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MAIN CHARACTERISTICS OF THE FIRST AURORAL ARC BRIGHTENING AND SUBSTORM ONSET LOCALIZATION

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Abstract. This study examines the main features of the initial auroral arc brightening and the localization of substorm onset. Our findings challenge the traditional large-scale magnetospheric dynamics framework, which predominantly relies on the idealized magnetohydrodynamic (MHD) model and the frozen-in condition—typically assumed to be violated only at a few specific points along certain magnetic field lines. Through detailed analysis, we demonstrate that the observed auroral breakup phenomena can be described by the existence of a high level of turbulence in the Earth's magnetotail and the penetration of large-scale interplanetary magnetic field into the magnetosphere.

1. Introduction

Large-scale magnetospheric dynamics have long been described by the *Dungey* (1961) model, which assumes ideal magnetohydrodynamics (MHD) and the frozen-in condition above the ion Larmor radius and ion diffusion length scales. However, recent findings (*Antonova et al.*, 2023, 2025) emphasize the importance of the Hall term in the generalized Ohm's law, demonstrating the breakdown of the frozen-in approximation. The relative contribution of the Hall term is determined by a ratio between the plasma and Alfvén speeds (see, for example, (*Paschmann et al.*, 2002)). Because large-scale magnetospheric plasma motion typically occurs at speeds much slower than the Alfvén speed, the analysis of relative contributions of different terms in the generalized Ohm's law shows a significant increase in the scale at which ideal MHD and the frozen-in condition become invalid (*Antonova et al.*, 2023, 2025). Furthermore, the plasma sheet has exhibited high levels of turbulent fluctuations since the beginning of the space age (see, for example, (*Antonova*, 1985)). Dungey himself recognized this as a major limitation of the frozen-in approach.

Considering the aforementioned advances in our understanding of key magnetospheric processes, it is necessary to revise the mechanisms describing the onset of magnetospheric substorms and the brightening of auroral arcs at the equatorial edge of the oval. The approaches to description of the magnetosphere, which were not based on the ideal MHD and frozen-in condition have been developing also since a long time. For example, beginning with the foundational work of *Chapman and Ferraro* (1931), the pressure balance at the magnetopause has been extensively studied. The pressure balance across the turbulent magnetotail has also been examined (see references in the reviews by *Ovchinnikov and Antonova* (2017), *Antonova and Stepanova* (2021)). Several studies have focused on the penetration of the large-scale interplanetary magnetic field deep into the magnetosphere (see *Borovsky et al.* (1998), *Vorobjev et al.* (2001), *Frank and Sigwarth* (2003), *Petrukovich* (2011), *Tsyganenko and Andreeva* (2020), among others). Numerous satellite observations have demonstrated the existence of field-aligned drops in the electrostatic potential that accelerate auroral electrons. However, none of these observations have been adequately explained by theories of large-scale magnetospheric dynamics based on the *Dungey* (1961) model.

This paper briefly examines the key features of auroral arc brightening at the onset of an isolated substorm and its spatial localization, which are important for revising the existent approaches to the key magnetospheric processes.

2. Localization of substorm expansion phase onset

The Dungey concept postulates the existence of laminar plasma flow and a non-fluctuating magnetic field in the tail, as well as the location of the substorm expansion phase onset at a relatively large geocentric distance. At this location, the frozen-in condition is disrupted, leading to magnetic reconnection accompanied by accelerated plasma flows, changes in the magnetic field line topology, and particle acceleration. The accelerated flows directed toward the Earth reach smaller geocentric distances, where the auroral arc brightens and the substorm expansion phase begins. The detection of accelerated plasma flows toward the Earth, known as bursty bulk flows (BBFs), appeared to confirm this idea. However, it became clear from the discovery of BBFs that such an explanation faced fundamental challenges, which were further confirmed by subsequent observations in the magnetotail from CLUSTER, THEMIS, and MMS missions. BBFs were observed far more frequently than magnetospheric substorms. Additional difficulties arose in

explaining magnetospheric substorms during magnetic storms, as substorms and discrete auroras were detected deep inside the magnetosphere.

The latest results in this direction include the works of *Vorobjev et al.* (2024, 2025), who showed, using DMSP data, that the onset of isolated substorm is associated with a narrow, well-defined peak in electron precipitation. This peak occurs near the boundary of the b2i ion precipitation region and is associated with a bright auroral arc with an intensity in the green line $I_{557.7} \sim 30$ kR. The latitude of the b2i boundary during quiet periods is $\Phi' = 68.3° \pm 0.6°$ corrected geomagnetic latitude (CGL), whereas before the onset of a substorm and during its initial stage, the b2i boundary shifts to latitudes of $\Phi' = 65.4° \pm 0.7°$ CGL. This finding is inconsistent with the prevailing ideas regarding the localization of substorm onset in the magnetotail or at the equatorial boundary of the plasma sheet. Furthermore, Fast satellite observations analyzed in previous studies (*Dubyagin et al.*, 2003; *Mende et al.*, 2003) recorded the formation of a powerful field-aligned electron beam, with a flux of approximately 10^{11} cm^{-2} s^{-1}, precisely at the moment of substorm onset. The CGL of the beam localization in these studies was approximately 65°. According to the Tsyganenko 1996 model (https://geo.phys.spbu.ru/~tsyganenko/empirical-models/magnetic_field/t96/), projecting this latitude into the nighttime hours corresponds to a geocentric distance of about 8 R_E (*Dubyagin et al.*, 2003). For a long time, therefore, the observational results from Fast were not considered as they significantly contradicted to established points of view. However, advancements in modeling the Earth's magnetospheric magnetic field have led to revised projections of the Fast data. Figure 1 presents the CGL projection around midnight, showing that the corrected geomagnetic latitude of approximately 65° corresponds to a geocentric distance of about 5 R_E. This places the location within the ring current region, thus resolving the issue concerning the localization of the isolated substorm onset.
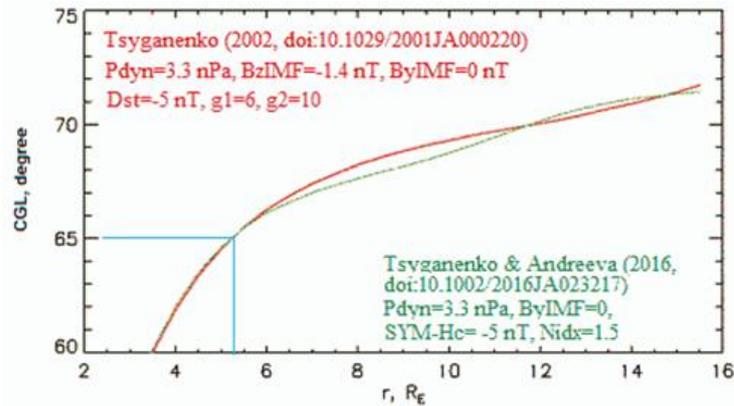

Figure 1. Mapping of the isolated substorm onset region in the night sector in magnetically quiet conditions according to the model (*Tsyganenko*, 2002) and (*Tsyganenko and Andreeva*, 2016).

3. Mechanism of substorm development and first auroral arc brightening

The localization of the onset of an isolated substorm at approximately 5 R_E, situated at the boundary of the ion distribution function's isotropization region, suggests the action of a mechanism within the ring current that is independent of changes in the magnetic field line topology. However, the most advanced substorm models fail to account for these observational findings.

Historically there are two competing models trying to explain substorm onset: the Outside-In model, based on reconnection in the magnetotail, and the Inside-Out model, attributing substorm onset to current disruption at ~10 R_E geocentric distance. The THEMIS project aimed to distinguish between these models, both of which assumed a laminar magnetic field in the tail. If the first scenario were to occur, the disturbance would first be observed on the satellite farthest from Earth, followed by a subsequent disturbance closer to Earth. Only after this the first auroral arc brightening would occur. If the second scenario were to occur, an initial disturbance would be observed at a geocentric distance of ~10 R_E, followed by auroral arc brightening, and then a disturbance at a greater distance. Neither model's predictions were definitively confirmed by the THEMIS data.

First, this verification was hindered by the consistently high level of turbulence in the plasma sheet and the frequent occurrence of bursty bulk flows (BBFs). Despite several studies, detecting a disturbance in the magnetotail prior to the brightening of the arc nearest the equator—which is subsequently observed at a distance of approximately 10 Earth radii (~10 R_E)—proved to be quite challenging. Another significant obstacle was the absence of a reliable model to accurately project the arc brightening observed from ground-based measurements onto the equatorial plane (see the discussion in Section 2 of this paper).

At the beginning of the space age, *Tverskoy* (1969, 1972) proposed a model that explained the structure of large-scale electric fields in the magnetosphere without relying on a reconnection framework. This model also predicted the configuration of large-scale field-aligned currents, which were later observed and measured during both magnetically quiet and disturbed periods. Further development of these ideas was carried out by *Antonova* (2002) and *Stepanova et*

al. (2002), who incorporated the presence of a turbulent magnetotail and the onset of the substorm expansion phase, marked by the brightening of auroral arcs closest to the equator. Figure 2a presents a schematic illustrating the mechanism at work, while Figure 2b contains a scheme illustrating the process of auroral arc brightening.
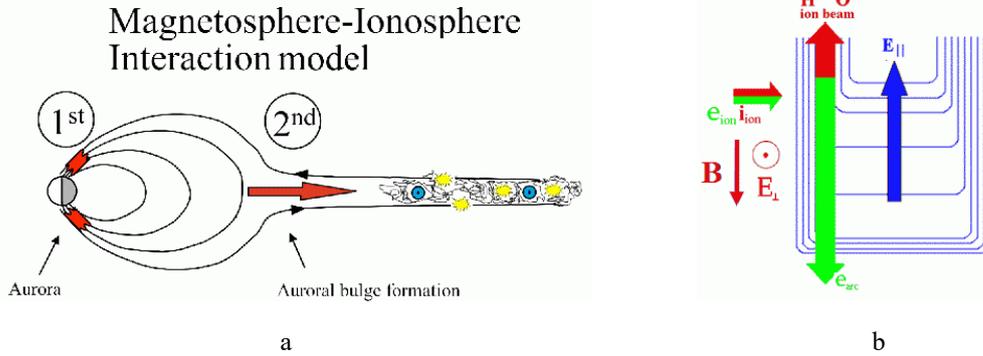

Figure 2. Scheme illustrating the action of mechanism suggested in (*Antonova*, 2002) (a) and the scheme illustrating the process of auroral arc brightening (*Stepanova et al.*, 2002; *Antonova*, 2022) (b).

The substorm theory (*Antonova*, 2002) addresses the development of instability in large-scale field-aligned currents, which results in their stratification and the formation of multiple large-scale inverted-V structures accompanied by large-scale field-aligned electric fields. As this instability develops, the pattern of large-scale convection evolves, and a component of the self-consistent electric field emerges, causing drift across the large-scale structure. This drift causes cold ionospheric plasma to be injected into the region of the field-aligned potential drop. At the boundary of this region, a powerful electron beam forms, accompanied by the brightening of an auroral arc. The field-aligned electron energy within this structure does not exceed energy of magnetospheric electrons accelerated in an inverted V, and the transverse energy remains below several electronvolts. The observed high level of Alfvénic fluctuations in this region is attributed to the development of instability in the transversely cold beam. This approach circumvents the difficulties associated with theories that explain the acceleration of observed beams by kinetic Alfvén waves (see the discussion in *Antonova*, 2022).

4. Discussion and Conclusions

The penetration of the IMF into the magnetosphere and the high level of turbulence in the tail resolve many issues that emerged from the previously dominant assumption that the ideal magnetohydrodynamics approach is valid everywhere except at specific points and along special "reconnection" lines. When IMF penetration occurs for IMF $B_z < 0$, the magnetic field strength decreases, causing the volume of the magnetic flux tube to increase. This increase results in a localized pressure drop, which can create a pressure gradient directed toward the tail. Consequently, a plasma channel with reduced pressure forms, driving plasma flow earthward that is observed as a bursty bulk flow (BBF). This flow is inherently unstable and serves as a major source of increased turbulence in the BBF region. The latest findings on tail turbulence have been obtained using MMS data (see *Naiko et al.* (2025)). Turbulence is observed in all three components of both the electric and magnetic fields within the tail. Furthermore, the spectral slopes of the electric and magnetic fields differ significantly (*Ovchinnikov et al.*, 2024), and double layers have been detected in the BBF regions (*Ergun et al.*, 2018).

This implies that the observed turbulence may have a significant electrostatic component. Experimental data supporting the dominant role of electrostatic fields in magnetospheric dynamics are gradually accumulating, strengthening the case for developing unconventional approaches to magnetospheric physics. In this context, the problem of establishing a magnetostatic equilibrium configuration amid changing external boundary conditions imposed by the solar wind becomes particularly important.

Our discussion of substorm phenomena leads to the following conclusions:

- An isolated substorm does not originate in the magnetotail; rather, it begins at approximately L=5, within the ring current region.
- The substorm expansion phase starts with the brightening of the arc closest to the equator, caused by the formation of a narrow, cold transverse electron beam.
- This electron beam forms due to the drift of ionospheric plasma into the region of a field-aligned potential drop.

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