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Title: Suggested Projects, Mentors and Mentor General Interest Areas for 2023 Los Alamos Space Weather Summer School

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Intended for: List of suggested research topics to be posted on Space Weather Summer School webpage
Web

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Suggested Projects, Mentors and Mentor General Interest Areas for 2023 Los Alamos Space Weather Summer School

Please contact mentors to discuss either the projects listed or suggest your own (mentor's general interests are listed to aid in choosing a mentor for your suggested projects.)

Additional projects will be added, so check back before finalizing applications.

Project: Radiation Belt Simulation and Modeling
Mentor: Greg Cunningham (cunning@lanl.gov)
General interests: modeling the evolution of natural and artificial radiation belts of MeV electrons using DREAM3D, a Fokker-Planck code
Project Ideas:
(1) Simulation -- Use DREAM3D code on LANL's high-performance computing cluster to model recent geomagnetic events and compare to observations from Van Allen Probes and other satellites, with an emphasis on comparing the model predictions to both low-altitude and high-altitude observations;
(2) Modeling -- Build a global specification of VLF wave properties for ground-based transmitters using a ray-tracing code that can be used in DREAM3D and calculate the diffusion coefficients using a new cold electron density model that has been developed for an NSF GEM project

Project: Kinetic Simulations of Plasma Processes and Particle Acceleration
Mentor: Fan Guo (guofan@lanl.gov)
General interests: Fully kinetic, hybrid (kinetic ions & fluid electrons), MHD, and particle transport simulations of heliospheric plasma processes including those in solar flares, coronal mass ejections and throughout the heliosphere.
Suggested Project: The main goal is to understand how particles are energized in such a weakly collisional space plasma system. The selected candidate will have opportunities to take advantage of the latest version of LANL's flagship VPIC code. Kinetic Simulations of Collisionless Shocks and Associated Particle Acceleration (e.g., Guo et al. 2013, ApJ, 773, 158)

Project: Single-photon camera aurora data analysis
Mentor: Rebecca Holmes Sandoval (rmholmes@lanl.gov, ISR-2)
General interests: Aurora imaging, pulsating and flickering aurora, time-frequency analysis, space accelerator experiments
Suggested project: This is an opportunity to develop creative new data analysis techniques with a unique aurora dataset. We have ~18 hours of aurora data recorded with a high-time-resolution single-photon camera at Poker Flat Research Range in March 2021. The camera records a sub-nanosecond timestamp for each photon, making this the fastest optical aurora data ever recorded. Use time-frequency analysis techniques such as wavelet decomposition to search for interesting time-dependent features (perhaps super-fast auroral waves or other phenomena). Explore correlations with other ground and/or space-based measurements such as magnetometer and EMCCD data. There may also be an opportunity to analyze artificial aurora produced by the Beam PIE suborbital accelerator experiment. Some basic Python skills are recommended to make the most of your time on this project.

Project: Storm-time ring current dynamics
Mentors: Vania Jordanova (vania@lanl.gov) and Kateryna Yakymenko (kyakymenko@lanl.gov)
General Interests: Physics of the inner magnetosphere, energetic particles, wave-particle interactions, numerical modeling
Suggested Project: To understand the dynamics of energetic particles during storms and substorms, we will carry out simulations with our large-scale kinetic inner magnetosphere model RAM-SCB. The model results will be validated through comparisons with observations from the Van Allen Probes, and anisotropic electron distributions will be used as input for the SPS model to study whistler wave excitation.

Project: Ionospheric irregularities
Mentors: Erin Lay (ISR-2) (elay@lanl.gov); Chris Jeffery (ISR-2) (cjeffery@lanl.gov)
General interests: Ionospheric/magnetospheric coupling, ionospheric conductivity in auroral regions, ionospheric irregularity scale sizes
Suggested Project: Ionospheric electron density and conductivity in the auroral regions. This project will involve collection and analysis of ionospheric data, specifically SuperDARN measurements in the auroral region. The project would involve learning how to use the PyDarn SuperDARN data analysis toolkit to plot ionospheric parameters. Additional co-located data sources are also of interest, such as GPS TEC, Fabry-Perot Interferometery, and the ISR radar measurements.

Project: Hybrid simulations of EMIC wave growth
Mentor: Misa Cowee (mcowee@lanl.gov)
Project Ideas: Energetic (keV) ring current ions with anisotropic velocity distributions provide free energy for the excitation of EMIC waves in the inner magnetosphere which, in turn, can scatter the population into the loss cone. We have recently incorporated a new hybrid (kinetic ion, fluid electron) simulation-based model of EMIC growth into the Ring Current Atmosphere Interactions Model (RAM) to try to understand the global distribution and effect of these waves in a more self-consistent manner. This project involves further hybrid simulations to better quantify the threshold conditions for growth and the wave properties. Specific simulation studies could include: (1) Understanding the role of a cold oxygen component in the wave growth, and re- deriving empirical scaling relations for wave amplitude and linear growth rate based on the methodology of Fu et al. 2016 (JGR, 121, 10954). The cold oxygen is expected to influence the He+ band waves and introduce a spectral gap near the O+ gyrofrequency. (2) Understanding the role of continuous addition of free energy on the wave growth, saturation, and decay. Previous simulations of ion cyclotron waves at Jupiter/Saturn/comets have shown how the instability behavior is influenced by the rates at which free energy accumulates over time due to dynamic changes in the ion density or anisotropy, sometimes yielding periodic cycles of growth and decay. This has yet to be quantified for EMIC in the ring current, but represents a potentially important growth pattern that should be accounted for in global models. Project would involve collaboration with Xiangrong Fu (NMC) and Vania Jordanonova.

Project: Learning wave-particle interaction physics with machine learning.
Mentors: Oleksandr Koshkarov (koshkarov@lanl.gov) and Kateryna Yakymenko (kyakymenko@lanl.gov)
General interests: machine learning, wave-particle interaction, quasilinear theory, modeling
Suggested Project: Wave-particle interaction (WPI) physics plays important role in the energization and loss of energetic electrons and dynamics of the the inner magnetosphere. However, even state-of-the-art inner magnetosphere simulations cannot account for WPI self-consistently because of the orders of magnitude scale separation between the electron-scale wave interactions and global-scale transport processes. Consequently, state-of-the-art inner magnetosphere models either use statistical wave models or event-specific models that rely on sparse satellite measurements. There is an ongoing effort to compute WPI diffusion coefficients from first principle kinetic codes and incorporate them into a global inner magnetosphere model via two-way coupling. The proposed summer project will focus on comparing the performance of different machine learning strategies to approximate diffusion coefficients from the output of the kinetic codes.

Project: Quantifying the expected size distribution of coronal rain
Mentor: Tim Waters (T-3) (waters@lanl.gov)
General interests: radiation-MHD simulations, astrophysical instabilities, the physics of active galactic nuclei
Suggested Project: According to a recent review article (see https://iopscience.iop.org/article/10.1088/1361-6587/ab5406), "the discovery of coronal rain and long-period intensity pulsations has kick-started a fascinating new field in solar physics that is rapidly advancing. We can only speculate that it will become a major driver of solar science within the next few years." The article concludes by listing several open questions, one of which is whether or not the dynamics of thermal instability (TI) sets the observed morphology of coronal rain. This project will attempt to answer this question by first analytically calculating the fastest growing modes of TI for the common cooling functions used in coronal rain MHD simulations. These fastest growing modes correspond to a particular wavelength and hence to a characteristic size blob of coronal rain plasma. There are theoretical predictions for the smallest and largest size scales also. MHD simulations can be performed to confirm this theoretical understanding of size scales, which can then be compared with current observations.

Project: System science of global magnetospheric codes
Mentors: Gian Luca Delzanno (delzanno@lanl.gov), Kareem Sorathia (Kareem.Sorathia@jhuapl.edu), Joe Borovsky (jborovsky@SpaceScience.org)
General interests: Magnetospheric physics, modeling
Suggested Project:
Global modeling of the Earth's magnetosphere is becoming increasingly important to understand the behavior of the system as well as to make predictions that can aid space weather efforts to protect space- and ground-based assets. Global models are also becoming more complex, with modern frameworks including a variety of subsystems (such as an ionospheric model, a ring current model, …) that mimic the various particle populations of the magnetosphere and their interaction. Validation against observational data is extremely critical to build confidence in global modeling. In this project,

we will explore a new approach to validation where we will use the tools of system science (in general, these are tools that have been developed to study the behavior of a complex system as a whole and in this specific project we plan to use multi-variable correlation analysis) to analyze the behavior of the Earth's magnetosphere (through a variety of magnetospheric response indices) and compare it side-by-side with that of global magnetospheric simulations. The objective will be to understand if the global model behaves as the real system does and propose a new validation methodology for the space physics community.
Reference: Delzanno GL and Borovsky JE (2022), The Need for a System Science Approach to Global Magnetospheric Models. Front. Astron. Space Sci. 9:808629. doi: 10.3389/fspas.2022.808629

Project: Day-side kinetic challenge with fluid-kinetic codes
Mentors: Gian Luca Delzanno (delzanno@lanl.gov), Oleksandr Koshkarov (koshkarov@lanl.gov)
General interest: magnetospheric physics, modeling
Suggested project:
Global modeling of the Earth's magnetosphere has been traditionally based on a magnetohydrodynamics (MHD) description of the underlying solar wind and magnetospheric plasma. While having remarkable success over the past few decades, MHD does not include kinetic effects which are known to be important for certain phenomena key to magnetospheric dynamics (such as magnetic reconnection, the ion foreshock, wave-particle interactions, …). This has prompted the development of a variety of approaches that go beyond MHD. One of these approaches is based on the expansion of the plasma phase space density into spectral basis functions and led to the development of the spectral plasma solver (SPS) code at Los Alamos. The strength of SPS is that kinetic physics can be dialed in or out by adding or subtracting terms in the spectral expansion so that the hierarchy of plasma models in use for magnetospheric dynamics (fluid, hybrid or fully kinetic) are enclosed in a single framework. This property is typically referred to as *fluid-kinetic coupling*. This project will apply the SPS code to the so-called dayside kinetic challenge (https://ccmc.gsfc.nasa.gov/challenges/gem-dayside-kinetics-challenge/). The objective is to explore the role of beyond-MHD physics on solar-wind magnetosphere coupling and to demonstrate for the first time the application of a spectral fluid-kinetic approach to this problem.
Reference: Koshkarov et al, 'The multi-dimensional Hermite-discontinuous Galerkin method for the Vlasov–Maxwell equations', Computer Physics Communications 264, 107866 (2021). https://doi.org/10.1016/j.cpc.2021.107866

Project: Secondary instabilities of magnetospheric waves enabled by cold plasma populations
Mentors: Gian Luca Delzanno (delzanno@lanl.gov), Justin Holmes (jcholmes@lanl.gov), Vadim Roytershteyn (vroytersh@gmail.com)
General interest: magnetospheric physics, theory and modeling, spacecraft data analysis
Suggested project:
Waves play a very important role in the Earth's magnetsosphere. Notably, waves represent an important mechanism of acceleration and transport of energetic particles and are responsible for precipitation of such particles into the Earth's atmosphere producing aurorae. Our ability to successfully model the magnetosphere and to predict fluxes of energetic particles (which may be damaging to spacecraft and humans) crucially depends on building a comprehensive understanding of the processes responsible for wave evolution. These include linear processes, such as dispersion, as well as nonlinear wave-particle and wave-wave interactions. This project focuses on a recently discovered class of nonlinear instabilities that arise when waves such as whistler, electromagnetic ion cyclotron, or magnetosonic propagate through regions where a significant cold plasma (energies of the order of a few eV) population is present. Such cold plasma populations originate in the ionosphere and are known to be

routinely present in the near-Earth environment. The new class of instabilities may thus be a very important, and yet poorly understood factor affecting the waves. The overarching goal of the project is to advance the understanding of the secondary instabilities associated with cold plasma using a combination of theoretical analysis, high-performance computer simulations, and data analysis. Depending on the needs of the project and specific interests of the participants, preference may be given to one or more modes of investigation.
Reference: V. Roytershteyn and G.L. Delzanno. “Nonlinear Coupling of Whistler Waves to Oblique Electrostatic Turbulence Enabled by Cold Plasma.” Physics of Plasmas 28, 4, 042903 (2021). https://urldefense.com/v3/__https://doi.org/10.1063/5.0041838__;!!Bt8fGhp8LhKGRg!E_MhNsp0pTxrMgzG2gcjJa6YdL_WjOia0O99YdjqR_6VWYnNJj9lmYISDDy9uA6g5nWPWtAqUsL6Q2WYu6k$

Project: The connection between cold plasma density and auroral structures
Mentors: Mike Henderson (LANL), Gian Luca Delzanno (LANL), Toshi Nishimura (BU)
General interest: magnetosphere-ionosphere coupling
Suggested project:
The structure of cold plasma density in the magnetosphere is important for modulating precipitating energetic particle fluxes and auroral intensity in the ionosphere. However, direct observations of the cold plasma are limited and it is not well understood how much auroral structures are related to cold plasma density structures in the magnetosphere. This project aims at determining the connection between cold plasma density structures and auroral structures using conjugate observations between LANL and ground-based all-sky imagers. The student will receive training to use the LANL particle observation data. The student will search conjunctions between the LANL satellites and all-sky imagers (such as THEMIS GBO) and compare cold plasma density and auroral intensity. This investigation is expected to address how often auroral structures are related to the cold plasma density and what types of auroral forms are influenced by cold plasma density. A prior experience in satellite and ground-based auroral data analysis is desired.

Project: Interpretation of magnetospheric cold particle distribution functions measured with active spacecraft control
Mentors: Pedro Alberto Resendiz Lira (resendiz@lanl.gov)
General interest: magnetospheric physics, plasma-material interaction, spacecraft charging, PIC simulations
Suggested project:
The cold (~eV) particle populations in the Earth’s magnetosphere play an important role in the dynamics of the magnetosphere, affecting key phenomena such as including solar wind-magnetosphere coupling, magnetosphere-ionosphere coupling, wave-particle interactions, etc. However, the magnetospheric cold plasma has been very sparsely measured due to the difficulties of in-situ measurements. A promising technique to measure the full distribution of these cold particle populations is through active spacecraft control, which however creates a complex sheath around the spacecraft that distorts the collected particle distributions. In order to accurately characterize the background cold plasma, a correction in the particle fluxes due to the spacecraft potential and sheath must be performed to accurately compute the moments of the distributions. However, this correction is not trivial. Methodologies to accurately account for the effect of the spacecraft potential in the measured fluxed are available. However, these corrections assume a symmetric electric field near the spacecraft which is not the case for realistic spacecraft geometries. The objective of this project is to assess the uncertainties associated with particle distributions measured under realistic, non-symmetric electric fields. Using PIC simulations, a parametric study will be carried out to assess the uncertainty on the

moments of the distribution as a function of spacecraft geometry, spacecraft voltage bias and placement of the particle detector on the spacecraft.
References: Delzanno et al. 2021. The impact of cold electrons and cold ions in magnetospheric physics. https://doi.org/10.1016/j.jastp.2021.105599; Lavraud et al. 2016. Correcting moments of in situ particle distribution function for spacecraft electrostatic charging. https://doi.org/10.1002/2016JA022591

Project: Anti-symmetric formulation of fluid-kinetic spectral methods
Mentors: Oleksandr Koshkarov (koshkarov@lanl.gov), Gian Luca Delzanno (delzanno@lanl.gov), Federico D. Halpern (halpernf@fusion.gat.com)
General interest: multi-scale plasma physics modeling, kinetic equations, spectral methods
Suggested Project:
The fluid-kinetic spectral approach is a technique to construct hierarchical fluid models which can incorporate kinetic physics incrementally. This is a potentially transformative approach for global magnetospheric modeling, where one cannot afford to resolve kinetic physics everywhere and is typically forced to adopt the magnetohydrodynamics description in the majority of the computational domain, regardless of the importance of microscopic physics in magnetospheric dynamics. This method led to the development of the spectral plasma solver (SPS) code at Los Alamos. This project aims to reformulate the SPS equations with an anti-symmetric approach recently developed in the literature, which can potentially lead to a more robust formulation of the fluid-kinetic spectral method. We will work with a toy 1D1V implementation in modern dynamic languages like Julia or Python and target fundamental kinetic plasma physics processes such as Landau damping.
References: Koshkarov et al, "The multi-dimensional Hermite-discontinuous Galerkin method for the Vlasov–Maxwell equations", CPC, 264, 107866 (2021). Halpern, et al. "Simulations of plasmas and fluids using anti-symmetric models.", JCP, 445, 110631 (2021).

Project: Machine learning based closures for fluid-kinetic spectral methods
Mentors: Oleksandr Koshkarov (koshkarov@lanl.gov), Gian Luca Delzanno (delzanno@lanl.gov)
General interest: modeling, kinetic equations, spectral methods, machine learning
Suggested Project:
The fluid-kinetic spectral approach is a technique based on an expansion of the plasma phase space density in basis functions. The low-order terms of the expansion give a fluid (macroscopic) description of the plasma, while microscopic/kinetic physics is retained by adding more terms to the expansion. This property is known as fluid-kinetic coupling. This is a potentially transformative approach for global magnetospheric modeling, where one cannot afford to resolve kinetic physics everywhere and is typically forced to adopt the magnetohydrodynamics description in the majority of the computational domain, regardless of the importance of microscopic physics in magnetospheric dynamics. This method led to the development of the spectral plasma solver (SPS) code at Los Alamos.
The SPS algorithm can be seen as a sophisticated fluid model with kinetic closure computed numerically and which can be improved with adding more terms to the spectral expansion. The computational cost of the closure can be improved dramatically with machine learning techniques which will encode the dependence of higher order expansion terms on the lower order ones. In this project we will experiment with such approaches on a prototype toy implementation in modern dynamic languages like Julia or Python and target fundamental kinetic plasma physics processes such as Landau damping.

References: Koshkarov et al, "The multi-dimensional Hermite-discontinuous Galerkin method for the Vlasov–Maxwell equations", CPC, 264, 107866 (2021).

Project: Learning wave-particle interaction physics with machine learning.
Mentors: Oleksandr Koshkarov (koshkarov@lanl.gov) and Kateryna Yakymenko (kyakymenko@lanl.gov)
General interest: machine learning, wave-particle interaction, quasilinear theory, modeling
Suggested Project:
Wave-particle interaction (WPI) physics plays important role in the energization and loss of energetic electrons and dynamics of the inner magnetosphere. However, even state-of-the-art inner magnetosphere simulations cannot account for WPI self-consistently because of the orders of magnitude scale separation between the electron-scale wave interactions and global-scale transport processes. Consequently, state-of-the-art inner magnetosphere models either use statistical wave models or event-specific models that rely on sparse satellite measurements. There is an ongoing effort to compute WPI diffusion coefficients from first principle kinetic codes and incorporate them into a global inner magnetosphere model via two-way coupling. The proposed summer project will focus on comparing the performance of different machine learning strategies to approximate diffusion coefficients from the output of the kinetic codes.

Project: Low-work-function tethers for active removal of large orbital debris
Mentors: Pedro Resendiz (resendiz@lanl.gov), Roxanne Tuchton (rtutchton@lanl.gov)
General interest: plasma physics, plasma-material interaction, orbital debris
Suggested project:
Space debris orbiting around the Earth are becoming an increasingly important problem which can potentially harm existing space-based assets as well as create a congested environment where it might be unsafe to place new satellites in certain orbits. It has been recently suggested that a new class of tethers (which are basically long, thin conducting structures) based on materials with low work functions could be used to create enough thrust for efficient removal of large (>10 cm) orbital debris. Initially, this project will investigate the performance of low-work-function tethers for orbital debris removal through conventional but simplified models. Next, first-principle kinetic simulations will be performed to understand current collection (which ultimately determines the tether thrust) of the tether in realistic conditions. Time permitting and in collaboration with material scientists at Los Alamos, we will attempt to combine the kinetic plasma simulations with the dynamic response of the tether material in a simplified form.

Project: Optimization of a radiation belt remediation strategy
Mentors: Gian Luca Delzanno (delzanno@lanl.gov), Justin Holmes (jcholmes@lanl.gov)
General interest: magnetospheric physics, wave-particle interactions
Suggested project:
A high altitude nuclear explosion (HANE) creates an artificial radiation belt (ARB) of relativistic electrons by beta decay of the debris fission products. Depending on the location and yield of the burst, the ARB can be much more intense than the Earth’s natural radiation belts and can last for years. Importantly, the ARB belt could disable in days to weeks the overwhelming majority of low-Earth orbit (LEO) satellites, which are typically not designed to withstand a nuclear event, and create a persistent hazardous environment in which it is not safe to launch replacement satellites. The most viable option to protect from the consequences of ARBs is the development of a radiation belt remediation (RBR) strategy that returns the environment to pre-event levels as quickly as possible – ideally, in less than a

week. LANL has developed a new modeling framework, called RBR-ACES, to assess the ability to remediate an ARB by scattering electrons into the atmosphere via space-based injection of electromagnetic plasma waves with antennas and electron beams. This project will use RBR-ACES to develop an optimized strategy for RBR. Our optimized strategy will (i) identify the most dangerous ARB electrons in terms of their radiation dose to spacecraft, (ii) tailor the antenna or electron beam properties to remediate those electrons, (iii) re-evaluate the target wave properties at a later time (for instance, daily) by repeating (i) based on the hazardous electron population that remains. The objective of the project is to develop an optimized RBR strategy with significantly reduced power requirements.

Project: Assessing uncertainty in geomagnetically induced currents for benchmark scenarios
Mentor: Steve Morley (ISR-1) (smorley@lanl.gov)
General interests: applied space weather; uncertainty quantification; geomagnetically induced currents; numerical modeling
Suggested Project: Benchmark scenarios are often used for vulnerability assessments, for example the reliability standard for the US power grid uses a scenario based on observed magnetometer data that is scaled so that the peak geoelectric field corresponds to an assumed 1-in-100-year event. There is uncertainty in the characterization as 1-in-100-year, as well as in the transformation from magnetic perturbation to geoelectric field. Further, the temporal evolution of the geomagnetic disturbance will differ between events. This project will aim to develop a set of benchmark scenarios that capture key sources of uncertainty and then provide an assessment of the uncertainty in the geomagnetically induced current (GIC) in a synthetic network. The work will build on an existing spectral surrogate model for generating realistic time series, and will blend data analysis, statistical modeling, and running simulations of power grids.

Project: Predicting small-scale solar wind structure for geospace forecasting
Mentor: Steve Morley (ISR-1) (smorley@lanl.gov)
General interests: applied space weather; spectral analysis; solar wind; machine learning; model validation
Suggested Project: Numerical models predicting the solar wind arriving at Earth (or at the L1 point) often perform well at predicting the large-scale variations in bulk plasma quantities. However, ongoing work shows that space weather forecasts are sensitive to the small-scale structure in the solar wind. This also presents a problem for synthetic events and for filling data gaps, as overly smooth drivers lead to less realistic dynamics in numerical simulations. This project will develop statistical or machine learning models that predict the small-scale structure of time-series data from the large-scale parameters and temporal structure (known as "downscaling", this is a well-established approach in terrestrial weather). Once downscaling models that capture the key properties of the small-scale structure have been developed, the impacts on, and the expected improvement to, geospace predictions can be assessed.

Project: Statistical study of magnetospheric cold electrons and their interaction with waves.
Mentors: Pedro Alberto Resendiz Lira (resendiz@lanl.gov) and Justin Holmes (jcholmes@lanl.gov)
General interest: magnetospheric physics, data analysis, magnetospheric cold plasma, wave-particle interaction
Suggested project:
Cold plasma plays an important role in the dynamics of the magnetosphere including solar wind-magnetosphere coupling, magnetosphere-ionosphere coupling, and wave-particle interactions. However, in-situ measurements of the cold plasma population – particularly cold electrons – are difficult due to contamination of the signal by photoelectrons. A unique dataset has been produced using electron fluxes measured by the HOPE instrument onboard the Van Allen Probes mission (RBSP) to infer density and temperature of the magnetospheric cold electrons during times where spacecraft charging mitigates the photoelectron signal. The first objective of this project is to carry out a statistical study to correlate the cold electron populations with space weather conditions. Inferred properties of the cold electron population will be compared with geomagnetic indices such as AL, Kp, Dst. We will also compare the properties of whistler waves (frequency band structure, amplitude, etc.) with the inferred cold electron density and temperature.

Reference:

1) Roytershteyn et al. 2021. Nonlinear coupling of whistler waves to oblique electrostatic turbulence enabled by cold plasma. https://doi.org/10.1063/5.0041838
2) Delzanno et al. 2021. The impact of cold electrons and cold ions in magnetospheric physics. https://doi.org/10.1016/j.jastp.2021.105599