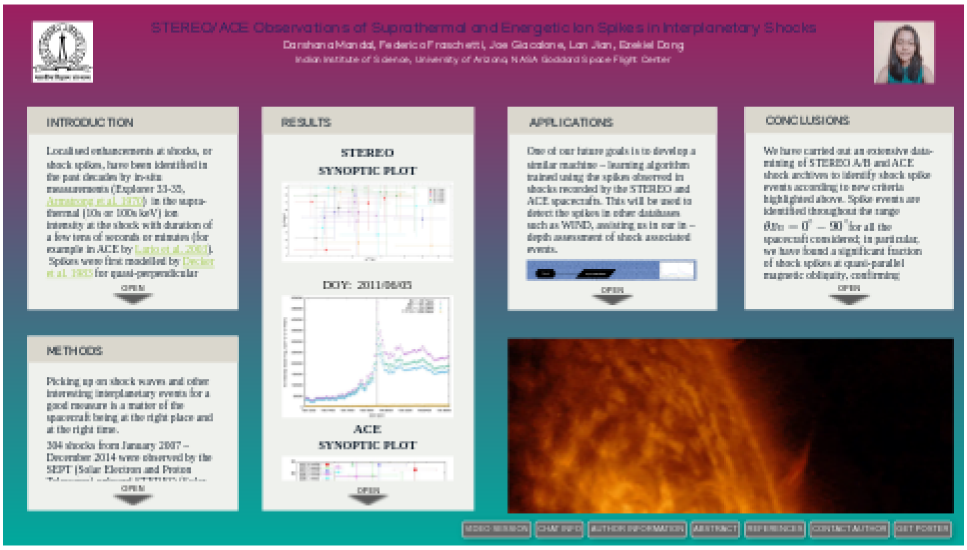
STEREO/ACE Observations of Suprathermal and Energetic Ion Spikes in Interplanetary Shocks



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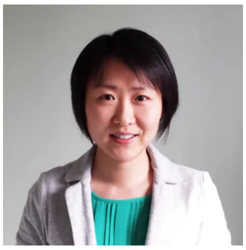
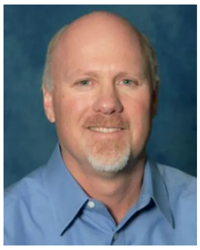


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INTRODUCTION

Localised enhancements at shocks, or shock spikes, have been identified in the past decades by in-situ measurements (Explorer 33-35, Armstrong et al. 1970 (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JA075i031p05980)) in the supra-thermal (10s or 100s keV) ion intensity at the shock with duration of a few tens of seconds or minutes (for example in ACE by Lario et al. 2003 (https://aip.scitation.org/doi/abs/10.1063/1.1618676)). Spikes were first modelled by Decker et al. 1983 (https://ui.adsabs.harvard.edu/abs/1983JGR....88.9959D/abstract) for quasi-perpendicular shocks $\theta_{Bn} > 70^{o}$, where θ_{Bn} is the angle between the local shock normal and the upstream unperturbed magnetic field) by using shock drift acceleration of a seed particle population. Erdos & Balogh et al. 1994 (https://ui.adsabs.harvard.edu/abs/1994ApJS...90..553E/abstract) proposed that spikes are generated by magnetic trapping of particles formed by multiple crossings of the turbulent magnetic field lines with the shock surface and showed qualitative agreement of their numerical model with the ISEE-3 data in the 5 minutes preceding the IP shock on 1978 Dec 25^{th}. The anisotropy at the origin of spike-structures is crucial to understand the relevance of seed particles in the particle acceleration at shocks.

Detailed numerical analysis of supra-thermal intensity profiles, pitch-angle distribution and momentum spectra at shocks was carried out over the θ_{Bn} range ($0^{\circ} - 90^{\circ}$) by Fraschetti & Giacalone et al. 2015 (https://ui.adsabs.harvard.edu/abs/2015MNRAS.448.3555F/abstract), by using an isotropic model for the pre-existing turbulence, with no seed partilcle population. The formation of spike-like enhancement was surprisingly found also at quasi-parallel geometries ($\theta_{Bn} \sim 0^{\circ}$). The pitch-angle distribution in distinct time windows before and after the STEREO-A reverse shock on 2008 DOY 069 in Yang et al. 2020 (https://iopscience.iop.org/article/10.3847/2041-8213/ab629d) was reproduced by test-particle simulations in the supra-thermal protons energy range (10-40 keV) by using the approach in Fraschetti & Giacalone et al. 2020 (https://ui.adsabs.harvard.edu/abs/2020MNRAS.499.2087F/abstract), with no need of seed particle population.

METHODS

Picking up on shock waves and other interesting interplanetary events for a good measure is a matter of the spacecraft being at the right place and at the right time.

304 shocks from January 2007 – December 2014 were observed by the SEPT (Solar Electron and Proton Telescope) onboard STEREO (Solar Terrestrial Relations Observatory) A/B Spacecraft.

The data has been recorded in four channels “sun,” “asun,” “north,” and “south.” These correspond to the nominal spacecraft status, with the apertures pointing sunward and anti-sunward along the Parker spiral and northward and southward in perpendicular to the ecliptic. “Omni” contains sector-averaged data (the result of adding asun, sun, north, and south datasets, divided by 4).

SEPT measures electrons in the energy range from 30 to 425 keV and protons from 60 to 6500 keV using 15 energy channels. [2.1] We investigated the ion intensity of the shocks in the following energy channels: 84.1 - 92.7 keV, 92.7 - 101.3 keV, 101.3 - 110.0 keV, 1111.9 - 1250.8 keV

We developed a Python Code (Github Link to the code) to create the plots of the shocks using data from 2 different databases (University of Kiel database (http://www2.physik.uni-kiel.de/stereo/index.php?doc=data)), (University of Helsinki database (http://ipshocks.fi/database)) and then visually inspected to decide if a spike was observed at the shock time according to the following criteria:

- proton density compression greater than 2;
- enhancement in suprathermal energy range with respect to uniform downstream profile;
- smearing out of the enhancement at higher energies (> a few MeVs)

Additional criteria to define shock spike used in this work are a flat downstream profile for at least ~0.02 days (28.8 minutes); namely profiles smoothly decaying downstream within 0.02 days were excluded. We have excluded shocks with downstream flux comparable with upstream; we also excluded shocks having downstream fluctuations comparable with the amplitude of the spike and having upstream fluctuations that hamper a smooth decay. We have treated as separate the 5 distinct channels (North, South, Sun, Asun and the Omnidirectional), so that if some spike is prominent in at least one individual channel (among the 4 North, etc.) but is smeared out in the Omni, it is considered a spike. These criteria are more restrictive than those used in Lario et al. 2003 (https://aip.scitation.org/doi/abs/10.1063/1.1618676).

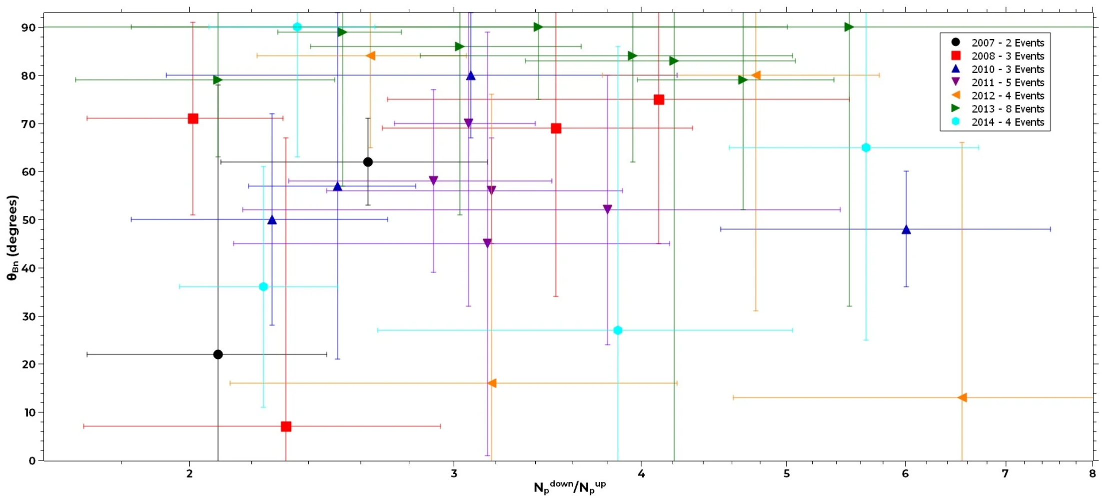
This code can be used to analyze other databases such as WIND, automating the entire profiles production. Several spikes with peak intensities lasting ~1 min were identified.

We also observed data from the Electron, Proton, and Alpha Monitor (EPAM) Particle Instrument aboard the Advanced Composition Explorer (ACE), which is one of the 6 sensors and 3 instruments aboard the spacecraft. Only the first four energy channels out of the total eight of the EPAM were utilized, with the following energy ranges: 47-66 keV, 66 – 114 keV, 114 - 190 keV, and 190 - 310 keV. The LEMS120 (Low-Energy Magnetic Spectrometer) detector was employed which measures ions at a 120-degree angle from the spacecraft's spin axis.

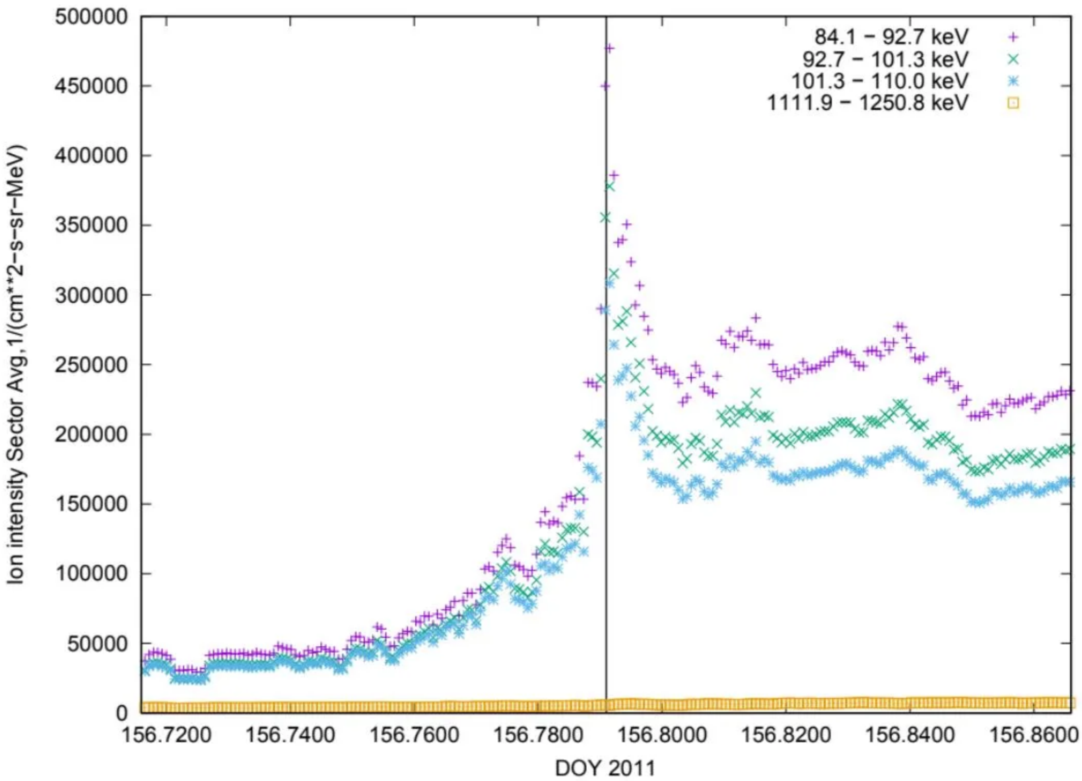
RESULTS

STEREO

SYNOPTIC PLOT

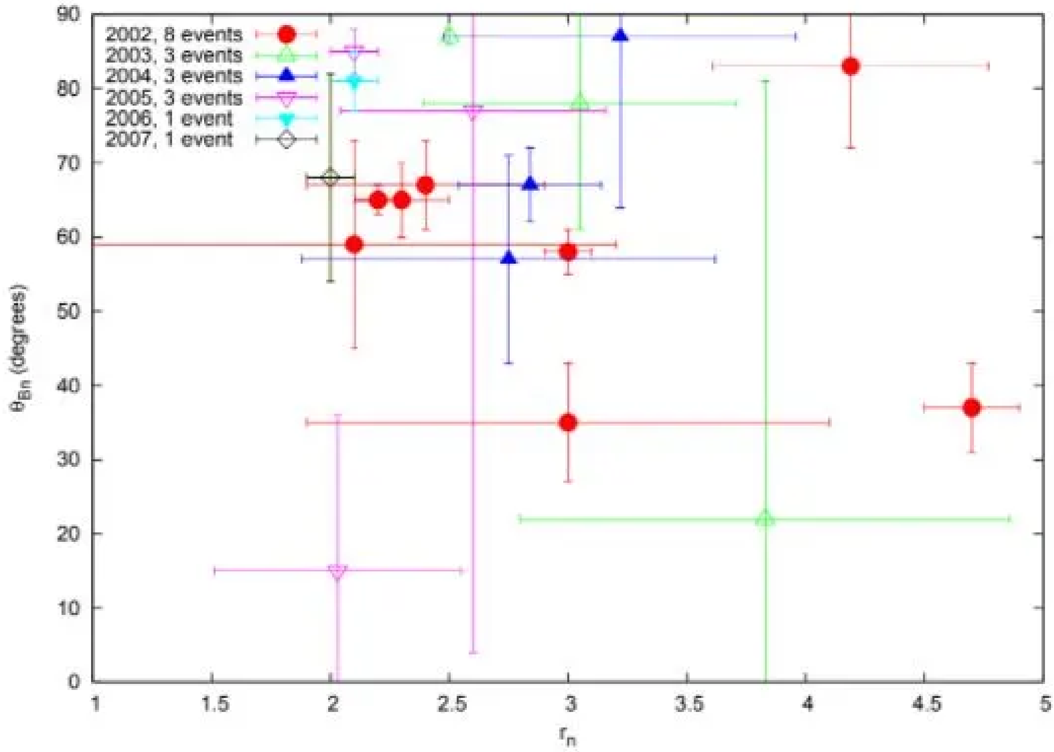


DOY: 2011/06/05



ACE

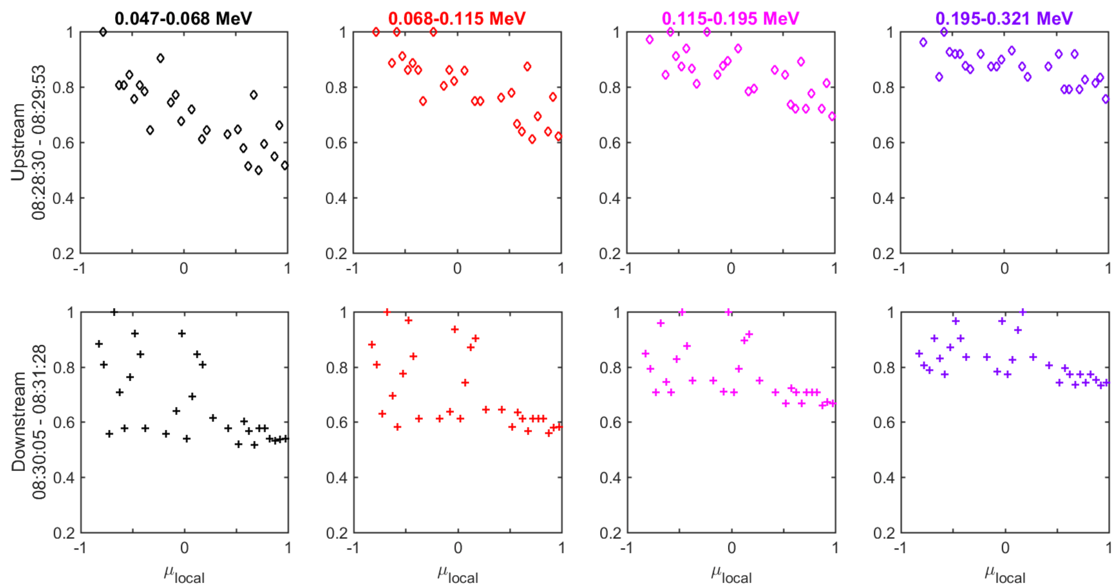
SYNOPTIC PLOT

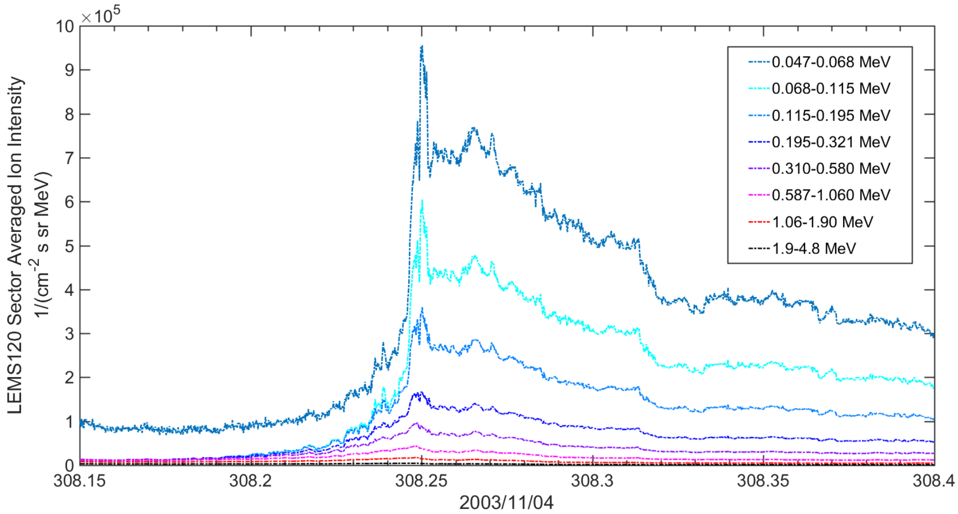


Plots of the intensity profiles and pitch angle distributions in 4 distinct energy bands

DOY: 2003/11/04

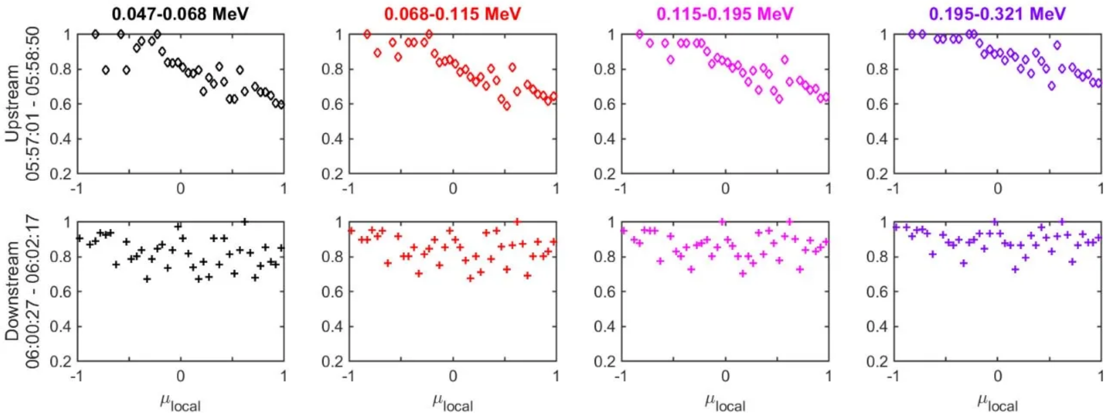
$$\theta_{Bn} = 22^{\circ}$$

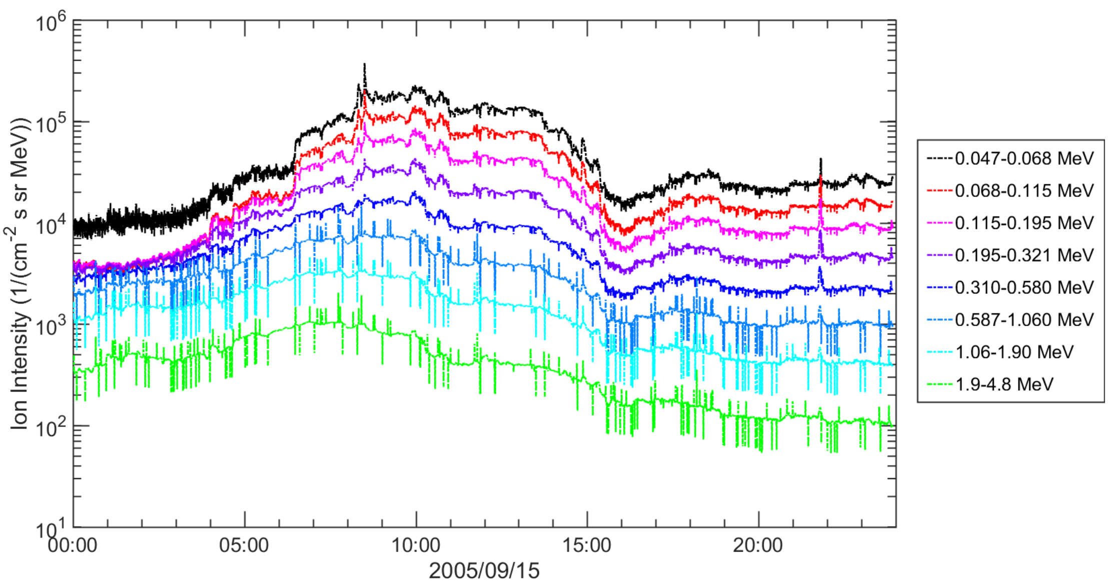




DOY: 2005/09/15

$$\theta_{Bn} = 15^\circ$$

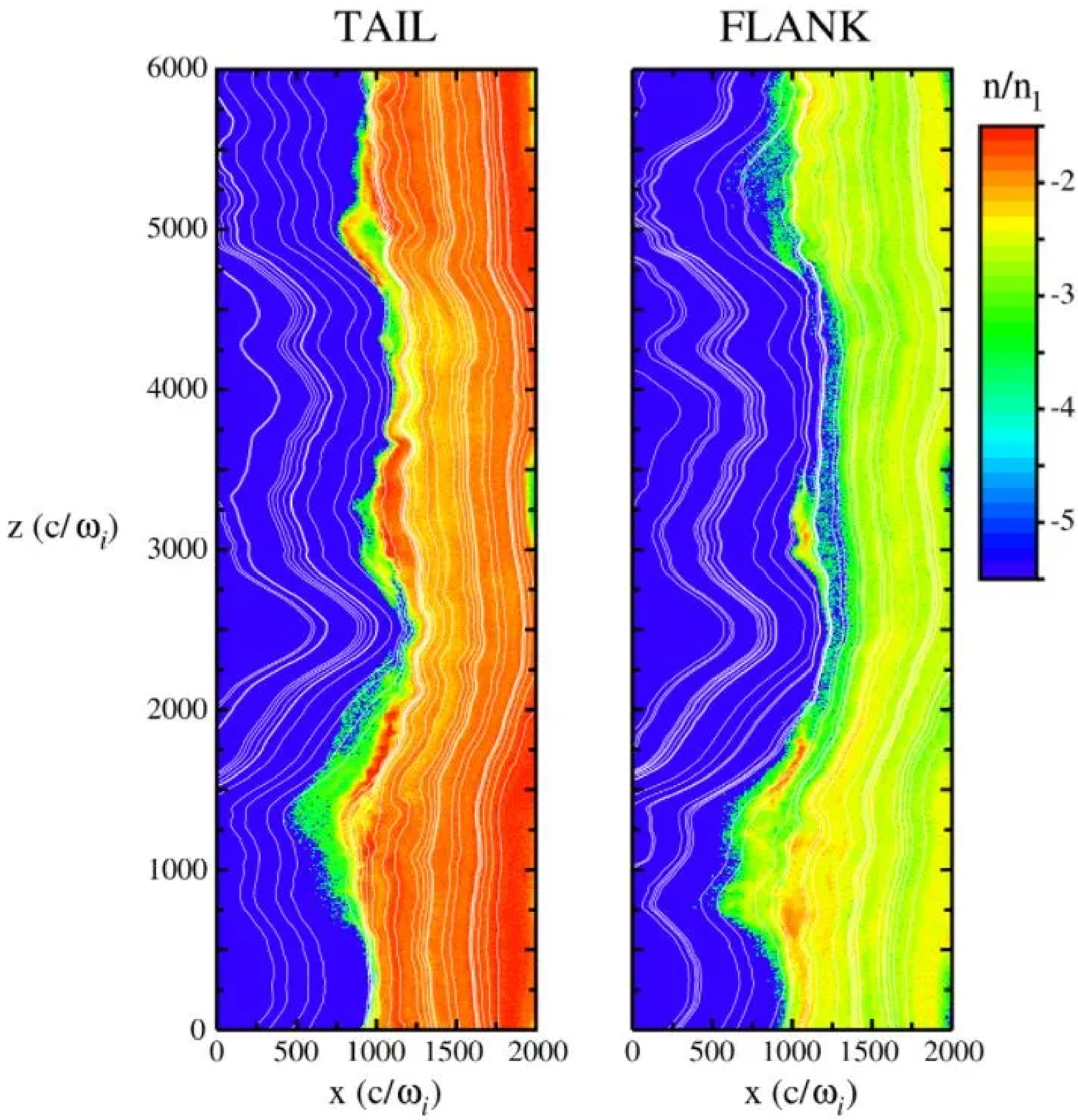




The above two examples are of quasi - parallel shocks which observations show are able to produce spikes. The pitch angle distributions shown above for the two ACE shocks (before and after the shock time) exhibit double-peak shape upstream and a near flat shape downstream as obtained in Fraschetti & Giacalone et al. 2015 (https://ui.adsabs.harvard.edu/abs/2015MNRAS.448.3555F/abstract).

HYBRID SIMULATIONS

The strength of accelerated interstellar pick - up ions at the solar-wind termination shock at three distinct places: the Voyager 2 crossing, the flank, and the downwind direction, or tail was estimated using a two-dimensional hybrid simulation.



[8]Simulations of the termination shock at the tail (left) and flank (right) regions of the heliosphere used a simulated number density of 10–20 keV pickup ions,i.e. plasma density (namely ion density) normalised to the upstream average density.The magnetic lines of force are depicted with the white curves. The right panel shows at z~3000 a little yellow-green island upstream (into the blue) almost detached from the shock surface. Because the acceleration of low-energy ions is significantly dependent on the local shock-normal angle, these hybrid simulations could be effective in localising spikes in these yellow-green patches. Since this is a speculation at the moment, we will work on this in the near future.

APPLICATIONS

One of our future goals is to develop a similar machine – learning algorithm trained using the spikes observed in shocks recorded by the STEREO and ACE spacecrafts. This will be used to detect the spikes in other databases such as WIND, assisting us in our in – depth assessment of shock associated events.

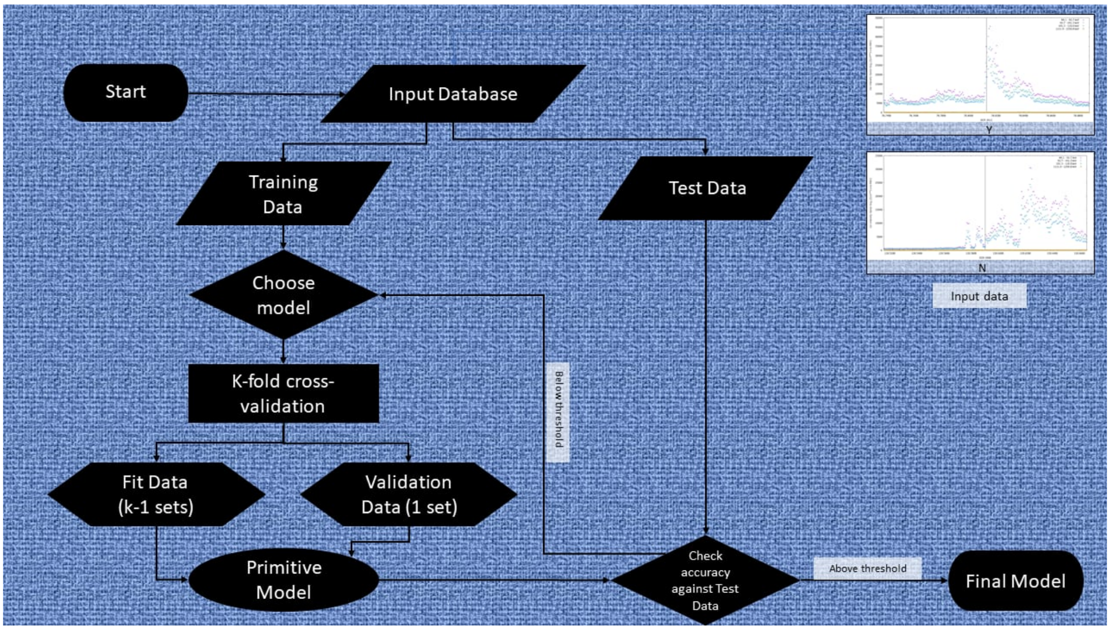


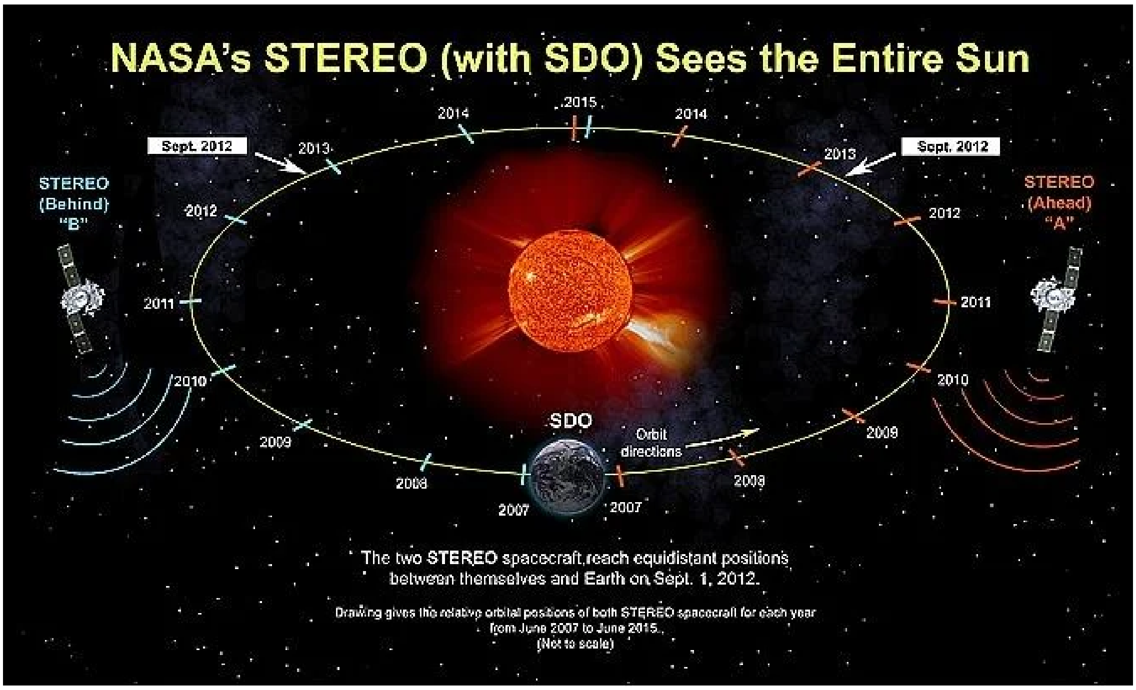
Image of flowchart describing future machine - learning applications
Image Credit: Prajjwal Kumar Das

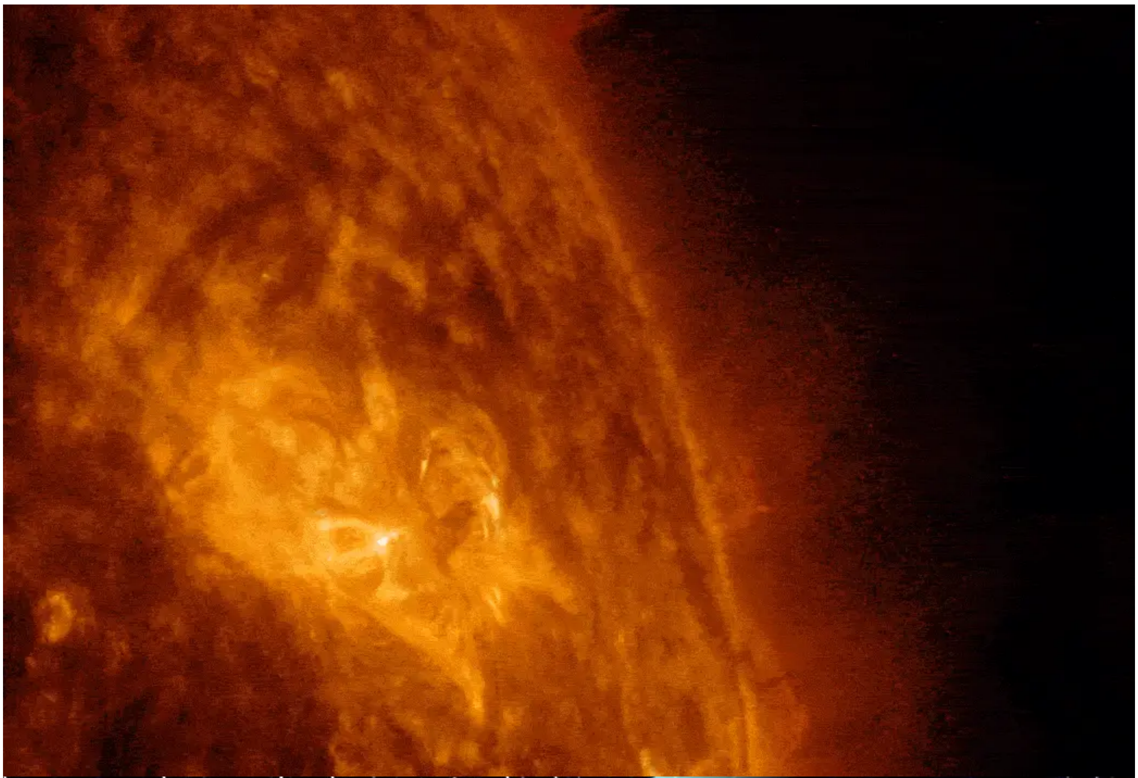
CONCLUSIONS

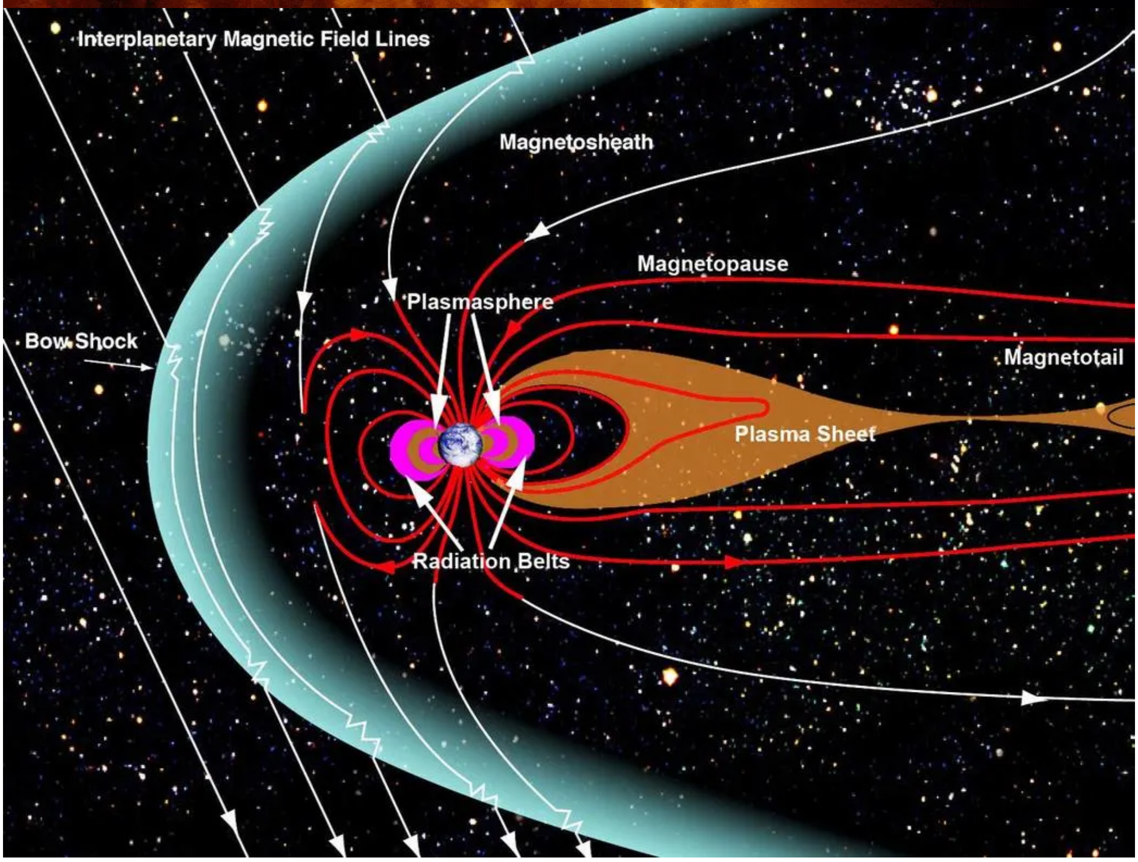
We have carried out an extensive data-mining of STEREO A/B and ACE shock archives to identify shock spike events according to new criteria highlighted above. Spike events are identified throughout the range $\theta_{Bn} = 0^\circ - 90^\circ$ for all the spacecraft considered; in particular, we have found a significant fraction of shock spikes at quasi-parallel magnetic obliquity, confirming previous numerical findings. The pitch-angle distributions both upstream and downstream of two ACE quasi-parallel shocks resemble qualitatively our numerical predictions.

ACKNOWLEDGEMENTS

This work was supported by NASA under Grants NNX15AJ71G and 80NSSC18K1213. This paper uses data from the Heliospheric Shock Database, generated and maintained at the University of Helsinki and STEREO/SEPT data pages generated and maintained at the Univeristy of Kiel.






Interplanetary Magnetic Field Lines
Magnetosheath
Magnetopause
Plasmasphere
Bow Shock
Magnetotail
Plasma Sheet
Radiation Belts

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ABSTRACT

Interplanetary shocks have been long known sources of suprathermal and energetic ions, and their origin will contribute in unveiling the origin of cosmic rays. Sudden ion intensity enhancements in the form of spikes that last anywhere between minutes to tens of seconds are observed during the passage of such shocks. Identification of spikes with peak intensities lasting ~1 min surveyed in over 304 shocks from January 2007 – December 2014 observed by the SEPT (Solar Electron and Proton Telescope) onboard STEREO (Solar Terrestrial Relations Observatory) A/B Spacecraft was performed using a new Python Code, followed by visual inspection. We also inspected the database of EPAM (Electron, Proton, and Alpha Monitor) onboard ACE (Advanced Composition Explorer) from 2003 to 2007. We present and discuss the statistical analysis of the shock spikes as a function of parameters such as shock normal angle and Mach number. The Python code can be used to analyse other databases such as WIND and this further paves the way for the employment of ML techniques to replace visual inspection. Such studies are vital in performing exhaustive and in-depth assessment of shock associated particle events.

REFERENCES

Acknowledgements

This work was supported by NASA under Grants NNX15AJ71G and 80NSSC18K1213. This paper uses data from the Heliospheric Shock Database, generated and maintained at the University of Helsinki and STEREO/SEPT data pages generated and maintained at the Univeristy of Kiel.

References

[1] D. Lario (https://aip.scitation.org/author/Lario%2C+D), G. C. Ho (https://aip.scitation.org/author/Ho%2C+G+C), R. B. Decker (https://aip.scitation.org/author/Decker%2C+R+B), E. C. Roelof (https://aip.scitation.org/author/Roelof%2C+E+C), M. I. Desai (https://aip.scitation.org/author/Desai%2C+M+I), and C. W. Smith (https://aip.scitation.org/author/Smith%2C+C+W) , "ACE Observations of Energetic Particles Associated with Transient Interplanetary Shocks", AIP Conference Proceedings 679, 640-643 (2003) https://doi.org/10.1063/1.1618676 (https://doi.org/10.1063/1.1618676)

[2]*Decker, R.*, 1983., "Formation of shock-spike events at quasi-perpendicular shocks", Journal of Geophysical Research 88, 9959–9974. doi:10.1029/JA088iA12p09959

[3]*Jian, L. K., Russell, C. T., Luhmann, J. G., Galvin, A. B., Simunac K. D. C.*, 2013, "Solar wind observations at STEREO: 2007 - 2011", Solar Wind 13 1539, 191–194. doi:10.1063/1.4811020

[4]*Dresing, N., Theesen, S., Klassen, A., Heber, B.,* 2016, "Efficiency of particle acceleration at interplanetary shocks: Statistical study of STEREO observations", Astronomy and Astrophysics 588. doi:10.1051/0004-6361/201527853

[5]*Fraschetti, F., Giacalone, J.,* 2015, "Localized enhancements of energetic particles at oblique collisionless shocks", Monthly Notices of the Royal Astronomical Society 448, 3555–3566. doi:10.1093/mnras/stv247

[6]*Fraschetti, F., Giacalone, J.*, 2020, "Bi-directional streaming of particles accelerated at the STEREO-A shock on 2008 March 9", Monthly Notices of the Royal Astronomical Society 499, 2087–2093. doi:10.1093/mnras/staa3021

[7] *Raúl Gómez-Herrero*, STEREO/SEPT level 2 science data format specification and caveats, pp. 1 - 2, accessed from Univeristy of Kiel database

[8]*Giacalone, J., Nakanotani, M., Zank, G.P., Kòta, J., Opher, M., Richardson, J. D.*, 2021, "Hybrid Simulations of Interstellar Pickup Protons Accelerated at the Solar-wind Termination Shock at Multiple Locations", The Astrophysical Journal 911. doi:10.3847/1538-4357/abe93a

[9] *Armstrong, T. P., Krimigis, S. M., and Behannon, K. W.*, 1970, "Proton fluxes at 300 kev associated with propagating interplanetary shock waves", J. Geophys. Res., 75(31), 5980– 5988, doi:10.1029/JA075i031p05980.

[10] *Erdos, G., Balogh, A.*, 1994., "Drift Acceleration at Interplanetary Shocks", The Astrophysical Journal Supplement Series 90, 553. doi:10.1086/191874

[11] *Yang L., Berger L., Wimmer-Schweingruber R. F., Wang L., Yu J., Galvin A. B., Mobius E.*, 2020, "The Pitch-angle Distributions of Suprathermal Ions near an Interplanetary Shock ",¨ ApJ, 888, L22

[12] *le Roux J. A., Webb G. M., Florinski V., Zank G. P.*, 2007, "A Focused Transport Approach to Pickup Ion Shock Acceleration: Implications for the Termination Shock", ApJ, 662, 350

SLIDESHOW IMAGE REFERENCES

1. Solar Flare accompanied with a Coronal Mass Ejection (CME) Image Credit: NASA/SDO/Goddard

2. Orbit of Stereo A and B Image Credit: NASA/SDO/Goddard

3. Regions of the Earth's Magnetosphere Image Credit: NASA/Goddard/Aaron Kaase