Autonomous Detection and Disambiguation of Martian Ion Trails Using Geometric Signal Processing Techniques

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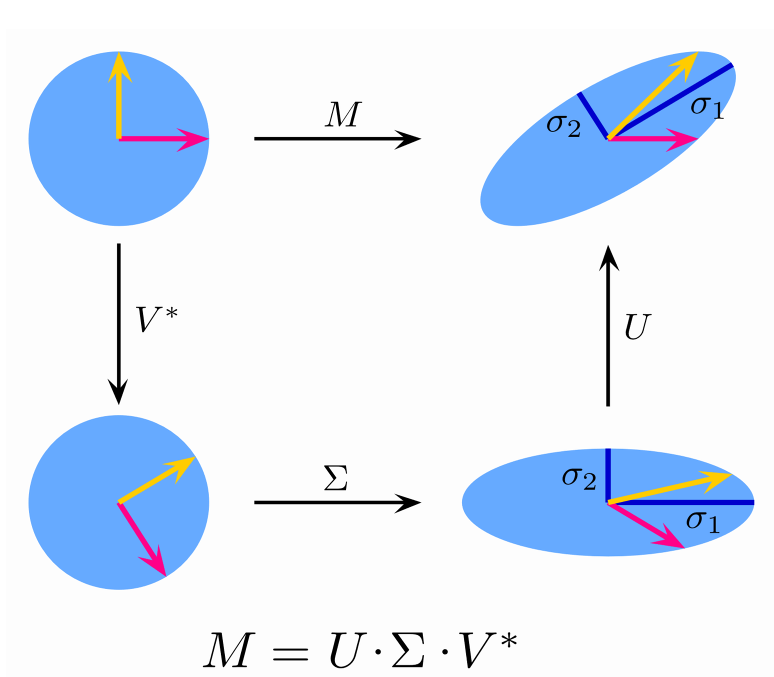
Abstract:
We present recently developed computational techniques that exploit spectral geometry of the energy spectra for differential energy flux over MAVEN data sets. The goal is to enable a large scale automated discovery detection of statistical analysis of ion trails in the Martian atmosphere. Specifically, we present a case study across a diverse portfolio of azimuthal (ϕ) and polar (θ) angles over the same time frame and demonstrate that angular separation helps us to distinguish between individual ion escape processes. We discuss the performance of our algorithms regarding precision of detection as well as interpretation of ion trail geometry. The potential of this algorithm is that it can enable large-scale statistical analysis that connects to individual ion trails with unique angular trajectories automatically detected across potentially hundreds of thousands of case studies.

Problem: Challenges to detecting ion trails autonomously

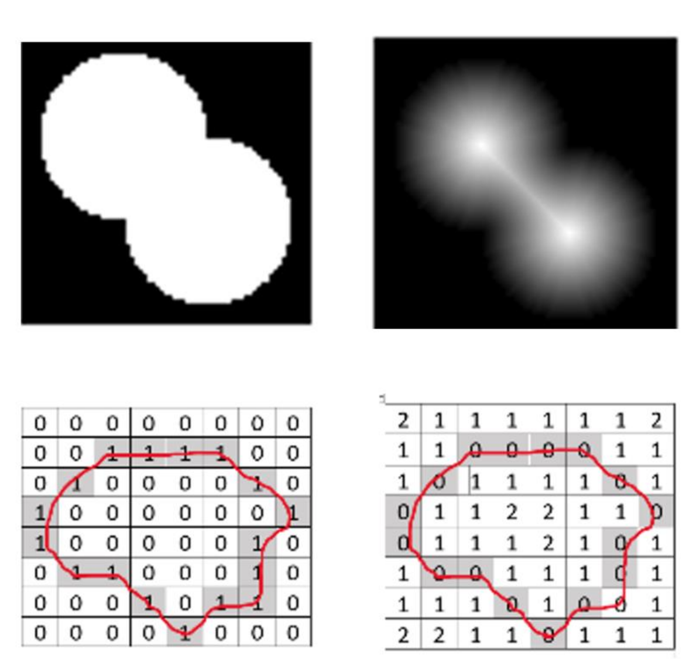
- Ion trails do not exhibit uniform features that can be modeled easily
- Ion trails may be buried against noise
- Ion trails may themselves overlap
- A single trail may exhibit significant microstructure

Technical Approach:
We propose to identify the dominant ion trails across energy spectra measured across different temporal epochs, energy bands and polar and azimuthal angles using two different signal processing techniques:
(a) Singular Value Decomposition (refer Figure 1)
(b) Distance Transform (refer Figure 2)
(c) Once the trail feature is identified (refer Figure 3), we employ the Ridge transform [4] to disambiguate the dominant microstructure, e.g. main "spine" of the ion trail (refer Figure 4).



$M = U \cdot \Sigma \cdot V^*$

Figure 1. Schematic illustration of SVD transform By Georg-Johann (Own work) [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]



a) BW Image   b) Distance Transform

Figure 2. Illustration of Distance transform

Technical Approach: Comparing Different Image Processing Techniques to Identify Ion Trails

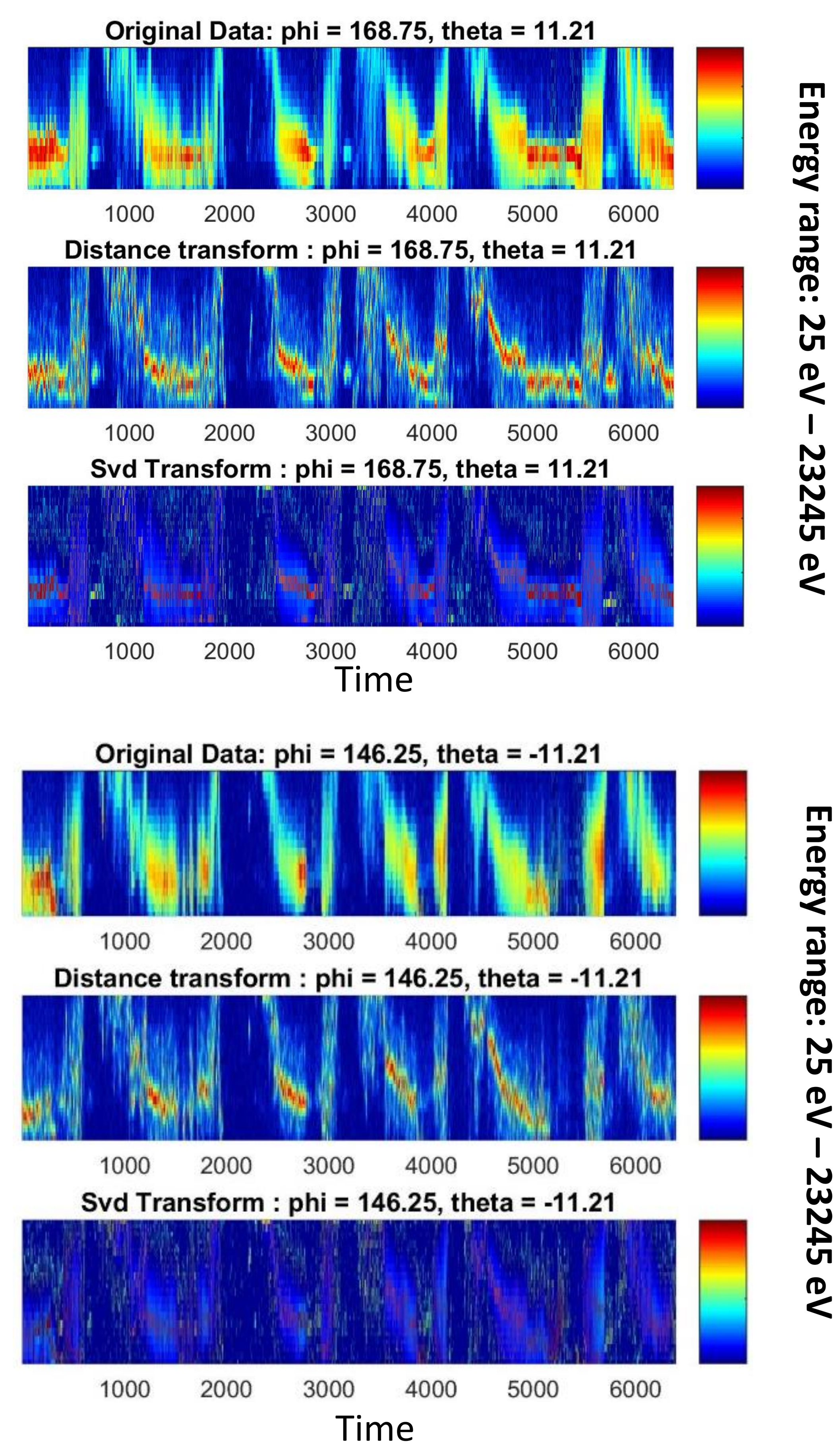


Figure 3. Tracing the dominant features of multiple ion trails using Distance Transform and SVD transform for different combinations ϕ and θ

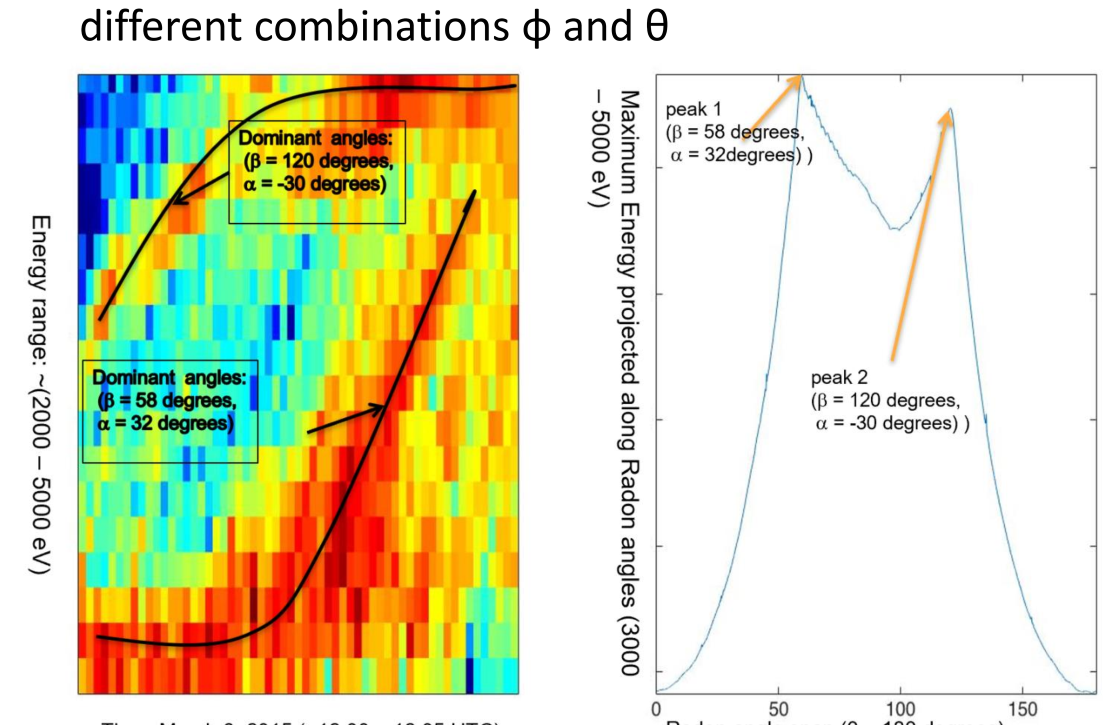


Figure 4. Disambiguating trail microstructure by employing the Ridge transform [4] across multiple peaks in the Radon domain.

Results and Discussion:
Figures 3 and 4 demonstrate the performance of our method across different scales of time and energy. Furthermore, Figure 5 provides a visualization of our data processing in the context of the MAVEN science mission.
The total energy spectra was integrated across several angles and distinct ion trails were identified. It was imposed for different values of ϕ and one value of θ, and the trails were manually derived for easier visualization.

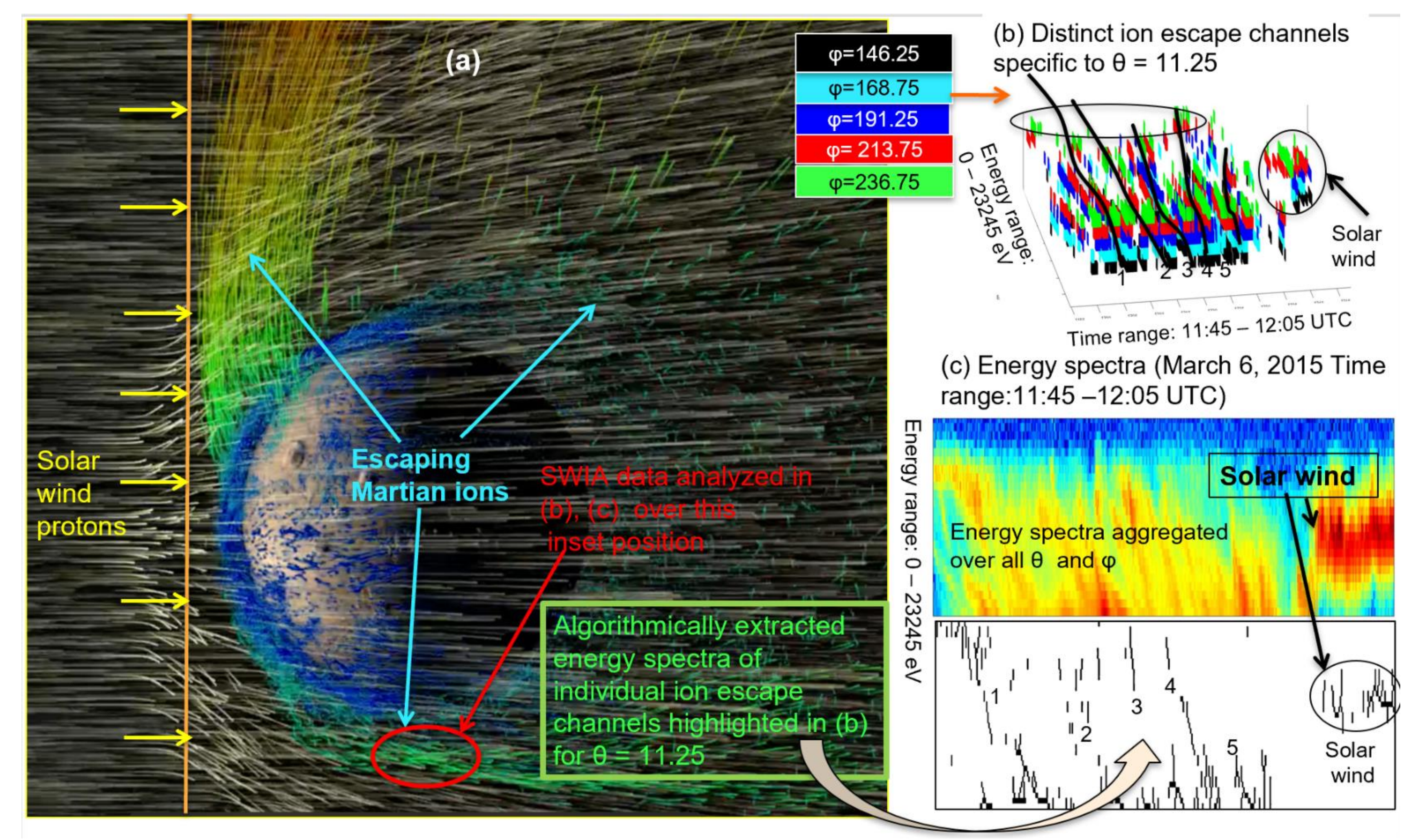


Figure 5 (a) Simulation of interaction between solar wind protons and escaping Martian ion trails. Right panels (b) and (c) show corresponding SWIA data analysis of escaping ion trails, resolved over azimuthal angle span of ϕ = {146.25°-236.75°} and polar angle θ = 11.25°

Future work
We will detect ion trails in the large scale using the proposed method over potentially terabytes of MAVEN remote sensing data across potentially millions of different epochs. We will organize the detected ion trails as well as their salient features on to graph-based representations, and isolate trails that have similar structure or spatial temporal characteristics using graph clustering methods [2,3].

Conclusions:

- Automated ion trail detection algorithm allows new types of studies on how ion escape processes are happening in the Martian atmosphere.
- Trail structure can be quite intricate and variable across θ and ϕ.

References:
[1] "Solar Wind Strips the Martian Atmosphere", credit to NASA's Scientific Visualization Studio and the MAVEN Science Team.
[2] Schaeffer, Satu Elisa. "Graph clustering." *Computer science review* 1, no. 1 (2007): 27-64.
[3] Zhou, Yang, Hong Cheng, and Jeffrey Xu Yu. "Graph clustering based on structural/attribute similarities." *Proceedings of the VLDB Endowment* 2, no. 1 (2009): 718-729.
[4] Sen Gupta, A., Kletzing, C., Howk, R., Kurth, W. and Matheny, M., 2017. Automated identification and shape analysis of chorus elements in the Van Allen radiation belts. *Journal of Geophysical Research: Space Physics*, *122*(12).