PROCEEDINGS OF SCIENCE

# Suprathermal ions at 1 AU in solar wind streams from near equatorial coronal holes in 2006-2010

**M. A. Zeldovich**
*Lomonosov Moscow State University, D.V. Skobeltsyn Nuclear Physics Research Institute, Moscow, Russia*
*E-mail:* mariya@srd.sinp.msu.ru

**Yu.I. Logachev**
*Lomonosov Moscow State University, D.V. Skobeltsyn Nuclear Physics Research Institute, Moscow, Russia*
*E-mail:* logachev@srd.sinp.msu.ru

**K. Kecskeméty**[1]
*Wigner Research Centre for Physics*
*Budapest, Hungary*
*E-mail:* kecskemety.karoly@wigner.mta.hu

**I.S. Veselovsky**
*Lomonosov Moscow State University, D.V. Skobeltsyn Nuclear Physics Research Institute, Moscow, Russia*
*and Space Research Institute (IKI RAS), Moscow Russia*
*E-mail:* veselov@srd.sinp.msu.ru

Ion energy spectra and abundance ratios are studied in 0.04-2 MeV/nucleon ion fluxes using ULEIS/ACE data during the solar minimum between solar cycles 23 and 24. The unique prolonged minimum of 2006-2009 permitted to select 35 quiet time periods when suprathermal ion fluxes originating from near-equatorial coronal holes (CH) were observed at 1 AU. The values of relative ion abundances indicate the presence of particle populations accelerated in different processes on the Sun and in the interplanetary space observed as suprathermal fluxes. The ratios of suprathermal C/O and Fe/O arising from coronal holes were found to correlate with their bulk solar wind ratios from CH (SWICS/ACE data) whereas 40-80 keV/nucleon $^{4}$He/O ratios were about two times higher than their bulk wind values. The $^{3}$He, $^{4}$He, Fe, C, and O ion energy spectra showed that ion intensities depend on solar wind speed and the fluxes were higher inside fast wind streams. The results obtained suggest that the bulk solar wind described by Maxwellian distribution appears to be the source of ions further accelerated to suprathermal energies thus forming the high energy solar wind tail. The ion spectra obtained here were fitted by power-law functions or combined power-law/exponential which suggests different mechanisms of acceleration.

[1]Speaker



PoS(ICRC2015)091

The 34th International Cosmic Ray Conference
30 July- 6 August, 2015
The Hague, The Netherlands

## 1. Introduction

The energy spectra and abundance ratios of $^{3}$He, $^{4}$He, C, O, and Fe ions originating from coronal holes (CH) are studied in the 0.04-2 MeV/nucleon energy range using ACE/ULEIS data [1] during the solar activity minimum between solar cycles 23 and 24. On the basis of «CHH – coronal hole history» [2] and using ACE/SWICS data [3] we selected 35 quiet periods where suprathermal ion fluxes from near equatorial CH at 1 AU were detected. Quiet time periods were selected with help of criteria worked out in [4, 5] guaranteeing minimum energetic particle contribution from any active processes on Sun and in the interplanetary space.

## 2. Suprathermal $^{4}$He, C, O, and Fe in solar wind from coronal holes

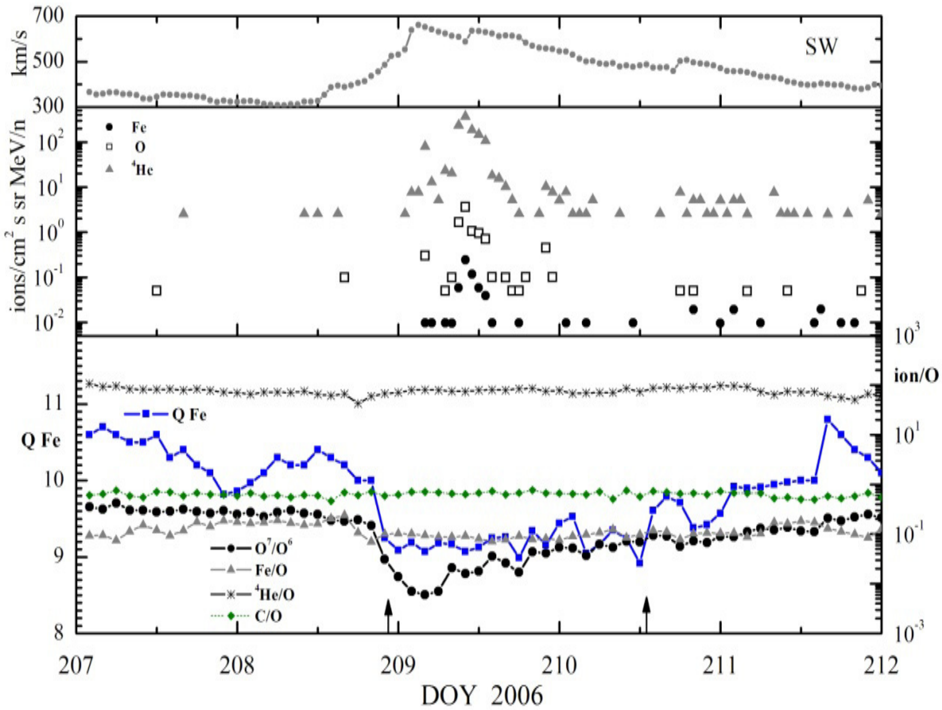


**Figure 1.** Solar wind speed (top panel), suprathermal ion intensities (middle panel) and bulk wind ion abundance ratios (bottom panel) in the fast solar wind stream from near equatorial coronal hole CH233 in 2006.

The values of relative suprathermal ion abundances C/O, Fe/O and $^{4}$He/O were determined using ULEIS/ACE data from a given CH requiring that solar wind value $O^7/O^6 \leq 0.145$ during the time interval of the CH [6]. Figure 1 displays the plasma speed; 0.08-0.16 MeV/nucleon He, and 0.04-0.08 MeV/nucleon O and Fe intensities in ULEIS data, and the values of $O^7/O^6$ and $^{4}$He/O, C/O, Fe/O from SWICS, respectively, during a fast solar wind period of 27-29 July 2006 at 1 AU originating from CH233 [2]. Figure 1 demonstrates that the enhanced suprathermal ion fluxes were observed simultaneously with the passage of a fast solar wind stream from a coronal hole. The decrease of the $O^7/O^6$ ratio and the drop of Q(Fe) as measured by SWICS confirm the passage of the wind stream from the CH by the Earth.

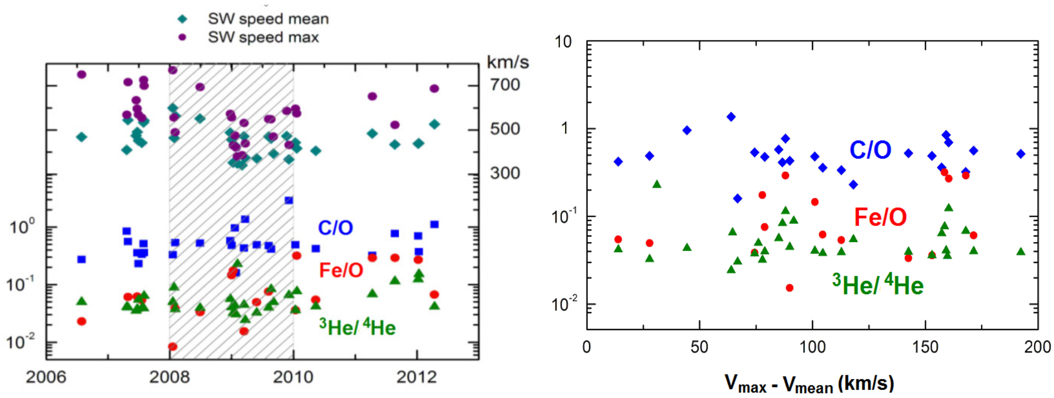


**Figure 2.** Left panel, top: difference between the maximum and average solar wind speed from selected coronal holes. Bottom: solar wind ion abundance ratios from coronal holes. Right panel: ion abundances from coronal holes as a function of solar wind speed difference between maximum and mean from coronal holes.

Figure 2 shows the maximum and mean solar wind speed values from selected coronal holes and indicates that the difference between maximum and mean speed varies with solar activity. The lowest plasma speed values and smallest difference between the maximum and mean velocities were both observed in 2009. The right panel of Figure 2 indicates that the C/O and $^3$He/$^4$He ratios were nearly constant whereas the Fe/O (low/high FIP) ion ratio had higher variability and increased from 2006 to 2012. Figure 3 compares the suprathermal and bulk solar wind values of the Fe/O ratio as a function of maximum solar wind speed from selected coronal holes. It should be noted that the Fe/O values displays a decreasing trend with increasing solar wind speed for both populations.

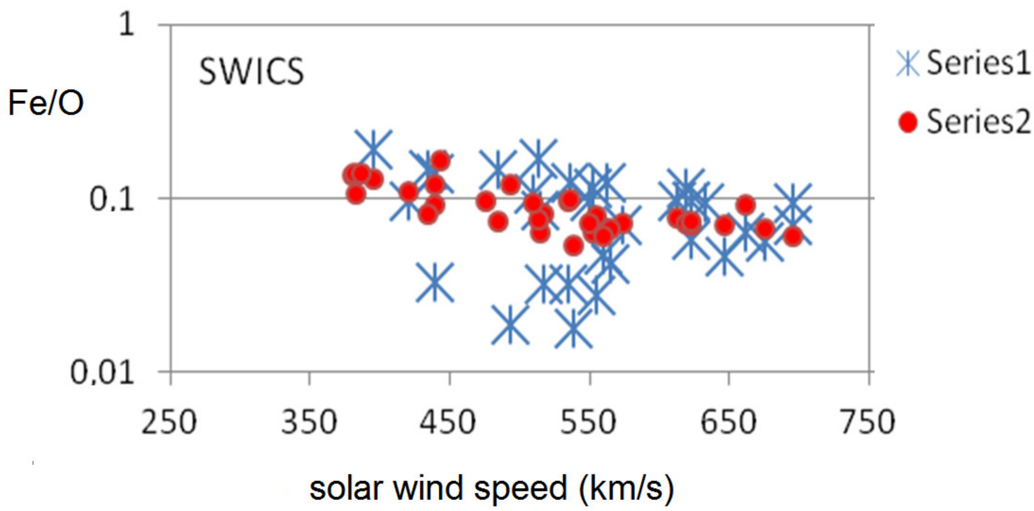


**Figure 3**. Fe/O ratio vs. maximum solar wind speed from CHs: a) asterisks – 40-80 keV/nucleon ions from ULEIS data in solar wind streams from coronal holes in 2006-2010; b) red circles – bulk solar wind Fe/O in streams from CH (SWICS data).

| 27-29/07/2006 | $O^7/O^6$ | Fe/O | C/O | He/O |
|---|---|---|---|---|
| 40-80 keV/n (ULEIS) | | 0.063 | 0.59 | 138 |
| bulk sw (SWICS) | 0.032 | 0.091 | 0.66 | 76 |

**Table 1.** Ion abundances in solar wind stream from CH233.

Table 1 shows the suprathermal and bulk wind ion abundances in the fast wind stream from CH233. It contains values of suprathermal He/O, C/O and Fe/O (ULEIS) and bulk wind abundances (SWICS). The average abundance values over all ion fluxes from 35 CHs are presented in Table 2. Suprathermal C/O and Fe/O ratios are near the bulk wind ones whereas He/O is ~2 times higher.

| 2006-2010 | $O^7/O^6$ | Fe/O | C/O | He/O |
|---|---|---|---|---|
| 40-80 keV/n (ULEIS) | | 0.110 | 0.67 | 140 |
| bulk sw (SWICS) | 0.049 | 0.090 | 0.70 | 74 |

**Table 2.** Average abundance values over all ion fluxes from 35 CHs investigated here.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">SC maximum (2006-07, 2010-12)</th><th colspan="2">SC minimum (2008-09)</th></tr>
<tr><th>slow</th><th>fast</th><th>slow</th><th>fast</th></tr>
<tr><td>Fe/O 80-160 keV/n (ULEIS)</td><td>CH*</td><td>0.2</td><td>0.11</td><td>0.088</td><td>0.056</td></tr>
<tr><td colspan="2">Fe/O bulk SW (SWICS)**</td><td>0.06-0.16</td><td>0.05-0.12</td><td>0.047-0.15</td><td>0.04-0.07</td></tr>
<tr><td>C /O 80-160 keV/n (ULEIS)</td><td>CH*</td><td>0.56</td><td>0.47</td><td>0.94</td><td>0.46</td></tr>
<tr><td colspan="2">C/O bulk SW (SWICS)**</td><td>0.48-0.83</td><td>0.6-0.78</td><td>0.6-0.9</td><td>0.64-0.78</td></tr>
</table>

* Fe/O and C /O in particle fluxes from coronal holes (present work)
**Data for slow and fast solar wind bulk ion ratios from SWICS/ACE [7].

**Table 3.** Average abundance ratios observed in solar activity maximum and minimum.

The relatively good agreement between suprathermal and bulk wind ion abundances permits assuming that bulk wind ions serve as seed population subsequently accelerated to high energies. Average ion energy spectra from coronal holes as a function of solar wind speed are presented in Figure 4. The spectra were obtained by averaging intensities for all quiet time periods where solar wind streams from coronal holes were observed in solar wind fluxes in 3 speed ranges: >500 km/s, 400-500 and <400 km/s separately, calculating weighted contribution of each quiet period.

## 3. Dependence of suprathermal ion spectra on solar wind speed

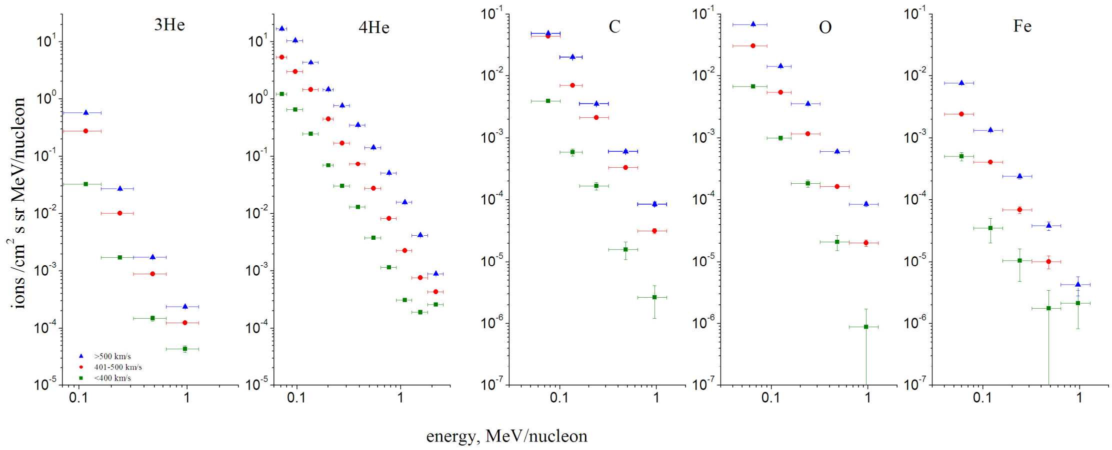


**Figure 4.** Average ion energy spectra from coronal holes vs. solar wind speed from CH in 3 speed ranges separately: >500 (blue marks), 400-500 (red) and <400 km/s (green).

Figure 4 exhibits average ion spectra from coronal holes as a function of plasma speed in solar wind streams from coronal holes. One can see that ion intensities depend on solar wind speed: the higher is the speed the higher are the ion intensities from the CH. It should be noted that spectra assume the same spectral changes for all ions – low FIP and high FIP ones. In contrast to spectra in different type quiet periods, where the strong dependence of FIP value was found [8], and to findings that low-FIP (<10 eV) elements are enriched in the corona [9] and in the solar wind as compared to high-FIP with respect to photosphere the enhancement was ~4 in the slow wind, 2 in the fast wind [10].

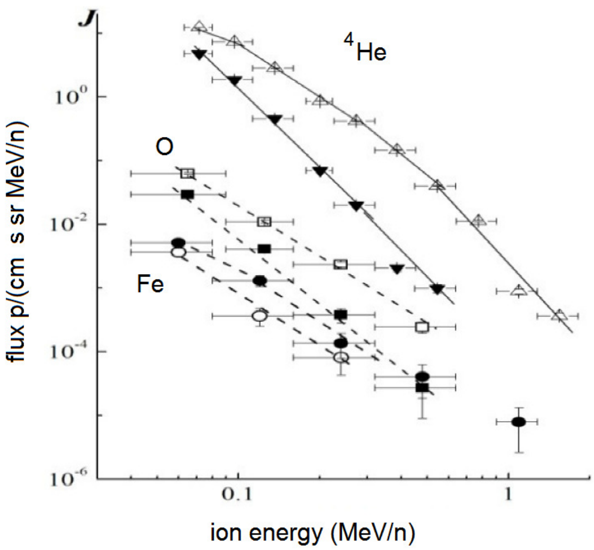


**Figure 5.** Energy spectra of $^{4}$He ions (triangles), O (squares) and Fe (dots) in the solar wind streams from two near equatorial coronal holes on June 26–29, 2008 (empty symbols), and January 20–22, 2010 (full symbols).

It is well-known that different acceleration mechanisms result in different shapes of the energy spectrum. Figure 5 displays the spectra of $^4$He, O, and Fe ions in the solar wind streams from two coronal holes on June 26–29, 2008, and on January 20–22, 2010. The spectra of $^4$He and O in the first case were clearly harder. The intensities of $^4$He and O were higher in 2008; however, the $^4$He spectrum was close to exponential in June 2008 but rather power-like in January 2010, as well as the spectra of O ions from both coronal holes. The Fe spectra also had power-law form, but the Fe flux was higher in January 2010, in contrast to the $^4$He and O intensities. It was shown [9, 10] that the dynamics of the ion content in the solar atmosphere and in the solar wind depends on the first ionization potential (FIP) of the ions. The observed difference in the spectra of suprathermal ions was likely due to the different FIPs of the ions observed (Fe: 7.8 eV, O: 13.0 eV, $^4$He: 24.6 eV). The results suggest that the low and high FIP ions in the corona were accelerated by different mechanisms and thus require different conditions in the region of these coronal holes. It is also possible that different active processes in interplanetary space at a distance from the Sun to 1 AU play a role in the formation of the spectra.

## 4. Conclusions

The energy spectra of $^4$He, C, O, and Fe ions with energies of 0.04–1 MeV/nucleon and their relative abundances at 1 AU were studied using ACE/ULEIS data in periods of quiet solar activity during solar cycles 23 and 24. The results obtained show that during periods of low solar activity the main source of the suprathermal background is accelerated ions of the solar wind. A unique period of extremely low activity in 2007–2009, during which fast speed solar wind from equatorial coronal holes was observed, allowed us to obtain the spectra and relative abundance of ions in the fast speed tail of the solar wind (suprathermal tail) as a function of solar wind speed. It was shown that the relative contents of suprathermal C/O and Fe/O during minimum and increasing periods of solar activity correspond to the relative abundance of bulk solar wind ions. The enhanced abundance of suprathermal $^4$He found here in solar wind streams from coronal holes permits to assume the existence of extra sources of $^4$He in addition to the bulk solar wind.

## References

[1] www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_ULEIS.html

[2] www.solen.info/solar/coronal_holes.html.

[3] www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_SWICS.html

[4] M.A. Zeldovich, et al., *Bull. Russ. Acad. Sci. Phys.,* **75**, 776, 2011

[5] V.N. Ishkov et al., *Adv. Space Res.*, **50**, 757, 2012

[6] L. Zhao, T. H. Zurbuchen, and L.A. Fisk, Geophys. Res. Lett., **36**, L14104, 2009

[7] S.T. Lepri, E. Landi, and T.H. Zurbuchen, *Astrophys. J.*, **768**, 94, 2013

[8] M. A. Zeldovich, Yu. I. Logachev, and G. M. Surova, *Astronomy Reports*, **55**, 374, 2011

[9] U. Feldman and K.G. Widing, *Space Sci. Rev.*, **130**, 301, 2007

[10] H. Peter, *Astron. and Astrophys.*, **335**, 691, 1998