Controlling Effect of Wave Models and Plasma Boundaries on the Dynamic Evolution of Relativistic Radiation Belt Electrons

Dedong Wang[1], Yuri Shprits[1,2,3], Irina Zhelavskaya[1,2], Alexander Drozdov[3]
Nikita Aseev[1,2], Frederic Effenberger[1], Angelica Castilo[1,2], Sebastian Cervantes[1,2]

1. GFZ German Research Center for Geosciences, Potsdam, Germany
2. University of Potsdam, Potsdam, Germany
3. University of California, Los Angeles, California, USA

2020 EGU General Assembly

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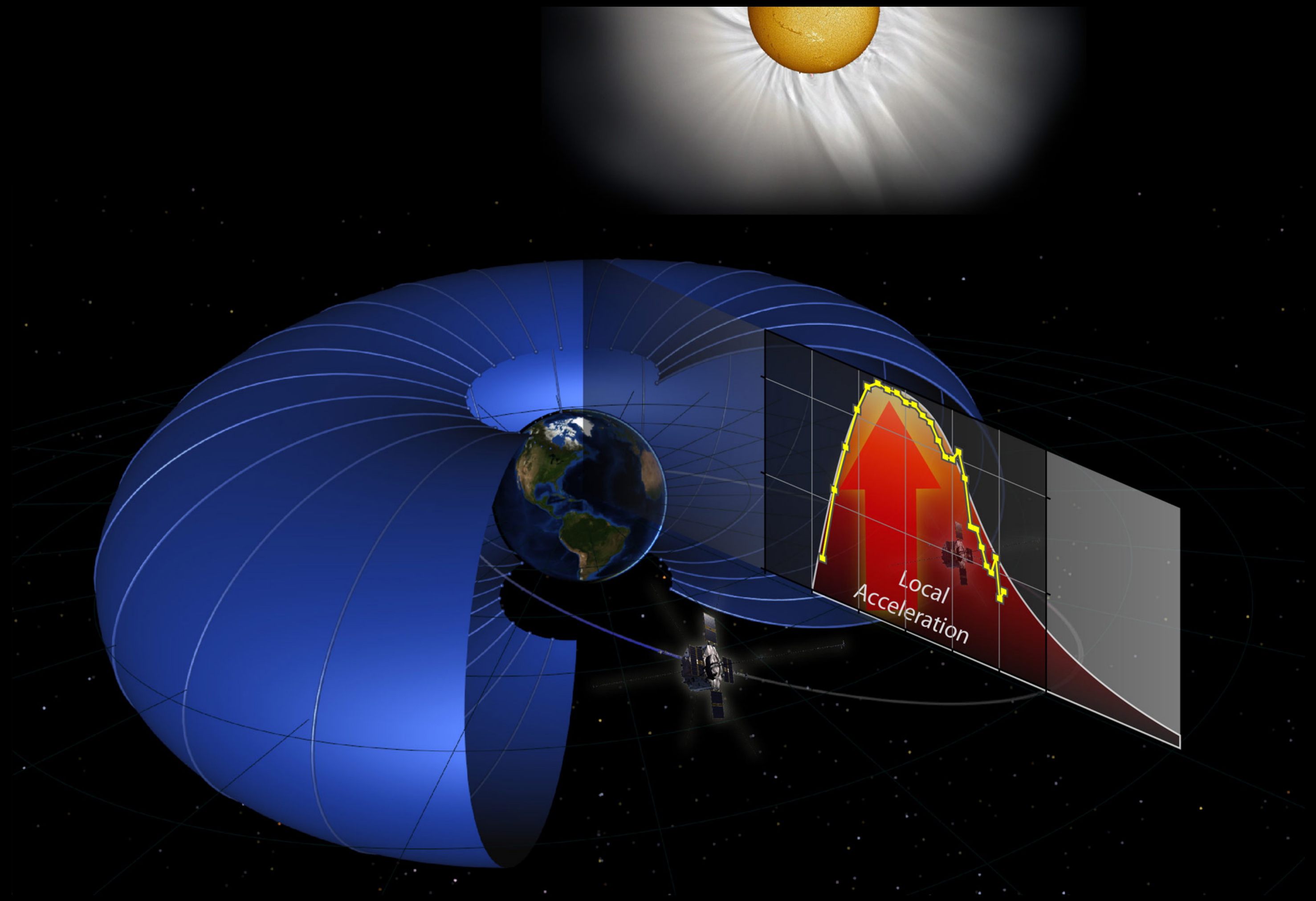
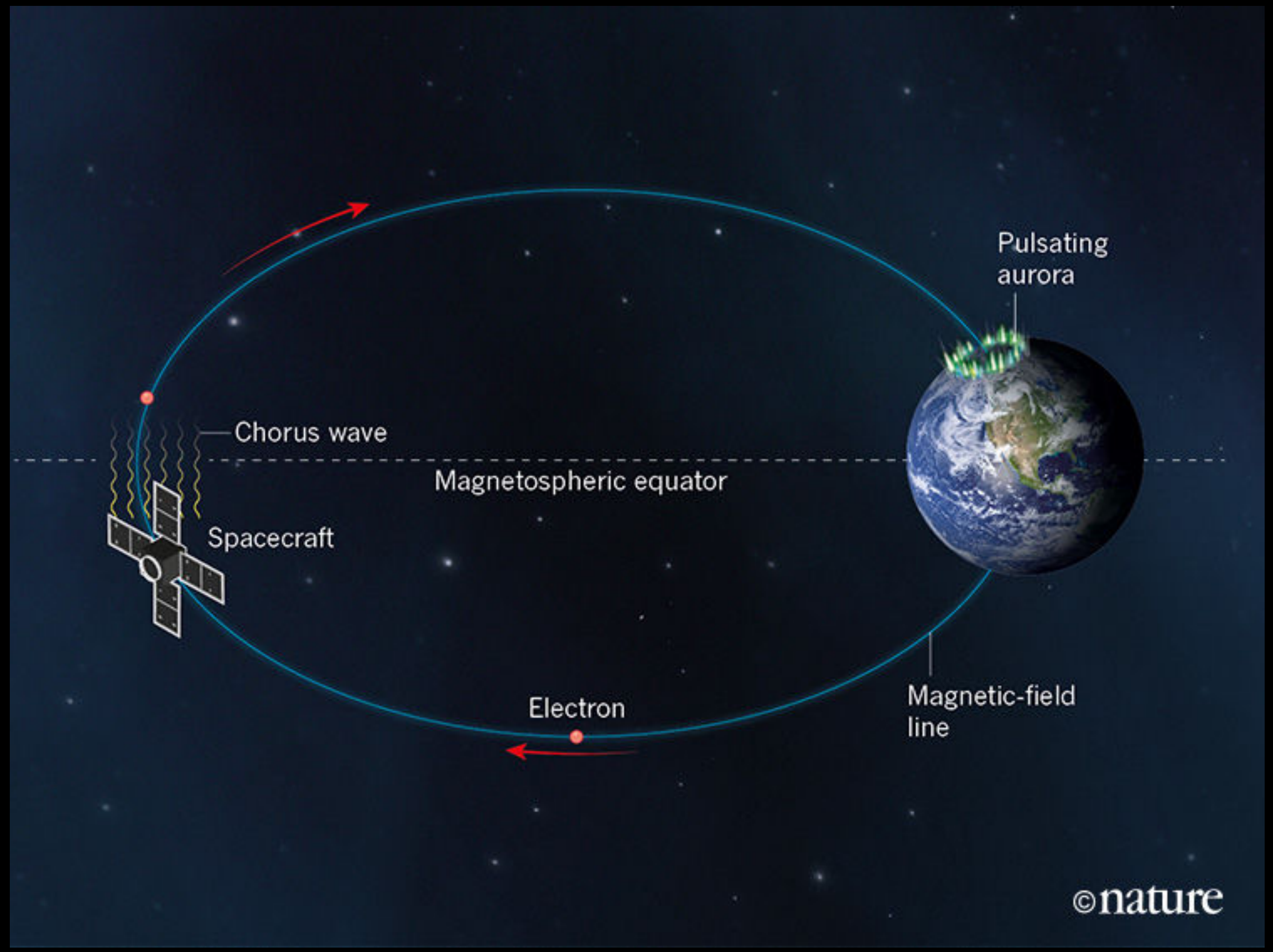
Chorus Waves Play Dual Roles in the Dynamic Evolution of Energetic Electrons

Fast Local Acceleration



[Reeves et al, 2013, science]

Precipitation Loss



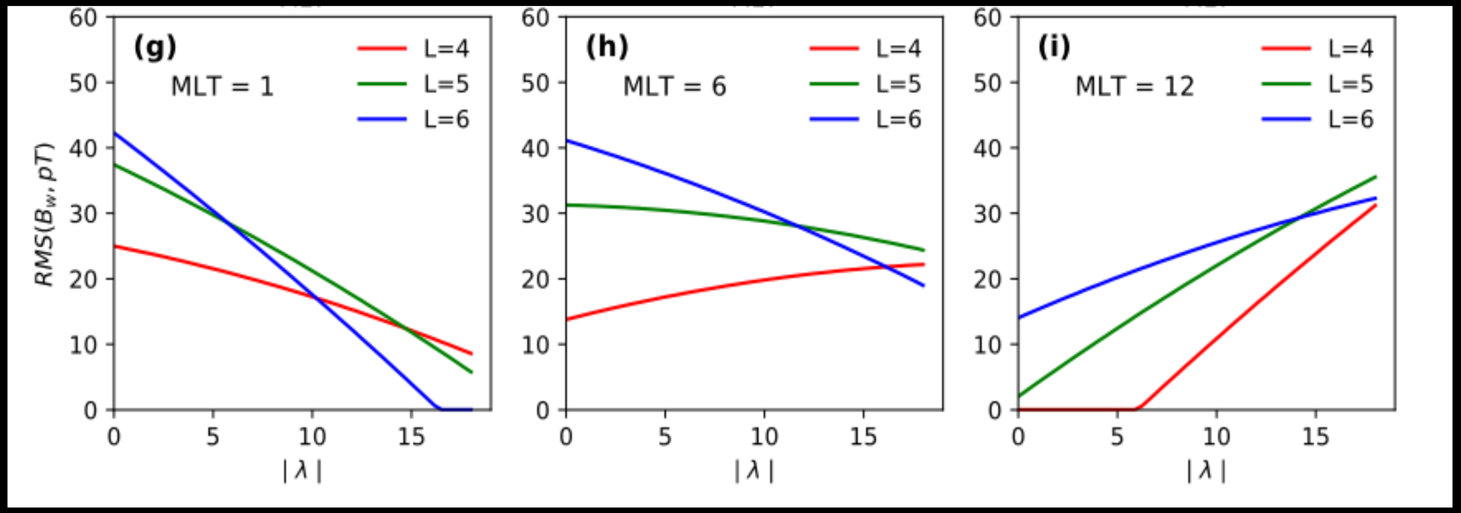
[Kasahara et al, 2018, nature]

What is the ***net effect*** of Chorus Waves on MeV electrons?

Net Effect of Chorus Waves on MeV Electrons

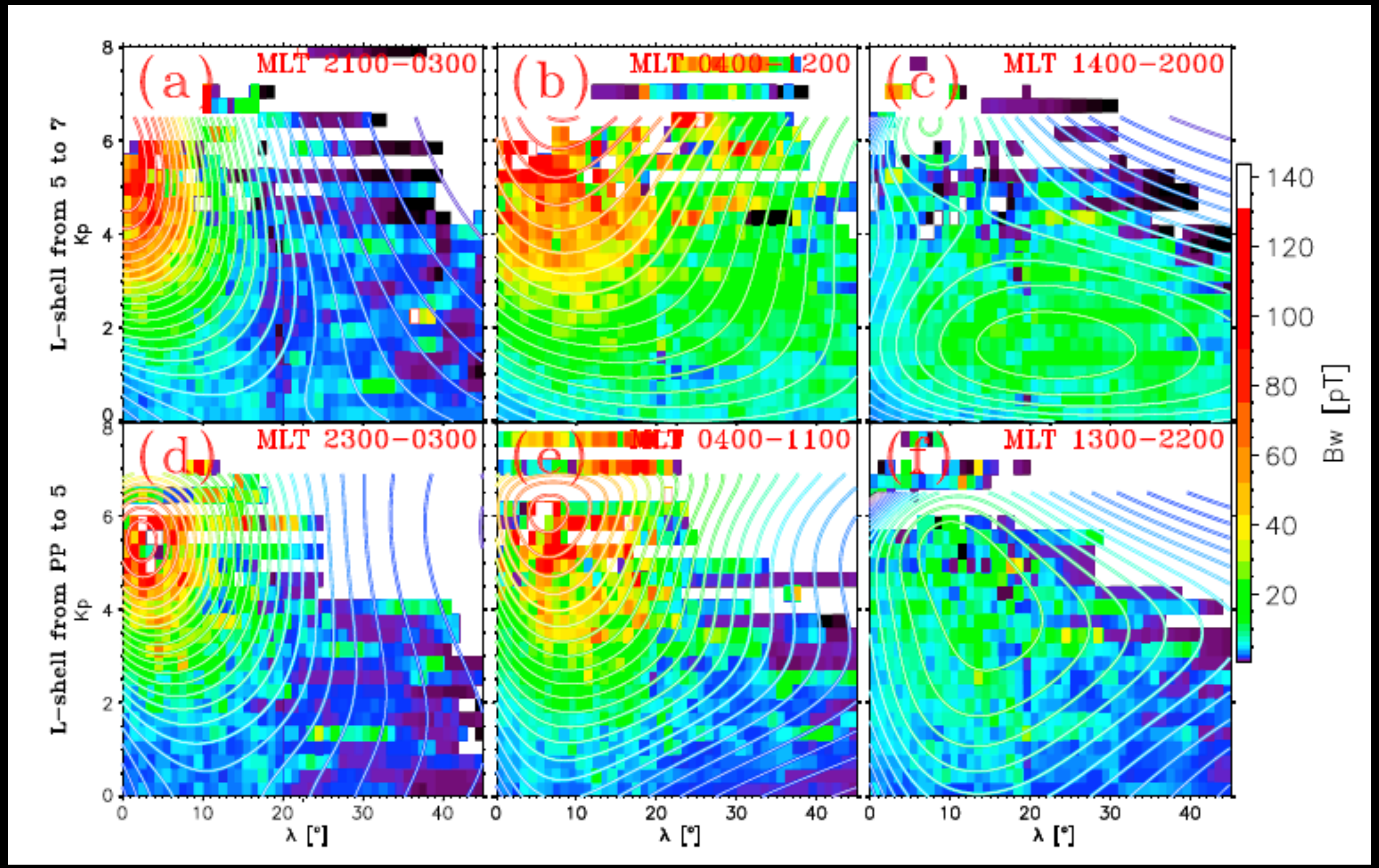
- Depending on the ***latitudinal distribution*** of chorus waves, they cannot only cause acceleration but also loss of relativistic electrons [e.g., Horne and Thorne, 2003; Thorne et al., 2005; Shprits et al., 2006].
- While dayside chorus waves produce loss and nightside chorus waves produce acceleration, previous studies suggested that the combination of them at 1 MeV results in net acceleration [e.g., Li et al., 2007; Shprits et al., 2008; Xiao et al., 2009; Thorne, 2010; Tu et al., 2013; Su et al., 2014; Turner et al., 2014].

Latitudinal Distribution of Chorus Waves



[Wang et al., 2019]

Wang, D., Shprits, Y., Zhelavskaya, I., Agapitov, O. V., Drozdov, A., Aseev, N. (2019): Analytical Chorus Wave Model Derived from Van Allen Probe Observations. - Journal of Geophysical Research, 124, 2, 1063-1084. https://doi.org/10.1029/2018JA026183



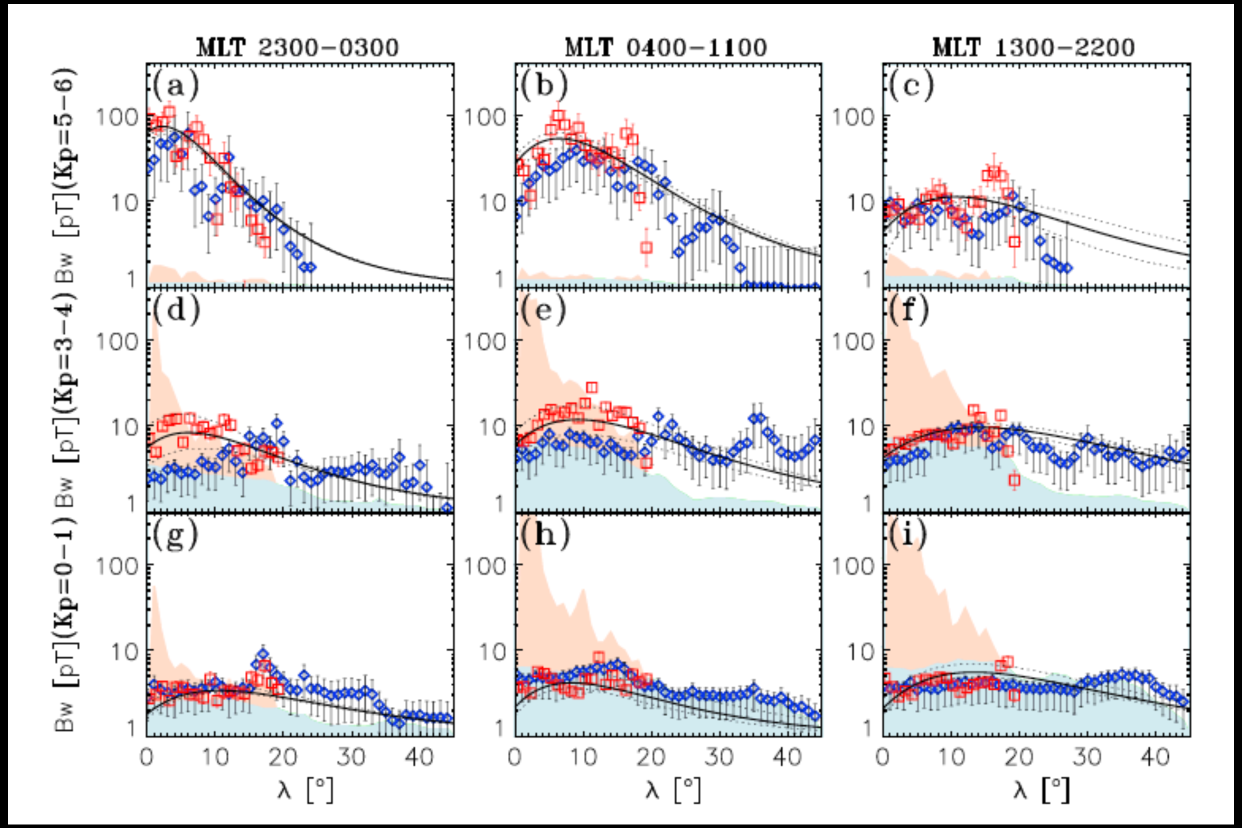
[Agapitov et al., 2018]

- Nightside chorus waves are confined to low latitudes, while the intensity of dayside chorus waves increase with latitude.
- However, measurements from Van Allen Probes are confined to low latitude.
- Cluster measurements show that chorus waves can extend to higher latitudes.
- The wave instrument on board the Van Allen Probes and Cluster have a different resolution, sensitivity and frequency range, which result in several times difference of wave amplitude.

Extend Dayside Chorus Waves to High Latitude

- For chorus waves at latitudes lower than 20 degree, we use the wave model derived from Van Allen Probe observations [Wang et al., 2019].

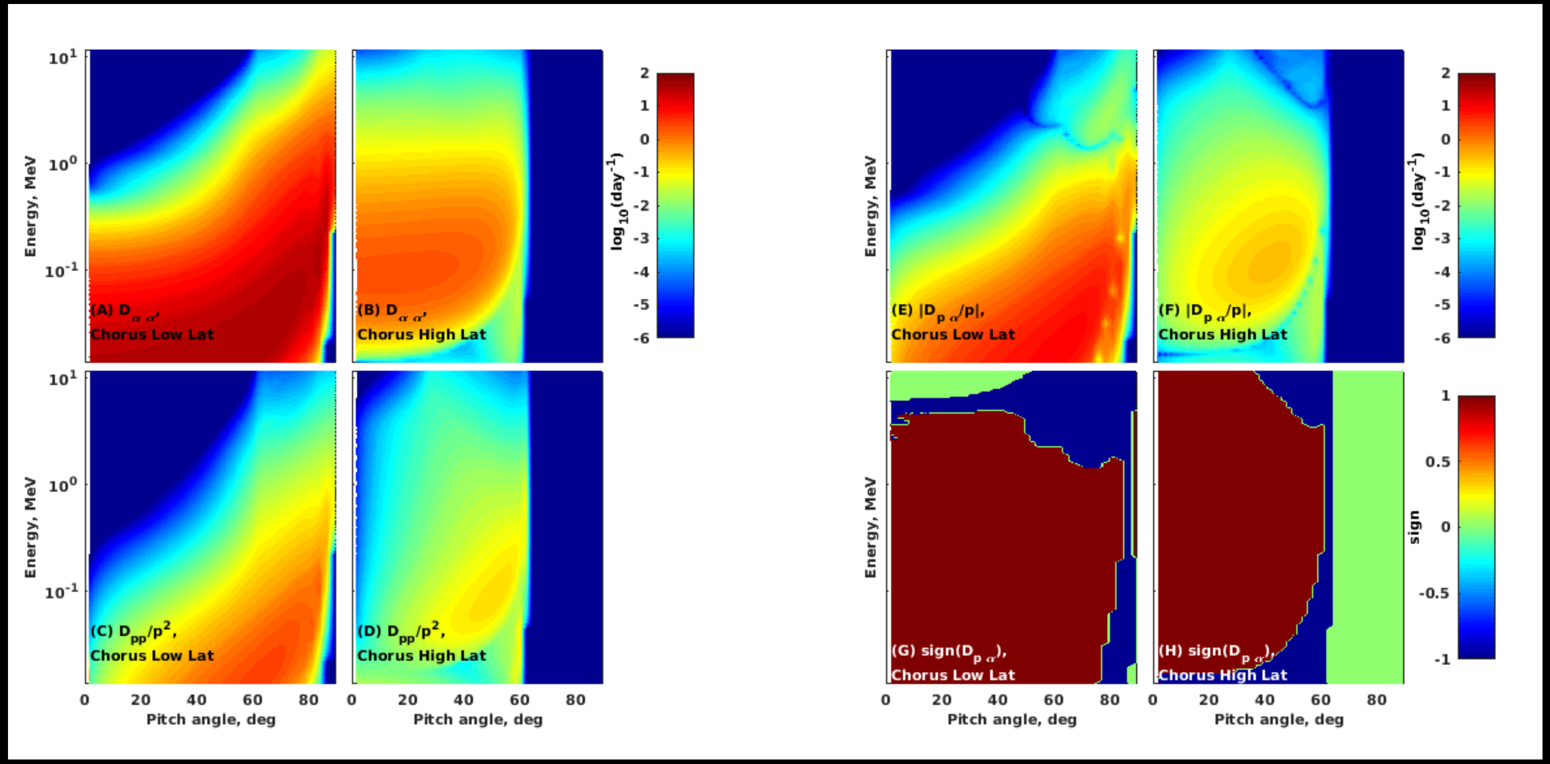
- Referring to Agapitov et al [2018], we extend chorus waves to 45 degree latitude when Kp <= 4, assuming that amplitudes of chorus waves at latitudes 20-45 degree are the same as the amplitudes at 20 degree.



[*Agapitov et al.*, 2018]

- MLT averaged diffusion coefficients from low-latitude chorus waves and high latitude chorus waves at L=6 and Kp = 4.

- The evolution is not only determined by diffusion coefficients, but also by the gradients in PSD [Allison et al., 2019]. To understand the net effect, we need to run long-term simulation.



[*Wang and Shprits*, 2019]

Versatile Electron Radiation Belt (VERB) - 3D Simulation Setup

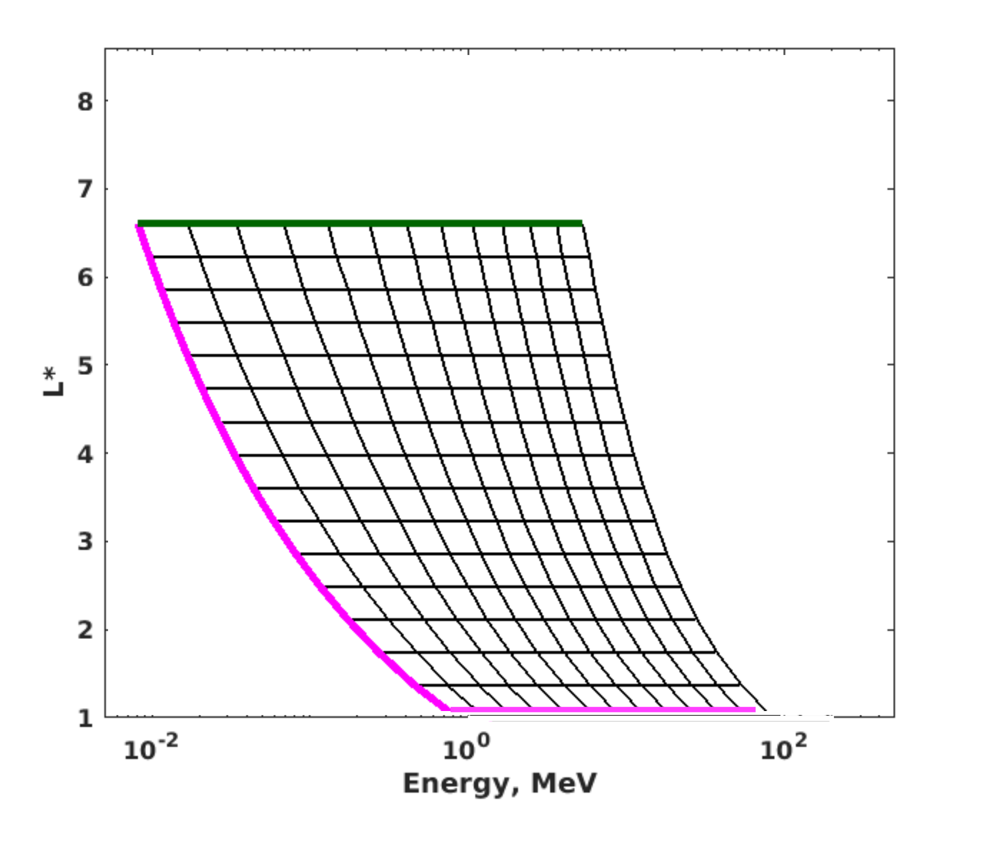
$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\left(\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}p^2\left(D_{pp}\frac{\partial f}{\partial p}\Big|_{\alpha_0,L^*} + D_{p\alpha_0}\frac{\partial f}{\partial \alpha_0}\Big|_{p,L^*}\right)$$

$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial f}{\partial \alpha_0}\Big|_{p,L^*} + D_{\alpha_0 p}\frac{\partial f}{\partial p}\Big|_{\alpha_0,L^*}\right) - \frac{f}{\tau_{lc}}$$

[*Schulz and Lanzerotti*, 1974; *Shprits et al.*, 2009]

No data from Van Allen Probes is used in the boundary conditions to drive the simulation.
We validate our results against observations from Van Allen Probe and GOES measurements.

Boundary	Condition	Physics
$\alpha_0 = 0.7^\circ$	$\partial f/\partial\alpha_0 = 0$	Strong diffusion regimes
$\alpha_0 = 89.3^\circ$	$\partial f/\partial\alpha_0 = 0$	Flat-top distribution
$E_{min} = 10\text{keV}$	$\partial f/\partial t = 0$	Balance convection and loss
$E_{max} = 10\text{MeV}$	$f = 0$	Absence of such electrons
$L^* = 1$	$f = 0$	Losses to the Atmosphere
$L^* = 6.6$	Scaling	Using GOES Measurements



Versatile Electron Radiation Belts (VERB) - 3D Simulation Setup

- Initial Condition is set up by calculating steady state solution of radial diffusion and prescribed loss.
- Besides chorus waves, hiss waves are included referring to Orlova et al [2017], lightning generated whistlers are included referring to Abel and Thorne [1998].
- Radial diffusion is calculated referring to Brautigam and Albert [2000].
- Magnetopause shadowing effect is modelled using last closed drift shell.
- Plasmapause position is calculated using Carpenter and Anderson [1992].

No data from Van Allen Probes is used in the boundary conditions to drive the simulation.
We validate our results against observations from Van Allen Probe and GOES measurements.

Long-term Simulation Results and Validation with Satellite Data

Satellite Observations from GOES and RBSP

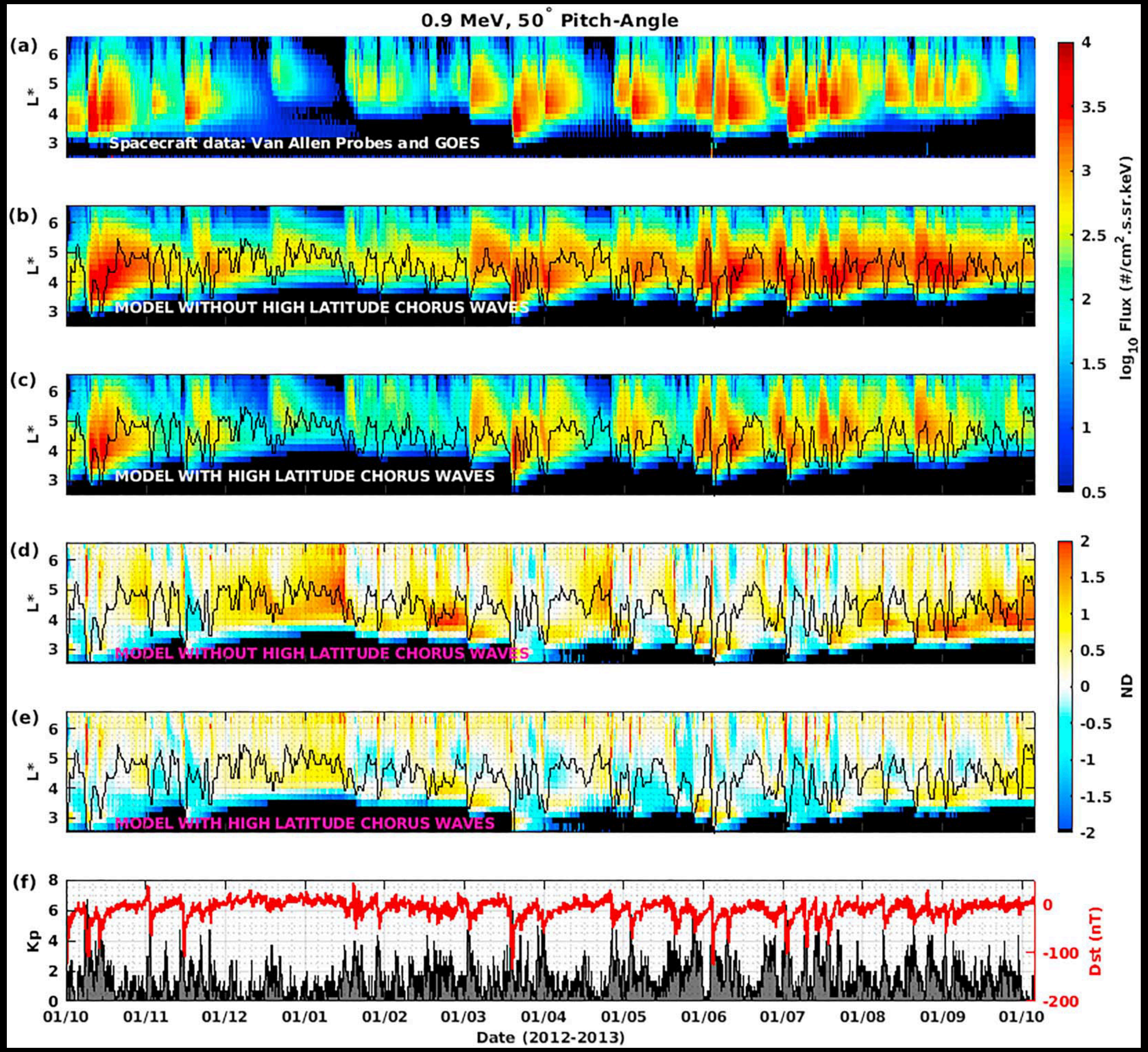
Model without High-Latitude Chorus waves

Model with High-Latitude Chorus waves

Normalised Difference

$$\mathrm{ND}(L^*, t) = 2 * \frac{J_S(L^*, t) - J_O(L^*, t)}{J_S(L^*, t) + J_O(L^*, t)}$$

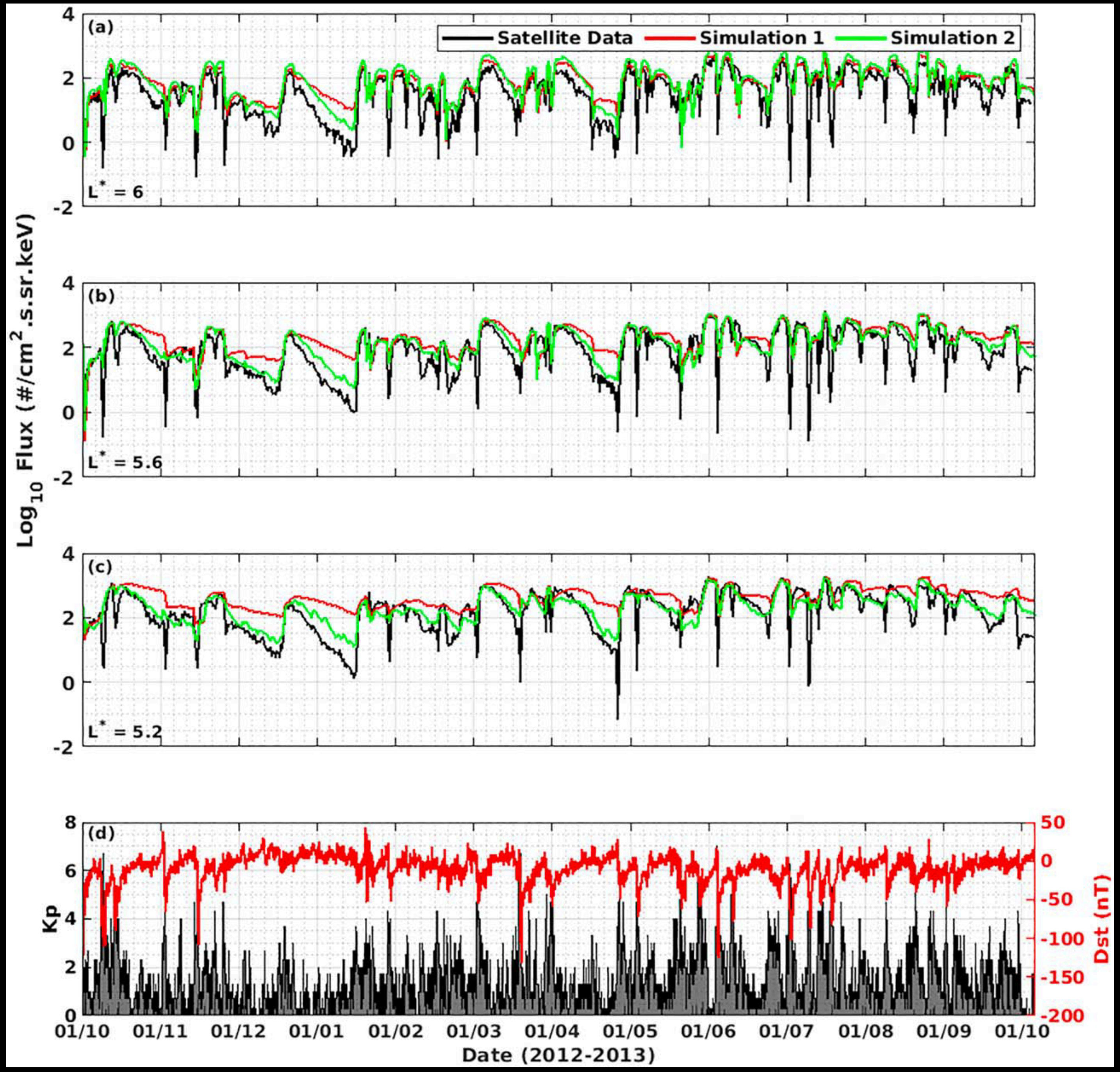
Kp and Dst



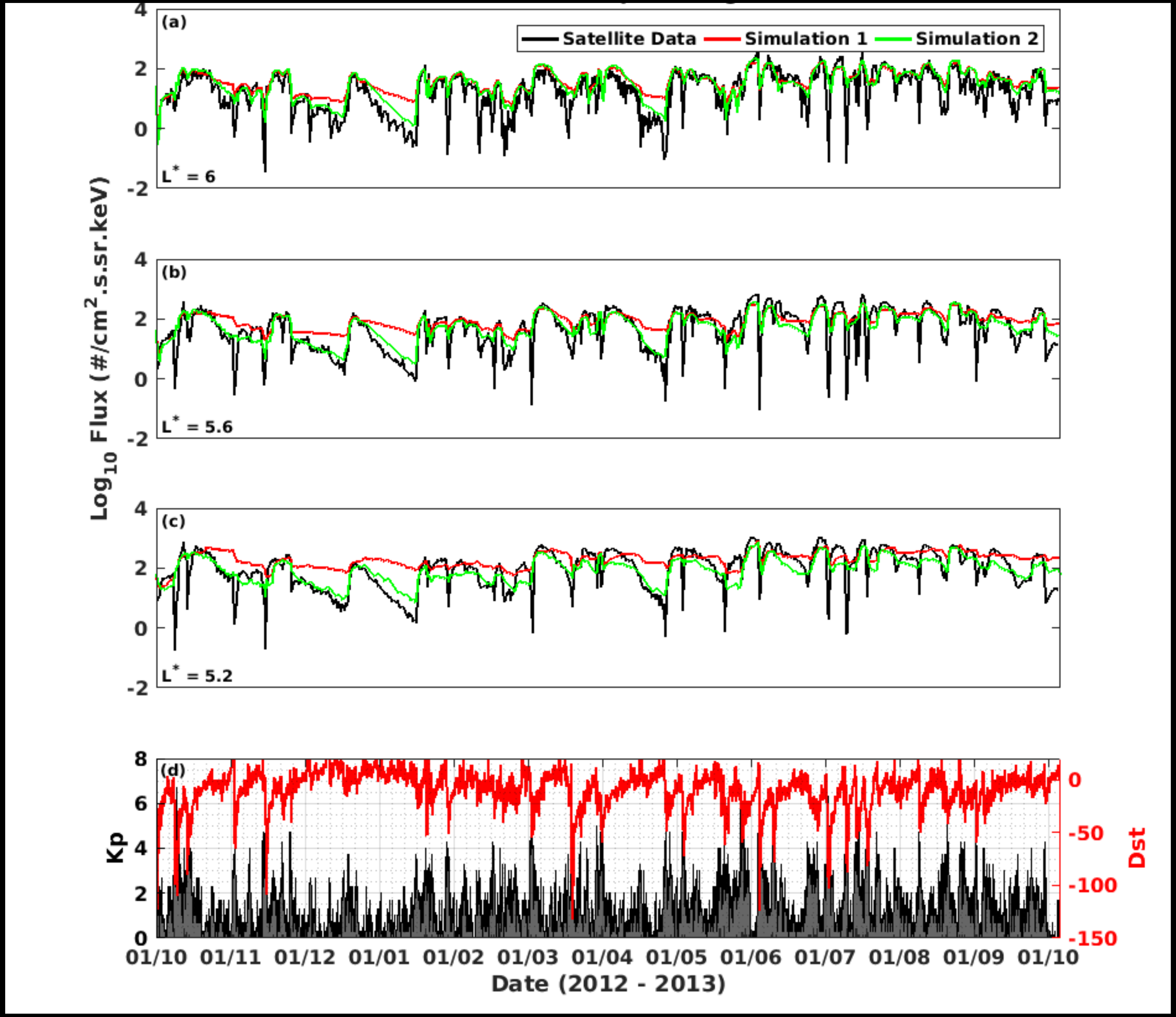
Long-term simulation results and Satellite Data at Different L-shells

Simulation 1: Without high-latitude chorus waves
Simulation 2: With high-latitude chorus waves

0.9 MeV, 50 degree pitch-angle



0.9 MeV, 20 degree pitch-angle



High-latitude Chorus Waves Tip the Balance between Acceleration and Loss

Satellite Observations from GOES and RBSP

Simulation without Chorus waves

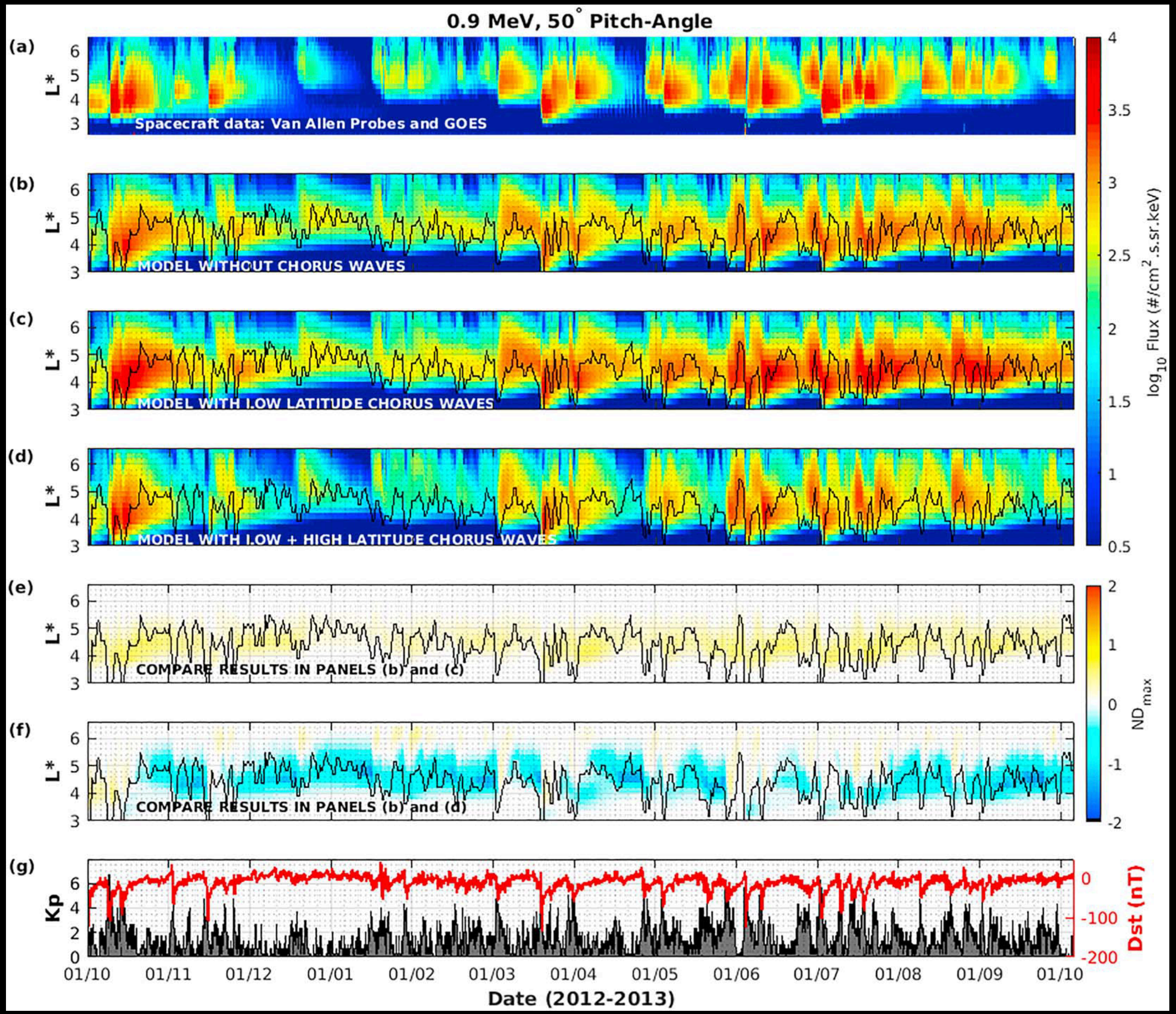
Simulation with Low-Latitude Chorus waves

Simulation with Low- and High-Latitude Chorus

Difference Normalised by Maximum Average

$$\mathrm{ND}_{\max}(L^*,t) = \frac{J_1(L^*,t) - J_2(L^*,t)}{\max|_{\mathrm{over}\,L^*\mathrm{at constant}\,t}\frac{J_1(L^*,t)+J_2(L^*,t)}{2}}$$

Kp and Dst



Wang, D., & Shprits, Y. Y. (2019). On how high-latitude chorus waves tip the balance between acceleration and loss of relativistic electrons. Geophysical Research Letters, 46, https://doi.org/10.1029/2019GL082681.

Effect of Plasma Boundaries

Satellite Observations from GOES and RBSP

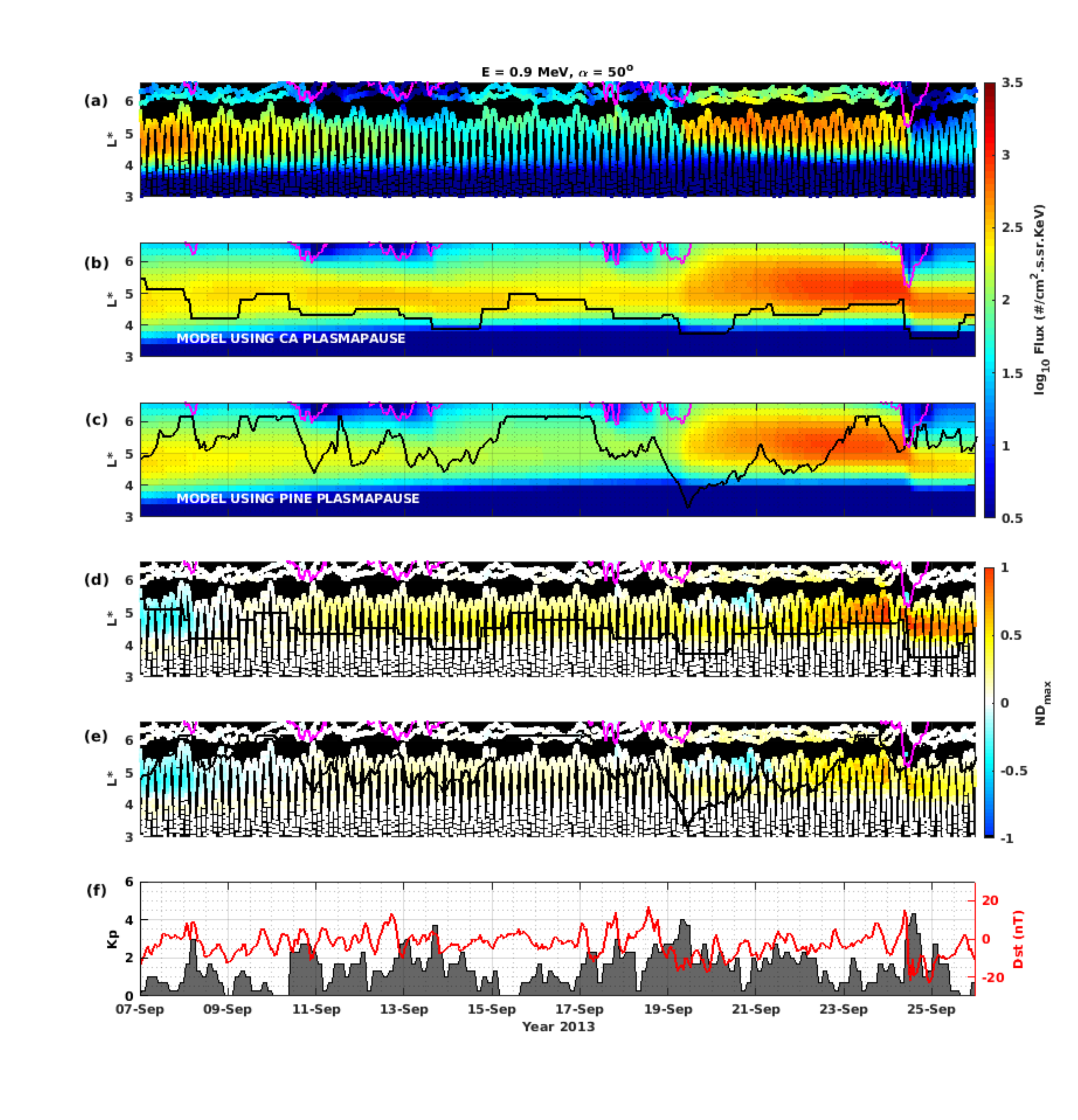
Model With Plasmapause Calculated from Carpenter and Anderson [1992]

Model With Plasmapause from PINE [Zhelavskaya et al., 2016, 2017, 2018]

Difference Normalised by Maximum Average over Every 8 Hours

$$\mathrm{ND}_{\max}(L^*, t) = \frac{J_S(L^*, t) - J_O(L^*, t)}{\max|_{\mathrm{over}L^*\mathrm{every8hours}} \frac{J_S(L^*,t) + J_O(L^*,t)}{2}}$$

Kp and Dst



Discussion and Conclusion

High latitude chorus waves can tip the delicate balance between the acceleration and loss and is critical for understanding the effects of chorus on 1 MeV electrons.

The plasma boundaries play an important role for the dynamic evolution of radiation belt electrons at MeV energies.

Simulation with high latitude chorus waves reproduces variability of MeV electrons well during multiple storm time and quiet time periods.

During disturbed periods, chorus waves mainly contribute to the acceleration of relativistic electrons, while during quiet geomagnetic conditions when waves may extend to high latitudes, the net effect of chorus is likely loss of MeV electrons.

Discussion and Conclusion

It is difficult to make definitive predictions, since chorus waves at latitudes higher than 20 degree have not been well quantified.

Cluster observations (Agapitov et al., 2018) indicate that chorus waves at high latitudes may be strongly damped when Kp > 4, but this trend is not very clear due to the limited number of available measurements.

Wave measurements from the ERG mission at high latitudes may be helpful for future quantification of the effects associated with high latitude chorus. Developing a chorus wave model combining Van Allen Probe and ERG measurements and all other available sources of data will be a subject of future research.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870452 (PAGER).

Prediction of Adverse effects of Geomagnetic storms and Energetic Radiation **(PAGER)** – EU Horizon 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870452 (PAGER).

Ensemble forecast from the Sun will allow a long-term probabilistic prediction.

Predictions at 20.5 R☉

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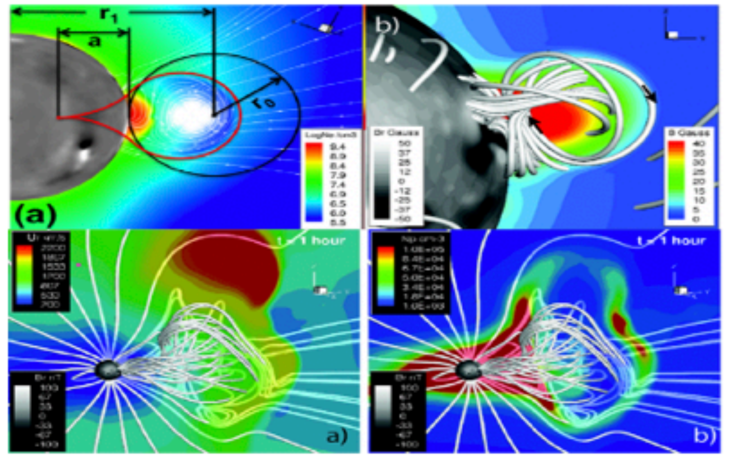
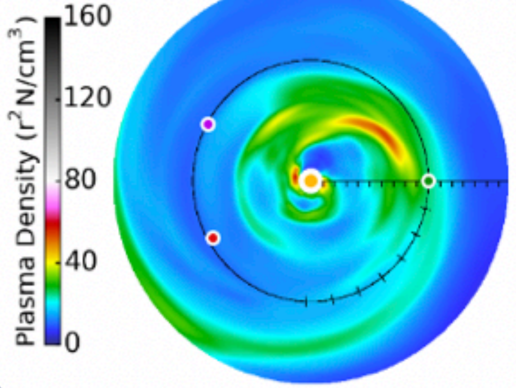
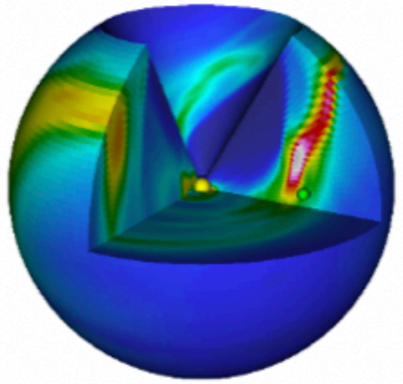


Ensemble predictions of the heliosphere





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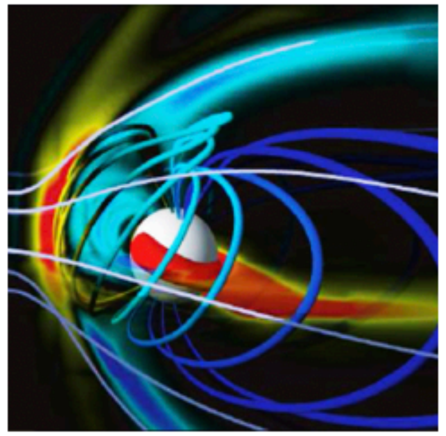
Global modelling of the magnetosphere dynamics



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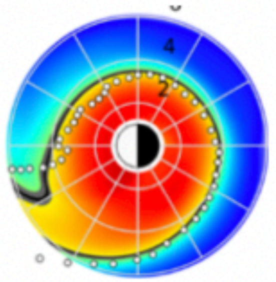

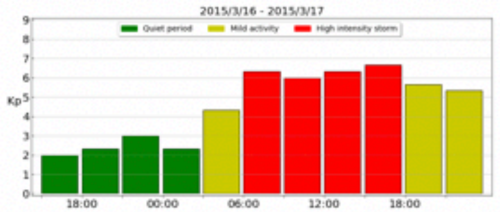

Ensemble predictions of the Plasmasphere and Kp

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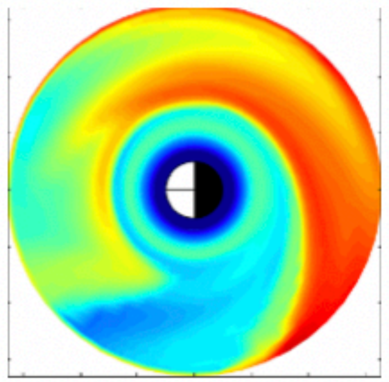
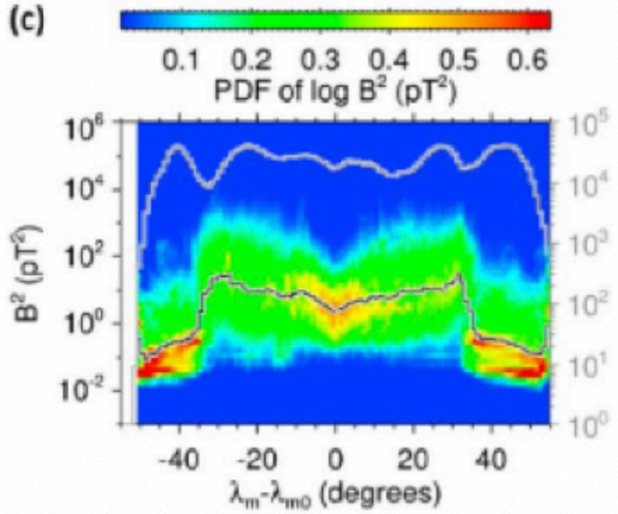
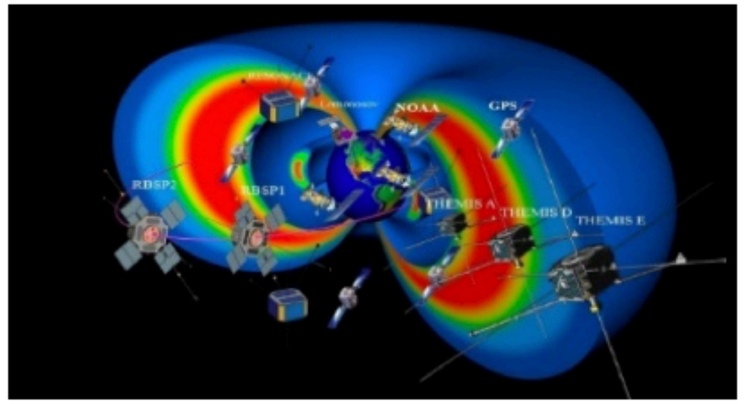


Ensemble predictions of the Ring Current



IAP

Statistical models of waves from multiple spacecraft



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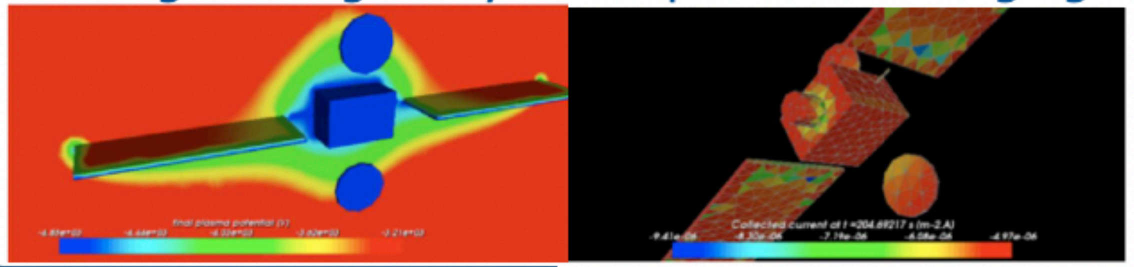
Ensemble predictions of the Radiation Belts

3D engineering analysis of spacecraft charging



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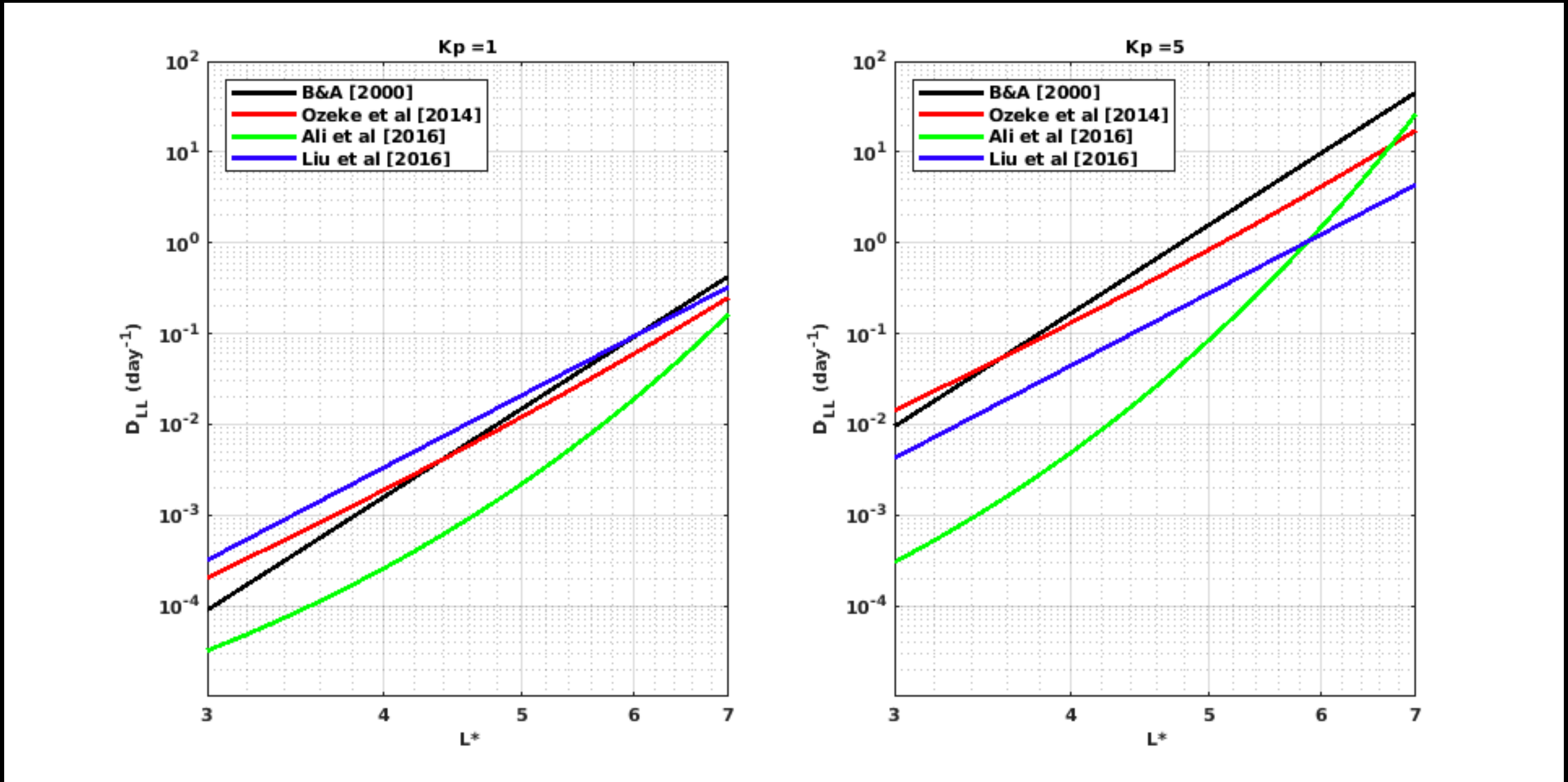
Various Space Weather applications (e.g. GIC, TEC, Kp prediction, etc.)

Thanks!

Backup Slides

Comparison of Different Radial Diffusion Coefficients (Dll)



[*Wang et al,* 2020]

Wang, D., Shprits, Y., Zhelavskaya, I., Effenberger, F., Castillo Tibocha, A. M., Drozdov, A., Aseev, N., Cervantes Villa, J. S. (2020): The Effect of Plasma Boundaries on the Dynamic Evolution of Relativistic Radiation Belt Electrons. - Journal of Geophysical Research: Space Physics, [early online release]. https://doi.org/10.1029/2019JA027422

Test Different Radial Diffusion (Dll) Coefficients for GEM Challenge Events

Satellite Observations

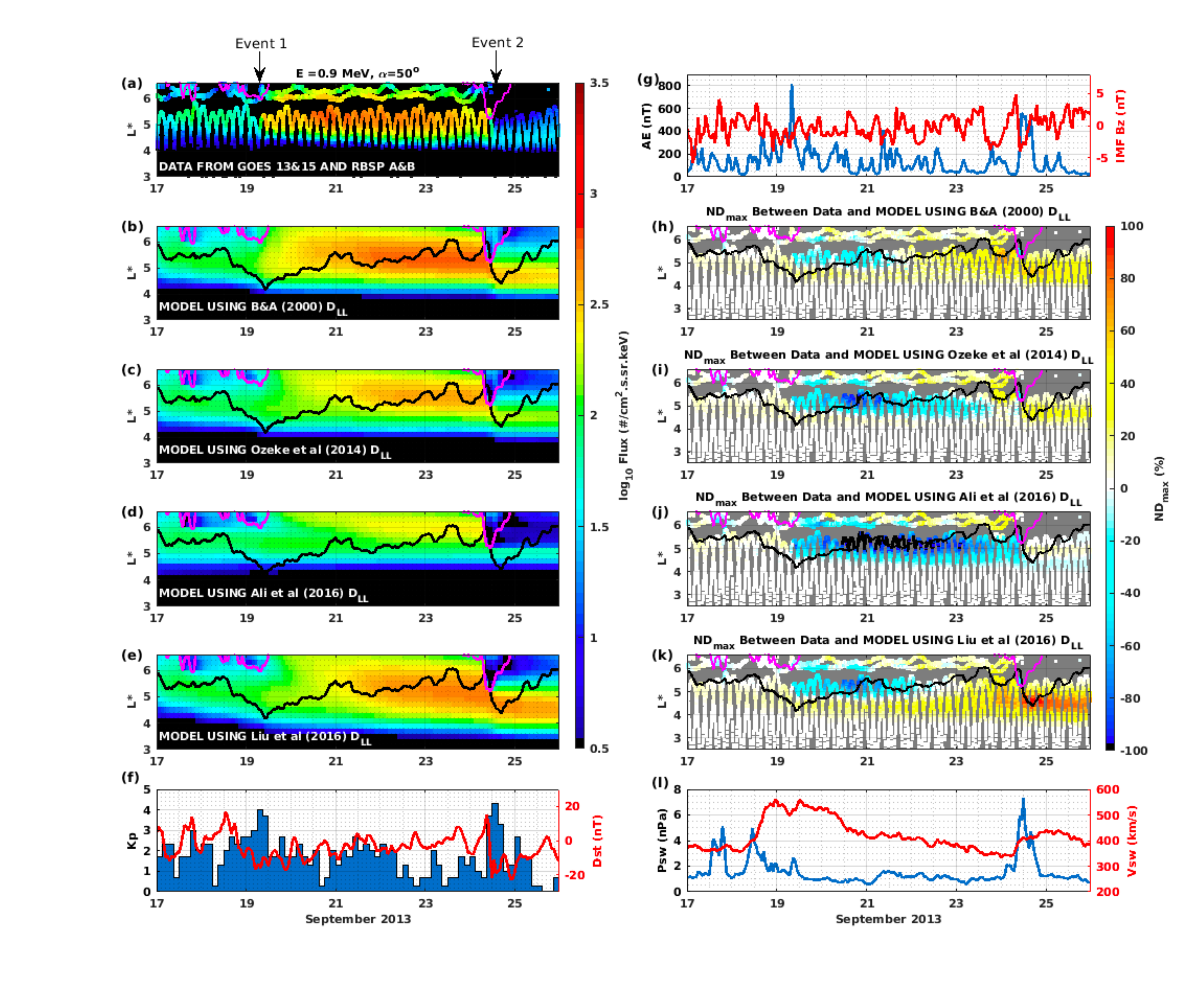
Dll B&A [2000]

Dll Ozeke et al [2014]

Dll Ali et al [2016]

Dll Liu et al [2016]

Kp and Dst



[*Wang et al*, 2020]

Test Different Radial Diffusion (Dll) Coefficients for Mar 17 2013 Storm

Satellite Observations

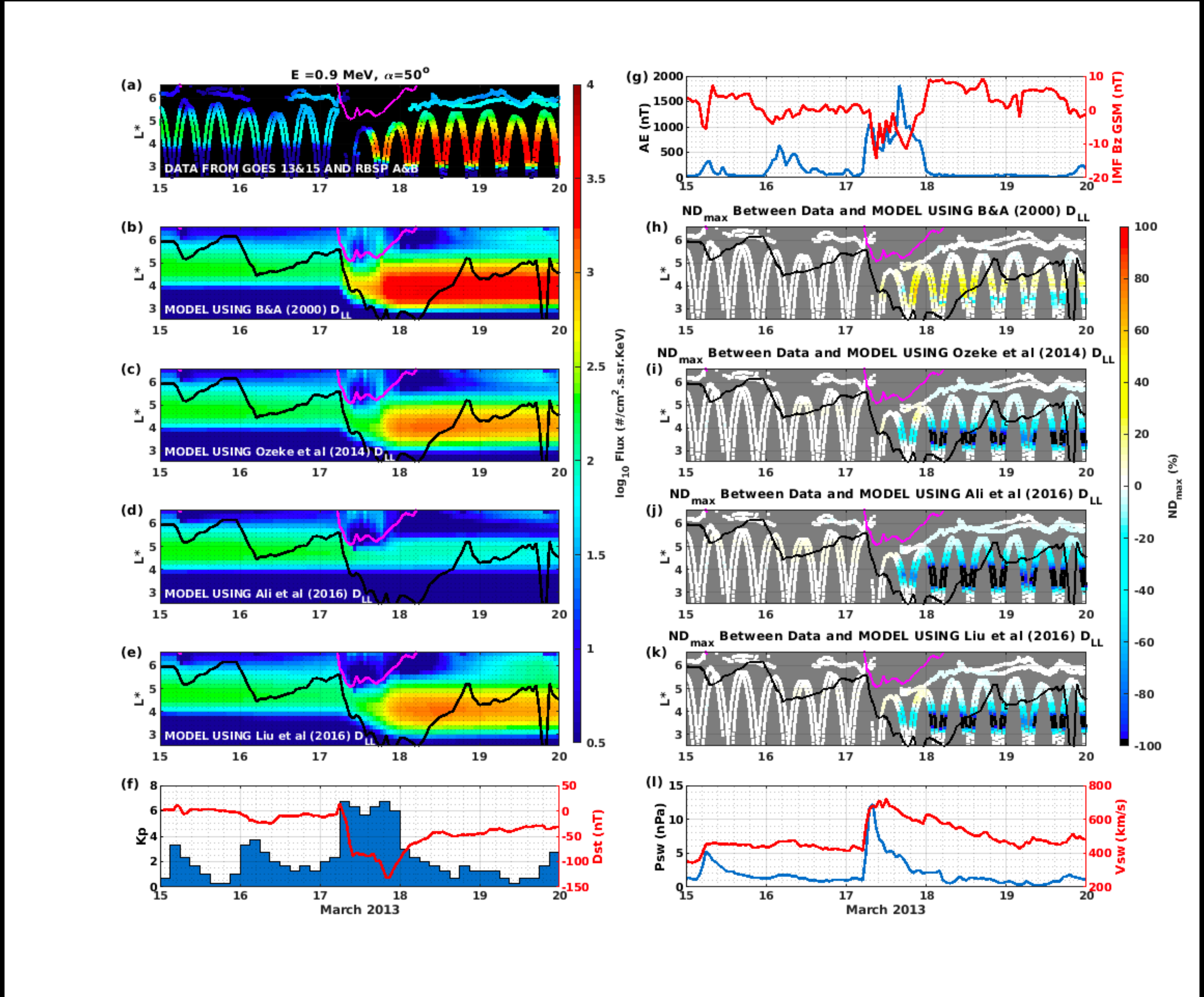
Dll B&A [2000]

Dll Ozeke et al [2014]

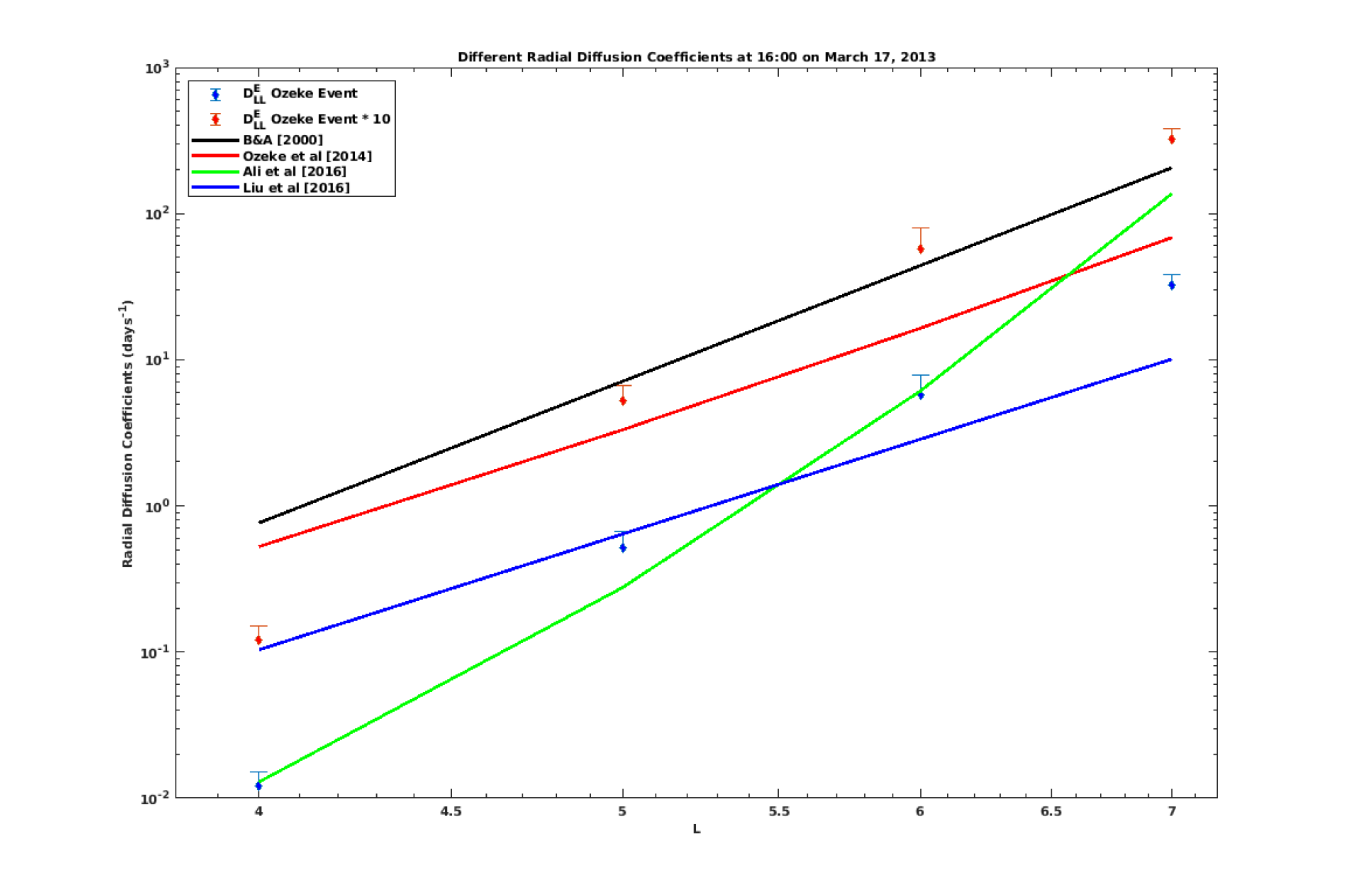
Dll Ali et al [2016]

Dll Liu et al [2016]

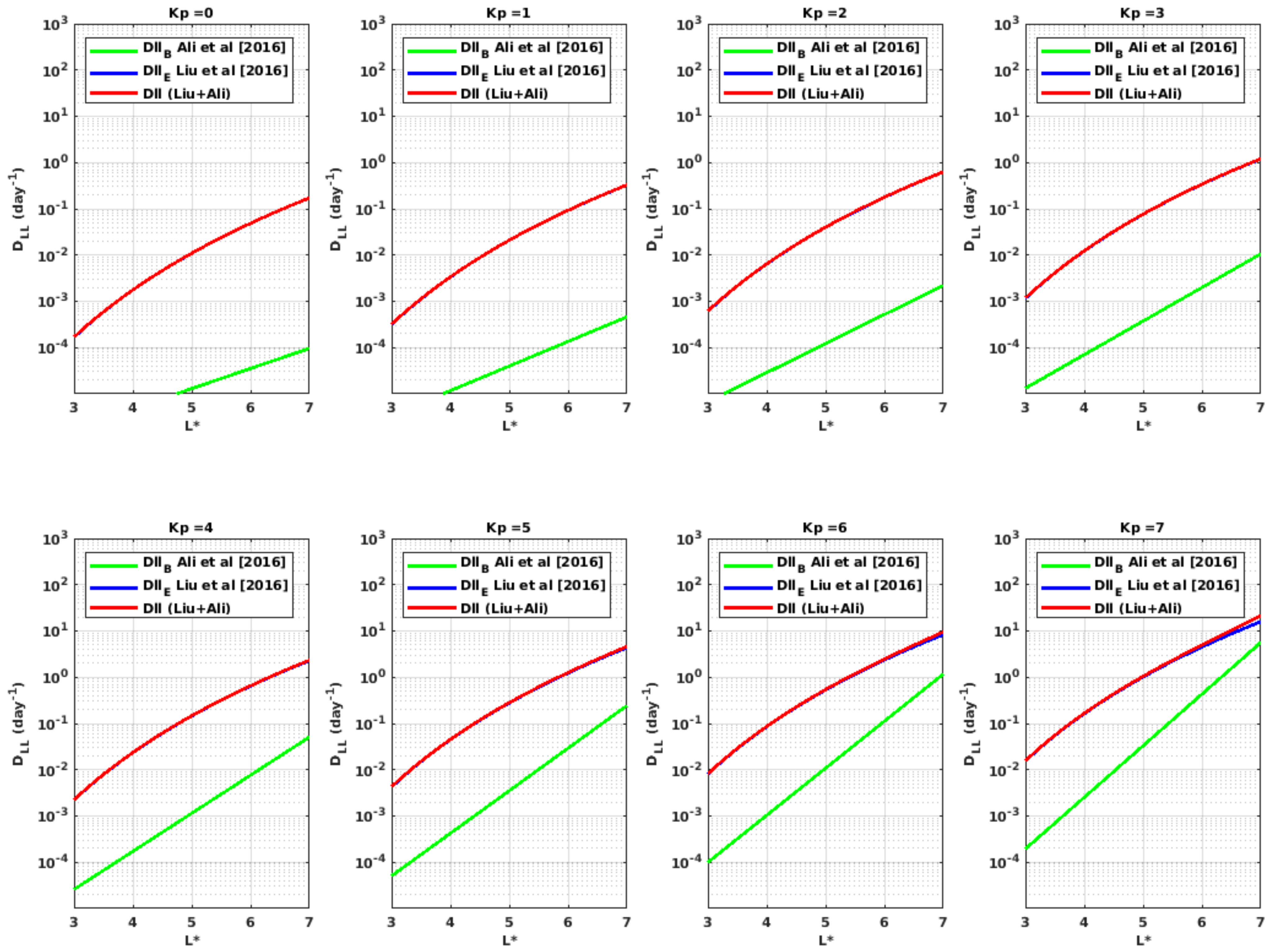
Kp and Dst



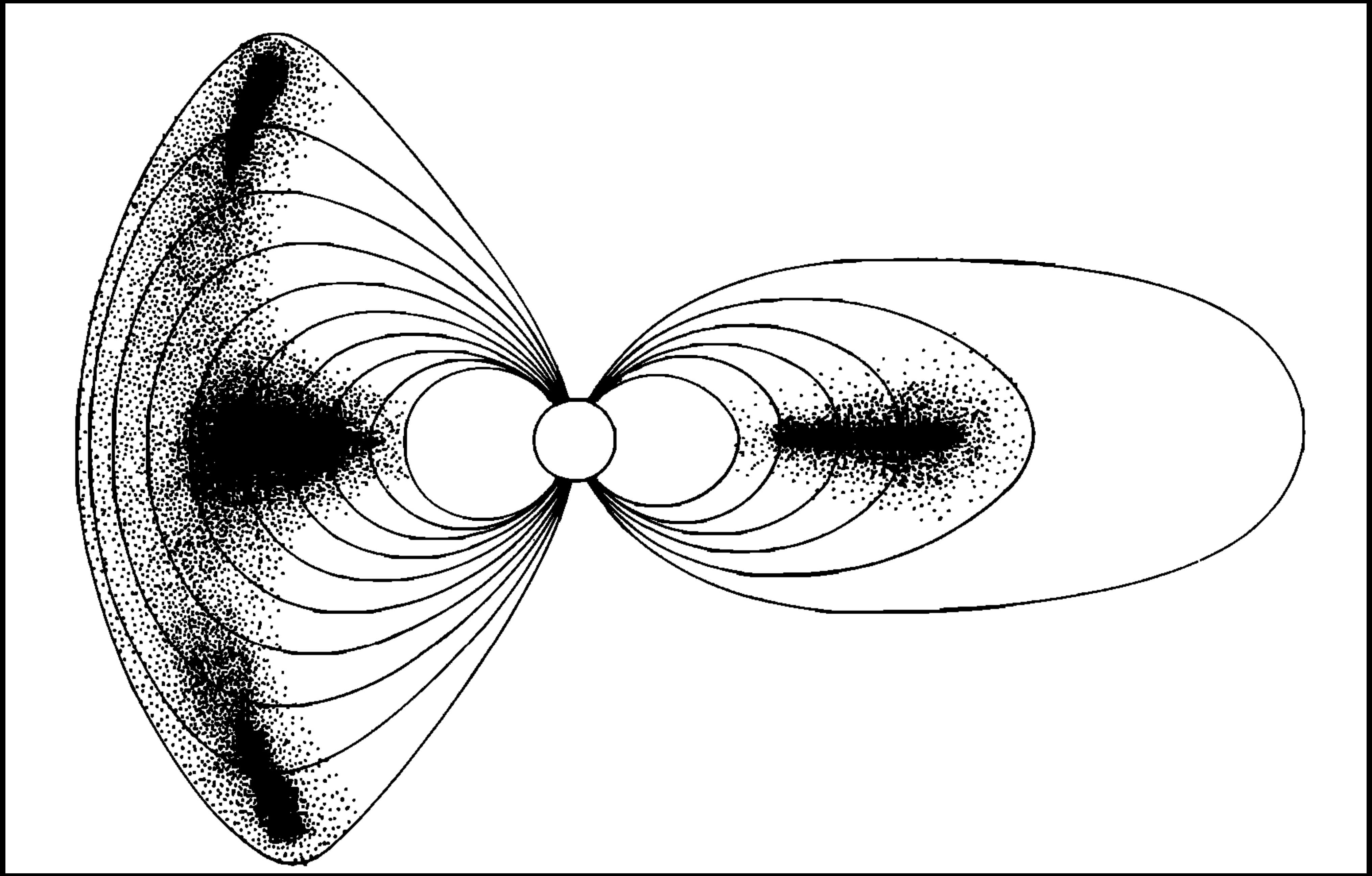
[*Wang et al*, 2020]



Different Radial Diffusion Coefficients at 16:00 on March 17, 2013
D_{LL}^{E} Ozeke Event
D_{LL}^{E} Ozeke Event * 10
B&A [2000]
Ozeke et al [2014]
Ali et al [2016]
Liu et al [2016]
Radial Diffusion Coefficients (days^{-1})
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
4
4.5
5
5.5
6
6.5
7
L



Kp =0
Kp =1
Kp =2
Kp =3
Kp =4
Kp =5
Kp =6
Kp =7
Dll_B Ali et al [2016]
Dll_E Liu et al [2016]
Dll (Liu+Ali)
D_LL (day^-1)
L*



[Tsurutani and Smith, 1977]