Data Visualization for a Solar Event Viewer (SEV) Dashboard

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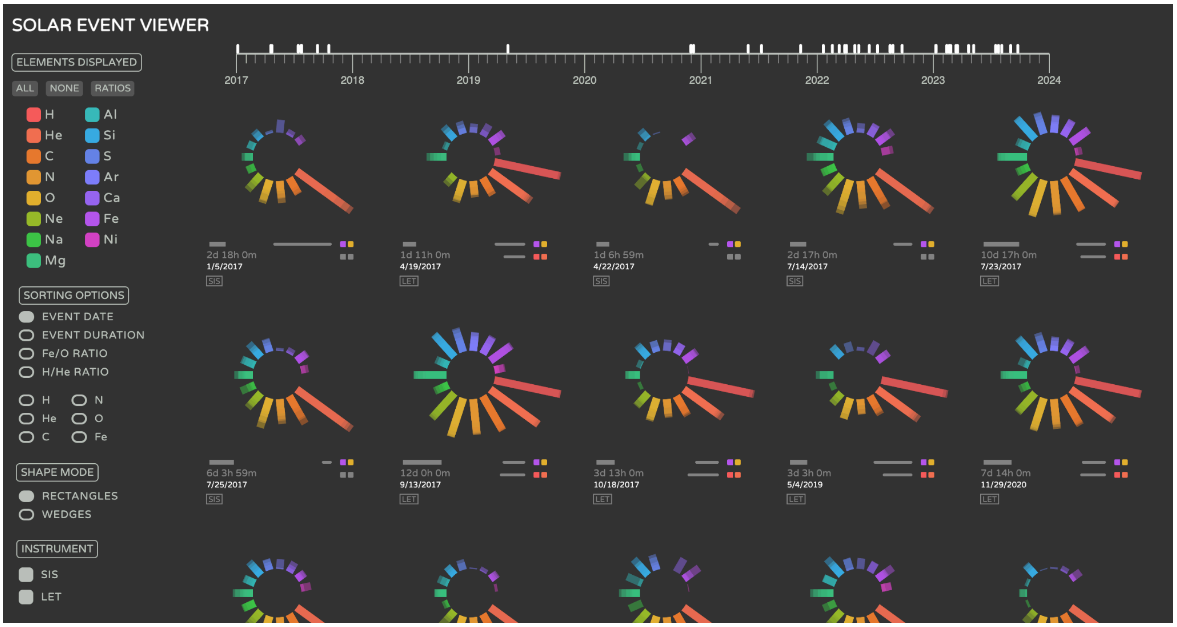

Figure 1. The SEV interface showing a list of solar flare event data, as described in Section 5.

Abstract

Understanding solar flare activity is a critical area of astrophysics due to its potential to disrupt satellites, communication systems, and power grids on Earth. With over 7 years of solar probe data totaling approximately 1 TB, efficient data summarization and visualization are essential for identifying trends in solar activity. We developed an interactive web-based visual analysis interface and dashboard utilizing data from the STEREO and ACE missions. This tool enables researchers to filter solar events by various determinants (including emission strength, classification, etc), examine specific time windows, and sort by various parameters. Researchers can explore relationships between key variables such as event duration, peak emission magnitudes of detected elements, element ratios (e.g., iron-to-oxygen), and overall flare intensity. This tool facilitates deeper insights into the dynamics of solar flare activity and lays the groundwork to integrate additional datasets from other solar probes and add additional features.

1. Introduction

Understanding solar flare activity is a critical challenge in heliophysics, since energetic particle emissions from solar flares can have consequential effects on the Earth, such as the disruption of satellites, communication systems, and power grids. Over the last decade, missions such as STEREO, ACE, and the Parker Solar Probe (PSP) have generated vast amounts of solar probe data, accumulating to over a terabyte of particle flux measurements from various elements. While these datasets hold immense potential for understanding trends in solar flare dynamics, the scale and detail of the event data make them difficult to summarize and interpret using existing tools. Furthermore, current user interfaces to analyze solar flare events lack the ability to easily compare across multiple events, sort events, and efficiently summarize how a given event compares to other events across all of time and across other events. To address these challenges, we developed an interactive Solar Event Viewer (SEV) tool that enables researchers to filter and sort events by various parameters, quickly analyze element ratios, and explore trends in different element flux measurements across time. This paper presents the design process and explanation of the SEV tool, developed in collaboration with astrophysics researchers at Caltech.

2. Background

2.1 Solar Event Probes & Flare Data

The dataset this dashboard summarizes data from includes the Solar TErrestrial RElations Observatory (STEREO) from the Low Energy Telescope (LET) instrument and the Advanced Composition Explorer (ACE) mission data from the Solar Isotope Spectrometer (SIS) instrument, both of which are open-source datasets. The STEREO LET instrument measures element particle flux across time for 17 ions from H to Ni over an energy range of ~3 to ~30 MeV/nucleon, though the He-3 and He-4 isotopes were excluded from the dataset for the SEV tool (Davis). The number of energy bands and the energy bounds for each energy band is dependent on the element, which is an important caveat when comparing particle flux data across elements. The ACE SIS instrument measures element particle flux across time for 14 ions from He to Ni over an energy range of ~10 to ~100 MeV/nucleon (*SIS Level 2 Data Documentation,* 2007). For the SIS instrument, each element has 8 energy bands, which again have different energy ranges depending on the element. Particle flux data from both instruments is measured in units of particles/(cm^2 Sr sec MeV/nucleon). To calculate total flux for a given event, the flux data was summed over the entire duration of the peak for each energy band for each element and this summarized data was used in the visualization.

While all of the element data (excluding the He-3 and He-4 isotopes mentioned previously) were used in the visualization, particle data from Hydrogen and Helium are of particular interest since they are the most abundant elements in the sun and serve as fundamental traces in solar flare activity. In addition, heavier elements including Iron and Oxygen are of special importance since their relative abundance in the Iron-Oxygen (Fe/O) ratio helps identify the origin and acceleration mechanisms of solar energetic particle events (Cane et al., 2006). The Hydrogen-Helium (H/He) ratio, while not as useful as the Iron-Oxygen ratio, is also an important ratio for solar flare event research, since it correlates with the solar flare intensity, peak intensity, and speed of exiting particles (Davidson).

2.2 Traditional Solar Event Visualization Tools

The previously used tool for visualizing solar flare event data is shown in Figure 2. Each event was displayed as a series of plots, one for each element. Within each plot, the x-axis represented time, the y-axis represented energy bands, and the hue of each cell indicated the particle flux intensity for that interval. Although this format preserved the detailed raw measurements, it lacked the ability to easily compare across elements and events and did a poor job of summarizing the events, which is an important feature for finding trends in solar flare data. Moreover, the Fe/O and H/He ratios could not be calculated directly in the software, which limited the researchers' ability to quickly understand the type of solar flare event and understand how it compared to others. Additionally, selecting events was a labor-intensive process, as the tool lacked a timeline, sorting option, or any summary overviews. These limitations underscored the need for a more interactive and user-friendly summary tool, one that enables the ability to compare events and explore the relationships between parameters of solar flare events.

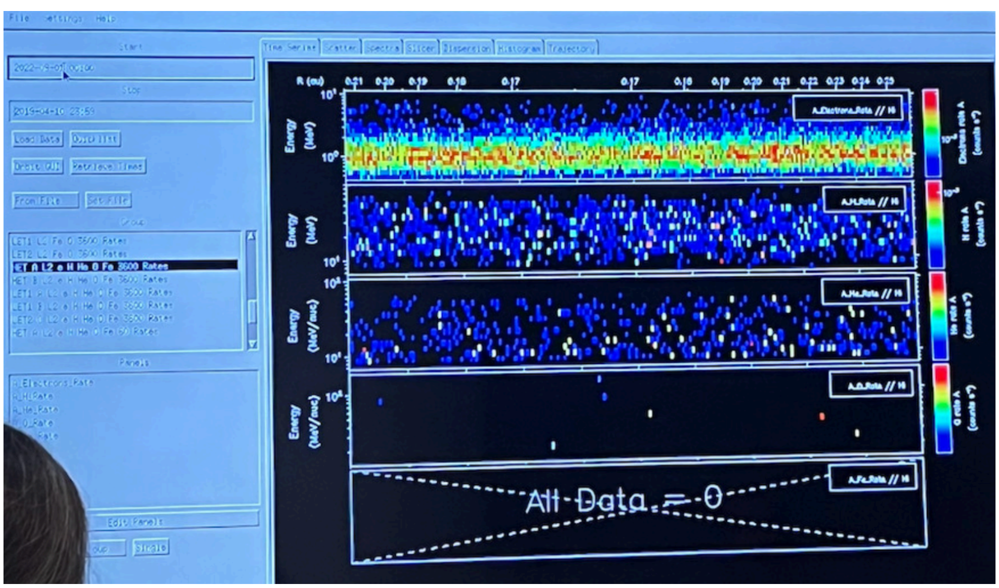

Figure 2. Old GUI for solar flare event visualization.

3. Design Study

As a part of the Summer Undergraduate Research Fellowship (SURF) Program mirrored after the Data to Discovery program, we spent 10 weeks working closely with astrophysics researchers to develop the SEV tool. The design process began with contextual inquiry interviews, including a full workflow demonstration with the old visualization tool. Based on these interviews, we began the sketching process. This included various representations of a given solar flare event as well as drafts of the user interface of the tool. These sketches were laid out in Miro and aided greatly in the prototyping process. In this phase, we used subsets of the data including a few high-magnitude solar flare events to test out different representations and color palettes using p5.js. After continuous feedback from the researchers, we developed a final tool, including all the sidebar features and interactive tools, using the p5 library in VSCode.

3.1 User Tasks

Heliophysics researchers using the SEV tool aim to discover and characterize trends between variables in solar flare events in order to better understand the mechanisms that cause solar flare events and eventually create a framework for predicting future events. We organize these goals for the SEV into the following four tasks:

Task 1. Have a concise visual summary for each event to easily compare the overall magnitude of element flux magnitudes across other events in a scrollable list for quick navigation.

Task 2. Calculate the Fe/O ratio and H/He ratio in the visualization tool and include visual indicators to compare across events.

Task 3. Find trends in solar flare event properties across time through an interactive timeline.

Task 4. Find trends in element flux magnitudes and event duration through toggleable element displays and sorting mechanisms.

3.2 Solar Flare Event Dataset

The dataset for the SEV tool was a zip file of 45 events, detected by both SIS and LET. Each event directory includes either 13 or 16 element directories, each of which includes between 8 to 11 files, each corresponding to a unique energy band range for which the intensity was measured. Each file contains a column of the time stamp and associated intensity measurement, as well as more information about the event in the header. This dataset was a subset of all the solar data used by the research group, since it excluded data from the Parker Solar Probe (PSP) due to its different format, and only included events from 2017 to 2023 rather than the full 25 years of data. Before creating the SEV tool, we reformatted this data into a directory of JSON files which included the peak value of the element flux for each element across all energy bands, the duration of the event, and the date the event occurred. We also wrote a simple python script to calculate the Fe/O and H/He ratios for each solar flare event and included this data in the summary JSON files.

5. The SEV Application

The SEV application is an interactive, fully functional tool which visualizes solar flare events and allows for easy cross-event comparison, sorting, and deeper analysis. *Figure 1* depicts a full image of the SEV tool. The main sections of the tool are a scrollable list of solar flare event representations over the entire duration of solar flare event data, an interactive timeline at the top, and a toolbar on the left side. In this section, we walk through the entire tool, as well as the interactive features and sorting and filtering mechanisms.

5.1 Elemental Representation

Figure 3ab shows an elemental representation of a solar flare event. Each flare event is depicted as a circle with protruding radial bars, inspired by real astrophysical imaging of the sun's corona. Each bar represents a unique element measured by the solar probe instrument, signified by a unique color. Composing each element bar is multiple bars with lower opacity overlaid, with each one corresponding to a different energy band range for a given element. The length of each bar is scaled logarithmically to the peak total flux across the duration of the solar flare event for a given energy band for a given element. The longest bars correspond to the red and red-orange color bars, which represent Hydrogen and Helium due to their high intensity in flare events, as expected. Within the toolbar, switching between 'rectangle' and 'wedge' shape modes allows for different views, as seen in Figures 3a and 3b, respectively.

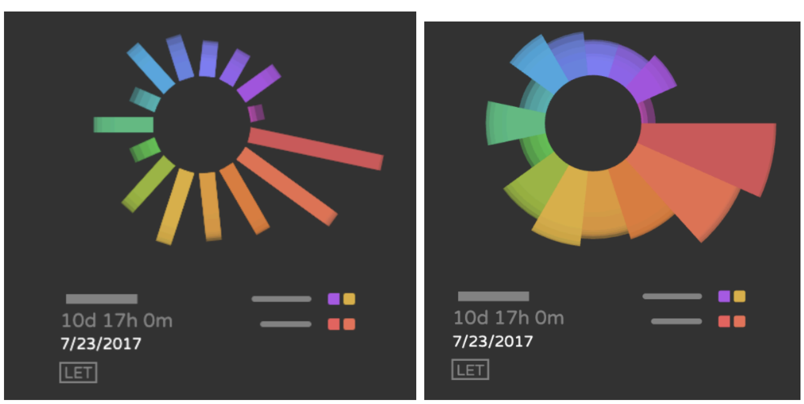

Figure 3. Elemental representation of a solar flare event, in (a) rectangle and (b) wedge shape modes.

Underneath each event circle is a small label which provides a succinct visual summary of some of the event's properties. In the left column, the top bar's length is scaled to the duration of the event, and the numerical duration is depicted directly below. Underneath this, the event start date in day/month/year format is listed, followed by the instrument which detected the event. The right column contains two bars which are scaled to the magnitude of the Fe/O ratio (top) and H/He ratio (bottom). These ratios are labeled by colored boxes to the right of each respective bar. In addition to the element ratio bars, hovering over any area within these element ratio label boxes causes a more detailed view of the element ratio calculations to appear, as seen in *Figure 4*. Within this view is a log-log plot of the intensity versus energy of each energy band for the elements Fe and O and associated lines of best fits. This is useful for identifying errors in element ratio calculations, since some events' intensity data does not follow a simple exponential relationship to energy.

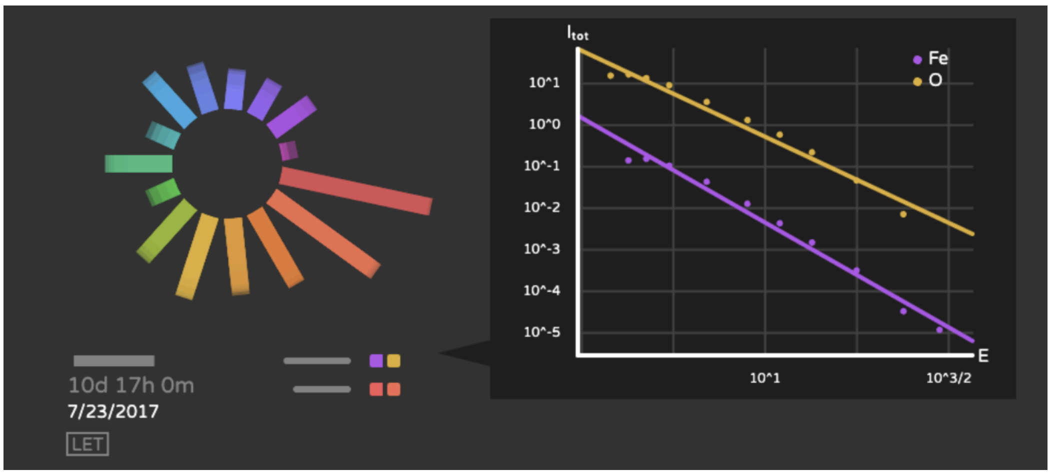

Figure 4. Expanded view of Fe/O element ratio calculation.

This elemental representation of solar flare events allows the user to quickly gain a summary view of the event's element flux intensities, event duration and date, instrument, and element ratios. This is extremely important for completing Tasks 1 and 2 (see section 3.1) since having a concise visual summary makes comparing across events simple.

5.2 Timeline

Figure 4 depicts the timeline feature for the SEV tool at the top of the user interface. This timeline spans the entire duration of the data, from 2017 to 2024. Each event is represented in time by a white marker above the timeline. This is particularly useful for noticing particularly high density of event observations across time, such as the time from early 2022 to late 2023.

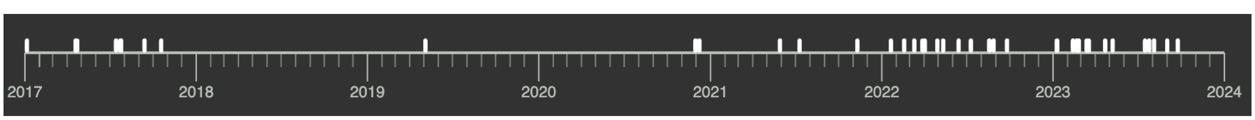

Figure 4. Timeline of solar flare events, located at the top of the tool interface.

The timeline also includes the ability for users to quickly identify events using the timeline and vice versa. When the user hovers over an event in the timeline, all other elemental representations of other events disappear, singling out the event of interest. This feature is shown in *Figure 5*. Similarly, when the user hovers over the element bars for a given event, the corresponding marker in the timeline is highlighted, while all others are grayed out. These features are important for accomplishing Task 3 (see section 3.1) and allow researchers to quickly identify events and find trends in the frequency of events over time.

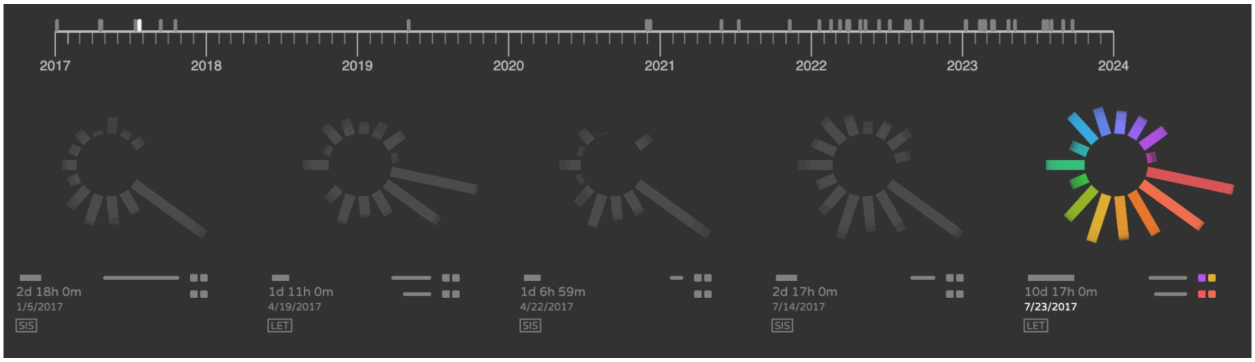

Figure 5. Expanded view of Fe/O element ratio calculation.

5.3 Filtering and Sorting

In order to allow researchers to accomplish Task 4 (see section 3.1), we created a toolbar with a multitude of interactive features, as shown in *Figure 7*. The main features of this toolbar are toggling on and off elements, sorting options, bar shape options, and instrument filtering. In the 'ELEMENTS DISPLAYED' section, the user is able to manually add or remove elements from all the elemental event representations, or use the 'ALL', 'NONE', and 'RATIOS' buttons to quickly turn on all elements, turn off all elements, or only display the elements used for the element ratio calculations (H, He, Fe, and O). This makes it easier to narrow the user's focus to only one or a few elements so that comparison across events is visually easier. In addition to the toolbar element filtering, as displayed in *Figure 6*, when the user hovers over a particular element for a given event, all other element bars for all events become desaturated, and the length of this event's element bar is displayed for all other events. This feature is useful for further making comparison of element intensity across events easier.

Figure 6. Cross-event element comparison hovering feature.

The ‘SORTING OPTIONS’ section provides invaluable sorting mechanisms to make finding the unique and edge-case solar flare events easier. The options for these sorting options include the event date, event duration, element ratio magnitudes, and individual element peak intensities for the most useful elements. This feature is particularly useful for identifying trends between various solar flare event variables, since the user can determine if certain characteristics are shared for events which have the highest/lowest values for each of the sorting options.

As mentioned in section 5.1, the ‘SHAPE MODE’ tool is used to switch between the element bars being rectangles or wedges. While the ‘RECTANGLE’ mode is easier for comparing element intensities across various events, the increased width of the element bars in the ‘WEDGES’ mode makes it easier to identify the distribution of intensities across energy bands for a given element. Lastly, the ‘INSTRUMENT’ tool allows for users to toggle on and off events detected by the SIS and LET instruments.

Figure 7. Toolbar for sorting options for the SEV dashboard.

6. Conclusion

We presented the design and implementation of the SEV tool, an interactive dashboard designed and implemented to address the challenges of analyzing complex and large-scale solar flare event data. By combining solar flare event data from the STEREO and ACE missions, the SEV tool enables researchers to filter, sort, and compare events across multiple parameters, while also providing concise visual summaries and interactive timelines. Through close collaboration with astrophysics researchers, the tool was developed to address the limitations in old solar flare event interfaces and support the ability to quickly identify and compare solar flare events, calculate element ratios, and discover relationships between element intensity magnitudes and event characteristics.

While this tool is a step in the right direction towards creating a tool able to be fully integrated with heliophysics research groups, it would be beneficial to improve aspects of the tool and integrate additional features. While the SEV tool effectively combines the data from the ACE and SIS missions, it lacks event data from the Parker Solar Probe. Furthermore, while it is somewhat apparent when an event is displayed twice (once from ACE, once from SIS) due to having very similar start dates and event durations, there is no visual indicator which identifies which events are measured twice. Additionally, the SEV tool lacks a more detailed, numerical view of individual events' element intensities since there are no numerical labels of the intensities of elements on any events. It would also be useful to have labels and filters for the users to better identify various energy bands for each element bar. Further, more user control over the scaling system of the element flux intensities rather than only log-log scaling. One way this could be improved is by introducing different scaling factors for each element, which would allow the user to compare element flux intensities across events more easily since some of the radial bars are short, making noticing differences in bar heights difficult. Another possible improvement of the SEV tool is to include more timeline interaction, such as a slider which would allow the user to control the time frame over which the events are displayed. With improvements to these limitations, the SEV tool has the potential to evolve into a comprehensive, researcher-centered platform that not only streamlines the study of solar flare events but also deepens our understanding of the mechanisms driving solar activity.

Acknowledgments

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