Are north-south aligned auroral structures the ionospheric manifestation of bursty bulk flows?

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Short title: ARE NORTH-SOUTH STRUCTURES BBFS?

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Abstract. Bursty Bulk Flow (BBF) events are an important means of plasma transport in the Earth's magnetotail during substorms. Despite the fact that several studies have been performed using in-situ plasma and field data to determine the characteristics and properties of BBFs, remarkably little attention has been paid to the question of whether or not these events also manifest themselves in the auroral ionosphere. In this paper, we present observations from the Viking UV imager, and the Los Alamos National Laboratory geosynchronous energetic particle detectors that strongly suggest that the north-south aligned structures formed impulsively and repetitively during the expansion phase of substorms may be the ionospheric manifestation of BBFs.

Introduction

Bursty Bulk Flows (BBFs) are transient, high-speed (> 400 km/s but can attain speeds of > 2000 km/s [*Fairfield et al.*, 1998]), azimuthally narrow plasma flow channels that are frequently observed to occur in the Earth's plasma sheet [*Baumjohann et al.*, 1990; *Angelopoulos et al.*, 1992]. These highly structured events display a wide variety of characteristics but typically last for ~ 10 minutes, are comprised of individual micro-bursts that occur on a time-scale of ~ 1 minute, are well correlated with ion heating and localized magnetic field dipolarizations, and are accompanied by a localized decrease in the ion density and pressure [*Sergeev et al.*, 1996]. Even though these high-speed flows are active for only a small fraction of the time, they are an important means of Earthward transport in the near Earth plasma sheet – even if BBFs operate for as little as 10% of the time, they can be responsible for as much as 80-100% of the Earthward transport of particles, energy, and magnetic flux [*Angelopoulos*, 1996].

Although they can occur under all geomagnetic disturbance levels, it is well established that BBFs occur most frequently during intervals of enhanced auroral electrojet activity (as measured by the *AE* index). A superposed epoch analysis study recently undertaken by [*Angelopoulos*, 1996], showed that BBFs tend to occur during the expansion phase of magnetospheric substorms. And *Hsu and McPherron* [1996] have established that a high degree of correlation exists between the occurrence of BBFs and Pi2 pulsations.

Despite the fact that several studies have been performed to characterize the *in-situ* properties of BBFs in the magnetotail, relatively little attention has been paid to the question of whether these events produce observable effects in the auroral ionosphere. In this paper we propose that north-south aligned auroral structures created during the expansion and early recovery phases of substorms are most likely the auroral manifestation of BBFs.

Observations

The evolution of north-south aligned auroral structures on a global scale and their role in the substorm process has been described using the Viking UV imager data [*Rostoker et al.*, 1987; *Henderson et al.*, 1994] and with an array of ground-based all-sky imagers [*Nakamura et al.*,

1993]. In this study, we present Viking auroral images for 3 different substorms which more clearly illustrate the manner in which these structures develop.

In Figure 1a, we show a sequence of observations of the northern auroral distribution acquired with the Viking UV imager on October 15, 1986. The eccentric dipole coordinate system is superposed on the first and last images.

The first frame of Figure 1a, taken at 1151:48 UT, shows an already well-developed auroral substorm bulge in the pre-midnight sector. As the auroral distribution evolves over the next several minutes, the arc at the poleward edge of the bulge brightens substantially. Then, between 1156:45 and 1205:40 UT, the poleward arc 'bifurcates' and a spectacular array of north-south aligned auroral forms are rapidly ejected equatorward into the bulge from the poleward edge. An analysis of the arc locations between 1156:45 and 1158:44 UT shows that the 'bifurcation' of the poleward arc system occurred as a result of a new arc forming poleward of the pre-existing one. As time progresses, the lower arc sinks equatorward into the bulge and becomes quite dim and distorted until by 1204:41 UT it has completely dissolved into the surrounding diffuse emissions.

Another example showing the development of north-south aligned auroral forms during substorms is presented in Figure 1b. This sequence of 12 images was acquired by Viking on December 1, 1986. In this case, multiple bright north-south aligned forms are ejected equatorward into the bulge from different locations along the poleward arc system. Note that the north-south aligned forms generated during this event tend to accumulate into bright diffuse patches at the equatorward edge of the bulge. The westernmost of these is at times even brighter than the surge head (located at approximately 72° MLAT on the 21 MLT meridian).

In Figure 2, we present a third example that was acquired on September 20, 1986. In this case, a single north-south aligned auroral form is ejected equatorward into the bulge following a brightening of the poleward-most arc system. The brightening began at 1839:40 UT and the north-south form can be seen first in the image taken at 1841:59 UT (see arrows on figure).

The image taken at 1842:58 UT is shown again in figure 3a in a projected polar coordinate system in which noon is at the top and dusk is at the left of the figure (0 MLT is drawn as a dashed line). Plotted on-top of this figure are the estimated footprint locations of geosynchronous satellites 1982-019, 1984-129, and 1984-037 which were all equipped with Los Alamos National Laboratory energetic particle instruments. As the north-south aligned structure descends toward

the equatorward regions of the bulge, it comes very close to the footprint of the 1984-037 spacecraft. Shown in figure 3b are; the differential fluxes of energetic electrons at 1984-037 and 1984-129, differential fluxes of protons at 1984-037, a frequency versus time spectrogram of (the envelope of) H-component pulsations at Kakioka, and the AU and AL indices. The vertical line is drawn at 1844 UT which is coincident with the arrival of the north-south structure in the equatorward part of the bulge. From the electron data at 1984-037 and 1984-129, we can see that the substorm produced an injection of particles as evidenced by the appearance of a delayed dispersed population at 1984-129 and an even more delayed drift echo observed at 1984-037. The highly structured dispersionless activity (in the electrons) at 1984-037 (which was situated within the injection region) is more difficult to interpret since it can result from real dispersionless particle injections or local magnetic field perturbations or a combination of the two. This type of long duration, highly structured injection is not typical but has been associated with large, highly localized ionospheric flows [*Morelli et al.*, 1993] and may be the characteristic signature of a BBF actually reaching geosynchronous orbit instead of being diverted at higher values of L.

The primary thing to note from figure 3b is the clear dispersionless dip in the electron fluxes at 1984-037 observed in all energy channels starting at 1844 UT which was accompanied by a small increase in the lowest energy proton fluxes. This behavior indicates that 1984-037 suddenly become temporarily enveloped in a different plasma environment because either; a) changes in the magnetic field changed the flux tube that the spacecraft was on, b) a different plasma population arrived at the spacecraft independent of field perturbations, or c) both of these things occurred. At the same time, we see associated with this feature, the onset of Pi2 pulsations at Kakioka. Thus, the arrival of the north-south aligned structure at the equatorward edge of the bulge appears to be coincident with the generation of Pi2 pulsations together with a change in the plasma population at geosynchronous orbit.

Discussion and Conclusions

We have presented Viking auroral imager data for 3 separate substorms which clearly illustrate the manner in which north-south aligned auroral forms can develop. The specific way in which these individual events relate to the global expansion of the auroral substorm bulge has been described in detail by *Nakamura et al.* [1993] and *Henderson et al.* [1994]. Typically, the

auroral expansion phase is comprised of a set of more elemental episodes of activity that recur at intervals of ≈5-15 minutes. Many of these events are associated with the creation of new arcs at the poleward edge of the bulge together with a rapid ejection of north-south aligned forms equatorward which evolve into diffuse pulsating auroral forms. Such episodes of activity are an important means by which the poleward expansion of the bulge (i.e. the envelope of auroral activity) occurs.

In the present study, we have found an association between the development of an isolated north-south aligned structure with the occurrence of Pi2 pulsations and dispersionless energetic particle fluctuations at geosynchronous orbit which are associated with either magnetic field perturbations (could be tail stretching and/or azimuthal shearing) and/or the arrival of a different plasma population at geosynchronous orbit.

All of this phenomenology taken together shows a remarkable similarity to the phenomenology associated with bursty bulk flows in the tail. Both north-south aligned structures and BBFs; are azimuthally narrow entities, are apparently related to Pi2 pulsations, and form at dynamic intensifications of substorm activity during the expansion and early recovery phases. North-south structures move rapidly equatorward in response to large-scale activations of the poleward arc system and BBFs move rapidly earthward in response to intervals of enhanced activity in the tail. In addition, theoretical analyses of flow channels in the tail indicate that they *should* be observable in the ionosphere at some stage because they are expected to produce field-aligned currents at their edges (e.g. *Chen and Wolf* [1993], *Sergeev et al.* [1996], *Birn et al.* [1998]). Given the alignment of north-south forms in the bulge and of BBFs in the tail together with all the other circumstantial evidence presented here and elsewhere, we propose that north-south aligned forms are very likely the ionospheric manifestation of BBFs.

A likely mechanism for the generation of BBFs in the tail has been advanced by *Chen and Wolf* [1993] who proposed that they are small-scale earthward moving plasma-depleted flux tubes or "bubbles". When such a flux tube is created it has lower particle pressure in the equatorial plane than the surrounding ambient flux tubes and in order to maintain pressure balance it has a stronger equatorial magnetic field. The bubble will charge up at its edges because the westward gradient and curvature drifts are weaker inside the bubble than they are outside. An enhanced dawn to dusk electric field therefore develops across the bubble and it gets accelerated rapidly

toward the earth. Since the foot of the flux tube in the ionosphere cannot keep up with the high equatorial speed, the flux tube will develop a rounder shape as it approaches the earth. This dipolarization results in the deceleration of the bubble and the diversion of more cross-tail current into the ionosphere at its edges. The identification of such objects in the tail in association with high-speed flows in the (expanded) plasma sheet has been confirmed by *Sergeev et al.* [1996] using ISEE1/2 data. They found bubble-like structures with cross-tail scale sizes on the order of 1-3 R_E. Here, we propose that the north-south aligned auroral forms are the ionospheric manifestation of this process (particularly during the late expansion and early recovery phases when the bulge is expanded).

A possible conflict with these observations and the modern version of the NENL model [*Birn et al.*, 1998] is that the expansion of the bulge in that model is expected to be caused by the tailward propagation of magnetic flux pile-up via the braking and diversion of fast flows in the near earth region. However, we see the north-south forms being ejected *into* the bulge in association with poleward expansion as opposed to seeing only a poleward expansion as one might expect from the model. A possible resolution to this problem may be that the north-south forms in the ionosphere map to bubbles in the tail and both are due to small-scale patchy reconnection, while the flow braking and diversion described by *Birn et al.* results from flow channels that have substantially larger cross-tail dimensions. However, if the NENL model is correct, it is still puzzling why no significant auroral emissions are typically observed poleward of the sharp poleward edge of the bulge (in any phase of the substorm).

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Figure Captions

Figure 1. Images of the Earth's northern auroral distribution acquired by the Viking ultraviolet auroral imager during substorms that occurred on: a) October 15, 1986, and b) December 1, 1986. The meridian lines are drawn every hour of MLT with the 0 MLT meridian shown as a dashed line and the magnetic latitude lines are drawn every 5°.

Figure 2. Images of the Earth's northern auroral distribution acquired by the Viking ultraviolet auroral imager during a substorm that occurred on September 20, 1986. Eccentric dipole grids are the same as in figure 1.

Figure 3. a) Footprint locations of the LANL spacecraft relative to the auroral distribution at 1842:58 UT. b) Energetic electron fluxes at 1984-037 and 1984-129; energetic proton fluxes at 1984-037; Kakioka H-component frequency versus time spectrogram; AU and AL indices.

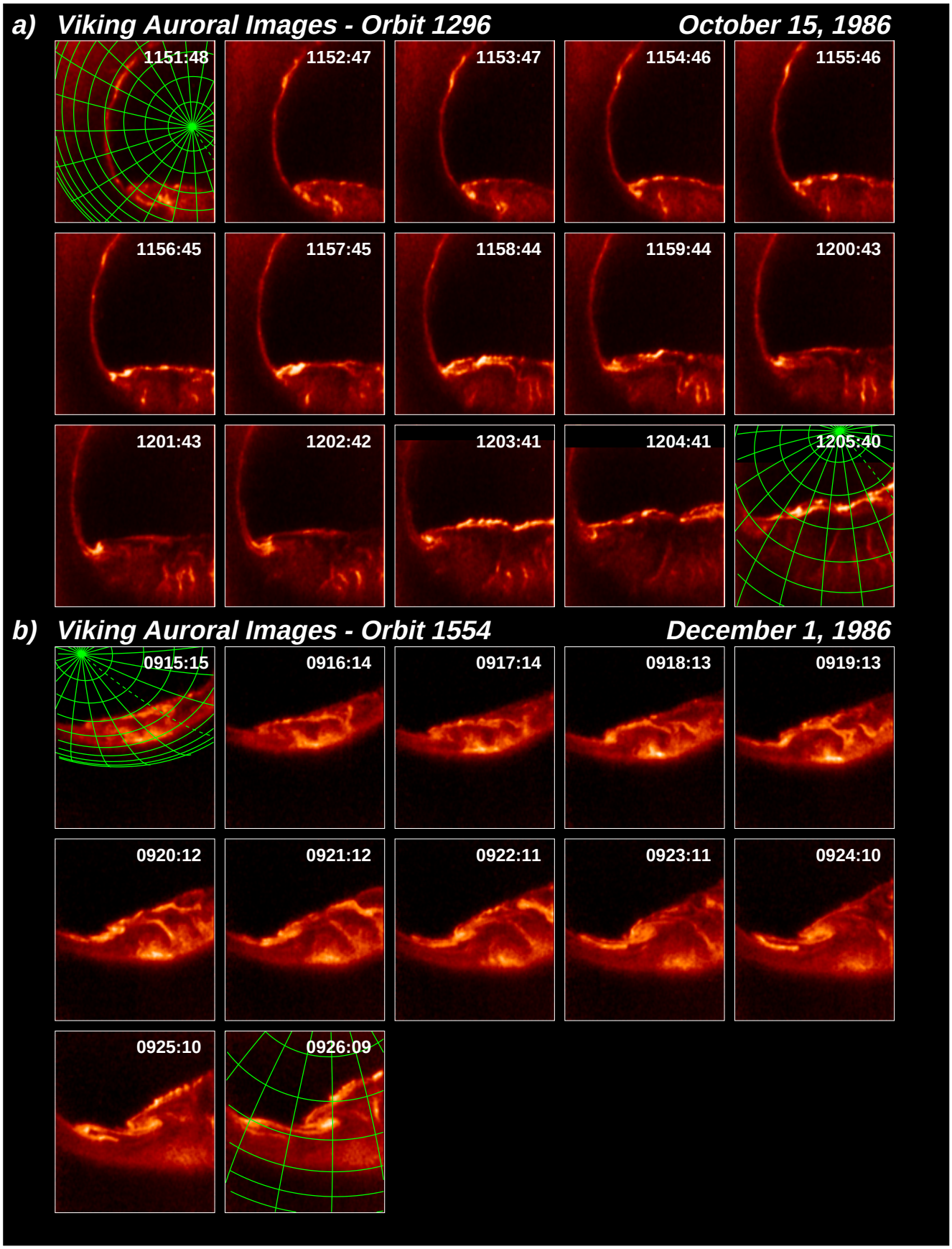
a) Viking Auroral Images - Orbit 1296
October 15, 1986
1151:48
1152:47
1153:47
1154:46
1155:46
1156:45
1157:45
1158:44
1159:44
1200:43
1201:43
1202:42
1203:41
1204:41
1205:40
b) Viking Auroral Images - Orbit 1554
December 1, 1986
0915:15
0916:14
0917:14
0918:13
0919:13
0920:12
0921:12
0922:11
0923:11
0924:10
0925:10
0926:09

Figure 1

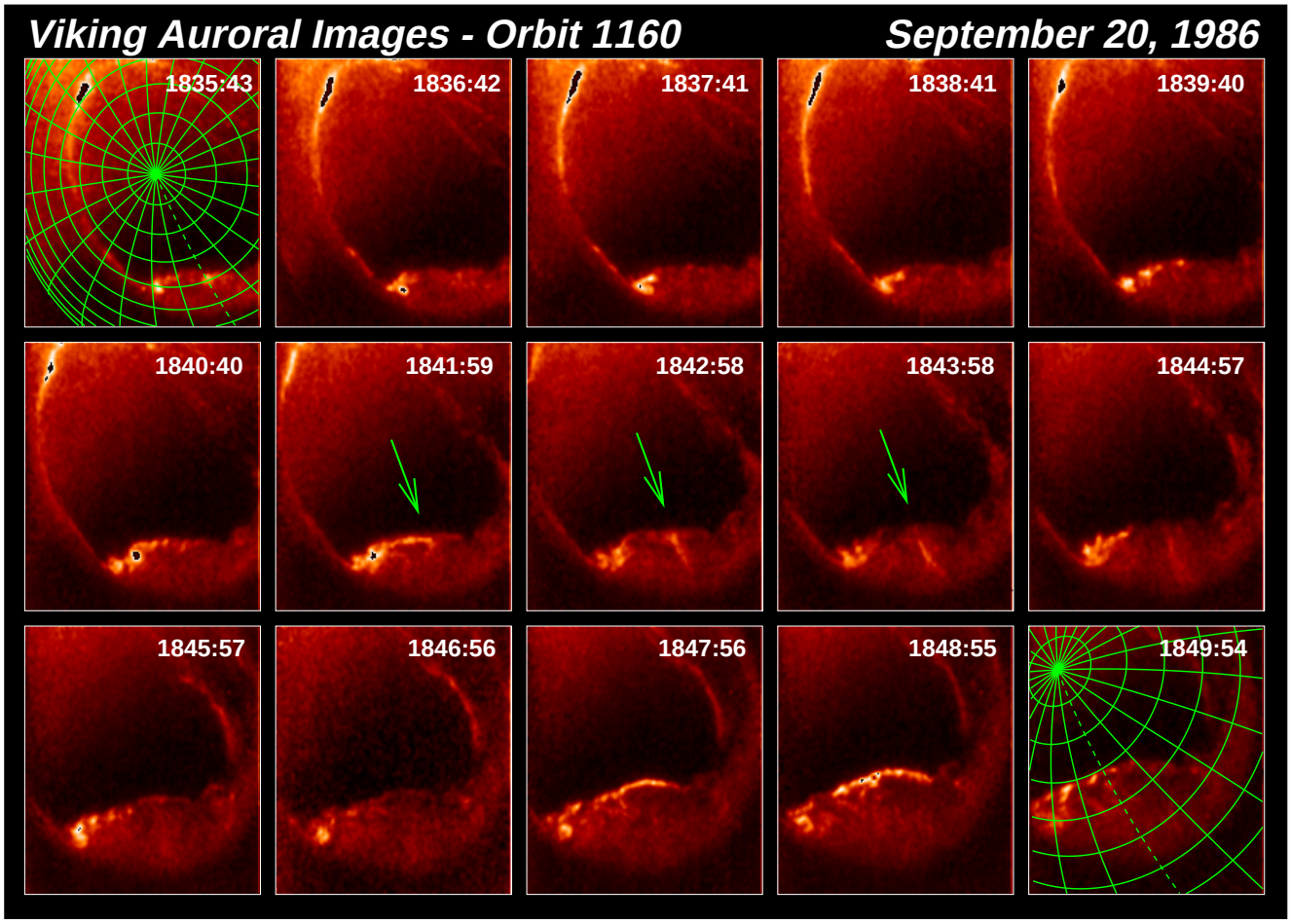
Viking Auroral Images - Orbit 1160
September 20, 1986
1835:43
1836:42
1837:41
1838:41
1839:40
1840:40
1841:59
1842:58
1843:58
1844:57
1845:57
1846:56
1847:56
1848:55
1849:54

Figure 2

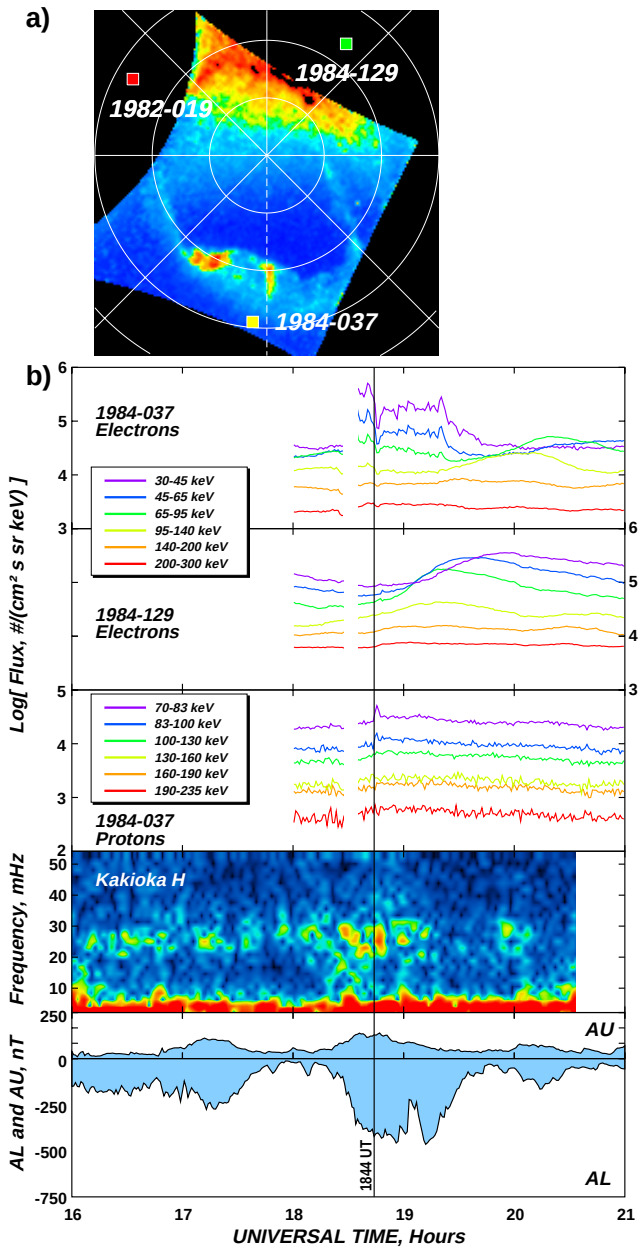
a)
1984-129
1982-019
1984-037
b)
1984-037
Electrons
30-45 keV
45-65 keV
65-95 keV
95-140 keV
140-200 keV
200-300 keV
1984-129
Electrons
70-83 keV
83-100 keV
100-130 keV
130-160 keV
160-190 keV
190-235 keV
1984-037
Protons
Kakioka H
AU
AL
1844 UT
Log[Flux, #/(cm² s sr keV)]
Frequency, mHz
AL and AU, nT
UNIVERSAL TIME, Hours

Figure 3