Phase Space Density Profiles within the Magnetosphere of Saturn: Investigation into Species-Dependent Processes.
R. C. Allen[1], C. P. Paranicas[1], S. K. Vines[1], and D. G. Mitchell[1], [1]Johsn Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA, Robert.Allen@jhuapl.edu.

Introduction: Studying the sources, losses, and radial transport of energetic charged particles is central to understanding the flow of mass and energy in magnetospheric systems. Relevant processes include: internal and external sources of magnetospheric plasma for different planetary systems [e.g., see 1, and references therein], the effects of charge exchange [e.g., 2, 3] and pitch angle scattering on trapped charged particle populations [e.g., 4], and losses due to collisions with moons and rings [e.g., 5; 6]. Magnetospheric plasma also undergoes radial diffusion, both inward and outward [e.g., 7; 3]. As demonstrated with recent investigations of plasma interactions with Ganymede and Europa [e.g., 8, 9], understanding the sources and loss processes of different plasma populations, and energization of those populations from various magnetospheric dynamics, is central to understanding interactions of plasmas with planetary moons and rings, particularly for outer planet magnetospheric systems.

Investigation Summary: We present phase space density (PSD) profiles for the major ions detected by the Cassini Magnetosphere Imaging Instrument/Charge-Energy-Mass Spectrometer (MIMI/CHEMS) over nearly 13 years of operation within Saturn's magnetosphere. Phase space density is used to characterize charged particle flux in magnetospheric contexts because it is a conserved quantity under certain conditions. Expressed at fixed values of the first two adiabatic invariants (μ and k) for a given ion species and charge state and as a function of L shell, the phase space density can indicate the locations of the main sources and losses of particles at that invariant pair, and also quantify how rapidly particles are moving radially [e.g., 7]. This study presents average PSDs derived from MIMI/CHEMS data while Cassini was in orbit within Saturn's magnetosphere, covering the L shell range of 5 to 25 (equivalent to 5-25 Saturn radii, R_S, at the magnetic equator) with observations of H^+, W^+ (i.e., O^+, OH^+, H_2O, H_3O^+), O^{++}, H_2^+, He^+, and He^{++} populations. Average profiles are used along with the computed phase space density profile near an injection event to estimate the original L shell of injected H^+ and W^+ ions to better elucidate spatial variations and processes leading to features in the PSD profiles observed by Cassini.

Dataset: The Cassini spacecraft launched on 15 October 1997 and entered into orbit around Saturn on 1 July 2004 before concluding its mission on 15 September 2017. This study uses data from MIMI/CHEMS [10]. CHEMS measures energetic ion composition (H^+, O^{++}, H_2^+, He^+, and He^{++}, and water group ions or W^+ consisting of O^+, OH^+, H_2O^+, and H_3O^+) through the use of an electrostatic analyzer (ESA) with a time-of-flight (ToF) section and a solid-state detector (SSD) at the end of the flight path [10]. This combination of components allows for the independent measurement of the mass, energy, and charge state of an ion. At lower energies, however, the SSD does not provide a signal, resulting in only a double coincidence measurement (from only the ESA and ToF) which results in the instrument being able to separate ions by mass-per-charge only. This study uses triple coincident data for all species other than H^+ and water group ions, which include both double and triple coincident observations. Due to the H^+ and W^+ ions dominating the double coincidence channels they reside within, this is still a reliable determination [see 11]. Data from the entire Saturn campaign (1 July 2004 to 15 September 2017) when Cassini was within a dipole L shell range of 5 to 25 R_S are used in this study. The inner limit of 5 R_S was chosen due to the fact that CHEMS often observed an enhanced level of background contamination within this distance. Despite the availability of many years of data, the CHEMS observations have found only weak temporal variations for magnetospheric observations [e.g., 12] which allows for the interpretation of the variations seen in this long survey as spatial in nature, rather than temporal.

Preliminary Conclusions: Similar to the proton and electron results of [3] at the lower energy range of their study, all species exhibit a decrease in phase space density within roughly 10 R_S. A change in slope at a specific distance would lead us to believe satellite absorption is important, as [3] concluded with the tens to hundreds of keV near Rhea's orbit. But the ion shapes here are likely more consistent with charge exchange being the dominant loss process at these distances.

While all distributions of all species increase more slowly with L in the outer magnetosphere than the inner magnetosphere, the degree of this flattening of the slope has a clear μ and k dependence. Additionally, the flattening of the outer magnetosphere radial phase space density profiles is seen to have a species dependence. Species known to exist only from endogenic sources (e.g., H_2^+) have far flatter profiles than those known to be of external source (e.g., He^{++}). These observations are also discussed in the broader context of phase space density profiles observed at Earth, Jupiter, Uranus, and Neptune.

Acknowledgments: This research was supported by the NASA CDAP grant 80NSSC19K0899. The MIMI/CHEMS data used in this study are publicly available at The Planetary Data System (PDS).

References: [1] Blanc, M., et al. (2015) *Space Science Reviews*, 192, 1-4, doi: 10.1007/s11214-015-0172-9. [2] Shemansky, D. R. and Hall, D. T. (1992) *J. Geophys. Res. Space Physics*, 97, doi: 10.1029/91JA02805. [3] Kollmann, P., et al. (2011) *J. Geophys. Res.*, 116, doi: 0.1029/2010JA016221. [4] Smith, E. J. and Tsurutani, B. T. (1983) *J. Geophys. Res.*, 88, doi: 10.1029/JA088iA10p07831. [5] Paonessa, M. and Cheng, A. F. (1987) *J. Geophys. Res.*, 91, doi: 10.1029/JA091iA02p01391. [6] Paranicas, C. P. et al. (1991) *J. Geophys. Res.*, 95, doi: 10.1029/JA095iA12p20833. [7] Van Allen, J. A. et al. (1980) *J. Geophys. Res.*, 85, doi: 10.1029/JA085iA11p05679. [8] Hansen, C. J. et al. (2022) *Geophys. Res. Lett.*, 49, doi: 10.1029/2022GL099285. [9] Harris, C. D. K. et al. (2022) *J. Geophys. Res.*, 127, doi: 10.1029/2022JA030569. [10] Krimigis, S. M. et al. (2004), *Space Science Reviews*, 114, doi: 10.1007/s11214-004-1410-8. [11] Allen R. C. et al. (2018) *J. Geophys. Res.*, 121, doi: 10.1029/2018JA025262. [12] DiFabio, R. D. et al. (2011), *Geophys. Res. Lett.*, 38, doi: 10.1029/2011GL048841.