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Recent advancements and remaining challenges associated with inner magnetosphere cross-energy/population interactions (IMCEPI)

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Abstract

The geospace inner magnetosphere, within about ten Earth radii, contains various plasma populations with energy from a few eV to MeV and plays important roles in regulating the energy density of the magnetosphere, the magnetic field configuration, and wave dynamics. As an integrated part of the magnetosphere, the inner magnetosphere region also ties to other regions and can change the global geospace circulation. Therefore understanding both internal and external cross-energy/population interactions can help further our knowledge of the inner magnetosphere dynamics and non-linear feedback processes. In view of this, in the past five years (2014-2018), the GEM Focus Group (FG) “Inner magnetosphere cross-energy/population interactions (IMCEPI)” has gathered and boosted community-wide interactions among observation, simulation and modeling studies. This commentary reports some major accomplishments of the interactive inner magnetosphere community that were advanced by the IMCEPI FG discussions and layouts remaining challenges that need to be carried on.

Key points:

1. Advancements on first-principle ring current models, new empirical models on IM fields/waves/plasma, and application of innovative techniques

2. Advanced knowledge of IM characteristics based on data, e.g., compositions, fields, coupling with ionosphere/tail region, and wave particle interactions
3. Challenges that remain in numerical representation of IM and its linkage with other related areas; validation needed across various IM models

Introduction

The GEM "Inner magnetosphere cross-energy/population (IMCEPI)" Focus Group (FG) was termed from 2014 to 2018, aiming to improve physical knowledge and modeling of the inner magnetosphere, particularly the ring current interactions and feedback with other populations in the magnetosphere and ionosphere. There are three main plasma populations in the inner magnetosphere, which reside in an overlapped region around the Earth ($3<L<7$) and are categorized based on their distinct features. The plasmasphere is populated with cold ions (<1 eV) with density of 100s to 1000s cm^{-3}. The ring current mainly consists of ions with energy from hundreds of eV to hundreds of keV with density of few cm^{-3}. The radiation belts are mostly dominant by MeV electrons with tenuous density (<< 1 cm^{-3}). Figure 1 shows the coupling relations between different populations via many processes. Although the plasmasphere and radiation belts do not contribute significantly to the inner magnetosphere current systems (Ganushkina et al. 2015b), they still play a very important role in the dynamics of the inner magnetosphere. The plasmasphere influences the plasma wave environment that controls pitch-angle scattering rates and subsequent precipitation losses of ring current and radiation belt particles (e.g., Jordanova et al. 2001; Albert 2004). In addition to directly altering the phase space density in the inner magnetosphere, the precipitation also enhances ionospheric conductivity and outflow rate, which modifies the inner magnetospheric electric field and composition and in turn influences the magnetic field via the modified current systems (Ebihara et al. 2004; Liemohn et al. 2005). All of these require the proper interactions among different populations and regimes in inner magnetosphere models.

The broad scientific goals of IMCEPI FG were, through implementation of physics in existing models, to contribute to the physics-based understanding of (1) the mechanisms responsible for the ring current growth and decay, (2) the interactions with particles in other regions, and (3) the nonlinear feedback mechanisms. The main deliverable was to obtain more comprehensive, self-consistent physics-based circulation models, the ultimate goal of the NSF/GEM program. The numerical blueprint is demonstrated in Figure 2, a framework for modeling the coupled inner magnetosphere system, which puts forward the guiding picture for models.

In this commentary, we describe recent achievements in the inner magnetosphere community towards the above goals and discuss near-future challenges remaining in the field. Note that roughly a dozen FGs are active at any one time within the GEM program, including several focusing on other aspects of inner magnetospheric physics.

The brief review below is not meant to be comprehensive but rather highlighting advancements in the specific scientific goals of the IMCEPI FG mentioned above.

Advancements on IMCEPI topics during the IMCEPI years (2014-2018)

In the past five years, the physics-based inner magnetosphere models become more mature, more self-consistent with more physics included. Different models are interconnected to represent the sophisticated, non-linearly coupled geospace system, allowing for a better understanding of the internal interactions. Compared to earlier models (e.g., Toffoletto et al. 2003; Lemon et al. 2004; Jordanova et al. 1994, 2010; Fok et al. 1993, 2001; Liemohn et al, 2001; Ilie et al. 2012), the inner magnetosphere models are now capable of resolving particle dynamics across a broader range of energy or regions, covering thermal-energy plasmasphere, warm ring current particles, and energetic radiation belt populations (Fok et al., 2014; Ganushkina et al. 2015a; Huba and Sazykin, 2014; Huba et al., 2017; Krall et al. 2017; Jordanova et al., 2014, 2016); They are more self-consistently linked with the ionosphere system by taking into account more physics-based ionosphere-thermosphere processes (Raeder et al. 2016; Yu et al. 2018a; Wiltberger et al. 2017; Xi et al. 2016); They can be driven by various tail dynamics using different approaches such as injecting particles within prescribed electromagnetic fields (e.g., Brito, et al. 2017; Jordanova et al., 2018; Ganushkina et al. 2014) or by earthward propagating bubbles (e.g., Cramer et al. 2017; Yang et al. 2015, 2016). They also include more realistic representation of the influence of plasma waves by including more types of waves or using newly derived pitch-angle/energy/cross-energy diffusion coefficients or loss rates based on tremendously increased data base in space, leading to significant improvement in the modeling of the energization/decay of inner magnetosphere populations (e.g., Tu et al. 2014; Kang et al. 2016; Jordanova et al., 2016; Aryan et al. 2017; Ma et al. 2018) and ionospheric precipitation/conductance (Chen et al., 2015a, 2015b; Yu et al. 2016; Perlongo et al. 2017). Following earlier efforts in combining kinetic models with global MHD models (De Zeeuw et al. 2004; Glcoer et al. 2009; Pembroke et al., 2012; Glocer et al. 2009, 2013; Ebihara and Tanaka 2013), more ring current models have been equipped with such capability during the past few years by coupling with global MHD models (e.g., Yu et al. 2014, 2015, 2017; Raeder et al. 2016; Cramer et al. 2017; Welling et al. 2018). The above advanced models are largely capable of reproducing various particle dynamics within the global magnetosphere, and providing important feedback processes on particle populations, the electric/magnetic fields, and dynamics in other geospace regions.

While the numerical representation of the geospace system is being greatly improved, better characterization of physics in the near-Earth environment has also been consistently obtained. For example, the wave dynamics and their impact on plasma dynamics have been analyzed in great detail (e.g., Zhao et al., 2014; Blum et al., 2015, 2016, 2017; Li W et al. 2014; Zhang J.-C et al. 2014; Murphy et al. 2015; Zhou et al. 2015; Yu J et al. 2015; Ma et al. 2016a; Shprits et al., 2016a; Kim et al. 2016; Usanova et al. 2016; Li J et al. 2016; Li L.Y. et al. 2016, 2017; Wang et al. 2017a, 2017b; Zhang X.-J et al. 2016;Turner et al., 2014, 2017; Li L et al. 2017; Fu et al. 2017; Shi et al., 2018). Furthermore, the diffusion rates of inner magnetosphere particles have been upgraded from simple and empirical rates (e.g., Albert 1999; Schulz 1998) to more comprehensive, pitch angle and energy-resolved, and even event-specific diffusion rates based on a larger plasma wave dataset. These new rates account for a variety of responsible causes, including EMIC waves (e.g, Ni et al. 2015; Cao et al. 2016; Kang et al., 2015; Usanova et al. 2014; Kersten et al. 2014), whistler-mode waves (e.g., Orlova et al., 2014; Orlova & Shprits, 2015; Horne et al., 2013; Glauert et al, 2014; Agapitov et al. 2014, 2018; Ma et al. 2017; Ripoll et al. 2017; Mourenas et al, 2014), field line curvature scattering (Ji & Shen 2014), magnetosonic waves (Shprits et al. 2016b), and radial diffusion (e.g., Ali et al, 2016; Liu et al. 2016). In addition, electron scattering and acceleration by broad electrostatic turbulence around plasma injection regions (e.g., Mozer et al. 2015, Ma et al. 2016b) and electron losses due to Alfven waves (e.g., Malaspina et al. 2015; Chaston et al. 2018) are found to play important roles in the inner magnetosphere dynamics.

Compelling knowledge is also achieved in the area of inner magnetosphere-ionosphere coupling. For example, it was found that small-scale electrojet turbulence plays a critical role in changing the electrodynamics in the ionosphere and the plasma transport in the inner magnetosphere (Wiltberger et al., 2017). Field-aligned electric potential drops, which had been long neglected in global models, was incorporated for the first time into the global MHD model and was found to impact remarkably on the tail reconnection as well as the plasma transport in supplying sources to the inner magnetosphere (Xi et al., 2016). Observational evidence of field-aligned currents (both Region 1 and 2) connecting the ionosphere with the magnetosphere was discovered with the aid of joint operation of Cluster and Swarm missions (Dunlop et al. 2015). Systematic physical insights were also gained on the origin of diffuse auroras (Ni et al. 2016; Zhang X.-J et al. 2015) and observational evidence was found for the chorus wave-associated precipitation being the driver of pulsating aurora (Kasahara et al. 2018). Moreover, during precipitation, the affiliated production of secondary super-thermal electrons reflected between hemispheres was found to participate in ionosphere-magnetosphere energy redistribution (Khazanov et al. 2014, 2015, 2017) enhancing ionospheric conductance (Khazanov et al. 2018). Other ionospheric phenomena were also investigated to search for the magnetospheric drivers. For instance, subauroral arcs in the premidnight during substorms were found to be connected to localized ring current pressure gradients in the R2 source region (Motoba et al., 2015). The subaruroal proton aurora was suggested to link to the flow bursts moving from the tail to the inner magnetosphere (Nishimura et al. 2014). In addition, a narrow luminous structure across the night sky in the sub-auroral region, called the Strong Thermal Emission Velocity Enhancement or “STEVE”, recently caught the attention of the scientific community. However, Gallardo-Lacourt et al. (2018) found that STEVE is unrelated to magnetospheric particle precipitation, and is likely to be generated by ionosphere-thermosphere interactions.

The in-situ and ground-based data sets have tremendously grown in the past few years due to active spacecraft missions such as Cluster, Van Allen Probes, and Arase, providing substantial data samples for understanding the inner magnetosphere environment. The ample data sets help derive long-term trends and evolutions of the physical processes within the inner magnetosphere in response to different driving conditions, by looking into various wave properties (e.g., occurrence rate, amplitudes, spatial sizes, obliquity, propagation) (Spasojevic et al., 2015; Saikin et al., 2015; Aryan et al., 2014, 2016; Fu et al., 2014; Meredith et al., 2014; Kersten et al., 2014; Ni et al., 2017; Yue et al., 2017; Malaspina et al., 2016, 2017; Zhima et al., 2014, 2015; Li W. et al., 2015, 2016; Artemyev et al., 2016; Nemec et al., 2016; Santolik et al., 2014a), inner magnetosphere plasma compositions (Fernandes et al., 2017; Yue et al., 2018; Sarno-Smith et al. 2015; Claudepierre et al. 2016; Kistler et al., 2016a, 2016b), ion mass density along closed magnetic field lines as well as mass loading in response to geomagnetic activity levels (Sandhu et al., 2016, 2017), plasmasheet composition outside the inner magnetosphere (e.g., Nose 2016; Denton et al., 2017), the spacecraft surface charging environment (Sarno-Smith et al., 2016), plasmapause model (Liu et al. 2015; Zhang X.-X. et al. 2017; He et al. 2017), electric field model (Califf et al. 2014), and global magnetospheric field model (Tsyganenko & Andreeva 2017) which upgraded from a series of previous models (e.g., Tsyganenko 1989, 1996, 2002, 2007).

With many kinds of inner magnetosphere models co-existing in the community, their application values are of particular interest for operational purposes. "Challenges" on realistically representing geospace have been conducted in order to show the capability and limitation of individual models. Therefore, a few models have participated in the challenges to determine different capabilities, such as reproducing global indices (i.e., Dst and Kp indices) (Rastatter et al. 2013; Glocer et al., 2016), ground-based magnetic perturbations delta-B or dB/dt (Rastatter et al. 2014; Pulkkinen et al. 2013; Welling et al. 2017), radiation belt electron dynamics (Ma et al. 2018), and spacecraft surface charging environment (Yu et al. 2018b). These challenge studies have shown to the community how these models compare to each other in capturing features of the system and in what circumstances they are applicable.

Future Challenges

Although remarkable progress has been made in modeling and understanding the inner magnetosphere during the IMCEPI years, a number of challenges still stand ahead. Modeling of the coupling of the inner magnetosphere to other regions remains an important topic, especially the coupling to the magnetotail and ionosphere. How the injected plasma is supplied to the inner magnetosphere and how the inner magnetosphere populations couple with the ionosphere-thermosphere via a more physics-based approach challenges the current techniques because these regions involve different physics and any single theoretical method cannot satisfy these complex cross-scale interactions.

In order to better represent the electromagnetic drivers for the inner magnetospheric plasma, it is necessary to capture the mutually consistent electric field and magnetospheric configuration. As inductive electric field is closely associated with time-varying magnetospheric configuration, its effects on the transport and energization of particles cannot be neglected (e.g., Zaharia et al., 2008; Ilie et al., 2017). On the other hand, the convective electric field involves complex physical and chemical processes in the ionosphere-thermosphere system. To represent a more accurate MI system, one of the next steps is to extend the inner magnetosphere modeling capability to include the ionosphere-thermosphere system. This requirement poses significant challenges for the modeling community and will require different techniques and collaboration across the CEDAR and GEM communities.

The bridge linking the inner magnetosphere with the ionosphere-thermosphere, to a large extent, pertains to wave-particle diffusion processes in the magnetosphere, because the plasma waves drive particle precipitation down to the upper atmosphere. The wave dynamics, such as wave excitation due to anisotropic plasma distributions, wave propagation, and wave diffusion processes, is essential to the particle acceleration and loss. However, it is challenging to incorporate the microscale wave dynamics self-consistently and efficiently into the macroscale models without simplifications. The first attempt was made by Jordanova et al. (1997; 2001) who were able to simulate the EMIC waves generation and resulting ion precipitation self-consistently with the evolving ring current ion dynamics using quasi-linear theory. These results were furhther expanded to calculate self-consistently the EMIC wave amplitude based on first principles by Khazanov et al. (2003) and Gamayunov et al.

(2009, 2014) and based on hybrid simulations by Bortnik et al. (2011) and Fu et al. (2016). Clearly, more studies of self-consistent modeling of the interactions between various types of waves and plasma are further needed. In addition, it is also challenging to move beyond the extensively applied quasi-linear theory to the non-linear wave-particle interactions (Albert et al. 2013) because quasi-linear theory fails with large wave amplitude (e.g., Tao et al. 2012; Santolik et al. 2014b) and the nonlinearity is particularly important in wave generation (e.g., Omura et al. 2013; Demekhov et al. 2017). Therefore, more work is needed to investigate how to substitute quasi-linear theory with non-linear theory for the inner magnetosphere study under unusual conditions.

Another challenge is to advance the plasmasphere modeling. In contrast to the ring current and radiation belt models that have been persistently improved in our community, the modeling of the low-energy plasmasphere regime seems left behind. While advancements have been recently achieved in the 3D ionosphere-plasmasphere model SAMI3, which is self-consistently coupled to the ring current model RCM (e.g. Huba & Sazykin 2014; Huba et al., 2017), many existing plasmasphere models incorporated in the inner magnetosphere models are decades old, and still empirical-based. Advancing the modeling of plasmasphere as part of the inner magnetosphere and its effects on other collocated populations and wave dynamics is thus needed.

We also need awareness of the complicated inner magnetosphere composition and their impact on the evolution of the ring current, especially oxygen and nitrogen ions. In the past years, oxygen ions have received extensive attention and investigation (Welling et al. 2015; Zhang B. et al. 2016; Kistler et al. 2017), but nitrogen ions, which behave similarly to oxygen, have not been well explored. It is not yet clear if the nitrogen ions contribute the same impact on the inner magnetosphere dynamics (Ilie & Liemohn, 2016). In addition, it was also suggested that the inner magnetosphere current systems be partitioned into several categories, including banana current, eastward ring current, and partial ring current (e.g., Liemohn et al. 2013; Ganushkina et al. 2015b). As controversies in determining these current densities exist, Liemohn et al. (2016) have elucidated the steps towards the resolution to tackle the issue, which requires dedicated community-wide effort. Furthermore, the magneto-tail currents can also contribute to the inner magnetospheric configuration (e.g., Luhr et al. 2016, Artemyev et al. 2018). It is therefore necessary to determine the individual contributions of these current systems.

Challenges further lie in how to take full advantage of the rapidly growing massive satellite measurements and maturing physics-based models by using effective tools, such as machine learning and data assimilation. While these techniques have been widely and successfully applied in the ionosphere, they are quite limited in the inner magnetosphere field (there are only a few research groups dedicating to this area, e.g., Shprits et al. 2013; Kellerman et al. 2014; Godinez et al, 2016; Bortnik et al. 2016; Chu et al., 2017; Zhelavskaya et al. 2017). How to extend their application to other geospace regions and dynamics to achieve a full 3D representation of the inner magnetosphere is one challenging objective.

Nanosatellites have recently emerged as an economical and valuable platform for understanding near-Earth space. For example, the Colorado Student Space Weather Experiment (CSSWE) successfully demonstrated the feasibility of studying inner magnetosphere at much lower cost (Li et al. 2013). One of the next goals would be to explore the space environment more economically by utilizing such CubeSats spacecraft.

Finally, a long-lasting challenge is associated with model validation. Since different models utilize different settings, parameters, and numerical schemes, and different models may show different levels of capabilities for different storm events, it is challenging to distinguish the key factors that control the model performance in capturing the inner magnetosphere environment. Standardizing assessment metrics will help, such as those put forward for geomagnetic indices by Liemohn et al. (2018). More challenge studies reproducing important geospace features are still needed to further look into the limitation of the models and to help improve them.

Summary

The Earth's inner magnetosphere plays a key role in governing global magnetospheric dynamics and its rich internal cross-population interactions, and coupling to other geospace regions has long been a fundamental scientific focus. With tremendous progress being made in the past few years in fulfilling more realistic physical models to better represent and understand the inner magnetosphere, it is noteworthy that challenges still remain towards fully comprehending the plasma and field dynamics and to eventually realize the science-to-operation application purpose. We need continued community-wide collaboration and investigation.

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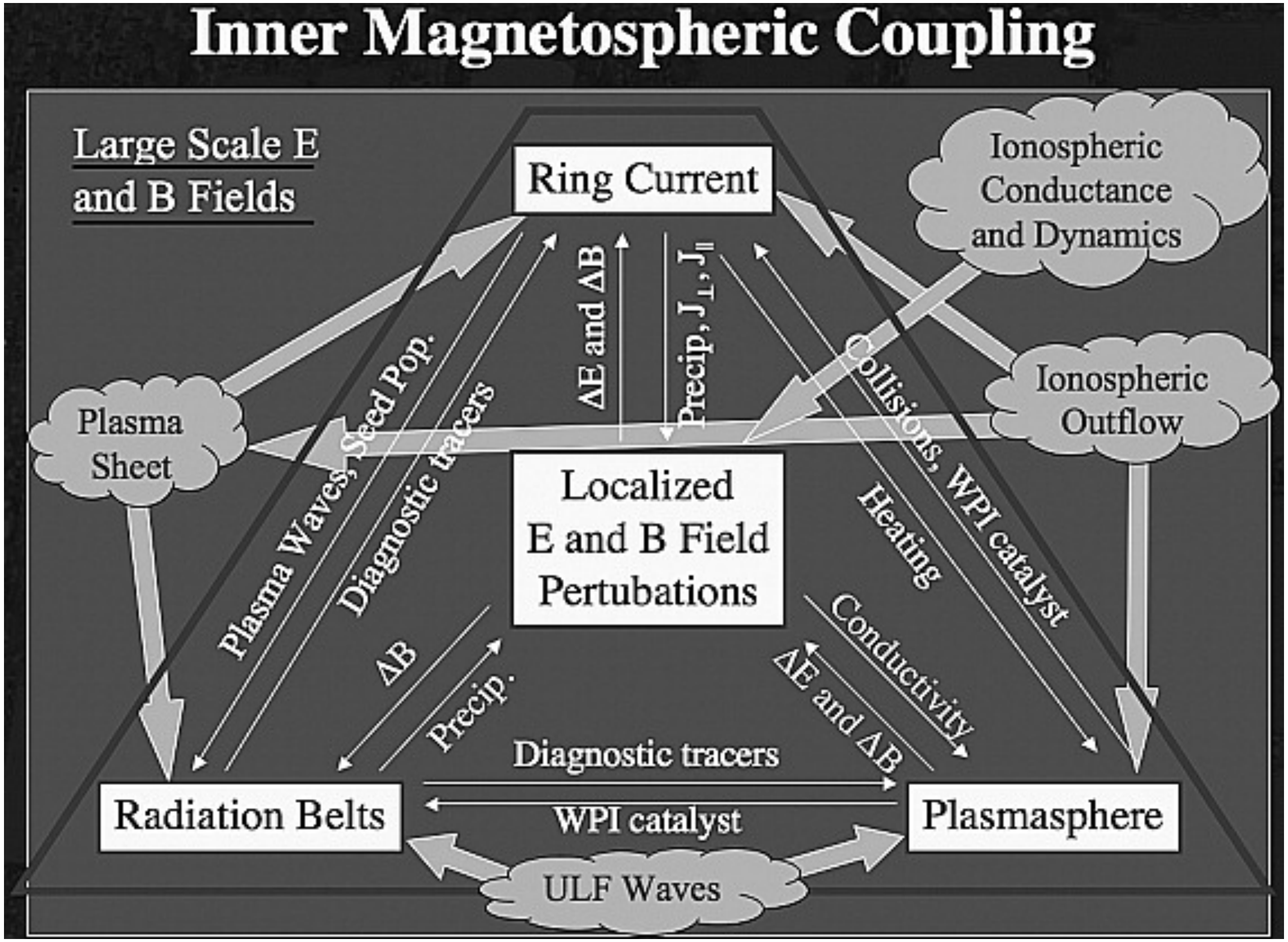
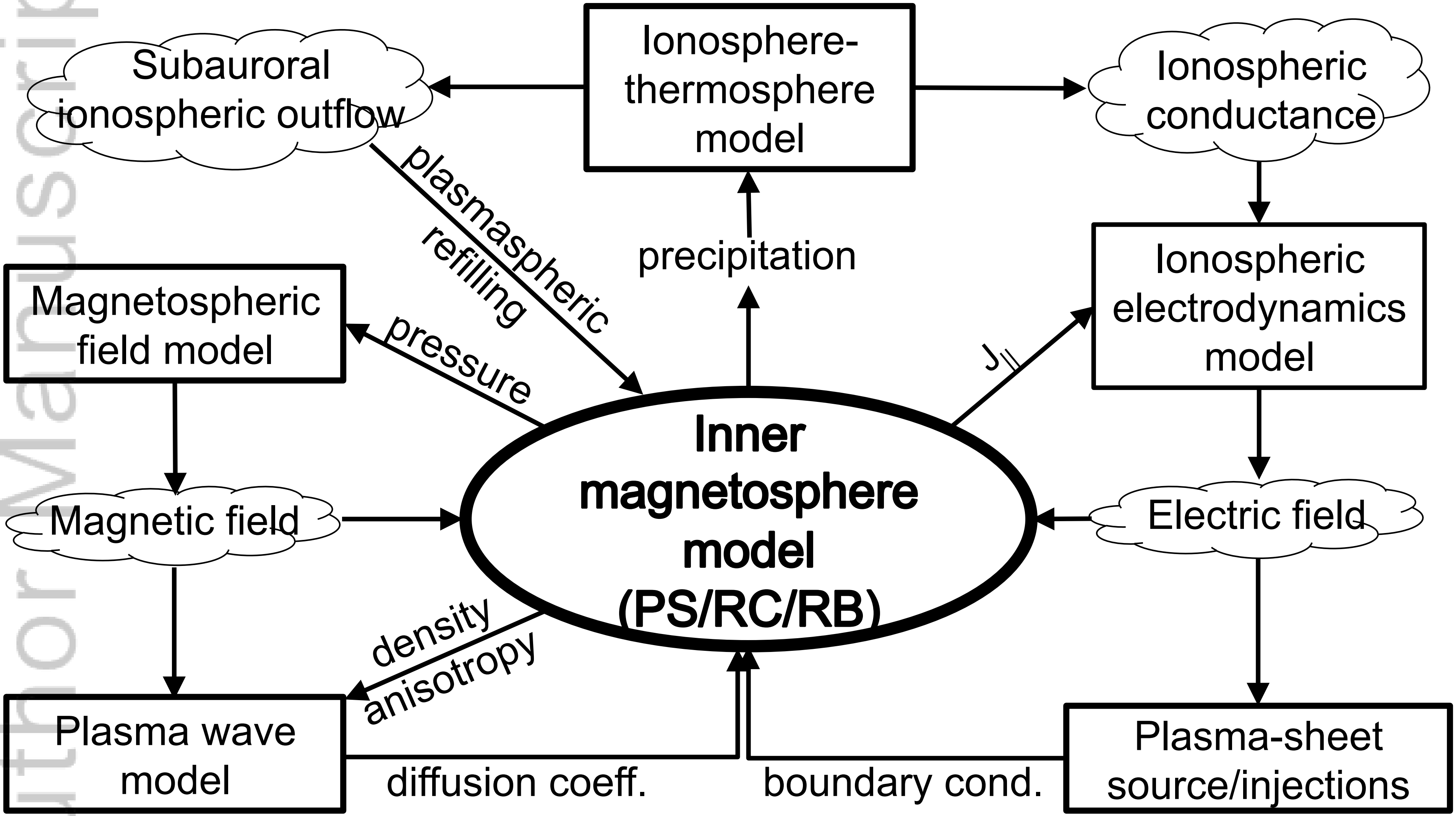
Figures

Figure 1. The schematics of inner magnetosphere coupling physics, showing the connection between the electric/magnetic fields with particles, together with other effects (adopted from Liemohn et al. (2006)).

Figure 2. The schematics of the modeling framework for the inner magnetosphere coupling processes. The center is the primary inner magnetosphere model for plasmasphere (PS), ring current (RC), and radiation belt (RB). The surrounding model components represent processes being coupled with the inner magnetosphere populations.



Inner Magnetospheric Coupling
Large Scale E and B Fields
Ring Current
Ionospheric Conductance and Dynamics
Ionospheric Outflow
Plasma Sheet
Localized E and B Field Pertubations
Radiation Belts
Plasmasphere
ULF Waves
ΔE and ΔB
Precip, J⊥, J∥
Plasma Waves, Seed Pop.
Diagnostic tracers
Collisions, WPI catalyst
Heating
ΔB
Precip.
Conductivity
ΔE and ΔB
Diagnostic tracers
WPI catalyst


Ionosphere-thermosphere model
Subauroral ionospheric outflow
Ionospheric conductance
plasmaspheric refilling
precipitation
Ionospheric electrodynamics model
Magnetospheric field model
pressure
$J_{\parallel}$
Inner magnetosphere model (PS/RC/RB)
Magnetic field
Electric field
density anisotropy
Plasma wave model
diffusion coeff.
boundary cond.
Plasma-sheet source/injections