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Emprical and modeling constraints for the shear flow ballooning onset on March 13, 2007.

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We present an empirical and modeling constraints based on THEMIS spacecraft and ground-based data and other ancillary observations, which support a shear flow ballooning instability (SFBI) at the near-Earth plasma sheet (NEPS) as a candidate mechanism for local substorm onset at around 0508 UT on March 13, 2007. The THEMIS constellation mapped to the central Canadian sector providing good conjunction of the THEMIS satellite and ground-based facilities. Observations suggesting SFBI include a pre-breakup arc intensification roughly 1-2^o poleward of the proton aurora peak; its further dynamics manifesting ripples and vortex formation; double sheet structure of field aligned currents (FACs) matching the proton aurora band (downward FAC) and arc (upward FAC); small k_y wave number; hot and dense near-isotropic "balloon" observed by the THEMIS at onset; and magnetic field and velocity variations expected for the SFBI vortex at the central plasma sheet. Pre-onset data were utilized to initialize SFBI computer modeling which further was used for the model-to-observation comparative study of this substorm dynamics. Overall we conclude that our study supports the near-Earth SFBI mechanism for this onset.

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1. Introduction

Amongst different models of substorm onset, some treat this process as an essentially internal instability of the near-Earth plasma sheet [e.g., *Lui et al.,* 1988, 1992; *Ohtani et al.,* 1999; Erickson et al., 2000]. Along with this idea, *Lyons et al.* [2002] presented several events in which a pre-breakup arc was observed equatorward of all pre-existing growth phase arcs, suggesting that this pre-onset arc is an intrinsic feature of the inner edge of the plasma sheet (PS). These arcs intensify prior to breakups at the late stage of the magnetic field line stretching. The breakup itself is seen as explosive poleward expansion of the vortex structure [*Voronkov et al.,* 2000, 2003]. *Dobias et al.* [2004a,b] performed nonlinear analysis of the energy storage in the near-Earth PS (NEPS) during the growth phase. It was suggested that quite reasonable stretching of the inner PS, which is in agreement with observations, provides sufficient conditions for the nonlinear growth of the ballooning instability which allows to overcome quick saturation of the linear stage. The analysis suggested a multi-stage unstable process: the linear growth, quasi-linear oscillatory saturation, and, providing a sufficient energy level, further fast nonlinear growth. This multi-stage scenario turns to be in reasonable agreement with high-resolution auroral optical observations of breakups with near-linear arc intensity growth and vortex formation, its saturation for pseudo-breakups, and explosive breakup behavior preceding full onset [*Voronkov et al.,* 2000; 2003; 2004]. Ballooning mode can be seeded and greatly enhanced by convection shears frequently observed in association with arcs [*Bristow et al.,* 2001; *Liang et al.,* 2004; *Voronkov et al.,* 1999] providing a so-called shear flow ballooning instability (SFBI). Ballooning type modes were seen *in situ* in some events [e.g., *Chen* *et al.,* 2003; *Kozelova et al.,* 2006] but a comprehensive analysis of satellite and ground-based observations of ballooning associated processes both in the magnetosphere and ionosphere has never been performed. THEMIS mission [*Angelopoulos,* 2008] opened a unique opportunity for such a study.

2. Data

In this paper we study a localized substorm which occurred on March 13, 2007 with onset around 0508UT over central Canada and registered by the THEMIS Ground Based Observatories [*Mende et al.,* 2008; *Donovan et al.,* 2006]. This mission supports a white light All Sky Imager [*Harris et al.,* 2008] and ground magnetometers [*Russell et al.,* 2008]. Other observations from the Canadian array of filter cameras, such as high resolution ASI, at the Athabasca University Observatory [*Sakaguchi et al.,* 2007] hosted at the Athabasca University Observatory, and the Saskatoon SuperDARN radar [*Greenwald et al.,* 1995] are also utilized. The THEMIS satellites (probes) mapped over the region of onset and measured the magnetic field [*Auster et al.,* 2008] on all probes. As the instruments were being turned on, shortly after launch, data from the electrostatic analyzer (ESA) on one of the probes, THEMIS-A, was available at the time [*McFadden et al.,* 2008]. The fact that THEMIS data was available for this, very early right-after-launch, interval and it far exceeded anything available in the past, it provided the very comprehensive observations in support of ballooning modes simultaneously from ground and space.

3. Observations

The growth phase before onset at 0508 UT was rather quiet which allows us to map the THEMIS spacecraft (SC) to the ground. Indeed, the comparison of the magnetic field obtained by SC with T89 [*Tsyganenko,* 1989] revealed a reasonably good agreement [*Connors et al.,* 2008; *Donovan et al.,* 2008] which allows us to trace the magnetic field lines during the growth phase up to onset.

Onset at 0508 UT was registered nearly simultaneously by the GBO and THEMIS satellites. Below, we simply list most important features supporting the NEPS SFBI constraint used for modeling. More detailed observations are given in [*Connors et al.,* 2008; *Donovan et al.,* 2008].

From the ground, onset was seen as a robust equator-most auroral breakup with clear local signatures in magnetic data. This allows us to treat it as a NEPS breakup launching a local substorm. An auroral intensification started at 0508 UT as an arc brightening around 65 MLAT and -45 MLONG (65, -45) (Figures 1a, 4a) roughly 100-200 km (depending on the longitude) poleward of the equatorward boundary of the auroral zone matched by the proton aurora band (Figure 1b). Figure 1b also illustrates the magnetic perturbation vectors from the surrounding stations.

Original brightening occurred within only a few degrees of longitude but in 8 seconds expanded to more than 30 deg. At this time, robust magnetic bays started at the breakup region indicating westward current associated with the arc. Stations positioned equatorward of the arc detected positive X-component magnetic bays suggesting the eastward electrojet, which is in agreement with the Z-component behavior [*Connors et al.,* 2008; *Donovan et al.,* 2008]. Overall picture from the optical and magnetic GBOs can be interpreted as a local breakup of the equator-most arc, which was associated with a double sheet field aligned current (FAC) structure: upward at the arc and downward around the proton aurora band. The latitudinal profile of this structure is shown in Figure 2: the proton aurora profile and position of the arc at the Athabasca meridian and electrojet directions with respect to the proton aurora peak.

The breakup arc intensified at 0508 UT (Figure 4A) and rapidly manifested arc-aligned ripples (Figure 4b) which further developed into the well defined vortical structure (Figure 4c). The greatest auroral vortex developed during this substorm is shown in Figure 4d. No significant perturbations were seen poleward and equatorward of this vortex suggesting the local substorm (in some studies referenced as "pseudo-breakup") nature of the event. Note that the whole onset and expansion phase occurred within the time interval of roughly two minutes.

THEMIS FGM showed changes (reduction of Bx, and an up-and-down variation of By) that started at onset and continued during the entire substorm. More abrupt variations were seen by SC E (most duskward) but all satellites registered this effect (Figure 3a). Providing that satellites covered a large meridional sector in the pre-midnight NEPS, this near-synchronous dynamics is very reminiscent of the small k_y ballooning vortex developing earthward of the THEMIS constellation. This is also consistent with near isotropic ion temperature increase and density growth (Figure 3b), suggesting that the observed magnetic variations may be due to a "dense and hot balloon" propagating or expanding tailward and duskward. Finally, it agrees with the growth of plasma velocity which is expected at the ballooning vortex.

Overall, these spacecraft observations along with ripples along the arc, double-sheet (sheared) FAC structure, and early saturation of this local substorm suggest that the

SFBI can be a dominant driver of this local substorm. In the next section, the modeling of the SFBI for this substorm is performed.

4. Modeling and observational constraints

In order to initialize the SFBI simulations, the following observations described in section 3 were utilized.

1. Relative positions of the proton aurora and arc (Figure 2) were projected to the equatorial PS using the T89 model just before the breakup.

2. The current shear was assumed to be associated with the convective flow shear. The nearest to the arc aligned direction (beam 1 os the Saskatoon SuperDARN radar) registered an enhanced flow of roughly 300 m/s (200 m/s if projected to the arc). This magnitude was projected to the equatorial plane and taken for the simulations. The initial azimuthal wavelength of the small radial perturbation and the width of the shear are taken from the arc observations as projected to the central PS using T89 as well. Note that the ratio $2\pi\delta/\lambda \sim 0.5$ in the ionosphere projected to the equatorial plane is roughly 1, which corresponds to the high growth rate of the SFBI [*Voronkov et al.,* 1997]

3. Plasma density and temperature in the ballooning region was taken from the THEMIS ESA data at the time when satellites detected upcoming hot and dense region at the beginning of onset. Plasma was assumed isotropic as follows from this data. Note that the observed temperature of ions larger than 20 keV is in agreement with proton energy above typical H_β bands similar to one in this case. Also, the electron temperature was around 10 keV which is in agreement to observations of electron energies above breakup arcs.

With these assumptions, the profiles of plasma pressure and velocity shear in the equatorial plane were constructed. The logistics and numerical code run for this modeling is the same as described in [*Voronkov et al.,* 2000] and we can refer this work for more detailed descriptions.

The auroral breakup images and modeled vorticities are compared in Figure 4 for the following major stages of the instability: the breakup arc and ripples (0508.00, 0508.18, Figures 4a, b, e, and f, respectively), vortex formation and growth (0509.12, Figures 4c,g), and large scale nonlinear vortex which reached the greatest expansion at roughly 0510 (Figures 4d,h).

The comparison of the integral auroral intensity (Figure 4i) and maximum of vorticity $\nabla \times V$ (Figure 4j) reveals reasonable agreement in the temporal evolution of the instability. Figure 4i shows the stages of the auroral intensity dynamics, as follows. Initial arc brightening and ripples at 0505-0508 went into faster quasi-linear hybrid SFBI vortex growth which saturated around 0509. The further vortex dynamics is purely nonlinear with saturation at 0510. At the same time, as shown in Figure 4j, the model reproduce very similar stages of the instability with the time scale which is close to observed.

Overall, we can assert that the modeled SFBI reproduces all observable stages of the auroral breakup and is in agreement with the spatial and temporal scales of the auroral vortex.

5. Conclusions

Vast THEMIS spacecraft and GBO facilities allowed us to test the shear flow ballooning model as a possible candidate for producing the near-Earth breakup. Observed data was used to initialize the numerical code. These include a position of the auroral arc poleward of the proton aurora maximum, proton aurora profile, width of the arc, wavelength of the arc-aligned wave, current structure seen by the GBO magnetometers, and plasma parameters observed by the THEMIS spacecraft. Features supporting the SFBI as a mechanism responsible for onset and expansion phase of this local substorm can be summarized as follows.

1. Narrow equator-most arc intensified at the poleward slope of the proton aurora.

2. Magnetic observations suggest a double sheet structure of the field aligned currents (Upward associated with the arc and downward at the proton aurora band), suggesting a shear.

3. At onset, the THEMIS spacecraft observed quite large wavelength of the initial perturbation, suggesting rather the ballooning than reconnection model for this onset.

4. At onset, THEMIS detected hot and dense "balloon" expanding tailward and duskward.

5. Both observations and simulations revealed similar stages of the instability, on the same time scale of a few minutes and similar spatial scale. These stages included arc wave-like perturbations, formation of the vortex structure and its poleward expansion and temporal saturation at the quasi-linear stage, and further fast nonlinear vortex growth.

6. As a final remark, we would like to emphasize that the considered event was rather a small and local substorm which did not affect regions poleward of the vortex and apparently did not propagate far enough to the mid-tail plasma sheet where the reconnection region might be expected. Nevertheless, we assert that for such near-Earth substorms,

the shear flow ballooning instability is a very reliable mechanism which manifested all features observed by THEMIS.

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