Origin of Suprathermal Ions Near 1 AU

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***Abstract*. We have surveyed the spectral and compositional properties of suprathermal heavy ions during quiet times from 1995 January 1 to 2008 December 31 using instruments on board ACE and Wind spacecraft in the interplanetary (IP) medium near 1 AU. We find that the composition of the quiet-time suprathermal heavy ion population (^{3}He and C-Fe) depends on the level of solar activity: the ions exhibit SEP-like composition signatures during solar maximum and CIR or solar-wind like composition during solar minimum. In addition, we find that during quietest times in the IP medium, all ion species exhibit suprathermal tails with power-law spectral indices ranging from 1.27 to 2.29, i.e., significantly different from recent observations and theoretical predictions of a unique 1.5 index. We discuss the implications of these new observations for the origin of the suprathermal ion population near 1 AU.**

***Keywords*: Energetic Particles, Interplanetary Medium, Acceleration.**

I. INTRODUCTION

Measurements on board Wind [1] and the Advanced Composition Explorer (ACE: [2]) spacecraft over solar cycle 23 have shown that a sizable fraction of CME-driven IP shocks ([3]), large solar energetic particle (LSEP) events (e.g., [4]), and particle events associated with corotating interaction regions or CIRs ([5]; [6]; [7]) exhibit substantial enrichments in the abundances of ions like He^+ and ^{3}He which are very rare in the solar wind ([8]). These ion species serve as tracers of their origin; the ^{3}He ions originate from solar flares (e.g., [9]) while the He^+ ions are interstellar neutral atoms that penetrate into the inner heliosphere inside 1 AU, and then get ionized and picked-up by the out-flowing solar wind ([10]). These observations provide compelling evidence that particles accelerated by CIR and CME-driven shocks do not originate primarily from the bulk solar wind, but rather from a hotter (∼1.5-2 times that of the bulk solar wind) and more complex unexplored regime (e.g., [11]). Thus in order to fully understand physical processes such as injection, acceleration, and interplanetary transport of SEPs and IP shock related events it is critical that we first identify the origin of the seed particles and characterize their properties.

Recent work has shown that during different plasma conditions in interplanetary (IP) space, the suprathermal tails, also known as quiet-time tails, exhibit a unique power-law spectral index of 1.5 when expressed as a function of differential intensity in energy E, or v^{-5} when expressed as a distribution function in velocity space (e.g., [12]; [13]). These ubiquitous power-law tails, observed in both protons and heavy ions, appear to be dominated by solar wind ions and CIRs at 1 AU, and interstellar pickup ions beyond 1 AU ([14]). Interestingly, these results could not be explained by two of the most widely-accepted ion acceleration processes in space, namely: (1) stochastic acceleration in the solar wind (e.g., [15]; [16]; [17]; [18]), and (2) diffusive shock acceleration, also known as first-order Fermi acceleration (e.g., [19]). Based on these observations, [20] suggested that there is an additional acceleration process that yields unique spectra under different plasma conditions and at distinct locations in the heliosphere, ranging from planetary magnetosheaths to the heliosheath beyond the solar wind termination shock (see [21]). They introduced a theory based on thermodynamic constraints suggesting that these unique spectral tails can be produced by stochastic acceleration due to compressional turbulence in the plasma, when no shocks are present.

During "quiet" periods, the IP medium is expected to be devoid of ions associated with transient solar activity or with quasi-steady interplanetary disturbances like CIRs. In this paper, we test the [13] model by surveying the composition and spectral properties of suprathermal heavy ions (^{3}He, and C-through-Fe) from 1995 January 1 to 2008 December 31 during quiet times at energies between ∼0.04 and 2.56 MeV/nucleon using instruments on board ACE and Wind spacecraft at 1 AU.

II. SELECTION OF QUIET-TIMES

Data analyzed in this paper are obtained from two instruments on board two spacecraft, namely: (1) The SupraThermal through Energetic Particle telescope (STEP) instrument within the Energetic Particles, Acceleration, Composition, and Transport experiment (EPACT: [22]) on board Wind, which was launched in November 1994 and (2) The Ultra-Low Energy Isotope Spectrometer (ULEIS: [23]) on board ACE, launched August 1997. STEP and ULEIS are time-of-flight (TOF) vs. residual energy mass spectrometers that resolve elements from H to Ni for energies between ∼0.02 MeV nucleon^{-1} and ∼10 MeV nucleon^{-1}.

We selected the quiet times for our study from the heavy ion (C-through-Fe) hourly-averaged intensity (hereafter referred to as the heavy-ion intensity) over 0.04-0.32 MeV nucleon^{-1} for STEP (see Figure 1),

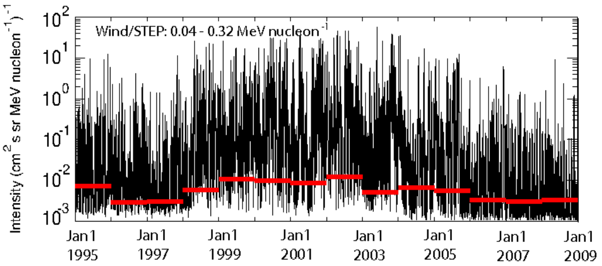

Fig. 1: Six-hour running averages of heavy-ion (C through Fe) intensity as measured by Wind/STEP between 0.04-0.32 MeV/n; horizontal bars mark the maximum intensity of the quiet times during each year.

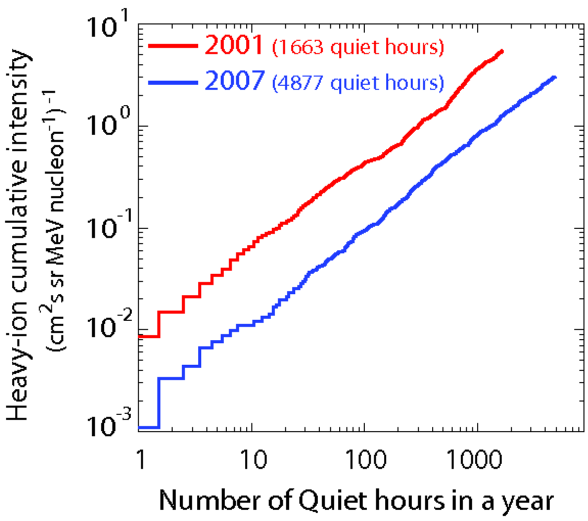

Fig. 2: STEP heavy-ion cumulative intensity during the quiet hours of 2001 and 2007. The smooth increase with increasing quiet hours indicates comparable intensities during all quiet hours.

and 0.06-2.56 MeV nucleon^{-1} for ULEIS. We use hourly-averages instead of daily-averages (as in [24]) to select the quiet times because it has allowed us to exclude multi-hour events (e.g., upstream events from the Earth's bow shock), short-time saturation periods on both spacecraft, and energy-specific enhancements (e.g., velocity dispersion during SEP events, see [25]). For each hour, this intensity represents all detected heavy ions (C through Fe) that fall within the selected energy range. For each year, we then created an intensity-hour histogram and defined the quiet times to be a certain variable fraction (between ∼20-60%) of the hours that represent the lowest values of the heavy ion intensity. This percentage difference is necessary because the number of hours with zero counts during solar minimum years is much higher than that during solar maximum years. We emphasize that our selected quiet-times represent a fraction of the total hours with the lowest values for the hourly-averaged heavy ion intensity over a wide energy range in a given year and should not be taken as indicative of an intensity threshold level for a certain species in a narrow energy range (for details see [26]).

Figure 2 shows the cumulative heavy-ion intensity during the quiet hours of 2001 and 2007. The smooth increase during both years implies that our selected quiet times are not dominated by large increases in the count rate within a relatively short period (few hours) compared with the total number of quiet hours used to derive the composition and spectra. We finally remark that our selection criteria has ensured that in any given hour, the maximum count rate used to derive the heavy-ion intensity did not exceed seven counts, while the average count rate for any given species in narrower energy ranges did not exceed the three count level.

III. Solar Cycle Variations

A. Composition

Figures 3a and 3b show the C/O and Fe/O ratios (from this work) and that calculated by [24]. The horizontal lines in Figures 3a & b indicate the average abundances of C/O and Fe/O measured in ^{3}He-rich ([27]) and large gradual SEP [4]) events, CME-driven IP shock events ([28]), fast SW ([8]), slow SW ([29]), and CIRs ([7]).

Figure 3a shows that during 1998−2006, the C/O ratio follows a trend similar to that shown by [24], reflecting SEP-like values during solar maximum, and SW and CIR-like material during solar minimum with overall variation by about a factor of ∼1.5. The Fe/O ratio in Figure 3b shows a strong dependence on the solar cycle activity varying by more than a factor of ∼4, with large enhancements during solar maximum (e.g., 2000 and 2001), and significantly lower values during solar minimum. The figure shows that the quiet-time Fe/CNO ratio varies by more than an order of magnitude between 2001 and 2007.

Figure 3c shows the ∼0.32-0.64 MeV nucleon^{-1} ^{3}He/^{4}He ratio measured by ULEIS compared with that measured by [24] at ∼0.35-1 MeV nucleon^{-1} along with the average SW value ([30]). The ^{3}He/^{4}He ratio is calculated by dividing the total number of ^{3}He counts by the ^{4}He counts detected during the quiet times for each year. ^{3}He ions were taken as those with mass between 2.65 and 3.2 amu and above the extrapolated tail of the ^{4}He distribution. The ^{4}He background is subtracted from the ^{3}He mass histogram. We remark that for all the years, the ^{3}He peak was well resolved (e.g., see [24]).

The figure shows that the yearly-averaged ^{3}He/^{4}He ratio during the quiet times lies between 3%-8% during 1998-2007 with an average of ∼6%. The ratio then drops by more than an order magnitude during 2005-2007 and lies between 0.3%-1.2% with an average of ∼0.7%. However, throughout our survey period the ^{3}He/^{4}He ratio remained significantly larger than the average SW value (∼0.04%). We note that even though the average ^{3}He/^{4}He ratio follows the same trend as that reported by [24] the values obtained in this work are somewhat higher, reaching a factor of ∼5 in some years. This discrepancy occurs probably because both studies

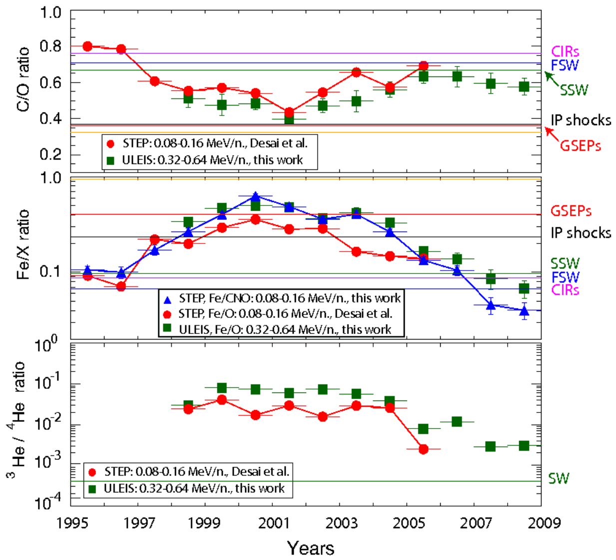

Fig. 3: (a) C/O, (b) Fe/O and Fe/CNO, and (c) ^{3}He/^{4}He ratios as measured by STEP and ULEIS at different energy ranges between 1995 and 2008. The circles represent values determined by [24]. The horizontal lines represent average abundances measured in different heliospheric particle populations (see text for details).

did not consider ^{3}He or ^{4}He in their selection of the quiet times and could be including different multi-day ^{3}He-rich periods that are not associated with discrete injections ([31]).

B. Energy Spectra

We use Wind/STEP CNO and Fe spectra between 0.04-0.32 MeV nucleon^{-1} to study the spectral properties of the suprathermal heavy ions during quiet times over the solar cycle from 1995 through 2008. We fitted the spectra by a power law of the form $j(E) = j_0 E^{-\gamma}$, where j_0 is the normalization constant, E is the energy-per-nucleon, and γ is the spectral index. In all cases, we fitted the spectrum of each species independently using a grid-search technique that minimized the chi-squared (χ^2) for each parameter. In general, all the spectral fits were excellent visually and statistically with a reduced χ^2 ranging between 0.59 and 1.12.

Figure 4 investigates the solar cycle variations of the quiet-time CNO and Fe energy spectral indices from 1995 to 2008. In 10 of the 13 years, the CNO spectrum is softer than that of the Fe, with 3 years (1998, 2002, and 2005) showing a harder CNO spectrum. Additionally, the Fe spectra during the first solar minimum (1995-1997) are softer than those observed during the second solar minimum (2005-2007). The hardest Fe spectrum occur during the solar maximum years of 2000 and 2001. Overall, the spectral indices of CNO and Fe deviate significantly from the 1.5 value and show no clear solar cycle dependence.

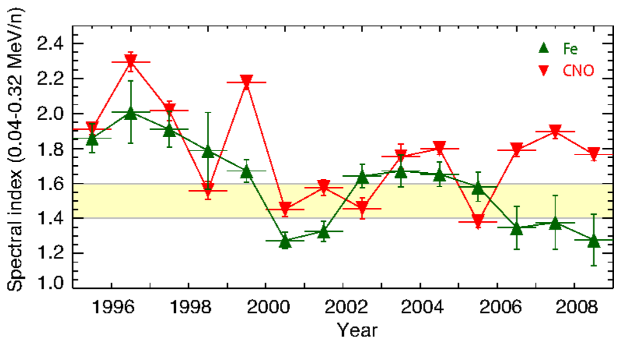

Fig. 4: Variations of the quiet-time spectral indices of CNO and Fe as measured by STEP for years 1995-2008 at 0.04-0.32 MeV nucleon^{-1}. The highlighted region identifies indices with values between 1.4 and 1.6.

IV. DISCUSSION

There are at least two hypotheses regarding the origin of these IP suprathermal ions, namely, (1) the ions are the low-energy component of particles that are accelerated during prior and ongoing solar and IP activity ([24]; [32]), and/or (2) the suprathermal ions are accelerated via some kind of stochastic acceleration mechanisms operating in the IP medium ([13]; [20]). Both these notions have specific expectations for the observations. In the former scenario, the dominant component of the suprathermal material is expected to vary according to the phase of the solar cycle. In other words, ions accelerated during solar energetic particles or SEPs should dominate the composition during solar maximum while ions from CIRs or from the suprathermal tail of the SW should dominate during solar minimum periods. In the latter scenario, there is no reason for the suprathermal heavy-ion composition to vary with solar activity while the low-energy portion (up to $\sim$0.15 MeV nucleon^{-1}) of the energy spectrum should consistently exhibit a power-law with a value of 1.5 for the spectral index.

During the quiet hours in our survey, the Fe/O and C/O ratios exhibit a clear dependence on the solar cycle with SEP-like abundances during solar maximum and SW or CIR-like composition during solar minimum (Figure 3). The depletion of Fe during the solar minimum is likely due to the sharp decrease in flare activity, with the ion abundances probably reflecting the SW ([8]; [29]) or CIR composition ([7]). This picture is also consistent with the frequent presence (see [26]) and higher abundance of ^{3}He in IP space during the quiet and all times (see [33]) of solar maximum from 1998 to 2005. These results are in agreement with recent work by [24] who showed that the elemental composition of $\sim$0.08-0.16 MeV nucleon^{-1} suprathermal population during quiet times (defined by setting a threshold on Fe intensity) is strongly correlated with solar activity.

On this basis, we conclude that during the quiet times of solar maximum from 1998 to 2004, the suprathermal heavy ion population is dominated by an admixture of ions that are accelerated in ^{3}He-rich and Fe-rich impulsive SEPs and by CME-driven shocks in the inner heliosphere. Since the occurrence rates of flares and CMEs vary significantly from one solar rotation period to the next, the amount, composition, and spectral properties of the suprathermal material in IP space is also highly variable and dynamic. In contrast, during solar minimum periods, the occurrence rates of flares and CMEs decline significantly and so the relative contributions of SEP material to the suprathermal ion population is significantly lower. Thus, the suprathermal heavy-ion composition resembles that measured in the two dominant sources the heated SW and previously accelerated CIR material.

Our results also show that although heavy ions exhibit suprathermal tails during quiet times, the Fe and CNO spectral indices between 0.04-0.32 MeV nucleon^{-1} vary over a wide range between 1.27 and 2.29. In other words, the theoretical prediction of the ubiquitous 1.5 suprathermal spectral index reported by [20] does not appear to be a special case and is therefore somewhat at odds with our observations.

It is worthwhile noting that the Fe and CNO spectral indices are closer to the predicted 1.5 value during solar maximum years. This is probably a coincidence since our composition results clearly indicate that the suprathermal heavy ion population above $\sim$0.04 MeV nucleon^{-1} is essentially dominated by SEP-like material which is most likely accelerated near the Sun during flares and CME-driven shock events, rather than from acceleration mechanisms occurring in the IP medium. On the other hand, during solar minimum years of 1995-1997, the flare and CME activity is lower and its contributions to the suprathermal population is sufficiently reduced. However, the spectral indices of CNO and Fe lie between a wide range from 1.6 to 2.3. In other words, given the SW/CIR-like composition signatures observed during periods of low solar activity, one would expect the dominant contributions to the suprathermal population to originate from IP acceleration processes like the one proposed by [20], and yet it is during these periods that the Fe and CNO spectral indices deviate most significantly from the predicted 1.5 value.

We suggest that the differences between our observations and those reported by [13] could be attributed to the fact that the selection criteria for the quiet times in the two studies are somewhat different. For instance, [13] defined quiet times as periods when the SW speed is less than 320 km s^{-1}. At present, however, we cannot quantify the consequences of using different selection criteria. A more thorough investigation of this issue is beyond the scope of this study. To fully reconcile the results from the different suprathermal ion instruments, we eventually need to combine measurements from other instruments such as Wind/STICS and ACE/SWICS.

V. Conclusions

Our results show that the quiet-time suprathermal heavy-ion population is highly variable and comprises ions from multiple sources such as impulsive and gradual SEPs, CIRs and the SW whose contributions with solar cycle activity. In particular, the suprathermal population is dominated by CIR-like or SW-like material during solar minimum conditions of 1995-1997 and 2005-2008, while it is dominated by SEP-like material during solar maximum conditions of 1998-2004. The quiet-time suprathermal heavy-ion energy spectra deviate significantly from the 1.5 value predicted by [20] indicating that the suprathermal ions above $\sim$0.04 MeV nucleon^{-1} are unlikely to be generated by interplanetary acceleration mechanisms that tend to produce unique power-law spectral indices of 1.5.

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