# Energetic Ions from Corotating Interaction Regions During Small Solar Events in May 2007

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***Abstract*— Using SIT instrument on STEREO we have surveyed abundances and energy spectra of $\sim 0.1-1.0\,\mathrm{MeV/n}$ heavy ions in two corotating interaction regions (CIRs) on May 18 (CIR1), and May 24 (CIR2), 2007, that occurred during two weak solar energetic particle (SEP) events. The intensity increases related to the CIR2 were much more pronounced compared with those associated with the CIR1, although the total pressure,the magnetic field magnitude and the speed difference between high and slow solar wind were less enhanced. We found that a ratio of $\mathrm{He}$ CIR2 and CIR1 fluences decreases with energy as a power-law below $\sim 1\,\mathrm{MeV/n}$ and the energy spectra of $\mathrm{H}$ and $\mathrm{He}$ inside the CIR2 are much softer compared to the spectra in the CIR1 region. On the basis of this we assume that larger intensities in the CIR2 could be due to additional source population. The abundances within the CIR2 and in the high speed streams of CIR1 region resembled a SEP event composition and the energy spectra of $\mathrm{H}$ and $\mathrm{He}$ inside the CIR2 were close to the preceding SEP event spectra. The similarity in the elemental composition and in the spectral slopes suggests that CIR2 has as seed population ions from the preceding SEP event while for CIR1 event we consider contamination by the SEPs.**

## I. Introduction

The interaction of the high-speed streams (HSSs), emerging from solar coronal holes, with upstream slow-speed streams leads to the formation of compression regions called corotating interaction regions (CIRs), and a pair of forward and reverse shocks is formed after collision usually beyond $\sim 2\,\mathrm{AU}$ [1]. These shocks presumably accelerate particles up to a few $\mathrm{MeV/n}$ in energy. In particular, energetic ions observed in HSSs at $1\,\mathrm{AU}$ are expected to be energized at the CIR reverse shocks and propagate back toward the Sun [2].

The elemental composition of the accelerated particle population associated with CIRs is still a puzzle. Although some of the elemental ratios (*e.g.* $\mathrm{Fe/O}$) are similar to those found in the solar wind, other ratios like $\mathrm{He/O}$ or $^3\mathrm{He}/^4\mathrm{He}$ are significantly enhanced [3]. The recent surveys suggest that low-energy solar flare particle may provide a seed population for CIR acceleration leading to the intensity increasing in the CIR events [4], [5], destroying the correlation between the ion intensity and the shock compression ratio [6], and explaining the overabundance of $^3\mathrm{He}$ [3].

Two weak SEP events which occurred between onsets of two CIR events on May 18 and 24, 2007 at solar activity minimum, present an ideal opportunity for research on a source population accelerated by CIRs. Also at this time STEREO-A, at $0.96\,\mathrm{AU}$, and STEREO-B, at $1.06\,\mathrm{AU}$, monitored the energetic ions while residing at heliocentric longitudes of W06 and E03, respectively, near the ecliptic plane. In this work we have surveyed solar particle and CIR associated events in the above mentioned period, examining the temporal variations of particle fluxes, energy spectra, and calculated abundances in the flares and CIR populations.

## II. Observations

The measurements presented here were made with the Suprathermal Ion Telescope (SIT) [7] onboard two STEREO spacecraft, A and B, launched in October 2006. SIT is a time-of-flight mass spectrometer with a geometric factor of $0.29\,\mathrm{cm}^2\mathrm{sr}$, a $10\,\mathrm{cm}$ flight path which measures H to Fe ions from $20\,\mathrm{keV/n}$ to several $\mathrm{MeV/n}$. For our study we further use energetic hydrogen ions measured by the LET instrument [8], solar wind measurements from the PLASTIC instrument [9], and magnetic field measurements obtained by the magnetometer [10].

### A. Corotating interaction regions

Figure 1 shows two CIR events observed by the SIT on STEREO, together with related solar wind plasma and magnetic field parameters from PLASTIC and magnetometer sensors. The top panels show hourly averaged values of the $0.16\,\mathrm{MeV/n}$ to $0.91\,\mathrm{MeV/n}$ $\mathrm{He}$ intensities. The bottom panels show $10-\mathrm{min}$ averages of total pressure $P$, the magnetic field magnitude $|B|$, and the solar wind speed $V_p$. The pair of vertical dashed lines marks the CIR leading and trailing edge, bounding the region of enhanced plasma densities and magnetic field intensities that precede the HSS and define the CIR itself [11]. The edges of May 17 CIR (hereafter CIR1) were adopted from the List of CIRs in Level 3 data [12]. The interplanetary medium in vicinity of STEREO spacecraft on May 22-23, 2007 was influenced by the presence of a interplanetary coronal mass ejection (ICME) and other CIR (hereafter CIR2). The time transit of the ICME, reported in the List of ICMEs (Level 3 data), is indicated by gray shaded region in Figure 1.

Figure 1 shows that the CIR1 resulted from interaction between $\sim 300\,\mathrm{km\,s^{-1}}$ slow and $\sim 670\,\mathrm{km\,s^{-1}}$ high speed solar wind flows as monitored by both satellites. The CIR2 HSS ($\sim 710\,\mathrm{km\,s^{-1}}$ and $660\,\mathrm{km\,s^{-1}}$ as sampled by STEREO-B and -A), separated from preceding stream less than a quarter of a solar rotation, interacted with the faster slow solar wind ($>$

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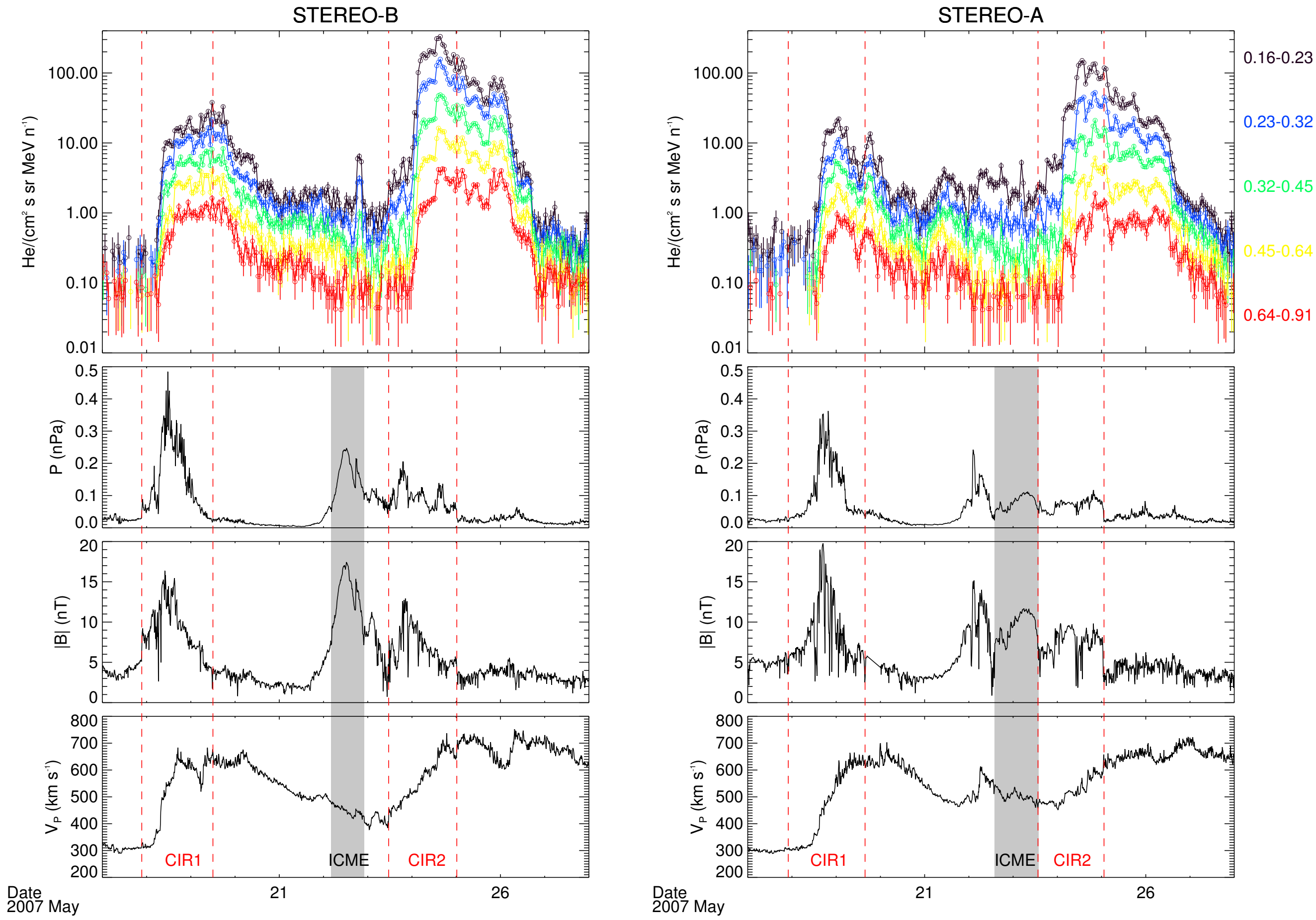


Fig. 1. STEREO-B (left) and STEREO-A (right) measurements associated with two CIR events. Top panel: Hourly averaged He intensities between 0.16 and $0.91\,\mathrm{MeV/n}$ measured by SIT for the period May 17-27, 2007. Panels 2 - 4: $10-\mathrm{min}$ averages of the total pressure $P$, the magnetic field magnitude $|B|$, and the solar wind speed $V_p$.

$400\,\mathrm{km\,s^{-1}}$ when seen from STEREO-B and $\sim 470\,\mathrm{km\,s^{-1}}$ when seen from STEREO-A).

Richardson et al. [11] observed near quiet time ion fluxes in CIRs when two streams were closely spaced in heliolongitude. They noted that this prevents the proper formation of the corotating shocks since interaction is between two HSSs rather than between slow and high-speed solar wind. The correlation between the intensity of CIR ions and speed-difference of high-speed solar wind from preceding slow solar wind in the quiet phase of solar activity was shown in the study by Kobayashi et al. [13].

As Figure 1 shows enhancements in the He intensity associated with region CIR2, with the smaller difference in solar wind speeds ($\sim 300\,\mathrm{km\,s^{-1}}$ at satellite B and $\sim 190\,\mathrm{km\,s^{-1}}$ at satellite A), were much more pronounced when compared with those associated with the CIR1, where speed-difference ($\sim 370\,\mathrm{km\,s^{-1}}$ at both spacecraft) was significantly higher. We also note that inside CIR1, the field magnitude and the total pressure were greatly enhanced when compared with the corresponding measurements inside CIR2.

In order to quantitatively describe an overabundance of energetic ions in the region CIR2, the ratio of He fluence ($/\mathrm{cm^2\,sr\,MeV/n}$) associated with CIR2 and CIR1 is plotted for different energies in Figure 2. The circles depict the ratios for fluences integrated only inside CIR and the squares are for the entire time period of the flux enhancement, both inside the CIR and in the HSS. As Figure 2 shows, at $0.19\,\mathrm{MeV/n}$ the He fluence within CIR2 is more than one order of magnitude higher than fluence inside CIR1. Below $\sim 1\,\mathrm{MeV/n}$ an overabundance of He ions decreases with energy, roughly linearly in log-log scale (with approximate slope $-1$), to the factor of 4.5 at $0.77\,\mathrm{MeV/n}$.

### B. *Solar energetic particles*

Figure 3 plots STEREO-A hourly averages of the $320\,\mathrm{keV}$ to $10\,\mathrm{MeV}$ proton intensities measured by SIT and LET. The dashed vertical lines in proton panels separate intervals (numbered from 1 to 7), where SIT intensities are believed to be dominated by contributions from different ion populations. The increases in time period (1), with peak inside CIR1

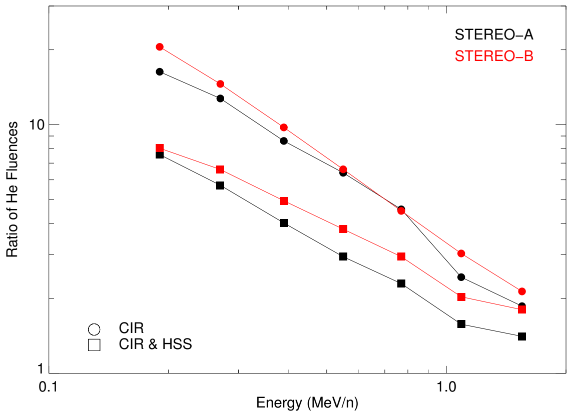


Fig. 2. The ratio of CIR2 to CIR1 He fluence as a function of energy for integration inside CIRs (circles) and over the CIRs and HSSs (squares).

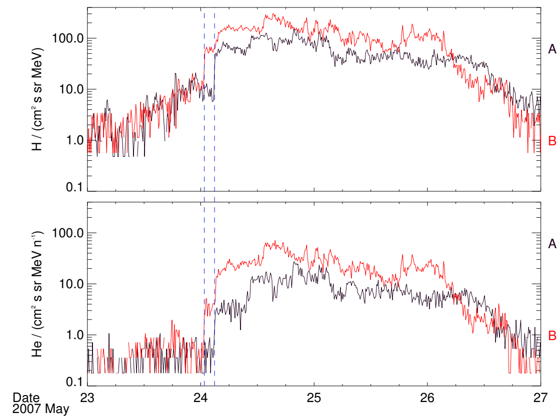


Fig. 4. 10 −min averaged H and He intensities at $0.32 - 0.45\,\mathrm{MeV/n}$ on STEREO-A (black) and B (red).

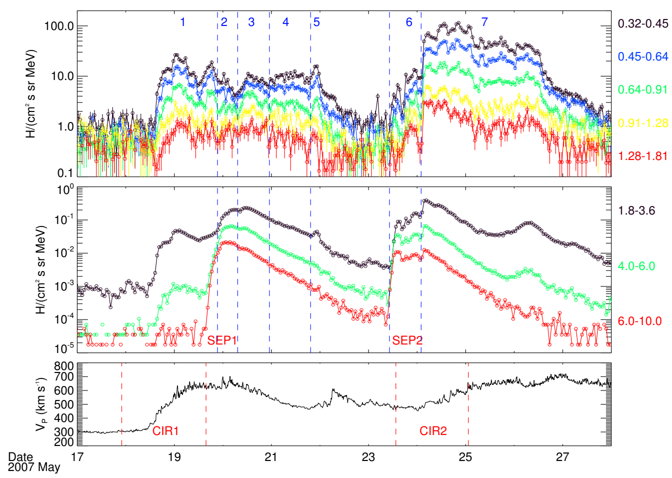


Fig. 3. Hourly averaged proton intensities between 0.32 and 10 MeV measured by SIT (upper panel) and LET (mid panel) on STEREO-A. Bottom panel: The solar wind speed $V_p$.

and in the HSS, were observed up to energy of $\sim 6\,\mathrm{MeV}$ and are presumably CIR related. The SEP event, identified by intensity onset of $6 - 10\,\mathrm{MeV}$ protons at 1630 UT on May 19 (hereafter SEP1) was associated with a B9.5 flare at W05 (Solar Geophysical Data), and with GOES X-ray flux maximum at 1302 UT on May 19. The low energy protons measured by SIT show no clear response to the SEP1 event. Around the intensity maximum of $6 - 10\,\mathrm{MeV}$ protons, time period (2), the fluxes in the SIT energy channels continued to decrease or remained flat, indicating that CIR low-energy ions may still dominate in the interval (2). Another, a B6.7 flare at 0556 UT on May 20 from the same active region also injected particles into the interplanetary medium [14], and may cause a additional rise at all energies observed in the interval (3). In period (4), high energy proton fluxes decreased gradually, while at lower energies ($< 1.28\,\mathrm{MeV}$) they remained essentially constant. Here likely connection to the CIR1 reverse shock sill exists. In the end of May 21, marked by (5), intensity below $3.6\,\mathrm{MeV}$ showed minor local increase, probably associated with interplanetary (IP) shock, that passed by the STEREO-A at 0159 UT on May 22 (listed in Level 3 data). Small enhancements in SIT energy channels within interval (6) were related to the next SEP event (hereafter SEP2), with $6-10\,\mathrm{MeV}$ proton intensity onset at 1030 UT on May 23, and associated with a B5.3 flare at W51 that peaked at 0732 UT. At lower energies the SEP2 event increase within period (7) was most likely overwhelmed by CIR event protons. Note, the $6-10\,\mathrm{MeV}$ peak intensity in our study is 4 orders of magnitude lower than median proton intensity at comparable energies in survey of the largest SEP events between 1977 and 1981 [15]. Comparing the $6-10\,\mathrm{MeV}$ proton peak intensities, the SEP2 event is about factor of 2 weaker than SEP1 event.

### *C. Solar versus CIR enhancement*

There may arise a question whether ion enhancements on May 24 which suddenly appeared quite a long time, $\sim 16\,\mathrm{hr}$, after onset of the SEP2 event, could not be of a solar flare origin. Figure 4 shows STEREO-A and B 10 −min H and He ion intensities in $0.32 - 0.45\,\mathrm{MeV/n}$ energy channel for period May 23-26, 2007. The approximate time delay of $\sim 2\,\mathrm{hr}$ between intensity onsets on A and B satellites on May 24 is marked by two vertical dashed lines. The increase was observed first by STEREO-B and later by STEREO-A. This is consistent with the expected co-rotation order for an interplanetary magnetic field line connected to the CIR source. In addition, the reverse situation was observed for the onset of $6-10\,\mathrm{MeV}$ SEP2 event protons. Mewaldt et al. [16] reported that in the 23 May 2007 SEP event the protons arrived more than $1\,\mathrm{hr}$ later on STEREO-B.

If CIR associated, the particle fluxes would by more pronounced on larger distances from the Sun due to positive radial gradients of CIR fluxes reported by Christon and Simpson [17]. Indeed, as shown in Figure 4, starting from May 24, ion fluxes observed by STEREO-B, located on $0.1\,\mathrm{AU}$ onward from A, are higher than fluxes on STEREO-A. On May 26,

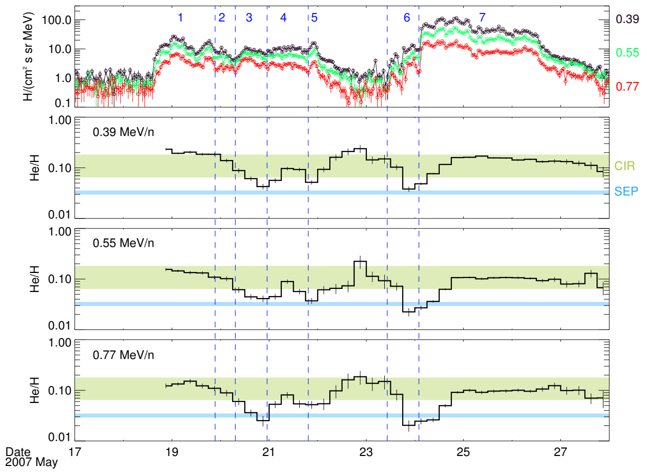

Fig. 5. Upper panel: Same as upper panel in Figure 3, but only at energies between 0.32 and 0.91 MeV. Panels 2-4: six-hour averaged He/H ratio.

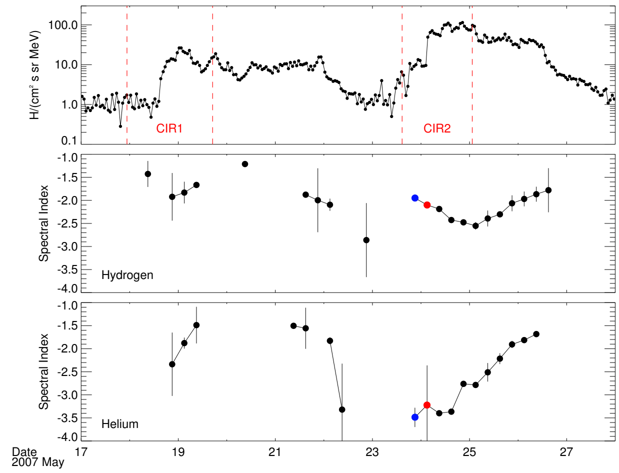

Fig. 7. Upper panel: Same as upper panel in Figure 6. Panels 2 and 3: six-hour H and He power-law spectral indices.

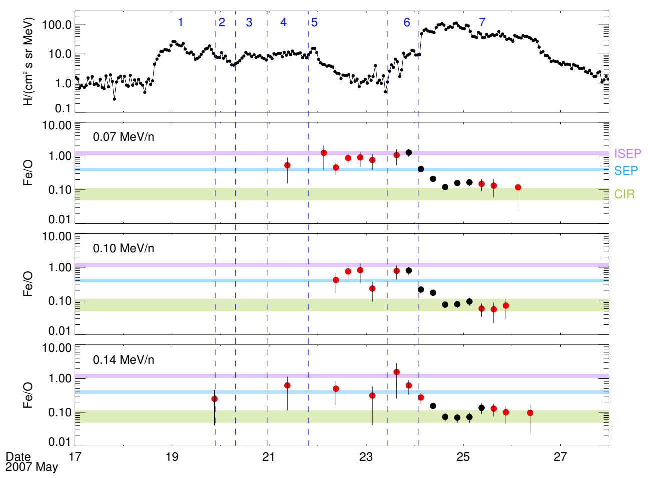

Fig. 6. Upper panel: Same as upper panel in Figure 3, but only at $0.32 - 0.45\,\mathrm{MeV}$. Panels 2 - 4: six-hour averaged Fe/O ratio.

fluxes on satellite B dropped below intensity measured aboard A. Note, on May 23 during the SEP2 event the ion fluxes on A and B satellites were on average equal.

### *D. Relative ion abundances*

*1)* He/H *ratio:* Upper panel in Figure 5 shows hourly proton intensities measured by SIT on STEREO-A in three energy channels. Lower panels display six-hour He/H ratios at corresponding energies with error bars indicating statistical uncertainties. The green and blue bands show ranges of He/H ratios measured in CIR [18] and SEP events [19], respectively. Inside the CIR1 region - period (1), the ratio remained between 0.1 and 0.2, close to CIR event ratio of $0.125 \pm 0.061$ for $0.15\,\mathrm{MeV/n}$ [18]. Around the SEP1 event intensity peak, time period (2), the ratio showed only minor decrease, still remaining at the CIR abundances. Interestingly, the He/H reached minimum in the end of interval (3), during the decay phase of SEP1 event. Here ratio is close to the SEP event ratio of $0.032 \pm 0.003$ for $> 0.3\,\mathrm{MeV/n}$ [19]. Within period (4), the ratio increased to the CIR-like values. The presence of the IP shock ions, marked by (5), is accompanied by the local decrease of He/H towards the SEP-like values. The enhanced ratio occurred during the ICME transit on May 22-23, 2007. In the mid of the interval (6), after the rise phase of the SEP2 event, the ratio dropped to the SEP event like values. At beginning of region (7), when inside CIR2, the He/H still remained around the SEP event ratio. The He/H reached the CIR-like values near the CIR2 trailing edge and remained relatively constant in the fast solar wind.

*2)* Fe/O *ratio:* Figure 6 plots six-hour heavy ion Fe/O abundance ratios in three energy channels between 0.06 and $0.16\,\mathrm{MeV/n}$. The red circles indicate ratios with statistical error greater than 35%. Note, in some six-hour intervals during the period of CIR1 and SEP1 events, there were no measurable intensities either in oxygen or iron mass bins. For reference, hourly proton SIT intensities at $0.39\,\mathrm{MeV}$ are shown in the upper panel. The green, blue and violet bands present ranges of Fe/O ratios for CIR [18], SEP [20], and $^3$He-rich or impulsive SEP (ISEP) events [21], respectively. Figure 6 shows that Fe/O was close to ISEP/SEP ratio on May 22-23 at times of ICME transit. The Fe abundance near the ISEP (SEP) Fe abundance in the period (6) was associated with the SEP2 event and similarly to He/H, the Fe/O ratio was still close to SEP-like ratios at beginning of period (7). Around the mid of May 24 (still inside CIR2), when SEP2 event continued to decline, the Fe/O approached the CIR-like ratio and remained at this value outside the compression region.

### *E. Energy spectra*

Figure 7 shows spectral indices obtained from fitting power laws in energy to H, and He intensities over the range $0.32 - 1.81\,\mathrm{MeV/n}$ and $0.16 - 0.91\,\mathrm{MeV/n}$ for each 6 hr time interval between May 17 and May 27, 2007. Only indices

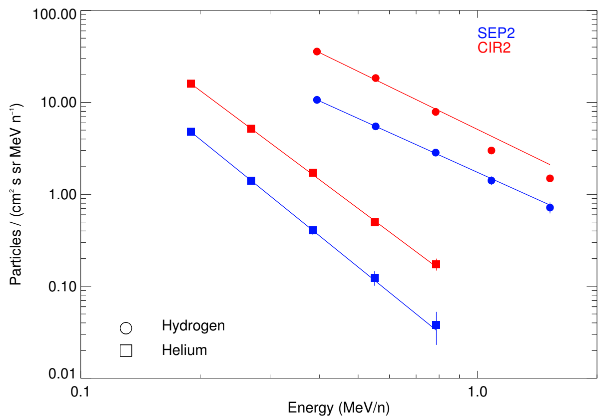


Fig. 8. The SEP2 and CIR2 energy spectra for H (circles) and He (squares). The lines are power-law fits.

with statistical errors less than $35\%$ are included in figure. One-hour H intensities at $0.32 - 0.45\,\mathrm{MeV}$ are shown for reference in the upper panel. The SEP2 event index at 18-24 UT on May 23, and CIR2 event index at 00-06 UT on May 24 are marked by blue and red, respectively. The H (He) spectral index associated with the SEP2 event, $-1.95 \pm 0.05$ ($-3.49 \pm 0.21$), showed only a little change to $-2.10 \pm 0.01$ ($-3.22 \pm 0.86$) over the next $6\,\mathrm{hr}$, even though related fluxes suddenly raised in all energy channels (see Figure 3).

Figure 8 shows energy spectra related to SEP2 and CIR2 events, discussed in previous paragraph. The He spectra show clear power-law shape. While the H spectrum for SEP2 event shows power-law shape, that for the CIR2 event changes around $1\,\mathrm{MeV/n}$. The power law spectral shape below $1\,\mathrm{MeV/n}$ and steepening of the spectrum above $1\,\mathrm{MeV/n}$ have been reported for H and He CIR ions [22].

The average energy spectral slope inside CIR2 at 00-24 UT on May 24 is $-2.30 \pm 0.01$ for H and $-3.19 \pm 0.22$ for He. The corresponding values derived for CIR1 between 1800 UT on May 18 and 1200 UT on May 19 are fairly harder, $-1.81 \pm 0.19$ for H and $-1.90 \pm 0.27$ for He. Below $\sim 1\,\mathrm{MeV/n}$ the spectral forms of CIR heavy ions are fitted with power-law with index of $-2.51 \pm 0.10$ [3]. The energy spectra of heavy ions form SEP events are typically harder with slopes ranging from $-1.0$ to $-1.5$ [21], [23].

## III. Discussion

### A. CIR2 event

As pointed out by Scholer, Morfill and van Hollebeke [24] and Desai et al. [6] the intensity of particles accelerated at the corotating shocks is determined only by the intensity of seed particles and the acceleration strength of the shock. In Section II-A we have shown that the speed difference between high and slow solar wind, probably related to the shock strength [13], was less enhanced in the CIR2 region. The similar feature is seen for total pressure and magnetic filed magnitude. From these observations we may assume that acceleration strength of CIR2 region beyond $1\,\mathrm{AU}$ may not be higher than that of CIR1 compression region. In addition, a harder spectra found in the CIR1 compared to the spectra in CIR2 may suggest a higher acceleration strength for the CIR1 region. On the basis of this, one would expect that if shock strengths for CIR1 and CIR2 are even similar and higher intensities are observed in association with compression region CIR2, than these shocks should accelerate particles out of seed populations with different intensities. In view of previous we consider following scenario that might account for the observations shown in Figure 2. The overabundance of the He fluences associated with CIR2 and its power-law decrease below $\sim 1\,\mathrm{MeV/n}$ probably reflects an additional particle population, not available for CIR1 acceleration.

Since SEP2 event is a western hemisphere event, STEREO is supposed to be well-connected to the nose of the shock early in the event and see rapid rise and decline [25]. A rather complex intensity-time profile has been observed at the highest energies with rapid rise and plateau in the period (6), and decline with CIR-ions contribution in the period (7) (see Figure 3). In spite of this it is likely that SEP2 ion fluxes, as measured by SIT, attained peak values within interval (6) and continued to decay in period (7). The H and He intensities in the interval (6) are one order of magnitude lower than intensities at the beginning of interval (7). Thus it is hardly for solar ions with intensities as observed in (6) substantially affect the CIR elemental composition in the period (7). Rather, observed SEP-like abundances of H, He, O, and Fe ions inside CIR2 may result from energizing of the low-energy *i.e.* more abundant solar flare ions. This is further supported by similarity of the corotating and the preceding solar event spectra. The ratio of CIR to flare spectral index is 1.08 for H and 0.92 for He, close to unit as would be predicted by Axford [26], if CIR-shock accelerated particles were energized out of flare population with flatter spectrum than the CIR shock would produce.

### B. CIR1 event

Around the intensity peak-time of $6 - 10\,\mathrm{MeV}$ SEP1 protons (May 20, 0100 UT) the solar wind speed of $\sim 650\,\mathrm{km\,s^{-1}}$ corresponds to a $1.01\,\mathrm{AU}$ Archimedean spiral path length at location of the STEREO-A. If we assume that the ions would propagate scatter free along the interplanetary magnetic field spiral with a zero pitch angle, the expected intensity maximum of $0.6\,\mathrm{MeV/n}$ solar ions, the middle energy in our survey, would be delayed in $3\,\mathrm{hr}$ with respect to the $6 - 10\,\mathrm{MeV}$ intensity peak. However the He/H ratio has attained the closest approach to the SEP-like values at ~2100 UT on May 20 (see Figure 5), $\sim 17\,\mathrm{hr}$ after the expected flux maximum.

A possible explanation for our observations could be that a contamination by SEPs from the flare on May 20, occurred $\sim 17\,\mathrm{hr}$ after previous solar flare, may lead to the He/H minimum in the end of period (3). However, particle signatures at highest energies are very faint and are difficult to relate unambiguously to the May 20 flare. Since there were no clear anisotropy observed in rise phase of $\sim 100\,\mathrm{keV}$ electrons in the SEP1 event [14], an assumption on scatter free propagation may not be valid. The delayed SEP-like $\mathrm{He}/\mathrm{H}$ ratios at lower energies in respect to the solar flux maximum (at highest energies) may be a consequence of a small scattering mean free path between the Sun and $1\,\mathrm{AU}$. We have shown that CIR1 event is essentially weaker compared to the CIR2 event. Therefore a contamination by solar flare ions from SEP1 event may be important here.

## IV. Conclusion

We have surveyed particle events at energies from $\sim 0.1$ to $\sim 1.0\,\mathrm{MeV}/\mathrm{n}$, associated with two compression regions, CIR1 and CIR2, with corotating streams closely spaced in heliolongitude, which immediately precede and follows two weak SEP event onsets. We suggest that an overabundance of ion fluxes in association of the CIR2, where difference between high and slow speed flows is lower and plasma parameters are moderately enhanced relative to corresponding values for weaker CIR1 event, could be due to additional source population. The relative abundances for H, He, O, and Fe inside the CIR2 and $\mathrm{He}/\mathrm{H}$ ratio in the HSS of CIR1 region are very close to the solar energetic particle relative abundances both in the flare in this survey and in previously published solar flare surveys. The similarity in elemental abundances and spectral slopes suggests that CIR2 has as seed population ions from the preceding SEP event. The elemental abundances late in the CIR1 event could be explained by the SEPs contamination.

## Acknowledgements

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