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Second-Class Citizen in the Heliophysics Community

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The study of solar energetic particles (SEPs) is an important area of solar research and space weather. An SEP event extends over large regions of the heliosphere, involves energy ranges varying by decades, and evolves over various time and spatial scales and with ion composition, but with SEP observations limited to *in situ* detections on a few spacecraft for any given event, we are unable to observe these properties synoptically. Solar studies in general are the beneficiaries of imaging and remote sensing observations over practically all wavelengths and timescales from ground and space based detectors that drive increasingly highly sophisticated models. I see this divide as creating a two-class system for researchers, with us SEP researchers as second class members. Following a brief review of my experience with solar imagery and failed ideas on remote imaging of SEP events, I review two remarkable developments that give hope for some new SEP imaging technique. Finally, I discuss two poorly understood questions of impulsive and gradual SEP events that I think can be feasibly approached with current modeling techniques.

Keywords: solar energetic particles, solar flares (1496), coronal mass ejection, solar corona and wind, heliospheric magnetic field

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INTRODUCTION

Solar-heliophysics encompasses a broad range of topics and research techniques. Over the past several decades I believe there has been a growing broad division in the community between those who work with remote observations and imaging techniques, and others, like me, who are confined to getting their primary solar data only from *in situ* observations. I have in mind observations of solar energetic particles (SEPs) that can be observed only at several heliospheric locations, currently confined to the ecliptic plane. It is great that we have Parker Solar Probe and Solar Orbiter, but the point is that no matter how many SEP detectors we have in space, we are still just drawing samples of a broadly distributed and evolving phenomenon, the SEP event (I'm thinking E > 10 MeV ions and maybe E > 0.5 MeV electrons). There may be multiple sources of unknown size scales from various seed populations and spatial distributions of unknown numbers of SEPs over wide (or maybe narrow) ranges of longitude and latitude for a given SEP event, and the story gets more complex as we ask about different SEP energy ranges and ions of different rigidities. We continue to depend on statistics of many SEP events just to get a rough handle on their basic energy and spatial distributions. The blind man is much better informed about his proverbial elephant than we are about SEP events in the heliosphere. In the meantime from the remote observers, I am dazzled by solar images and model representations of increasing spatial, temporal, and thermal or energy resolution with ever more detailed physics.

Maybe years of frustration are catching up with me. It didn't always seem this way. I began with analysis of SEP proton events in grad school, then at NRL I worked with OGO-V X-ray flares from the NRL full-sun proportional counter. A definite change of focus from SEPs to flare X-rays, but the basic tool was still analysis of time series of detector counting rates at different energy bands. The object was to get temporal variations of X-ray spectra (flare temperatures and emission measures) or SEP energies and their characteristic values. While one case was *in situ* observations (SEPs) and the other remote observations of full disk emission from the Sun, that seemed like a minor distinction. It was all solar flare physics.

SOLAR IMAGES CONFRONT AUTHOR

I remember my first encounter with a full disk solar X-ray rocket image, proudly presented for my consideration in an early meeting with my new boss, Pippo Vaiana, the American Science and Engineering (AS&E) physicist in charge of solar observations within the Ricardo Giacconi X-ray astrophysics group. I had a sense of panic that I would somehow have to make a big transition from working with simple time series data to getting physics out of those dark photographic blobs representing solar active regions. Then came the AS&E X-ray telescope on Skylab with lots of solar X-ray images on film. Locations and evolution of coronal holes or numbers and distributions of bright points seemed like straightforward approaches to take from solar X-ray images, and after a poor start (Kahler, Krieger, and Vaiana, 1975), I got used to analyzing X-ray flare images and later analyzed X-ray coronal hole boundaries (e.g., Kahler and Hudson, 2002). Continued interest in SEP events led to correlations of radio bursts and CMEs with SEP events, which did not require image analysis. I began collaborating with Don Reames and Ed Cliver about 1982, again looking only at CME or radio burst listings, not needing image analysis. Work using SEP events as probes of magnetic clouds followed (Kahler et al., 2011), again no remote images needed.

THE DIVIDE OF IMAGING VERSUS *IN SITU*

During the past 2 decades it has been impressive to see the great successes of solar imaging missions. SOHO images greatly eclipsed the pioneering Skylab images, thanks to the revolution from film detectors to CCDs, with ever greater fields of view and spatial resolutions as images of Hinode, SDO, IRIS, PSP, and other missions are presented and analyzed in detail. Advances in physical models combining detailed calculations with quantitative images of magnetic field lines and ionic radiation have led to deeper appreciation of the physical processes in space and time in the solar atmosphere and interplanetary space. **Figure 1** shows several recent examples in which authors have combined models and data to extend imagery to heliospheric SEP ion distributions.

In stark contrast, the observation of SEPs can be made only with *in situ* detectors, from which we can produce intensity-time profiles (**Figure 2A**), evolving or fluence energy spectra, and spatial distributions of SEP events by compiling event averages (Lario et al., 2006; Cohen et al., 2017; see **Figure 2B**), but a host of questions about spatial/temporal/compositional/energetic evolution of SEP events remains untouched and unapproachable. As a researcher of SEP events, I am frustrated and envious of my first-class colleagues who traffic in spiffy, eye-catching solar/heliospheric images even more spectacular than those of **Figure 1**. If you are a magazine or journal science editor hoping to engage your reader with a single image from heliospheric SEP physics, do you go with an example from **Figure 1** or from **Figure 2**? Are the SEP distributions of **Figure 1** right on or badly off the mark? We'll never know because we can't image the SEP events we now study.

This is not my first whine on the physical barrier to becoming a first-class heliospheric research citizen with images of real SEP particle distributions, evolving in time, and color-coded for energy, maybe even (I'm dreaming here) composition. With co-author B. Ragot we set the goal (**Figure 2C**) of exploring possible ways that SEPs might interact with the SW to produce neutral radiation that can be imaged by a detector and maybe deconvolved to produce 3-D spatial reconstructions. We (Kahler and Ragot, 2008) found that 4–7 MeV ion de-excitation from SEP collisions with heliospheric ^{16}O and ^{12}C would be far too weak for observation, but that π^0-decay γ-rays as detectable signatures of E ≥ 300 MeV nuc^{-1} SEP ions was possible in large events.

Further candidate remote SEP signatures of positron-decay 0.511 MeV line emission from E > 300 MeV protons; neutrons and the 2.23 MeV neutron-capture line from E > 30 MeV nuc^{-1} ions; synchrotron emission from E > 0.3 MeV electrons; and transition radiation (TR) from E < 100 keV electrons and from ions were discussed in Kahler and Ragot (2009). TR arises any time a particle crosses an inhomogeneous medium with variation in refractive index and has likely been observed in decimetric bursts of turbulent flares (Fleishman et al., 2005) and in type II bursts from narrow density structures in wakes of CMEs (Chernov et al., 2007). It is best generated by electrons in dense regions where $\omega_p >> \omega_B$, but by protons only in tenuous regions of $\omega_p << \omega_B$ (Fleishman and Kahler, 1992). A common theme is that it is not enough to detect such radiation, but it must be imaged to distinguish populations trapped in the corona from those of interplanetary space.

TWO HOPEFUL SURPRISES

SEP Event ENAs

At the time of our second paper (Kahler and Ragot, 2009) energetic neutral atoms (ENAs) were known as messengers of distant energetic particle populations and the basic tool of the then recently launched (2008) Interstellar Boundary Explorer (IBEX) mission (McComas et al., 2009) to explore the heliospheric termination shock and heliosheath. We acknowledged, but did not explore, ENAs as possible probes of SEPs, so it was an exciting surprise to learn that a SEP event on 5 December 2006 had been detected on STEREO with ENAs by Mewaldt et al. (2009). This was an appropriately big deal at the time and a quick glimpse of ENAs as a promising basis of SEP imaging, as they propagated directly to Earth through a thick sludge of heliospheric magnetic turbulence that retarded the arrival of the charged SEPs composing the main event. The

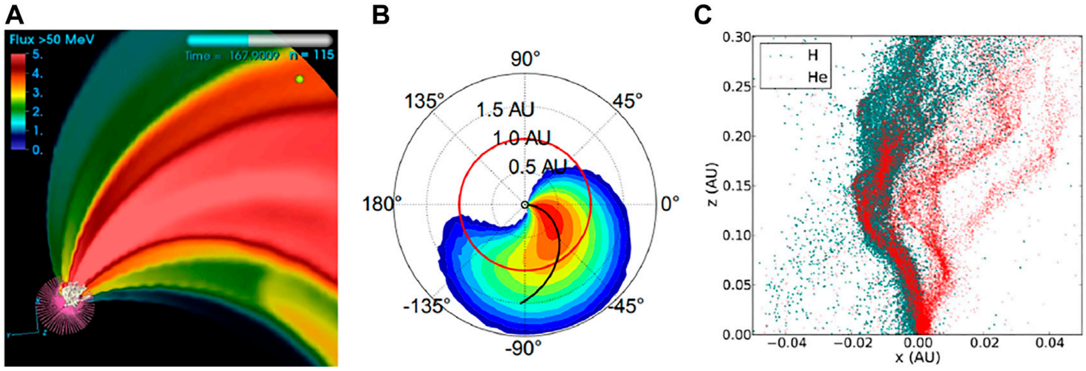

FIGURE 1 | (A): E > 50 MeV proton distribution of the 14 July 2000 event 3 h after injection with the STAT model of Linker et al. (2019). **(B)**: Equatorial log color-coded distribution of 10 MeV protons 3 h after impulsive injection based on the FP-FLRP model of Laitinen et al. (2016). **(C)**: model images of H (turquoise) and 4He (red) SEP spatial distributions following spatially separated but simultaneous impulsive injections (Guo et al., 2022).

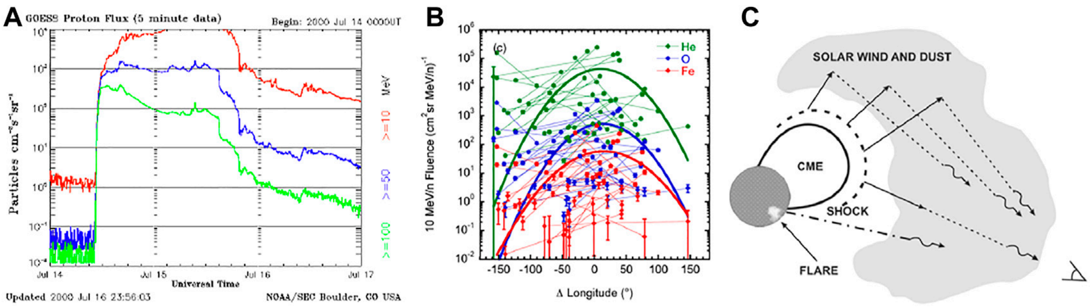

FIGURE 2 | (A): GOES profiles of the 14 July 2000 SEP event modeled in **Figure 1**. **(B)**: Longitude of event fluences for 10 MeV nuc^{-1} He, O, and Fe with best fit curves (Cohen et al., 2017). **(C)**: schematic of remote observation of SEPs against a grey background of SW and dust (Kahler and Ragot, 2008).

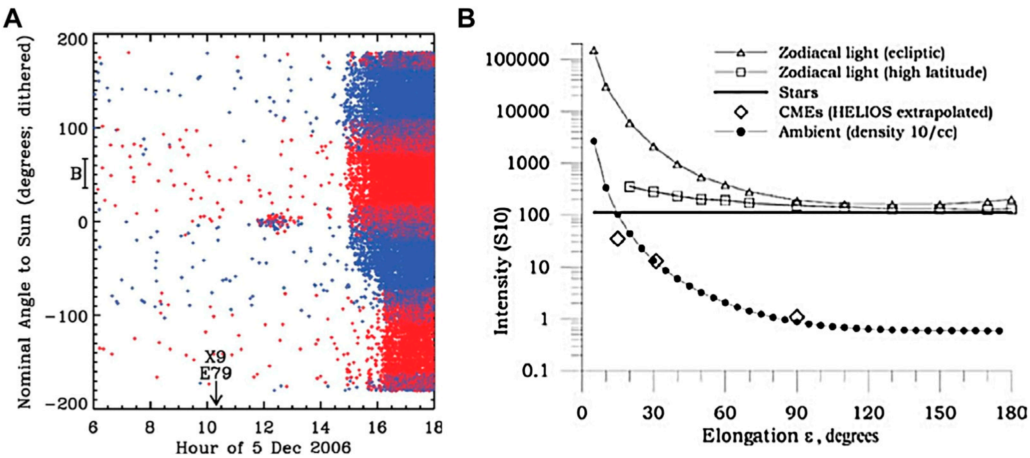

FIGURE 3 | (A): Plot of the measured angle to the Sun for individual 1.6–12 MeV proton events on 5 December 2006 (red = LET-A; blue = LET-B). Note the group of counts within ±10º of the Sun from ~1130 UT to ~1350 UT, well before the SEP onset at ~1445 UT (Mewaldt et al., 2009). **(B)**: Surface brightness in S10 units versus solar elongation angle for zodiacal and star light, and of expected CME brightness extrapolated from Helios measurements. A calculation of an ambient medium having a density of 10 e– cm^{-3} at one AU and an inverse-square density drop off with solar distance is also shown (Jackson et al., 2004).

STEREO A/B Low Energy Telescopes (LET-A and LET-B) were not designed to select neutrals, so it was the timing profile and directional information that confirmed the presence of SEPs (**Figure 3A**). While the LETs are not ENA detectors, separating charged and neutral particles, there were favorable conditions to observe that event. It was a very big (2000 pfu for E > 10 MeV proton) event, able to produce an observable ENA flux at one AU, and it originated on the east limb, allowing a sufficient temporal delay of the onset of the far larger SEP event. The ENAs were further confined to E < 5 MeV, as the cross section for the charge exchange cross section with ambient O^{+6} coronal/SW ions drops rapidly with energy (Mewaldt et al., 2009). Finally, the SW density drops at least as r^{-2}, presumably negating their use as heliospheric probes of SEPs, although charge exchange calculations of protons with atomic H, O^{6+}, and C^{4+} by Wang et al. (2014) suggest that ENA detectors of sufficiently low background could detect particle acceleration in the low corona. The Earth's dipole magnetic field may be such a detector, channeling high energy charged particles to the poles and converting low energy (>0.8 MeV) ENAs into quasi-trapped magnetic equatorial protons (Mason et al., 2021).

White Light Interplanetary CMEs

Imaging the SW was thought impossible until Helios B white-light photometer observations revealed the passages of CMEs through its heliospheric field of view (Jackson, 1985). Observing Thomson-scattering of solar white-light photons was also at one time considered a difficult challenge, but because of a very steady zodiacal and stellar white-light background the Solar Mass Ejection Imager imaged CMEs two orders of magnitude fainter than that background (Jackson et al., 2004; **Figure 3B**). The combination of interplanetary scintillation (IPS) and white-light observations now enable the SW velocities and densities to be reconstructed throughout the inner heliosphere (Jackson et al., 1988, 2020); see https://ips.ucsd.edu), a feat considered impossible at one time and suggesting that there may yet be hope for some new way to image SEPs in space.

Coronal/Interplanetary SEP Imaging

The hope and plea here is that somebody somewhere will get a brilliant idea to detect some kind of neutral radiation from energetic ions and electrons distributed throughout the heliosphere as a SEP event. The odds are really long, but the rewards are enormous. We (currently second-class research citizens stuck with our *in situ* observations) will be able to join our fellow first-class citizens in proudly displaying images of SEP events and making direct comparisons with increasingly sophisticated model outputs. The advances in understanding where SEPs originate relative to shocks and coronal and solar wind features, followed by their transport histories will greatly accelerate our understanding of SEP physics.

A PLEA FOR TWO NEEDED SEP MODELS

I will end this story with a modest request to the SEP modeling community for two efforts addressing currently neglected targets that I think well within the capabilities of several SEP models. Rather than the usual procedure of starting with SEP events observed at one AU to estimate injection spectra and numbers, the models would start with injected SEP profiles and calculate resulting SEP numbers and energies observed in one AU detectors.

Total Numbers in ^{3}He Events

For nearly 50 years (Reames, 2021) SEP events have been observed with substantial enhancements (>100 ×) of $^3He/^4He$ over the coronal/SW abundance of 5×10^{-4} in the few MeV/nuc energy range. Those events are generally small and impulsive, with source regions in coronal flares and jets. The ^{3}He acceleration process was first explained by absorption of electromagnetic ion cyclotron waves, but currently favored (Reames, 2021) is magnetic reconnection in confined coronal volumes, which may account for upper limits to the observed ^{3}He event fluence distribution observed at one AU (Ho et al., 2005; **Figure 4**). The ^{3}He acceleration process appears to occur differently from that of ^{4}He (Ho et al., 2019) and may even completely strip a coronal source region of all ^{3}He ions (Reames, 2021).

Well-developed models of jets (Panesar et al., 2016, 2017; Wyper et al., 2018) and extensive observations of ^{3}He coronal sources (Bučík, 2020; Bučík et al., 2021) make it imperative that we compare a calculated ^{3}He ion injection population with corresponding one AU observations to determine the accelerated fraction of the source ^{3}He as a measure of the strength of the acceleration process. This has not been attempted since the Reames (1999) estimate assuming a source region area of 3,000 km^2, density of $\rho = 10^{10}$ cm^{-3}, scale height of 10^4 km, $^3He/^4He = 5 \times 10^{-5}$ for a total 5×10^{31} ^{3}He in the volume. He assumed a large one AU event of 10^5 cm^{-2} ^{3}He (see **Figure 4A**) resulting from uniform injection in a 20° cone followed by scatter-free propagation and concluded that >10% of the source ^{3}He was accelerated. Surely we (the modelling community intended) can do much better than that. The basic goal is to connect the number of ^{3}He in the source region to the number accelerated and injected from the corona. A size estimate of a reconnection region of an observed jet source could serve as the basis of an input ^{3}He number with a nearly delta function injection in space and time assumed for the accelerated population.

Nearly all 0.02–2 MeV/nuc ^{3}He-rich events are associated with type III radio bursts (Wang et al., 2012; Bučík et al., 2016; Bučík et al., 2018; Bučík et al., 2021), which are used for timing ^{3}He injections but could also aid substantially in the ^{3}He source volume estimate. If we are lucky, the coronal injection regions of the type III-burst electrons are shared by the ^{3}He ions, so the coronal size and location of a ^{3}He event and its extent into the heliosphere will be defined by that of the type III radio burst. It is not yet feasible to image type III radio bursts, but that is exactly one of the goals of the NASA SunRISE mission, due for launch in 2023 (Kasper et al., 2019). SunRISE consists of six small spacecraft at supra-geosynchronous orbit with radio telescopes operating the in the 0.1–22 MHz region, which extends from 10 Rs to one AU.

Shock SEPs for CME Energetics

Fast CMEs are the drivers of shocks that accelerate coronal and SW seed particles to energies sometimes reaching GeV energies (Reames, 2020). That SEP energy is ultimately derived from the

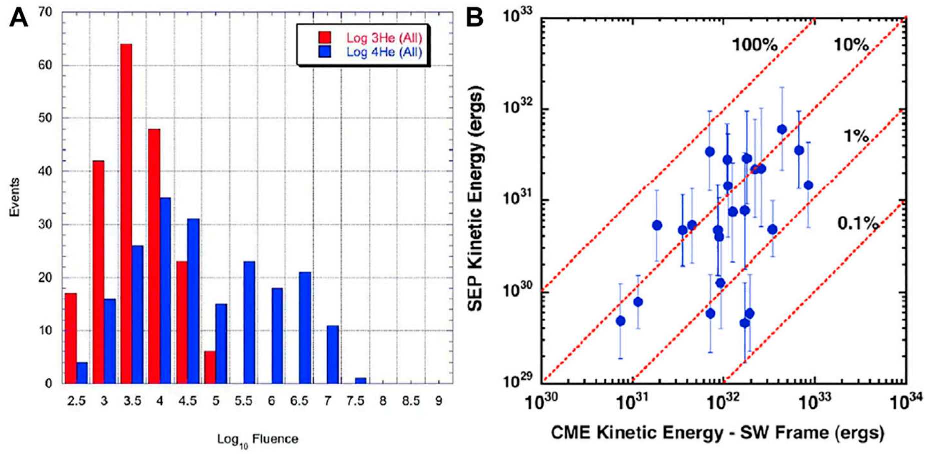

FIGURE 4 | (A): Plot of ^{3}He events versus fluence (cm^{2} sr MeV/nucleon)$^{-1}$ observed 1997 to 2003 on ACE (Ho et al., 2005). **(B)**: Plot of SEP event energies versus the associated CME kinetic energies for 23 events (Mewaldt et al., 2008).

kinetic energy of the CME, so an important question is the conversion efficiency of the CME energy into that of SEPs. Mewaldt et al. (2008) examined this question for the 50 biggest E > 30 MeV SEP events of 1996–2003 using associated CME speeds and masses given for 23 of those events in Gopalswamy et al.(2004, 2005). The CME energies are estimated to be accurate within a factor of 2, but the hard part of the comparison was to estimate the total SEP energies, which Mewaldt et al. (2008) calculated with fluence spectra observed from 10 keV/nuc to 1,000 MeV/nuc. Included in their energy calculation were numbers of H and He particle crossings at one AU and adiabatic energy losses for each crossing. The source longitude and latitude distributions were assumed to fall off exponentially from central meridian with e-folding drop-offs of 25° east of CM and 45° to the west and 35° with latitude. For six events the abundances of He and heavier ions were measured, and for the remaining 17 events protons were assumed to be 75 ± 7% of the total energy. Assuming that the shock properties depend on the CME speed relative to the SW, Mewaldt et al. (2008) subtracted an assumed SW speed of 400 km/s from the CME speeds to calculate the CME kinetic energies. The resulting comparison is reproduced in **Figure 4B**, where the median efficiency is 6.5%.

A similar improved comparison based on simulations of one AU SEP scatterings and energy losses by Chollet et al. (2010) and Gaussian spatial distributions of SEP events adopted by Lario et al. (2006) was carried out by Emslie et al. (2012) for 20 SEP events with results (their **Figure 2B**) comparable to those of **Figure 4B**. Another comparison of 94 SEP and CME energies by Kahler and Vourlidas (2013) used CME speeds at measured centers of mass rather than the leading edge speeds and a rotationally symmetric exponential distribution with an e-folding angle of 45° for SEP events with spectra determined by only the 2 and 20 MeV H fluences. Their Figure 7 also showed high SEP efficiencies, including some exceeding unity.

The preceding works all used spatial, spectral, and transport assumptions to convert one AU observed SEP fluences to total numbers and energies of the produced SEPs. The results can be very model-dependent, however. With a simple CME latitude correction Gopalswamy et al. (2021) increased the number of interplanetary E > 500 MeV protons by about an order of magnitude in five of 14 SEP events calculated by de Nolfo et al. (2019) in their study of solar sustained gamma-ray events. In general, however, the assumption parameters are not tested in these SEP calculations. I propose that modelers go the other way, starting with a CME shock model producing SEP events of known spatial, temporal, and energy distributions. The model, with full transport properties, would then track and predict both the total accelerated SEP energies and the intensities and fluences observed at a designated one AU detector. In this scheme the shock longitudinal and latitudinal widths and acceleration timescale variations with energy could all be tracked. The advantage of this approach is that the SEP distributions and energies are known and can be compared with resulting one AU SEP observations and CME energies. Multiple model runs can then establish the uncertainties of the reverse process of estimating SEP energies solely from the one AU observations. The SEP efficiencies of CMEs are too important to be left in their current state of understanding.

CONCLUSION

I am resigned to continue my SEP investigations as a second-class citizen of the heliospheric research community, operating in the slow lane of *in situ* observations, while hoping for a better future through some great discovery. In the meantime I would be delighted to see acceptance of my challenges of the preceding Section.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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