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Key Points:

- The streamer-induced thin arc is another ionospheric manifestation of a bubble
- A bubble may trigger a thin arc if it can reach the transition region
- The westward and eastward leading edges of the arc propagate azimuthally

Supporting Information:

- Readme
- Movie S1
- Movie S2
- Figure S3
- Figure S4

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RCM-E simulation of a thin arc preceded by a north-south-aligned auroral streamer

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Abstract The Time History of Events and Macroscale Interactions during Substorms (THEMIS) all-sky imager data have recently revealed a repeatable sequence that occurs during many auroral substorms, in which a newly formed thin arc is preceded by an equatorward propagating streamer. The paper aims at modeling this sequence using the Rice Convection Model–Equilibrium. The simulation shows a thin arc arising when a plasma sheet bubble with its $PV^{5/3}$ reduced to the transition region value arrives at the magnetic transition region. The modeled thin arc consists of two parts: the one east of the streamer is the result of the bubble pushing high $PV^{5/3}$ flux tubes ahead of it, strengthening the upward region 2 current, and the one west of the streamer is associated with westward drifting bubble particles, sliding along the transition region. The model predicts that (1) the westward and eastward leading edges of the thin arc propagate azimuthally at a speed of ~ 0.5 – 2.7 km/s and (2) the streamer-induced thin arc is accompanied by classic signatures of bubble injections.

1. Introduction

Two scenarios have dominated substorm arguments for decades, i.e., the outside-in model [e.g., Hones, 1977] and the inside-out model [e.g., Lui *et al.*, 1992]. With the aid of unprecedented high-spatial- and temporal-resolution auroral data provided by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) all-sky imager (ASI) arrays, a revised auroral sequence has been proposed [Nishimura *et al.*, 2010, 2011; Lyons *et al.*, 2010; Mende *et al.*, 2011]. They suggest that a substantial fraction of auroral breakups occur on a bright thin arc that is preceded by an equatorward moving auroral streamer that originated from a poleward boundary intensification (PBI). Compared with the outside-in and inside-out models, the new model (referred as Nishimura–Lyons model hereafter) has twofold significance. First, it suggests that bursty bulk flows play an important role even before a substorm onset. The growth phase is no longer viewed as a quiescent state of the magnetotail. Prior to a substorm onset, earthward bursty flows are embedded in the plasma sheet. Some of these flows can give rise to a pre-onset arc or brighten a preexisting arc, and some may trigger poleward expansion on a thin arc [Nishimura *et al.*, 2011; Mende *et al.*, 2011]. Second, it suggests that equatorward moving streamers originate from PBIs. There is an evidence that the source of earthward bursty flows that are responsible for pre-onset arcs and/or auroral breakups may be at the open-closed boundary, i.e., the distant neutral line beyond 45 *Re* [Nishimura *et al.*, 2013].

Our previous work has demonstrated how large-scale quasi-static convection can give rise to a thin arc during a substorm growth phase in the absence of bursty flows [Yang *et al.*, 2013, referred as Paper 1 hereafter]. In this paper, we aim at exploring how an earthward bursty bulk flow (BBF) can lead to a thin arc, i.e., a subset of the Nishimura–Lyons model. It has been widely accepted that an earthward BBF is a plasma sheet bubble, which contains lower $PV^{5/3}$ than its neighbors (here P is the plasma pressure and $V = \int ds/B$ is the flux tube volume) [e.g., Pontius and Wolf, 1990; Sergeev *et al.*, 1996]. Therefore, we will model the transport of a bursty flow by applying a bubble in the midnight sector of the tailward boundary of the Rice Convection Model–Equilibrium (RCM-E).

2. RCM-E Simulation

2.1. Simulation Setup

The RCM-E couples the Rice Convection Model (RCM) with an equilibrium solver that keeps the magnetic field in force balance with model-computed pressures [Toffoletto *et al.*, 2003]. The RCM assumes that proton and electron distributions are isotropic along a magnetic field line, and particles are tracked assuming $E \times B$ and gradient/curvature drifts. No field-aligned potential drop is currently included in the model. However, we

Figure 1. Ionospheric view of (left) modified electron precipitation energy flux f_{en}^* in the units of $\text{erg}/\text{cm}^2/\text{s}$, (middle) FAC density with blue being upward and red being downward, and (right) $PV^{5/3}$ in the units of $\text{nPa}/(\text{Re}/\text{nT})^{5/3}$.

have developed a postprocessing procedure to calculate synthetic aurora on the assumption that the electron auroral energy flux (f_{en}^*) is proportional to the sum of the diffuse auroral contribution and a second term that is proportional to the upward field-aligned current (FAC) above a threshold [Yang *et al.*, 2012, equation (1)]. The high grid resolution and the initial conditions used in RCM-E are the same as in Paper 1.

We designed a three-stage idealized event. In the first stage, we simulate a 60 min long substorm-growth-phase-like interval using a 30 kV polar cap potential drop and an average $PV^{5/3}$ of $\sim 0.16 \text{ nPa}/(\text{Re}/\text{nT})^{5/3}$ on the midnight high-latitude boundary. The overall convection is deliberately designed to be weaker than that in Paper 1, so that the suggested mechanism for thin arc formation in Paper 1 does not operate. (Note that the growth-phase-arc-like synthetic aurora in the post-midnight sector seen at $T=60$ min in Movies S1 and S2 in the supporting information is associated with an upward region 2 FAC. Because of our crude way in modifying the precipitating energy flux, the synthetic aurora will be particularly bright wherever the upward FAC is substantial.) In the second stage, we apply a bubble injection through the tailward boundary for 10 min. The bubble, which is assumed to be centered at midnight, has a width of 0.5 h in local time on the boundary. $PV^{5/3}$ inside the bubble is reduced to two thirds of that in the pre-bubble injection time. The potential drop inside the bubble is set to be ~ 24 kV, significantly enhanced from ~ 4 kV for the same range of local time in the pre-injection time. In the third stage, which started at $T=70$ min, the $PV^{5/3}$ and electric potential distributions are set equal to those in the first stage. The magnetic field is reequilibrated every 5 min in the first stage and every 1 min in the second and third stages.

2.2. Results

Figure 1 shows the overview sequence of bubble injection in the ionosphere. A bright streamer first appears from the high-latitude boundary along the westward edge of the bubble. As the bubble moves earthward inside 10 Re , the region 2 FAC ahead of the bubble is enhanced (Movie S1 in the supporting information), as suggested by Yang *et al.* [2012]. The bubble does not penetrate deep inside geosynchronous orbit. Instead, when it reaches the inner edge of the plasma sheet where $PV^{5/3}$ decreases from more than 0.16 to less than

Figure 2. (left) FAC density mapped to the equatorial plane with blue (negative) being upward, (middle) $PV^{5/3}$ in the units of $\text{nPa}(\text{Re}/\text{nT})^{5/3}$, and (right) plasma pressure. The black lines are V contours every $0.02 \text{ Re}/\text{nT}$.

$0.08 \text{ nPa}(\text{Re}/\text{nT})^{5/3}$ at $7\sim 10 \text{ Re}$, the bubble tends to drift westward. Within $1\sim 2$ min, a very thin arc starts to emerge roughly at the same location in the pre-midnight sector. The full width at half maximum of the modified energy flux at magnetic local time (MLT) = 22.5 is only about 16 km at $T=01:18$. Movie S1 in the supporting information also indicates that the pre-midnight arc continues to move equatorward. A thin arc also appears in the post-midnight sector within $1\sim 2$ min, which is associated with the high $PV^{5/3}$ flux tubes pushed ahead of the eastside of the bubble.

Figure 2 shows how the upward (blue) FACs are generated in association with pressure and $PV^{5/3}$ gradients. When the bubble is traveling in the plasma sheet (Figure 2, top), earthward $E \times B$ drift is dominant. The streamer maps to the westward edge of the bubble. When it reaches the transition region, the bubble becomes more azimuthally elongated along the deformed inner edge of the plasma sheet. The arc-associated upward FAC flows just poleward of the main region 2 downward FAC in the pre-midnight sector and is related to the eastward decrease of $PV^{5/3}$. In the post-midnight sector, the arc-associated upward FAC is the enhanced region 2 FAC. It is related to the flux tubes intruding earthward with higher $PV^{5/3}$ than that the existed prior to the bubble injection time. In the plasma distribution, the increased upward FACs and the arcs are associated with the earthward (tailward) part of a local plasma pressure ridge in the post-midnight (pre-midnight) sector at $r \approx 7\sim 8 \text{ Re}$, which is induced by the bubble injection [Yang *et al.*, 2011].

Figure 3 (left) shows keogram-like plots of f_{en}^* . It is clear that (1) both the pre-midnight and post-midnight arcs form equatorward of the streamer and (2) the longitudinal extensions of both arcs are wider than the streamer; (3) both arcs move equatorward but at a much slower rate than the streamer. Figure 3 (right) shows the MLT-time map of f_{en}^* , averaged between 64° and 66° latitude, where the arc is located. It indicates that after the bubble reaches 66° latitude at $T=67$ min, the westward leading edge of the arc propagates

Figure 3. (a–c) Time-latitude map of f_{en}^* in the units of $\text{erg}/\text{cm}^2/\text{s}$ at three MLTs. (d) MLT-time map of f_{en}^* , averaged between 64° and 66° latitude.

Figure 4. (a) FAC density, (b) ionospheric $E \times B$ drift velocity, and (c) proton differential fluxes at a fixed location in the ionosphere.

westward at an average speed of ~ 2.7 km/s in the following 5 min and then at a slower speed of ~ 0.5 km/s, while the eastward leading edge of the arc propagates eastward at an average speed of ~ 0.8 km/s.

We shall pay more attention to the pre-midnight arc, since a pre-onset arc is known as more frequently observed in that sector than in the post-midnight. Figure 4 shows the FAC and bubble injection signatures at a fixed point to the west and equatorward of the streamer in the ionosphere. The FAC first exhibits a sharp peak in the downward direction before turning into an upward current. The calculated equatorward $E \times B$ velocity at the center of the bubble is ~ 500 m/s in the ionosphere, roughly consistent with the observations of Shi *et al.* [2012]. The northward drift velocity in Figure 4b is the return flow on the westward edge of the bubble at MLT = 22.5 h, which is accompanied with a strongly enhanced westward drift primarily on the equatorward edge of the bubble. The arc is also associated

Figure 5. Cartoon of a bubble injection, an auroral streamer and thin arcs.

its depletion boundary: higher-energy ions have stronger westward drift velocities, placing the westward edges of their depleted regions farther westward (Figures S4d–S4f in the supporting information). Thus, partial FACs associated with larger-energy invariant ions are shifted westward compared to smaller energy invariant ions (Figures S4a–S4c in the supporting information). Our calculation also shows that the flux tube average drift velocities for ions ($\frac{E \times B}{B^2} - \frac{P_i}{|q|n_i V B^2} B \times \nabla V$) and for electrons ($\frac{E \times B}{B^2} + \frac{P_e}{|q|n_e V B^2} B \times \nabla V$) in the ionospheric footprint of the arc are about 0.5–2.5 km/s in the westward direction and 0.5 km/s in the eastward direction, respectively, consistent with the azimuthal propagation speed of the arc in the ionosphere (Figure 3d).

Therefore, our simulation suggests that the streamer and the subsequent arc are two ionospheric manifestations of a depleted bubble. The streamer is associated with the westward edge of the bubble when it is moving earthward in the plasma sheet, while the subsequent thin arc is associated with the disruption of the $PV^{5/3}$ profile near the plasma sheet inner edge by the bubble when it arrives at the magnetic transition region. It implies that this mechanism for making a thin arc may only work under the circumstance that the bubble can reach the magnetic transition region. Theoretically, if the inertial effects, such as overshoot and bouncing, are negligible [Wolf *et al.*, 2012], only those bubbles which have their $PV^{5/3}$ in the range of transition region values or below that range can be injected at the transition region. After the earthward injection, their subsequent motion will be mainly in the azimuthal direction dominated by energy-dependent gradient/curvature drifts.

The mechanisms described in Paper 1 and in this paper have distinct differences. A thin arc appears gradually as a result of quasi-static enhanced convection in Paper 1. That mechanism probably cannot operate if the convection is not strong enough to make a highly stretched configuration of the tail magnetic field. In this paper, a thin arc forms when a bubble hits the transition region, a more transient process accompanied with particle injection signatures. A relevant peculiar feature is the rapid azimuthal propagation of the arc's leading edges, which is not seen in Paper 1. Although we intentionally modeled the streamer-arc mechanism

with typical particle injection signatures at equatorial points that map to that fixed point in the ionosphere (Figure 4c).

3. Discussion

It is widely accepted that a N-S-aligned streamer in the auroral zone is the ionospheric footprint of the westward edge of a bubble, along which upward FAC is flowing (Figure 5a) [e.g., Nakamura *et al.*, 2001]. When a bubble is traveling through the middle plasma sheet, earthward charge- and energy-independent $E \times B$ drift is dominant, making the bubble elongated roughly in the Sun-Earth direction. Thus, contributions to FACs from ions with different λ values are nearly colocated in the middle plasma sheet (Figure S3 in the supporting information). (Here the energy invariant λ is given by $W_K V^{2/3}$, where W_K is the kinetic energy.) However, when the bubble arrives at the transition region, azimuthal gradient/curvature drifts become dominant, stretching the bubble in east-west direction (Figure 5b). Because of the energy dependence of those drifts, the bubble cannot preserve the sharpness of

under a relatively weak convection interval, there is no reason to exclude the possibility that this mechanism can also make an arc under strong convection intervals.

The modeled features described in Paper 1 and in this paper also have similarities. When a thin arc forms, the FACs in both mechanisms have a double-sheet structure, with an additional region 1 sense FAC immediately poleward of the main region 2 FAC. The modeled thin arc consists of both east and west parts, with a very small gap in between and with the east part at slightly lower latitude.

This paper is a report on an initial attempt to model the streamer-arc auroral sequence. Nishimura *et al.* [2011] and Mende *et al.* [2011] have shown that a streamer may (1) intensify the brightness of a preexisting arc, (2) induce another thin arc separated from the preexisting arc, or (3) lead to an entirely new thin arc in the background without a preexisting arc. In order to keep the physical picture simple, we only modeled the third category by purposely designing a situation without a preexisting arc before the introduction of a streamer. However, future efforts will be needed to investigate whether our mechanism can also be applied to the situations that include a preexisting arc (e.g., the first and second categories). Meanwhile, we need to carry out more systematic studies in at least two areas. First, since $PV^{5/3}$ controls the injection depth of a bubble, we plan to study how the formation of the thin arc is affected by preconditioning of the background that the bubble is traveling through and by the degree of depletion inside the bubble. Second, since the gradient/curvature drifts control the deformation of the bubble in the transition region, we will also investigate the effects of plasma temperature both in the background and inside the bubble.

In addition, we need to improve our simulation of synthetic aurora by modeling FACs to a more realistic degree and including the field-aligned potential drops. For example, the arc-like auroral structures in the post-midnight and dawnside seen at $T = 60$ min in Movie S1 in the supporting information are very bright, which did not appear to be consistent with the average auroral morphology in the substorm growth phase. We believe that there are two reasons for the unrealistic bright aurora. (1) The RCM-E produces unrealistically strong and thin upward FACs in the post-midnight sector. Erickson *et al.* [1991] found that depleting the dawnside plasma sheet outer boundary, which was not done in this simulation, could thicken the upward region 2 FACs on the dawn side, which would likely result in no arc-like structure. (2) The RCM-E does not include the effects of low-energy electron component in computing the field-aligned potential drops. We expect that if we can properly include the effect of these electrons, then the dawnside upward FACs will be less likely result in field-aligned acceleration, because mirror points of low-energy electrons can easily be moved down into the atmosphere [e.g., Mende *et al.*, 2003].

We also need to include the inertial effects. It is possible that arcs are generated by inertial effects such as the Kelvin–Helmholtz instability. These effects are currently not included in the RCM-E. However, our view is that in the nightside inner plasma sheet, where flows are very subsonic during substorm growth phase, large-velocity shears result from steep gradients in $PV^{5/3}$ that impact ionosphere-magnetosphere coupling through the Vasyliunas equation. These steep gradients in $PV^{5/3}$ are the primary source of the main auroral structures that result in strong velocity shears, in which inertial effects become important through Kelvin–Helmholtz instability and auroral curls, etc. [e.g., Vogt *et al.*, 1999].

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