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Key Points:

- MI coupling is the key element in the formation of diffuse aurora
- Taken into account MI coupling in diffuse aurora can double or triple the energy fluxes into atmosphere
- Both magnetically conjugate ionospheres play important role in the formation of precipitated electron fluxes

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Is diffuse aurora driven from above or below?

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Abstract In the diffuse aurora, magnetospheric electrons, initially precipitated from the inner plasma sheet via wave-particle interaction processes, degrade in the atmosphere toward lower energies, and produce secondary electrons via impact ionization of the neutral atmosphere. These initially precipitating electrons of magnetospheric origin can also be additionally reflected back into the magnetosphere, leading to a series of multiple reflections by the two magnetically conjugate atmospheres that can greatly impact the initially precipitating flux at the upper ionospheric boundary (700–800 km). The resultant population of secondary and primary electrons cascades toward lower energies and escape back to the magnetosphere. Escaping upward electrons traveling from the ionosphere can be trapped in the magnetosphere, as they travel inside the loss cone, via Coulomb collisions with the cold plasma, or by interactions with various plasma waves. Even though this scenario is intuitively transparent, this magnetosphere-ionosphere coupling element is not considered in any of the existing diffuse aurora research. Nevertheless, as we demonstrate in this letter, this process has the potential to dramatically affect the formation of electron precipitated fluxes in the regions of diffuse auroras.

1. Why Are Diffuse Aurora Regions Important?

The diffuse aurora receives the majority (about 75% [*Newell et al.*, 2009]) of the total kinetic energy (precipitating electrons and ions) that enters the atmosphere from the magnetosphere driven by wave-particle interaction (WPI) processes. Electron fluxes with energies of 0.1–30 keV dominate the auroral energy input compared to the energy corresponding to precipitating ions [*Hardy et al.*, 1989].

Electron precipitation into the ionosphere at all latitudes is the result of magnetospheric processes within the relevant topological regions of the magnetosphere. Therefore, precipitating fluxes and energies are strongly connected with global electrodynamics [*Wolf et al.*, 2007], with processes that form the plasmasphere [*Huba and Krall,* 2013], the ring current [*Ebihara et al.*, 2005], radiation belt seed populations [*Khazanov et al.*, 2004], and heavy ion outflows from the ionosphere [*Strangeway et al.*, 2005]. The outflow of heavy ions from the ionosphere ultimately connects the aforementioned regions with magnetic reconnection in Geospace, and in particular, with electrons and ion populations in the central plasma sheet. That is why closing the magnetosphere-ionosphere (MI) coupling loop related to the electron aurora precipitating processes is extremely important.

2. What Is Known?

It is generally accepted that the diffuse electron aurora is generated by WPI processes in the Earth's plasma sheet [e.g., *Belmont et al.*, 1984; *Roeder and Koons,* 1989; *Johnstone et al.*, 1993; *Nishimura et al.*, 2011]. Among the WPI processes that are the major drivers of diffuse aurora are whistler mode chorus waves and electron cyclotron harmonic (ECH) waves resonating with electrons that have energies from approximately hundreds of eV up to tens of KeV [*Lui et al.*, 1977; *Anderson and Maeda,* 1977; *Ni et al.*, 2008; *Meredith et al.*, 2009]. Which type of wave, whistler mode chorus or ECH, is more important in generating the diffuse aurora is still the subject of debate. *Meredith et al.* [1999] reported on pancake particle pitch angle distributions, which along with spacecraft wave observations presented by *Meredith et al.* [2009] led *Thorne et al.* [2010] to argue that whistler chorus waves are the most significant contributor in the formation of electron precipitation in the diffuse aurora regions.

3. How Is Diffuse Aurora Studied?

There is no unified theoretical description for the formation of electron distribution functions in the region of diffuse aurora that includes self-consistent MI coupling processes between the magnetosphere and both

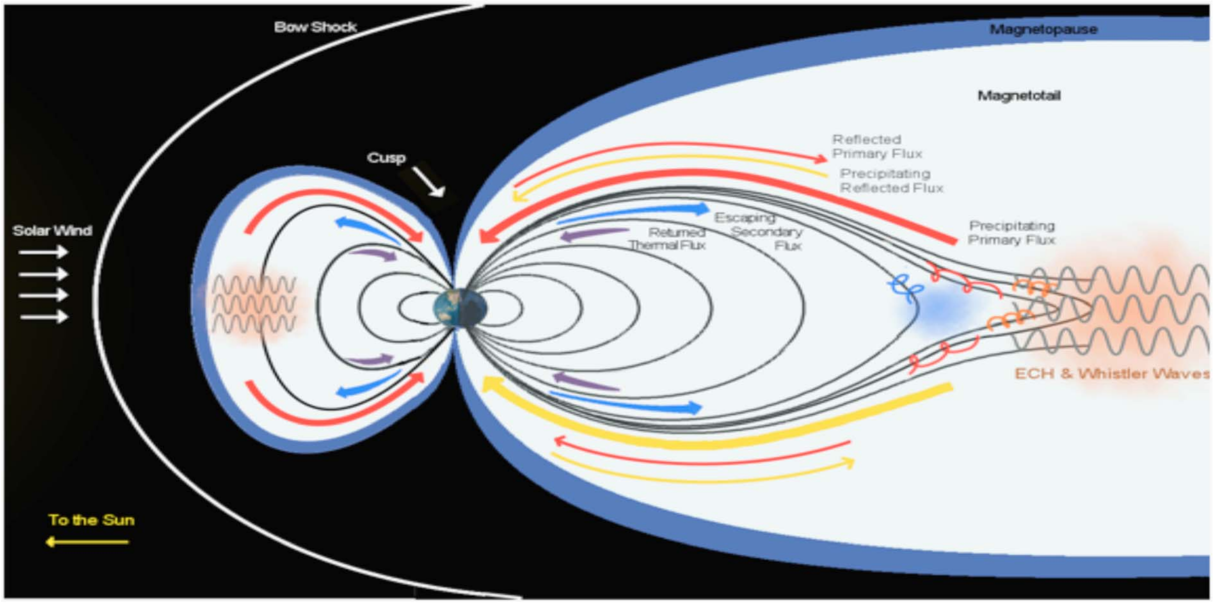

Figure 1. Scenario of MI coupling simulations by STET code.

magnetically conjugate ionospheric regions. Historically, however, two groups of studies have been performed about the region that is typically called the diffuse aurora. The ionospheric group of studies focused primarily on electron precipitation into the upper atmosphere assuming some upper boundary conditions for the electron distribution function at altitudes of several hundred kilometers above of the F_2 region. This community considered the details of precipitating flux degradation in the atmosphere, the production of secondary electrons, optical emissions resulting from the precipitation, and energy deposition to the thermal ionospheric electrons. Monte Carlo simulations [*Solomon,* 1993], two-stream calculations [*Banks et al.*, 1974], and angular-dependent or multistream calculations [*Strickland et al.*, 1976; *Stamnes,* 1981; *Lummerzheim et al.*, 1989] have been successfully applied to aurora electron transport at ionospheric altitudes. These studies, however, did not consider the magnetospheric processes that drive the precipitation electron distributions to begin with, nor did they consider the effect of the magnetically conjugate ionospheric regions in the process of altering the initial and forming the observed electron distribution function.

On the other hand, magnetospheric studies of diffuse aurora focused on the analysis of WPI processes that drive the precipitating electron distribution functions to begin with, and the relative importance of both whistler mode chorus waves and ECH waves as mechanisms for plasma sheet electron precipitation [e.g., *Kennel et al.*, 1970; *Horne et al.*, 2003; *Meredith et al.*, 2009; *Thorne et al.*, 2010]. Thus, both the ionospheric and magnetospheric communities have so far studied the diffuse aurora electron precipitation processes in their individual and separate domains and implicitly assumed that electron precipitation forms *only* via magnetospheric processes. In other words, the assumption has been that the observed diffuse aurora is solely driven from *above*, from magnetospheric altitudes.

4. What Is Missing and What Should Be Done?

As will be demonstrated in this letter, the MI coupling electron dynamics can significantly modify the intensity of the spectrum of diffuse aurora electrons during their initial precipitation from the inner plasma sheet (via WPI processes) to the ionosphere and back and forth after that. Figure 1 (taken from *Khazanov et al.* [2015]) illustrates the MI coupling electron diffuse aurora phenomena that was completely missing from previous considerations in aforementioned papers. Wave-particle interactions (orange cloud regions) scatter the inner plasma sheet electrons into the loss cone and initiate auroral precipitation into both the northern and southern ionospheres as seen by the thick red and yellow arrows pointing toward both ionospheres. This process can be considered as the first step in the formation of the electron distribution function in the region of diffuse aurora.

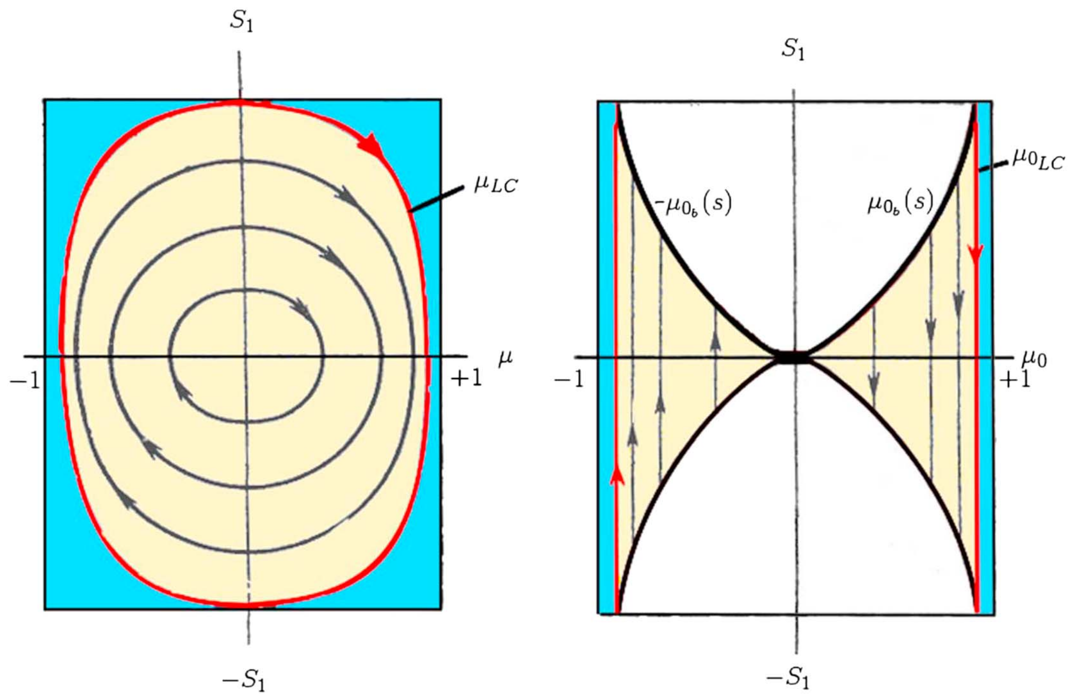

Figure 2. Regions where we solve the kinetic equation (1) using different pitch angle variables (2).

The high-energy plasma sheet electrons that are scattered into the loss cone by WPI processes and precipitate to the ionosphere lose their energy due to nonelastic collisions with the neutral atmosphere and produce secondary electrons (energies less than about 0.5–0.6 keV). These initial auroral precipitation electrons loose their energy upon exciting and ionizing atmospheric neutrals, and producing new secondary electrons, do not disappear into the ionosphere completely but rather escape to the magnetosphere as seen by the red, yellow, and blue arrows pointing toward the magnetosphere. *Khazanov et al.* [2014] demonstrated that 15–40% of the total aurora energy returns back to the magnetosphere and the conjugate ionosphere. Some of the escaping electrons are trapped in the inner plasma sheet via Coulomb collision or wave-particle interactions (orange and blue clouds) that scatter them out of the loss cone. Other escaping electrons (primary and secondary) can reach the conjugate ionosphere along closed magnetic field lines (thin red and yellow arrows pointing toward the ionospheres) and continuously ionize the upper atmosphere at the conjugate locations. After the first bounce electrons that are precipitating having originated in the conjugate ionosphere are also following the same cycle as the primary precipitating electrons of magnetospheric origin, and a portion of them can be again reflected back to the original ionosphere along closed field lines, continuing the collisional processes with the neutral atmosphere. This reflection process is repeated multiple times in the diffuse aurora regions of both magnetically conjugate points and, as we demonstrate below leads to a dramatic enhancement of the intensity of electron fluxes which ends up stabilizing between the ionosphere and magnetosphere altitudes.

Thus, multiple atmospheric reflections of the primary WPI driven magnetospheric electrons precipitating into both magnetically conjugate regions, and following up on their energy redistribution in the MI system via collisional and WPI processes, should be considered as Step 2 (driven from *below*) in the formation of electron fluxes that precipitate into the Northern and Southern Hemispheres in the regions of diffuse aurora. Therefore, in the approach that we present in this letter, the MI system is considered as one merged unit with linked transport processes of precipitated, secondary, reflected, bounced, etc., electrons.

5. Kinetic Formalism

We use the SuperThermal Electron Transport (STET) code [see *Khazanov et al.*, 2015] to simulate the scenario discussed in the previous section and illustrated by Figure 1. STET solves a kinetic Boltzmann-Landau equation for the superthermal electrons:

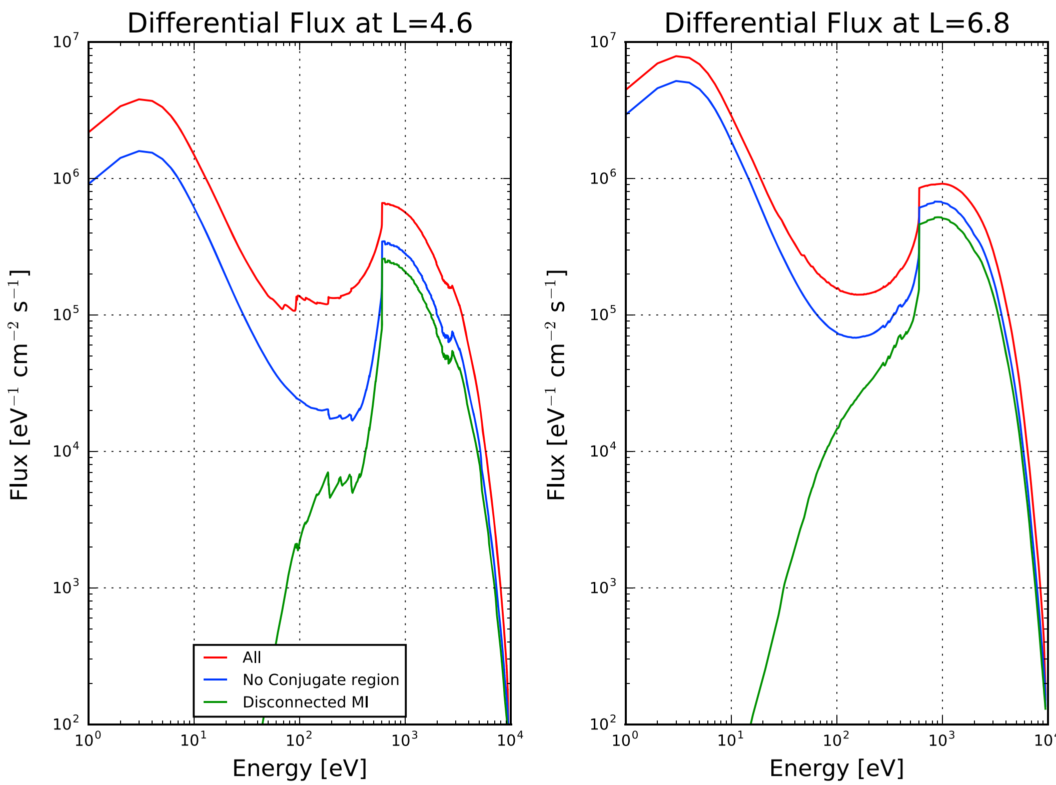

Figure 3. Downward electron flux from 1 eV to 10 keV at 800 km for $L = 4.6$ and $L = 6.8$ calculated for three different scenarios as described in the text.

$$\frac{1}{v}\frac{\partial \Phi}{\partial t} + \mu \frac{\partial \Phi}{\partial s} - \frac{1-\mu^2}{2}\left(\frac{1}{B}\frac{\partial B}{\partial s} - \frac{F}{E}\right)\frac{\partial \Phi}{\partial \mu} + EF\mu \frac{\partial}{\partial E}\left(\frac{\Phi}{E}\right) = Q + < S > \tag{1}$$

where the electron number flux (Φ) is a function of time (t), s is the distance along the magnetic field, μ is the cosine of the pitch angle, and E is the electron energy. The right-hand side represents the source term Q due to photoionization and the source and loss term $\langle S \rangle$ due to the different collisional processes. The collision term includes elastic collisions between charged and neutral particles, all nonelastic collisions between electrons and neutrals, and wave-particle interactions between electrons and the whistler mode chorus waves and ECH waves. STET can provide a full energy distribution of superthermal electrons along closed magnetic field lines without interruption between the magnetosphere and the ionosphere, thus providing a useful tool to understand the MI coupling dynamics in the regions of diffuse electron aurora. STET is a well-established code developed and improved in the past few decades [*Khazanov et al*., 2014, 2015, 1994; *Khazanov*, 1979, 2011]. *Khazanov* [2011] and *Khazanov et al.* [2014, 2015] provide extensive details on the current STET code.

Further, as has been discussed by *Khazanov et al.* [2014, 2015, 2016a, 2016b], we transform equation (1) from (μ, s) to (μ_0, s) variables, where

$$\mu_0(s) = \frac{\mu}{|\mu|}\sqrt{1 - {}^{B_0}/_{B(s)}(1-\mu^2)} \tag{2}$$

with B_0 and μ_0 denoting the magnetic field and the cosine of the pitch angle at the magnetic equator of the flux tube. After the change of variables, $\Phi(\mu_0, s)$ now becomes a slowly varying function with s that greatly reduces computational effects associated with approximation errors of the derivatives [*Khazanov*, 2011]. For a given superthermal electron (SE) energy, E, the Figure 2 shows the region of the solution of equation (1) in the old and new variables that is defined by equation (2). The loss cone area in this figure is shown in blue, and the trapped zone with the trajectories of bouncing particles is shown in yellow.

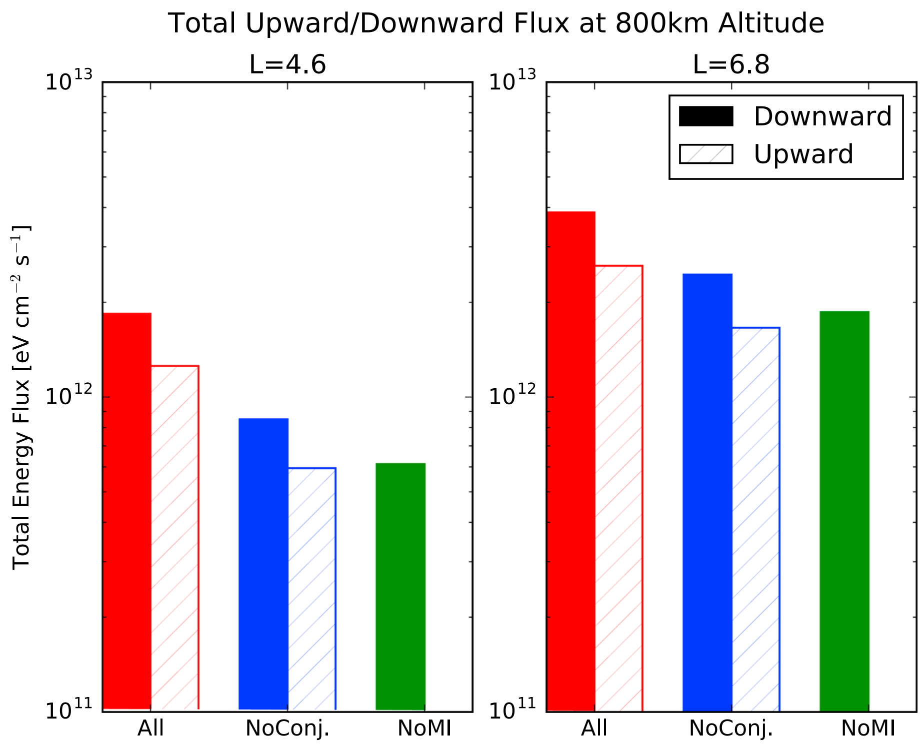

Figure 4. Upward and downward integrated electron fluxes calculated for the same scenarios as Figure 3.

Khazanov et al. [2015] initiated electron precipitation from the magnetosphere to the ionosphere via interaction with whistler and ECH waves within the Earth's plasma sheet. The boundary conditions were set up in velocity space above 600 eV and in the loss cone (see red lines in Figure 2.). It was also assumed that there is no communication between the initially trapped magnetospheric electrons (yellow region in Figure 2) and the electrons with the same energies that return through the loss cone (blue area in the same figure) after reflection and degradation in both magnetically conjugate ionospheres. Now we are removing these assumptions by allowing atmospheric reflection of magnetospheric electrons to communicate back and forth between the loss cone and trapped zones and to the magnetically conjugate ionospheric regions [*Khazanov et al.*, 2016a]. We also naturally demonstrate the role of the multiple atmospheric electron reflections that were introduced by *Khazanov et al.* [2016b] and the role of magnetically conjugate atmospheric regions based on the first principles of the solution of the Landau-Boltzmann equation (1) in the entire MI coupling system.

To demonstrate how MI coupling of SE influence on the electron distribution function, as in the previous work by *Khazanov et al.* [2015], we assume the trapped electron fluxes to exhibit Maxwellian distribution

$$\Phi_{\text{trap}}(E) = AE \ \exp(-E/E_0) \tag{3}$$

with the normalization factor $A = 10^3$, and the characteristic energy of the trapped plasma sheet electrons $E_0 = 1$ KeV. These parameters are selected to be identical for the two L shells 4.6 and 6.8 that were simulated in this manuscript. Plasma and wave parameters for these specific distances are selected as follows:

$$\text{for } \ L = 4.6 : n_c = 21.5 \ \text{cm}^{-3}, \ \ T_c = 4 \ \text{eV}, B_o = 312 \ \text{nT}$$
$$\text{for } \ L = 4.8 : n_c = 12.0 \ \text{cm}^{-3}, \ \ T_c = 10 \ \text{eV}, B_o = 92.5 \ \text{nT}'$$

where the index *c* denotes cold plasma. As in *Khazanov et al.* [2015], the amplitudes of the magnetic field for the lower band chorus (LBC) and upper band chorus (UBC) whistler waves were taken to be 10 pT and 1 mV m^{-1} for ECH waves. The same wave amplitudes were used for both L shell values, and they are within the range of the observed values in the CRRES wave database [*Meredith et al.*, 2009]. We assumed that LBC waves are located within ±15° of the magnetic equator, while UBC and ECH waves were within ±10° and ±3° of the magnetic equator, respectively [*Ni et al*., 2011]. The pitch angle diffusion coefficients for these waves are the same that were used in *Khazanov et al.* [2015].

6. Results and Summary

The MI simulation results presented below are performed using the STET code as formulated by *Khazanov et al.* [2014–2016]. Figure 3 shows downward fluxes at the altitude of 800 km in the Northern Hemisphere for $L = 4.6$ (left window) and $L = 6.8$ (right window). We compare these fluxes (red lines) with different MI coupling conditions, when the Southern Hemisphere was disconnected from the simulations (blue lines), as well as with completely decoupled ionosphere and magnetosphere system (green lines). Figure 4 shows the total downward (solid bars) and upward (dashed bars) directional energy fluxes at 800 km integrated from 1 eV to 10 keV for $L = 4.6$ (left) and $L = 6.8$ (right). These energy fluxes are calculated for the same MI coupling conditions presented in Figure 3. The histogram further demonstrates the important role of MI coupling processes in the formation of SE fluxes that precipitate into the upper atmosphere. As mentioned above, for the different L shells, we used identical wave amplitudes and plasma sheet parameters as described in the previous section of this paper. Nevertheless, similar to Figure 3, precipitation is stronger at $L = 6.8$ due to the greater efficiency of WPI processes at that L shell. To emphasize the role of MI coupling processes in the formation of downward energy and/or particle fluxes in the regions of diffuse aurora, one can compare the red and green lines and bars shown in Figures 3 and 4, respectively. The change in calculated electron energy fluxes is 300% for $L = 4.6$ and more than 200% for $L = 6.8$. Therefore, considering as the source of observed precipitation fluxes and energy only electrons that are driven by whistler and/or ECH waves in the Earth's plasma sheet is not sufficient to account for all the precipitating fluxes. The MI coupling element in their formation of the precipitating fluxes *must* also be taken into account. As shown by *Khazanov et al.* [2016b], the effect of MI coupling process in the formation of electron distribution function in the regions of diffuse aurora becomes even stronger with increasing mean energy leading to higher impact of the MI coupling processes, and as a result, enhancing the precipitating electron fluxes.

The aurora is one of the most important and fundamental phenomena in space physics, related to the interaction of the solar wind with the planetary magnetospheres of Earth, Jupiter, and Saturn. Our results definitively show that the MI coupling element in forming the electron precipitation responsible for the observed diffuse aurora is very strong and must be taken into account in future auroral studies of planetary systems with strong magnetic fields. *The diffuse aurora is driven from above and below!*

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