Understanding and Quantifying Multi-Scale Poynting Flux and Its Fate in the Coupled Magnetosphere-Ionosphere-Thermosphere System

Delores Knipp, Olga Verkhoglyadova, Kristina Lynch and J. Morton

Description of the Current State and Shortcomings. The magnetosphere/solar-wind dynamo is the primary source of the auroral-particle (kinetic) and electromagnetic energy (Poynting vector) available to the high-latitude thermosphere and ionosphere. This energy source, which is roughly estimated to contribute 20-25% of the annual upper atmospheric energy budget, may be responsible for > 60% of the energy input during extreme space weather events (*Knipp et al.*, 2004). Impulsive increases in energy deposition are linked to anomalous increases in satellite drag and inability to track low Earth orbiting (LEO) spacecraft. Although nearly two decades have passed since these model estimates were made, global and regional quantification of the Poynting vector has made only halting and incremental improvement, mostly via simulation. This is largely due to inadequate distribution of field and particle sensors for measuring the field components at the appropriate length and time scales.

In the dynamo process the conversion of solar wind energy into electrical energy strengthens electric fields. The electric fields in turn do work on charged particles and contribute to their redistribution. Highly conducting space plasmas carry currents. These currents generate their own disturbance magnetic fields which superpose to deform Earth's dipole magnetic field. Closure of these currents in Earth's upper atmosphere allows energy to be redistributed and dissipated in the ionosphere-thermosphere (IT) via Joule heating (e.g., Thayer & Semeter, 2004). Thus, electromagnetic energy transfer (the Poynting vector) is a key input for energizing the IT system. The formal terminology for transfer of incident electromagnetic energy flux through a volume is the *Poynting vector*, **S,** which is related to cross product of the electric, **E** and magnetic, **B** fields. A magnetic field in its lowest energy (dipole) state is nondivergent, allowing energy transfer through a volume, but no dissipation in the volume (e.g. Richmond, 2010). Non-potential variations support energy deposition. For practical purposes, then, it is the perturbation of the magnetic field, **δB**, due to field aligned currents (FACs) that is of interest to geospace studies:

$$\mathbf{S_P} = \mu_0^{-1}(\mathbf{E} \times \boldsymbol{\delta}\mathbf{B}) = \mathbf{S}_{||} \text{ (if field-aligned)} \quad \sim \sigma_p E^2 \qquad (1)$$

Most literature refers to the vector quantity, $\mathbf{S_P}$ as Poynting flux and the right-most term as Joule heat (JH) (see, *Richmond*, 2010 and *Aikio et al*., 2012 for the substantial set of assumptions in approximations for the RHS of Eqn. 1). Removal of the 'background' **B** is problematic. If the perturbation is considered as due to quasi-steady (Direct Current-DC) FACs, then the background is geomagnetic field is removed. If **δB** is the result of small-scale rapid (Alternating Current-AC) fluctuations then a local-field average is removed. There is no general agreement about an appropriate demarcation between DC and AC frequencies.

The fate of $\mathbf{S_P}$ transferred from the magnetosphere to the upper atmosphere has been the subject of numerous studies and individual and satellite constellations. Even so, the state of knowledge about the multitude of ways that this energy is manifest and distributed in the upper atmosphere is poorly characterized. With near exponential increases in cubesat launches this century and likely next, this poor state of characterization could be disastrous for satellite collision avoidance efforts (*Berger et al.,* 2020).

The statistical view of $\mathbf{S_P}$ comes from a number of near-Earth satellites: DE-2—early 1980's, Astrid-2—early 2000's, FAST—late 1990's, DMSP—early 2000's to present, Cluster— late 2000's to present, THEMIS— late 2000's to present, and Swarm—present (See *Hartinger et al.,* 2015 for examples). Some of these missions were short-lived and, in several cases, only one component of **E** was

available, so the derived $\mathbf{S_p}$ is an estimate only. Some of these missions provided only AC or DC $\mathbf{S_p}$. In the case of DMSP, the data are assumed to provide DC $\mathbf{S_p}$; however, there may be a mix of frequencies in the results.

Studies from ground-based observations have shed some light on the large-scale fate of the energy deposition. *Aikio et al*. (2012) studied the effect of E-region neutral winds on the energy exchange rates between the magnetosphere and the ionosphere-thermosphere (IT) system using EISCAT incoherent scatter radar measurements over two multi-week intervals. Estimates based on calculated **E**, conductivities and E-region neutral winds in the nightside auroral oval suggested the median EM energy transfer to mechanical work is 20% (at maximum). Presumably the remaining 80% goes to heating of the gas-plasma mixture. Small scale variations and changes during levels of extreme activity remain unknown as is the behavior outside the auroral zone.

For the near-term improved simulations offer some hope of addressing the knowledge deficit. Recently *Rastätter et al.* (2015) compared the *Weimer* (2005) and *Cosgrove* (2014) DC $\mathbf{S_p}$ empirical models as well as output from eight physics-based models, against orbit-integrated DMSP $\mathbf{S_p}$. Their six-event challenge focused on quiet to moderate activity and was run by the NASA Community Coordinated Modeling Center. The physics-based models included 3-D models of the ionosphere/thermosphere and 3-D ionospheric electrodynamics modules of global magnetosphere MHD models. The unsettling results were: Overall, for each model tested there was a significant spread of yields across the six events … a consistent relation between $\mathbf{S_p}$ and model Joule dissipation could not be established because the standard deviations in model outputs were comparable to the average yield. This may not be a fully model problem since satellite-based $\mathbf{S_p}$ estimates are limited by the assumption of no horizontal divergence in Poynting flux.

Another significant issue is the role of AC $\mathbf{S_p}$. *Lotko* (2004), *Lysak* (2004) and *Lysak & Song* (2006) analyzed dynamic processes that occur at meso- and short-scales (including ULF waves) for their contribution to electromagnetic energy budget of the MIT system. In a recent simulation/case study, *Verkhoglyadova et al*. (2018) estimated that Alfven wave energy deposition in the frequency band from 0.5 Hz to several Hertz was 10%- 30% of the value of static Joule heating in localized regions. This AC energy is largely unaccounted for in global models and may influence other aspects of MIT energy coupling. Alfven waves are related to auroral electron acceleration and conductance (*Chaston* et al. 2005), which in turn influences auroral kinetic energy deposition in the high-latitude ionosphere (See *Keiling* 2009 and *Keiling et al.,* 2019 and references therein). Alfvenic waves potentially modify the efficiency of Joule heating by any form of incident energy flux (*Pakhotin et al.,* 2018)

Recently observations during large storms have raised another controversy. *Huang et al*. (2017) reported sporadic intense Poynting fluxes measured by DMSP satellites at polar latitudes and asserted there is a body of evidence in favor of solar wind energy directly entering the polar cap and significantly changing neutral density at very high-latitudes. A study by *Horvath et al.* (2018) reported extreme $\mathbf{S_p}$ during strong northward IMF in the summer hemisphere. *Li et al.* (2011) using the Open Geospace General Circulation Model showed that such extreme Poynting flux is caused by high-latitude reconnection under conditions of large IMF clock angle and large IMF magnitude. There is significant controversy on this issue and on the impact if any of associated local heating and neutral density upheaval (*e.g. Lu et al*., 2016).

Proposed Science Investigations/Methodology/Vision for 2050. NSF Geospace Environment Modelling (GEM) and Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) focus groups are hosting MIT challenge sessions that lay groundwork for future studies of multi-scale Poynting Flux and its fate in the coupled system. Additionally, new knowledge will likely come from proposed NASA and ESA missions. However, the large science missions are typically limited to a few orbit

planes. Investigating EM (and particle) energy deposition and its fate in future decades will need a decidedly more global, vertically-differentiated and simultaneous view from above and below. To forecast and specify the orbital environment for constellations of large and small spacecraft the following should be encouraged:

1. Measure from the ground, conductance, electric field and neutral winds from multiple locations in the polar cap, auroral and sub auroral regions
2. Consistently measure and assimilate DC, AC $\mathbf{S_P}$ and particle deposition from distributed arrays of heterogeneous LEO and ground-based observational platforms, providing the necessary truly multipoint observations of the coupled system parameters (NRC, 2013)
3. Develop methods to leverage GNSS measurements from ground-based network and from polar-orbiting LEO cubesats to map ionization and irregularities for inversions to gather information on upper atmosphere disturbances due to local energy deposition.
4. Form international collaborations to field ground-based portable radars to estimate JH globally.
5. Government agencies that monitor spacecraft locations and trajectories should release historical data that match intervals of science accelerometer missions.
6. Extract all possible information from prior and current LEO $\mathbf{S_p}$ spacecraft constellations perhaps using re-analysis techniques, as has been done for terrestrial weather and climate
7. Space missions /constellations that would benefit from the JH and $\mathbf{S_p}$ investigations should be tasked to host payloads that report particle and fields in real time. This aligns with current practice of having commercial aircraft telemeter data to national terrestrial forecasting agencies in real time.
8. There is real and immediate need for developing physics-based local and global models of $\mathbf{S_p}$, conductivity, JH, neutral composition and neutral winds across different scales and in combination with modern data assimilation techniques.
9. High-performance computing and machine learning techniques will be required to achieve predictive energy deposition and neutral density forecasts by 2050 for operational needs.
10. These will enable ensemble methods that can start with different conditions, process to most likely outcomes, but also run extreme event scenarios.

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