Challenges associated with near-Earth nightside current

Michael W. Liemohn, Natalia Y. Ganushkina,[1] Raluca Ilie, and Daniel T. Welling

Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, United States

[1]Also at Finnish Meteorological Institute, Helsinki, Finland

Submitted to the *Journal of Geophysical Research – Space Physics*

To the special section on Unsolved Problems in Magnetospheric Physics

Paper type: Commentary

AGU index terms:

2721	Magnetospheric Physics: Field-aligned currents and current systems (2409)
2778	Magnetospheric Physics: Ring current
2788	Magnetic storms and substorms (4305, 7954)
2740	Magnetospheric Physics: Magnetospheric configuration and dynamics
2730	Magnetosphere: inner

Keywords:

Magnetospheric currents, current density, current systems, tail current, ring current, partial ring current, banana current

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2016JA022948

Abstract. Every magnetic field of solar and planetary space environments is associated with a current of differentially flowing charged particles. Electric potential patterns in geospace and near other planets are also closely linked with currents. Close to the Earth, particularly in the near-Earth nightside magnetosphere, several current systems wax and wane during periods of space weather activity. The velocity-dependent drift, energization, and loss processes in this region complicate current system evolution. There is a discrepancy about the magnitude, timing, and location of these currents, however, and this Commentary pitches the case for a concerted community effort to resolve this issue.

Key points:

- Current densities in the near-Earth nightside magnetosphere are not well quantified
- Current density partitioning between current systems is dynamic and not well understood
- Resolution of current system issues is important for better space weather forecasting

1. Introduction: The Controversy

Electric currents are ubiquitous in the solar and planetary space environments, as every magnetic field is associated with a current [*Parker*, 2000]. Near Earth, currents flowing in the outer core generate a planetary magnetic field that's close to a dipole (with some higher harmonics [e.g., *Finlay et al.*, 2010]), and deviations away from this dipolar configuration requires a current somewhere in geospace to explain the new field topology. The ionosphere electric field associated with cross-field currents, due to a build up in net charge densities at the deposition locations of field-aligned currents, sets up an electric potential pattern, which is a convenient tool for describing plasma drift within the geospace system. Furthermore, it is important to understand the physics governing the particle energization, transport, and loss resulting in net charge flow (i.e., current density) as electrons and ion flow through near-Earth space.

Of particular interest for space weather applications are the current systems of the inner magnetosphere, within which there are several currents that intensify and distort the near-Earth magnetic and electric fields during periods of enhanced space weather activity. As plasma moves inward from the magnetotail towards the Earth, particles are energized, increasing their gradient-curvature drift velocity, resulting in energy-dependent motion of the injected population. Furthermore, Coulomb collisions, wave-particle interactions, and charge exchange have reaction rates that are dependent on the charge particle's velocity space location. Plus, pre-existing plasma populations contribute to the overall pressure distribution. The particular flow of particles can lead to strong variations in current density within a region, such as thin current layers embedded within a thicker and less intense current sheet [e.g., *Dubyagin et al.*, 2013a, b]. That is, the governing physics gets complicated for the particles carrying the currents in the inner magnetosphere. This is also the place where our understanding and eventual prediction of space weather critically matters because it is where most operative satellites are located and where the space currents often close via field-aligned currents through the ionosphere to significantly influence ground-based systems like power lines and pipelines [e.g., *Boteler and van Beek*, 1999; *Kappenman*, 2004; *Pirjola et al.*, 2005; *Forbes and St. Cyr*, 2008; *Gaunt et al.*, 2016]. Therefore, understanding the controversies and unresolved issues of the inner magnetosphere [see, e.g., *Daglis et al.*, 2003; *Liemohn and Kozyra*, 2003; *Maltsev*, 2004; *Antonova*, 2004; *Li et al.*, 2011; *Dubyagin et al*., 2014; *Ganushkina et al.*, 2015] is a useful and important component within the field of space physics.

An unresolved controversy of space storms and the inner magnetosphere surrounds the current density in this region. Using individual satellite data, *Lui et al.* [1987] found storm-time current densities peaking at 5-8 nA/m^2 (for two moderate storms) and the complementary quiet time study by *Lui and Hamilton* [1992] calculated non-storm current density peaks of 2-4 nA/m^2. These values lead to estimates of total westward currents below 10 MA. Other studies also calculating current densities from individual satellites revealed similar values [e.g., *Ijima et al.*, 1990; *Le et al.*, 2004; *Jorgensen et al.*, 2004]. In contrast, *Vallat et al.* [2005] used the curlometer technique from the Cluster near-Earth tetrahedral campaigns, finding 10-20 nA/m^2 westward currents in nearly every usable near-Earth pass, with extreme values above 50 nA/m^2 for moderate storm conditions. That is, the quiet time values from *Vallat et al*. [2005] are larger than the storm-time values from all other methods. This calculation of large, persistent current densities from the Cluster perigee curlometer measurements has been upheld by several other studies [*Zhang et al.*, 2011; *Grimald et al.*, 2012; *Shen et al*., 2014]. These current densities are from the "smooth ring current" current density values right near perigee (~4 R_E near the equator), not from the highly filamentary and variable current densities at higher latitudes, which the authors attribute to the spacecraft being in the inner plasma sheet region.

The discrepancy cannot be dismissed just a matter of comparing statistical studies [e.g., *Jorgensen et al*., 2004; *Le et al*., 2004] with the individual Cluster pass values. For example, the median values shown in the plots of *Jorgensen et al.* [2004] rarely exceed 10 nA/m^2, only in the dusk and midnight regions during intense storms, and the error bars on these plots indicate that nearly all values are below 15 nA/m^2. For quiet times of Dst > -30 nT, the error bars are usually barely noticeable relative to the line thickness of perhaps 1 nA/m^2, indicating a robust conclusion. Therefore, during quiet times, the disparities between the studies are well beyond statistical significance, and even for storm times the differences are very large and are, at best, at the edge of reasonable overlap with each other. Furthermore, the case study analyses from individual satellites do not converge.

Thus, there is a large discrepancy regarding the magnitude of near-Earth current densities. This Commentary is given with the hope of compelling future collaborative efforts towards consensus, first by discussing why it is useful to know about current densities and then a brief overview of the measurement techniques for determining current density from satellite data.

2. The Usefulness of Current Analysis

One reason that it is useful to know the current density and, more specifically, how that current density is partitioned into current systems within near-Earth space, is because some current systems are related to electric potential pattern formation. "Current systems" refers to the representation of the total current as a linear superposition of one or more different closed current loops; a convenient and useful technique for gaining insight into power generation and dissipation in geospace. *Southwood and Wolf* [1978] showed that field-aligned currents closing the partial ring current in the inner magnetosphere have a substantial influence on the further development of the inner magnetospheric pressure distribution. Figure 1a, from *Liemohn et al*. [2015], is a schematic of the relationship of the partial ring current to the plasma pressure peak and the local plasma flow direction. Depending on the structure of the plasma pressure peak and the ionospheric conductance in the closure region, the feedback can be strong and the drifts can be radically altered from the typical sunward flow direction. *Rowland and Wygant* [1998] showed that the inner magnetospheric electric field is large inside of geosynchronous orbit during storms, larger than in the near-Earth tail region. They did not relate it specifically to hot plasma structure, however. One such study is *Liemohn and Brandt* [2005], who analyzed the small-scale structure in the hot plasma created by the internal feedback of localized electric potential peaks from the partial ring current.

The partial ring current can greatly alter the local electric field and therefore have a profound impact on the development of the plasma pressure in the inner magnetosphere. Not all $\mathbf{J}_\perp$ current density derived from the satellite observations, however, is partial ring current. Some of it is symmetric ring current, banana current (the system flowing around localized pressure peaks) [e.g., *Liemohn et al*., 2013a], or cross-tail current.

Figure 1b shows a simplistic schematic of the current systems in the near-Earth nightside magnetosphere [*Liemohn et al.*, 2015]. There are two eastward current segments and four westward current segments in the near-Earth tail, seen in Figure 1b. The westward current segments all depress the field at Earth, thin the current sheet, and stretch the field into a more taillike configuration, but they each have a distinct closure path giving them unique contributions to the magnetic and electric field configuration of geospace. Also, each one of these loops is distributed throughout a volume, perhaps with a complicated topology or even as multiple loop structures. The exact location of each moves around throughout a storm sequence and indeed with every injection of plasma from the near-Earth tail region. Knowledge of the large-scale current systems, in particular the relative contribution of the partial ring current and therefore the influence on the electric potential, can be obtained through a systematic analysis of local current density measurements.

3. Calculating Current Density

To determine current system geometry, it is necessary to calculate current density. As discussed in the review by *Ganushkina et al.* [2015], there are three primary methodologies for calculating current density in space from in situ measurements. The first method is to determine current density **J** from the local net charge flux,

$$\mathbf{J} = \sum_j q_j n_j \mathbf{v}_j \tag{1}$$

where the summation j is over all plasma species of charge state q_j, density n_j, and bulk velocity $\mathbf{v}_j$. It is the most direct approach for finding J and only requires plasma observations, not magnetic field values. This technique, however, requires a robust measurement of the entire velocity space distribution for all species and charge states, which can be difficult to accurately obtain on a reasonable time cadence. The satellites of the Magnetosphere MultiScale constellation, however, might be capable of such calculations during burst mode observing intervals [*Burch et al.*, 2016].

In the second method, the cross-field current density $\mathbf{J}_\perp$ can be determined from the gradients of the plasma pressure and magnetic field [e.g., *Parker*, 1957],

$$\mathbf{J}_\perp = \frac{\mathbf{B}}{B^2} \times \left[\nabla P_\perp + \left(P_\parallel - P_\perp \right) \frac{\nabla B}{B} \right] \tag{2}$$

This technique is often applied to one or two near-equatorial satellites [e.g., *Lui et al.,* 1987]. For a spatially isolated single spacecraft, ∇P and ∇B must be found assuming temporal stationarity of the plasma and differencing the values along the space trajectory. When two spacecraft are in close proximity, then a difference can be made between the values at the two locations. Azimuthal current is obtained when the satellite motion is nearly radial (inbound or outbound segments of a very elliptical orbit). It has also been applied to pressures derived from energetic neutral atom images [e.g., *Roelof et al.,* 2004].

The third method to get the local current density uses the curl of the local magnetic field vector (i.e., Ampere's Law). When applied to spacecraft data, this is known as the curlometer technique, described in detail by *Dunlop et al.* [1988, 2002]. This method can be used with anywhere from one to four spacecraft. When used with data from a single spacecraft, stationarity of the magnetic topology must be assumed in order to use the motion of the spacecraft to obtain the spatial differencing. This also yields an incomplete **J** vector, calculating a minimum value for the current density. It is used, for instance, to obtain field-aligned currents from low-Earth-orbiting satellite magnetic field perturbations [e.g., *Iijima and Potemra*, 1976; *de la Beaujardiere et al.*, 1993; *Anderson et al.*, 2000; *Knipp et al.*, 2015] and from near-equatorial elliptical-orbit satellite data [e.g., *Iijima et al.*, 1990; *Le et al.*, 2004; *Lui*, 2013; *Dubyagin et al.*, 2015]. When two spacecraft are in close proximity, then the curl differencing is done between the measurement sets. When applied to a four-spacecraft tetrahedron, the full current density vector can be obtained [e.g., *Vallat et al.,* 2005].

4. Steps Toward Resolution

Recent studies have tried to resolve current densities in the inner magnetosphere and near-Earth nightside. For instance, new empirical models have been created that more accurately define the parameter space for these currents [e.g., *Tsyganenko*, 2014; *Stephens et al.*, 2016]. Several studies have focused on comparisons against the Dst index as a measure of capturing the correctness of near-Earth currents [e.g., *Ganushkina et al.*, 2010, 2012; *Cramer et al.*, 2013; *Rastätter et al.*, 2013]. Some have investigated the current systems with circuit models of the magnetosphere-ionosphere system [e.g., *Ohtani and Uozumi*, 2014; *Patra and Spencer*, 2015]. The advent of the Iridium and AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) data sets have greatly enhanced our understanding of ionospheric high-latitude field-aligned currents [e.g., *Anderson et al.*, 2000; 2008; *Clausen et al.*, 2012; *Coxon et al.*, 2014]. Others have extracted currents from framework-level geospace system modeling to understand the timing and intensity of stormtime currents [e.g., *Siscoe et al.*, 2000; *Liemohn et al.*, 2011, 2013b; *Merkin et al.*, 2013].

Full resolution could be achieved by taking into account the plasma and magnetic field observations from multiple spacecraft. Note that because one current density calculation is derived from phase space density integrals, another depends on a pressure gradient, and the other on magnetic field vorticity, these methods (especially the last two) can be applied independently to measurements from the same spacecraft. Similarly, closely-spaced satellites can be used either independently or in combination to yield multiple values for $\mathbf{J}_\perp$ for comparison against each other. The known relationships between plasma pressure, magnetic perturbation, current density, and electric fields should be used to assess the validity of the derived current density values and reach closure on the controversy regarding the true level of current in the inner magnetosphere during quiet times and storm intervals.

By putting together current density values from several spacecraft in combination with other complementary observations, a pattern of current density throughout near-Earth space should then be constructed for each moment throughout a magnetic storm event. This would allow for an estimation of the partitioning of current between the various current systems, at the very least between asymmetric (tail, partial ring, or banana) and symmetric ring (eastward or westward) currents and perhaps to a finer scale than this, depending the exact spacing and location of the satellites.

Numerical modeling can also aid in resolving these discrepancies and uncertainties regarding near-Earth nightside current densities and the large-scale current systems. Statistical and empirical models that best-fit the available data across a large number of similar events are very useful for determining the average state of the currents for a particular activity level or driving condition. Drift physics models that solve the velocity-space dependence of the particle motion, acceleration, and loss are useful for quantifying the relationship between plasma dynamics and the timing and intensity of the various current systems. Global magnetospheric models are useful for relating the near-Earth nightside phenomena with the rest of geospace, exploring the nonlinear processes within the larger system.

Therefore, full resolution and consensus on this issue will require a community-wide effort. The tools are available and the methods are clear for how to solve this problem. What is needed to achieve success is a dedicated contingent of researchers focused on the activity.

Acknowledgments. The authors thank the sponsors of this research, in particular research grants from NASA (NNX11AO60G, NNX14AF34G, and NNX14AC02G) and NSF (AGS-1102863, AGS-1414517). Part of the research done by M. Liemohn and N. Ganushkina leading to these results has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement 637302 PROGRESS. The authors also thank the International Space Science Institute (ISSI) in Bern, Switzerland for its support of three international teams on which authors have or are participating: "Resolving Current Systems in Geospace," “Analysis of Cluster Inner Magnetosphere Campaign data, in application the dynamics of waves and wave-particle interaction within the outer radiation belt,” and “Ring current modeling: Uncommon Assumptions and Common Misconceptions.” In addition, the authors thank the organizers of the "Unsolved Problems in Magnetospheric Physics Workshop" in Scarborough, UK for inviting M. Liemohn to speak on this topic at the meeting. Finally, the authors would like to thank the Editor and Reviewer for their helpful suggestions to focus the message of this Commentary.

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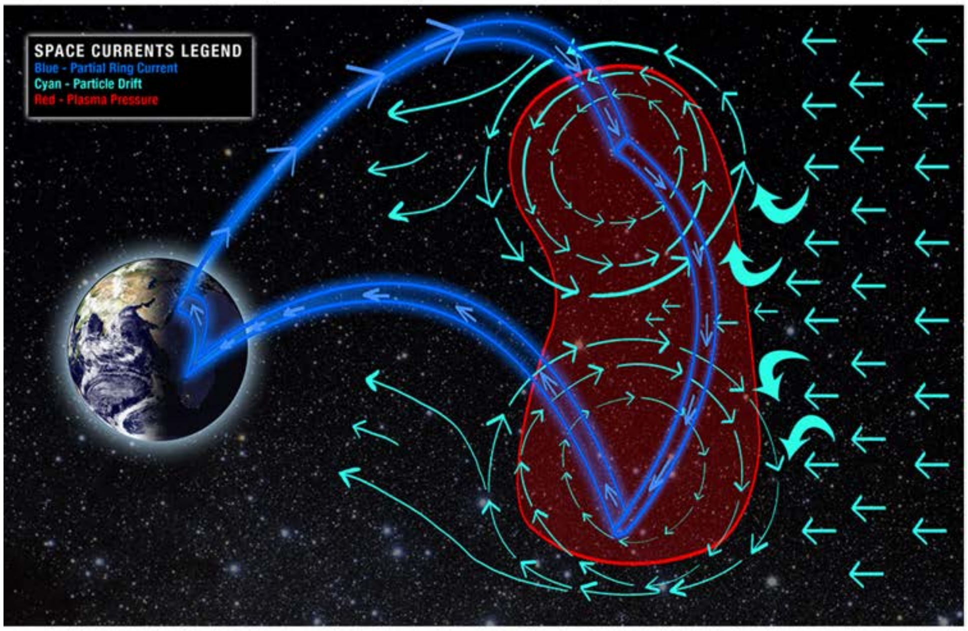
Figure 1

(a) Relationship of partial ring current with plasma pressure and flow



(b) Schematic of near-Earth nightside current systems

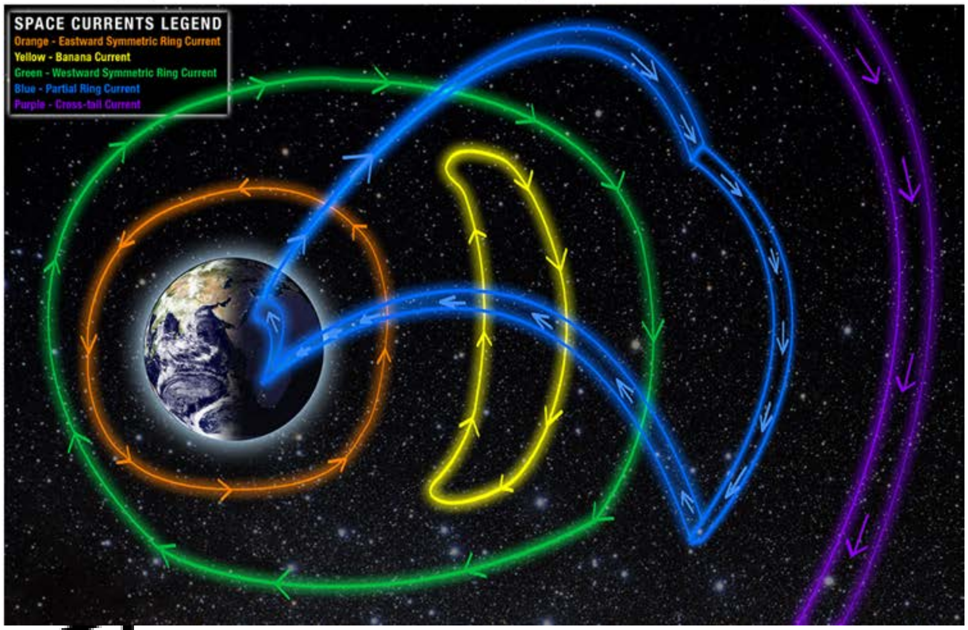
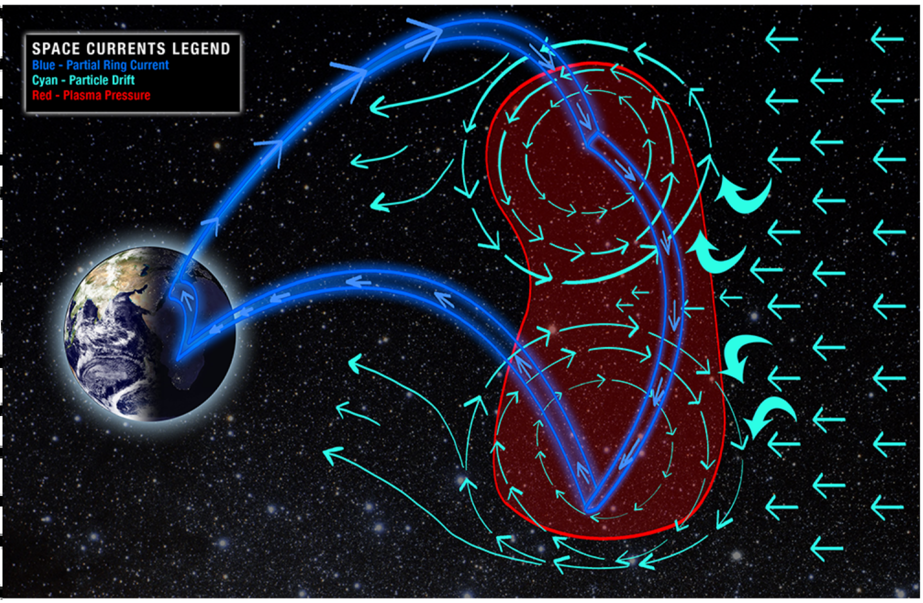
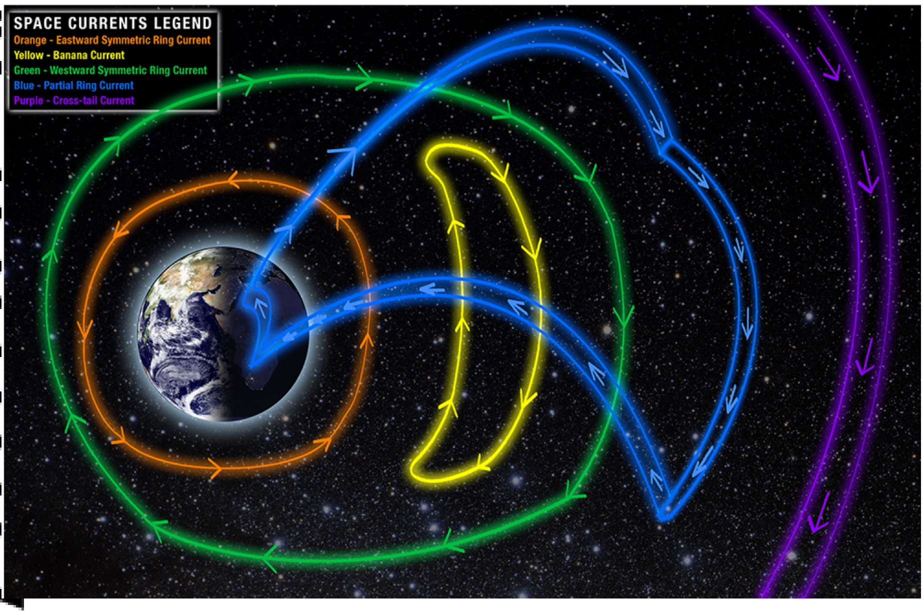


Figure 1. Current systems and feedback on particle drifts in the near-Earth nightside magnetosphere, from *Liemohn et al.* [2015]. (a) Schematic of the relationship of the partial ring current (in blue) to a localized plasma pressure peak (in red) and the plasma flow directions (cyan). (b) Schematic of near-Earth nightside current systems, showing the eastward symmetric ring current in orange, the banana current in yellow, the westward symmetric ring current in green, the partial ring current in blue, and the cross-tail current in purple.

(a) Relationship of partial ring current with plasma pressure and flow



(b) Schematic of near-Earth nightside current systems



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