Recurrent $^3$He-rich Solar Energetic Particles

Radoslav Bučík

Bučík, Innes, Mall, Korth, Mason 2013, in Proc. 33$^{rd}$ ICRC, paper 0552
• brief introduction to SEPs

• properties of $^3$He-rich SEPs and motivation

• approach to the problem (multi-point & multi-instrument); introduce the period of interest

• observations of $^3$He-rich SEPs by different s/c

• solar sources of $^3$He emission

• summary & further study
Large (Gradual) SEP events during STEREO era

Reames (1999)

GOES >10 MeV protons/(cm² s sr)

STEREO

SDO

CME Shocks

Large SEPs

Flares

³He-rich SEPs

Reames (1999)
3He-rich SEPs: key features

“One of the most extreme fractionation processes known to occur in astrophysical sites” (Mason et al. 1986).

- anomalous abundances arise from resonant wave-particle interaction (e.g. Temerin & Roth 1992; Miller 1998)
- larger ionization states of heavy ions than in the corona (Klecker et al. 1984)
- kilovolt electrons (Reames et al. 1985) & type III radio bursts (Lin 1974; Reames & Stone 1986); minor X-ray flares (Reames et al. 1988)
- EUV jets near coronal holes (Nitta et al. 2006, 2008; Wang et al., 2006)
3He-rich SEPs: multiple events

- multiple events from the same AR with a single s/c (Reames & Stone 1986; Mason et al. 1999, 2000; Wang et al. 2006)

- recurrent events suggest almost continuous acceleration of 3He (Pick et al. 2006)
Multi-point study of recurrent events

Delay between events on different s/c corresponds to co-rotation time.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft (s/c)</td>
<td>STEREO-B</td>
<td>ACE</td>
<td>ACE</td>
<td>STEREO-A</td>
</tr>
<tr>
<td>s/c Carrington Lon.</td>
<td>283°</td>
<td>296°</td>
<td>280°</td>
<td>281°</td>
</tr>
<tr>
<td>s/c Heliographic Lat.</td>
<td>-6.9°</td>
<td>3.6°</td>
<td>3.7°</td>
<td>5.0°</td>
</tr>
<tr>
<td>³He-Rich Interval (doy)</td>
<td>182.9–183.6</td>
<td>188.9–190.0</td>
<td>190.0–191.0</td>
<td>197.5–198.3</td>
</tr>
<tr>
<td>³He/⁴He d</td>
<td>0.74±0.17</td>
<td>0.42±0.04</td>
<td>2.35±0.13</td>
<td>4.08±0.29</td>
</tr>
<tr>
<td>Fe/O d</td>
<td>…</td>
<td>0.91±0.15</td>
<td>1.31±0.20</td>
<td>1.19±0.31</td>
</tr>
<tr>
<td>³He Fluence d (×10³)</td>
<td>3.73±0.63</td>
<td>20.6±1.6</td>
<td>127±4</td>
<td>96.1±3.2</td>
</tr>
</tbody>
</table>

Similar CL – common solar origin?

Quite high typical of ³He SEPs
STEREO-B $^3$He-rich event (2011 July 1)

AR1244 (NOAA SWPC)

July 1 & CIR (all $^4$He) events

Mass histogram reveals clear $^3$He peak.

- $^3$He-rich SEPs preceded by an electron event
- associated with B-class X-ray flare
STEREO-B $^3$He-rich event: Solar Source

- Identify connection region on Sun
  - Parker spiral for IP space - determines s/c foot-point longitude on SS
- PFSS model for corona based on SDO magnetograms (Schrijver & DeRosa 2003)
- check with in-situ magnetic polarity
- examine SDO & STEREO EUVI

Schatten et al. (1969)
STEREO-B $^3$He-rich event: Solar Source

Taking into account in-situ polarity STEREO-B could be connected to the both ARs 1243 & 1244.

- marked brightening in AR 1244 but no significant activity in AR 1243
- AR 1244 - the most probable candidate for the $^3$He event.
ACE $^3$He-rich events (2011 July 7 & July 9)

<table>
<thead>
<tr>
<th></th>
<th>Jul 7</th>
<th>Jul 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vel. disper</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Electrons</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>X-ray flare</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>CIR</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>IMF polar</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Pizzo (1978)
ACE July 7 $^3\text{He}$-rich event: Solar Source

ACE connected to same AR as STEREO-B.

- the same AR was producing energetic electrons & $^3\text{He}$ after almost 7 days
- this is 1st ever example of such long lasting energetic particle production in solar flare

4-min diff. images around X-ray flares
AR checked with STEREO-A EUVI
ACE July 9 $^3$He-rich event: Solar Source

In-situ polarity: ACE connected to low-latitude CH

Time of particle release on the Sun unknown – no X-ray flare & solar electrons, $^3$He onset dispersionless.
**ACE July 9 $^3$He-rich event: Solar Source**

- type III burst at the time of the jet
- escaping electrons reached 1 AU
- ACE not connected to AR 1246
- $^3$He onset - 8 hours after jet (consistent with travel time to 1 AU)
STEREO-A $^3$He-rich event (2011 July 16)

- no solar electron event before $^3$He increase
- the onset dispersionless
- only slight anisotropy; reflecting boundary beyond the observer
- ion intensities start at the stream interface with a maximum in the vicinity of CIR trailing edge
- such features typically observed in CIR events
- consistent with simulations of $^3$He-rich SEPs in CIRs (Kocharov et al. 2003, 2008)
STEREO-A $^3$He-rich event: association with CIR

$^3$He-rich SEPs could be trapped and re-accelerated in CIRs
STEREO-A $^3$He-rich event: Solar Source

STEREO-A connected to same CH as ACE during July 9 event
STEREO-A $^3$He-rich event: Solar Source

- the brightenings coincide with type III
- escaping electrons reached 1 AU
- STEREO-A not on field lines connected to AR 1246
- candidates for populating the CIR
Summary

• the study for the 1st time presents observations of:

  1. solar regions with long-lasting conditions for $^3$He acceleration
  2. solar energetic $^3$He that is temporary confined/re-accelerated in interplanetary space

• the two examples show that solar regions with different size/morphology/flaring could produce a $^3$He-rich event

• with new high cadence images on multiple s/c the properties of $^3$He solar sources could be probed as never before
Next study: other recurring $^3$He-rich SEPs?

We have identified another 11 cases when $^3$He-rich SEPs from the same AR were consecutively seen on ACE and STEREO-A.

### 2010-2012 events

<table>
<thead>
<tr>
<th>Year</th>
<th>Start time</th>
<th>$^3$He/$^4$He</th>
<th>Fe/O</th>
<th>$^3$He Fluence (x10$^3$)</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Jan 27.3</td>
<td>0.13±0.02</td>
<td>0.58±0.10</td>
<td>5.72±0.83</td>
<td>1041</td>
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<tr>
<td>2010</td>
<td>Feb 2.8</td>
<td>0.29±0.04</td>
<td>0.57±0.21</td>
<td>7.78±0.91</td>
<td></td>
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<tr>
<td>2010</td>
<td>Feb 8.7$^b$</td>
<td>0.21±0.02</td>
<td>0.89±0.16</td>
<td>21.5±1.6</td>
<td>1045</td>
</tr>
<tr>
<td>2010</td>
<td>Feb 14.3</td>
<td>0.54±0.05</td>
<td>1.50±0.34</td>
<td>16.0±1.3</td>
<td></td>
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<tr>
<td>2010</td>
<td>Oct 17.9</td>
<td>0.46±0.04</td>
<td>1.27±0.23</td>
<td>21.0±1.6</td>
<td>1112</td>
</tr>
<tr>
<td>2010</td>
<td>Oct 21.4</td>
<td>1.12±0.24</td>
<td>2.25±1.35</td>
<td>4.48±0.69</td>
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<tr>
<td>2010</td>
<td>Oct 17.9</td>
<td>0.46±0.04</td>
<td>1.27±0.23</td>
<td>21.0±1.6</td>
<td>1112</td>
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<tr>
<td>2010</td>
<td>Oct 24.6</td>
<td>0.16±0.03</td>
<td>1.17±0.65</td>
<td>3.52±0.61</td>
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<tr>
<td>2010</td>
<td>Nov 14.6</td>
<td>0.20±0.02</td>
<td>1.20±0.18</td>
<td>26.3±1.8</td>
<td>1124</td>
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<td>2010</td>
<td>Nov 22.4</td>
<td>1.24±0.16</td>
<td>1.00±0.43</td>
<td>13.8±1.2</td>
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<td>2010</td>
<td>Nov 17.7</td>
<td>2.75±0.33</td>
<td>1.25±0.34</td>
<td>32.8±2.0</td>
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<td>2010</td>
<td>Nov 22.4</td>
<td>1.24±0.16</td>
<td>1.00±0.43</td>
<td>13.8±1.2</td>
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<td>2011</td>
<td>Jan 27.9</td>
<td>0.08±0.01</td>
<td>1.15±0.18</td>
<td>10.7±1.1</td>
<td>1149</td>
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<tr>
<td>2011</td>
<td>Feb 1.8</td>
<td>0.09±0.02</td>
<td>4.67±2.97</td>
<td>1.71±0.43</td>
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<tr>
<td>2011</td>
<td>Apr 29.8</td>
<td>0.02±0.01</td>
<td>3.90±0.62</td>
<td>0.95±0.34</td>
<td>1197</td>
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<tr>
<td>2011</td>
<td>May 6.4</td>
<td>3.90±0.62</td>
<td>1.43±0.70</td>
<td>18.5±1.4</td>
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<tr>
<td>2011</td>
<td>Jul 9.0</td>
<td>2.35±0.13</td>
<td>1.31±0.20</td>
<td>127±4</td>
<td>1246</td>
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<tr>
<td>2011</td>
<td>Jul 16.4</td>
<td>3.28±0.20</td>
<td>1.13±0.28</td>
<td>105±3</td>
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<tr>
<td>2012</td>
<td>Jan 7.3</td>
<td>1.33±0.26</td>
<td>1.67±1.22</td>
<td>7.15±0.92</td>
<td>1392</td>
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<tr>
<td>2012</td>
<td>Jan 16.0</td>
<td>0.82±0.22</td>
<td>7.36±0.89</td>
<td>2.45±0.51</td>
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<tr>
<td>2012</td>
<td>Apr 24.9</td>
<td>0.11±0.01</td>
<td>0.97±0.18</td>
<td>23.4±1.7</td>
<td>1461</td>
</tr>
<tr>
<td>2012</td>
<td>May 2.0</td>
<td>0.05±0.01</td>
<td>0.97±0.18</td>
<td>7.36±0.89</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Nov 20.5</td>
<td>6.72±0.52</td>
<td>0.89±0.16</td>
<td>154±4</td>
<td>1613</td>
</tr>
<tr>
<td>2012</td>
<td>Nov 30.9</td>
<td>0.80±0.27</td>
<td>1.60±0.41</td>
<td>154±4</td>
<td></td>
</tr>
</tbody>
</table>

Properties of associated jets investigated by Martina Chen (new postdoc at MPS).
Next study: what type of flaring?

Long-lasting $^3$He source: ACE Feb 8, STEREO-A Feb 14 - 08 UT

- where is the source of $^3$He in large ARs?
- is always newly emerging (small) region required for $^3$He production?
Thank you !