# Investigation of Superdiffusive Energetic Particle Transport Ahead of Traveling Shocks

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## Results

After analyzing 44 shock events, it was concluded that the vast majority of strong shocks exhibit superdiffusive behavior, with some events showing normal diffusion.

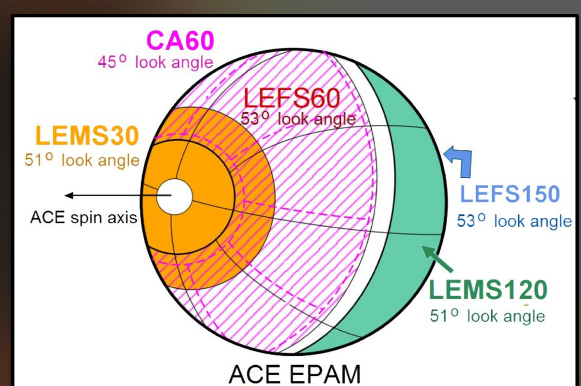
Contrary to what was previously hypothesized, there is no significant correlation between the level of superdiffusion α, and the shock obliquity angle $\theta_{bn}$ or particle energy.

No correlation was found between α and the value of the anomalous diffusion coefficient K, magnetic field or proton density shock ratio, Alfven or magnetosonic mach numbers. However, we detected a weak correlation between average α and average K, and a high correlation between Δα and ΔK/Avg K. The interpretation of the latter is difficult given that K itself depends on α.

| | Avg α vs Avg K | Δα vs ΔK/Avg | Avg α vs $\theta_{bn}$ |
|---|---|---|---|
| Correlations: | 0.33 | 0.91 | -0.04 |

## Data

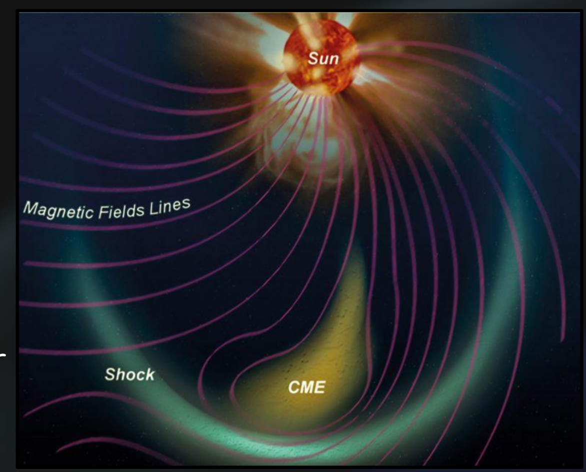
The ACE spacecraft is located at about 1 AU from the Sun, and is composed by 9 instruments: SWIMS, SWICS, ULEIS, SEPICA, SIS, CRIS, SWEPAM, EPAM, and MAG. We used energetic particle data from the EPAM instrument gathered in Caltech's ACE EPAM Level 2 5-min averaged data.




Khabarova and Zank (2017)

## Background

Understanding anomalous superdiffusive transport of energetic particles ahead of strong interplanetary shocks, such as those driven by Coronal Mass Ejections (CME), is key to explain space weather events and interactions.



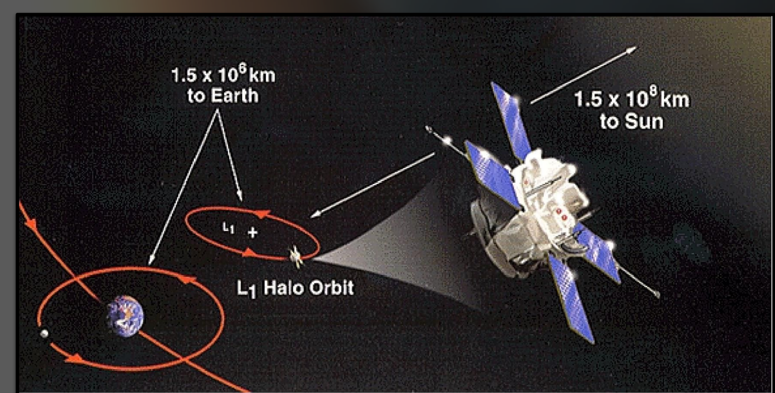

Ebert (2019)

Three strong shocks were recently studied by Zimbardo, Prete, and Perri (2020). They found mostly superdiffusive behavior characterized by: (i) More energetic particles are more superdiffusive and, (ii) energetic particles ahead of shocks with larger shock normal angles ($\theta_{bn}$) are less superdiffusive.

$$J_T(0,T)\sum_{k=0}^{\infty}\frac{\left(-\left(\frac{x}{L}\right)^{\alpha-1}\right)^k}{\Gamma(\alpha k+1)}$$

A Mittag-Leffler function can be used to describe the flux intensity of solar wind ahead of the shock as a function of distance from the shock. This is then transformed into a time-intensity profile to match that of the data plot.

$J_T$ is the flux at the shock, α is the fractional index for anomalous diffusion and, L, the scale length over which the function decays. α and L being the variables optimized, and α limited by 1<α≤2. In the process of graphing the Mittag-Leffler function, it was found that L = 1e5 km was a good initial guess for shocks that had speeds comparable to those we were being investigating. This can be seen in Methods (1).

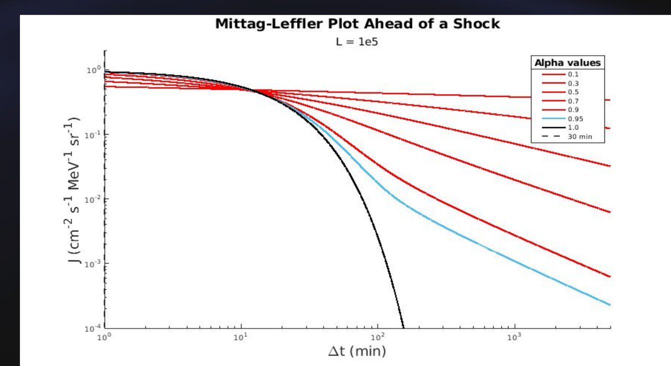


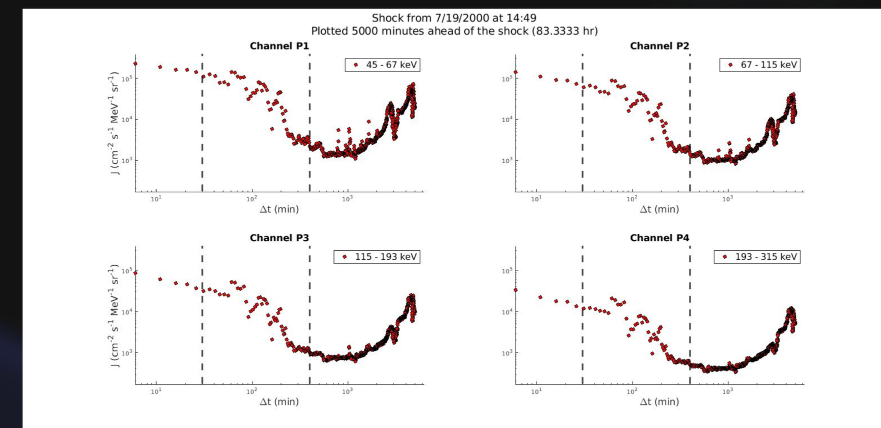

Credit: NASA, Caltech

EPAM stands for Electron, Proton, and Alpha-particle Monitor, and measures these energetic charged particles in different energy channels. We used 4 of these: 45-67 keV, 67-115 keV, 115-193 keV, and 193-315 keV, as measured by the LEMS30 lens. LEMS120 was used as a replacement for energy channels with incomplete data, given its similar look angle. Strong shock events investigated were selected based on information about shock events in the Database of Heliospheric Shock Waves (ipshocks.fi)

## Methods

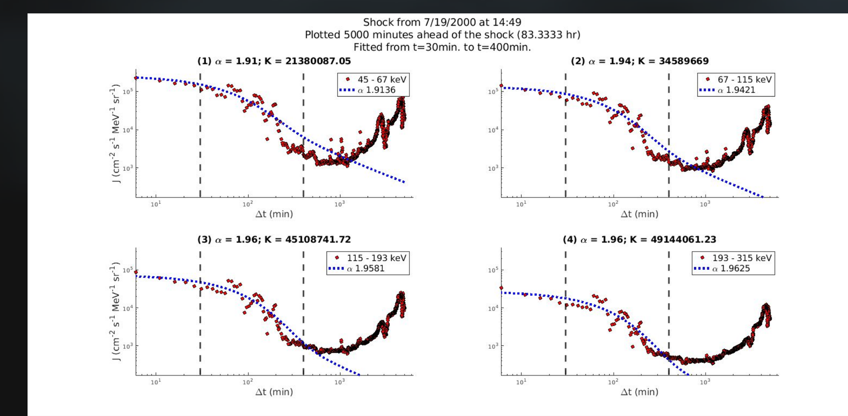
1. Graphing a theoretical solution for superdiffusive propagation of energetic particles ahead of a traveling shock described by the Mittag-Leffler function.




2. Plotting Intensity-time profiles of 4 energy channels of a shock using data from ACE's EPAM. Selected strong shocks in ipshocks.fi database.

3. Fitting the 1 parameter Mittag-Leffler function[1] to the time intensity profiles, and finding the best fit for α (fractional index for anomalous diffusion), and L (scale length over which the function decays) using the fminsearchbnd[2] function. The range for this fit is 30-400 mins ahead of the shock, which seems to be a common range for power-law behaviour.




MATLAB

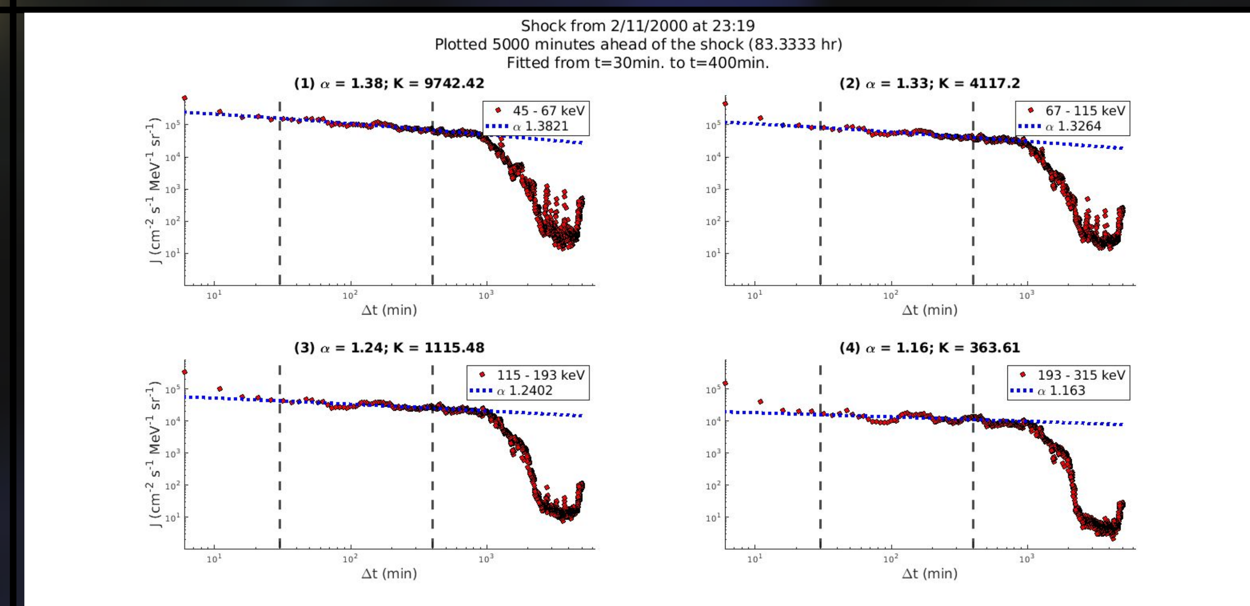
[1] Roberto Garrappa (2021).
[2] John D'Errico (2021).

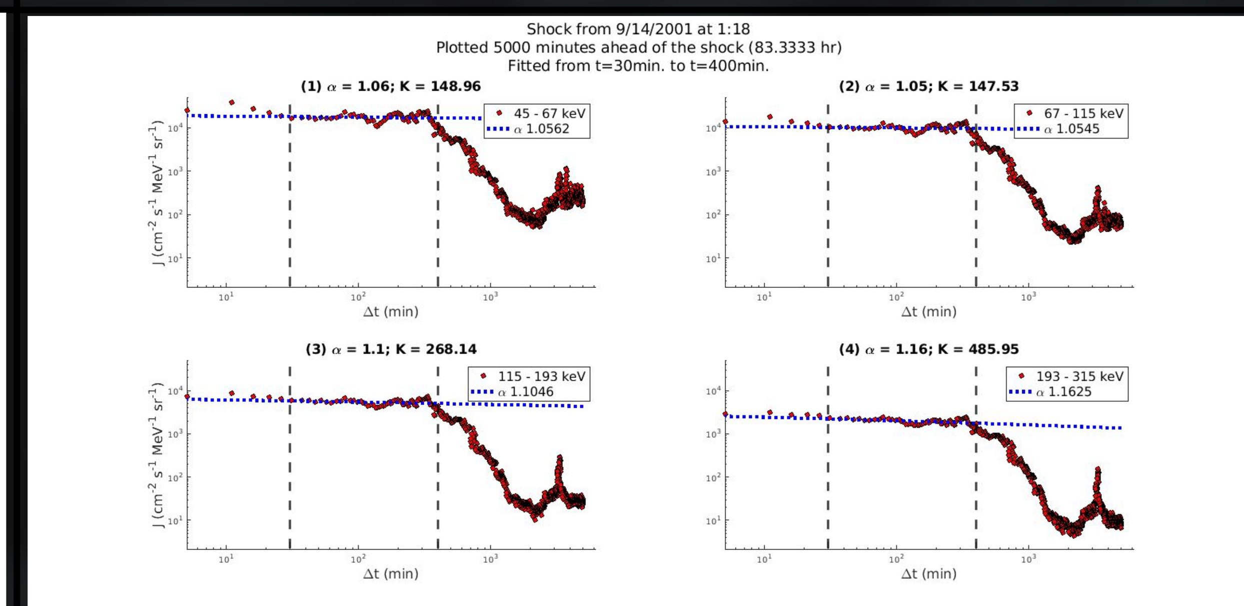
## Cases

### Cases Where Higher Energy Particles are More Superdiffusive

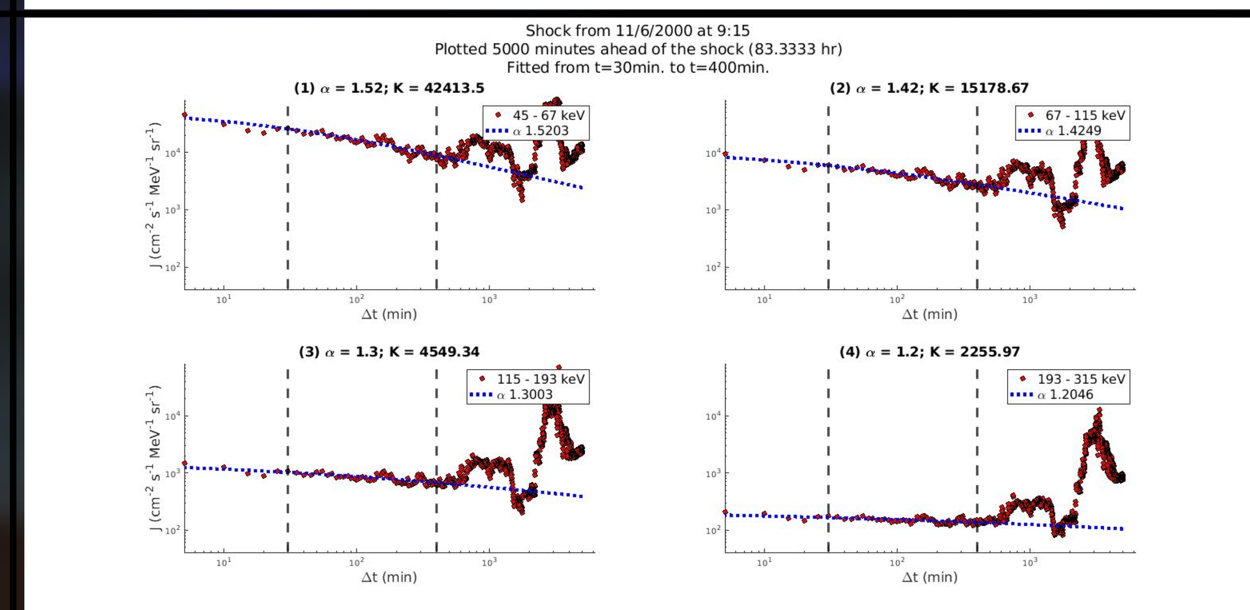
### Cases Where Higher Energy Particles are Less Superdiffusive

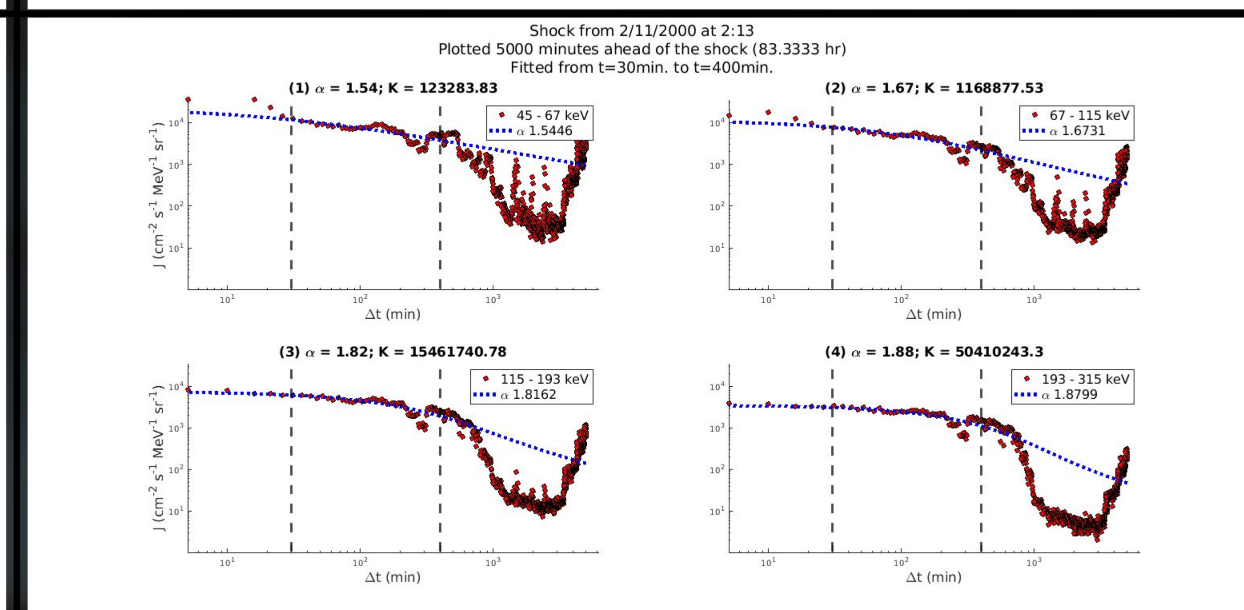
**Strong Super-Diffusion** $\alpha \gtrapprox 1$



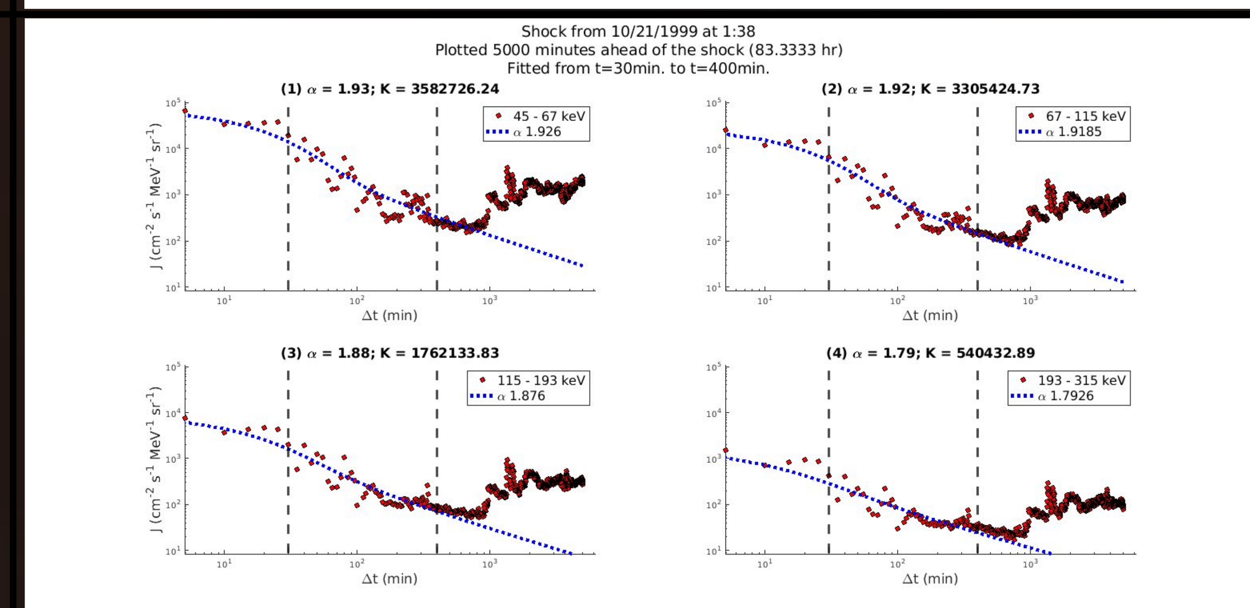



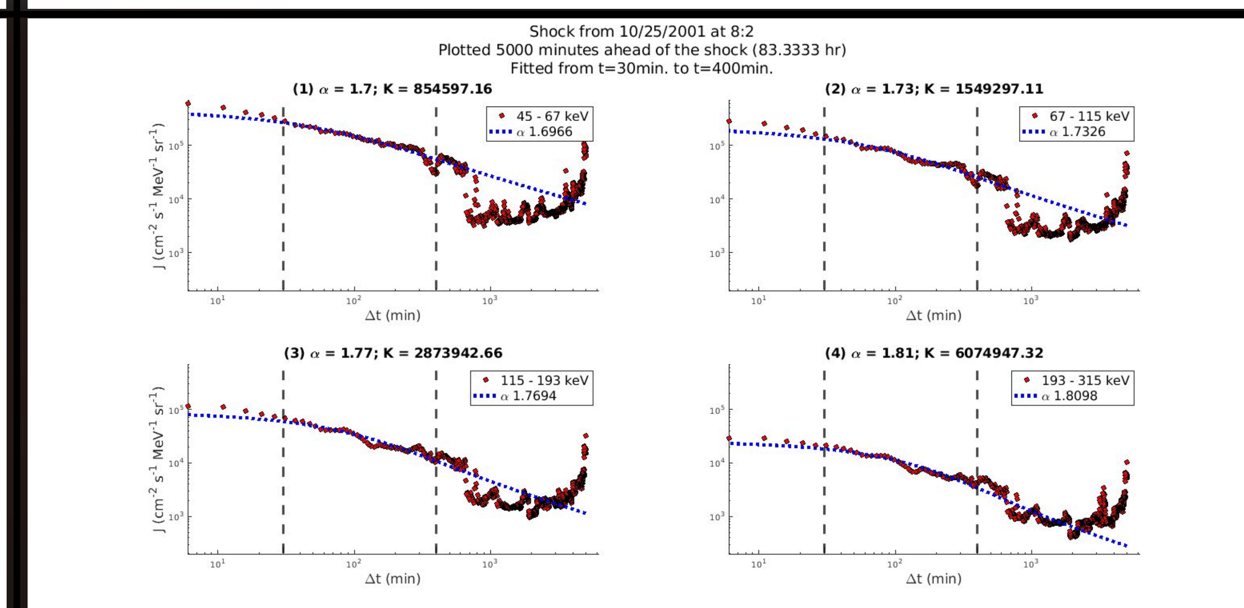

**Partial Super-Diffusion** $\alpha \approx 1.5$




**Regular Diffusion** $\alpha \lessapprox 2$




## In Depth...

- Abstract
- Poster
- 44 Strong Shocks Spreadsheet
- 44 Strong Shocks Plotted
- References

www.linktr.ee/Heliophysics

## Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. AGS-1950831 for the UAH CSPAR/NASA MSFC Heliophysics REU program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.