Quiet-time low-energy ion fluxes in the 23rd and 24th solar cycles at 1 AU

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Abstract: The relative abundances of 3He, 4He, C, O and Fe ions in the energy range 0.04 to 1 MeV/nucleon and the energy spectra of 3He and Fe are investigated during quiet-time periods in the 23rd and 24th solar cycles using ACE/ULEIS data. Quiet-time fluxes of suprathermal ions with low first ionization potential (FIP) ≤ 10 eV were found to exhibit higher variability than those with high FIP (above 10 eV). The quiet periods selected were divided into three groups according to the value Fe/O in the energy range of ~40-320 keV/nucleon. In the 23rd SC except for the minimum the Fe/O ratio was within the interval of values comparable with those of impulsive SEP events or was near the mean abundance in solar corona. During solar minimum Fe/O was close to the solar wind values. Ions of these 3 groups originate from different seed particle populations: ions of the upper solar corona, those accelerated in impulsive micro SEP events, ions of quiet corona and solar wind ions, respectively. Noticeable differences in the energy spectra and energy dependences of relative abundances of suprathermal ion fluxes were found between SC 23, the 2008-09 minimum and the first 4 years of SC 24.

Keywords: low-energy ions, quiet solar activity

1 Introduction

The origin of ubiquitous low-energy ions (below ~1 MeV/n) in the heliosphere under quiet Sun is not entirely understood yet. Previous investigations of the time variations of quiet-time low energy proton fluxes, energy spectra and radial gradients indicated that at 1 AU these protons are predominantly of solar origin over the whole solar cycle [1, 2]. Recent investigations of ion abundances in various phenomena of solar activity revealed considerable differences in the C/O and Fe/O ratio between the solar atmosphere [3], fast and slow solar wind [4, 5], impulsive and gradual solar energetic particles (SEP) events [6-9], as well as in particle fluxes accelerated in corotating interaction regions and at interplanetary shocks [10, 11].

The elemental abundances in suprathermal particle fluxes during quiet time periods of solar activity were studied in [12-14]. They showed that the values of C/O and Fe/O exhibited clear dependence on the level of solar activity. At solar cycle (SC) maximum these ratios corresponded to the SEP values whereas at minimum they were near the ratio observed in the solar wind or in corotating events. The solar component of the quiet time population can consist of SEP event remnants and particles accelerated by weak active processes on the Sun such as microflares and X-ray bright points. To assess the possible sources of low-energy particles on the Sun during quiet periods including solar cycle minima we examined the flux variations along with values of the abundance ratios Fe/O and C/O.

This study uses measurements of heavy-ion abundances in the 0.03 to 1 MeV/nucleon energy range by the ULEIS instrument aboard the ACE spacecraft and flux measurements of 4–8 MeV/n protons and He nuclei by the COSTEP/EPHIN instrument on SOHO in 1998-2013. The quiet time periods were selected using criteria worked out in [15] which guaranteed the negligible contribution to background fluxes from previous large solar flares and the absence of transient particle intensity enhancements of any origin – coronal mass ejections, corotating, transient, and recurrent events. We compared the 40–80 keV/nucleon Fe/O abundance ratios with average relative ion abundances in the solar corona, in impulsive SEP events, and in the solar wind, respectively. It was found that quiet-time particle fluxes split into 3 well-defined groups according to the Fe/O values corresponding to the average ratios observed in: impulsive SEP events (group I), the solar corona (II), and in the solar wind (III), respectively [15].

2 Suprathermal ion abundances in the 23rd and 24th solar cycles

Figure 1 shows the temporal profiles of the 27 day averaged relative ion abundances 3He/4He, C/O, Fe/O over the 23rd SC and the beginning of the 24th SC. One can see clear difference in time dependences of suprathermal ion ratios in dependence of the ion value of first ionization potential: Fe/O (low FIP ion and high FIP) exhibit higher variability than ion ratios 3He/4He, C/O both with high FIP (above 11 eV).

Fig. 1 27-day averages of relative ion abundances 3He/4He, C/O, Fe/O in 1998-2012.
The distribution histograms of ion relative abundances $^3$He/$^4$He, C/O, Fe/O displayed in Figure 2 also demonstrate the higher variability of Fe/O ratio in the solar cycles 23 and 24 as well as a different Fe/O value between the two subsequent solar cycles. The abundance features obtained indicate a possibly lower content of suprathermal $^3$He and Fe in the 24$^{th}$ SC at 1AU in comparison with the 23$^{rd}$ SC, whereas the $^4$He and O abundances are known to remain nearly stable over the solar cycle [15, 16].

**Fig. 2.** Distributions of the $^3$He/$^4$He, C/O, and Fe/O ratios at 0.08-0.16 keV/n for 5 day averages in the first 4 years of SC 23 (1998-2001, top), in the minimum (2008-09, middle), and at the beginning of SC 24 (2010-April 2013, bottom).

### 3 Quiet time ion energy spectra

As we found earlier in [15, 16] the $^3$He and Fe energy spectra during quiet-time periods were different for three groups of suprathermal particle fluxes. The hardest spectra were observed in group I – for suprathermal fluxes with particle contribution from micro impulsive SEP events, where spectrum roll off occurred in energy region below 1 MeV/n. The steepest spectra were found in group III periods up to 1 MeV/nucel and exhibited minima near 1 MeV/n [16].

**Fig. 3.** Upper panels: weighted average ion energy spectra $^3$He (left) and Fe (right) in quiet-time periods for I (blue triangles), II (red squares) and III (green circles) groups in the SC 23. Lower part: the same for SC 24. Figure 3 shows the weighted averages of $^3$He and Fe quiet time spectra over quiet time periods, respectively, separately for the groups I, II, and III as defined above.

The spectral shape reflects the particle acceleration mechanism. Suprathermal $^3$He as well as Fe spectra in the SC 23 and 24 are different in the three groups but display similar peculiarities in each group. It should be noted that in SC 24 spectra $^3$He and Fe in groups I, II, and III differ in shape and are considerably lower in intensity for group I in comparison with the spectra in the 23$^{rd}$ SC (see Figure 4). In contrast, group III spectra show higher intensity in SC 24 than in SC 23 due to the dominant contribution to group III during the very low solar activity minimum (2007-2009).

**Fig. 4.** $^3$He (upper panels) and Fe (lower panels) suprathermal ion energy spectra during quiet-time periods for the I(a), II(b) and III(c) groups in SC 23 (1998-2009, red squares) and SC 24 (2010-2013, black dots).

### 4 Relative abundances of $^3$He/$^4$He and Fe/O as a function of energy

Figure 5 demonstrates the suprathermal ion relative abundances $^3$He/$^4$He and Fe/O observed during quiet-time periods for three groups as a function of energy in SC 23 and 24. The ratios given are weighted averages, i.e. averaged for quiet time periods in each group considering the relative contribution of each period. On can see that the averaged $^3$He/$^4$He and Fe/O ratios vary with energy and significantly depend on the group for which the ratio was calculated. These differences suggest the presence of different particle acceleration mechanisms and/or different populations accelerated. The highest and nearly constant ratios $^3$He/$^4$He and Fe/O were observed during quiet periods of SC 23 in group I. In group II Fe/O increases with energy while $^3$He/$^4$He...
slightly decreases. In group III the both ratios decreases with energy.
In the present, 24th cycle the energy dependence of \(^{3}\text{He}/^{4}\text{He}\) and \(^{4}\text{He}/^{40}\text{Fe}\) ratios demonstrated other features, suggesting different conditions in the solar corona for particle acceleration.

5 Conclusions
The investigation of suprathermal ion \(^{3}\text{He}, ^{4}\text{He}, ^{4}\text{O}\), and \(^{8}\text{He}\) energy spectra and their relative abundances \(^{3}\text{He}/^{4}\text{He}\) and \(^{4}\text{He}/^{40}\text{Fe}\) as a function of energy during quiet Sun showed that the accelerated particles of solar corona give the main contribution during all phases of the SC (increasing, maximum and decreasing) except minimum. During solar activity minima the accelerated solar wind particles represent the main source of suprathermal particles. The difference in \(^{3}\text{He}\) and \(^{4}\text{He}\) forms and energy dependence of \(^{3}\text{He}/^{4}\text{He}\) and \(^{4}\text{He}/^{40}\text{Fe}\) ratio obtained indicate the presence of different ion acceleration processes in each group and different ion populations accelerated in these processes. The activity minimum between the 23rd and 24th SC was extremely quiet and prolonged; the beginning of the 24th SC was characterized by weak activity what appeared in the suprathermal ion spectra and distributions presented in Figures 2 and 3.

The comparison of results obtained for the last two solar cycles showed a characteristic difference both in the ion energy spectra and in the energy dependence of relative abundances. A possible explanation of these differences is that other conditions in the solar corona are giving rise to lower fluxes of suprathermal ions the 24th solar cycle as compared to the previous one.

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References