Differential Behaviors of Suprathermal $^4$He and Fe Populations in the Interplanetary Medium during Solar Cycle 24

Bijoy Dalal$^{1,2}$, D. Chakrabarty$^1$, and N. Srivastava$^3$

$^1$Physical Research Laboratory, Ahmedabad—380009, India; bijoydalal.at@gmail.com
$^2$Indian Institute of Technology Gandhinagar, Gandhinagar—382055, India
$^3$Udaipur Solar Observatory, Physical Research Laboratory, Udaipur—313001, India

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Abstract

Investigations on the solar cycle variation of the properties of suprathermal populations (H and other heavy ions like $^3$He, $^3$He, C, O, and Fe) in the solar wind are sparse and hence poorly understood. In the present investigation, solar cycle variations of “quiet” time suprathermal elements are investigated using $<\sim 1$ MeV n$^{-1}$ particle flux data obtained from the Ultra-Low Energy Isotope Spectrometer on board the Advanced Composition Explorer satellite during solar cycles 23 and 24. The analysis reveals that helium ($^4$He) shows zero or positive lags with respect to sunspot numbers in solar cycle 23 while it shows zero or negative lag in solar cycle 24. On the contrary, although iron (Fe) shows a zero or positive lag in cycle 23 similar to $^3$He, it shows only a zero lag in cycle 24 and no negative lag is seen. Further, significant differences in the spectral indices are seen between $^4$He and Fe in cycle 24 compared to cycle 23. These results suggest that generation mechanisms responsible for suprathermal $^4$He and Fe underwent changes in cycle 24 and these mechanisms are probably dependent on the first ionization potential and mass-to-charge ratio. This proposition gets credence from the fact that changes in the lags and spectral slopes for C and O are not significantly different in cycles 23 and 24.

Unified Astronomy Thesaurus concepts: Solar energetic particles (1491); Corotating streams (314); Solar wind (1534); Solar coronal mass ejections (310)

1. Introduction

Suprathermal particles with energies from $\sim 10$ keV per nucleon (keV n$^{-1}$) to $\sim 1$ MeV per nucleon (MeV n$^{-1}$) are thought to act as seed populations for further acceleration by interplanetary (IP) shocks associated with solar eruptive events like coronal mass ejections (CMEs) (Gosling et al. 1981; Desai et al. 2003, 2004 etc.) and corotating interaction regions (CIRs) (e.g., Fisk & Lee 1980; Chotoo et al. 2000; Allen et al. 2019). The two most widely known acceleration mechanisms, namely first-order Fermi acceleration (or diffusive shock acceleration) (Krymskii 1977; Bell 1978 etc.) and the second-order Fermi acceleration (Fermi 1949), necessitate the initial presence of suprathermal particles in the acceleration framework. Energetic protons as well as heavy ions from $^3$He to Fe and beyond constitute the suprathermal ion pool in the IP medium. Compositional abundance studies reveal that possible sources of the suprathermal ion pool include solar wind ions (Desai et al. 2003), particles associated with previously occurred transient events (Fisk & Lee 1980; Giacalone et al. 2002 etc.), and interstellar pick-up ions (Allen et al. 2019). In general, a dominant contribution from pick-up ions in the suprathermal populations is observed beyond 1 au (Fisk 1976). Suprathermal particles exhibit a power-law distribution, also known as a “quiet” time tail, when the velocity distribution function (differential directional flux) is plotted against velocity (energy). Often, a spectral index of $\sim -5$ ($\sim -1.5$) (Fisk & Gloeckler 2006, 2007) has been reported in the past regardless of the species considered. In this work, the spectral index of the differential flux versus energy convention ($\sim -1.5$) is chosen.
studying the relative abundances of “quiet” time suprathermal ions at 1 au, Kecskemety et al. (2011) found out that during solar cycle minima, the suprathermal Fe/O ratio resembles the corresponding ratio in the solar wind. These results were supported later on by Dayeh et al. (2017), in which the solar cycle dependence of suprathermal C/O, Fe/O, and $^3$He/$^4$He with very strong correlations with the yearly averaged sunspot number (SSN) were reported. They argued that suprathermal particles are transported from remote places during “quiet” times and are accelerated locally. Regardless of the acceleration process involved, it is expected that during the course of transport of suprathermal particles through the IP medium, the particles may show a systematic time delay with solar activity proxies (for example, SSN) and this may provide important clues for understanding the source of these particle populations. Although indicated in a few earlier works (e.g., Mason et al. 2012; Allen et al. 2019) detailed investigations on these time delays are sparse. Further, comparison of these time delays and spectral indices for various elements for multiple solar cycles may lead to new insights related to the role of solar/IP processes for the generation of these particles. Keeping these issues in mind, the suprathermal particle flux data from the Ultra-Low Energy Isotope Spectrometer (ULEIS) (Mason et al. 1998) on board the Advanced Composition Explorer (ACE) (Stone et al. 1998) for solar cycles 23 and 24 (henceforth, SC23 and SC24, respectively) have been extensively analysed and the results are presented in the present work. The results reveal important differences between SC23 and SC24 as far as the above aspects are concerned.

2. Data Set

ACE is a spin-stabilized spacecraft revolving around Lagrangian point L1 of the Sun–Earth system in a halo orbit. In this work, one-hour-integrated differential directional flux (level 2) data corresponding to different energy channels for H, $^3$He, $^4$He, O, C, and Fe from 1998 March 1 to 2020 August 31 obtained by ULEIS on board ACE are used. ULEIS is a time of flight mass spectrometer, which measures the time of flight ($\tau$) and deposited energy (E) of isotopes with $Z = 2$–28. Using the measured $\tau$ and corrected energy (see Mason et al. 1998 for details), the mass (M) of the isotope is determined. The uncertainties in the energy measurements of ULEIS may affect mass separation near the low-energy threshold in the presence of significant noise (see Mason et al. 1998 and references cited therein). This problem is particularly relevant for $^3$He and $^4$He. Nevertheless, we have avoided using low-energy (<100 keV n$^{-1}$) channels for all the elements in our investigation. The data set spans almost 22 yr covering SC23 and SC24 and is available at https://cdaweb.gsfc.nasa.gov/index.html. A list of CIR events identified based on the measurements at the L1 point and reported by Allen et al. (2019), is also used to remove the concomitant enhancements in the suprathermal flux associated with CIR events. In addition, as stated in the next section, we also remove any other transient event that causes enhancements in the suprathermal flux. We have termed these events as “non-CIR” transient events. This step leads to a time series corresponding to “quiet” time. Here “quiet” is put inside the inverted commas as we will argue later that in either case—whether it is exhaustive removal of the transient events or removal of transient events based on a cut off flux level—the propagation of the suprathermal flux from the transient events (CIRs, interplanetary coronal mass ejections (ICMEs)) into the “quiet” time suprathermal ion pool cannot be completely eliminated in presence of a significant lag with the SSN. We will come back to this point later on in more detail. The daily averaged SSN data are available at http://www.sidc.be/silso/datafiles.

3. Selection of Quiet Periods, Sensitivity Analyses, and Validation

As indicated in the previous section, the data set used in the present work pertains to periods devoid of transient events (e.g., CIR and any other non-CIR events) that cause enhancements in the suprathermal flux. From the entire data set spanning over 22 yr, it is noted that transient CIR or non-CIR events take flux levels much higher than the background flux level encountered at other times. Therefore, these transient flux variations are apparently easy to remove by choosing a threshold flux level (e.g., Kecskemety et al. 2011). However, in the present work, we do not initially choose any cut off flux level as a reference level to remove transient events. Rather, we remove the flux variations associated with these transient variations in totality (from base flux level to peak flux level) so that the propagation of the peak flux into the “quiet” time flux is minimized significantly. It is possible that some minor transient injections will remain in the time series even after doing this. Therefore, we also perform detailed sensitivity analyses and cross check critically to show that the results obtained through present analysis procedure (no cut off level, removal of transient events) remains nearly unchanged with those obtained with four different cut off flux levels (much lower than the peak levels of the transient injection events from base to peak levels). Note, at least two of these cut off levels are below the lowest flux level encountered during solar minima (between SC23 and SC24) in the original time series. We also subject these to sensitivity analyses for different averaging windows (in days). These detailed sensitivity analyses with different cut off levels and averaging windows are provided as supplementary Figures A1–A12. It is found that the correlation coefficients and the lags, thus derived, between the suprathermal fluxes for each element (at different energy channels) and the SSN remain nearly invariant for different choices of cut off levels and averaging windows. Therefore, we will not discuss this point subsequently in this paper.

We now come back to the methodology adopted in this work. This aspect is illustrated in Figure 1. Figures 1(a) and 1(b) show the variations in the proton fluxes for the original and “quiet” (after removal of the transient events from base to peak) data set, respectively, from 2007 June 2 to August 3. Different colors correspond to different energy channels. The mean of the upper and lower limits of each energy channel is taken to represent (legend) the corresponding energy channel. During the representative interval shown in Figure 1, there was one CIR event (according to Allen et al. 2019), the start and end times of which are marked in red and blue vertical dashed lines, respectively. The other transient events are termed as “non-CIR transient events” and no attempt is made here to characterize those events. Figures 1(c) and 1(d) respectively show the original and corresponding “quiet” time fluxes of $^4$He at various energy channels during the same time interval as that of H. It is to be noted that durations of transient events removed from the time series of $^4$He may be different from those removed from the H time series. This is because of the fact that the enhancement and depletion of different elements at the
measurement location are not simultaneous in many cases (Reames 2018). Considering this important aspect, we have removed the transient events for each element manually. The complete exclusion of the transient events for the whole duration of the data set for each element under consideration is shown in Figure 2. The daily averaged SSN data are shown in Figure 2(a). Please note that detailed correlation analyses of this SSN time series are performed with the elemental flux time series using different averaging windows. These aspects are discussed in Figures 3–5 and in Figures A1–A12. In Figure 2, subplots (b), (d), (f), (h), (j), and (l) show the temporal variations of the suprathermal H, ³He, ⁴He, Fe, C, and O fluxes,
respectively. The corresponding “quiet” time fluxes are shown in subplots (b) and (c), respectively. The scatter plots in subplots (d) and (e) represent variations of the averaged and adjusted ³He fluxes with respect to the SSN in SC23 and SC24, respectively (see the text for details). Pearson’s correlation coefficient (R) between flux and SSN and corresponding p values are mentioned at the bottom of panels (d) and (e).

Figure 3. Panel (a) shows typical variations of the 370 day averaged ⁴He flux (black) corresponding to 0.55 MeV n⁻¹ (mentioned at the right corner) and SSN (red). Variations of the normalized cross-correlation coefficients between the ²He flux and SSN with respect to the lags (in multiples of 370 days) for SC23 and SC24 are shown in subplots (b) and (c), respectively. The scatter plots in subplots (d) and (e) represent variations of the averaged and adjusted ⁴He fluxes with respect to the SSN in SC23 and SC24, respectively (see the text for details). Pearson’s correlation coefficient (R) between flux and SSN and corresponding p values are mentioned at the bottom of panels (d) and (e).

4. Results

4.1. Correlation Coefficients and Lags with the Variations in the SSN in SC23 and SC24

Correlations between the “quiet” suprathermal fluxes and SSN during SC23 and SC24 are investigated in this section. Fluxes of different particles at different energy channels and SSN have been subjected to averaging over 240 days to 400 days in steps of 10 days. In each such step, the maximum cross-correlation coefficient and corresponding lag between the flux and SSN is determined. In order to get an idea about the significance of these correlations, we use these lags, apply them to the time series data, and calculate the Pearson’s correlation coefficient (CCs) and corresponding p values (probability of acceptance of the null hypothesis that these correlations are occurring by chance) between the lagged fluxes and SSN. The method adopted in this work to compute CCs and lags is depicted in Figure 3. Figure 3(a) shows typical variations of the 370 day averaged ⁴He flux with energy 0.55 MeV n⁻¹ and SSN for SC23 and SC24. In each case, the SSN variation is subjected to positive and negative lags with respect to the flux variation to maximize the cross-correlation coefficient. The results obtained by this method for SC23 and SC24 are shown in Figures 3(b) and 3(c), respectively. The lags corresponding
to the maximum cross-correlation coefficients (marked by vertical red dotted–dashed lines) are considered as the lags of interest. A positive lag value indicates that the flux variation lags the SSN variation. On the other hand, a negative lag reveals that the flux variation leads the SSN variation, which essentially means that the increase in flux has started earlier than the increase in SSN. The above two scenarios are clear from Figures 3(b) and 3(c), respectively. It can be seen that the 370 day averaged \( \text{He} \) flux lags the SSN variation in SC23 by 370 days and leads it in SC24 by the same number of days. Once the lag is noted, the flux variation is adjusted for the lag, and then Pearson’s CC and the corresponding \( p \) value are estimated. Figures 3(d) and 3(e) show Pearson’s CCs and \( p \) values for SC23 and SC24, respectively. Note, in both the cases Pearson’s CC (R) is higher than 0.8 and the \( p \) values are <0.05, which indicate that these high correlations are real.

Figure 4 shows the variations of Pearson’s CCs with respect to the averaging window during SC23 and SC24 for various elements. Every vertical pair of subplots in this figure corresponds to the variations of Pearson’s CCs of an element in SC23 and SC24. It can be seen from Figure 4 that the CC values corresponding to any particular energy channel of any element do not vary significantly depending on the averaging windows. In most of the cases it is observed that \( p < 0.05 \).

Variations of the lags corresponding to each point in Figure 4 are shown in Figure 5. Some interesting outcomes from this figure are discussed in the following part of this section. "Quiet" time suprathermal H at L1 point does not show any noticeable time delay with respect to the SSN variation in SC23. The time lags are inconsistent in SC24 as positive, zero, and negative lags are observed in different energy channels of \( \text{H} \). Interestingly, although \( \text{He} \) shows zero and positive lags in SC23, zero and negative lags are observed on some occasions in SC24.

\( \text{He} \) flux variation does not lag the SSN variation in both SC23 and SC24 except for at 0.96 MeV \( n \) energy channel when negative lags are seen in SC24 for some averaging periods. While zero or positive lags are observed for the Fe fluxes in SC23, predominantly zero lags are there in SC24. C and O show mostly zero lags in both solar cycles.

4.2. Variations in the Spectral Index of Different Elements at Different Phases of SC23 and SC24

In order to evaluate the variabilities of the spectral indices of different suprathermal elements during the different phases of SC23 and SC24, seven phases are identified from the SSN data spanning from 1998 March to 2020 August. The duration of each phase is two years. These phases are: (1) maximum of SC23 (from 1999 November 11 to 2001 November 11), (2) descending phase of SC23 (from 2003 July 15 to 2005 July 15), (3) minimum of SC23–24 (from 2007 July 05 to 2009 July 05), (4) ascending phase of SC24 (from 2009 September 24 to 2011 September 24), (5) maximum of SC24 (from 2012 April 20 to 2014 April 20), (6) descending phase of SC24 (from 2015 July 8 to 2017 July 8), and (7) minimum of SC24–25 (from 2018 August 31 to 2020 August 31). “Quiet” time suprathermal ion fluxes of each element are then averaged over each phase.
Variations of the lags between the averaged fluxes and SSN with respect to the averaging window. Panels (a), (c), (e), (g), (i), and (k) show the variations of the lags for H, $^4$He, $^3$He, Fe, C, and O, respectively, during SC23. Panels (b), (d), (f), (h), (j), and (l) represent the same during SC24. Energy channels corresponding to H, $^4$He, and $^3$He are written on the left side of the left column of the figure. The same corresponding to Fe, C, and O are mentioned on the right of the right column of the figure.

and plotted against the corresponding energies (represented by colored dots), as shown in Figure 6. Each subplot in Figure 6 corresponds to the spectra of an element mentioned at the right upper corner of each subplot. Lines with seven different colors are the least-squares fitted lines corresponding to the seven phases of solar cycles as mentioned earlier. The spectral indices denoted by $m_i$ (where $i = 1, 2, 3, 4, 5, 6,$ and 7) are the estimated mean slopes of the fitted lines corresponding to different phases. The margin of errors (MoE; which sets a lower and upper bound on the estimated value corresponding to a specified confidence level) within 95% confidence bounds in estimating the mean slopes are also mentioned here. It is to be noted that the MoE depends on the variability of the data points, sample size, and confidence level (e.g., Agresti & Coull 1998). Bootstrap sampling (Efron & Tibshirani 1993) is a useful method to calculate the confidence intervals and MoE of an estimated (fitted) parameter like the spectral index.

Figure 7 summarizes the results shown in Figure 6. It shows the variations of the spectral indices of (a) H, (b) $^3$He, (c) C and O, and (d) $^4$He and Fe with different phases of the solar cycles as mentioned above. The MoEs are also shown. Note, the y-axis scales are made different for each subplot in Figure 7 to provide better visualization.

Figure 7(a) shows the variations in the mean spectral indices for suprathermal H at different phases of the solar cycles. The mean spectral index is found to vary from 1.51 (mean $m_2$) to 1.88 (mean $m_3$) except for that at the minimum of SC24–25 when it changes to 2.2 (mean $m_4$). It can be seen that the spectral index changed significantly during the minimum of SC24–25. However, since the variabilities of the fluxes are large and the number of data points is only three (corresponding to the three energy channels), the MoE is relatively large. This argument is justified as Bootstrap sampling depends on the number of original data points and the more the data points, the better is the normal approximation used in Wald’s method (see, for example, Agresti & Coull 1998). Therefore, a larger sample size and smaller variability of the sample data lead to a smaller MoE.

Figure 7(b) shows the corresponding variations of the spectral indices of $^3$He similar to what is shown in Figure 7(a). It is noted that the $m_i$ of $^3$He vary from 2.35 (mean $m_1$) to 2.64 (mean $m_2$). The MoEs are also quite high (except for the MoEs of the mean $m_1$ (0.69) and mean $m_6$ (0.80)). Comparative variations of the spectral indices of C and O (Figure 7(c)) reveal that these two elements go almost hand in hand over all the phases of the solar cycles, with the largest difference between the mean $m_i$ appearing to occur during the minimum of SC23–24. This is in contrast to $^4$He and Fe wherein the largest difference between the spectral slopes seems to occur during the minimum of SC24–25. The spectral indices (from $m_1$ to $m_3$) of $^4$He and Fe vary almost hand in hand in between the maximum of SC23 and the maximum of SC24. However, during the descending phase of SC24, $m_i$ of $^4$He reaches a minimum value (1.72) and in the next phase, the index $m_4$ of $^4$He changes abruptly to a maximum value (2.50). Such abrupt changes are not seen in case of Fe during the minimum of SC24–25.
5. Discussion

Variations of “quiet” time suprathermal heavy ion ratios (C/ O, Fe/O, and $^3$He/$^4$He) with solar activity were reported in the past (e.g., Dayeh et al. 2009; Kecskemety et al. 2011; Dayeh et al. 2017; etc.). It was also suggested that these ratios exhibit a solar energetic particle (SEP)-like signature during solar maximum and a CIR/solar wind-like signature during solar minimum. Therefore, the contribution from SEP and CIR events to the suprathermal ion pool in the IP medium during solar maximum and minimum, respectively, have been indicated in the past. Our investigation explicitly brings out not only the solar activity dependence (based on significant CCs) but also the time delays between the SSN and “quiet” time suprathermal fluxes. Therefore, our results augment and consolidate the earlier results (e.g., Dayeh et al. 2017) on the solar activity dependence of suprathermal particles in the IP medium. It appears that as the occurrence of SEP (both impulsive and gradual events) and CIR events vary with solar activity, so does the suprathermal population in the IP medium. The most striking point in this context emerges when we see conspicuous lags on many occasions despite the removal of transient events. This strongly suggests that the so-called “quiet” time suprathermal population in the IP medium may possibly be composed of leftover particles from previous solar and IP transient events. Therefore, the “quiet” time population of suprathermal population may not be truly “quiet” (even after the removal of the transient events).

This investigation, for the first time, shows that there exists negative lags between the suprathermal $^4$He fluxes and SSN in SC24. This essentially means that suprathermal $^4$He flux levels started rising in the IP medium before the SSN started rising during SC24. This indicates toward source processes that dominate during the minimum phase of the solar cycle. Since CIRs are the major source of energetic particles in the IP medium during the minimum of solar cycles, the negative lags of suprathermal $^4$He during the minimum of SC23–24 probably indicate the production of these suprathermal particles from CIR events in the IP medium. The deep minimum of SC23–34 provides an ideal background condition for this. This argument is supported by the negative lags observed in the 0.96 MeV $n^{-1}$ $^3$He flux in SC24. It is known that impulsive flare events contribute to the energetic $^3$He population in the IP medium (e.g., Mason et al. 2002). Therefore, a negative lag in the $^3$He fluxes may additionally suggest the role of remnant flare particles that were accelerated by CIR events during the minimum of the solar cycle and contributed to the suprathermal ion pool.

Mason et al. (2012) used ACE/ULEIS data from 1998 to 2011 and found that CIR event-averaged suprathermal Fe/O lagged behind SSN in SC23 but became more in phase in SC24. The results of Mason et al. (2012) also got extended and supported by the work of Allen et al. (2019) wherein similar behavior for the CIR averaged suprathermal Fe/O (in the energy range of 0.32–0.45 MeV $n^{-1}$) was brought out using ACE/ULEIS data from both SC23 and 24 (1998–2018). Interestingly, the present results that deal with “quiet” time suprathermal populations show consistency with the results obtained by both Mason et al. (2012) and Allen et al. (2019) as far as the difference in lags of the suprathermal Fe is concerned within both cycles. This result also indicates the contribution of CIR-associated particles in the “quiet” time suprathermal particle population.
Drastic changes in the spectral index of $^4$He occur after the maximum of SC24. In the descending phase of SC24, the mean spectral index ($m_6$) of $^4$He reaches its minimum value at 1.72. In the next phase, the index ($m_7 = 2.50$) is the highest among all the phases. The change is greater than any of the MoEs for $^4$He. On the other hand, the spectral indices of Fe vary quite smoothly and reach a maximum in the minimum of SC24–25. These variations in the spectral indices of $^4$He and Fe suggest that there were some differences in the production and (or) processing of these two suprathermal elements in the IP medium. Earlier, we have noted different lags of these two elements in SC23 and SC24. Therefore, it is clear that as far as the generation and processing of suprathermal $^4$He and Fe are concerned, there exist significant differences in SC24. In fact, SC24 is special in many ways. One such specialty is that SC24 is the weakest solar cycle in the last century and succeeds an extended minimum. Janardhan et al. (2018) also reported unusual polar field reversal in the Sun. Therefore, it is natural to assume that the differential behavior of suprathermal $^4$He and Fe in SC24 may be associated with changes in the Sun itself. However, the lags and spectral index variations of C and O look similar in both solar cycles. This contradiction leads us to think about the preferential processing of suprathermal particles in the IP medium. The acceleration of suprathermal population in the IP medium has also been suggested to depend on the mass-to-charge ratio ($M/q$) (e.g., Drake et al. 2009; Zhao et al. 2017; Reames 2018) and first ionization potential (FIP) effects (e.g., Feldman & Widing 2002). Owing to the significant $M/q$ and FIP differences, it is possible that the processing of $^4$He and Fe in the IP medium were affected in SC24. This argument gets credence from the fact that C and O have similar FIP and $M/q$ values. Hence, no differential changes are noticed in the lags and spectral indices of C and O in SC23 and SC24. Therefore, the present investigation suggests a sensitive dependence of the generation of a suprathermal population in the IP medium on FIP and $M/q$. In the context of SC24 being different, a few other results are also relevant here. Mewaldt et al. (2015) revealed that the fluence of SEP particles were conspicuously lower during the initial phase of SC24 and this reduction is attributed to two factors—a lower interplanetary magnetic field (IMF) in the IP medium and depletion in the seed population (suprathermal particles). While a reduced IMF
reduces the efficiency of acceleration leading to an underpopulation in the SEP energy domain (e.g., Gopalswamy et al. 2014; Mewaldt et al. 2015; Allen et al. 2019), lower densities of the seed population may limit the maximum energies that particles can be accelerated to by Alfvén waves through wave–particle interaction at the shock front (e.g., Li & Lee 2015). Another possibility is the changes in the spectral slopes through variations in the pick-up ion populations in the IP medium.

The relative importance of the acceleration and deceleration processes in the changes of suprathermal $^4$He that we see

Figure A1. Variations of Pearson’s CC between the averaged and shifted H fluxes at different energies (written in the middle column) and the averaged SSN with respect to the averaging window during SC23 (left) and SC24 (right) are shown. The fluxes are shifted based on the calculated lags with respect to the SSN variation. The green dots are Pearson’s CCs when there is no cutoff on the fluxes (as shown in Figure 3 in the main text). The red, black, pink, and blue dots represent Pearson’s CCs obtained in the similar way after putting cutoffs on the fluxes. The threshold values of the fluxes in units of particles $/(cm^2-s-sr-MeV/n)$ are written above each subplot.

Figure A2. Variations of Pearson’s CC between the averaged and shifted $^4$He fluxes at different energies (written in the middle column) and the averaged SSN with respect to the averaging window during SC23 (left) and SC24 (right) are shown. The fluxes are shifted based on the calculated lags with respect to the SSN variation. The green dots are Pearson’s CCs when there is no cutoff on the fluxes (as shown in Figure 3 in the main text). The red, black, pink, and blue dots represent Pearson’s CCs obtained in the similar way after putting cutoffs on the fluxes. Threshold values of the fluxes in units of particles $/(cm^2-s-sr-MeV/n)$ are written on the left and right of each pair of subplots corresponding to SC23 and SC24, respectively.
Figure A3. Similar to Figure A2 but for $^3$He.

Figure A4. Similar to Figure A3 but for C.

Figure A5. Similar to Figure A4 but for O.
during the minimum of SC24–25 also deserves attention at this stage. Dayeh et al. (2017) discussed that suprathermal tails are either generated due to (1) continuous acceleration of the seed populations in the IP medium (e.g., Fisk & Gloeckler 2006, 2008, 2014; Zank et al. 2014 etc.) or due to (2) deceleration of energetic particles from solar and IP events (e.g., Fisk & Lee 1980; Giacalone et al. 2002 etc.). Earlier studies have suggested that the lower-energy part of the CIR- (or stream interface region, SIR)-associated suprathermal populations gets affected primarily by local acceleration processes (e.g., Schwadron et al. 1996; Giacalone et al. 2002; Ebert et al. 2012; Filwett et al. 2017, 2019; Allen et al. 2020, 2021) while the higher-energy part gets affected by shock acceleration occurring far away (e.g., Ebert et al. 2012; Filwett et al. 2019). Therefore, the importance of acceleration, whether local or shock-induced, is undeniable in the observed changes that are reported in the present investigation.

Schwadron et al. (2010) theorized that variable superpositions of stochastic processes (distribution functions represented by exponential and Gaussian functions) could give rise to a power-law distribution function with an exponent of $-5$ ($f \propto v^{-5}$) or $-1.5$ in differential intensity w.r.t. the energy approach. This work essentially suggests that variable acceleration and heating processes may be in operation in the IP medium for the
generation of suprathermal particles. Antecki et al. (2013) adopted stochastic acceleration under a pressure balance condition—the timescale of acceleration is in balance with the timescale of adiabatic cooling in the solar wind as an effective means of producing a $-1.5$ spectral index. On the other hand, the possible role of deceleration processes for the observed changes in the suprathermal $^4$He particles during the minimum of SC24–25 cannot be ruled out also. This is because the particles that are accelerated at the distant shock fronts can be thrown back into the inner heliosphere leading to increased scattering and magnetic cooling processes. This may result in modulations in the intensity and spectral index (e.g., Fisk & Lee 1980; Mason et al. 1999; Zhao et al. 2016; Allen et al. 2021). Most importantly, particles accelerated through previous transient events, while speeding through the IP medium, experience adiabatic expansion of the solar wind resulting in the deceleration of these particles. As a consequence, the energetic particles slow down and enter into the suprathermal...
pool. According to Fisk & Lee (1980), this type of particle is expected to show a rollover below $\sim 0.5\text{ MeV n}^{-1}$ in the spectra. However, no such rollover is observed by Mason et al. (1997). We also do not see such a rollover feature in the present investigation. Nevertheless, although difficult to comment, the relative role of deceleration processes on the significant changes in the spectral slope of $^4\text{He}$ during SC24–25 cannot be ruled out. It seems, therefore, reasonable to argue that variable contributions of acceleration and deceleration or distribution functions may lead to variations in the spectral indices with varying solar activity. These processes might have undergone changes in the minimum of SC24–25 so as to cause changes in the spectral indices as far as heavier ions like Fe and $^4\text{He}$ are concerned. These aspects need more critical attention in the future, and the multidirectional suprathermal particle measurements on board India’s forthcoming Aditya-L1 mission (Goyal et al. 2018) may throw important light on some of these issues.

6. Summary

In this work, by analysing 22 yr of flux variations of suprathermal H, $^3\text{He}$, $^4\text{He}$, C, O, and Fe measured by the ACE spacecraft from the first Lagrangian point of the Sun–Earth system, we show that these particles follow a solar cycle variation with varying lags or time delays. These time delays are shown to vary with energy and element. It is inferred that the suprathermal population in the IP medium during “quiet” times is not free from particles originating from earlier transient events. Further, this investigation, for the first time, reveals that suprathermal Fe and $^4\text{He}$ show discernible changes in lags and spectral slopes in SC24. It is hypothesized that these changes in lags and spectral slopes may result from acceleration/
deceleration processes that depend on the mass-to-charge ratio and FIP. This suggestion gets credence from the behavior of C and O wherein no such differential changes are noticed. Further investigations are needed to understand the underlying physical processes that are responsible for the differential changes in the suprathermal helium and iron in the IP medium in SC24.

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Data Sources: The suprathermal particle flux data used in this paper are available at https://cdaweb.gsfc.nasa.gov/index.html. The daily estimated SSN data can be downloaded from http://www.sidc.be/silso/datafiles.

Appendix

Rigorous sensitivity tests to validate the results regarding lags of suprathermal particles with respect to SSN variation are performed. These plots reveal how the correlation between the “quiet” suprathermal fluxes and SSN varies depending on the flux thresholds. Four sets of flux thresholds have been selected at random in decreasing order for each energy channel of each element. We have repeated the same exercise depicted in the main text to calculate the lags and Pearson’s CCs between SSNs and fluxes with the above mentioned cutoffs. The results of the same are shown in Figures A1–A12. Figures A1–A6 show the variations in Pearson’s CC for H, $^3$He, $^3$He, C, O, and Fe, respectively. It can be seen from Figure A1 to Figure A6 that irrespective of the thresholds, the flux and Pearson’s CC do not change significantly if we compare these values with the CCs calculated by only removing transient events. Not only the CCs, but also the time delays between the fluxes and SSN also do not change depending on the flux baselines (see Figures A7–A12). These give direct credence to the methodology adopted here for generating quiet time data by removing the transient events.

ORCID iDs

Bijoy Dalal @ https://orcid.org/0000-0001-8993-9118
D. Chakrabarty @ https://orcid.org/0000-0003-2693-5325
N. Srivastava @ https://orcid.org/0000-0002-0452-5838

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