Searching for the $E^{-3/2}$ Suprathermal Power Law Tail in Parker Solar Probe's IS⊙IS Data

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Abstract

The *Advanced Composition Explorer* (ACE) and the *Ulysses* spacecraft revealed the presence of a common power-law spectrum of ions in the solar wind, the shape of which is independent of solar activity. The highest energy particles in this distribution are a direct interest to human affairs as they can serve as the seed population for large, destructive events that can harm ground- and air-based equipment. The mechanisms that create this common distribution are unknown, but by studying the behavior of the spectrum at closer radii more can be learned about their origin. Furthermore, this relationship is altogether poorly studied within 1 au. I investigate the first year and a half of Parker Solar Probe's data to find evidence of this spectrum in this previously unstudied region. I find weak evidence to suggest the existence of a common spectrum of protons from 60 to 200 keV inside the region being studied. Further work is required to uncover the phenomena in this region that determine the shape of the solar wind spectra.

Need to note that everyone has so far only looked at big radius, so it may be the case that we see different stuff closer.

1 Introduction

The solar wind in regions above 0.3 au has been studied directly [*McComas et al.*, 2007], and a considerable understanding of the population of solar wind particles and their distributions has been gained about these regions [*Giacalone et al.*, 2002; *Fisk and Gloeckler*, 2012, 2006, 2008;

Gloeckler et al., 2000]. One particular phenomenon that our current understanding of accelerating processes in the solar wind fails to explain is the existence of an omnipresent power law spectrum of solar wind speed with a spectral index of -5; alternatively, this can be expressed as a power law of particle energy with spectral index of $-\frac{3}{2}$ [*Fisk and Gloeckler*, 2012].

1.1 The Seed Population and its Significance

Observations from ACE show significant differences in the composition of solar energetic particle (SEP) events and solar wind [*Mewaldt et al.*, 2012]. Additionally, SEPs have been measured to have densities of ^{3}He and He$^+$ much greater than thermal solar wind (ie. ^{3}He is an ion abundant in flares with energy >10 keV and He$^+$ is an interstellar pickup ion), and thus loan themselves to be used as tracers of the source material of the SEP. Finally, the heavy ion composition of SEP events correlates significantly with background suprathermal densities. These results suggest that SEPs draw their source material from the suprathermal region [*Desai et al.*, 2006]. The population of ions in the suprathermal region responsible for the acceleration of SEP events has been coined the *seed population*.

The seed population for SEP events is of particular interest to human affairs as large SEP events can cause significant harm to humans and machinery in space and, in extreme circumstances, even those on the ground [*Desai and Giacalone*, 2016]. This seed population is directly concerned with the power law spectrum seen in the solar wind as the seed population for SEP events is composed of suprathermal ions, the amount of which is dictated by the power law spectrum. I search for the existence of this spectrum of ions in the solar wind in regions below 0.3 au.

1.2 The Quiet Time Spectrum

1.3 Instrumentation

Parker Solar Probe (PSP) provides a previously unseen view of the solar wind inside Earth's orbit. Diving from more than 60 to less than 10 $R_\odot$, the spacecraft plunges into the solar corona to observe the phenomena that accelerate the solar wind and inflate the heliosphere. In particular, PSP's closer view of the Sun can help explain how the corona is heated and how this power law spectrum is created in the solar wind [*McComas et al.*, 2014, 2007].

I use data from PSP's IS⊙IS EPI-Lo instrument to look for the existence of the common power law tail in these regions close to the Sun. EPI-Lo is a time-of-flight based mass-spectrometer capable of measuring ions and electrons varying from approximately 20 keV to 5 MeV. Of interest here are EPI-Lo's specific capabilities surrounding protons, for which the instrument is capable of measuring between 0.04 and 7 MeV [*McComas et al.*, 2014]. EPI-Lo is made of eight 45° wedge segments, each of which has 10 entrances for particles to strike a solid state detector. I use EPI-Lo's Channel T data, which is a time-of-flight (ie. SSD not used) total ion channel calibrated assuming only hydrogen.

2 Analysis

At the time of beginning the analysis, data from the beginning of PSP's flight (end of September 2019) through early January 2020 were available. Events were selected by plotting a spectrogram of hourly- and directionally-averaged time-of-flight high energy resolution proton fluxes (Channel T Flux in the IS⊙IS EPI-Lo Level 2 dataproducts) against time and energy for the entire duration of time for which data was available. Fifteen events were found in PSP's data during this time, the parameters for which can be found in Table 1. The spectrogram from which events were selected is shown in Figure 1. Increased flux is apparent on a periodic basis occurring approximately every 5 months. This coincides with solar encounters and has little relation to actual events.

Fisk and Gloeckler [2006] suggest a model of compressional acceleration in solar wind turbulence that predicts a functional dependence of flux on energy in the suprathermal tail as

$$j = j_0 T^{\frac{-3}{2}}. \tag{1}$$

I attempt to recover this model from fits to the spectra of each event.

The first approach to find evidence of the model in Equation 1 fitting the spectra of the events was to simply apply a fit to the data between 40 and 160 keV of an event-duration- and directionally-averaged spectrum of each event. This energy region was determined by visual inspection of the events to to fit the region most like a power-law inside the suprathermal region described by *Fisk*

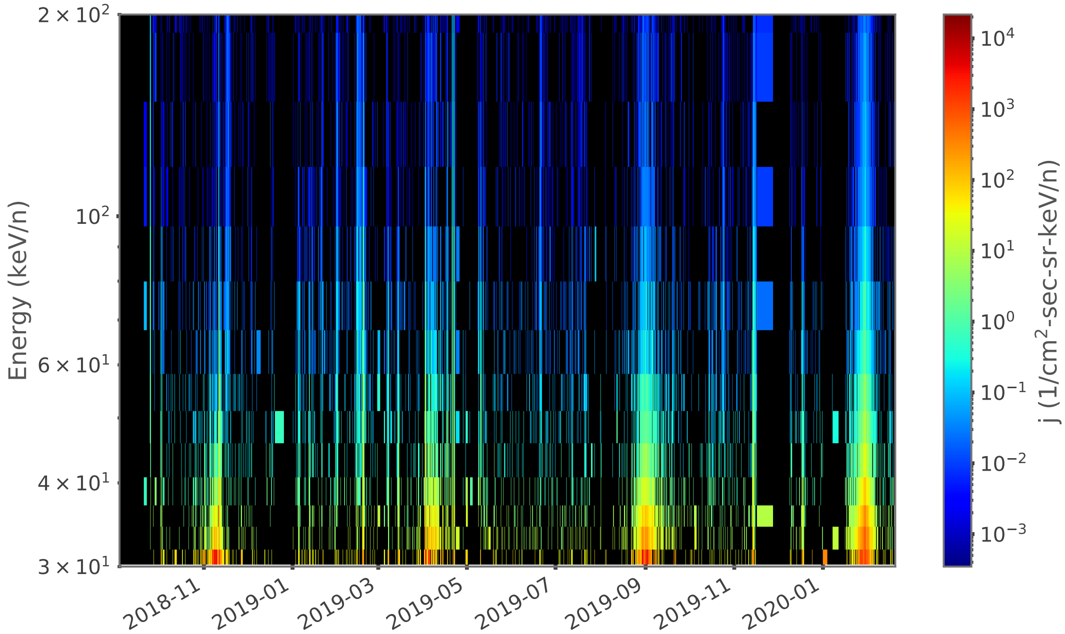
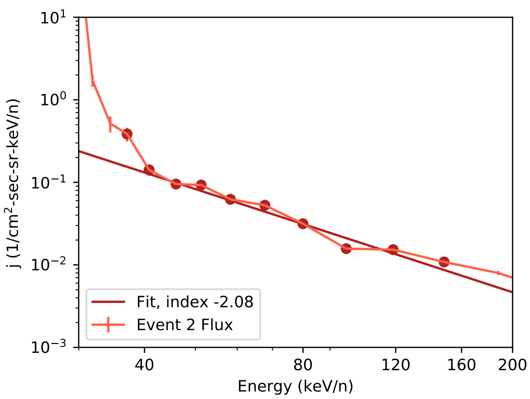


Figure 1: Flux (j) versus energy and time for the duration of the mission at the time data analysis was started. Individual events generally lasted for the approximate duration of a few days, making them too small to indicate on the spectrogram. Notice that solar encounters are visible occurring approximately every 5 months starting in November 2018.

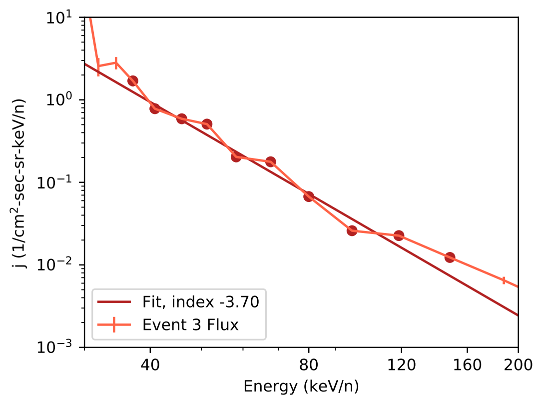
Event	Start	Stop	Spec. Index	R (au)	Peak Flux (n/keV cm^2 s sr)	η^2
0	2018-09-25 01:54	2018-09-25 22:57	-2.06	0.81	2.92	0.0327
1	2018-11-11 01:39	2018-11-12 01:36	-5.99	0.24	56.29	0.0345
2	2018-11-15 16:33	2018-11-19 23:37	-2.08	0.38	3.07	0.0161
3	2019-01-31 00:21	2019-02-01 17:00	-3.70	0.92	2.73	n/a
4	2019-02-13 17:43	2019-02-18 00:03	-3.12	0.85	2.83	n/a
5	2019-02-18 05:00	2019-02-19 20:55	-5.06	0.83	11.68	n/a
6	2019-03-06 09:17	2019-03-08 05:04	-5.82	0.67	4.60	0.0249
7	2019-03-13 23:33	2019-03-15 12:34	-6.29	0.56	6.10	0.1070
8	2019-04-02 05:44	2019-04-03 00:36	-8.34	0.18	159.11	0.0130
9	2019-04-04 02:36	2019-04-04 20:01	-5.46	0.17	30.60	0.0042
10	2019-04-17 15:36	2019-04-18 06:51	-5.21	0.41	7.18	n/a
11	2019-04-20 10:58	2019-04-23 19:32	-3.21	0.49	5.33	0.0112
12	2019-06-19 15:10	2019-06-21 22:20	-3.03	0.94	1.76	n/a
13	2019-10-22 11:09	2019-10-26 08:04	-2.62	0.88	1.67	n/a
14	2019-11-13 08:30	2019-11-16 22:08	-4.88	0.94	6.23	n/a

Table 1: Parameters of the fifteen events identified. Events for which magnetic field data was unavailable show n/a for η^2.

and Gloeckler [2008]. This yielded fits like those shown in Figure 2. The exponents of these fits did not match well to the expected $-\frac{3}{2}$.



(a) Event 2



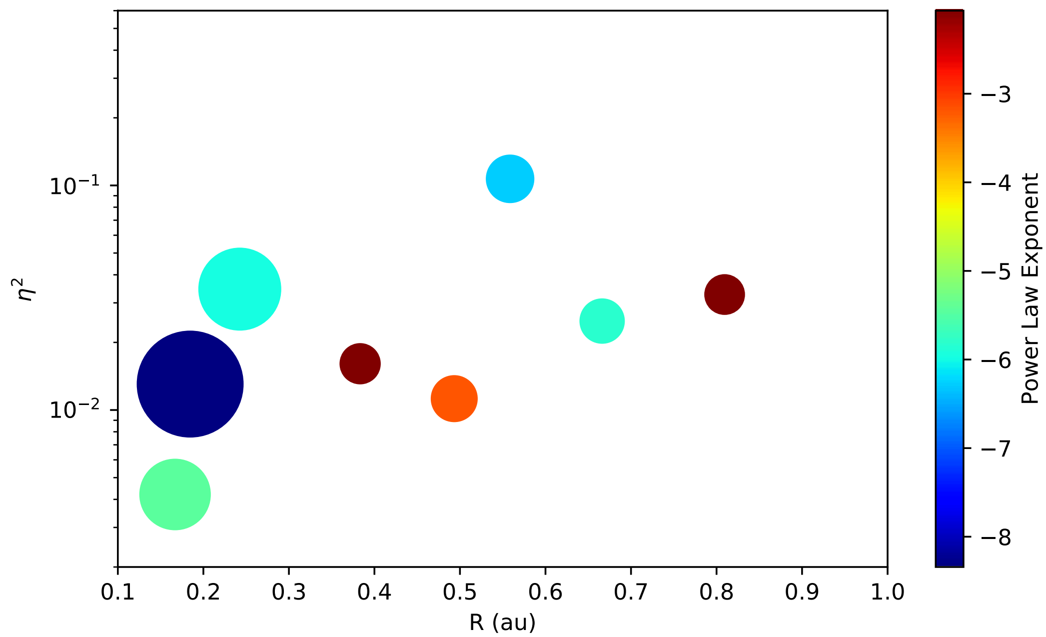
(b) Event 3

Figure 2: Fits of the spectra from Events 2 and 3. Red points on the spectrum of either plot indicate points used for the fit.

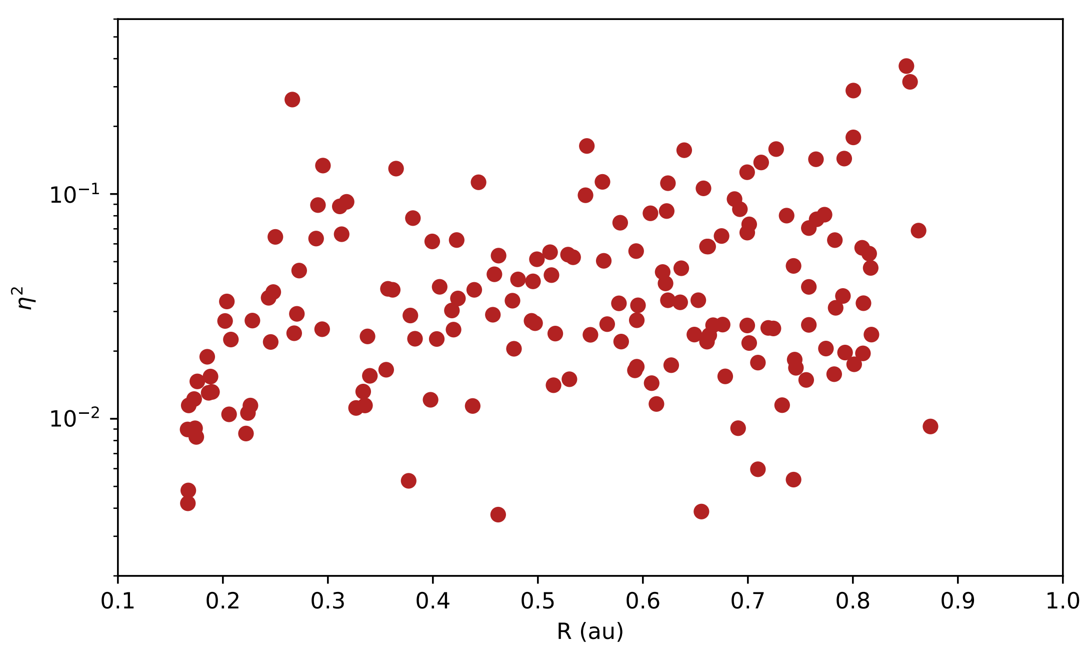
Failing to see evidence of the $-\frac{3}{2}$ index of the power law, I reconsidered the importance of event type on this predicted observation. *Fisk and Gloeckler* [2006] point out that the common spectrum appears in populations of charged particles subject to non-shock (ie. quiet time) acceleration, such as in gradual SEP events like those associated with coronal mass ejections. I analyzed a combination of properties of the magnetic field to distinguish gradual SEP events from others.

I also considered magnetic variance acting as a proxy for magnetic turbulence to indicate accelerating processes in the region of the spacecraft. *Schwadron et al.* [1996] suggest the statistical quantity η^2 to act as a proxy of magnetic turbulence. Magnetic turbulence indicates the relative strength of acceleration associated with magnetic turbulence [*Fisk and Gloeckler*, 2006]. Plots of η^2 is shown in Figure 3. An association between magnetic variance and spectrum harness was not found. However, a pattern showing events at smaller radii to have less magnetic turbulence is observed.

I finally considered a relationship between radius and spectral index. A plot this data can be seen in Figure 4. An apparent "spectral hardening" occurs as radius increases: events appear to have less negative power laws when their flows are observed at greater radii. Furthermore, this seems to be consistent with the relationship between turbulence and radius observed in Figure 3.



(a) Variance of magnetic field versus radial distance for each event compared with its peak flux and its spectral index. Size indicates peak flux, color indicates spectrum hardness. *Schwadron et al.* [1996] propose magnetic variance η^2 to be a proxy for plasma turbulence. It appears that a trend exists such that events closer to the sun have less variance in the magnetic field. Events for which magnetic field data was not available are not shown.



(b) Variance of magnetic field versus radial distance for each day included in the analysis, (ie. mid September 2018 to January 2020). The apparent upper limit of magnetic turbulence as a function of radius seen in Figure 3a is even more apparent here.

Figure 3: η^2 versus radial distance.

This would suggest that as mechanics in the solar wind drive greater and greater turbulence at larger radii, the spectrum hardens as ions accelerate.

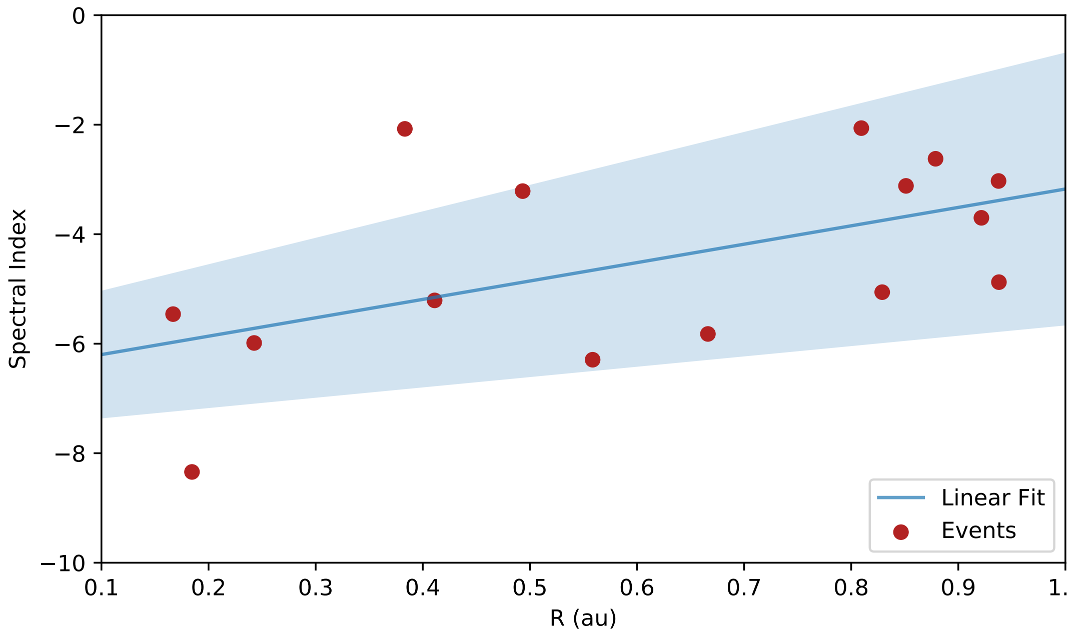


Figure 4: An apparent relation between radial distance R and the spectral index can be seen in the event data. Locally this relationship can be modeled by a line, though this is demonstrably not the case at greater radii as the spectral index approaches $-\frac{3}{2}$ [*Fisk and Gloeckler*, 2008, 2006]. This fit suggests that spectral index $-\frac{3}{2}$ may be approached by an asymptote with respect to radius. The linear fit between radius and spectral index has slope $3.0 \pm 1.5\,\mathrm{au}^{-1}$ and intercept -7.0 ± 1.0.

3 Discussion & Conclusion

I analyze proton flux data from Parker Solar Probe's first year and a half to find evidence for the common power law tail described in *Fisk and Gloeckler* [2006]. I do not find evidence to suggest a common spectrum among these data.

I consider a naive approach without disregarding any event that may include processes originally excluded in *Fisk and Gloeckler* [2006]. Failing to find the common power law tail here, I then attempt to exclude events based on changes to the magnetic field. Manually inspecting field data for shocks and excluding associated events does not improve the net statistics of the fits to the event spectra; subsequently analyzing magnetic variance (as a proxy for magnetic turbulence [*Schwadron* *et al.*, 1996]) does not show any patterns in the spectral index, (see Figure 3).

4 Future Work

Some extensions to this study could include the following:

- Analysis on a moving average of each event may show different results or evidence of the common spectrum. Upon writing, it became apparent that the spectra of many events harden as time goes on, (ie. the exponent of spectrum, if the range of the spectrum is taken to move in time, increases from more negative to less negative).

- Compare events with other authors and observatories and exclude events on this basis.

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