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Resolving of magnetospheric substorm controversies in thermodynamic view

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Abstract

In magnetospheric physics, the substorm development, understood as the forming of explosive release of energy from Earth's magnetotail into the ionosphere and the near magnetosphere, is a subject of long-standing scientific debates. Yet, despite obvious progress, the emergence of a substorm demonstrates some effects that cannot be easily interpreted based on the existing observational and analytical models. These effects are frequently referred to as "controversies," as they can support entirely opposing physical frameworks. In this report, some well-known controversies are discussed in the light of possible resolution based on the thermodynamical model of conserved energy links.

1. Introduction

Models serve as the foundational architecture in understanding magnetospheric substorms, so the close attention to the controversies appearing in substorm's development (Song and Lysak, 2023) is easily explained. In this sense, while classical substorm models such as *NENL* and *CD* have historically provided robust explanatory power, some empirical evidences still cannot be intuitively clarified by the traditional analytical reasonings.

This paper proposes a relatively new thermodynamic framework to critically examine the known controverses and suggest the way of their resolution. Ultimately, this analysis discusses the consensus platform to reconcile the theoretical and experimental findings and provide a more cohesive understanding the substorm's mechanism (Alberti et al, 2022).

2. Data and methods

This communication does not provide the detailed description of the data, restricting the text by general referencing to the existence of established empirical relations collected for years from the ground and satellite archives.

The theoretical methodology is a thermodynamical framework featuring the conserved energy links (*CEL*) model, which assumes an infinite number of bidirectional channels between the magnetotail taken as an open thermodynamic system (*OTS*) and its environment adopted to magnetospheric conditions (Moldavanov, 2024; Moldavanov, 2025).

3. Results

1. The Energy Threshold Paradox. Traditional theoretical models assume that a substorm expansion phase triggers when the total magnetic flux or total energy accumulated in the magnetotail crosses a specific threshold. However, observations show that it is not perfectly true. Even when solar wind (*SW*) energy input varies by an order of magnitude, the average growth

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phase signatures for small and large substorms remain remarkably similar (Ren et al., 2026; Chen et al., 2022). So, possibly, the other discriminating factor should be considered.

Resolution: *CEL* dictates that at continuous circulation of energy through the infinite network of sources and sinks the trigger mechanism shifts from a localized state transition to a global thermodynamic one. As a result, the growth-expansion transition is controlled by the system energy rate y, not the total system energy E accumulated in the magnetotail. So, substorm's expansion starts if $y > y_F$, where y_F is the threshold rate of energy exchange.

2. "Domino" Sequence Paradox. Up until recently, the space physics community was split into two parts regarding where a substorm originates in the magnetotail: in the mid-tail area $\sim 20-30R_E$ away from the Earth (*NENL* model), or in the near-tail area $\sim 8-12R_E$ away from the Earth (*CD* model). At that, traditional models treated the magnetosphere like a series of physical phenomena that activated one after another like failed dominoes. So, a simple question to come is which domino falls first (Mahr, 2022; Wang, 2026)?

Resolution: *CEL* completely flips above perspective by treating the entire geomagnetic tail as a single open thermodynamic system (*OTS*). *CEL* treats the mid-tail reconnection region and the near-Earth current sheet as not the physically separated independent regions but as the different stochastic manifestations within the same global energy infrastructure. So, the correct answer to the above "domino" question is that both dominos fall at the same time, meaning that a substorm as a system-wide thermodynamic collapse provides support for all responses simultaneously (Wang, 2026).

3. The Storm-Substorm Relationship Paradox. Intense substorms inject energetic particles into the inner magnetosphere, driving the ring current that forms a geomagnetic storm. Yet, substorms can also occur when the ring current is entirely quiet, proving that substorms do not require a storm to exist. So, the question is about the existence of any logical relationship between the appearance of a storm and a substorm? (Akasofu, 1964; Kamide, 1992).

Resolution: Rather than treating storms and substorms as entirely independent events, the *CEL* framework views them as concurrent, system-driven indicators of energy evolution in *OTS* (magnetotail) where focus shifts from localized to global thermodynamics. Then, the intercoupling between the magnetotail's inherent structural factors and the raw incoming energy flux from *SW* can produce different time-spatial forms of magnetospheric activity simultaneously including both storms and substorms (Alberti et al, 2022).

4. The Steady Magnetospheric Convection Paradox. Under prolonged intervals of southward-directed interplanetary magnetic field, the magnetosphere absorbs a continuous supply of *SW* energy. Typical substorms theory affirms that this regime should trigger explosive featuring cyclic substorms to release the stress. However, instead of that, the system can enter a state of steady magnetospheric convection (*SMC)* dissipating energy continuously and smoothly without ever triggering a substorm (Sergeev, 1988).

Resolution: This paradox can be easily explained within the *CEL* framework, wherein, in accordance with the above, the system is capable of explosive-like response only if the total energy rate $y > y_F$, regardless of the accumulated total energy. In this case, the only regime available for the *OTS* is the convectional one, *i.e.,* the *SMC*.

5. The Ionospheric Conductivity Paradox. It is known that during a growth phase the development of substorm demonstrates the prolonged periods when the energy flow inwards *OTS* exceeds the energy flow outwards *OTS*. In other words, even after the accumulation of a significant portion of energy (up to $\sim 10^{16}$ joules), no gradual dissipation happens for nearly an hour. So, the question to come is whether the magnetotail as a system forces the ionosphere to

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react in this way, or ionospheric feedback actively dictates the magnetosphere what to do (Erickson, 1980).

Resolution: As was already highlighted, within the *CEL* framework, for the substorm onset to happen, the critical system condition $y > y_F$ should be met. On the other hand, ionospheric conductivity grows simultaneously with the growth of total rate y. As a result, the maximum conductivity occurs exactly at $y = y_F$. From this standpoint, the magnetosphere forces the ionosphere to react as above, and at the same time, ionospheric plasma creates the most favorable conditions for a magnetospheric plasma to implement substorm breakup.

6. The Continuous Transport vs. Explosive Onset Paradox. Standard *MHD* processes involve continuous magnetic flux transfer and gradual energy transport. This physical pattern, generally, fails to cleanly explain the sudden, explosive nature of the growth-expansion transition (auroral breakup) without invoking ad hoc external triggers (Akasofu, 2022).

Resolution: *CEL* naturally accommodates all the gradual as well as sudden state changes, still presenting a solution in the continuous non-linear form. At the same time, there are accompanying discrete solutions in the form of a energy spectrum.

7. The Directly-Driven vs. Unloading Paradox. For decades, scientists debated whether substorms are entirely "directly driven" by *SW* or are an "unloading" process of stored energy. Observations paradoxically support both mechanisms happening concurrently (Sun, 1996).

Resolution: As was already mentioned, *CEL* accepts and utilizes different energy forms. Because the tail is defined as *OTS* with an infinite number of external links and sinks, *CEL* can simultaneously process incoming external energy (directly driven) and accept the global internal configuration changes (unloading) without violating the global energy conservation laws. Ultimately, it also allows generation of both gradual and explosive-like energy outputs.

8. The Nature of Energy Scaling and Discrete Energy Exchanges Paradox. Satellite observations regularly show discrete energy levels, or "quantized" modes of energy exchange, in macro-scale space plasmas, but classical magnetospheric cavity modes or field-line resonances (like Pc5 range pulsations) could not completely explain their roots (Lysak, 2022).

Resolution: *CEL* shows that energy exchange in space is naturally quantized into a discrete energy spectrum. This quantization is not caused by the boundaries of the magnetospheric cavity or field-line resonances but rather by the fundamental, process-based limitations imposed on the nature of energy exchange.

4. Results/Discussion/Summary

The conducted short comparison of experimental and theoretical data shows that the known substorm's controversies can be resolved within thermodynamical framework of *CEL*.

Competing interests

Author explicitly declares the absence of conflict of interests.

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References

S.-I. Akasofu, S.-I. The development of the auroral substorm. Planetary and Space Science, 12(4), 273-282, 1964.

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Alberti, T., Faranda, D., Consolini, G., De Michelis, P., Donner, R.V., Carbone, V. Concurrent Effects between Geomagnetic Storms and Magnetospheric Substorms. Universe, 8, 226. https://doi.org/ 10.3390/universe8040226, 2022.

Chen, L., Shiokawa, K., Miyoshi, Y., Oyama, S., Jun, C.-W., Ogawa, Y., et al. Observation of source plasma and field variations of a substorm brightening aurora at $L \sim 6$ by a ground-based camera and the Arase satellite on 12 October 2017. Journal of Geophysical Research: Space Physics, 127, e2021JA030072. https://doi.org/10.1029/2021JA030072 , 2022.

Erickson, G. M., and R. A. Wolf, *Is steady convection possible in the Earth's magnetotail?* Geophysical Research Letters, **7**(11), 897-900 10.1029/GL007i011p00897, 1980.

Kamide, Y. *Is a magnetic storm a completion of successive substorms?* Eos, Transactions American Geophysical Union, 73(37), 395-398. 1992.

Kleimenova, N. G., L. I. Gromova, S. V. Gromov, Malysheva L. M. and I. V. Despirak, Polar Substorms and the Harang Discontinuity, Geomagnetism and Aeronomy, 64 (4), 490–499. Pleiades Publishing, Ltd., 2024.

Lysak, R.L. Field Line Resonances and Cavity Modes at Earth and Jupiter. Front. Astron. Space Sci. 9:913554. doi: 10.3389/fspas.2022.913554 2022.

Mahr, N. Domino Effect Meaning & Examples. *Study.com*, 5 September 2022, study.com/academy/lesson/domino-effect-overview-examples.html], 2022.

Mende, S. B., Harris, S. E., Frey, H. U, Angelopoulos, V., Russell, C. T., Donovan, E., Jackel, B., Greffen, M., Peticolas, L. M. The THEMIS Array of Ground-based Observatories for the Study of Auroral Substorms, Space Science Reviews, 2008 141 (1-4), 357-387 doi: 10.1007/s11214-008-9380-x.

Moldavanov, A. Forming of magnetospheric disturbances by system behaviour of geomagnetic tail, *JASTP*, 259, 106257, 2024.

Moldavanov, A. Signatures of Substorm Onset in Thermodynamic Model of Geomagnetic Tail. *Adv. Space Res.* 75 (2) 2425-2432, 2025.

Ren Y., Zhu, M., Lei, D., Gonzalez, W., Wang, S., Wang, C., Escoubet, C.P., Zhang J., Zong, Q. Solar-Wind Triggering of Substorm Onset During the May 2024 Superstorm: Coordinated Global Observations and Simulations 53 (4) e2025GL119629, 2026.

Rostoker, G., Eastman, T. A boundary layer model for magnetospheric substorms. 92 (A11). https://doi.org/10.1029/JA092iA11p12187, 1987.

Sergeev, V. A., and W. Lennartsson (1988), Plasma sheet characteristics during quasi-steady magnetospheric convection, Planetary and Space Science, 36 (4), 353-370, 1988.

Song Y. and Lysak R.L. A mechanism of the auroral substorm expansion onset: electric discharge in the double layer, Frontiers in Astronomy and Space Sciences, 10:1296626. doi: 10.3389/fspas.2023.1296626, 2023.

Sun, W., Akasofu, S.-I., Kamide, Y.: Development of the substorm current system in the equatorial plane of the magnetosphere deduced from ground-based magnetometer records. *J. Geophys. Res.*, 101(A11), 24655–24659, doi:10.1029/96JA02606, 1996.

Wang, T., Dai, L., Escoubet, C.P., Gonzalez, W., Ren, Y, Zhu, M, Wang, S., Wang, C., Wang, X., Wang, K. and Liu J. Substorm expansion embedded in a global cycle of field-aligned currents and auroral electrojets. Nature Communications 17(1), 2970. doi: 10.1038/s41467-026-69753-x, 2026.