# Ballooning-interchange instability at the inner edge of the plasma sheet as a driver of auroral beads

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GAMERA
Grid Agnostic MHD for Extended Research Applications

## Introduction

Near the inner edge of the plasma sheet, where the geomagnetic field transitions from dipolar to the stretched magnetotail, low values of the northward magnetic field (Bz) are known to be exhibitied, particularly in the substorm growth phase.

It has been suggested that these weak-field regions are indicative of localized magnetic field minima. These minima, notoriously difficult to observe in situ, are significant as they are unstable to ballooning-interchange instability (BICI), and have been hypothesized to cause auroral beading and play a role in substorm onset (see Sitnov+ 2019 and references therein).

Prior work has investigated BICI using localized particle-in-cell simulations with imposed Bz minima as an initial condition. However, evidence of the formation of localized Bz minima and subsequent BICI instability has been very limited in self-consistent global magnetospheric simulations.

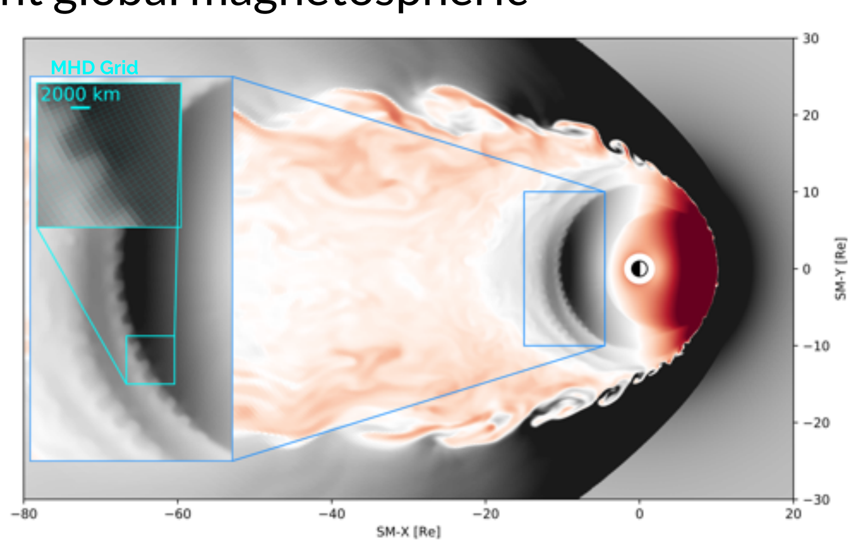


Fig 1: GAMERA resolution

## Methodology

We use our newly-developed global MHD code GAMERA (Zhang+ 2019), the successor to LFM, to simulate a synthetic substorm event at previously inaccessible resolution. The featured simulation has double the resolution in each dimension relative to the highest resolution LFM simulation ever performed (Fig. 1): ~300 km in the central plasma sheet, approaching the ion kinetic scale, and ~30 km in the auroral ionosphere.

After a period of preconditioning, a series of alternating northward and southward IMF orientations, the IMF is turned southward and held constant: Bz=-5 nT, Vx=400 km/s, n=5 #/cc.

## Growth Phase

The substorm growth phase (Fig. 2) occurs between T=0, the final southward turn, and T~1 hr when reconnection begins ~40Re downtail and drives earthward BBF's. During this period nightside and flank magnetic flux is depleted, stretching the magnetotail, while in the ionosphere the current system transitions from a typical NBz configuration, to an R1-dominated configuration due to dayside reconnection.

Early in this process, starting at T~15min, and particularly visible at T=30min we find balloon-like heads, ~0.5Re, forming on two equatorial arcs and beads in the FAC's.

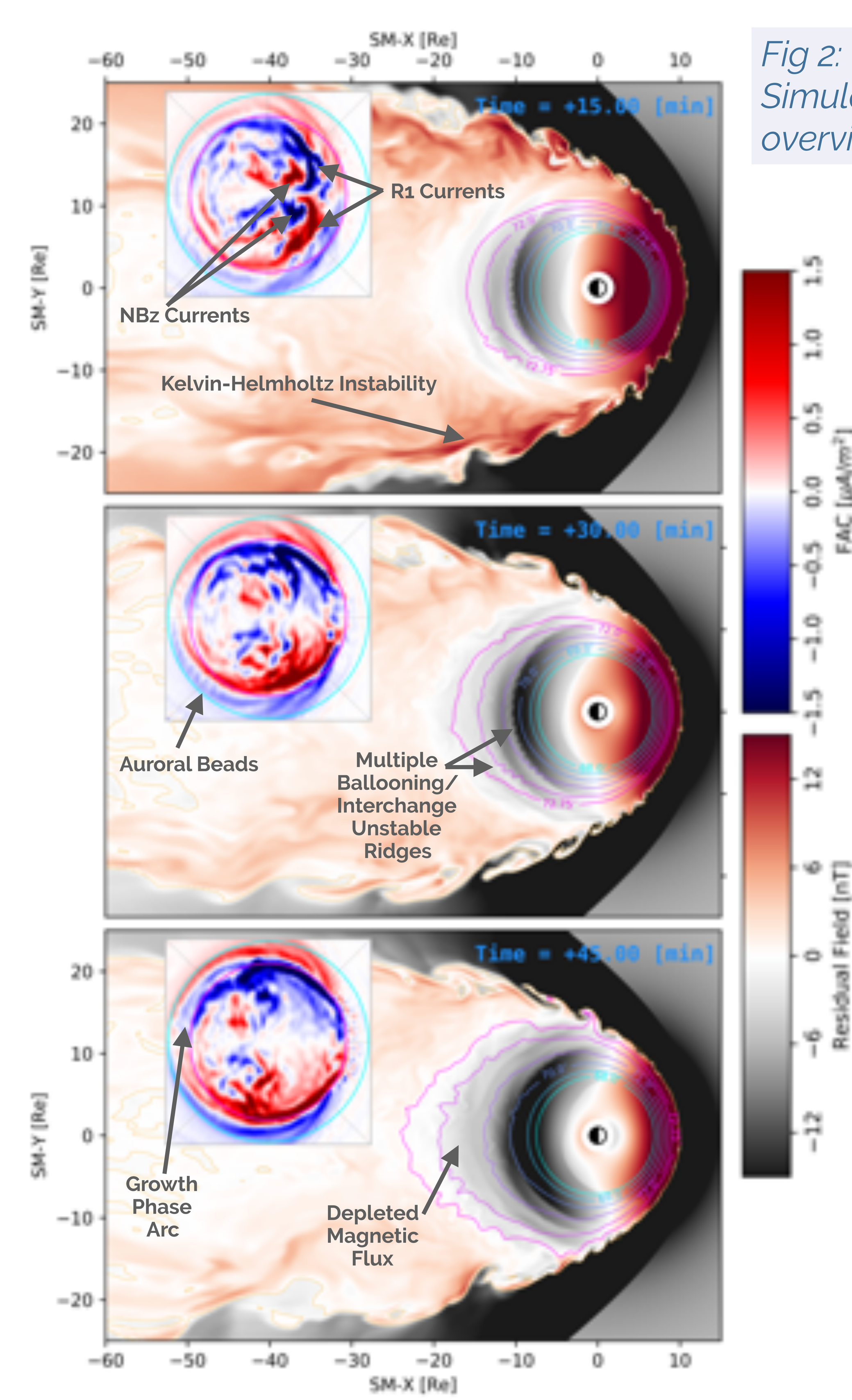


Fig 2: Simulation overview

## Flux Redistribution

Beginning at southward turn and prior to reconnection onset in the tail, thinning occurs due to nightside flux being convected sunward (Fig. 3). Flux evacuation occurs primarily through dayside reconnection, which drives earthward and azimuthal flow (Hsieh & Otto 2014), and is further amplified via convection into KH vortices on the flanks. We show, for the first time, the importance of the latter as approximately 25% of flux removed from the midtail is "scooped" into large-scale KH vortices, with the remaining flux convected towards the subsolar region.

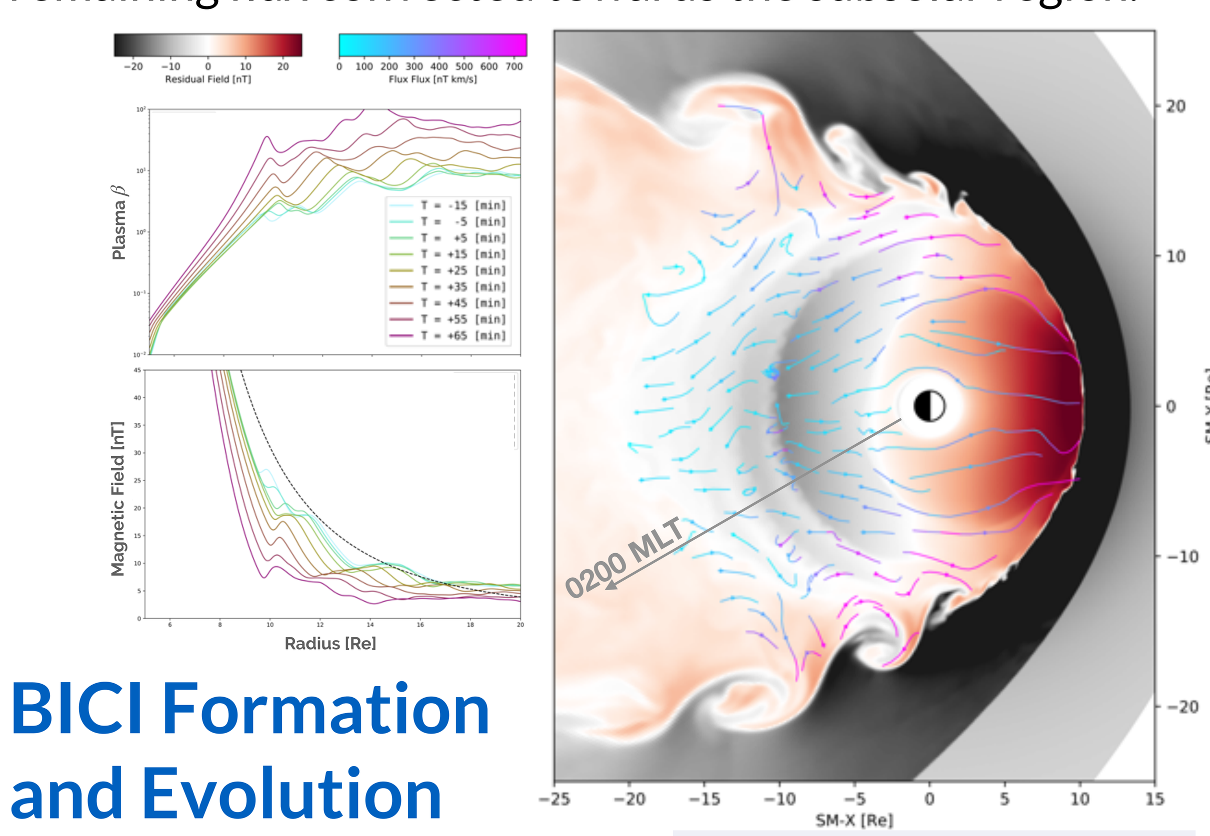


Fig 3: Flux redistribution

## BICI Formation and Evolution

Prior to the southward turn there is a marginally unstable near-Earth Bz minima (Fig. 3). During the growth phase flux evacuation creates a deep depletion further tailward which dramatically increases the plasma beta (Fig.3) and amplifies the interchange instability growth rate by 10x (Maltsev & Mingalev 2000).

Two ridges of unstable plasma form and produce saturated, sometimes detached, BICI heads which radially transport flux to erase tailward-Bz gradients. During the radial evolution of the BICI heads, radially-localized azimuthal flows transport the heads sunward due to flow from the tail diverging away from midnight. Typical azimuthal speeds are O(10 km/s).

These heads form up until BBF's from a new downtail reconnection region disrupt the inner magnetosphere.

## Auroral Beads

The evolving BICI heads create equatorial pressure gradients and flow vorticity which drive field-aligned currents into the ionosphere (Fig. 4). Tracing field lines from the magnetosphere to the ionosphere shows that the ionospheric beads are driven at the edges of the BICI heads.

The BICI heads, ~0.5 Re, in the magnetosphere result in bead-like structures with ionospheric scales ~100 km which propagate in the ionosphere at speeds O(1 km/s) in agreement with observed statistics (Nishimura+ 2016, Panov+ 2019) despite the synthetic nature of the simulation.

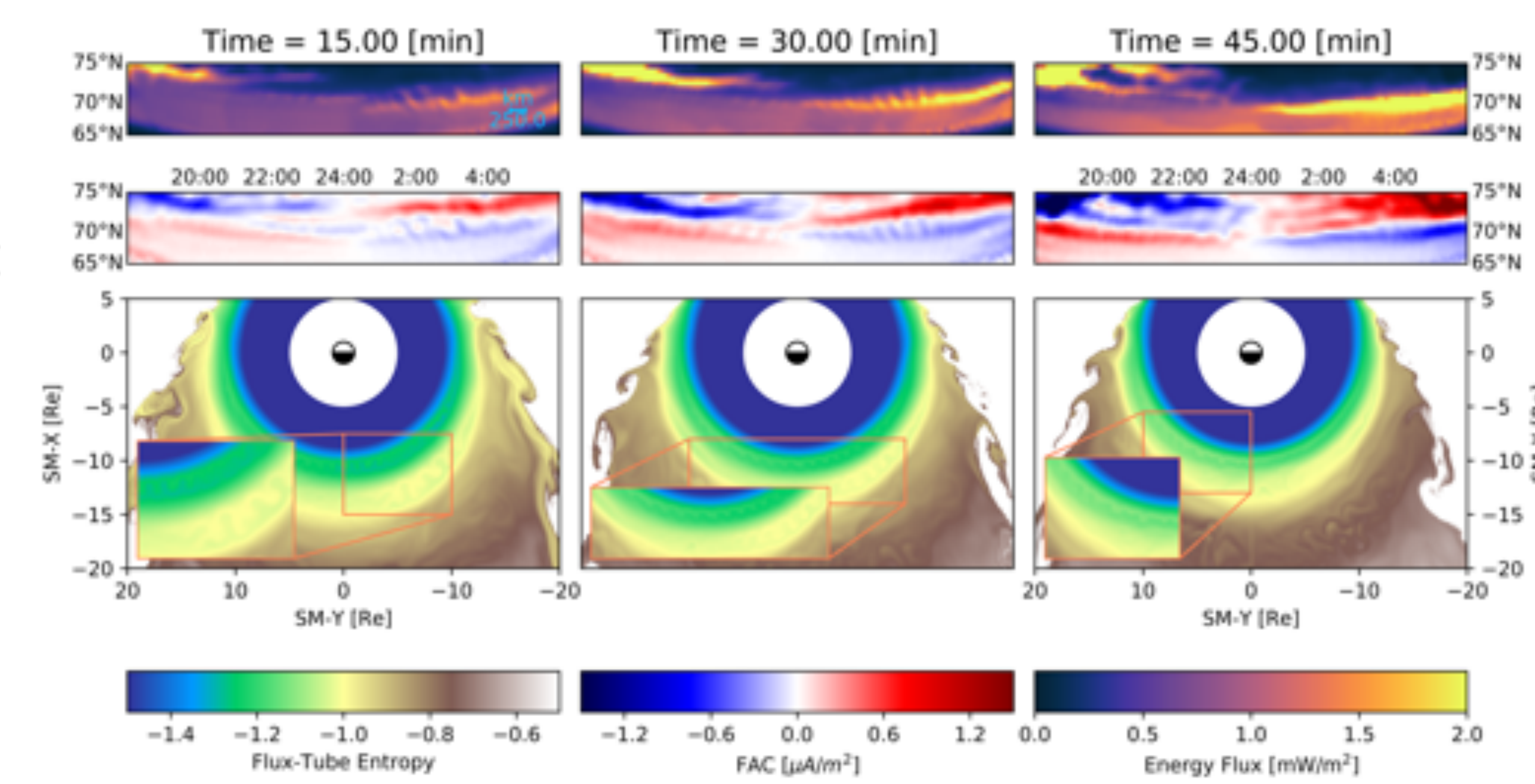


Fig 4: BICI heads and auroral beads

## Conclusions

- First global magnetosphere simulation to reveal interchange instability of a narrow flux tube entropy minimum in the near-Earth magnetotail.
- The instability is most prominent during the substorm growth phase and generates earthward entropy bubbles with embedded magnetic fronts.
- The bubbles drive mesoscale ionospheric field-aligned currents and auroral structures (beads) with properties matching observations.

### References

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