The energy dependence of relative ion abundances during quiet-time periods in the 23rd solar cycle

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Abstract. The origin of 0.03-1 MeV/nucleon ions is investigated on the basis of ULEIS (ACE) data during quiet time periods in 1998-2011. The energy spectra of 3He, 4He, O, and Fe ions and the energy dependence of their relative abundances are obtained. The comparison of Fe/O abundance ratios during quiet time periods with the average relative ion abundances in various phenomena of solar activity shows that the ion fluxes tend to split into 3 groups. Over the entire solar cycle excluding minimum the Fe/O values corresponded to those observed in impulsive solar energetic particle (SEP) events (group I) and in the solar corona (group II). Near the activity minimum, however, the Fe/O values were usually near their solar wind values (group III). The energy spectra of suprathermal ions and the energy dependence of ion abundance ratios in different groups are also different depending on the ion first ionization potential. These results suggest that various acceleration mechanisms are at work in the different groups. The nearly constant values Fe/O ≈ 1 and 3He/4He ≈ 0.065 up to 0.8 MeV/nucleon obtained for ion group I possibly result from ion acceleration in small impulsive SEP events rich in Fe and 3He. This ratio Fe/O is about 15 times higher than the photospheric value and corresponds to the Fe abundance in the upper corona in old active regions. We suggest that ions in these coronal regions represent the population accelerated in impulsive SEP events.

1. Introduction

Investigations of ion abundances in various phenomena of solar activity revealed considerable differences in relative abundances of 3He, 4He, C, O, Ne-S and Fe in the solar atmosphere [1, 2], in the fast and slow solar wind [3-6], in impulsive and gradual solar energetic particle (SEP) events [7-11], in particle fluxes accelerated in the interplanetary space in CIR [12], and at interplanetary shocks [13].

The origin of the ubiquitous low-energy particle population in the heliosphere under quiet Sun is not entirely understood yet. Previous investigations of the time variations of quiet-time low energy (0.3–1 MeV) proton fluxes, energy spectra and radial gradients indicated that these protons are predominantly of solar origin over the whole solar cycle at 1 AU [14].

The relative ion composition with energies of 0.1–1 MeV/n in quiet periods in the 23rd solar cycle (SC) was studied in [15-17], leading to the discovery that the values of C/O and Fe/O in the suprathermal ion population depend on the level of solar activity. It was shown that the composition was close to that in SEP events at the SC maximum, and similar to the solar wind composition or to corotating interaction regions at the SC minimum. According to [17] the quiet-time 0.32–0.64 MeV/n 3He/4He ratio measured by ULEIS was elevated with respect to solar wind value by a factor of ~100.

Our previous investigations [18-20] of the quiet-time abundance ratios of C, CNO, O, Ne-S and Fe ions based on ACE and WIND data in 1998-2009 showed that the background fluxes of suprathermal ions Fe/O value in the energy range of ~40-320 keV/n split into three separate groups. For almost a
half of the quiet time periods during the SC ascending, maximum, and descending phases coincided with the average element abundances of the solar corona whereas the rest lied within the ratio intervals characteristic for impulsive SEP events. At solar cycle minimum the ratios, however, were near their solar wind values. It was assumed that these 3 groups of suprathermal ion fluxes originate from different seed particles: ions of solar upper atmosphere – group I, ions of quiet coronal plasma - II and solar wind ions – III. In this paper we examine the energy spectra of quiet-time $^3$He, $^4$He, O and Fe ions as well as their ratio dependence on energy using ACE data in the 23rd SC.

2. Observations
This study uses the measurements of the abundances of 0.03 to 1 MeV/n $^3$He, $^4$He, O and Fe ions by the ULEIS instrument aboard the ACE spacecraft and of 4–8 MeV/n proton and helium nuclei by the COSTEP/EPHIN instrument on SOHO in 1998–2011. The experimental data were obtained from the URLs: www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_ULEIS.html and www2.physik.uni-kiel.de/SOHO/phpeph/EPHIN.html.

Quiet time periods were selected using the criteria worked out in [18]: (1) during the quiet periods particle intensity enhancements of any origin – SEP events, coronal mass ejections, corotating and recurrent events, etc. – should be absent; (2) the daily averaged 40–80 keV/nucleon Fe intensity should be $J \leq 5 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ MeV/n; (3) the daily averaged proton intensity with energies 4–8 MeV should not exceed $10^{-4}$ protons/cm$^2$ s sr MeV; (4) the intensity ratio H/He should be $\leq 10$ for energies 4-8 MeV/n. The selection criteria of quiet periods accepted here ensured the absence of remnant particles from previous large gradual SEP events during quiet periods. 59 quiet-time periods were selected in 1998–2011 with durations from 2 days at the SC maximum to 34 days at the SC minimum.

3. Quiet-time $^3$He, $^4$He, O and Fe abundance ratios in 1998-2011
The values of the 40–80 keV/n Fe/O abundance ratios obtained in 51 quiet-time periods in the 23rd and the onset of the 24th SC in [18-20] were compared with the mean relative ion abundances in the solar corona, in gradual and impulsive solar energetic particle events, and in the solar wind, respectively. It was found that Fe/O values split into three, sufficiently well separated groups. During the ascending, maximum and descending phases of solar activity (1998–2006) in the half of the periods Fe/O lied within the interval characteristic for impulsive SEP events – these form group I, whereas during the remaining periods they corresponded to the average abundance of elements in the quiet solar corona – group II. At solar cycle minimum the ratios were near their solar wind values – group III.

![Figure 1](image-url)  
**Figure 1.** Values of abundance ratios: a) Fe/O with energies 40-80 keV/n; b, c, d) 80-160 keV/n $^4$He/O, $^3$He/O and $^3$He/$^4$He ratios during 59 quiet periods in 1998-2011. The horizontal lines I represent the mean Fe/O values in impulsive SEP events [8, 9]. The lines II and III show the average abundances in the quiet solar corona [1] and in the solar wind [3, 5]. Ratios of group I are marked by triangles, group II – by squares and group III - by circles.

The abundance ratios Fe/O, $^3$He/O, $^4$He/O and $^3$He/$^4$He obtained in 59 selected quiet periods were divided into 3 groups according to the 40–80 keV/n Fe/O values (figure 1a). One can see that ion ratios observed in 2010-2011 (onset of the 24th SC) differ from those in the 23rd SC possibly reflecting different circumstances in the solar corona during these consequent cycles. Here in further study we used 37 quiet-time periods in 1998-2009.
Figure 2 displays the distributions of the Fe/O and $^3$He/$^4$He ratios. The former exhibits 3 peaks whereas the latter has a distinct maximum representing mostly the ion fluxes belonging to group III. The other quiet-time groups I and II account for the widening of this maximum. Previously in [19] we obtained that the distributions of the ratios of low and high first ionization potential (FIP) ions (Fe/C, Fe/O and Fe/CNO) show 3 well distinguished groups discussed here whereas ratios (figure 3 in [19]) of two high FIP ions do not exhibit any clear separation.

![Figure 2](image)

**Figure 2.** Distributions of the Fe/O and $^3$He/$^4$He values for 37 quiet time periods.

4. Quiet-time $^3$He, $^4$He, O and Fe energy spectra in the 23rd SC

Figure 3 shows the average $^3$He, $^4$He, O and Fe quiet-time spectra for groups I, II, III. These spectra were constructed by using the averaged ion intensities in all quiet periods in each of the groups I, II and III separately using the procedure worked out in [19, 20]. The solid lines represent the best fitting spectral functions $J(E) \sim E^{-\gamma}$ where $E$ is the ion energy and $\gamma$ is the spectral index. The $^3$He and Fe spectra show clearly different indices for the different groups. The hardest $^3$He and Fe spectra were observed in the group I. The steepest spectra were observed in group III (figures 3a, c) and both had the minima near 1 MeV/nucleon. At the same time $^4$He and O spectra exhibit little difference for the 3 groups. The difference in $^3$He and Fe spectra in groups I, II and III confirms the previous assumption [19, 20] that different ion acceleration mechanisms are responsible for the different groups.

![Figure 3](image)

**Figure 3.** Average $^3$He, $^4$He, Fe and O quiet-time spectra for groups I, II, and III.

5. Abundance ratios as a function of energy

The energy dependence of the average $^3$He/$^4$He and Fe/O ratios are displayed in figure 4. The ratios were obtained by the same averaging as in the case of energy spectra. In figure 4 one can see that the energy dependence of Fe/O and $^3$He/$^4$He is significantly different in the 3 groups: I – ratios are the highest and approximately constant, II – Fe/O increases while $^3$He/$^4$He slightly decreases, III – both ratios decrease with energy. This obviously significant difference in the ratio energy dependences in the 3 groups also confirms the presence of different particle acceleration processes in these groups.

![Figure 4](image)

**Figure 4.** Left panel: energy dependences of the Fe/O ratio in 1998-2009 for the 3 ion groups. Right panel: the same for $^3$He/$^4$He ratio.
6. Discussion
To determine the possible seed particles accelerated to suprathermal energies we compare the variations of the abundance ratios $^{3}\text{He}/^{4}\text{He}$ and Fe/O. It is known that impulsive SEP events are rich in Fe and in $^{3}\text{He}$ with the mean values of Fe/O near 1 and $^{3}\text{He}/^{4}\text{He}=0.07-0.1$, respectively [15, 22]. Here we obtained (see figure 4) that the highest average quiet time values are Fe/O $\approx 0.9$ and $^{3}\text{He}/^{4}\text{He}$ up to 0.64 MeV/n. So one can assume that the suprathermal ions in group I are accelerated in minor impulsive events.

On the other hand, it was established [1] that in the solar corona, when compared with the photosphere, elements having FIP $\leq 10$ eV (low-FIP ions) were often overabundant by about a factor 4–5 whereas elements with FIP $\geq 11$ eV (high-FIP ions) remained unchanged. The FIP bias is defined as the ratio of the low-FIP elemental abundance in the solar upper atmosphere (SUA) to its value in the photosphere. The magnitude of FIP bias is time dependent and values as high as 15 were measured in old active regions [2]. In this work the average Fe/O value in group I was estimated as Fe/O $I = 0.9\pm 0.05$. As the photosphere Fe/O$_{\text{ph}} = 0.06\pm 0.006$ [23] we obtain that $(\text{Fe/O}_I)/(\text{Fe/O}_{\text{ph}}) = 14.8\pm 2.3$.

The value of FIP-bias found here coincides with the FIP bias measured SUA in old active regions. This result suggests that the ions present in these SUA regions can possibly serve as a seed population accelerated to suprathermal energies thus forming group I fluxes.

The results obtained by examining of the $^{3}\text{He}/^{4}\text{He}$ ratio confirm our earlier suggestions [19-20] based on C, O, CNO, Ne-S and Fe ion investigations that different seed particle populations were accelerated to suprathermal energies by different acceleration processes.

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