Title: **Overview, Progress and Next Steps of the G3 Cluster (near-Earth Space Radiation and Plasma Environment)**

Contributing authors:

Yihua Zheng, Weichao Tu, Yoshizumi Miyoshi, Yuri Shprits….

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1. Introduction

The G3 Cluster under the COSPAR/ISWAT (International Space Weather Action Teams) initiative (https://www.iswat-cospar.org/g3) mainly refers to the near-Earth radiation and plasma environment. The goal of the Cluster is to perform impact-driven model assessment; to advance science understanding and modeling capability of the region; to stay connected with other relevant clusters' progress and seek collaborative inter-cluster efforts; and to help end users with better tools and products.

The near-earth radiation and plasma environment consist of diverse particle populations of different origins that often evolve dynamically over time and space, and span across a broad energy range. Such an environment poses challenges from both science and space weather-impact perspectives. It brings about deleterious effects on spacecraft electronics and/or life in space.

Figure 1 summarizes the main space weather impacts and their environmental sources for the G3 Cluster. Ring current, aurora and plasma sheet particles can be potential space environmental sources for surface charging (e.g., Ganushkina, Jaynes, and Liemohn, 2017). Electrons greater than 100 keV and up to several MeV (mainly from radiation belt electrons) are responsible for internal charging. Strict energy limit for surface charging and internal charging can be ambiguous as the effects are highly dependent on the materials. GCR (Galactic Cosmic Rays) particles (hundreds of MeV to many GeVs in energy) originating outside our solar system and from supernova explosions and SEPs (Solar Energetic Particles) from solar eruptive events (with energies in the range of a few keV up to several GeV) can find their way into the near-Earth region depending on their energy and the strength/variations of fields they propagate through. South Atlantic Anomaly (SAA) region is another source for high-energy trapped protons/ions. GCRs, SEPs and SAA trapped protons constitute three major sources for radiation hazards in terms of single-event effects on space hardware, avionics and radiation dose effects on human activties in space and at aviation altitudes. Energetic electrons (>100 keV), protons (>1 MeV), heavy ions and neutrons can lead to total dose effects over time.

Due to the complexities of this cluster G3, the diverse populations of particles involved, and its rich and far-reaching space weather impacts, this review reflects the limited yet unique views of this important region of space, focusing on recent progress, gaps in research and applications, and our recommendations on priorities for the next 5-10 years by taking heed of both science and space weather operations needs.

2. Current Understanding of the Near-Earth Environment and the Modeling Status

- Knowledge of the near-Earth Space radiation and plasma environment
    - Different plasma populations and their system connections to different S and H clusters
        - Ring current and aurora
        - Radiation belts

      What we know about ring current (cite review papers

      Different species behaviors

      External solar wind drivers

Behaviors of different phases of a storm

Quiet times

O+ difference during CIR or CME storms

Seed population of plasma sheet

Tail connections

Adjacent neighhood connections

Energy dependent two different proton population (Gkioulidou et al, 2016)

Convective <=80 keV protons

Diffusive >100 keV protons

Nonadiabatic process, cross-scale energy transfer

Radiation belt

Energy dependent physics (penetration into inner region) xinlin Li, Baker et

Limiting flux also energy dependent (Man Hua et al)

Substorm: maximum fluxes strongly correlate to cumulative effects of substorms instead of storms, with the strongest dependence on the time-integrated AL

Impenerable barrier Baker 2014

Storage ring (three-belt structure of ultrarelativistic electrons) sub-MeV too (Hao et al., 2020)

ultrarelativistic electrons

energy -depdent acceleration, different acceleration mechanisms at play during different stages

Fast precipitation (Zhang Xiajia)

Energy dependent precipitation

Wave - particle interactions (progress)

Loss /magnetopause, loss to the atmosphere, etc.

Better diffusion due to better wave characterization

Machine learning progress (models, boundary conditions,

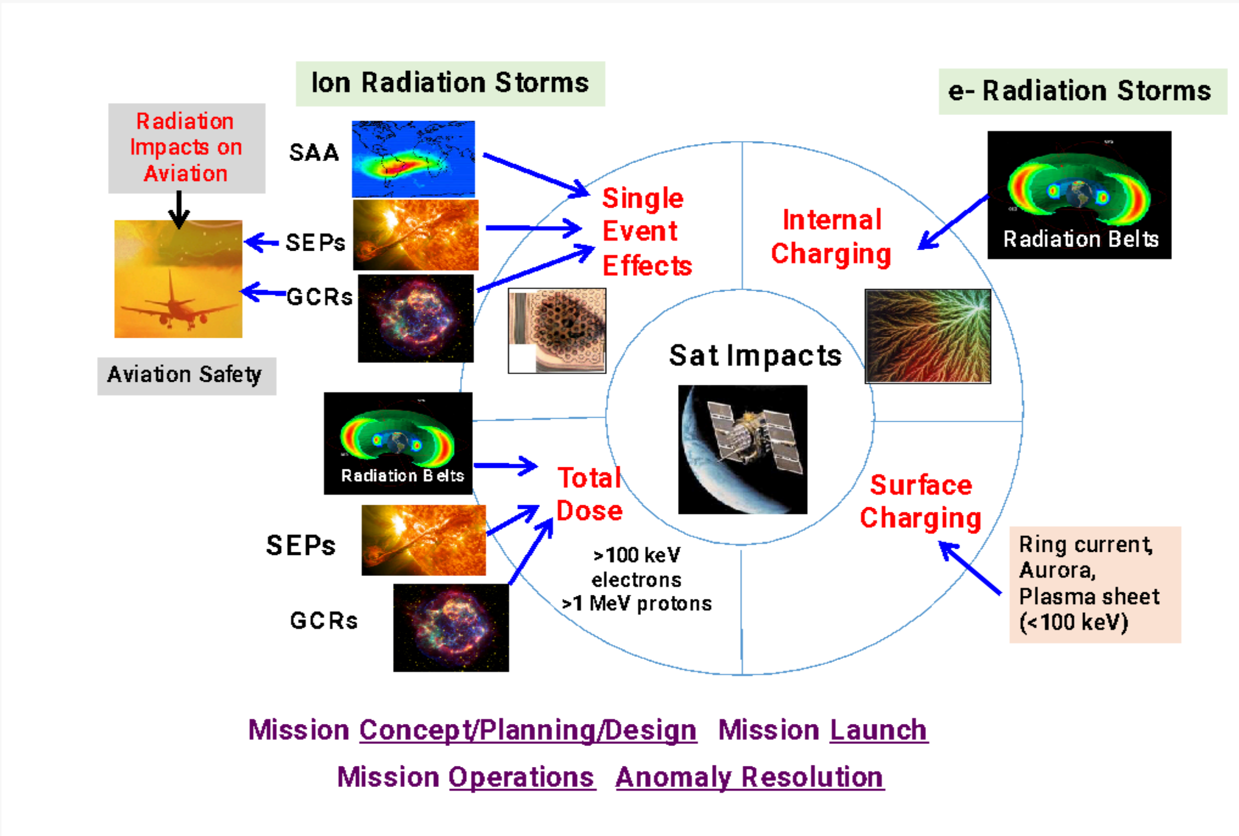
Gap

Nonlinear wave-particle interactions (e.g., large amplitude waves)

Time domain structures, alfven waves,

- SEPs in the magnetosphere

the natural upper limit of the electron acceleration is driven by chorus waves (Man Hua



- Gaps
    - Cold plasma population – not well measured & understood, important for ring current and radiation belt particle dynamics, critical element for surface charging
    - Ring current particles
        - tail/plasma sheet connections (seed population)
        - Wave effects
    - Radiation belt electrons
        - tail/plasma sheet connections (seed population)
        - Nonlinear wave-particle interactions

        - Rapid variations (different temporal scales) of radiation belt electron dynamics
            - Around shock impingement, dynamic tail reconfiguration (for both ring current and radiation belt populations

              Ref: Zong (2022), Zong, Yue, Fu (2021), Yue et al (2017)
    - SEPs in the near-Earth region
        - Limited observations
        - Not well-characterized
        - Access to the region depends on geomagnetic activities/magnetic field (rigidity cutoff)

These gaps also form the basis for our recommendations (more on the science advances aspect).

- Overview of current models
    - Ring current/auroral energies (current capability and gaps)
        - Note: Reference to G1 paper's chapter on auroral precipitation
    - Radiation belt electron environment (current capability and gaps)
    - SEP models in the inner magnetosphere (..)
        - Including rigidity cutoff models
        - SPAM (Janet Green et al's model)
        - others

- Models of assessing radiation exposures at aviation altitudes

- Multi-purpose model validation efforts

Impacts	Effect Metric	Science Predictands	Time Period (Space Weather)
Surface Charging	>10 keV e- flux	>10 keV e- flux; Te; Ne	seconds
Internal Charging	>100 fA/cm^2 [100 mils]	1 MeV and > 2 MeV e- flux	24-hour, 72hr averaged
Single Event Effects	SEE rate [100 mils]	>30 MeV p+ flux; >15 MeV.cm^2.mg^{-1} LET flux	5-min, daily, weekly (worst)
Total Dose	Dose in Silicon[100 mils; 4 mils]	30-50 MeV p+ flux; >1.5 MeV e- flux 1-10 MeV p+	Daily, weekly, yearly
Aviation	Dose rate in aircraft (D-index)	2 spectral parameters (power law with rigidity)	5-min, Hourly

- Internal charging
- Surface charging
- Radiation Effects at Aviation Altitudes

Space Weather Effects Models: current status and needs

- Surface charging – Joe Minow leads a review paper
- Internal charging - Wousik Kim leads a review paper
- Total dose
- Effects of SEPs
- Radiation Effects at Aviation Altitudes

Space Weather Operational Needs

- Data assimilative capabilities
- Observational needs

Recommendations for the next 5 years

Internal charging

- Observations:
    - Needs to have SCATHA like missions of to measure charging directly (space weather impacts on space hardware)
    - Global coverage of 300 keV – 10 MeV electron flux with on-orbit sensor data, to close gaps in MEO and for HEO. data buys from commercial satellites (e.g., GPS)

    - Connecting LEO and GTO - including LEO radiation data for belt specification (Weichao suggested a modeling challenge can be done using the LEO measurements as model constraints instead of GEO)
- Modeling
    - More User-oriented Model validation (participation of different types of models and newly developed models) and identify modeling inadequacy -> improvement; scoreboard of models relevant to internal charging
    - Modeling the space environment relevant to internal charging from a system perspective (including the solar source/drivers..)
- End users (e.g., satellite operators)' feedback on the desired model capabilities

Surface charging

- More User-oriented Model validation (participation of different types of models and newly developed models) à identify modeling inadequacy -> improvement
- Modeling the space environment relevant to surface charging from a system perspective
- End users (e.g., satellite operators)' feedback on the desired model capabilities
- Cold plasma population
- Daylight charging and its signature
- Develop realtime charging indicator for users
- Lack of consensus across industry whether surface charging is an issue for LEO assets
- Surface charging for cislunar (model, data, both needs improvements)
- Organizing Surface Charging Benchmarking Challenge II: Validation of Surface Charging Models (e.g., SPIS, NASCAP, CPIC, ...)

Radiation Effects at Aviation Altitudes

- Developing a strategy for continuous measurements and identifying the regions that need those measurements. Including measurements for improving model inputs (energy spectra) and for model validation
- More measurements on multi-platforms (balloon, airplanes, ISS, etc), especially during SEP events
  - Characterizing radiation measuring instruments
  - Defining standards of radiation monitoring at aviation altitudes.
- Characterizing radiation weather from the surface to space, of which the aviation environment is but one part. Assimilation of data into models is the tried-and-true method for doing this in the tropospheric weather, ionosphere, neutral atmosphere communities and for radiation community is the same. Ensemble modeling is also good for helping define the uncertainties in the system and is the other part of the task.
- End users' feedback on the desired model capabilities
- More model validation (important)
  - ICAO space weather advisory centers use different aviation radiation effects models and they don't agree with each other
- Products need to be impact based, not intensity based such as S3 scales, easy to use, consistent color schemes for the same type of products

Specification of SEPs in the Magnetosphere

- Develop a unified SEP model/or well-validated model(s) for the magnetosphere (currently a gap)
- Modeling the space environment relevant to SEPs in geospace from a system perspective, scientists working on SEPs in solar & heliospheric physics domain should work together with scientists (far fewer) working in the magnetospheric domain
- End users (e.g., satellite operators)' feedback on the desired model capabilities
- Observations at different altitudes/longitudes are important to see transportation of SEP.

- Ground-based observations about SEP including GLE at different latitudes are essential to monitor SEP variations.
- Model validation is critically needed

General points/Common needs:

- Data assimilative capabilities for modeling all space environments (internal charging, surface charging, radiation environment, etc)
- Continuous communications/feedback between model/product developers (including impact analysis tools) and end users
- Develop orbit, region specific tools/products (datasets, models, or hybrid) for users (for example, different LEO orbits, MEO, GEO and fine distinctions)
- Better descriptions and educational materials for end users about different models (capabilities and caveats)
  - How to increase awareness among various user communities (including the general public, stakeholders, policymakers, etc) and train/educate them about the impacts of Space Weather on operational systems and society?
  - Knowledge capture and transfer: how to ensure that what was built up (our heritage/legacy, especially on impact testing, mitigation, prevention) is properly handed over to new generations?
- Central location/depot for all models

Observation needs

1. recommend developing and/or procuring low-cost, low-power consumption, and compact sensor suites and flying them on all future missions in order to measure and quantify space weather impacts, in addition to the main instrumentation
    - Heavy ions - high energies (SEP) for spacecraft anomaly resolution and for aviation safety
    - Low energies, cold plasma
        - Surface charging analysis
    - Need impact measurements (charging, radiation effects, etc) on more modern/recent spacecraft/spacecraft hardware
2. Commercial data buys (for critically need data that can improve current space weather products and capabilities), RFI for data purchase

Better understanding of cislunar plasma/radiation environment and plasma-dust interactions (maybe not)

Applying System science approach, across different clusters and beyond

Take advantage of machine learning for model boundary conditions and stand-alone models

Scoreboard activities for science and application

Data calibration, standarization and archive

Value of OSSE (Observing System Simulation Experiment) for optimizing future measurements and strategy planning

Promoting interdisciplinary and transdisciplinary work and collaboration

An anomaly database - always a challenge and a desired resource

note : Both SPEs and energetic electron precipitation can have a long-lasting impact on the stratospheric composition, particularly, the stratospheric ozone during polar winter; as ozone is one of the key species in radiative heating and cooling of the stratosphere, changes in its concentration induce dynamical changes in the middle atmosphere, which can couple down even into the troposphere and affect regional climate patterns. The impact of SPEs and aurorae on atmospheric composition is well constrained by observations and reasonably well reproduced by model studies. The impact of relativistic electrons from the radiation belts on the mesosphere above ≈70 km is now also well established from observations; however, a direct impact of relativistic electrons on stratospheric composition is still a matter of debate. More specific information on the different sources of particle precipitation and their variability as well as their treatment in state-of-the art climate models can be found in reviews by, for example, Sinnhuber et al. (2012), Mironova et al. (2015), and Matthes et al. (2017).

Users involved

- Satellite (design, launch, operations, anomaly resolution)
- Aviation
- Emergency Management(radiation impacts on HF communication in the polar cap)
- Human exploration

Acknowledgement

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References

[Space Environment Engineering and Science Applications Workshop Roadmaps](https://cpaess.ucar.edu/sites/default/files/2022-06/atr-2019-00431-seesaw-sorkshop-roadmaps.pdf)

https://cpaess.ucar.edu/sites/default/files/2022-06/atr-2019-00431-seesaw-sorkshop-roadmaps.pdf

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G3 papers I know of

Tier 1:

- **Jordanova et al.**, The RAM-SCB model and its applications to advance space weather forecasting
- **V. Kalegaev** et al. , Medium-term prediction of the fluence of relativistic electrons in geostationary orbit using solar wind streams forecast based on solar observations" (AISR-D-22-00161R2)
- **Merenda et al.,** Spacecraft Charging with EMA3D Charge, submitted to ASR and review in progress.

Tier 2:

- **Alex Boyd et al.**, Environment specification accuracy requirements for anomaly resolution in various orbits
- **Wousik Kim et al**., Lightening in Spacecraft: A Review of Internal Charging — Environment, Effect, Prevention, and Mitigation
- **Minow et al.**, Surface Charging overview
- **Zheng et al.,** Overview, Progress and Next Steps of the G3 Cluster (near-Earth Space Radiation and Plasma Environment)

Accepted Tier 1 papers

JASR 16216

AISR-D-22-00318

The RAM-SCB model and its applications to advance space weather forecasting

V.K. Jordanova, S.K. Morley, M.A. Engel, H.C. Godinez, K. Yakymenko, M.G. Henderson, Y. Yu, Y. Miyoshi

JASR 16206

AISR-D-22-00177

A statistical relationship between the fluence of magnetospheric relativistic electrons and interplanetary and geomagnetic characteristics

O.N. Kryakunova, A.V. Belov, A.F. Yakovets, A.A. Abunin, I.L. Tsepakina, B.B. Seifullina, M.A. Abunina, N.F. Nikolayevskiy, N.S. Shlyk

JASR 16172

AISR-D-22-00161

Medium-term prediction of the fluence of relativistic electrons in geostationary orbit using solar wind streams forecast based on solar observations

V. Kalegaev, K. Kaportseva, I. Myagkova, Yu. Shugay, N. Vlasova, W. Barinova, S. Dolenko, V. Eremeev, A. Shiryaev

JASR 15917

AISR-D-21-00738

The DIARieS Ecosystem: A software ecosystem to simplify Discovery, Implementation, Analysis, Reproducibility, and Sharing of scientific results and environments in Heliophysics.

Rebecca Ringuette, Alec Engell, Oliver Gerland, Ryan M. McGranaghan, Barbara Thompson

R. Ringuette, A. Engell, O. Gerland et al., The DIARieS ecosystem – A software ecosystem to simplify discovery, implementation, analysis, reproducibility, and sharing of scientific results and environments in Heliophysics, Advances in Space Research, https://doi.org/10.1016/j.asr.2022.05.012

JASR 15931

AISR-D-22-00163

Unifying the Validation of Ambient Solar Wind Models

Martin A. Reiss, Karin Muglach, Richard Mullinix, Maria M. Kuznetsova, Chiu Wiegand, Manuela Temmer, Charles N. Arge, Sergio Dasso, Shing F. Fung, José.Juan González-Avilés, Siegfried Gonzi, Lan Jian, Peter MacNeice, Christian Möstl, Mathew Owens, Barbara Perri, Rui F. Pinto, Lutz Rastätter, Pete Riley, Evangelia Samara

M. A. Reiss, K. Muglach, R. Mullinix et al., Unifying the validation of ambient solar wind models, Advances in Space Research, https://doi.org/10.1016/j.asr.2022.05.026

JASR 16144

AISR-D-22-00456

Review of Solar Energetic Particle Models

Kathryn Whitman, et al

References

Baker, D. N., Kanekal, S. G., Hoxie, V. C., Henderson, M. G., Li, X., Spence, H. E., Elkington, S. R., Friedel, R. H. W., Goldstein, J., Hudson, M. K., Reeves, G. D., Thorne, R. M., Kletzing, C. A., & Claudepierre, S. G. (2013). A long-lived relativistic electron storage ring embedded in Earth's outer Van Allen belt. *Science*, 340(6129), 186–190.

Baker, D.N., Erickson, P.J., Fennell, J.F. et al. Space Weather Effects in the Earth's Radiation Belts. Space Sci Rev 214, 17 (2018). https://doi.org/10.1007/s11214-017-0452-7

Boyd, A., T. P. O'Brien, J. Cox, B. Larsen, Environment specification accuracy requirements for anomaly resolution in various orbits, Advances in Space Research, submitted.

Camporeale, E. (2019). The challenge of machine learning in Space Weather: Nowcasting and forecasting. Space Weather, 17, 1166–1207. https://doi. org/10.1029/2018SW002061

Ebihara, Y., Watari, S. & Kumar, S. Prediction of geomagnetically induced currents (GICs) flowing in Japanese power grid for Carrington-class magnetic storms. Earth Planets Space 73, 163 (2021). https://doi.org/10.1186/s40623-021-01493-2.

Ganushkina, N., Jaynes, A. & Liemohn, M. Space Weather Effects Produced by the Ring Current Particles. Space Sci Rev 212, 1315–1344 (2017). https://doi.org/10.1007/s11214-017-0412-2

Guo, J., et al., Particle Radiation Environment in Heliosphere: Status, limitations and recommendations, to be submitted to ASR (Advances in Space Research).

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

Delzanno, Gian Luca, Joseph E. Borovsky, Michael G. Henderson, Pedro Alberto Resendiz Lira, Vadim Roytershteyn, Daniel T. Welling (2021), The impact of cold electrons and cold ions in magnetospheric physics, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 220, 105599, https://doi.org/10.1016/j.jastp.2021.105599.

Hao, Y. X., Zong, Q.-G., Zhou, X.-Z., Zou, H., Rankin, R., Sun, Y. X., et al. (2020). A Short-lived three-belt structure for sub-MeV electrons in the Van Allen belts: Time scale and energy dependence. Journal of Geophysical Research: Space Physics, 125, e2020JA028031. https://doi.org/10.1029/2020JA028031

Man Hua, Jacob Bortnik, Qianli Ma, Upper Limit of Outer Radiation Belt Electron Acceleration Driven by Whistler-Mode Chorus Waves, Geophysical Research Letters, 10.1029/2022GL099618, 49, 15, (2022).

Man Hua, Jacob Bortnik, Xiangning Chu, Homayon Aryan, Qianli Ma, Unraveling the Critical Geomagnetic Conditions Controlling the Upper Limit of Electron Fluxes in the Earth's Outer Radiation Belt, Geophysical Research Letters, 10.1029/2022GL101096, 49, 22, (2022).

Ilie, R., Bashir, M.F. and Kronberg, E.A. (2021). A Brief Review of the Ring Current and Outstanding Problems. In Magnetospheres in the Solar System (eds R. Maggiolo, N. André, H. Hasegawa, D.T. Welling, Y. Zhang and L.J. Paxton). https://doi.org/10.1002/9781119815624.ch20

Jaynes, A. N., et al. (2015), Source and seed populations for relativistic electrons: Their roles in radiation belt changes, *J. Geophys. Res. Space Physics*, 120, 7240– 7254, doi:10.1002/2015JA021234.

Shrikanth Kanekal, Yoshizumi Miyoshi, Dynamics of the terrestrial radiation belts: a review of recent results during the VarSITI (Variability of the Sun and Its Terrestrial Impact) era, 2014–2018, Progress in Earth and Planetary Science, 10.1186/s40645-021-00413-y, 8, 1, (2021).

Li, W., and Hudson, M. K. (2019). Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era. *J. Geophys. Res. Space Phys.* 124, 8319–8351. :10.1029/2018JA0doi25940

Maliniemi, V., Arsenovic, P., Seppälä, A., and Nesse Tyssøy, H.: The influence of energetic particle precipitation on Antarctic stratospheric chlorine and ozone over the 20th century, Atmos. Chem. Phys., 22, 8137–8149, https://doi.org/10.5194/acp-22-8137-2022, 2022.

Meredith, N. P., Horne, R. B., Iles, R. H. A., Thorne, R. M., Heynderickx, D., and Anderson, R. R., Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus, *J. Geophys. Res.*, 107(A7), doi:10.1029/2001JA900146, 2002.

Miyoshi, Y., I. Shinohara, S. Ukhorskiy et al., Collaborative Research Activities of the Arase and Van Allen Probes, Space Sci Rev, 218, 38, doi:10.1007/s11214-022-00885-4, 2022

Morley, S. K. (2020). Challenges and opportunities in magnetospheric space weather prediction. *Space Weather*, 18, e2018SW002108. https://doi.org/10.1029/2018SW002108

Sinnhuber, M., H. Nieder, and N. Wieters (2012), Energetic particle precipitation and the chemistry of the mesosphere/lower thermosphere, Surv. Geophys., 33, 1281–1334, doi:10.1007/s10712-012-9201-3.

Sinnhuber Miriam, Bernd Funke (2020),Chapter 9 - Energetic electron precipitation into the atmosphere, Editor(s): Allison N. Jaynes, Maria E. Usanova, The Dynamic Loss of Earth's Radiation Belts, Elsevier,2020, Pages 279-321, ISBN 9780128133712, https://doi.org/10.1016/B978-0-12-813371-2.00009-3.

Tozzi, R., De Michelis, P., Coco, I., & Giannattasio, F. (2019). A preliminary risk assessment of geomagnetically induced currents over the Italian territory. Space Weather, 17, 46– 58. https://doi.org/10.1029/2018SW002065

Ripoll, J.-F., Claudepierre, S. G., Ukhorskiy, A. Y., Colpitts, C., Li, X., Fennell, J., & Crabtree, C. (2020). Particle Dynamics in the Earth's Radiation Belts: Review of Current Research and Open Questions. Journal of Geophysical Research: Space Physics, 125, e2019JA026735. https://doi.org/10.1029/2019JA026735

Shprits, Y., Kellerman, A., Kondarashov, D., & Subbotin, D. (2013). Application of a new data operator-splitting data assimilation technique to the 3-D VERB diffusion code and CRRES measurements. *Geophysical Research Letters*, 40, 4998– 5002. https://doi.org/10.1002/grl.50969

Shprits, Y. Y., Allison, H. J., Wang, D., Drozdov, A., Szabo-Roberts, M., Zhelavskaya, I., & Vasile, R. (2022). A new population of ultra-relativistic electrons in the outer radiation zone. *Journal of Geophysical Research: Space Physics*, 127, e2021JA030214. https://doi.org/10.1029/2021JA030214

Temmer, M., et al., CME Propagation Through Ambient Solar Wind - Observations and Model Development

Temmer, Living Reviews in Solar Physics (2021) 18:4 https://doi.org/10.1007/s41116-021-00030-3(012345678

Tu, W., Li, W., Albert, J. M., & Morley, S. K. (2019). Quantitative assessment of radiation belt modeling. Journal of Geophysical Research: Space Physics, 124, 898–904. https://doi.org/10.1029/2018JA026414

Whitman, K., et al, Review of Solar Energetic Particle Models, Advances in Space Research (2022), doi: https://doi.org/10.1016/j.asr.2022.08.006

Yu, Y., Liemohn, M. W., Jordanova, V. K., Lemon, C., & Zhang, J. (2019). Recent advancements and remaining challenges associated with inner magnetosphere cross-energy/population interactions (IMCEPI). Journal of Geophysical Research: Space Physics, 124, 886– 897. https://doi.org/10.1029/2018JA026282

Yue, Chao, Lunjin Chen, Jacob Bortnik, Qianli Ma, Richard M. Thorne, Vassilis Angelopoulos, Jinxing Li, Xin An, Chen Zhou, Craig Kletzing, Geoffrey D. Reeves, Harlan E. Spence, The Characteristic Response of Whistler Mode Waves to Interplanetary Shocks, Journal of Geophysical Research: Space Physics, 10.1002/2017JA024574, 122, 10, (10,047-10,057), (2017).

Zhao, H., Li, X., Baker, D. N., Claudepierre, S. G., Fennell, J. F., Blake, J. B., Larsen, B. A., Skoug, R. M., Funsten, H. O., Friedel, R. H. W., et al. (2016), Ring current electron dynamics during geomagnetic storms based on the Van Allen Probes measurements, J. Geophys. Res. Space Physics, 121, 3333– 3346, doi:10.1002/2016JA022358.

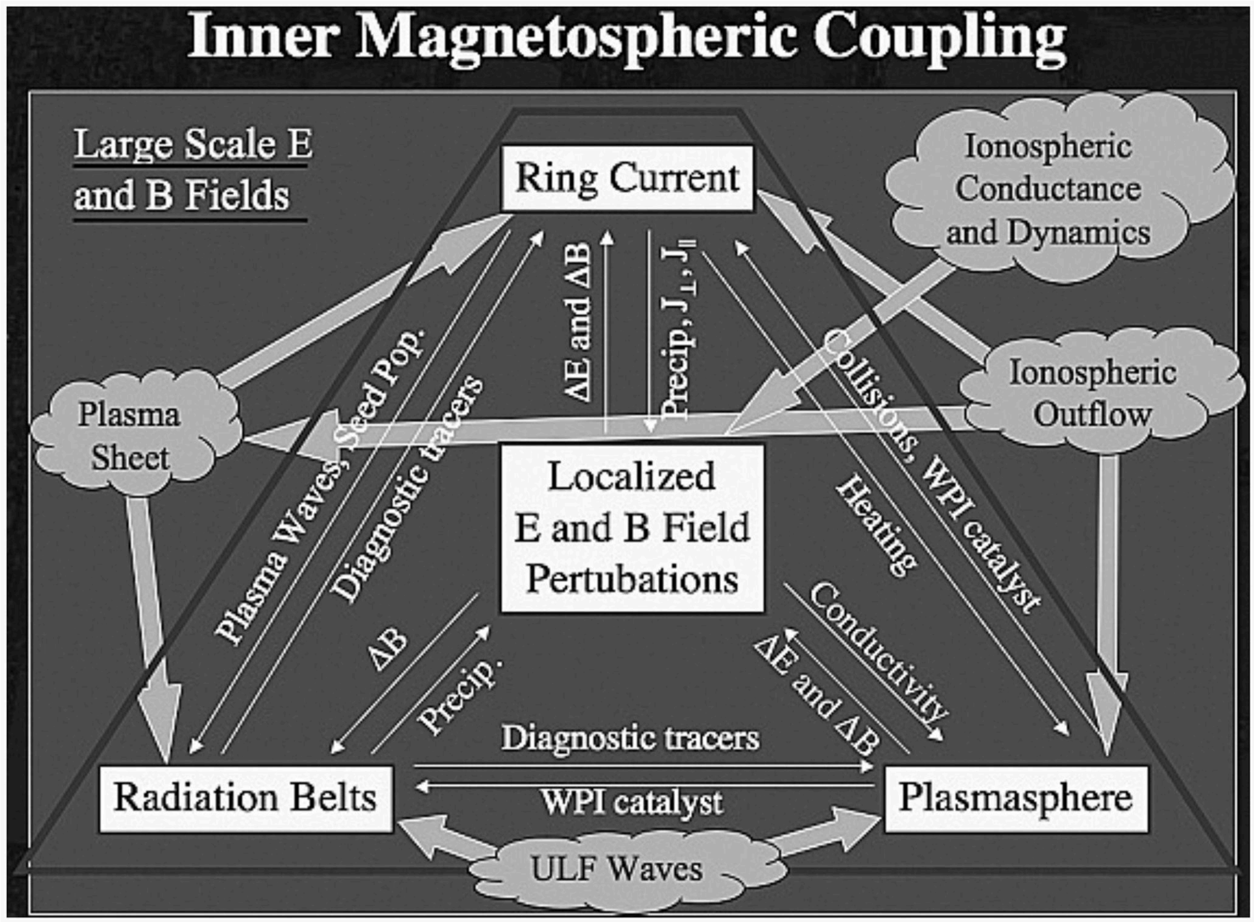
Zhao, H., Baker, D. N., Li, X., Malaspina, D. M., Jaynes, A. N., and Kanekal, S. G. (2019). On the acceleration mechanism of ultrarelativistic electrons in the center of the outer radiation belt: A statistical study. J. Geophys. Res. Space Phys. 124, 8590–8599. doi:10.1029/2019JA027111

Zheng, Y., Ganushkina, N. Y., Jiggens, P., Jun, I., Meier, M., Minow, J. I., et al. (2019). Space radiation and plasma effects on satellites and aviation: Quantities and metrics for tracking performance of space weather environment models. Space Weather, 17, 1384– 1403. https://doi.org/10.1029/2018SW002042

Zhou, R., Ni, B., Fu, S., Teng, S., Tao, X., Hu, Z., et al. (2022). Global distribution of concurrent EMIC waves and magnetosonic waves: A survey of Van Allen Probes observations. *Journal of Geophysical Research: Space Physics*, 127, e2021JA030093. https://doi.org/10.1029/2021JA030093

Zong, Q-G., C. Yue, S.-Y. Fu, Shock Induced Strong Substorms and Super Substorms: Preconditions and Associated Oxygen Ion Dynamics, Space Science Reviews, 10.1007/s11214-021-00806-x, 217, 2, (2021).

Zong, Q-G., Magnetospheric response to solar wind forcing: ultra-low-frequency wave–particle interaction perspective, Ann. Geophys., 40, 121–150, https://doi.org/10.5194/angeo-40-121-2022, 2022.



Yu et al 2019 review paper

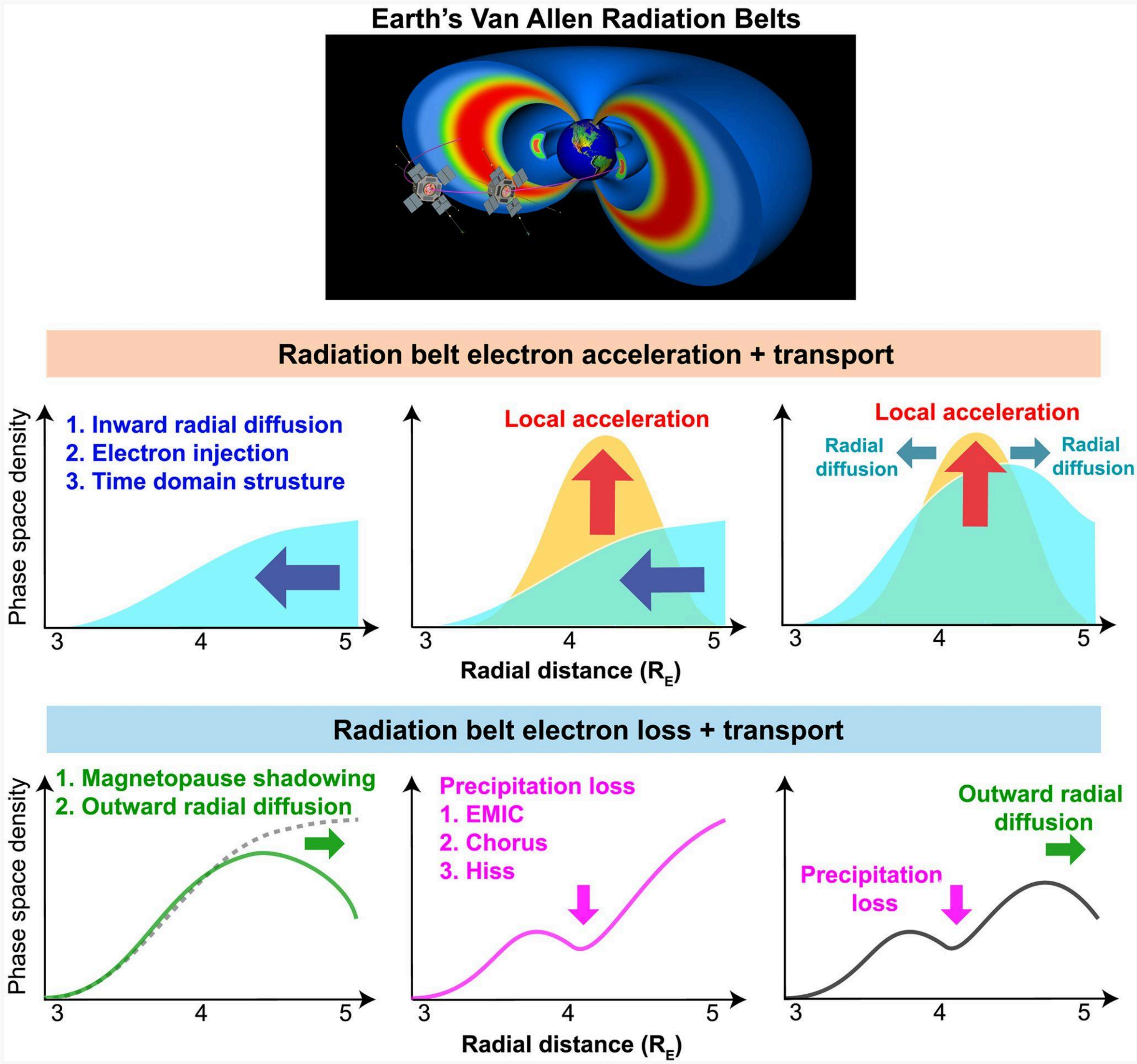
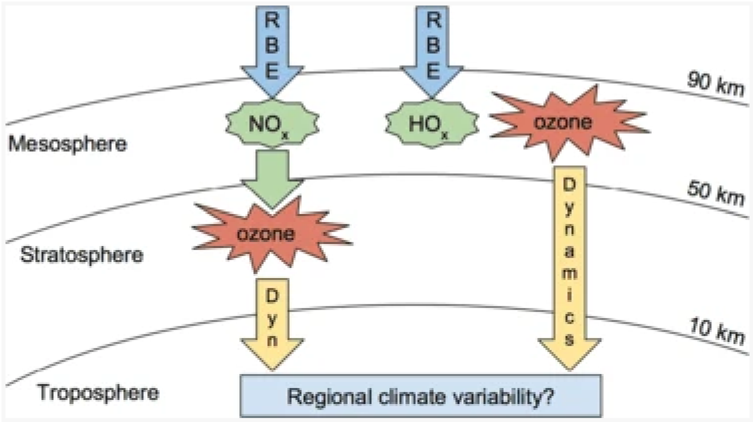
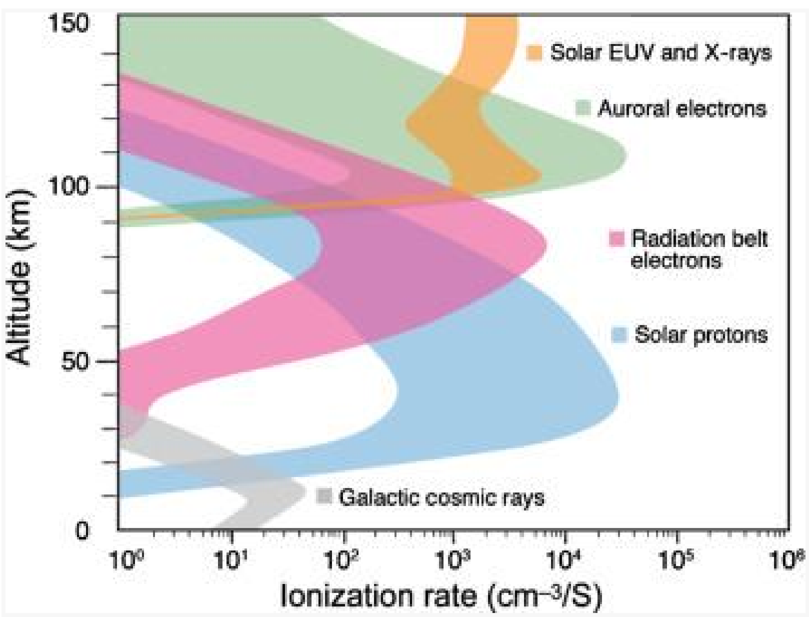


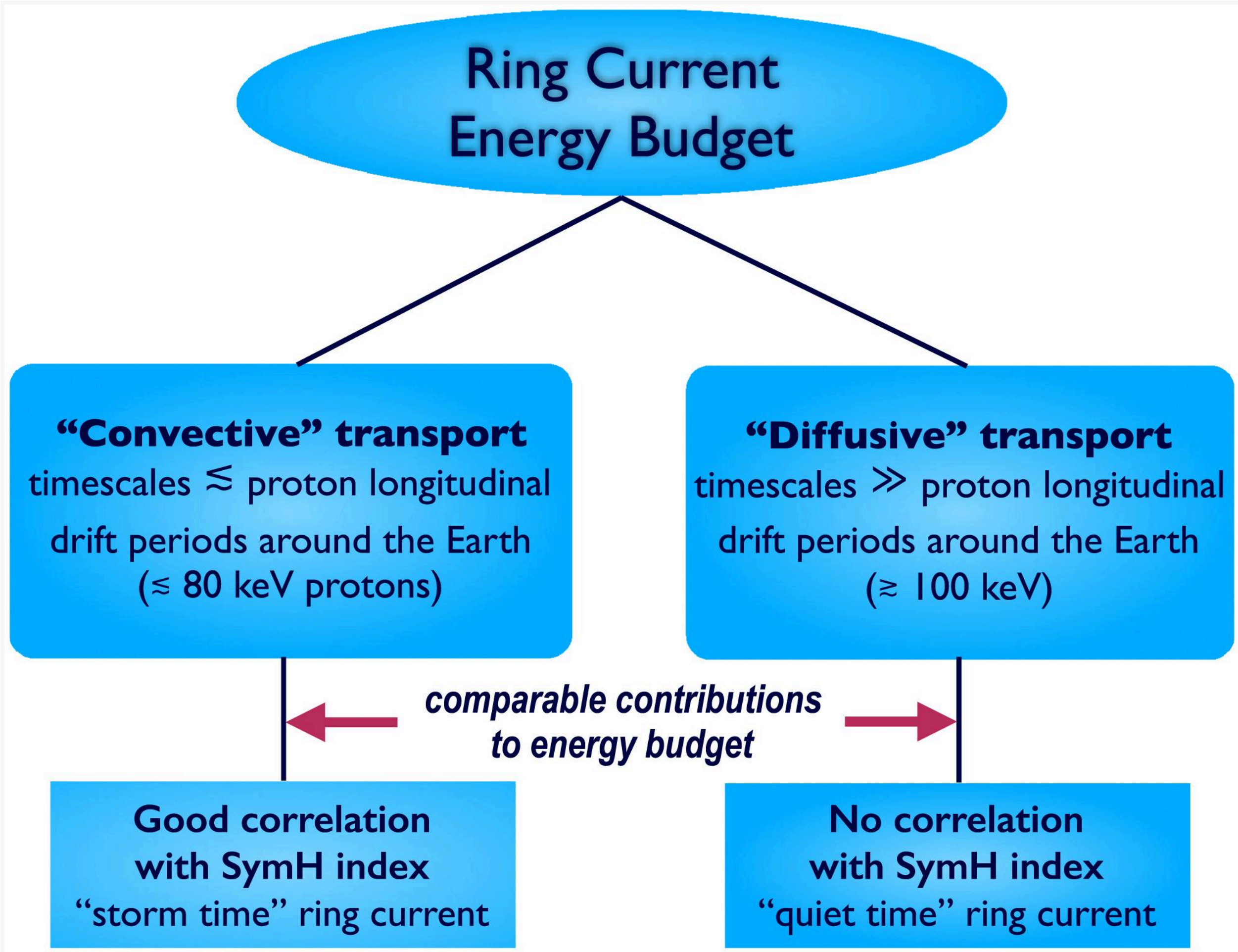
Figure 16 in Li and Hudson 2019



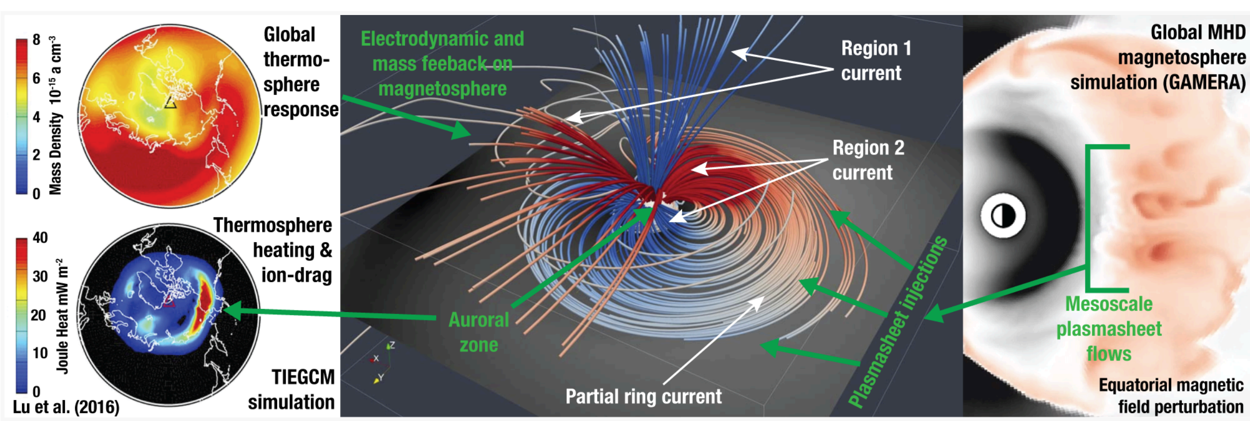
Baker et al 2018 review paper



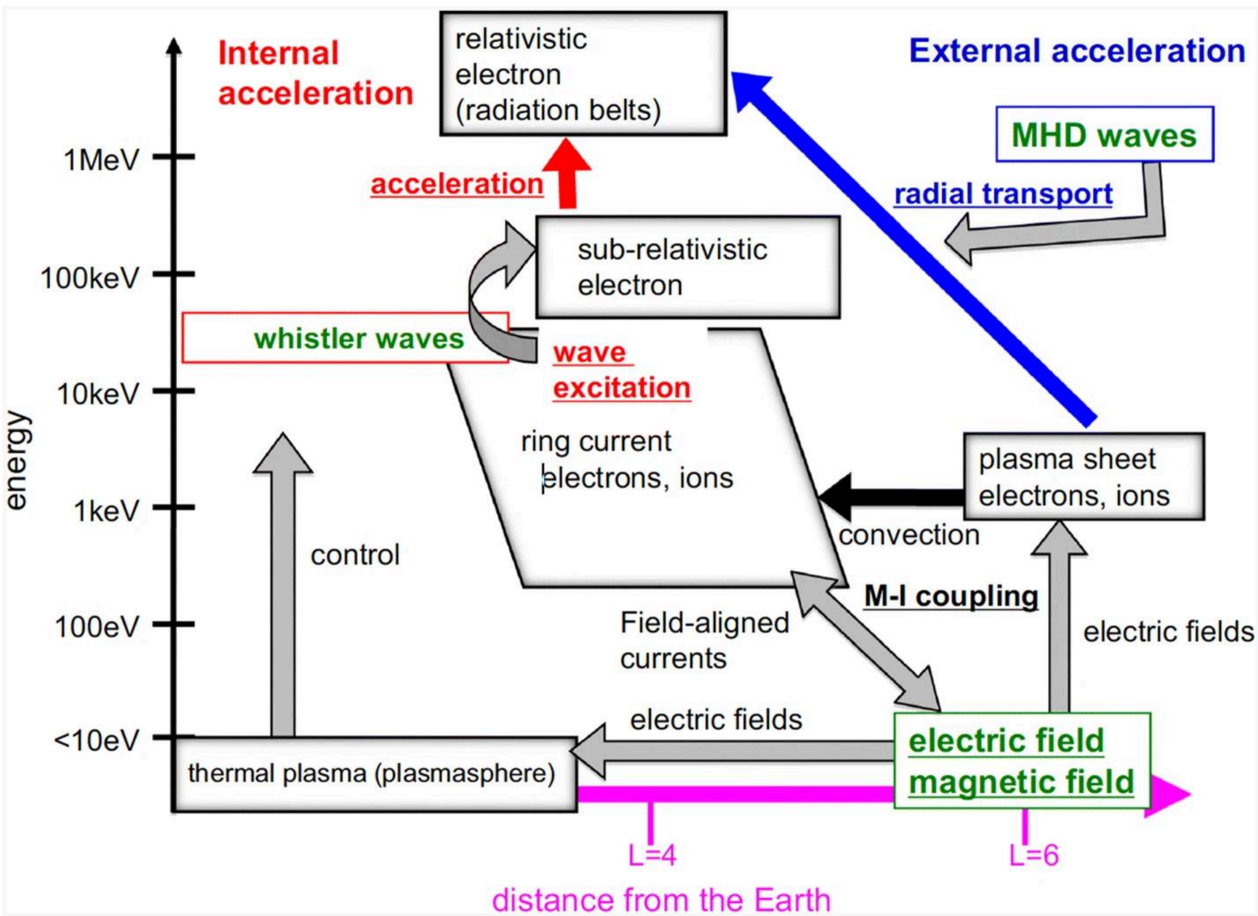
Sinnhuber, Miriam & Bernd Funke (2020)



Ring Current Energy Budget
"Convective" transport
timescales ≲ proton longitudinal drift periods around the Earth
(≲ 80 keV protons)
"Diffusive" transport
timescales ≫ proton longitudinal drift periods around the Earth
(≳ 100 keV)
comparable contributions to energy budget
Good correlation with SymH index
"storm time" ring current
No correlation with SymH index
"quiet time" ring current



Mass Density 10^-15 a cm^-3
8
6
4
2
0
Global thermo-sphere response
Joule Heat mW m^-2
40
30
20
10
0
Thermosphere heating & ion-drag
TIEGCM simulation
Lu et al. (2016)
Electrodynamic and mass feeback on magnetosphere
Region 1 current
Region 2 current
Auroral zone
Partial ring current
Plasmasheet injections
Global MHD magnetosphere simulation (GAMERA)
Mesoscale plasmasheet flows
Equatorial magnetic field perturbation



Internal acceleration
relativistic electron (radiation belts)
External acceleration
MHD waves
radial transport
1MeV
acceleration
sub-relativistic electron
100keV
whistler waves
wave excitation
10keV
energy
ring current electrons, ions
plasma sheet electrons, ions
1keV
control
convection
M-I coupling
100eV
Field-aligned currents
electric fields
<10eV
electric fields
electric field
magnetic field
thermal plasma (plasmasphere)
L=4
L=6
distance from the Earth