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Spectral energy of multisource and multielement of solar energetic particles during the spotless days on solar cycle 24

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Abstract. We characterized solar energetic particle power-law spectra from selected two sunspotless events with more than 30 consecutive day’s length on July 21 to August 20, 2008 (31 days) and July 31 to August 31, 2009 (32 days) in the solar cycle 24. Their spectral of energetic interplanetary multielements of seven charge particles (H, He, C, O, Ne, Si, and Fe) from 15 keV to 0.5 GeV per nucleon have been compiled from onboard instruments of several satellites with different distances from the Sun (GOES, ACE, STEREO, and Voyager). Their spotless spectral energetic particles were also compared with appearances of AR12192, owing very large sunspot area (>2000 millionth of solar hemisphere) without foreshortening effect, on October 19-27, 2014. Our results from six charge elements show that there were intrinsic differences among those events on aspects of flux particles enhancement by double power-law or V-shape. Flux enhancements occurred after 10 MeV for sunspotless days and 20-30 MeV for AR 12192 passage. The effects of very strong magnetic field in AR 12192 influences two mechanisms, flux enrichment of charge particles in lower energy and on the contrary to inhibit streaming of particles in higher energy. It is suggested that interactions of multielements of solar energetic particles with interplanetary magnetic fields and plasma speed play an important role, as seen from the variations of rollover power-law of spectral energy.

1. Introduction
The Sun, as a star, emits wide range energies of photon and plasma particles or Solar Energetic Particles (SEPs). Solar energetic particles constitute a flock of multielement energetic plasma particles, which can be often observed in the near Earth space and heliosphere. They bear information about processes of energy enhancement and turbulence propagation of charged particles in the solar and heliospheric magnetic fields. Many studies concentrated on high energetic solar events related to flare, coronal mass ejection (CME), solar proton events (SPEs), shock, etc. which may abruptly cause relativistic events. Interplanetary SEP observations have already focused to study high-energy particles, plasma physics or space weather. In powerful plasma events, the particle fluxes occupy more than eight orders of magnitude and the energy range extends over more than four orders of magnitude, from MeV to tens of GeV. After more than a half century years, observation results have still remained unknown physical mechanism about plasma interactions and acceleration processes in the interplanetary space [1,2,3,4].

Energetic particles are accelerated near the Sun in at least two distinct locations, namely in solar flares via magnetic reconnection-driven mechanisms so-called impulsive SEPs [5] and at large-scale shock waves driven by fast coronal mass ejections or CMEs known as large gradual SEP events [6].
Their spectra yield a power-law energy spectrum [7]. The power-law index is fully determined by shock properties and is independent of species [8]. The slope of the spectrum of interplanetary fluctuations is important in that it gives us evidence for the dynamics of their evolution. However, the energy spectra often show breaks or rollover power-law at a few to tens of MeV per nucleon and having distinct characteristic in different species of charge particle. Moreover, energy spectra vary from event to event, with their formation, interactions and parameters, depending on the measurement time and location. These SEPs have larger fluences and are responsible for significant disturbances of space weather that can pose serious unrecoverable hazards to technological assets and humans in space. The behavior of the energy spectra in large SEP events is directly indicative of the intrinsic nonthermal radiation threat and has been the subject of many previous studies [9,10].

In this paper, we studied power-law properties of plasma with energy 15 keV–500 MeV per nucleon for seven charged species (H, He, C, O, Ne, Si, and Fe) spectra during at least 30 consecutive sunspotless days cases at July 21 to August 20, 2008 (31 days) and July 31 to August 31, 2009 (32 days) in solar cycle 24. We also compared those very quiet solar activity periods of sunspotless with 9 days passage of the largest area of Jupiter size active region (>2500 msh) on the solar disk, AR 12192 on October 19-27, 2014. All data have already been made publicly available by NASA using interface of The Virtual Energetic Particle Observatory (VEPO) - Multi-Source Spectral Plots (MSSP) of energetic particle (http://vepo.gsfc.nasa.gov/). We have used one hour temporal resolution for ACE [11], GOES 8-11, and STEREO A-B satellites [12], except Voyager 1-2 satellites with 6-hour resolution [13]. At altitude of 6.6 Re, GOES satellite is a geosynchronous satellite, so spacecraft are inside, but near (when on the day side), the Earth's magnetopause, so GOES energetic particle fluxes are representative of fluxes in the nearest interplanetary medium. ACE satellite orbit has a unique location called Lagrange point, or L1 at altitude 1.5x10⁶ km. This orbit is a gravity neutral point in space, allowing satellite to essentially hover between the Sun and Earth at all times, maintaining a constant view of the Sun and sun-lit side of Earth. Twin satellites STEREO A and B move along a distance of about 1 AU encircling the Sun with opposite directions. Voyager 1 and 2 satellites located at about 24 AU in year 2008 to 2009. For each satellite, it carried several instruments for specific range of energy spectra. The energy spectral points for each source were fitted to a simple power-law relation in logarithmic scale, log (flux) = log (A)+b*log (energy), where A and b are the fitting parameters, which are determined by a linear least squares fit.

2. Distribution of proton speed, density, electric field, and beta ratio
Figure 1 shows proton speed, density, electric field, and beta ratio distribution during two periods of one-month spotless days and passage of the largest area of sunspot group AR 12192 on solar disk. They revealed a similar pattern in density distribution. The last event blew up the fastest average proton speed of (442.32±65.79) km/s with shifted top speed distribution and the lowest density of (4.60±2.07) particles/cm³. Spotless days of July 31-August 31, 2009 generated the lowest average plasma speed and the largest density of (384.29±65.92) km/s and (5.58±3.10) particles/cm³, respectively. On the other hand, spotless days on July 21-August 20, 2008 caused (430.41±100.65) km/s and (5.00±3.53) particles/cm³ for average speed and density, but it poured out up to 30 particles/cm³. Median of electric field strengths were -0.03 mV/m, -0.07 mV/m for spotless day’s period in year 2008 and 2009, and significantly increased to 0.55 mV/m for passage days of AR 12192. Electric field is guided by plasma speed and magnetic field in Z-axis component or Bz (in GSM coordinates). The negative value of Bz denotes southward direction of interplanetary magnetic field. It means that AR 12192 had the strongest positive Bz, and in year 2009 was the smallest variations of electric field with negative Bz. Moreover, influence of strong magnetic field during passage of AR 12192 was also pointed out by minimum value of interplanetary beta ratio with median 1.11, compared with sunspotless days in year 2008 with median 2.35, and year 2009 with median 2.57. Small value of dimensionless parameter beta ratio indicates stronger magnetic filed pressure than gas pressure, and vice-versa. These interplanetary magnetic field environments will subsequently have impact on spectral energetic particles, as described below.
Figure 1. Distribution of proton speed (a; top-left), density (b; top-right), electric field (c; below-left), and beta ratio (d; below-right) during spotless days on July 21-August 20, 2008 (N=792; red diamond), July 31-August 31, 2009 (N=768; black circle), and AR 12192 (N=216; blue triangle).

Figure 2. Spectra energy of proton and flux in logarithmic scale during spotless days on July 21-August 20, 2008 (top-left) and July 31-August 31, 2009 (top-right), during passage of the largest active region AR 12192 on October 19-27, 2014 (bottom). Symbols refer to GOES 8-11 (black triangle), Voyager 1-2 (red filled-circle), ACE (blue diamond), STEREO (open circle) satellites.
3. Multisources of proton spectra energy

Figure 2 shows spectra energy for spotless days in years 2008 and 2009 for different satellites. In the range of energy 0.03 – 300 MeV, we can obtain similar parameter slopes of -1.74 and -1.77, respectively. The peak of proton flux (with $4.11 \times 10^{11}$ particles/(sec cm$^2$ ster MeV/n)) appeared at very low energy of 619 eV, that observed by ACE satellite in year 2009. See figure 2b.

Homogenous proton spectra energy penetrated across interplanetary region or heliosphere up to 24 AU during spotless days, as detected by Voyager satellites. In the figure 2c, during the passage on the solar disk of the largest area of sunspot group AR 12192 on October 19-27, 2014, gradient reached to -1.95, which was slightly steeper than two periods of sunspotless day. A broken power-law can be seen for energy larger than 10 MeV, which has a slope of -2.1, then rollover with positive gradient.

4. Spectra energy of multielements

4.1. He

During sunspotless days in year 2008 and year 2009, gradients or He (alpha particle) power spectra were -3.31±0.22 and -2.54±0.24 (0.01 MeV<E<10 MeV), respectively. Passage of AR 12192 gave more soft gradient of -2.21±0.11 (0.01 MeV<E<100 MeV). The peak of alpha particle flux took place at energy 1 keV with $2.84 \times 10^9$ particles/(sec cm$^2$ ster MeV/n), which were two-folds fewer than proton. See figure 3a. In general, spotless days supply more low energy alpha particles with higher rate through dominant open magnetic field structures. On the other side, alpha particles flux increased for higher energies by changing to positive power-law gradient. This particle injection will shift V-shape of higher energy spectra due to increasing particle flux.

4.2. C

In figure 3b, a similar V-shape power-law can be detected near 10 MeV for all spotless cases, and shifted to about 30 MeV for AR 12192 passages. However, they differed in their gradients. In case of AR 12192 passage, this event produced larger particle flux up to E<30 MeV, then decreased for E>30 MeV. Very large magnetic field strength of AR 12192 clearly shielded outward stream of high energetic particles. In year 2008, energy smaller and larger than 10 MeV contributed to power-law gradient -3.21±0.11 and 0.77±0.08, respectively. In year 2009, their gradients were -2.40±0.12 and 0.78±0.08, respectively. During AR 12192 passage, the turning point occurred with slopes -2.42±0.09 and 0.91±0.13 for smaller and larger than about 30 MeV, respectively. So, very strong magnetic field triggered larger positive gradient or increasing flux of C charge particles.

4.3. O

The turning point of a broken power-law shifted to a larger energy at about 20 MeV for spotless days and about 30 MeV for AR 12192. See figure 3c. Starting for 10 MeV, particle flux during sunspot group passage were gradually smaller than spotless days. In year 2008, power-laws were -2.21±0.07 and 0.46±0.05 for smaller and larger than about 20 MeV. A similar pattern in year 2009, their pairs were obtained -1.44±0.06 and 0.42±0.04. In year 2014 of AR 12192 passage days, gradients were -2.35±0.07 and 0.66±0.06 for smaller and larger than about 30 MeV, respectively. AR 12192 caused larger gradient of growing flux than spotless periods.

4.4. Ne

Shifted energy of V-shape power-law was similar to O element, also particle flux variations, as seen in figure 3d. Their gradient pairs were -1.31±0.17 and 0.57±0.06, -1.59±0.11 and 0.46±0.04, -3.25±0.14 and 0.96±0.17 for year 2008, 2009, and 2014, respectively. Spotless period significantly showed smaller positive gradient for Ne charge particles.
4.5. Si
Shifted energies of rollover power-law at 10 MeV and 20 MeV were similar to C element, also particle flux variations, as seen in figure 3e. Their power-law pairs were -1.70±0.20 and 0.52±0.06, -2.11±0.29 and 0.45±0.06, -2.79±0.15 and 0.74±0.10 for year 2008, 2009, and 2014, respectively.

4.6. Fe
Shifted energies of broken power-law from 10 MeV to 20 MeV were similar to C and Si elements, also particle flux variations, as seen in figure 3e. Their gradient pairs were -2.90±0.17 and 0.55±0.07, -2.51±0.21 and 0.55±0.06, -2.48±0.09 and 0.54±0.04 for year 2008, 2009, and 2014, respectively. For heavy element, the positive gradients were not depend on those two extreme conditions.

Figure 3. From left to right. Spectra energy of He - alpha particle (a), C (b), O (c), Ne (d), Si (e), and Fe (f) in logarithmic scale during sunspotless days on July 21-August 20, 2008 and July 31-August 31, 2009, during passage of the largest active region AR 12192 on October 19-27, 2014. Symbols refer to sunspotless in year 2008 (red diamond), 2009 (open circle), and AR 12192 (blue triangle)
5. Conclusions
We have clearly showed that there were shifted broken or V-shape power-law for two extreme cases of long sunspotless days and the largest sunspot area passage of AR 12192 for six charge elements. The turning point energy occurred at 10 MeV for sunspotless days and 20-30 MeV for AR 12192 passage. During the sunspotless days, less particle fluxes have been emitted than AR 12192-passage period in lower energy. Then, in higher energy, flux enhancements with positive gradient have been seen for all events, but more fluxes outpouring for sunspotless periods. Strong magnetic field obviously shielded energetic particle streaming.

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