The Need to Understand the Cold-ion and Cold-electron Populations of the Earth's Magnetosphere: Their Origin, Their Controlling Factors and Their Impact on the System

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Introduction. The Earth's magnetosphere comprises multiple ion and electron populations with a broad range of energies, from the sub-eV particles of the ionosphere to the relativistic particles of the radiation belts. These diverse particle populations are co-located and interact through a variety of processes, including various plasma waves. The focus of this white paper is on the cold particle populations with total energy less than ~100 eV, i.e. the energy range for which measurements are difficult (regardless of species) but which often dominates the plasma density.

The particle populations of the Earth's magnetosphere originate from either the solar wind, the ionosphere, or the hydrogen geocorona. Most of the cold populations come from the ionosphere, where cold outflows are commonly seen. It may be possible that some cold-electron populations come from the solar wind, particularly (1) under low-Mach-number conditions when the solar wind is only mildly heated in crossing the bow shock or (2) if the lower-energy core of the magnetosheath thermal population is captured into the magnetosphere.

The cold-ion and electron populations have multiple known impacts on the dynamics of the magnetosphere, yet these populations are sparsely measured and very poorly understood. This leaves a major gap in our understanding of the magnetosphere-ionosphere system.

Cold particle populations. The cold magnetospheric populations are: plasmaspheric (and plume) ions, plasmaspheric (and plume) electrons, cloak ions, cloak electrons, charge-exchange-byproduct protons from the hydrogen geocorona, structured cold electrons in the post-midnight dipolar regions, ion outflows, and electron outflows. Cold-electron populations are expected in the polar wind where outflowing ionospheric electrons must accompany ion outflows to maintain charge neutrality, in downwards field-aligned current regions where ionospheric electrons carry the current, in the post-midnight to dawn region where the hot electron plasma sheet precipitates away to make diffuse aurora and backscattered secondary electrons from the atmosphere will enter the magnetosphere, and at the inner edge of the electron plasma sheet where the ion plasma sheet flows radially Earthward while the electron-plasma sheet flow turns eastward. There are also plasmaspheric-refilling cold-ion and cold-electron outflows into open-drift-trajectory flux tubes on the dayside and cold plasma inflow to the ionosphere during active conditions. Note that cloak particles have energies between a few eV and few hundreds eV, thus overlapping only partially with our definition of cold populations. The cloak, however, remains poorly understood.

Impacts of the cold populations in the Earth's magnetosphere. There is growing evidence that the cold populations play critical roles in several important processes that drive the dynamics of the Earth's magnetosphere. For example:

1. The cold ions of the polar wind are a source population for the plasma sheet and ring current. As the polar wind is convected into the mid-plane of the magnetotail, the cold ions are accelerated to plasma-sheet, warm-plasma-cloak and ring-current energies by their drift in the

cross-tail potential. Measurements have shown that the lobes can be continuously filled with cold ions and electrons which flow, often unobserved, anti-sunward and which can be carried into the mid-plane of the magnetotail by the convection electric field.

2. Cold-ions (in plumes and in the warm plasma cloak) impact solar wind/magnetosphere coupling during geomagnetically-active times by mass loading the dayside reconnection rate. They can also affect reconnection at a microscopic level, acting on the Hall currents.
3. Similar cold-ion effects are expected to play a role in the magnetotail during substorms, and might contribute to the characteristics of bursty reconnection, the generation of bursty bulk flows and auroral streamers, and mass loading of reconnection late in the substorm as field lines containing polar wind are reconnected.
4. The mass density of cold ions (specifically the warm plasma cloak) also affects the magnetopause stability to Kelvin-Helmoltz (KH) waves, altering the resulting viscous interaction (and potentially localized reconnection events associated with nonlinear growth of KH vortices) and hence the transport of solar wind into the magnetosphere.
5. Cold electrons (ions, including composition) control the generation of whistler (electromagnetic-ion-cyclotron (EMIC)) waves by the cyclotron instability and the propagation (with amplification and damping) of those waves in the environment. Cold ions affect the frequencies and amplitudes of ultra-low-frequency waves. By controlling the waves' properties, the cold populations control scattering and energization rates of the higher-energy populations, impacting the dynamics of the plasma sheet, ring current and radiation belts.
6. Because of their effect on wave-particle interactions, cold electrons have been implicated for the structuring of the pulsating aurora. Shear-flow instabilities between cold plasmaspheric and hot plasma-sheet plasmas at the plasmapause are believed to be the generation mechanism for giant undulations (and associated Pc5 pulsations), and have recently been implicated as a potential driver for STEVE emissions. Other areas where the cold populations should play a role include refilling in the open-drift trajectories and the remnant layer.
7. Cold electrons play an important role in determining the self-consistent ambipolar electric fields parallel to magnetic field lines, and these electric fields play critical roles in polar ion outflows and plasmaspheric refilling. Equatorially heated cold electrons can also carry energy back into the ionosphere, dynamically affecting ionospheric processes including outflow.

Thus, it is clear that the cold particle populations affect the Earth's magnetosphere globally, from solar wind/magnetosphere coupling to the feedback between ionosphere and magnetosphere.

The difficulty of cold-plasma measurements. The cold populations of the magnetosphere often have the highest density, but are also the least studied. For ions this is because issues associated with spacecraft charging make reliable measurements difficult. In sunlight, spacecraft typically float from a few volts positive to several tens of volts positive, preventing the lower part of the cold ion spectrum from reaching spacecraft instruments. For electrons, spacecraft-produced photoelectrons and secondary electrons overwhelm the fluxes of magnetospheric low-energy electrons. In eclipse, spacecraft can charge strongly negative preventing low-energy electrons from reaching the spacecraft. Note that it is necessary to measure the full cold-plasma distribution functions to fully understand the origin, evolution, and some of the impacts described above.

Innovations are needed for measuring the cold-particle populations in space. Innovations are needed in the design of low-energy ion instruments, including ion composition. Resources must be devoted to instruments with large geometric factors. To overcome unfavorable positive spacecraft potentials, either (a) the use of a plasma contactor or (b) the mounting of the ion detector on a negatively-biased boom or (c) other innovations will be necessary.

For cold electrons, designs using shadowing of the electron instrument combined with differential biases to reduce the fluxes of photo-electrons and secondary electrons at the electron instrument may be feasible. Smart spacecraft material designs that suppress electron emission would be another valuable development. The emission of an electron beam from the spacecraft to drive its potential positive with respect to the plasma potential would result in the acceleration of ambient cold electrons to energies above the spacecraft-generated photo-electrons and secondaries. A time-varying beam bias coordinated with smart electron data analysis could further isolate the ambient cold-electron signal from the overwhelming photoelectron signal.

Robust and reliable measurements of the cold-particle populations are necessary to fully understand the Earth's magnetosphere. Much remains unknown about the cold populations of the Earth's magnetosphere: they are not well measured and have not been thoroughly surveyed, their origins are often not understood, their controlling factors and drivers (e.g. the geomagnetic-activity time history) are often unknown, and their interactions with other particle populations are poorly understood. Most work on the impact of cold populations has focused on cold ions, arguably because of their importance in determining the local mass density in the magnetosphere. Less is known about the cold-electron populations, which however also play critical roles. It is also likely that the cold-ion and cold-electron particle populations have impacts that are not yet known but that can be discovered with a dedicated effort to study them.

The lack of knowledge about the cold-particle populations hinders attempts to develop predictive models for space weather. For instance, most ring-current or radiation belt models only include the cold-plasma density and the cold plasma only plays a passive role, i.e. is not actively coupled with the higher-energy particle populations. Global space weather models that include cold ion outflow are beginning to appear, although in this early phase they still contain a lot of limitations. Much progress could be made by providing comprehensive measurements of the cold populations to guide, constrain and test the next generation of space-weather models.

In a complex system of interconnected parts like the Earth's magnetosphere, a lack of understanding of several of the components of the system (i.e. the cold-ion and cold-electron populations) and their connections to the other components is disabling and potentially misleading: we cannot fully understand the magnetosphere-ionosphere system until we fully understand the cold populations. A dedicated effort to definitively understand the cold-particle populations is therefore necessary and pressing. Such effort will need to include:

1. The development of new measurement techniques and instrumentation to overcome spacecraft-charging issues, with testing in laboratory and in space. This includes techniques to discern the ambient cold-electron distribution function in the presence of spacecraft-generated photo-electrons and secondary electrons;
2. The integral inclusion of remote sensing of He^+ and O^+ ions to establish qualitative context and global quantitative morphology of cold-plasma system-level dynamics;
3. The development of new space missions to perform comprehensive in-situ and remote measurements of the cold-particle populations and their interactions and association with other particle populations and phenomena throughout the magnetosphere;
4. A data-analysis effort to use old and new data to survey the cold-particle populations, understanding their origin, drivers and controlling factors.
5. A theory and modeling program which includes merged ionosphere/magnetosphere models, operating in concert with data analysis, to understand the local and global impacts of the cold populations and how to include those impacts in the next generation space-weather models.