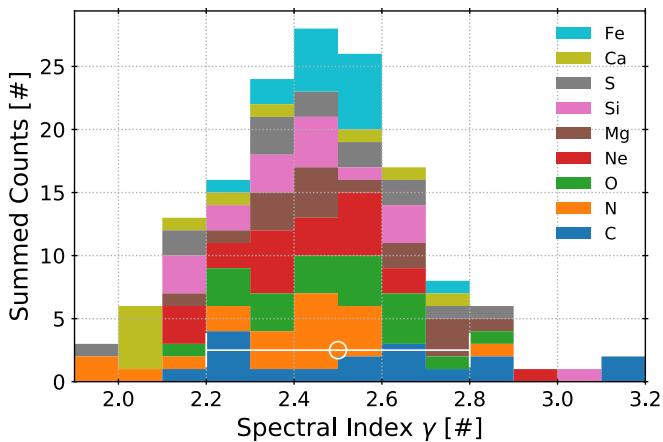


Figure 4. A stacked histogram of the observed spectral indices. The legend indicates the species added to the histogram and is organized such that species included can be read from bottom to top through the legend. The mean of the distribution (2.5) is given as a white circle and the error bars show the standard deviation (0.3).

the weighted mean of each species's γ across the period of observation. The weighted mean of these average γ is $\gamma = 2.5$ with a standard error of the weighted mean (SEM) of 0.08. The

average of all γ , irrespective of species, is $\gamma = 2.5$ with a standard deviation of 0.3. Figure 4 takes $\gamma = 2.5 \pm 0.3$ as the typical value and plots it as a white circle with error bars.

The spectral index predicted for most continuous processes is $E^{-1.5}$ or v^{-5} (Fisk & Gloeckler 2006, 2008, 2012, 2014; Gloeckler et al. 2008; Schwadron et al. 2010; Zhang 2010; Anteki et al. 2013). Our reported γ in the energy range 0.3–1.28 MeV nuc^{-1} is steeper than this. Schwadron et al. (2010) assume that observed suprathermal ions are a superposition of Gaussian distributions of different temperatures and densities averaged over long time periods. The exact form of the observed spectra depends on the constraints on the underlying Gaussian distributions during unspecified acceleration processes for which the occurrence rate of the acceleration is proportional to $1/T$, for temperature T . For suprathermals scaling as $E^{-2.5}$ or v^{-7} , the constraints are that density and internal energy per unit volume of the accelerated particles are constant and therefore pressure fluctuations are proportional to temperature fluctuations. Such heating is inconsistent with Fisk & Gloeckler's (2006) theory and weaker than what would result from strong compressive fluctuations or other active heating processes (Schwadron et al. 2010).

4. Conclusion

Quiet times are periods when particle enhancements due to discrete processes like CME-driven shocks, solar flares, and CIRs are absent and enhancement due to continuous acceleration processes are minimal (Gloeckler 2003). As such our observations do not directly address the acceleration processes nor the transport effects themselves. Desai et al. (2006c), Dayeh et al. (2009, 2017), and Alterman et al. (2023) demonstrated that suprathermal abundances are most similar to CIRs during solar minima and GSEP events during solar maxima, with a minor contribution from ISEP events at higher energies. We observe that the quiet-time suprathermal spectral index in the energy range 0.3–1.28 MeV nuc^{-1} is $\gamma = 2.5 \pm 0.3$, irrespective of solar activity. We infer that the combined effect of acceleration history and transport processes on suprathermal ions are also independent of solar activity, even if each process or its occurrence rate separately depends on solar activity. Such an interpretation is consistent with arguments that suprathermal spectra are the result of the superposition or average of Gaussian distributions over long time periods under the constraint that the density of the underlying distributions are constant (Schwadron et al. 2010). This constant density requirement implies that pressure fluctuations are proportional to temperature, inconsistent with Fisk & Gloeckler's (2006) theory,

and weaker than what would be expected from strong heating due to compressive fluctuations or other mechanisms (Schwadron et al. 2010). Such a superposition of various, possibly changing underlying distributions does not contradict the prediction that suprathermal intensities decay following discrete acceleration events and therefore are remnants of them (Jokipii & Lee 2010).

There is one caveat to this discussion that must be addressed. The compressional heating theories are derived based, primarily, on observations from ACE's Solar Wind Ion Composition Spectrometer (SWICS; Gloeckler et al. 1998, 2008; Fisk & Gloeckler 2006, 2008, 2012, 2014). SWICS's energy range is 0.49 keV e^{-1} to 100.0 keV e^{-1} for elements heavier than He and 0.11 keV e^{-1} to 15.05 keV e^{-1} for He and H, which are below ULEIS's energy range and the $0.3\text{--}1.28 \text{ MeV nuc}^{-1}$ range on which this Letter reports. In other words, the analysis presented here does not rule out the existence of a spectral rollover below ULEIS's energy ranges. As such, this analysis is agnostic to whether the identified suprathermal $\gamma = 2.5 \pm 0.3$ is universal across all energy ranges or limited to the higher-energy range of the suprathermal regime from 0.3 to $1.28 \text{ MeV nuc}^{-1}$.

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