Cassini Data Analysis and Drift-Physics Modeling of Energetic Plasma Events in Saturn's Magnetosphere

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Abstract

CHEMS (CHarge Energy Mass Spectrometer) identified high-energy plasma injection events, which appeared as a sudden increase in ion flux intensity. However, the morphology of these energetic injections of plasma toward the planet is unknown. Knowing the morphology, or shape, of the injection events can inform calculations related to understanding system-wide plasma transport at Saturn. The primary goal of this work is to determine the morphology of injections identified from a list produced by Azari et al., 2018 of 816 standardized and automatically identified interchange injections from the CHEMS data over the course of Cassini. Only 243 of the 816 discovered events were used in this analysis because a majority of the spacecraft trajectories did not intersect the magnetosphere a second time around. Slight adjustments to the model improved our fit to the modeled particles on the spectrogram, including altering the corotation rate of Saturn's magnetosphere. The model was set to assume Wilson et al. (2017) 50th percentile corotation velocity. After applying corrections to the model, such as using Wilson et al. 2017 25th and 75th percentile ranges along with multiplying a "corotation factor" to the velocity, the corotation rate of Saturn's magnetic field was on average 8.8% faster than previously predicted. Another change made to the model was the gradient curvature drift. Decreasing the drift of the magnetic field decreased the proximity between high and low energy particles, which allowed the particles to intersect one another in a shorter span of time. The final analysis concluded that the gradient drift curvature was 9.1% less than the model, meaning the particles intersected each other in a shorter time span than previously predicted. Altering Saturn's corotation rate and gradient curvature drift resulted in a final analysis of the number of channel-like injections to be 75% (181) of the total 243 Cassini intersection plasma events.

Introduction

The Cassini spacecraft left Earth in 1997 and reached Saturn in 2004, where it orbited Saturn for over a decade before plunging into the planet in 2017. Cassini collected energetic plasma (3-220 keV) and magnetic field data from the CHarge Energy Mass Spectrometer (CHEMS) and magnetometer (MAG) instruments. These instruments collected information about Saturn's magnetosphere in which Enceladus, an icy moon of Saturn, outgasses dense neutrals. These neutrals become ionized through different collisional processes creating a region of dense plasma. Density dynamics drive the plasma transport. One of these processes is likely driven by Rayleigh-Taylor instability primarily from Saturn's rotation rate. This causes an energy exchange between particles: cool low-energy particles are transported outward from Saturn's inner magnetosphere whereas hot high-energy particles are transported to the inner magnetosphere. Centrifugal forces also drive the injection interchange because the rapid rotation rate (10.8 hours) creates an outward equatorial pull of the denser plasma. CHEMS identified high-energy plasma injection events, which appeared as a sudden increase in ion flux intensity. This data was analyzed by Azari et al., 2018 and determined that there were 816 plasma injection events discovered from CHEMS. A. Azari created a Python developed model that ran these events and modeled the particles from these injections around Saturn's magnetosphere. From this, observed injections were evolved around the equatorial plane of Saturn (fig. 1a-1h). The evolved events were then considered to intersect the Cassini spacecraft co-located within 0.25 Saturn Radii (fig. 2.). The purpose of this work was to study the morphology of the particles when placed on the intersection spectrogram to see if most injections have a channel-like shape.

Fig. 1.

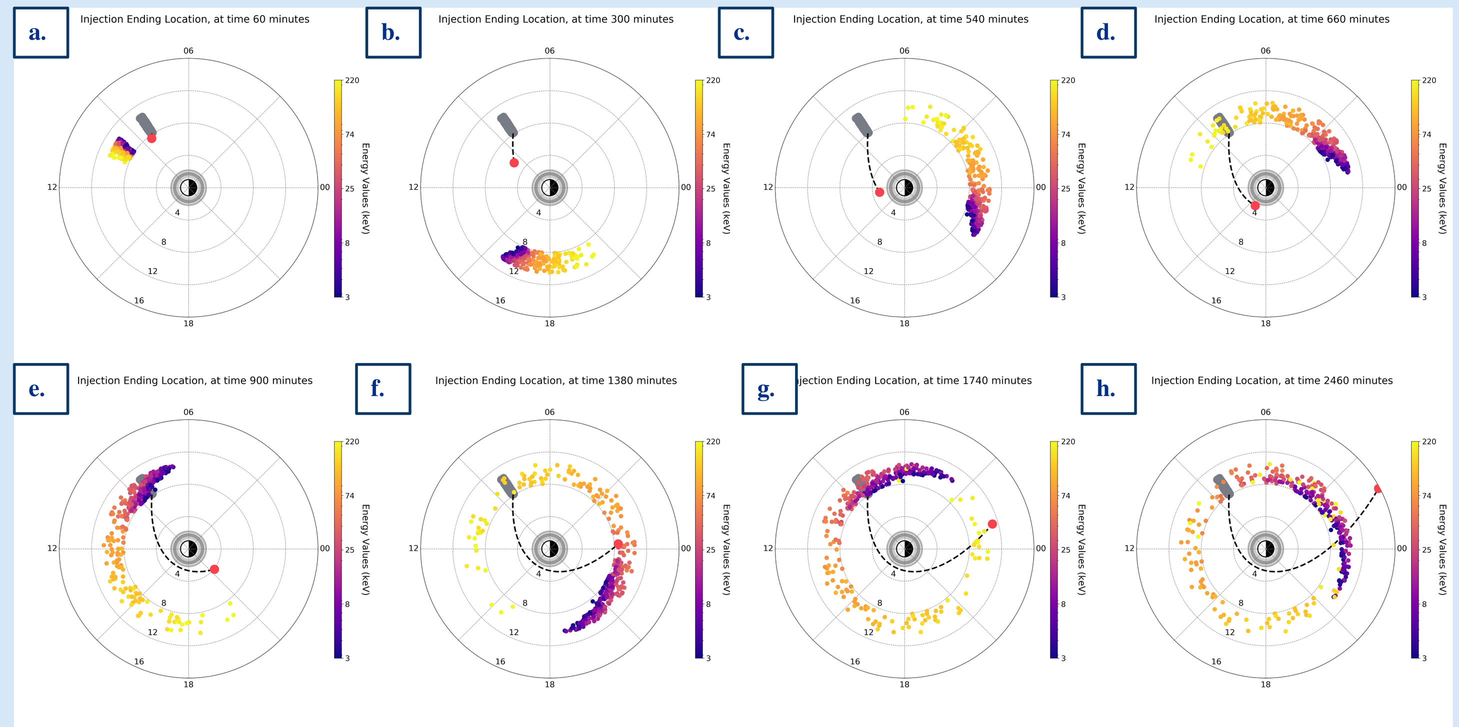


Fig. 1a-1h.
Modeled particles from injection event at an azimuthal perspective where the red dot represents Cassini and its trajectory traveling along Saturn's magnetosphere. This model assumed that the injection events were channel-like. The yellow dots represent particles with the highest energy (keV) and purple dots with the lowest energy.

Fig. 2.

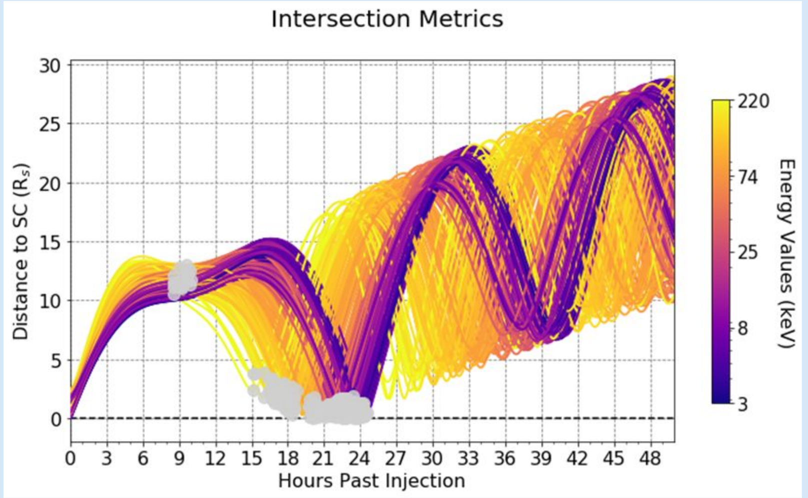


Fig. 2.
Model of particles intersecting with Cassini within a limit of 0.25 Saturn Radii. The grey dots represent the closest approach of the particles to Cassini. Plot is in the perspective of Cassini. If the particles do not intersect within 0.25 Saturn Radii (dashed line), further analysis cannot be conducted on the particles.

Methods

The primary methods used in this project were analyzing the injection event data containing 816 events from CHEMS which were determined by Azari et al., 2018. We use a Python developed model which input the injection events along with corotation estimates, flux data, pitch angles, and gradient curvature estimations to recreate the Saturnian environment. Only one event could be input into the model at a time, so a sheet of all 816 events was used to keep track of the events. The Python model produced an intersection metric plot (fig. 2) to display Cassini and modeled particles which was important because the closest approach particles had to intersect within 0.25 Saturn Radii or else the event could not be used for further analysis. If the particles intersect within that range, the particles were displayed on the intersection spectrogram (fig. 3). From this, the morphology of the particles could be determined if they matched the overall shape of the background flux. Often, the particles were slightly off from the spectrogram flux, so the Wilson et al., (2017) corotation velocities were altered (fig. 1b and 1c), along with the addition of another variable multiplied to fit the data even better, named as "c const" in the first equation below. The deviation of the corrected corotation velocity from the original 50th percentile velocity was statistically determined. The gradient curvature was also altered to suit the model (fig. 4a and 4b.) which altered the drift proximity between the high and low-energy particles, named as the "gc const" in the second equation. This created a smaller or larger "bend" within the particle morphology. Applying these changes to the model allowed the morphology of the particles to be determined.

$$\omega_\phi = \varepsilon\omega_c{}^* c_{const} + \omega_{gc} \qquad \varepsilon = \text{corotation fraction from Wilson et al. 2017}$$

Fig. 3.

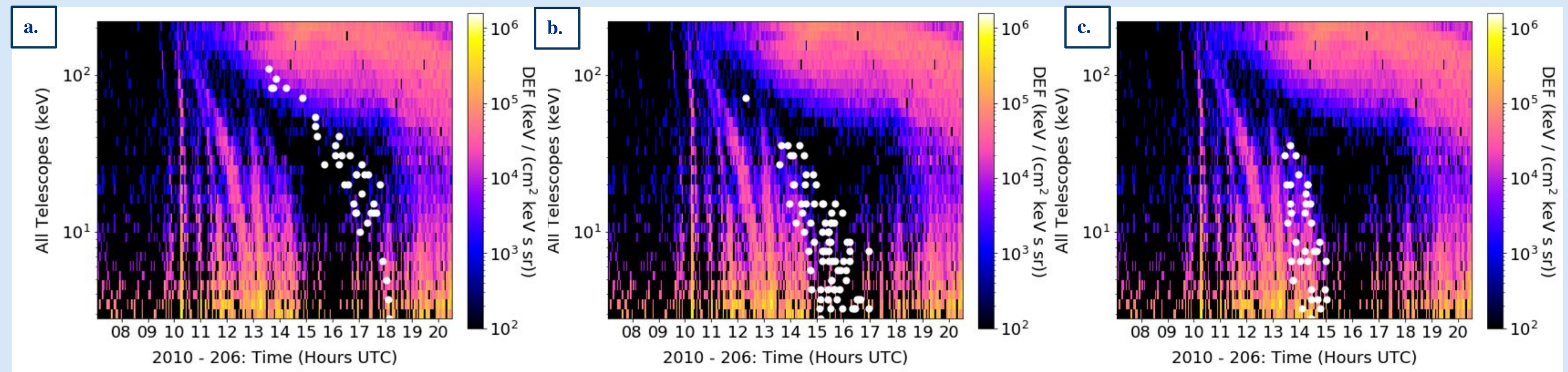


Fig. 3a-3c.
Intersection Spectrogram plots all displaying the same plasma energy in keV vs time (hours) where the differences in energy of the plasma are displayed in a range of colors where light yellow is the highest energy. The white dots in plots 1a. to 1c. represent the closest approach of the modeled particles as they traveled along Saturn's magnetosphere. Fig. 1a. represents the intersection spectrogram plot where no changes were made to the code. The corotation velocity was set at Wilson et al. (2017) 50th percentile range. The corotation velocity was altered in 1b and 1c to Wilson et al (2017) 75th percentile velocity which is a higher velocity range for Saturn's magnetosphere at a given Radii distance. Fig. 1c. contains the 75th percentile velocity along with an added 'corotation multiplier' to fit the model precisely. In this example, the corotation factor value was set at 1.03.

$$\omega_{gc} = \frac{6Wr\xi}{qB_o R_S^2} * gc_{const} \qquad \xi = 0.35 + 0.15\sin(\alpha) \qquad \alpha = 0.10° \text{ pitch angle}$$

Fig. 4.

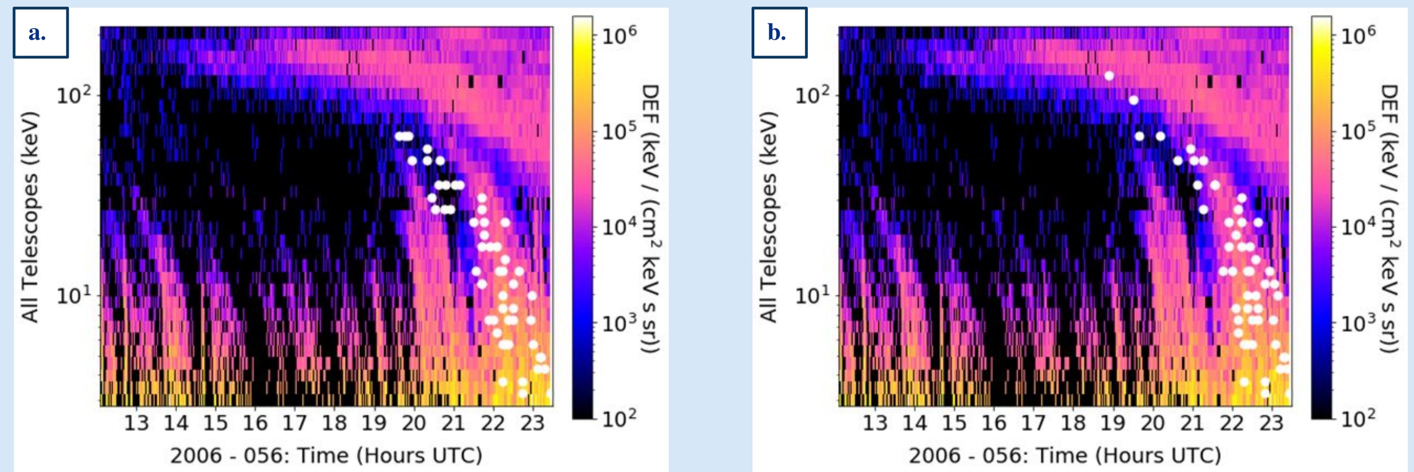
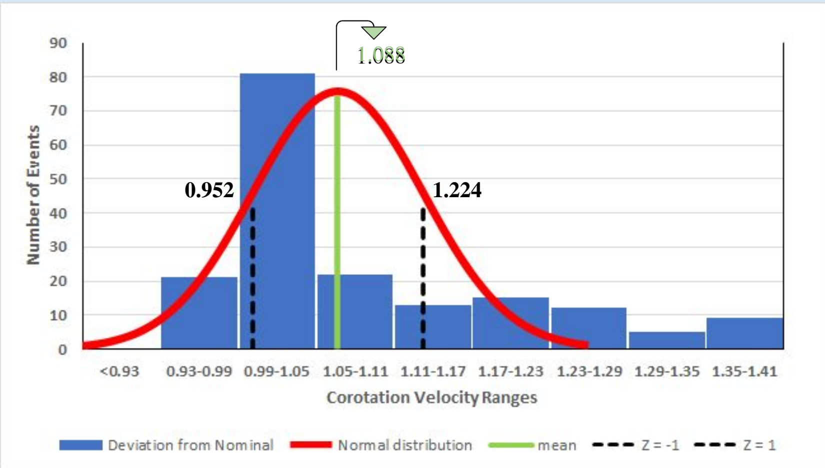
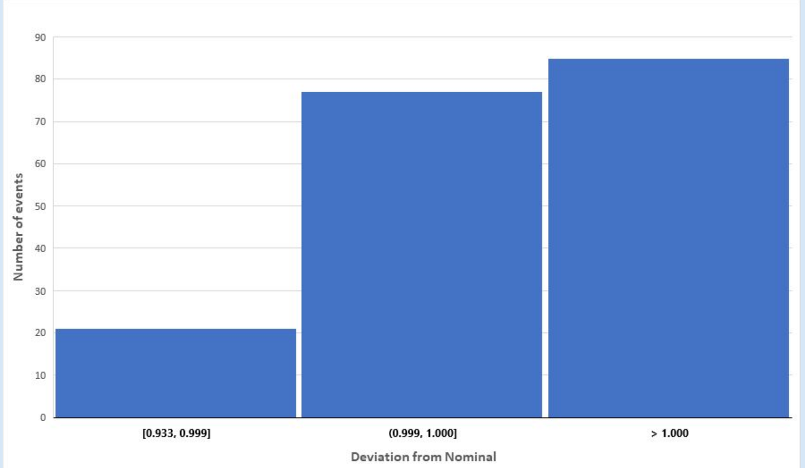


Fig. 4a-4b.
The gradient curvature of the magnetic field was also changed to suit the model better. No change (fig. 4a) and a 30% decrease of the gradient curvature drift (fig. 4b) which fit the channel event better than the original parameters.

Results

The corotation range originally set in the model was altered to best fit the flux spectrogram data for most events. The magnitude of the change set for each event was different. Approximately 43% (77) events, out of the 181 did not require any change necessary to fit the flux spectrogram. Most events needed to be altered slightly to fit the model better. The corotation rate often needed to be increased for a majority of events. Approximately 47% (85) events out of 181 needed the corotation rate increased to match the model to the spectrogram flux. Despite most events averaging in the original model's corotation rate, the corotation velocity should be increased ~9% faster to suit the model because the value of the altered corotation velocity is 1.088 times faster than the original. Also, the gradient curvature drift should be decreased so that there is a closer proximity to the high and low-energy particles so that they reach each other in less time. On average, the drift should be 91% of the original drift set in the prior model.





Conclusion

- **Majority of plasma injection events could not be used due to Cassini's outward trajectory or the particles did not intersect within 0.25 Rs**
- **Most injections (75%) closely match up to a channel-like model**
- **Magnetosphere corotation rate fits model closer if increased ~8.8%**
- **Gradient curvature drift should be decreased by 9.1% to match the "bend"**

References

Azari, A. R., Liemohn, M. W., Jia, X., Thomsen, M. F., Mitchell, D. G., Sergis, N., et al. (2018). Interchange injections at Saturn: Statistical survey of energetic H+ sudden flux intensifications. *Journal of Geophysical Research*: Space Physics, 123, 4692–4711. https://doi.org/10.1029/ 2

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