Christian-Albrechts-Universität zu Kiel

Mathematisch-Naturwissenschaftliche Fakultät

3He rich periods measured by the Suprathermal Ion Telescope on STEREO-A during solar cycle 24

Marlon Köberle[1], Radoslav Bučík[2], Nina Dresing[3], Bernd Heber[1], Andreas Klassen[1] and Linghua Wang[4]

[1]Institute of experimental and applied physics, Kiel University, [2]Space Science & Engineering Division, Southwest Research Institute, San Antonio, USA, [3]Department of Physics and Astronomy, University of Turku, Turku, Finland, [4]Institute of Space Physics and Applied Technology, Peking University, Peking, China

ST1

Open Session on the Sun and Heliosphere

vEGU 21

Abstract

3He-rich solar energetic particle (SEP) events are characterized by a peculiar elemental composition with rare species like 3He or ultra-heavy ions tremendously enhanced over the solar system abundances. We report on 3He rich SEP periods measured by the Suprathermal Ion Telescope (SIT) onboard STEREO-A beginning in 2007 until 2020, covering the whole solar cycle 24. The mass resolution capabilities of SIT do not allow to easily distinguish between 3He and 4He especially in cases of a low 3He to 4He ratio. We therefore developed a semi-automatic detection algorithm to find time periods during which a 3He enhancement can be statistically determined. Using this method we found 112 3He rich periods. These periods were further examined in regards of their 3He/4He and Fe/O ratio. Previously about ten 3He-rich SEP periods measured by SIT on STEREO-A have been reported. An association with in-situ electron measurements by STEREO-SEPT and STEREO-STE showed that ≈ 60% of the 112 periods are accompanied with electron events. The here presented catalogue of 3He rich periods is intended to serve as a reference for the community.

Introduction

3He rich *Solar Energetic Particle* (SEP) events are characterised by an enhancement of 3He isotopes by factors of up to 10^4 above solar wind or coronal abundances as well as an enhancement of heavier ions like Fe up to a factor of 10. They are associated with type-III bursts, indicating the presence of outward-streaming near-relativistic electrons(see e.g. (Bučík 2020), (Mason 2007) and references therein)

Previous studies by (Nitta et al. 2006) and (Ho et al. 2001) have shown a $\approx 95\%$ association of 3He events with type-III bursts but only a $\approx 60\%$ association with > 30 keV solar electron events. So far, most previous works treated escaping ions and electrons separately, which is why we want to specifically address the following questions in our ongoing study:

1. How different are solar sources in events with a common ion and electron detection compared to sources where only one particle component is dominant?
2. To what extent is the injection/transport to/in interplanetary space responsible for lack of ion or electron detection?

Here we present our first measures taken by reporting a new list of 3He rich periods measured by the Suprathermal Ion Telescope (SIT) (Mason et al. 2008) onboard STEREO-A, whose 3He measurement capability hasn't been utilised to it's full extent yet.

3He Detection

The SIT is a time-of-flight mass spectrometer with a mass resolution of $\frac{\sigma_m}{m} \approx 0.1$ for particles within 0.1-1 $\frac{MeV}{nuc.}$. Figure 1 shows two pure 4He example periods from 2012 and 2014. The top panels show the mass spectrograms and the bottom panels the mass histograms of these periods in various energy channels marked as dots and a coresponding fit of a gaussian distribution. From the mass histograms some instrumental constraints can be found.

- The histograms show a positive skewness
- Beginning at 226 $\frac{keV}{nuc.}$, a small proportion of proton spillover
- The distributions shift towards lower AMU and broaden up with rising energy
- The mean of the distributions varies with time, whereby no correlation with the energy spectra could be found

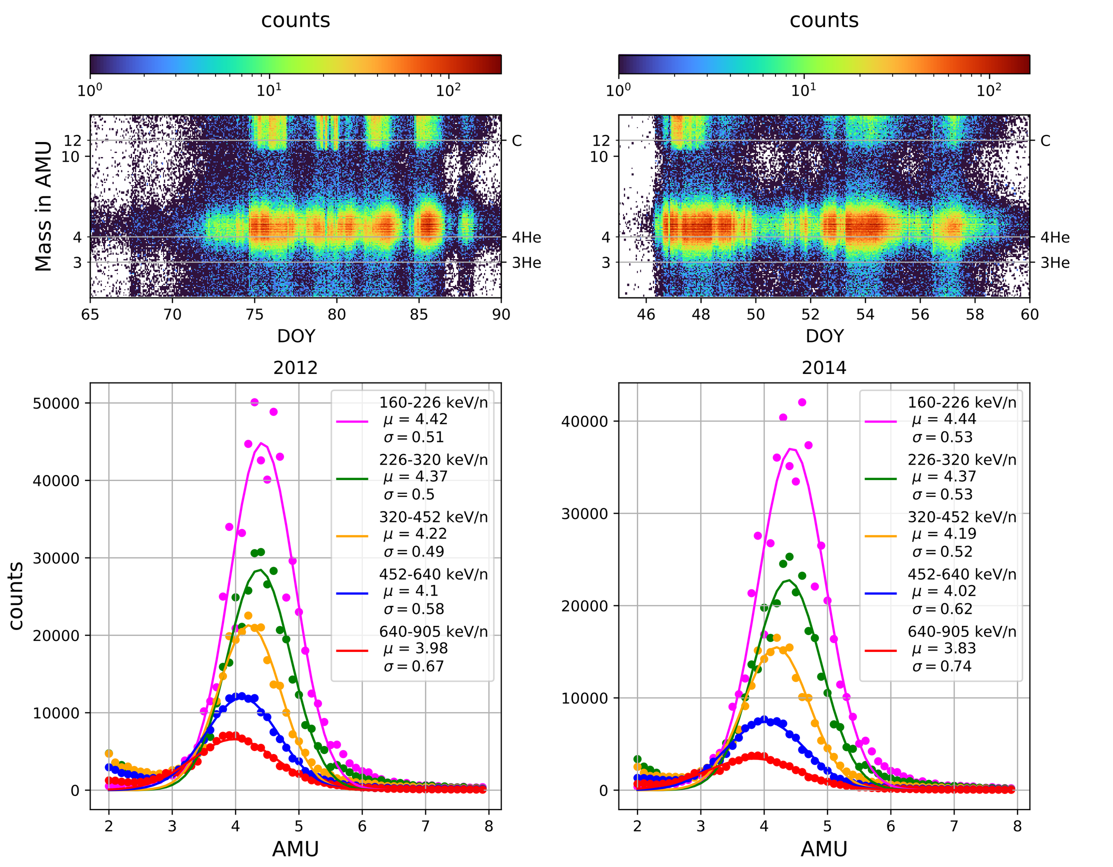

Figure 1: Two example periods of 4He measurements without 3He detection from 2012 DOY 65-90 (left side) and 2014 DOY 45-60 (right side). Top panels show the coresponding mass spectrograms and the bottom panels the mass histograms for a set of energy channels ranging from 160 to 905 keV/nuc. Individual fit parameters for the respective gaussian distributions are given in the legend.

Given these constraints, we chose an empirical approach to identify 3He periods based on the assumption that the overall abundance of 3He is negligible compared to the abundance of 4He by performing three steps:

1. draw a reference distribution $f_r \pm 60$ days around the DOY/ period distribution f_p of interest
2. perform a 2-sample Kolmogorov-Smirnov(KS) test for f_r and f_p in individual energy channels
3. normalise both distributions and calculate the residuals

Now the following three criteria had to be met in order to be classified as a 3He enhancement candidate:

1. at least 2 channels yields a P-value of the KS test < 0.05.
2. the sum of the normed residuals within the estimated 3He intervals needs to be < 0.
3. a total of at least 25 counts/energy channel.

This procedure was performed for 1 day and 0.3 day periods from 2007 to 2020 and in the aftermath all resulting candidates were examined by eye. The beginning and end of a period was determined manually by performing 0.1 day steps of the procedure where statistically applicable. Figure 2 shows an example 3He rich period of 2010 with a strong 3He enhancement. The top panels shows the normed residuals and the middle panels the mass histograms of the individual energy channels. The corresponding KS-test P-values are given in the legend of the middle panels. The bottom panel shows the mass spectrogram around that period with black vertical lines marking the beginning an end of the 3He rich period.

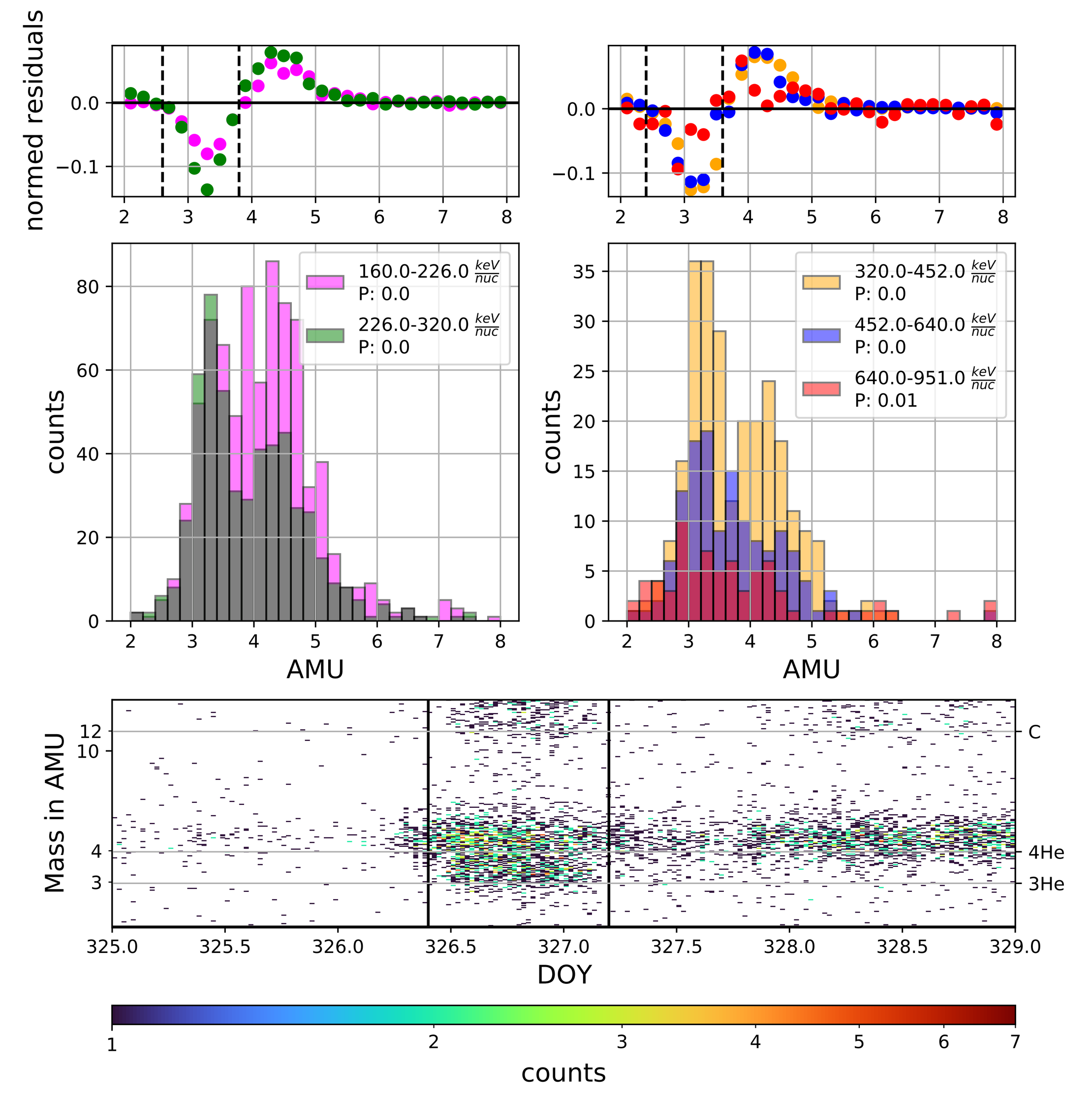

Figure 2: 3He rich period example from 2010 DOY 326.4-327.2. Top panels show the normed residuals, middle panels the mass histograms and bottom panel the mass spectrogram around that period enclosed by black vertical lines

Spillover

To calculate the actual amount of 3He in each period we took the following steps as sketched in figure 3:

(a) find a reference period without 3He close to the 3He rich period with good statistics up to high energys and fit a gaussian distribution.

(a)→**(b)** subtract the gaussian from the histogram

(b) estimate the remaining protons by an exponential fit $f(x) = a \cdot \exp(-b \cdot (x - 1.75))$ and extrapolate till 3.5 amu.

(b)→**(c)** subtract the estimated protons from the original histogram.

(c) calculate the ratio of counts $> \mu$ of the clean 4He histogram.

(c)→**(d)** apply the ratio of counts $> \mu$ to the 3He rich period

(d) take the counts $> \mu$ of the 3He rich period to calculate the amount of 4He and subtract it from the total counts to get the 3He counts.

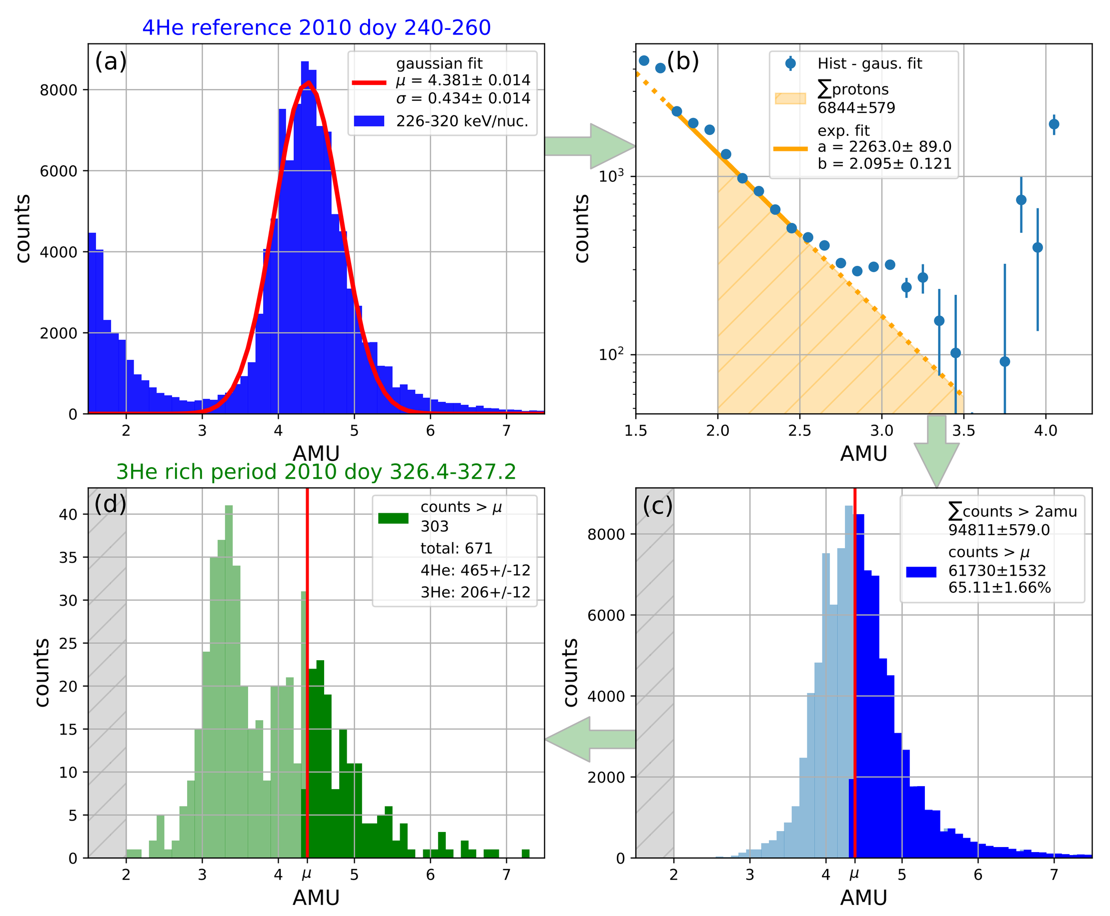

Figure 3: Sketch of Spillover calculation. Errors labeled are methodical errors only.

First results

Using our approach we identified 112 periods of 3He enhancement, during which we calculated the 3He/4He as well as the Fe/O ratio. Figure 4 shows the Fe/O ratio of 80-113 keV/nuc. versus the 3He/4He ratio of 226-320 keV/nuc. indicating no correlation. The median values are 0.23 for 3He/4He and 1.02 for Fe/O which is in general agreement of previous studies as in (Bučík et al. 2018) who reported median values of 0.15 and 1.13. The slightly higher median of the 3He/4He ratio in our study might be due to a different energy range and/or the limitations of the mass resolution of SIT.

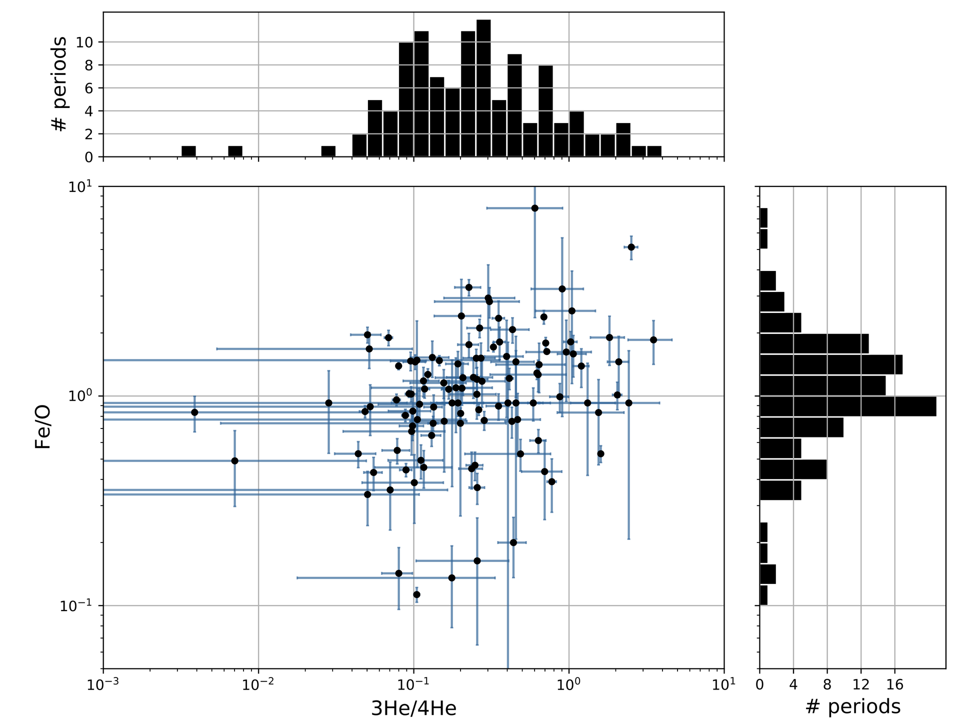

Figure 4: Fe/O vs. 3He/4He at 80-113 keV/nuc. and 226-320 keV/nuc.

Electron association

A **preliminary** association of the 112 3He rich periods with near-relativistic electrons was done by testing STEREO-STE and SEPT measurements for a 3-σ rise above the 60 minute pre-event mean within a timeframe of 3-12 hours prior to the 3He rich period. Instrumental effects like contamination as well as methodical uncertainties have to be further evaluated to finalise the association. Nevertheless, this method is comparable to the studies mentioned above and with a positive association of 60 out of the 112 periods already yields similar results.

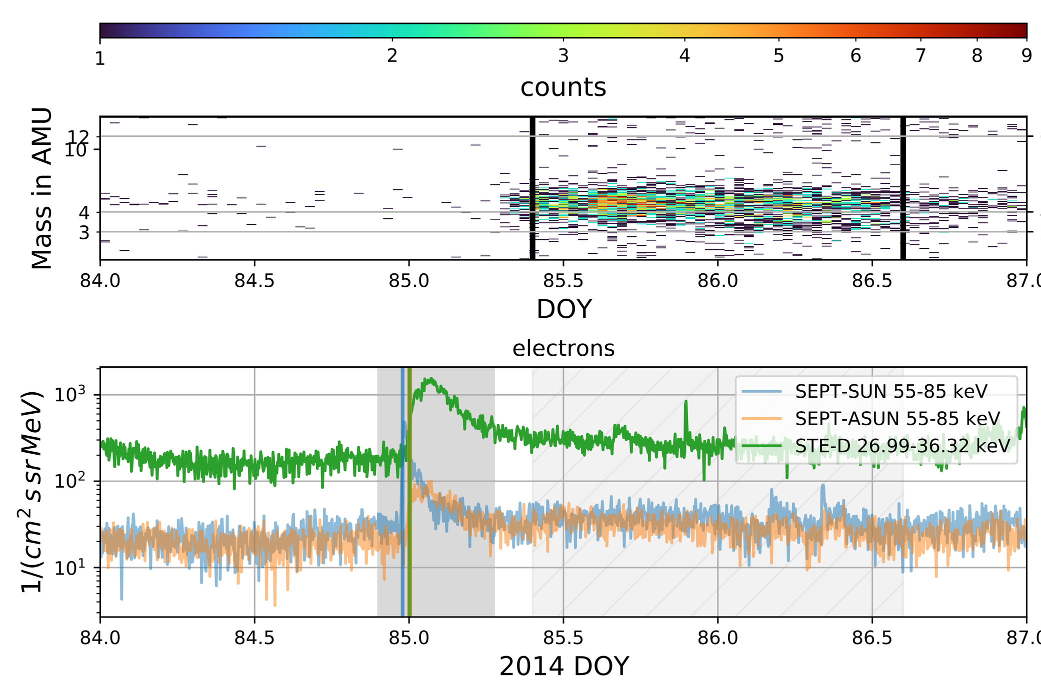

Figure 5: Example of a positive association between a 3He rich period and an electron event. Top panel shows the mass spectrogram of the period enclosed by black vertical lines, bottom panel combined STE-D measurements and SEPT measurements. Vertical lines mark the electron onset of the respecting channel.

Summary and outlook

We strived to detect all 3He rich periods measured by SIT and due to the instrumental constraints propose an automatic empirical approach. This approach utilises a running reference distribution to validify potential 3He rich periods via a KS test. Going through all data from 2007-2020, covering the whole solar cycle 24, we found 112 such periods, including all previously reported cases known to us. These periods were evaluated in regards of their 3He/4He and Fe/O ratios showing comparable results to studies performed with other instruments. The same holds true for a preliminary association with electron events which leaves us with a completely new catalogue of 3He rich periods for further exploration.

In the near future we plan to finalise the electron association in order to compare common and different features of the ions and electrons measured in situ and link those to the physical processes happening at the source and during transport.

Contact:
Marlon Köberle
koeberle@physik.uni-kiel.de
Extraterrestrische Physik
IEAP
Christian-Albrechts-Universität zu Kiel
Leibnizstr. 11, 24118 Kiel

acknowledgements

Period	Startdate	Days	3He/4He	Fe/O	electrons
1	2007-01-14 07:12:00	14.3-14.5	1.55 ± 0.71	0.83 ± 0.36	X
2	2007-01-24 12:00:00	24.5-26.8	0.1 ± 0.02	0.72 ± 0.11	✓
3	2007-02-26 09:36:00	57.4-57.8	0.24 ± 0.82	0.0 ± 0.0	X
4	2007-03-04 04:48:00	63.2-64.2	0.2 ± 0.19	0.74 ± 0.47	X
5	2009-04-29 00:00:00	119.0-120.0	0.96 ± 0.43	1.62 ± 0.68	✓
6	2010-02-02 16:48:00	33.7-35.3	0.24 ± 0.04	0.45 ± 0.09	✓
7	2010-02-14 07:12:00	45.3-46.0	0.43 ± 0.04	0.76 ± 0.13	X
8	2010-02-16 07:12:00	47.3-48.3	0.26 ± 0.03	0.37 ± 0.06	✓
9	2010-02-17 14:24:00	48.6-50.1	0.25 ± 0.08	1.02 ± 0.24	✓
10	2010-02-21 16:48:00	52.7-53.4	0.49 ± 0.27	0.53 ± 0.09	✓
11	2010-08-24 02:24:00	236.1-238.1	0.1 ± 0.01	1.02 ± 0.09	✓
12	2010-10-21 07:12:00	294.3-298.2	0.13 ± 0.04	1.53 ± 0.3	X
13	2010-11-22 09:36:00	326.4-327.2	0.63 ± 0.08	0.61 ± 0.08	X
14	2011-01-27 16:48:00	27.7-28.8	0.1 ± 0.03	0.85 ± 0.2	✓
15	2011-02-01 19:12:00	32.8-33.0	0.23 ± 0.04	3.3 ± 0.29	X
16	2011-02-18 12:00:00	49.5-50.1	0.43 ± 0.12	2.07 ± 0.29	✓
17	2011-02-19 12:00:00	50.5-51.1	1.07 ± 0.22	1.59 ± 0.36	X
18	2011-03-20 16:48:00	79.7-80.3	0.25 ± 0.02	1.51 ± 0.16	✓
19	2011-04-04 07:12:00	94.3-94.9	0.1 ± 0.25	1.48 ± 0.8	X
20	2011-04-05 02:24:00	95.1-95.9	0.18 ± 0.16	0.14 ± 0.06	X
21	2011-04-26 02:24:00	116.1-116.5	0.11 ± 0.11	0.77 ± 0.31	X
22	2011-05-01 00:00:00	121.0-122.8	0.05 ± 0.01	1.96 ± 0.17	✓
23	2011-05-06 09:36:00	126.4-127.3	2.09 ± 0.32	1.46 ± 0.47	X
24	2011-06-14 16:48:00	165.7-166.8	0.44 ± 0.09	0.2 ± 0.06	X
25	2011-07-16 12:00:00	197.5-198.7	1.6 ± 0.06	0.53 ± 0.05	X
26	2011-07-18 09:36:00	199.4-200.3	0.26 ± 0.15	0.16 ± 0.1	X
27	2011-09-01 09:36:00	244.4-247.0	0.7 ± 0.2	0.44 ± 0.18	X
28	2011-09-19 04:48:00	262.2-262.7	0.46 ± 0.3	0.93 ± 0.72	✓
29	2011-10-28 12:00:00	301.5-302.0	0.05 ± 0.0	0.84 ± 0.06	✓
30	2011-10-29 02:24:00	302.1-303.7	0.08 ± 0.0	1.39 ± 0.06	✓
31	2011-10-30 19:12:00	303.8-305.0	0.12 ± 0.01	1.08 ± 0.1	✓
32	2011-11-04 02:24:00	308.1-308.4	0.19 ± 0.13	1.09 ± 0.43	✓
33	2011-11-22 12:00:00	326.5-327.0	0.12 ± 0.06	0.46 ± 0.09	✓
34	2012-01-13 12:00:00	13.5-14.7	0.16 ± 0.06	0.76 ± 0.32	X
35	2012-01-16 00:00:00	16.0-17.9	0.6 ± 0.31	7.87 ± 5.51	X
36	2012-06-05 16:48:00	157.7-159.3	0.08 ± 0.02	0.55 ± 0.08	X
37	2012-06-21 09:36:00	173.4-173.6	0.0 ± 0.09	0.84 ± 0.16	✓
38	2012-07-15 02:24:00	197.1-197.8	0.12 ± 0.01	1.27 ± 0.08	✓
39	2012-07-16 00:00:00	198.0-198.3	0.07 ± 0.0	1.9 ± 0.16	✓
40	2012-07-17 09:36:00	199.4-200.0	0.1 ± 0.02	1.45 ± 0.12	✓
41	2012-08-14 12:00:00	227.5-228.3	0.13 ± 0.02	0.65 ± 0.07	✓
42	2012-08-15 16:48:00	228.7-230.5	0.2 ± 0.05	1.09 ± 0.19	✓
43	2012-09-07 12:00:00	251.5-252.0	0.01 ± 0.04	0.49 ± 0.19	X
44	2012-11-06 19:12:00	311.8-312.5	0.05 ± 0.05	0.89 ± 0.24	✓
45	2012-11-07 12:00:00	312.5-313.2	0.05 ± 0.05	1.68 ± 0.32	X
46	2012-11-14 09:36:00	319.4-320.0	0.1 ± 0.06	0.68 ± 0.16	✓
47	2012-11-30 12:00:00	335.5-336.4	0.4 ± 0.28	0.93 ± 0.88	X
48	2012-12-10 04:48:00	345.2-345.9	0.1 ± 0.05	0.39 ± 0.14	✓
49	2013-02-17 07:12:00	48.3-49.3	0.35 ± 0.03	2.35 ± 0.49	✓
50	2013-03-02 04:48:00	61.2-61.5	0.09 ± 0.0	1.03 ± 0.04	✓
51	2013-05-10 19:12:00	130.8-132.2	0.1 ± 0.0	0.11 ± 0.01	✓
52	2013-05-12 12:00:00	132.5-133.3	0.11 ± 0.04	0.49 ± 0.09	✓
53	2013-05-13 09:36:00	133.4-134.6	0.59 ± 0.05	0.93 ± 0.17	✓
54	2013-05-14 16:48:00	134.7-135.3	0.05 ± 0.06	0.34 ± 0.1	X
55	2013-05-15 09:36:00	135.4-136.5	0.09 ± 0.01	0.44 ± 0.03	✓
56	2013-07-02 09:36:00	183.4-184.4	0.06 ± 0.01	0.43 ± 0.08	X
57	2013-07-16 07:12:00	197.3-198.1	0.9 ± 0.33	3.24 ± 2.44	X
58	2013-07-25 12:00:00	206.5-207.5	0.13 ± 0.01	0.74 ± 0.06	✓
59	2013-08-04 19:12:00	216.8-217.8	1.02 ± 0.1	1.81 ± 0.22	X
60	2013-08-16 00:00:00	228.0-228.9	0.03 ± 0.06	0.93 ± 0.39	X
61	2013-10-16 16:48:00	289.7-290.2	0.63 ± 0.32	1.26 ± 0.22	X
62	2013-10-17 07:12:00	290.3-290.8	0.64 ± 0.3	1.41 ± 0.38	✓
63	2013-11-18 12:00:00	322.5-323.5	1.04 ± 0.44	2.55 ± 1.4	X
64	2013-11-25 12:00:00	329.5-331.0	0.21 ± 0.07	1.22 ± 0.22	X
65	2013-12-14 00:00:00	348.0-349.0	0.15 ± 0.0	1.48 ± 0.08	✓
66	2013-12-15 00:00:00	349.0-350.2	0.09 ± 0.0	0.81 ± 0.06	✓
67	2013-12-16 04:48:00	350.2-351.1	0.04 ± 0.01	0.53 ± 0.08	X
68	2013-12-25 07:12:00	359.3-360.0	0.16 ± 0.06	1.15 ± 0.18	X
69	2014-01-02 07:12:00	2.3-3.0	0.28 ± 0.01	0.76 ± 0.08	✓
70	2014-01-03 09:36:00	3.4-6.0	0.62 ± 0.02	1.29 ± 0.09	X
71	2014-01-06 02:24:00	6.1-6.8	0.87 ± 0.12	0.99 ± 0.16	✓
72	2014-01-15 21:36:00	15.9-16.7	0.12 ± 0.03	1.18 ± 0.19	X
73	2014-01-25 09:36:00	25.4-27.1	0.47 ± 0.19	0.77 ± 0.26	X
74	2014-02-02 02:24:00	33.1-36.3	0.2 ± 0.01	0.83 ± 0.05	X
75	2014-03-26 09:36:00	85.4-86.6	0.26 ± 0.04	1.2 ± 0.17	✓
76	2014-04-06 02:24:00	96.1-99.3	0.13 ± 0.02	0.89 ± 0.13	X
77	2014-04-12 14:24:00	102.6-103.2	0.07 ± 0.09	0.36 ± 0.13	✓
78	2014-04-25 02:24:00	115.1-117.3	0.08 ± 0.0	0.96 ± 0.06	X
79	2014-04-29 21:36:00	119.9-122.6	0.71 ± 0.01	1.79 ± 0.11	✓
80	2014-05-03 14:24:00	123.6-125.5	0.69 ± 0.02	2.38 ± 0.18	✓
81	2014-05-05 14:24:00	125.6-127.1	0.26 ± 0.01	0.86 ± 0.05	✓
82	2014-05-07 04:48:00	127.2-128.0	0.24 ± 0.08	1.23 ± 0.25	✓
83	2014-05-08 21:36:00	128.9-130.2	0.41 ± 0.02	1.21 ± 0.14	X
84	2014-05-27 19:12:00	147.8-148.7	0.2 ± 0.07	2.41 ± 1.19	✓
85	2014-06-15 00:00:00	166.0-166.5	1.32 ± 0.67	0.93 ± 0.51	✓
86	2014-06-23 21:36:00	174.9-175.9	0.33 ± 0.01	1.71 ± 0.09	✓
87	2014-06-25 00:00:00	176.0-176.5	0.17 ± 0.02	1.08 ± 0.11	✓
88	2014-06-26 19:12:00	177.8-179.0	0.45 ± 0.14	1.46 ± 0.47	✓
89	2014-06-28 04:48:00	179.2-180.3	0.28 ± 0.11	1.18 ± 0.29	X
90	2014-07-17 16:48:00	198.7-202.3	0.72 ± 0.01	1.63 ± 0.04	✓
91	2014-07-25 00:00:00	206.0-207.3	0.3 ± 0.15	2.93 ± 1.29	✓
92	2014-07-26 14:24:00	207.6-208.6	1.82 ± 0.45	1.9 ± 0.5	✓
93	2014-07-27 16:48:00	208.7-209.6	2.52 ± 0.25	5.13 ± 0.66	X
94	2014-08-07 12:00:00	219.5-221.2	0.35 ± 0.06	0.9 ± 0.13	✓
95	2014-08-18 00:00:00	230.0-231.5	0.25 ± 0.03	0.47 ± 0.07	X
96	2014-11-01 00:00:00	305.0-306.0	1.2 ± 0.14	1.39 ± 0.29	X
97	2014-11-11 00:00:00	315.0-317.0	0.36 ± 0.03	1.81 ± 0.32	X
98	2015-12-17 21:36:00	351.9-353.3	0.18 ± 0.1	0.93 ± 0.56	✓
99	2016-01-01 09:36:00	1.4-2.5	0.31 ± 0.17	2.82 ± 0.47	✓
100	2016-01-02 14:24:00	2.6-4.0	3.5 ± 1.1	1.85 ± 0.44	X
101	2016-01-16 21:36:00	16.9-18.0	0.08 ± 0.02	0.14 ± 0.05	X
102	2016-02-11 09:36:00	42.4-43.7	0.77 ± 0.05	0.39 ± 0.11	X
103	2016-02-16 21:36:00	47.9-49.1	0.4 ± 0.11	1.54 ± 0.75	X
104	2016-02-18 14:24:00	49.6-51.5	2.05 ± 0.14	1.01 ± 0.15	✓
105	2016-04-30 00:00:00	121.0-122.2	0.27 ± 0.06	1.52 ± 0.27	X
106	2016-06-26 04:48:00	178.2-179.2	2.43 ± 1.41	0.93 ± 0.72	✓
107	2016-11-19 14:24:00	324.6-325.7	0.19 ± 0.03	1.42 ± 0.21	✓
108	2016-11-21 14:24:00	326.6-329.2	0.27 ± 0.05	2.11 ± 0.21	X
109	2017-04-17 19:12:00	107.8-108.2	0.1 ± 0.02	1.47 ± 0.15	✓
110	2017-06-02 00:00:00	153.0-153.8	0.19 ± 0.05	0.93 ± 0.13	✓
111	2017-06-02 21:36:00	153.9-155.0	0.11 ± 0.05	0.91 ± 0.15	X
112	2018-03-31 00:00:00	90.0-91.8	0.23 ± 0.03	1.76 ± 0.23	X

Table 1: Table of 3He rich periods. Ratios for 3He/4He are in the energy range of 226-320 keV/nuc. and the Fe/O ratio in the energy range of 80-113 keV/nuc

References

Bučík, R. 2020, Space Science Reviews, 216, 24

Bučík, R., Innes, D. E., Mason, G. M., et al. 2018, Astrophysical Journal, 852, 76

Ho, G. C., Roelof, E. C., Hawkins III, S. E., et al. 2001, The Astrophysical Journal, 552, 863

Mason, G. M. 2007, Space Science Reviews, 130, 231

Mason, G. M., Korth, A., Walpole, P. H., et al. 2008, Space Science Reviews, 136, 257

Nitta, N. V., Reames, D. V., De Rosa, M. L., et al. 2006, The Astrophysical Journal, 650, 438