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# Occurrence of $^{3}$He-rich Solar Energetic Particles near Earth and Closer to the Sun

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$^{3}$He-rich solar energetic particle (SEP) events, which result from the acceleration of energetic particles in association with reconnection events on the Sun, are identified on the basis of $^{3}$He/$^{4}$He enhancements of at least several orders of magnitude over the solar coronal value of ~0.04%. The ULEIS and SIS instruments on the Advanced Composition Explorer (ACE) have been measuring the occurrence of SEP $^{3}$He in the interplanetary medium near Earth over nearly two full solar cycles. The $^{3}$He isotope has been observed nearly 90% of the time at solar maximum, but no more than a few percent of the time at solar minimum. NASA's Parker Solar Probe (PSP) spacecraft was launched in August 2018 on a mission designed to include 24 close flybys of the Sun over seven years. PSP's scientific objectives include the study of the acceleration and transport of $^{3}$He-rich SEPs, and the spacecraft carries a two-instrument suite, IS⊙IS, that has the capability to perform these studies. The first two orbits of PSP occurred under extremely quiet solar-minimum conditions, which will provide an opportunity to search for small $^{3}$He-rich SEP events in the previously unexplored region <0.2 AU from the Sun under conditions with extremely low energetic-particle backgrounds. We present an update of the long-term record of SEP $^{3}$He occurrence near 1 AU and, with this context, discuss some advances that can be expected from PSP.

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## 1. Introduction

In "gradual" solar energetic particle (SEP) events, protons and heavy nuclei are accelerated by shocks driven by coronal mass ejections (CMEs). Some key early observations [1, 2] from NASA's Advanced Composition Explorer (ACE) mission showed that gradual SEP events sometimes include the isotope $^3$He at levels relative to $^4$He that greatly exceed the ratio found in the solar wind, ~0.04% [3]. These observations led to the suggestion that shocks preferentially accelerate suprathermal ions and that one important source of such suprathermals must be "impulsive" (magnetic-reconnection related) SEP events, which typically have $^3$He/$^4$He ratios that are orders of magnitude enhanced over the solar wind ratio.

It has been reported [4] that the rate of occurrence of impulsive SEP events near solar maximum must be large, ~1000/yr on the visible disk of the Sun (see also [5]). With a rate this high, it appeared plausible that there could be sufficient suprathermal $^3$He in the corona to account for the enhancements of this isotope observed in gradual events.

In a series of papers over the past 16 years [6, 7, 8], we reported results from an on-going study of how often $^3$He from impulsive SEP events can be observed at ACE. In this paper, we update the results from those earlier studies to cover the time period from August 1997 through June 2019. This period encompasses nearly two full ~11-year solar cycles, or one full ~22-year Hale cycle, which comprises two solar cycles with opposite polarities of the solar magnetic field.

## 2. $^3$He Near Earth

The ACE observations of SEP He isotopes come from two instruments, ULEIS, the Ultra-Low-Energy Isotope Spectrometer [9], which is optimized for energies below a few MeV/nuc, and SIS, the Solar Isotope Spectrometer [10], which makes measurements at higher energies. To identify time periods having SEP $^3$He, we construct mass spectrograms for each 27-day Bartels rotation [11], examples of which are shown in Figure 1. The upper two panels show data from a pair of energy intervals measured by ULEIS and the lower two show data from SIS. Signals from the various sensors that make up the two instruments are telemetered to the ground for individual detected particles. On the ground, we derive the particle charge, mass, and energy and accumulate He counts for each hour and each mass bin of width 0.2 amu. In each 1 hr $\times$ 0.2 amu interval, we show the number of accumulated counts. When the number of counts is low ($\leq$ 10) we plot a dot for each count and when the number exceeds this level we display the number using a logarithmic color scale.

We classify each time interval within each Bartels rotation according to whether it has 1) a statistically significant increase of $^3$He counts over background (for example, at MeV energies due to galactic cosmic ray $^3$He that has undergone solar modulation) and 2) minimal contamination due to spillover from $^4$He. We calculate the fraction of time with SEP $^3$He by dividing the total duration of the time periods that meet these criteria by the total observation time. There can be significant statistical variation in the derived time fraction among different Bartels rotations, even at the same phase of the solar cycle. This is attributable to short-term variations in solar activity.

Figure 2 shows the He mass spectrograms from the ULEIS high-energy interval for Bartels rotations 2240 through 2535, which cover the time interval from shortly after the launch of ACE in

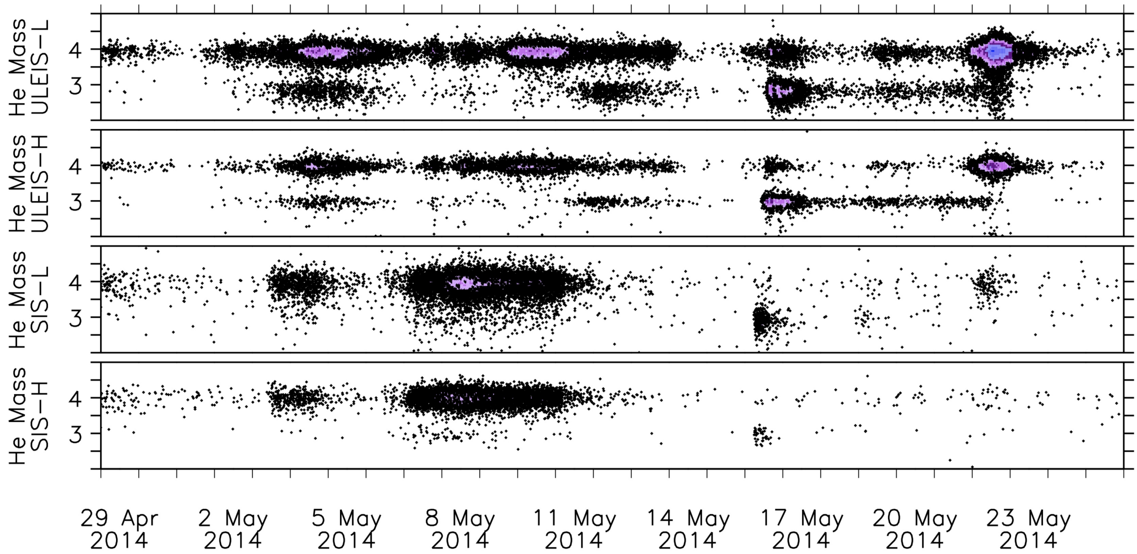


**Figure 1:** Helium mass spectrograms from Bartels rotation 2466 (29 Apr to 25 May 2014). From top to bottom, the four panels show data from the ULEIS low-energy (0.2–0.4 MeV/nuc) and high-energy (0.4–1.0 MeV/nuc) intervals and the SIS low-energy (4.5–7.6 MeV/nuc) and high-energy (7.6–16.3 MeV/nuc) intervals.

August 1997 through June 2019. The strong contrast between the years around the solar maxima and those around the solar minima is evident. Note that in the quietest years (e.g., 2009 and 2018), small $^4$He events are still fairly common, mostly due to acceleration in interplanetary co-rotating interaction regions (CIRs). However, there are essentially no $^3$He-rich events observed. This may be attributable, in part, to the much lower intrinsic size of $^3$He-rich events.

To study the longer-term trend in the $^3$He observations, we have averaged the Bartels-rotation results over half-year time periods. The resulting averages are plotted as the red points in Figure 3. During the years around the maxima of solar cycles 23 ($\sim$1999 through $\sim$2003) and 24 ($\sim$2012 through $\sim$2015), SEP $^3$He was detected more than $\sim$40% of the time. During some individual Bartels rotations, the occurrence was nearly $\sim$100%. In the subsequent solar minima, in 2009 and 2018, the $^3$He detections fell to $<$0.5% of the time. This strong contrast in $^3$He between solar maximum and solar minimum was also be seen in results from Reames [4, 5] for the 1985-88 solar minimum.

The time variation of sunspot number [12] is shown averaged over the same half-year intervals by the blue points in Figure 3. The two curves track one another remarkably closely, particularly when one considers that the $^3$He fractions have a ceiling of 100%. It is interesting to note that both curves have a small increase in their most recent data point, possibly providing early hints of the increase toward the cycle 25 maximum. During this most recent interval (January through June 2019), ULEIS observed small but clear $^3$He-rich SEP events in March and April.

The inset in Figure 3 contains the same data with the two dependent variables plotted versus one another, which again shows their close correlation. The red curve in the inset is a straight-line fit of the form $\ln(\%\text{ with }^3\text{He}) = c_0 + c_1 \times \ln(\text{SSN})$, which yielded coefficients $c_0 = -1.6831$ and

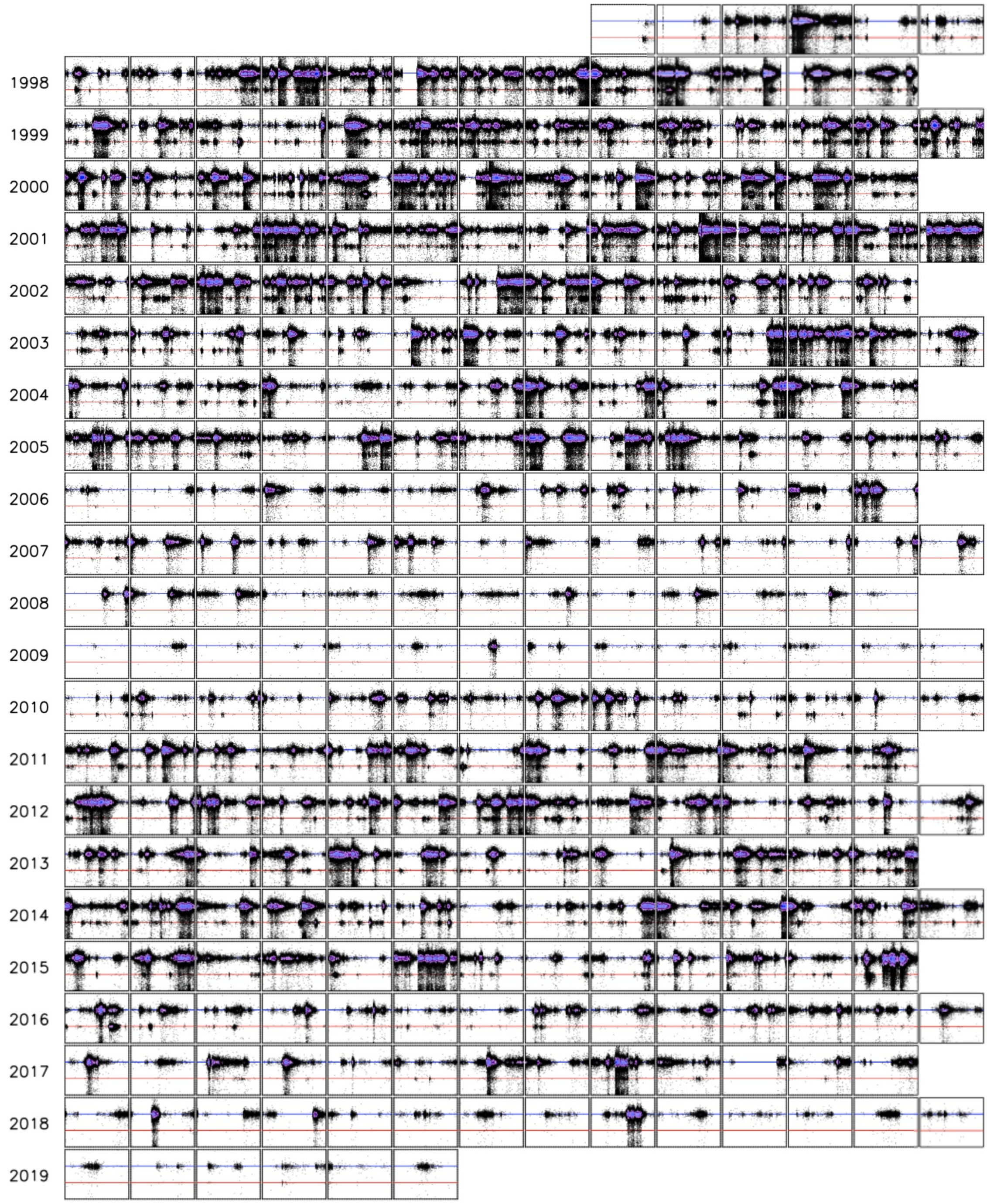


**Figure 2:** Collected He mass spectrograms from the ULEIS 0.4–1.0 MeV/nuc energy interval. Each panel covers one Bartels rotation. Each row starts with the first rotation that began in the indicated year. Red and blue lines indicate the nominal locations of He mass 3 and 4 isotopes, respectively. Dark vertical bands extending over most of the vertical range of a panel are mainly due to spillover associated with intense $^4$He events.

$c_1 = 1.2044$. In the next section, we use this fit in obtaining predictions for how the occurrence of $^3$He-rich events can be expected to increase over the next few years.

The quantitative association between $^3$He-rich SEPs and sunspots is not accidental. The magnetic configuration thought to lead to x-ray jets [13] and escape of accelerated particles into the interplanetary medium [14, 15] depends on reconnection between open field lines and emerging closed loops. Boundaries of active regions are natural locations for this topology to occur, and sunspots are visual indicators of active regions. In fact, it has been shown [16] that even under very quiet conditions, such as occurred in 2008, small $^3$He-rich SEP events are associated with active regions.

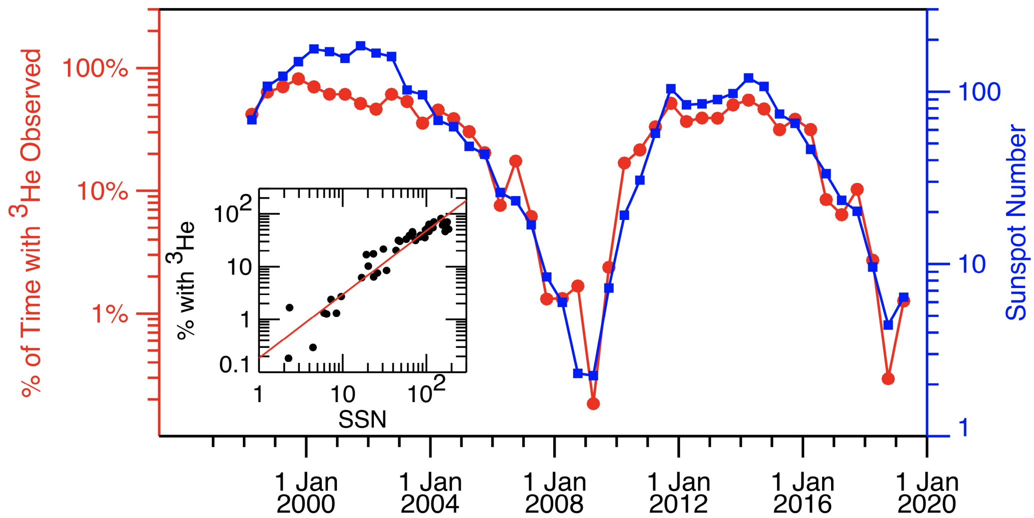


**Figure 3:** Variation of the fraction of time that $^3$He was observed by the ULEIS and SIS instruments on ACE (red) and of sunspot number (blue) over the past 22 years. The inset shows the two dependent variables plotted versus one another and a straight-line fit to this correlation.

## 3. $^3$He Closer to the Sun

The payload of NASA's Parker Solar Probe (PSP) spacecraft [17], which was launched in August 2018, carries a two-instrument suite called the Integrated Science Investigation of the Sun (IS⊙IS) [18] designed to study the solar energetic particle environment close to the Sun. As of July 2019, PSP had completed the first two of its planned 24 orbits of the Sun and was heading inward on its third orbit. Early IS⊙IS results are reported in [19]. One of the IS⊙IS objectives is to investigate the acceleration and transport of the particles observed in $^3$He-rich SEP events [20].

On strictly geometric grounds, it can be argued that energetic particle fluences in $^3$He-rich events should vary approximately as $1/r^2$ with the distance, $r$, of the observer from the Sun. Peak particle intensities may have a stronger variation, possibly as strong as $1/r^3$, because particles from an instantaneous, point injection at the Sun undergo velocity dispersion and pitch angle scattering (a portion of which may be compensated by adiabatic focusing) and become more spread out in time at larger distances from the Sun. An earlier study [21] using data from IMP-8 and ISEE-3 near 1 AU and Helios-1 and Helios-2, which orbited between 1 AU and ∼0.3 AU, reported some examples of events that had relatively low intensities and slow onsets when observed near Earth, but could be seen as superpositions of multiple injections with orders of magnitude greater peak intensities and rapid onsets when detected near ∼0.3 AU. Another study [22], using data from ISEE-3 and Helios-1, reported He peak intensities at 0.3 AU that exceed the values seen near Earth in the same event by nearly three orders of magnitude.

Thus, it is conceivable that at solar minimum a large number of $^3$He-rich events could be occurring but with fluences and peak intensities that are too low to be detectable at 1 AU from the Sun using available instrumentation.

Direct, quantitative comparisons between PSP and ACE will be complicated by differences in instrument geometrical factors and energy thresholds (which play an important role due to the typically very soft energy spectra in $^3$He-rich events [23]). The total PSP/EPI-Hi geometrical factor is larger than that of ACE/ULEIS but smaller than that of ACE/SIS. The EPI-Hi energy threshold is lower than that of SIS but significantly higher than that of ULEIS. Furthermore, EPI-Hi has a broader field of view than either SIS or ULEIS.

The PSP observations are made over a wide range of heliocentric radii and are subject to "blackout" periods outside 0.25 AU when observing time is restricted by spacecraft operations.

Comparisons will also be complicated by the fact that the difference between the heliographic longitudes of the magnetic foot-points of the two spacecraft can vary greatly from event to event, and even during an event. Indeed, comparisons between $^3$He-rich event observations at ACE and the two STEREO spacecraft have shown [24] that peak intensities and rise times observed in a given event can very greatly depending on the longitudinal separation between the solar source region and the magnetic foot-point of the observer.

In spite of these complications, comparisons between $^3$He-rich SEP observations at PSP and near Earth should be of great interest as solar activity increases and PSP explores the energetic-particle environment progressively closer to the Sun.

## 4. Future Prospects

The PSP mission is expected to continue through at least another 22 orbits extending into 2025. A series of gravity assists from fly-bys of Venus are planned for reducing the perihelion's heliocentric distance in steps from the present 0.16 AU to ∼0.046 AU (9.9 solar radii) in 2024. The next Venus encounter, which is scheduled for December 2019, should reduce the perihelion distance to ∼0.13 AU. Over this same time period, solar activity should be increasing, with sunspot maximum predicted to occur within a few years of the PSP reaching its ultimate perihelion distance.

Figure 4 shows the fraction of time that PSP is expected to spend within various heliocentric distances during successive half-year periods. PSP's close approaches to the Sun should yield data needed to address the question of whether a population of small $^3$He-rich events is occurring at solar minimum. Indeed, at perihelion in the first two PSP orbits, the spacecraft reached heliocentric distances of ∼0.16 AU, which is nearly a factor of two closer to the Sun than the Helios perihelion. Figure 4 also shows our prediction for how the fraction of time with $^3$He present at ACE should be varying over the next few years. This was obtained using predictions for how the sunspot numbers will be varying [12] and applying the correlation fit shown in the Figure 3 inset.

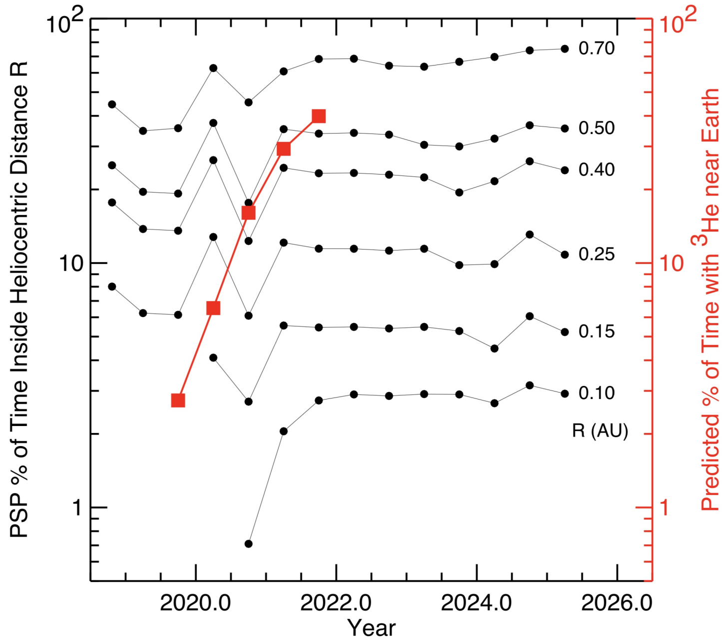


**Figure 4:** Black: Fraction of the time that the Parker Solar Probe will be inside various heliocentric radii during half-year time intervals during the remainder of its prime mission. The jaggedness of the curves occur because the PSP orbits are not synchronized with Earth years. Red: Predicted fraction of the time that SEP $^3$He will be observable by ACE/ULEIS and ACE/SIS during the rising phase of solar cycle 25.

Comparisons of $^3$He-rich event observations between PSP, ESA's upcoming Solar Orbiter spacecraft [25] (launch anticipated in 2020), and various 1 AU spacecraft can be expected to contribute significantly to the understanding of the acceleration and transport of solar energetic particles in $^3$He-rich events.

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